Article

Space, Time & Quantum Mechanics: A Process Approach (Part I)

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Abstract

Since the time of Newton, physicists have imagined a background "stage" called space and time (later spacetime) permeating the entire universe. The contents of the world around us are then seen as objects embedded in this background at a defined location, and with a defined size and other properties (color, mass, spin etc.).We refer to this traditional view as the Objects in Space and Time (OST) model. It works very well for picturing classical physics; but once we move into the quantum domain it is no longer of much use. In the quantum realm objects no longer have defined locations at all times, their properties can become entangled and undefined until observed. In this paper, we seek to present an alternative to the OST model in which the "weirdness" of quantum phenomena goes away and is replaced by clarity, obviousness and inescapability. In this model the world is viewed as a network of fundamental processes by which indivisible units called *tomas* bring each other into and out of existence. We show that this model yields the same equations and predictions as the current OST-based formalism of quantum mechanics. While not contradicting the success of quantum theory, the toma model lets us get rid of the "weirdness" of the quantum world and understand reality at a deeper level than the OST model. We illustrate this by discussing two classic quantum experiments and their interpretations.

Part I of this two-part article includes: 1. Introduction; 2. Ontic Networks; 3. Quantic Networks; and 4. Measurement.

Keywords: spacetime, quantum mechanics, process philosophy, philosophy of physics, toma, ontic network, quantic network.

1. Introduction

The near-universal view of the nature of reality among physicists and most scientists is what we refer to as the *Objects in Space and Time* (OST) model. In it, we imagine an all-pervasive, all-penetrating background "stage" called space and time (or spacetime). Embedded in this background are the everyday physical objects making up the world. These objects all have independent continuous existence, a defined location on the "stage" of spacetime, a defined size and defined properties (color, mass, spin, etc.). The OST model is the foundation for materialism and atomism and is taken to be so obvious, intuitive and successful that it is rarely questioned. Indeed, for many physicists it is a sort of dogma, and the OST model, which is just a *model* we have made up in our heads, is often confused with, and taken to be the same as, reality.

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Yet cracks in the universal applicability of OST are numerous. In the domain of physics, this is evidenced by how "weird" quantum phenomena appear when viewed through the OST lens. How can a particle be in two places at once? How can a cat be in a superposition of being dead and alive? How can properties of particles become dependent on each other (entangled) even when no information can travel between them at the speed of light? How can properties be undefined until measured by an "observer" at which point they are chosen at random according to some probability distribution? How can the choice of what we measure affect the very properties we measure?

At a more fundamental level, the OST model is an inadequate explanation of the universe. It does not explain what spacetime is, nor what atoms or particles are, nor fields or forces. Their existence is just taken as an axiom of the model. Yet no one has ever seen or experienced a particle, a field, or spacetime itself—these are all our inventions. What, fundamentally, is space made of? What is a vacuum? These questions are not answerable by the OST model.

At a deeper level still, in the realm of metaphysics and philosophy, the OST model is weaker yet. Where do thoughts reside? Is love made of particles? Where does a perfect Platonic triangle exist? Does math exist in spacetime or outside it—if so, what is outside spacetime? What are feelings? Is consciousness made up of particles? The OST model has nearly no explanatory power when it comes to these sorts of questions. Yet, if we are serious about the project of physics, we should want one fundamental model of nature that has the potential to encompass all these layers, from physics to biology to psychology to philosophy.

The OST model, while successful in many domains, simply cannot be the last word on the nature of reality. There must exist a deeper reality, a way we can understand nature at a more fundamental level. As Quine [1] notes, physical objects, things, particles "are postulated entities which round out and simplify our account of the flux of existence ... The conceptual scheme of physical objects is a convenient myth, simpler than the literal truth and yet containing that literal truth as a scattered part."

It is the goal of this paper to present such a deeper model of reality. To be successful this new model must first of all match the experimentally-verified predictions of existing physics, specifically quantum mechanics, as viewed using the OST model. It must provide a structure of reality that makes the "weirdness" of quantum phenomena understandable. Most important, it must bring a new vantage point, a deeper reality, a new set of techniques to bear on the project of physics, so that we have a chance of making new discoveries and predictions which are unreachable from within the OST model.

So, how do we begin to construct an alternative to OST? What is the "literal truth" to which Quine refers to? How can we describe a theory without, or at a deeper level than, particles, space and time? In answering this question, we initially find common ground with Wheeler [2]: "Can we deduce the *quantum* from an understanding of *existence*?". Wheeler makes progress on this goal by stating the following working hypothesis: **It From Bit**. "... every **it**—every particle, every field of force, even the spacetime continuum itself—derives its function, its meaning, its very existence entirely—even if in some contexts indirectly—from the apparatus-elicited answers to yes or no questions, binary choices, **bits**.".

We strongly agree with a foundational role of yes-or-no questions in the nature of the literal truth of reality. Wheeler goes on to ask, "But how come existence? Its as bits, yes; and physics as information, yes; but *whose* information? How does the vision of one world arise out of the information-gathering activities of many observer-participants?" Now this is problematic: what is an "observer-participant?" A "conscious" being? And what, precisely, is that? How can different observer-participants agree on one world? Or does each one exist in solipsistic isolation, each with their own truth about the world?

It is at this point where we part company with Wheeler in our thinking. Our key idea is to answer the question "*whose* information" not with "observer-participants' ", but "reality's". By this we mean, that if the **bit** is 1, the **it** is a fundamental indivisible entity which *exists*—which manifests in reality, is an *actuality*. **It** *is*. If the **bit** is 0, the **it** does not exist—does not manifest in reality, it is a *potentiality*. **It** *is not*.

