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An Information Ontology for the Process Algebra Model of Non-Relativistic Quantum Mechanics

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Abstract: The Process Algebra model has been shown to provide an alternative mathematical framework for non-relativistic quantum mechanics (NRQM). It reproduces the wave functions of non-relativistic quantum mechanics to a high degree of accuracy. It posits a fundamental level of finite, discrete events upon which the usual entities of NRQM supervene. It has been suggested that the Process Algebra model provides a true completion of NRQM, free of divergences and paradoxes, with causally local information propagation, contextuality and realism. Arguments in support of these claims have been mathematical. Missing has been an ontology of this fundamental level from which the formalism naturally emerges. In this paper it is argued that information and information flow provides this ontology. Higher level constructs such as energy, momentum, mass, spacetime, are all emergent from this fundamental level.

Keywords: information; process; process algebra; causal tapestry; process tapestry; transience; contextuality; emergence

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1. Introduction

The Process Algebra model of non-relativistic quantum mechanics (NRQM) has been proposed as a complete theory of NRQM [1-3]. It is a causally local, contextual, realist theory which claims to reproduce the wave functions of NRQM with a high degree of accuracy. It further claims to do so without the usual paradoxes and conceptual obfuscation [1,2]. Some tentative extensions to the relativistic regime, quantum electrodynamics, have also been carried out [4,5]. The model proposes a discrete ontology of fundamental entities upon which the usual quantum entities supervene. Being discrete, it is divergence free. An outline of the model is presented in the appendix, but for technical details one should examine the original literature [1-5]. The argument in support of the Process Algebra model is primarily mathematical. The goal of this paper is to present an ontology for the model which is more physical.

Following the seminal work of von Neuman, NRQM has been formulated using the language of self adjoint operators on Hilbert spaces [6]. The Process Algebra model utilizes the fact that the Hilbert space of NRQM is a reproducing kernel Hilbert space [7]. Given a reproducing kernel Hilbert space H(X) with base space X, there exists a discrete subspace Y of X (sampling subspace), and a Hilbert space H(Y) on Y, such that each function in H(Y) can be lifted to a function in H(X) via an interpolation procedure. Interpolation means that if $\Psi(z)$ is a function in H(X), then for each y $\in$ Y there exists an interpolation function $\Psi_y(z)$ on H(X) such that $\Psi(z) = \Sigma_{y \in Y} \Psi(y)\Psi_y(z)$. There are usually are infinity of these sampling subspaces. If the subspace Y has the form of a regular lattice the interpolation functions may be taken to be sinc functions [7]. If the subspace has an irregular structure with sufficient density, Fechtinger-Grochenik interpolation theory may be used [7].

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Interpolation does not reproduce all functions on H(X) but rather a more limited set of band-limited functions, that is, functions whose Fourier transform is limited to a bounded set. This particular feature has been used in other interpolation based approaches to quantum field theory [8] to ensure the existence of an ultraviolet cutoff.

All of the necessary physics can be defined on the sampling subspace Y and interpolation may be used to recover all of the physics on the larger space X. One can then think of the sampling space Y as the "real" space, and the space X as an emergent (or even illusory) version. In the case that the NRQM system is in a superposition of states $\{\mathbf{\Psi}_n\}$, it can be shown that a distinct sampling subspace Y_n may be associated with each process $\mathbf{P}_n$ generating the state $\mathbf{\Psi}_n$. In this way every sampling point in the sampling subspace Y is associated with one, and only one, quantum state. Superpositions in the Process Algebra model occur at the level of the wave function, not at the level of the sampling points, so that there is never any ontological confusion. Moreover, the probability associated with the wave function of NRQM via the Born rule is also an emergent feature, arising from interactions among processes. The Process Algebra model appears to be a true completion of NRQM, possessing a form of (causally) local realism, all the while behaving more or less exactly as does NRQM. The arguments are mathematically sound but to make the model physically plausible an ontology is needed, to which we turn to complex systems theory for inspiration.

