An Accumulative Model for Quantum Theories

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Abstract. For a general quantum theory that is describable by a path integral formalism, we construct a mathematical model of an accumulation-to-threshold process whose outcomes give predictions that are nearly identical to the given quantum theory. The model is neither local nor causal in spacetime, but is both local and causal is in a non-observable path space. The probabilistic nature of the squared wavefunction is a natural consequence of the model. We verify the model with simulations, and we discuss possible discrepancies from conventional quantum theory that might be detectable via experiment. Finally, we discuss the physical implications of the model.

Keywords: quantum theory, quantum mechanics, pre-space, Born rule, signal processing, threshold process, path integral, causality

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1. Introduction

The paradoxical, apparently indeterministic nature of quantum theory has prompted numerous attempts to provide a deterministic, causal basis for the theory. One possible approach is to admit the possibility of causes outside of space and time. Bohm and Hiley take this point of view, and identifies spacetime events as "unfoldings" of a more fundamental "implicate order" that is manifested within "pre-space" ([1],[2]). Frescura and Hiley, building on this foundation, have developed an algebraic representation of pre-space dynamics [3]. A somewhat different tack is taken in [4], which essentially proposes a conceptual model of pre-space and a local, deterministic (but statistically random) dynamics within that pre-space that produces quantum particle transmission when "unfolded". The model derives from an analogy with signal detection in wireless communications: particle detection is represented as the outcome of a signal accumulation process which occurs in spacetime augmented by an extra, non-spacetime dimension (referred to as the a-dimension). The quantum wavefunction corresponds to in-phase and quadrature-phase components of an amplitude and phase-modulated carrier signal field that is present throughout spacetime augmented by the a-dimension. The location of particle detection is determined when an accumulated signal reaches a threshold (so that attaining the threshold effects the "unfolding"). The paper derives the Born probability rule is a mathematical consequence: however, the paper gives no explanation of the origin or formation of the carrier signal field required for the model.

The current paper provides a more comprehensive interpretation of quantum probabilities than [4] by taking a related, but somewhat different approach. The approach is based on the observation that both quantum mechanics and quantum field theory may be derived from a path integral formalism. We conjecture that path integrals correspond to a universal physical process which essentially performs a numerical integration. As in the previous paper, this process unfolds in a non-spacetime dimension, and the observable universe is the outcome of the process upon attaining a threshold.

The paper is organized as follows. Section 2 presents a simplified preliminary mathematical model which illustrates the basic model structure. We demonstrates the model's ability to generate quantum probabilities both theoretically and with simulations. Section 3 gives a more detailed model which is designed to conform more closely with the hypothesized physical processes involved. Results of model simulations are also presented. Section 4 discusses the possibility of experimental verification of the model; and Section 5 gives a summary discussion. For the sake of completeness, the Matlab/Octave source code used in the simulations is given in Section 6.

2. Preliminary model

Let $\mathcal{U}$ represent the space of all possible configurations of the observable universe. We emphasize that any $u \in \mathcal{U}$ expresses the entire configuration of the universe over all times, not just its configuration at a single time. We do not need to specify whether we are employing a quantum-mechanical or field-theoretic representation of the universe's configuration space – our argument does not depend on the specific nature of $\mathcal{U}$.

In both quantum-mechanical or the field-theoretic representations of $\mathcal{U}$, the wavefunction can be expressed in terms of a path integral $\Psi : \mathcal{U} \to \mathbb{C}$ of the form::

$$\Psi(u) \equiv \frac{1}{|\Gamma_u|} \sum_{\gamma \in \Gamma_u} e^{iS(\gamma)}, \tag{1}$$

where Γ_u is a space of paths corresponding to the configuration u, and $S(\gamma)$ is the action associated with the path γ. Here we have used summation notation to facilitate the connection with simulations that we will describe later. We shall suppose that $|\Gamma_u|$ is independent of u, so that $|\Gamma_u| = |\Gamma|/|\mathcal{U}|$ where $\Gamma \equiv \cup_u \Gamma_u$. We also suppose that the $\{\Gamma_u\}_{u \in \mathcal{U}}$ are disjoint, which implies that for every $\gamma \in \Gamma$ there exists a unique $u_\gamma \in \mathcal{U}$ such that $\gamma \in \Gamma_{u_\gamma}$.

The path integral is associated with a probability distribution:

$$P_S(u) \equiv \frac{|\Psi(u)|^2}{\sum_{v \in \mathcal{U}} |\Psi(v)|^2}. \tag{2}$$

The fact that this probability is written in terms of a summation (or integral) suggests that some sort of accumulation process could be involved. The main purpose of this paper is to show that such an interpretation is indeed feasible, and provides a simple, plausible explanation of the hidden dynamics that give rise to quantum theories. Preliminarily, we note that our interpretation must address two issues:

- Why is probability obtained from a squared complex amplitude?
- What physically corresponds to the division in (2)?