We will call this **it** which exists if the **bit** is 1 a *toma*. A "toma" is like the philosopher's "atom", in that it is a fundamental indivisible unit of existence, but different in that it can pop into and out of existence. It is not eternal.

Where to now? How do we develop "a *derivation* of the structure of quantum theory from the requirement that everything have a way to come into being[?] ... We can ask ourselves if it is not absolutely preposterous to put into a formula anything at first sight so vague as law without law and substance without substance. How can we hope to move forward with no solid ground at all under our feet?" [3]

We propose to meet this challenge by founding our theory of reality on the *Principle of Dependent Origination* [4]: "Every toma depends for its existence on the existence of other tomas." Recall a toma is a **bit** which, when 1, becomes an **it**, a unit which exists. The principle of dependent origination states that the values of all these **bits** depend on each other. That is, there exist Boolean functions which determine the status of each **bit** taking as input the state of some set of **bits**. As these Boolean functions get evaluated, the status of the **bits** is updated, and the corresponding **its** come into existence or cease to be. Instead of the static, eternal philosopher's "atoms", we have dynamic, interdependent fundamental units, "tomas".

By Occam's razor, there is no global "clock" to synchronize the evaluation of all these Boolean functions. The functions can be evaluated at any time, in any order. The universe, in our view, is just a vast asynchronous network of logical dependencies between tomas.

You may quite reasonably ask, who or what "evaluates" these Boolean functions? By assuming that something must exist which does the evaluating, this question reveals how ingrained the OST model is in our thinking, especially in the form of materialism. A contrasting view, *process philosophy*, with roots in ancient Eastern philosophy [5], has been developed by Whitehead [6] and others [7]. It claims that *processes*, change, relationships are fundamental, and substance or matter, if it even exists and is not mythical as per Quine, is secondary.

In the OST model, *matter* (atoms, particles) is taken as fundamental, and it just happens to undergo change through the occurrence of *processes*. In the process-based toma model, the *processes* (Boolean functions) are fundamental and there just happen to be *tomas* which these processes act on.

Process philosophy has developed into a very rich and complex body of work with many variants. A simple illustration should capture the basic idea at this worldview's core. Consider the question "what is a cat?". In the OST model, we would say that it is a collection of billions of atoms. A furry bag of "stuff" weighing so-and-so much and with such-and-such dimensions embedded at a given location in space. In this model, a dead cat would be essentially the same as a live cat―same dimensions, same weight, same atoms, same place in space. Clearly though, a live cat is **very** different from a dead cat. The OST model does not provide a lens through which we can clearly distinguish a live and dead cat - therefore the OST model is simply incomplete.

Process philosophy answers this question differently. We don't take the cat to be a furry bag of atoms. Instead, we look at it as a *network of processes*: respiration, digestion, circulation, movement, cognition and so on. In this view, a dead cat consists of a dramatically different network of processes to the live cat: cooling, cell breakdown and so on. By placing *process* as the foundation, we can correctly identify the dramatic difference between a live cat and a dead cat.

The contrast between process philosophy and the OST model is even more stark when we consider everyday inanimate objects. Consider a box of matches [8]. On the OST view, this is an arrangement of real physical inanimate matter made up of individual atomic units at defined locations in space which endures in time. In contrast, on the process view, the box of matches is the result of, that is depends on, many processes by which it was manufactured, as well as a set of processes it can give rise to. Thus, the flame which results when a match from the box is struck is already contained in the process description of the box of matches. On the OST view, we see the box of matches *is* some "stuff" somewhere "out there" in space. On the process view, the box of matches is a description of everything that needs to be *done* to create it, and everything it can *do*. Matter *is*, processes *do*.

An analogy with computer science is appropriate. One way to describe a computer program is as a map from the set of all possible input sequences of bits to the set of output sequences of bits which the program generates for each possible input sequence. This corresponds to the OST model―the program takes the form of arrangements of "stuff," bits in this case, of inanimate, concrete units. But there is another way to represent a program, as an *algorithm*―a set of *processes*, transformations, which take place depending on the input and each other and give rise to to the output of the program. This corresponds to the process view―there is no inanimate "stuff", no "matter", but only a network of interdependent processes, a description of how things are created and what they can create. An algorithm, or a network of processes, can be equally well executed on a computer, or with pencil and paper, or using an abacus―it is the network of *processes* that is key, not the "stuff" which performs the processes.

The central tenet of process philosophy can thus be expressed as follows: If you completely describe what an object *does* in relation to what all other objects *do*, that description is a complete specification of what that object *is*―no further specification is necessary *or possible*.

In physics, we almost exclusively look at the world as arrangements of units of matter, of physical "stuff" in space and not at the algorithm, the network of interdependent processes taking place all around us. It is the goal of this paper to show that such a process description of reality can lead to a mathematically precise model of reality which matches the predictions of the current best OST-based fundamental theory of motion—quantum mechanics.

The reader may well still insist that we must provide in the process model something corresponding to physical objects in a physical space. Even if we are to view everyday physical objects (chairs, boxes of matches, socks) as networks of processes, we still must explain why they seem to have a physical size, a physical extension and location in some sort of space. We answer this potential criticism by taking Bohm's [9] view of perception. Bohm points out that we never perceive matter as a thing in itself. What we do perceive are *invariants*. For example, we never "see" a whole pencil, all sides and the interior of it at the same time. Instead, from multiple views of it we infer that the endpoints of the pencil are, say, 20 cm apart in space. This model of perception allows us to view physical objects not as arrangements of "matter" somewhere "out there", but as a set of invariants, or *relationships*, among their parts. On the process view, these relationships or dependencies between the parts of a physical object are a network of processes, which is only one subnetwork of the complete description of the object, which also includes all the processes that give rise to it and it can give rise to, such as the flame contained in the box of matches. We will see in section 5 of this paper that any network of relationships among parts naturally leads to observations (measurements) of the parts being located at points separated by invariant distances in a three dimensional space. Thus we will recover physical extension in space as a consequence of one part of the description of an object in our process model of reality.