2. Physics from the Top Up

During the past century, physics has learned that the fundamental constituents of matter possess three characteristics that clearly separate them from the classical Newtonian ontology. First of all, these fundamental constituents are transient. Some are transient by virtue of having a short half life, so that they readily decay into other fundamental constituents. Although stable, others are transient by virtue of being able to transform into other fundamental constituents through interactions. The fundamental constituents in the Newtonian ontology were, however, considered to be eternal. Second, these fundamental constituents are subject to contextuality. It appears to be impossible to assign to a fundamental constituent a definite set of properties associated with a set of non-commuting measurements. Each ordering of successive measurements serves as a distinct context, and the measurement depends upon the context. In the Newtonian ontology such order effects are absent, often referred to as observer independence, so that properties can be attributed to the fundamental constituent. Third, some if not all, of the fundamental constituents are emergent. For example, hadrons are formed as complexes of interacting quarks, acquiring properties distinct from those of its constituent quarks. Most obviously, quarks are never free, whereas hadrons can frequently be found free. Even a basic phenomenon, a bubble chamber track, was shown decades ago to be an emergent phenomenon [9]. As noted by Anderson [10], emergence abounds and there have been a few attempts at an emergent theory of fundamental phenomena [11,12].

The famed biophysicist Robert Rosen expressed the opinion that physics had much to learn from the study of complex adaptive systems, in particular living organisms [13]. They too possess all three attributes described above: they are transient, they are contextual, and they are emergent. It is possible that insight into fundamental physics can be gained by examining which aspects of complex adaptive system dynamics might be fruitfully brought done to the level of fundamental constituents. This does not imply a return to vitalism. Transience, contextuality and emergence can be framed in entirely formal terms and applied to a wide range of dynamical systems: physical, biological, mathematical, psychological, economic or computational.

A metaphysics already exists within which to address many of the problems associated with complex adaptive systems. That is Process Theory, as conceived by Whitehead early in the Twentieth century [14]. Whitehead described his metaphysics as a philosophy of organism. Transience, contextuality and emergence are fundamental to his metaphysics. He postulated the existence of a fundamental level of entities which he called *actual occasions,* which come into being in successive generations through the activity of *processes*, persist long enough so that the information embodied within becomes incorporated into the next generation of actual occasions through something called *prehension*, and then fade from existence. Becoming is prior to being in his metaphysics. The actions of a process are contextual. Fundamental constituents are emergent, and supervene upon actual occasions.

Whitehead proposed that reality was generated by process. It does not exist in its entirety in some eternal form but rather is generated moment to moment, a version of presentism [15]. Since the advent of relativity, modern physics has denied the existence of a transient now [16,17] although in recent years others have stepped up to suggest otherwise [18,19]. The main argument against a transient now is the absence of a notion of simultaneity within the relativistic framework. However, as pointed out by Wigner [20], what special relativity actually asserts is the non-existence of *any* universal frame of reference. A global frame of reference is a mathematical fiction. *No* observer can ever directly observe any events that are space-like separated from them. They can, however, reconstruct a surface of simultaneity as they move forward in time by keeping track as information about previously simultaneous events arrives. The reconstructed surface of simultaneity demonstrates that the surface of simultaneity once *existed* even though it was not directly observable. An observer can *only ever* experience their own past light cone. One cannot speak of how the universe *is*, only how the universe *was.* One can no more prove that the universe is eternal and of block form, then that it consists of a transient now.

3. The role of continuity

In Whitehead's Process Theory, actual occasions are distinct, discrete wholes. The Newtonian ontology treats spacetime as a continuum, infinitely divisible, and described mathematically by continuous structures. Research into quantum gravity has strongly supported the idea that the continuous appearance of spacetime breaks down as one approaches Planck length and time. This appears to be necessitated by the Heisenberg Uncertainty Principle, which places limits on the accuracy with which measurements may be carried out at the smallest scales. In the context of quantum non-locality, Gisin [21] presented an inequality involving quantum correlations, which is violated by quantum mechanics, and which implies that either the speed of transmission exceeds any possible fixed, finite value for the speed of light (i.e. transmission is instantaneous) or the principle of continuity must be violated. Gisin argued for the instantaneous speed of transmission, even though it clearly violates the Special Theory of Relativity.