In the following, we give what we believe to be satisfactory answers to these two questions.

We define an accumulation process as follows. Given the sequence of paths $\gamma_1, \gamma_2, \ldots$ in Γ, we define an *accumulated amplitude* $\mathcal{A}_K$ $(K \in \mathbb{Z}_+)$ as:

$$\mathcal{A}_K \equiv \Sigma_{k=1}^{K} e^{iS(\gamma_k)}. \tag{3}$$

One possible interpretation of each factor $e^{iS(\gamma_k)}$ is as the phasor representation [5] of an oscillation (of unknown frequency) which depends on γ_k. The summation then corresponds to the complex amplitude of a harmonic oscillator (with the same frequency) that is successively perturbed by these oscillations.

Although we are using discrete notation, the sequence $\{\gamma_k\}$ should be thought of as a discrete approximation of a path-valued function of a continuous index, corresponding to a continuously-varying path within the space Γ of all possible paths. The continuous index corresponds the the a-dimension introduced in [4]: and the variation within Γ corresponds to an evolutionary process within this dimension which uniformly samples

Γ over the long term. Note that as γ_k varies, the corresponding state of the universe $u_k \equiv u_{\gamma_k}$ also varies. In the process we will define, the accumulated amplitude grows to reach a fixed threshold at a particular index K, at which point u_K gives the configuration of the observable universe.

In order to obtain the probabilities (2) via this process, we impose additional conditions on the sequences $\{\gamma_k\}$ and $\{u_k\}$ as follows.

(a) There exists $N \gg 1$ and $M \gg 1$ such that $u_{kNM+1} = u_{kNM+2} = \ldots = u_{(k+1)NM}, \forall k \in \mathbb{Z}_{\geq 0}$;

(b) For each $k \in \mathbb{Z}_{\geq 0}$, the sequence $\{\gamma_{kN+1}, \gamma_{kN+2}, \ldots, \gamma_{(k+1)N}\}$ uniformly samples $\Gamma_{u_{kN}}$;

(c) The sequence $\{u_{NM}, u_{2NM}, \ldots\}$ is mixing [6] and uniformly samples $\mathcal{U}$.

These conditions correspond to a situation where $\{\gamma_k\}$ varies throughout Γ such that the sequence $\{\gamma_k\}$ uniformly samples each Γ_u that it visits before passing on to the next Γ_u. In this simple model, the dwell time within each Γ_u visited is the constant N: in our subsequent model, this assumption will be relaxed. The significance of M will be explained later.

Let η_k $(k = 1, 2, \ldots)$ be a sequence of independent, identically distributed (i.i.d.) complex-valued random variables with zero mean and finite variance, and define:

$$\mathcal{A}'_K = \sum_{k=1}^{K} \eta_{\lceil k/N \rceil} e^{iS(\gamma_k)}. \tag{4}$$

Finally, given $\Theta > 0$, we define the *threshold index* as the random variable:

$$K_\Theta \equiv \min(k || \mathcal{A}'_k| < \Theta \text{ and } |\mathcal{A}'_k| \geq \Theta). \tag{5}$$

Given the above conditions and definitions, we have the following result:

Proposition: As $N, M, \theta \to \infty$, we have

$$P(u_{K_{\theta N\sqrt{M}}} = u) \to P_S(u). \tag{6}$$

In other words, the probability distribution on $\mathcal{U}$ at the stopping time defined by attaining the threshold $\theta N\sqrt{M}$ agrees with the probability distribution (2) obtained from the path-integral formalism.

The proof of this proposition is similar to that given in [4]. Notice that (4) can be rewritten as

$$\frac{\mathcal{A}'_{KN}}{\theta N\sqrt{M}} = \frac{1}{\theta N\sqrt{M}} \sum_{k=1}^{K} \eta_k \left(\sum_{n=1}^{N} e^{iS(\gamma_{(k-1)N+n})} \right) \tag{7}$$

$$\underset{N\to\infty}{\longrightarrow} \frac{|\mathcal{U}|}{\theta|\Gamma|\sqrt{M}} \sum_{k=1}^{K} \eta_k \Psi(u_{\lceil k/M \rceil}) \tag{8}$$

$$= \frac{|\mathcal{U}|}{\theta|\Gamma|} \left(\sum_{k=1}^{\lfloor K/M \rfloor} \Psi(u_k) \Big(\frac{1}{\sqrt{M}} \sum_{m=1}^{M} \eta_{(k-1)M+m} \Big) + \Psi(u_{\lceil k/M \rceil}) \Big(\frac{1}{\sqrt{M}} \sum_{m'=M\lfloor K/M \rfloor+1}^{K} \eta_{m'} \Big) \right). \tag{9}$$