Many authors have noted that adopting a process philosophy viewpoint may be useful in creating a theory of reality that makes sense of quantum phenomena. Folse [10] compares Whitehead's process philosophy with Bohr's principle of complementarity [11]. He summarizes his conclusion thus: "In stipulating that what is described by the state equations of quantum mechanics is not the properties of a substance but a process of interaction which cannot be unarbitrarily subdivided into separate physical systems in determinate states, the framework of complementarity essentially puts the notion of process at the heart of its characterization of the ontological status of the objects of experimental observation, or in other words, of experience." There is a large body of work trying to reframe quantum mechanics in terms of process philosophy, a sample of which is given in the references [12 - 14], but none of these attempts to date which we are aware of have, in our view, been entirely satisfying.

Our model of interdependent tomas is an instance of process philosophy. So, back to the question, "who, or what, evaluates the Boolean functions that determine the status of all the **bits** and **its**?" Answer: nobody—processes are all that there is—they are the fundamental building blocks of reality. The tomas are secondary, a by-product of the processes having to have something to act on.

We develop these ideas as they apply to space, time and quantum mechanics in the remainder of this paper. We begin by introducing a mathematical model of interdependent tomas called an "ontic network" in section 2. We then reinterpret the number system in process terms thus creating the "quantic networks" of section 3. In section 4 we examine the *process* of measurement as being one by which a number (in a quantic network) depends on the state of a system (an ontic network). In section 5 we build on to this to understand what motion is in the process worldview and how velocity can be measured. In the final section, we discuss two key "mysteries" of quantum mechanics: Schrödinger's cat and entanglement, and how these can be straightforwardly understood by taking processes, not substance, as fundamental.

2. Ontic Networks

So far, we have argued that the universe is an interdependent set of tomas which depend on each other to come into, or out of, existence. We will refer to such a set of tomas and dependencies as an *ontic network*. The word "ontic" signifies "related to existence" and the word "network" captures the dependencies among the tomas. We define the terms toma and process dependency as follows:

A *toma* is an entity which can be in one of two states:

"1" - when it is an indivisible unit which manifests in reality, or *exists*—an *actuality*.
"0" - when it does not manifest in reality—a *potentiality*.

A *process dependency* is a Boolean function of the states of some subset of all tomas in the ontic network (the *input tomas*) and which is associated with one specific toma, the *dependant* toma.

An *update* is when a dependency function is evaluated, the values of the arguments being the current states of the input tomas. At least one of the input tomas must be in state 1; an update can only occur if at least one input toma exists. The result of the evaluation of the function is assigned to the dependant toma, replacing its previous state. Through such an update, a toma may come into existence or cease to be. The evolution of the state of an ontic network is the occurrence of an ongoing sequence of updates. The order in which the updates are performed, that is to say, in what order the dependency functions are evaluated, is random, with each possible update having equal probability of being selected to occur next. We justify this mechanism by symmetry: since in accord with process philosophy we view every process as a fundamental and indivisible entity, there is nothing to favor the selection of any one specific process over any other one. If a toma is the dependent toma of more than one process, then its state is the result of the dependency function which was evaluated last: the most recent update "wins."

Each process dependency can be thought of in two ways. First, as a *process*, it is something that brings a toma into or out of existence. Secondly, as a *dependency*, it is that by which a toma's state depends on other tomas' states. Using the term "process" emphasizes the "forward" aspect of a process dependency, from input to the dependant toma. The term "dependency" emphasizes the "reverse" aspect, from the dependant to the input tomas. Both terms, however, should be understood to refer to the same construct, a process dependency.

In order to be able to talk about a specific toma or dependency we will need to refer to it by some label. The primary label of a toma or dependency will be how we refer to it in text and diagrams. For a toma, it will typically be a Latin letter or short piece of descriptive text; while for a dependency it will typically be a lower case Greek letter or short piece of descriptive text.

All tomas and processes in a given ontic network also have a unique *index label* which is a natural number. Consider an ontic network with n tomas and m processes. The tomas' index labels will range from 1 to n, while those of the processes will range from 1 to m. We are not particularly interested in the specific mapping of the tomas to particular values of these numbers. Rather, we will denote the index label of a toma as its primary label indexed with the symbol #. For example, if we have an ontic network with $n = 3$ tomas with primary labels A, B and C, then we refer to their index labels by $A_{\#}$, $B_{\#}$ and $C_{\#}$ respectively. The actual index labels will be 1, 2 and 3, although which specific numerical value corresponds to which specific toma is not important to us. Similarly, a process's index label will be referred to by its primary label indexed with a #.

The state of an ontic network with n tomas is given by a column vector $\boldsymbol{\Theta} \in \mathbb{B}^n$. The entry at row i of $\boldsymbol{\Theta}$ will be denoted $\boldsymbol{\Theta}[i]$. The state of a toma, for example toma B, will be given by $\boldsymbol{\Theta}[B_{\#}]$. Here, "B" is the primary label of the toma. By adding a # index we make reference to this toma's index label, a unique number which we then use to index the state vector. Thus, if $\boldsymbol{\Theta}[B_{\#}] = 1$ then toma B exists, and if $\boldsymbol{\Theta}[B_{\#}] = 0$, it does not.