Interpolation, as pointed out by Kempf [8], can provide a bridge between the discrete and the continuous. He showed that it is perfectly possible to have a discrete reality at the fundamental level and the appearance of a continuous reality at the macrolevel. Even if reality only manifests at discrete spacetime points, it is possible to calculate the values at intermediate spacetime points through the interpolation procedure. In essence, the appearance of continuity is illusory and is a result of a fundamental inability to resolve spacetime at any smaller scale. The illusion of continuity is widespread. Organisms, matter, motion pictures, all appear continuous at the macrolevel, but as his breaks down at smaller scales. A discrete reality at the lowest level discrete eliminates the problem of divergence which plagues so many continuous models. Heuristically, one can switch easily from the discrete to the continuous through the interpolation procedure. Both models will agree in value at the sampling points. The integral of the continuous function over the base space X equals the sum over the sampling set Y, so computation is often unaffected. The problem of wave-particle duality is also resolved, becoming merely a matter of scale of observation and interaction. At very small scales reality appears to be discrete while at macroscopic scales reality appears to be continuous.

The suggestion that the fundamental constituents of reality be discrete and reside within a discrete spacetime appears reasonable and consistent with known physics.

According to Whitehead, actual occasions are generated by processes, successively, one complete generation following another. This imparts discreteness to time. But what time? Since processes generate spacetime, it is possible that the action of process takes place in a time outside that of our usual 4 dimensional spacetime. The idea of physics on a 5-dimensional spacetime is not new [22] but has not been widely accepted. In such a case, the action of process would attribute to each actual occasion a location in a 4 dimensional spacetime such that each complete generation forms a discrete sampling of a space-like hypersurface, that is, they appear to occur simultaneously. Another possibility is that the action of process occurs according to proper time. This has the advantage that it would be invariant under relativistic transformations. In this case the actual occasions could be assigned different time coordinates while still forming a discrete sampling of a spacelike hypersurface. However, if the proper time required for the creation of a complete generation of actual occasions was sufficiently small, say a small multiple of Planck time, they could be treated as if they occurred simultaneously, without much loss of accuracy.

4. The Ultimate Determinant of Events: Energy versus Information

Classically one of the fundamental concerns of physics was the study of motion. Physics studied the laws governing how physical objects move *through* spacetime. Physical objects, being inanimate, move in a reactive manner. They do not act or behave. They are passive, merely responding to the vicissitudes of energy as it is distributed in spacetime, always following paths which extremize some function or another, like least action. In the standard block universe model of reality, nothing really *happens*. All events exist simultaneously. Each physical object is associated with a set of spacetime locations which form a history, and physics simply studies how these different histories related to one another. Motion is an illusion, a by product of histories being more than single spacetime points.

The process theory view is strikingly different. Spacetime is no longer a pre-existing, eternal entity. Instead, spacetime, like the physical entities manifesting within it, is generated by processes. Prior to the appearance of an actual occasion, a spacetime point is merely a conceptual potentiality. It is only realized once an actual occasion is associated to it and it becomes identified with a something, to which a measurement apparatus can interact. In the Process Algebra model, spacetime consists of the collections of actual occasions that are generated by processes. Each fuzzy actual occasion both represents and manifests an equally fuzzy region of spacetime. Processes thus exist outside of spacetime. They are free to generate an actual occasion and to locate it in relation to any other actual occasion in any manner possible. There are only two restrictions. The first is that an actual occasion cannot be identified or attributed to a location assigned to any other actual occasion. Second, the information of a prior actual occasion can propagate to a nascent actual occasion only causally. In keeping with special relativity, no signal can propagate at greater than light speed, and propagating information constitutes a signal which must respect this principle.

An actual occasion comes into being, persists until its information has been incorporated into the nascent actual occasions, and then fades away. The triad of prior generation, generating processes and nascent generation form the compound present of the process model. Everything is either in a state of becoming or of fading away. Everything is *happening*, and *nothing* is eternal, except for the processes, and even they shift between activity and inactivity.