The proof is based on the fact that $\frac{\mathcal{A}'_{KN}}{\theta N\sqrt{M}}$ can be approximated in distribution as a Brownian motion $B(a)$ in $\mathbb{C}$ with absorbing boundary at $|z| = 1$, where $a \equiv \frac{K}{\theta^2 NM}$. For any fixed a, near the boundary the probability density of an absorbing Brownian motion is proportional (to first order) to the distance from the boundary. This can be used to show that for any K, the probability $P(K_{\theta N\sqrt{M}} = K | u_K = u)$ is approximately proportional to $E[|\eta_K \Psi(u)|^2]$, which is proportional to $|\Psi(u)|^2$. Since for $P(u_K = u)$ is independent of u when $1 \ll K < K_{\theta N\sqrt{M}}$, it follows that $P(K_{\theta N\sqrt{M}} = K \; \& \; u_{K_{\theta N\sqrt{M}}} = u)$ is proportional to $|\Psi(u)|^2$, and summing over K gives the desired result.

Figure 1 shows the results of simulations of the model specified by conditions (a)–(c) and equations (4)–(5). The simulations were performed on a discrete system with 11 possible states. To shorten computational time, the simulation was based on equation (8) rather than performing the full computation (7) on a path-by-path basis. The random variables $\{u_{NM}, u_{2NM}, \ldots\}$ referred to in (c) were generated uniformly randomly. The curves show the difference between the simulated probabilities and actual probabilities for two different probability distributions $|\Psi|^2$, for different values of the threshold θ. The errors are shown on the y-axis, versus the actual probability values which are shown on the x-axis. As θ increases, the errors decrease: for $\theta = 40$, the maximum error is under 5 percent. The pattern of error apparently depends on the type of probability distribution being modeled. However, in both cases the larger probabilities are underestimated, and there is a range of intermediate probabilities that are overestimated. These phenomena may possibly enable an experimental test of the model: this possibility is explored further in Section 4.

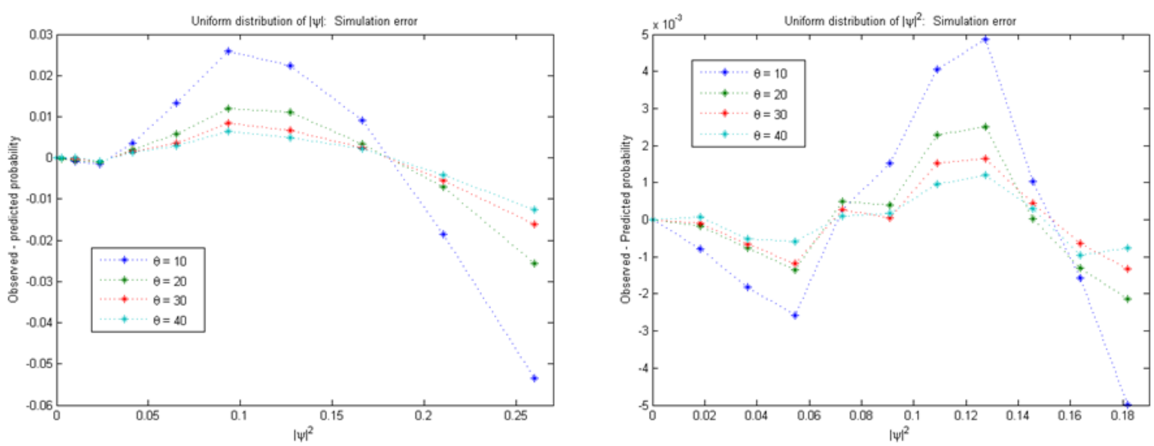

Figure 1. Deviations of computed probabilities from quantum values, for simulated preliminary accumulation model with $\theta = 10, 20, 30, 40$ and $M = 10000$, where $\{\eta_k\}$ are i.i.d. standard normal random variables. Each simulation was run 100,000 times. All simulations used 11 configurations u. For the figure at left, $|\psi(u_j)| \propto j$, $(j = 0, \ldots, 10)$, while for the figure at right, $|\psi(u_j)|^2 \propto j$ $(j = 0, \ldots, 10)$.

3. Refined model

The process we have presented above has some seemingly artificial features:

- Why should $\{u_k\}$ remain constant for intervals of size MN?
- What is the physical significance of the η_k's?