There is an important nuance here, in that the state of a real ontic network (e.g. the universe) at an instant is, in general, not knowable. Since the network is asynchronous—the updates are performed in a random order—there is no way for any one part of the network to learn the instantaneous state of every other toma in the network. From within the network, therefore, there is no way to capture a global snapshot of the entire network's state.

The only time it makes sense to talk about the state of an ontic network, and to give a specific value for the vector $\boldsymbol{\Theta}$, is when we are dealing with the simulation of such a network (e.g. performed on a computer), or when we study a hypothetical ontic network mathematically. The state of the network is only "visible" from a vantage point "outside" the network, and is meaningless if no such place exists.

Ontic networks lend themselves easily to being visualized. We can draw each toma as an oval with its primary label inside it. Connecting the tomas are the dependencies represented by arrows from the input tomas to the dependent toma. These arrows may, optionally, display the dependency's primary label. Different Boolean dependency functions are represented using standard logic gate symbols. If we wish to indicate the state of a toma, we write a 0 or 1 in a circle placed at the left side of the interior of the oval representing the toma. If the circle is omitted or left blank, the state of the toma is not known, or not significant for the discussion at hand. Examples of diagrams of ontic networks are presented in figures 1 - 4. Note that nothing prevents there being more than one dependency between two tomas, as illustrated in figure 5.

Fig. 1: a) Toma A is in state 1, toma B is in state 0. The function μ is $\boldsymbol{\Theta}[B_{\#}] := \boldsymbol{\Theta}[A_{\#}]$.
b) When μ is selected for an update, this function is evaluated and the state of toma B changes to 1.

Fig. 2: A small bubble represents a logical NOT:
a) Tomas A and B are both in state 1. The function μ is $\boldsymbol{\Theta}[B_{\#}] := \neg\boldsymbol{\Theta}[A_{\#}]$.
b) When μ is selected for an update, this function is evaluated and the state of toma B changes to 0.

Fig. 3: The logic gate representing the AND operation:
a) Toma A is in state 0, tomas B and C are in state 1. The function μ is $\boldsymbol{\Theta}[C_{\#}] := \boldsymbol{\Theta}[A_{\#}] \wedge \boldsymbol{\Theta}[B_{\#}]$.
b) When μ is selected for an update, this function is evaluated and the state of toma C changes to 0.

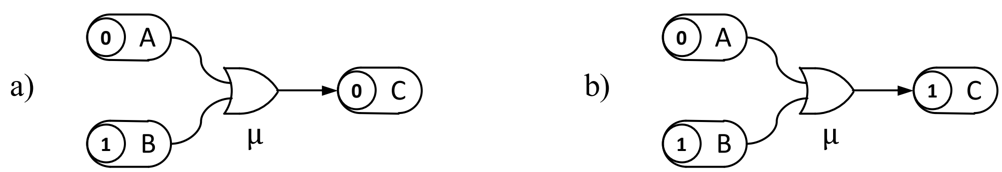


Fig. 4: The logic gate representing the OR operation:
a) Toma B is in state 1, tomas A and C are in state 0. The function μ is $\boldsymbol{\Theta}[C_{\#}] := \boldsymbol{\Theta}[A_{\#}] \vee \boldsymbol{\Theta}[B_{\#}]$
b) When μ is selected for an update, this function is evaluated and the state of toma C changes to 1.

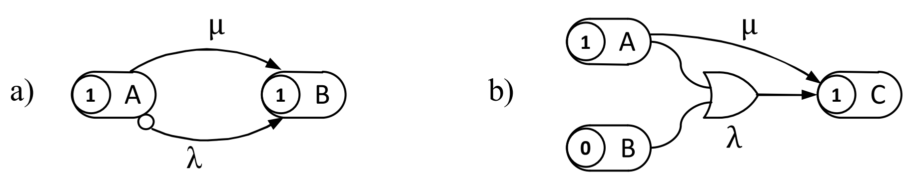


Fig. 5: There can be more than one dependency between two tomas:
a) Tomas A and B are in state 1. The function μ is $\boldsymbol{\Theta}[B_{\#}] := \boldsymbol{\Theta}[A_{\#}]$ and λ is $\boldsymbol{\Theta}[B_{\#}] := \neg\boldsymbol{\Theta}[A_{\#}]$. Either μ or λ can be randomly selected for an update. If μ is selected, B remains in state 1 but if λ is selected, it changes to state 0. The evolution of the state of the network continues through an ongoing sequence of such selections and updates.
b) Tomas A and C are in state 1, toma B is in state 0. The function μ is

$\boldsymbol{\Theta}[C_\#] := \boldsymbol{\Theta}[A_\#]$ and λ is $\boldsymbol{\Theta}[C_\#] := \boldsymbol{\Theta}[A_\#] \vee \boldsymbol{\Theta}[B_\#]$. Either one can be randomly selected for an update, and the state of the network continues to evolve through an ongoing sequence of such selections and updates.

3. Quantic Networks

To build our ontic network based theory of reality we will first need to develop an ontic network version of the number system, wherein each toma corresponds to a specific numerical value. We will call such an ontic network version of the number system a *quantic network*, indicating that the tomas in this network correspond to specific *quant*ities.