It is important to recognize that actual occasions *do not move*. They come into being and then fade away. They *manifest* a spacetime location; they do *not* move from one spacetime location to another. They do not interact with one another. Processes interact, actual occasions do not. There is no energy associated with actual occasions because there is no motion against which to define a kinetic energy and no interactions to define a potential energy.

Energy is frequently, and somewhat causally, said to underlie everything in physical reality. Energy is said to be exchanged, much like money, or property or other material objects are exchanged. This way of thinking suggests that energy is a thing in its own right, which physical objects can possess. If this is so, then it should be possible to assign a definite quantity of energy to any physical object. However, consider the following thought experiment. Consider a solitary observer in an otherwise empty universe. They possess a rocket backpack. They have a clock with which they can time the duration of firing of the rocket. Initially the rocket is quiet. They are in an inertial frame, and so cannot determine whether or not they are in motion. Thus their kinetic energy is 0. Their potential energy is also 0 since there are no other entities with which they could interact. Now suppose that the rocket fires for a duration t and produces an acceleration a. They need not measure it. Assume that the manufacturer told them so. During the firing of the rocket, they feel the acceleration, which according to the equivalence principle would feel like being in a gravity well. After the rocket has fired they return to an inertial frame. They are still alone in the universe. They still cannot detect if they are in motion even though intellectually they should be moving with velocity ta. But they have no means to detect that. As far as they know, they are still at rest. They still have no kinetic energy even though to an external observer they should have kinetic energy $\frac{1}{2}m(ta)^2$. But such an external observer does not exist, at least not in our universe.

Suppose now that there are two observers, one of rest mass m, the other of rest mass n. The two observers face each other and move towards one another along their line of sight with relative speed v. To the first observer, the second observer approaches with speed v, momentum -n**v** and energy ½ nv^2. The total momentum therefore is -n**v** and energy ½ nv^2. To the second observer, the first observer approaches with speed v, has momentum -m**v** and energy ½ mv^2. The total momentum is therefore -m**v** and energy ½ mv^2. Neither the total momentum nor the total energy is the same for both observers. Nevertheless, in any interaction between them, the total momentum and total energy will remain constant, albeit with different constant values.

Momentum and energy can only be defined with respect to a relationship between physical objects. Energy has no intrinsic value in and of itself. If energy were a natural kind, an actual something passed between physical objects, then it should be possible to assign it a definite value. But it can be assigned any possible value in any frame of reference. All that is required is that conservation of energy hold. That is, the bookkeeping should balance out in the end, but otherwise the numbers attached to independent events can be assigned at will. Momentum is similar in that it too cannot be assigned to single physical objects but only to relations between objects.

From an ontological perspective, Noether's theorem [23] shows that momentum and energy describe relations between dynamical trajectories of physical objects. They are a consequence of symmetries in the equations of motion that govern such trajectories. They are not actually properties of the objects per se. They have meaning only in relation to trajectories. Once assigned, a value of energy provides information about which trajectory a physical object might be following. Interactions can result in changes of trajectories, and therefore changes in the assigned energy. That is, an interaction results in a change in information.

Since energy and momentum reference trajectories, it would seem more reasonable that they be associated with the generator of the trajectory, which in the Process Algebra framework, would be the generating process. This does not eliminate the observer dependency of these quantities. One possibility is to try to link these two to the causal structure of the content sets within the informons of a causal tapestry. It is possible that as far as reality is concerned there is a preferred frame of reference against which such quantities can be measured, but that this frame of reference is inaccessible to macroscopic observers. If so then it might be possible to recover the idea of energy as a natural kind. This idea is still in its infancy.

As physics evolved over the centuries, its focus shifted from a study of motion and forces to a study of energy. Information has been gaining attention in physics [24,25], primarily through the relationship between Shannon's concept of information [26] and the physical concept of entropy, which mathematically are the same but for a sign. The Shannon concept of information lacks however, any reference to meaning. He wrote [26](p.31): "The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point. Frequently the messages have *meaning*; that is they refer to or are correlated with certain physical or conceptual entities. These semantic aspects of communication are irrelevant to the engineering problem. The significant aspect is that the actual message is one *selected from a set* of possible messages. The system must be designed to operate for each possible selection, not just the one which will actually be chosen since this is unknown at the time of design. (SIC)"