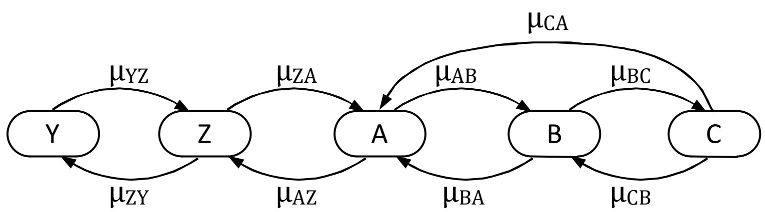
In detail, a quantic network is an ontic network with *n* tomas and *m* processes, together with two functions, $N(i)$ and $D(j)$. For every toma t in the network, $N(t_\#)$ gives the specific numerical value this toma corresponds to. Since ontic networks are fundamentally discrete structures, these values will be integers or vectors of integers.

Furthermore, in a quantic network all the processes are of a very simple kind. Every process has exactly one input toma and one dependant toma. Let the input toma be denoted by p and the dependant toma by q, and let the process's primary label be μ_{pq}. Then all the processes in a quantic network are functions $\boldsymbol{\Theta}[q_\#] := \boldsymbol{\Theta}[p_\#]$. For every process μ_{pq} in the quantic network, $D(\mu_{pq\#})$ gives the difference between the numerical values corresponding to tomas p and q. Specifically:

$$D(\mu_{pq\#}) = N(q_\#) - N(p_\#) \tag{1}$$

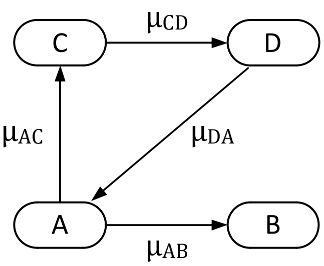
An example of a quantic network is shown in figure 6. Let us suppose the state $\boldsymbol{\Theta}$ of the network starts off equal to zero—no tomas exist. We take this as corresponding to a null set of integers. Suppose a process from outside this network, not shown in the figure, brings toma C into existence, by setting $\boldsymbol{\Theta}[C_\#] = 1$. The value corresponding to toma C is 2 because $N(C_\#) = 2$. We take this network as corresponding to the set of integers {2}. Now if process μ_{CA} is selected for an update, toma A will come into existence, and the network will correspond to the set {0, 2}, since $N(A_\#) = 0$. Then if, for example μ_{AB} is selected for an update, toma B will come into existence and the network will correspond to the set {0, 1, 2}. Thus we see each toma can be thought of as a specific value of a number, and each process an increase or decrease of this number by a specific value.

Thus far we have used integers as the specific numerical values which the tomas correspond to. It is straightforward to use vectors of integers of a given dimension instead. Each toma will then correspond to a specific value of a vector—that is one in which every entry is a specific value of an integer. The processes connecting the tomas then correspond to vector differences between the vectors corresponding to the tomas. Figure 7 shows an example of such a quantic network, in which the tomas correspond to specific values of two-dimensional vectors of integers.



$$N(Y_\#) = -2 \qquad D(\mu_{YZ\#}) = D(\mu_{ZA\#}) = D(\mu_{AB\#}) = D(\mu_{BC\#}) = 1$$
$$N(Z_\#) = -1 \qquad D(\mu_{ZY\#}) = D(\mu_{AZ\#}) = D(\mu_{BA\#}) = D(\mu_{CB\#}) = -1$$
$$N(A_\#) = 0 \qquad D(\mu_{CA\#}) = -2$$
$$N(B_\#) = 1$$
$$N(C_\#) = 2$$

Fig. 6: A quantic network with 6 tomas and 9 processes.



$$N(A_\#) = \begin{bmatrix}0\\0\end{bmatrix} \qquad D(\mu_{AB\#}) = \begin{bmatrix}1\\0\end{bmatrix}$$
$$N(B_\#) = \begin{bmatrix}1\\0\end{bmatrix} \qquad D(\mu_{AC\#}) = \begin{bmatrix}0\\1\end{bmatrix}$$
$$N(C_\#) = \begin{bmatrix}0\\1\end{bmatrix} \qquad D(\mu_{CD\#}) = \begin{bmatrix}1\\0\end{bmatrix}$$
$$N(D_\#) = \begin{bmatrix}1\\1\end{bmatrix} \qquad D(\mu_{DA\#}) = \begin{bmatrix}-1\\-1\end{bmatrix}$$

Fig. 7: A quantic network wherein each toma corresponds to a specific value of two-dimensional vector of integers.

4. Measurement

In physics we perform experiments. In these, a *result* is a numerical quantity that depends on the state of a *system* through a *process of measurement*. Let us now examine each of these three key parts of every experiment in our process worldview using ontic and quantic networks.

A *system* can be defined as a "regularly interacting or interdependent group of items forming a unified whole." [15] This is exactly what an ontic network is—a set of interdependent items. We will refer to this system ontic network by the script letter $\mathcal{S}$ and its state vector by $\boldsymbol{\Theta}$.

A *result* is a numerical quantity; that is, it corresponds to a toma in a quantic network. Only one result can exist at a time, and once a result exists it cannot cease to exist. Therefore, we must use a special type of quantic network. In this type of quantic network, all the tomas start off in state 0, non existing. The dependencies in the network are arranged so that each toma depends for its existence on all the other tomas not existing. Additionally, the dependencies are such that once a toma comes into existence it cannot then cease to exist—it "latches on". We will call such a network a *mutually exclusive*, or for short a *mex* quantic network. We will refer to the mex quantic network in which the result is a toma by the script letter ℛ. Its state vector will be denoted by $\boldsymbol{\Omega}$. If no result exists, as before an experiment is performed, then $\boldsymbol{\Omega}$ is zero. Once a result comes into existence, $\boldsymbol{\Omega}$ will contain exactly one entry equal to 1, with all the other entries 0. The result of the experiment will be the numerical value which corresponds to the toma with the entry equal to 1 through the function $N(i)$ as discussed in section 3.

We define *measurement* as a set of dependencies by which result tomas in ℛ depend on the system tomas in 𝒮. We will call this set of dependencies the *interconnect* and denote it by the script letter ℳ, standing for measurement.

Consider the experiment shown in figure 8. The system 𝒮 consists of two tomas A and B each of which can be in state 0 or 1. These states are determined by processes which prepare the system prior to the measurement; they are not shown here as we are only interested in the measurement itself. The state of the system is given by the vector $\boldsymbol{\Theta}$ which may or may not be known to the experimenter.

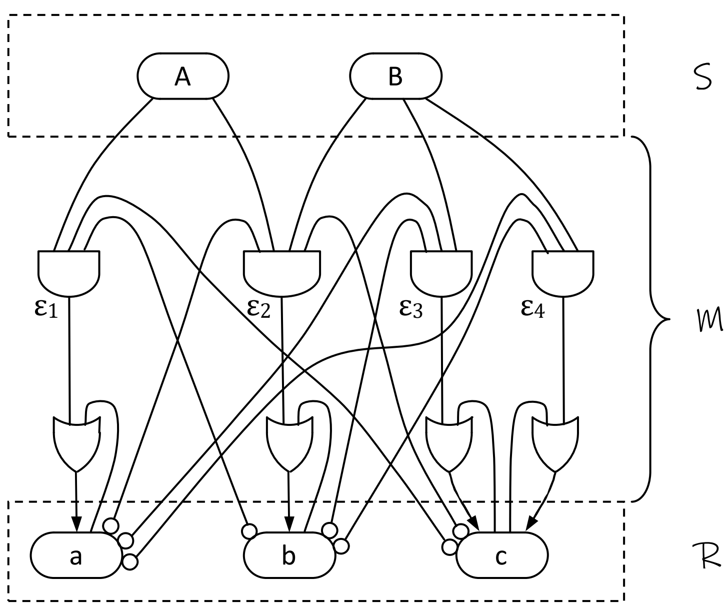


Fig. 8: A measurement of a system 𝒮 with two tomas and three possible results in the result quantic network ℛ. The interconnect ℳ consists of the dependencies of the result tomas on the system tomas. The dashed boxes delimit the tomas belonging to the networks 𝒮 and ℛ. Dependencies between tomas within ℛ have been omitted for clarity. The OR

gates ensure that once a toma in R comes to exist it cannot then cease to exist, while the AND gates ensure only one toma in R can exist.

The three possible results of this experiment are 1, 2 and 3, corresponding to the tomas a, b and c in the quantic network R. We denote the state of this network by ***Ω***. Before a measurement is made, the state of this network is zero—no tomas exist in R; before a measurement is made, there is no result. When a measurement is made, exactly one toma will come into existence. The numerical value corresponding to this toma is what we call the result of the measurement.

While the logic of the mex network R is simple, it leads to visual clutter as can be seen in figure 8. We therefore introduce a simplified representation of a mex network in figure 9.

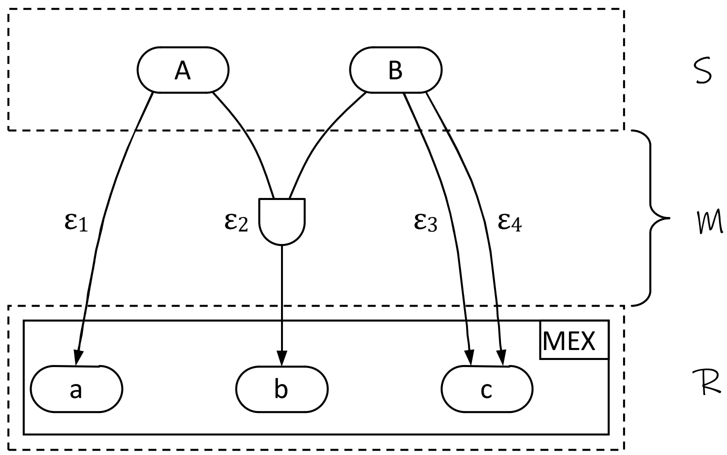


Fig. 9: To reduce visual clutter, we use a solid box labelled mex to indicate the dependencies of the tomas contained in it are structured so that at most one of them can exist, and once it exists it cannot cease to exist. The network shown here is logically identical to that of figure 8.

In our example experiment, there are four processes ε_1 ... ε_4 which constitute the interconnect M. Through these processes the states of the result tomas in R depend on the states of the system tomas in S. Recall that according to the toma model and process philosophy these processes are the fundamental units of reality and that, by symmetry, any one of them can be selected at random with equal probability for an update during the evolution of the state of the network. That is, any one of these four processes can "happen" first. When one of them does happen, it will bring one toma in R into existence. Because R is mex, this toma cannot then cease to exist and no other result toma can come into existence. The first result to come into existence is thus "latched on". This corresponds to the common sense notion that once we have made a measurement, the result is fixed.

We see therefore that in the toma model the result of measurement depends on the state of the system in a fundamentally non-deterministic fashion. The core reason for this is that there is nothing to distinguish any one process in the interconnect M from any other one, as they are all considered fundamental indivisible units of reality. Thus which process happens first and whose result is "latched on" by the mex network $\mathbb{R}$ is random. However, since the different result tomas in $\mathbb{R}$ depend on different subsets and through different Boolean functions of the system tomas, the state of the system affects the probabilities of each result coming into existence, by affecting which of the processes in $\mathbb{M}$ can bring a result toma into existence.