In the setting of complex adaptive systems, however, energy plays a subordinate role. Most organisms are adapted physiologically to act within a wide range of energy states and flows. An organism can carry out the same behaviours whether hungry or sated, and sometimes even when starved or obese. Energy is necessary for an organism to act, but energy alone does not determine the specific behaviour which is carried out. The main determinants are physiological, psychological and ecological, and each of these influences the organism through information. The information used by organisms, unlike that studied in engineering or physics, is meaning laden, or salient, and transferred from one organism to another through either signals or signs. The term salience is preferred to meaning since it does not imply the presence of an entity which can interpret the meaning. It merely implies that the information creates a difference. The study of signs in a biological context is called biosemiotics [27]. The role of information in determining the behaviour of organisms has become prominent in recent years. In the context of fundamental constituents, Whitehead believed that information played a central role along with energy.

Information propagates from prior actual occasion to nascent actual occasion and is incorporated into the nascent actual occasion through prehension. The simplest mechanism by which information could propagate from actual occasion to actual occasion is diffusion. Another possible mechanism is dissipation. There have been several attempts to describe quantum mechanics as a diffusion process [28,29].

Information from a prior actual occasion can be incorporated into many nascent actual occasions; likewise, a nascent actual occasion may receive information from many prior actual occasions. It appears that information has an inherent tendency to flow. Prehension is an elusive concept but work into the formal aspects of information flow offers a suggestion for modeling it. In the context of information flowing along a network of channels it has been shown [30] that information transmitted simultaneously across multiple channels should be summed at the receiver, whereas information passed from one channel to another, and then to another must be multiplied at the receiver. It is quite striking that this is exactly the rule which is applied for calculating amplitudes in path integrals. Applied to the process algebra model, it suggests that information from multiple prior occasions should be summed, and when that information is incorporated into the nascent actual occasion it should be multiplied against any prior information.

4. Process Strength

The most basic kind of information that could be passed from actual occasion to actual occasion is that of local coupling effectiveness (and thus local process strength). Processes are assumed to interact with one another according to Trofimova's Compatibility Principle [31]. This principle is based on observations of complex adaptive systems where interactions appear to take place only between systems that are compatible with one another. Indeed among the elementary particles, interactions only occur between particles that can exchange certain mediating particles – photons, gluons, mesons. Incompatible particles do not interact. The local coupling effectiveness and local process strength provide a contribution to the determination of compatibility between two or more processes

The units of the NRQM wave function are inverse volume. This has been interpreted as a probability density, but perhaps it should better be interpreted as a process strength density. Instead of saying that a particle is detected at a particular location one says that the particle process and measurement apparatus process achieved compatibility and interacted at a particular location. The particle process need not be "localized" to that particular location. Indeed, the particle process will be generating informons over a spatial region. It just happens that particle and measurement apparatus informons at that location were deemed compatible and triggered the interaction that resulted in a "measurement".

Classical information theory is about meaningless information, being more about the carrying capacity of signals than about the content of those signals more a theory of signals than of information [26]. Semiotics on the other hand concerns itself with signs and with meaning, and how meaning is transmitted by virtue of signs [27]. In semiotics, meaning is closely related to form. Consider a key and a lock. The key is compatible with the lock if it possesses the correct length, the correct grooving to match the tumblers and is oriented in the correct direction when insertion is attempted. The form of the key is essential to its function. Likewise in physics, the form of the information may be critical to determining the behaviour and types of interactions between physical objects. Fundamental particles are associated with different kinds of mathematical representations (scalars, spinors, vectors, tensors) defined over various number fields (integral, real, complex, quaternion, octonion).

Since compatibility involves information and meaning (whether physical or abstract), it is expected that the local coupling effectiveness would possess a form which expresses this meaning. The particular mathematical form of the local coupling effectiveness should express, when formally combined with the mathematical forms of the local coupling effectiveness of candidate processes, the determination of compatibility between the processes. When viewed from a process perspective, the form of the wave function no longer appears so inscrutable. The choice of number field need no longer be tied to simplistic connections to measurements, which represent only a specific set of interactions. Instead the number field and the mathematical form represent deep algebraic relationships between the associated processes, presumably expressing some deep symmetries or relationships. The idea of compatibility provides a more subtle interpretation of the wave function than as a mere probability.