Let us examine this in more detail and develop some formalism to keep track of these changing probabilities in our example. The system $\mathbb{S}$ can be in one of four possible states:

$$\boldsymbol{\Theta}_1 = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad \boldsymbol{\Theta}_2 = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad \boldsymbol{\Theta}_3 = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \qquad \boldsymbol{\Theta}_4 = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \tag{2}$$

where we use the index labels $A_\# = 1$ and $B_\# = 2$ to index the vectors. For the network $\mathbb{R}$ we will use the index labels $a_\# = 1$, $b_\# = 2$ and $c_\# = 3$.

Let us take each one of these system states in turn. With the system in state $\boldsymbol{\Theta}_1$, both system tomas A and B do not exist. Thus there is no way for any of the result tomas to come into existence. We define the *ways vector* $\boldsymbol{\Phi}$ as a column vector with the same dimensions as the state vector $\boldsymbol{\Omega}$ of the result network $\mathbb{R}$. The entry at a given row in $\boldsymbol{\Phi}$ is a non-negative integer equal to the number of ways the toma with this row's index label can come into existence with the system in a given state. This is just the number of processes in $\mathbb{M}$ which can bring the result toma into existence with the system in a given state. In our example, with the system in state $\boldsymbol{\Theta}_1$, the corresponding ways vector will be zero:

$$\boldsymbol{\Phi}_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{3}$$

In the system state $\boldsymbol{\Theta}_2$, toma A exists and B does not. The only possible result toma that can come to exist is a, via the process ε_1. Thus the ways vector with the system in this state is:

$$\boldsymbol{\Phi}_2 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \tag{4}$$

In the system state $\boldsymbol{\Theta}_3$, toma B exists but toma A does not. The only result toma that can come into existence is c, and it can do so through either of two processes ε_3 or ε_4. Thus the ways vector with the system in this state is:

$$\boldsymbol{\Phi}_3 = \begin{bmatrix} 0 \\ 0 \\ 2 \end{bmatrix} \tag{5}$$

Finally, with the system in state $\boldsymbol{\Theta}_4$ both tomas A and B exist. Any of the result tomas can come into existence. Toma a can do so through one process ε_1, toma b through one process ε_2 and toma c through either of two processes ε_3 or ε_4. The ways vector with the system in this state is therefore:

$$\boldsymbol{\Phi}_4 = \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix} \quad (6)$$

Let *r* be the number of tomas in the result network R. In our example from figures 8 and 9, *r* = 3. We define the 1-normalized ways vector $\boldsymbol{\Phi}'$ as:

$$\boldsymbol{\Phi}' = \frac{\boldsymbol{\Phi}}{\sum_{i=1}^{r} \boldsymbol{\Phi}[i]} \quad (7)$$

Given a result tomat, the entry $\boldsymbol{\Phi}'[t_\#]$ gives the probability that toma t will come into existence first and become "latched on" in the mex result network. Thus, this entry is the probability that the result of the measurement is the numerical value corresponding to t, namely $N(t_\#)$. We represent this probability by $P(N(t_\#))$ so that:

$$P(N(t_\#)) = \boldsymbol{\Phi}'[t_\#] \quad (8)$$

In our example, the 1-normalized ways vectors corresponding to each of the four possible system states are:

$$\boldsymbol{\Phi}'_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \qquad \boldsymbol{\Phi}'_2 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \qquad \boldsymbol{\Phi}'_3 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \qquad \boldsymbol{\Phi}'_4 = \begin{bmatrix} 0.25 \\ 0.25 \\ 0.5 \end{bmatrix} \quad (9)$$

With the system in state $\boldsymbol{\Theta}_1$we see $\boldsymbol{\Phi}'_1$ is zero and so no result toma can come into existence. We see from $\boldsymbol{\Phi}'_2$ that with the system in state $\boldsymbol{\Theta}_2$ toma a will come to exist with probability 1. With the system in state $\boldsymbol{\Theta}_3$ we see from $\boldsymbol{\Phi}'_3$ that toma c will come to exist with probability 1, Examining $\boldsymbol{\Phi}'_4$ we see that when the system is in state $\boldsymbol{\Theta}_4$, result tomas a and b each have a 0.25 probability of coming into existence, while toma c has a 0.5 probability of doing so. Therefore, in a large number of runs of the experiment with the system in state $\boldsymbol{\Theta}_4$ we expect the result of the measurement to be 1 in a quarter of the runs, 2 in another quarter, and 3 in the remaining half of the runs. These results (1, 2, 3) are the numerical values corresponding to each result toma, respectively: $N(a_\#)$, $N(b_\#)$ and $N(c_\#)$.

When working with vectors it is more common to normalize them using the 2-norm:

$$|\boldsymbol{a}| = \sqrt{\sum_i (\boldsymbol{a}[i])^2} \quad (10)$$

rather than the 1-norm as we used in equation (7). So that we can rewrite that equation using the 2-norm, we define a vector $\boldsymbol{\Psi}$, called the *wavefunction*, of the same dimensions as the ways vector $\boldsymbol{\Phi}$ and with elements given by:

$$\forall_{i \in \{1,2,\dots,r\}} \boldsymbol{\Psi}[i] = \sqrt{\boldsymbol{\Phi}[i]} \quad (11)$$

We can normalize the wavefunction $\boldsymbol{\Psi}$ using the 2-norm:

$$\widehat{\boldsymbol{\Psi}} = \frac{\boldsymbol{\Psi}}{|\boldsymbol{\Psi}|} \tag{12}$$