3. Intrinsic versus Extrinsic Characteristics

The formal description of informons includes two parameters, a set of intrinsic properties $\mathbf{p}$ and a set of extrinsic properties $\mathbf{\Phi}$. Intrinsic properties are inherited from the process which generated the informon. Technically speaking, they are not really an ontological aspect of the informon per se, but

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rather they serve to identify which process generated it and which process will propagate its information forward into the nascent collection of informons. These intrinsic properties distinguish one process from another. Since processes are held to exist outside of spacetime (being generators of spacetime), they must exist apart from any particular observer (since they generate the informons upon which any observer supervenes). Thus any intrinsic property should be an invariant of the process, independent of any particular reference frame used to model the process. There are many candidates for intrinsic characteristics. For fundamental constituents one can think of charge, rest mass, lepton status, baryon status and so on. These are all invariant quantities. The dimension of the spin representation is another such invariant. Spin may be 0, ½, 1, 3/2, 2 or higher, corresponding to scalars, spinors, vectors and tensors. The mathematical structures representing the spin state of a fundamental constituent is an invariant, even though the particular representative from that structure is observer dependent. Likewise, the mathematical structure of the wave function (generally related to the spin structure) is also an invariant. Causal distance is another invariant which can be attached to an informon as an intrinsic characteristic (referenced to the collection of prior informons) and which can be attributed to the informon itself. Causal distance appears in the structure of the content. The causal structure suffices to define the topology of any causal manifold into which the informons are embedded [32]. The local coupling effectiveness is another invariant which is attributed to the informon itself although it as its origin in the action of the generating process.

Extrinsic characteristics are those which are observer dependent. Unlike the intrinsic characteristics, the external characteristics must be referenced to some reference frame or to some observing system and will vary from frame to frame. Position, momentum, energy are all external characteristics as are the interpolation functions which enter into the local Hilbert space interpretations. They can be freely chosen although their usefulness and effectiveness will be affected by poor choices. They are not part of the reality at the informon level but serve as bridges between the informon level and the macroscopic level of the observer. There are deep questions related to whether momentum and energy can be associated with a generating process as intrinsic characteristics and which will not be addressed here.

4. Conclusion: The Primacy of Information

In Whitehead's process theory, information plays a fundamental role. Only it is meaning laden information, information which makes a difference in the generation of actual occasions by processes. Energy, while necessary, is no longer sufficient to determine the flow of events. This is true for complex adaptive systems and it is suggested that this is also true for fundamental physical processes as well. The Process Algebra model explicitly postulates that below the standard level of fundamental constituents there exists a level of actual occasions. These manifest at Planck scales, and so are effectively unobservable to macroscopic observers. Information is propagated among actual occasions by processes in a manner akin to a diffusion process, following a Schrodinger equation. The standard fundamental physical constituents manifest as emergent from causally coherent collections of actual occasions as generated by processes. Spacetime, and the entities that manifest within it, are all generated by processes. The resulting reality, according to Process

Algebra models, is realist, causally local, and contextual. It is divergence free, paradox free, and free of conceptual confusion. In keeping with the principles of Occam's razor, it offers a mathematically simpler description of reality without recourse to an ever expanding zoo of fundamental particles, strings and multiverses.

Appendix: Summary of the Process Algebra Model

The Process Algebra model was developed as a reformulation of non-relativistic quantum mechanics which could serve as a proper completion [3]. It draws inspiration from several sources: complex adaptive systems theory, Whitehead's process theory, combinatorial game theory. Whitehead's actual occasions are modeled as informons. Informons are generated sequentially through the actions of processes. Each informon takes the form $[n]<\mathbf{p},\mathbf{\Phi},\mathbf{\Gamma}>\{G\}$ where n is a heuristic mathematical label, **p** is a structured set of intrinsic properties, **Φ** is a structured set of extrinsic properties, **Γ** is the local coupling effectiveness, and G is a causally ordered collection of informons called the content. The local process strength at an informon n is given as $\Gamma^*\Gamma$. The information residing in the informons of the content is utilized by the generating process to create the informon. The intrinsic properties **p** are attributed to the generating process ***P*** and imparted to each informon generated by ***P***. The extrinsic properties are unique to each informon but are frame dependent. Each process, during a single action cycle (round), incorporates information from a fixed maximum number r of informons into each informon which it generates. Each process carries out a fixed number N of rounds. During a round a process may generate a single informon (primitive process) or multiple (R) informons (compound process). These parameters are intrinsic attributes of a process and vary from process to process.

The collection of informons generated after N rounds is called a *causal tapestry.* The union of content sets over all informons in the causal tapestry must itself form a causal set [29]. Given a prior causal tapestry ***I***, the action of a process ***P*** is to generate a nascent causal tapestry ***I′***, following which the elements of I are erased. The triple of prior causal tapestry, process and nascent causal tapestry is a compound present. Information *only* flows causally from prior to nascent informons, represented by the causal ordering of informons in the content set. Information *never* flows within a causal tapestry so that there are no causal relations between the informons within a causal tapestry (thus it forms a causal antichain).

In the context of NRQM, there are two main extrinsic characteristics. First, each informon n is interpreted as a point x_n in some causal manifold ***M***. Its content set G causally embeds into ***M***. Each causal tapestry forms a causal antichain in ***M***, and thus represents a discrete sampling of a spacelike hypersurface in ***M***. Second, each informon n is associated with a local Hilbert space interpretation of the form $\varphi_n(z)=\Gamma_n f_n(z,x_n)$. When the informons of a causal tapestry embded into the causal manifold as a discrete lattice, it is possible to replace each f_n by a spatial translation of a single generic sinc function. Each causal tapestry is associated with a global Hilbert space interpretation over the causal manifold of the form $\Psi(z) = \Sigma_n \varphi_n(z)=\Sigma_n \Gamma_n f_n(z,x_n)$.

Interactions among processes are described within the Process Algebra, which possesses 9 commutative operations, and 1 non-commutative operator. The operations describe the different ways in which the timing of the generation of informons is distributed among processes, how information is shared among informons, and how compound processes are formed. These are termed couplings since the state of the processes involved in a coupling do not change as a result of the coupling. Interactions may also result in the activation or of processes, or the creation of a new process. These give rise to true interactions in which the processes involve change states or activation status or result in new processes.

In a coupling between two processes, the processes may generate their informons simultaneously (products) or concurrently (sums). Information may be shared among the informons generated by the two processes (free) or information from each process may remain restricted to the informons generated by that process (exclusive). Each of the above has an interaction counterpart. Interactions between processes may activate an inactive process or inactivate an active process. In addition, an interaction among processes $\boldsymbol{P_1}, \boldsymbol{P_2}, .., \boldsymbol{P_n}$ generates a new process, $\boldsymbol{P}$, which can be described in functional form as $F(\boldsymbol{P_1}, \boldsymbol{P_2}, .., \boldsymbol{P_n}) = \boldsymbol{P}$. If $\Theta(\boldsymbol{P_1}, \boldsymbol{P_2}, .., \boldsymbol{P_n})$ describes a coupling among $\boldsymbol{P_1}, \boldsymbol{P_2}, .., \boldsymbol{P_n}$ then the functional relation may be described using the operation of concatenation, as $\Theta(\boldsymbol{P_1}, \boldsymbol{P_2}, .., \boldsymbol{P_n})\, \boldsymbol{P}$. Sums and products are commutative, concatenation is non-commutative. There is an additional operation, ",", which means that the two processes are independent of one another. The zero process, O, is the process that does nothing.

An important concept is that of epistemological equivalence. Epistemological equivalence of two processes $\boldsymbol{P}$ and $\boldsymbol{Q}$ means that the global Hilbert space interpretations $\Psi(z)$, $\Psi'(z)$, respectively, are equal as functions over the causal manifold. In other words,

$$\Psi(z) = \Sigma_n \Gamma_n f_n(z,x_n) = \Psi'(z) = \Sigma_m \Gamma'_m f_m(z,x_m)$$

The significance of epistemological equivalence is that if one deals only with epistemologically equivalent processes then the specific details of informon generation do not matter. Thus one can choose heuristic representations of processes for the purpose of developing theory, so long as those representations result in effective physical theories.