Given a toma t in the result network ℛ and using equations (10), (11) and (12) we find that:

$$\widehat{\boldsymbol{\Psi}}[t_\#] = \frac{\boldsymbol{\Psi}[t_\#]}{\sqrt{\sum_{i=1}^{r}(\boldsymbol{\Psi}[i])^2}} = \frac{\sqrt{\boldsymbol{\Phi}[t_\#]}}{\sqrt{\sum_{i=1}^{r}\boldsymbol{\Phi}[i]}} \tag{13}$$

and so using equations (7), (8) and (13) we have:

$$\left(\widehat{\boldsymbol{\Psi}}[t_\#]\right)^{\mathbf{2}} = \frac{\boldsymbol{\Phi}[t_\#]}{\sum_{i=1}^{r}\boldsymbol{\Phi}[i]} = \boldsymbol{\Phi}'[t_\#] = P(N(t_\#)) \tag{14}$$

Now let us define an *r*×*r* diagonal matrix ***X*** as follows:

$$\boldsymbol{X} = \begin{bmatrix} N(1) & & & \\ & N(2) & & \\ & & \ddots & \\ & & & N(r) \end{bmatrix}_{\boldsymbol{r}\times\boldsymbol{r}} \tag{15}$$

The entries on the diagonal of ***X*** are the numerical values corresponding to each result toma in the quantic network ℛ. This matrix has *r* eigenvectors $\boldsymbol{\Psi}_{\mathbf{1}} \ldots \boldsymbol{\Psi}_r$ such that:

$$\forall_{i\,\in\,\{1,2,\ldots,r\}}\boldsymbol{X}\boldsymbol{\Psi}_i = N(i)\boldsymbol{\Psi}_i \tag{16}$$

where the eigenvectors are given by:

$$\forall_{i,j\,\in\,\{1,2,\ldots,r\}}\boldsymbol{\Psi}_i[j] = \begin{cases} 1 & if \quad i = j \\ 0 & if \quad i \neq j \end{cases} \tag{17}$$

We note that for any normalized wavefunction $\widehat{\boldsymbol{\Psi}}$ we have:

$$\widehat{\boldsymbol{\Psi}}\boldsymbol{X}\widehat{\boldsymbol{\Psi}} = \sum_{i=1}^{r}\widehat{\boldsymbol{\Psi}}[i]N(i)\widehat{\boldsymbol{\Psi}}[i] = \sum_{i=1}^{r}N(i)P(N(i)) \tag{18}$$

which is the average numerical result of measurement we expect to obtain from a large number of runs of the experiment. We refer to this average as the *expectation value* and denote it by $\langle X\rangle$ so that:

$$\langle X\rangle = \widehat{\boldsymbol{\Psi}}\boldsymbol{X}\widehat{\boldsymbol{\Psi}} \tag{19}$$

Let us now summarize the above toma-based theory of measurement and compare it to the quantum mechanical idea of the "collapse of the wavefunction". In the toma model of measurement, there is no result until the measurement is made. This is a radical departure from the OST model, in which we believe all things have well-defined properties, whether or not we have measured them. We see in the toma model that a result of measurement comes into existence only as a result of a *process* happening in the measurement interconnect M. Which of these processes happens is, by symmetry, random, thus explaining the deep reason why measurement is non-deterministic. The probability of obtaining a given result with the system in a given state is given by the square of the corresponding entry in the normalized wavefunction—see equation (14). If the wavefunction is one of the eigenvectors $\boldsymbol{\Psi}_i$, we know the result of measurement will be $N(i)$ with probability 1. The average result we would obtain in a large number of runs of the experiment is the expectation value given by equation (19), which is the toma model equivalent of the quantum mechanical equation for the expectation value:

$$\langle X \rangle = \langle \boldsymbol{\Psi} | \boldsymbol{X} | \boldsymbol{\Psi} \rangle \tag{20}$$

In the toma model, the wavefunction is related via equation (11) to the number of processes in M that can bring each result toma into existence. In quantum mechanics, we call the wavefunction the "state of the system". In the toma model, it is more accurate to call it the "state of the experiment", this encompassing the entire ontic network made up of the system network S, the result network R and the interconnect M.

In the OST model, when we measure, say, x = 42, we think x must "be" 42 "out there" as a property of some physical "stuff." We believe that our *model* of the world "x = 42," derived from observations, is how things *really* are "out there." In the process view, "x = 42" is not a property of any "stuff" but just one possible toma that can come to exist depending on what processes happen, and how they relate to each other.

In quantum mechanics, we would call a wavefunction with more than one non-zero entry a "superposition of states" or a "mixed state". Then, when a measurement is made, we would say that the wavefunction "collapsed" so it only has one non-zero entry, corresponding to the actual value of measurement obtained. This terminology is influenced heavily by the OST model, wherein everything, every system, "has" a determinate state. In contrast, in the toma model, we don't view such a mixed wavefunction as a superposition of system states; rather we see it as as accounting of the number of different processes in the interconnect M which can bring each result toma into existence. The wavefunction, in the toma view, is a distillation of the structure of the experimental ontic network composed of S, R and M which contains only the information needed to compute the probabilities of each result through equation (14).

The wavefunction as discussed in this section is a vector of real numbers, while we know that in quantum mechanics the wavefunction is a complex vector. The reason for this is that in this section we have not considered motion or time. In the next section we see how we can understand motion and time in the toma model. We will derive time-evolution equations and find these equations introduce an imaginary component to the wavefunction, and so we will end up with complex wavefunctions as in quantum theory.

(*Continued on Part II*)