In the context of NRQM, local coupling effectiveness is taken to be the value of the wave function at a given informon, and the global Hilbert space interpretation becomes the wave function for the quantum system. In the Process Algebra framework, a decomposition of a wave function as a sum of the form $\Psi(z) = \Sigma_n w_i \Psi_i(z)$ implies that the informons are being generated by a process $\boldsymbol{P}$ which can be decomposed into a sum of primitive processes as $\boldsymbol{P} = \Sigma_i w_i \boldsymbol{P_i}$, where each subprocess $w_i \boldsymbol{P_i}$ generates the wave function contribution $w_i \Psi_i(z)$. Moreover the set of informons associated with each subprocess can be chosen to be separate from those of any other subprocess. Thus each informon represents a contribution from one and only one physical state. There is no confusion of ontological states within the Process Algebra framework.

Measurement within the Process Algebra framework is simply a specific class of interactions between an observed system process and a specialized measurement apparatus process. There is no separate theory as in NRQM.

A simple model of NRQM for a single scalar particle involves the propagation of the wave function (local coupling effectiveness) by means of a discrete version of the propagator for the corresponding Schrodinger equation. It can be shown that even such a simple model reproduces the usual quantum mechanical wave function to a very high degree of accuracy [1,2,3].

The local and global Hilbert space interpretations are constructed by means of sinc interpolation [7]. Sinc interpolation requires the use of a lattice embedding into the causal manifold. Maymon and Oppenheim [33] have shown that non-uniform embeddings will still provide a highly accurate approximation using sync interpolation so long as the spatiotemporal separation error is small. A more realistic model requires the use of non-uniform embeddings and more sophisticated interpolation techniques, such as Fechtinger-Grochenik theory [7].

It can be shown that all of the information necessary for carrying out the actions of process and thus the wave function resides within the informons of the causal tapestries, not the causal manifold or the Hilbert space. Thus the physics resides solely within the causal tapestries, enabling the assertion that reality resides within the causal tapestries, while our perception of a continuous spacetime with continuous entities and events is a consequence of the interpolation procedure.

The wave function of the Process Algebra model is an ontological wave function, meaning that it describes a particular instance of a causal tapestry, a particular collection of generated informons, a particular state of reality. A significant difference between NRQM and the Process Algebra model appears when computation is the goal. Every action of a process potentially results in a different causal tapestry, with a different set of informons, different causal manifold embeddings, and different global Hilbert space interpretations. To take these different possibilities into account, which is necessary in order to carry out computations, one must consider the *Process Covering Map*. This is a set valued map which associates to each process $\boldsymbol{P}$ and to each causal tapestry $\boldsymbol{I}$ a set of global Hilbert space interpretations $\{\Psi_i\}$, one for every possible causal tapestry generated by $\boldsymbol{P}$ with $\boldsymbol{I}$ as prior tapestry. This map $\Pi_{P}(\boldsymbol{I}) = \{\Psi_i\}$ is called the process covering map. It holds for single processes. A more complicated map, the configuration space covering map, holds in the case of compound processes.

It can be shown [1,2,3] that under suitable conditions, namely in the asymptotic limit as Planck length and Planck time tend to 0, that $\Pi_{P}(\boldsymbol{I}) \rightarrow \{\Psi(z)\}$, a single wave function. Thus in the case of a primitive process, in the asymptotic limit, the process generates only a single wave function which corresponds to the usual NRQM wave function. Thus in the case of a primitive process, the wave function becomes *both* ontological and computational. This is not true in the case of compound processes, so that the ontological wave function which describes a single instance of reality, and the computational wave function which is used for making predictions, are no longer the same. It is possible that the failure to appreciate the distinction between the case of a primitive process and that of a compound process resulted in the persisting confusion as to whether or not the wave function is ontological or epistemological. No such confusion holds in the Process Algebra framework.

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