As to the first point, instead of supposing that $\{u_k\}$ remains constant on intervals of size N, we may suppose that $\{u_k\}$ varies slowly with k, so that

$$p(u_{k+1} \neq u_k) = \mathcal{O}\left(\frac{1}{N}\right). \tag{10}$$

Supposing that $\{\gamma_k\}_{k=1.2.3....}$ is generated by a Markov process, it is reasonable to suppose that residence times in each u state visited are (approximately) i.i.d. geometrical random variables. This is because under reasonable conditions, hitting times in Markov chains are asymptotically exponentially distributed [7]. (The geometrical distribution is the discrete analog of the exponential distribution.) Accordingly, we may modify the model by replacing the constant M with a geometrically-distributed random variable with the same mean.

As to the second point, we must recognize that we have failed to account for the fact that in practice we never measure the state of the entire universe, but only a subsystem. So we must take into account the effect of variations in the external system during the accumulation process. Accordingly we let Ω be the possible states of the measured subsystem, while Ω' denote the possible states of the universe external to the measured subsystem. Thus we may represent any element $u \in \mathcal{U}$ uniquely as $u = (w, w')$, where $w \in \Omega$ and $w' \in \Omega'$.

We suppose that any path in Γ can be factored into a part for Ω and a part for Ω': more precisely, that there are path spaces $\mathcal{C}$ and $\mathcal{C}'$ respectively such that any $\gamma \in \Gamma$ can be decomposed as $\gamma = (c, c')$ where $c \in \mathcal{C}, c' \in \mathcal{C}'$, and such that $u_\gamma = (w_c, w'_{c'})$. We define $\mathcal{C}_w \equiv \{c | w_c = w\}$, and suppose (as in the simple model) that $|\mathcal{C}_w|$ is independent of $w \in \Omega$, so that $|\mathcal{C}_w| = |\mathcal{C}|/|\Omega| \ \forall w$. We similarly definine $\mathcal{C}'_{w'}$, and suppose $|\mathcal{C}'_{w'}| = |\mathcal{C}'|/|\Omega'| \ \forall w'$. Finally, we suppose that the action S is additive: $S(\gamma_k) = S(c_k) + S(c'_k)$. From this it follows that we may write:

$$\Psi(u) = \Psi((w, w')) = \psi(w)\phi(w'), \tag{11}$$

where

$$\psi(w) \equiv \frac{|\Omega|}{|C|} \sum_{c \in C_w} e^{iS(c)}; \quad \phi(w') \equiv \frac{|\Omega'|}{|C'|} \sum_{c' \in C_{w'}} e^{iS(c')}. \tag{12}$$

We may also rewrite (3) as

$$\mathcal{A}_K \equiv \Sigma_{k=1}^K e^{iS(c_k)} e^{iS(c'_k)}. \tag{13}$$

We now postulate the existence of a Markov chain $\{(c_1, c_1'), (c_2, c_2'), \ldots\}$ that satisfies the following properties. Define inductively a sequence of random times $\{\mathcal{X}_k\}$ such that

$$\mathcal{X}_0 \equiv 1; \qquad \mathcal{X}_{k+1} \equiv \min(j | w_j' \neq w_{\mathcal{X}_k}').$$

We suppose the Markov chain has transition probabilities such that $w_j \neq w_{j+1} \implies w_j' \neq w_{j+1}'$. This supposition reflects the assumption that the external state varies more rapidly than the observed state, which is reasonable since the external state is much, much larger and has many more possibilities for variation. In this case, it is possible to define inductively a sequence of random times $\{\mathcal{Z}_k\}$ such that $\mathcal{Z}_0 = 1$ and $\mathcal{Z}_{k+1} \equiv \min(j | w_{\mathcal{X}_j} \neq w_{\mathcal{X}_{\mathcal{Z}_k}})$. According to these definitions, the state w' does not change on each time interval $[\mathcal{X}_k, \mathcal{X}_{k+1} - 1]$, and the state w does not change on each time interval $[\mathcal{X}_{\mathcal{Z}_k}, \mathcal{X}_{\mathcal{Z}_{k+1}-1}]$. We also suppose the paths vary much faster than the states, so that the space $C_{w_{\mathcal{X}_k}}$ is uniformly sampled on the time interval $[\mathcal{X}_k, \mathcal{X}_{k+1} - 1]$.

Based on the Markov chain described in the previous paragraph, we may formulate the following model assumptions:

(A) There exists a $N \gg 1$ and a sequence $\{\xi_1, \xi_2, \ldots\}$ of i.i.d. geometrically-distributed random variables with $E[\xi_k] = N$, such that $w'_{\mathcal{X}_K+1} = w'_{\mathcal{X}_K+2} = \ldots = w'_{\mathcal{X}_K+\xi_k}$ $\forall K \in \mathbb{Z}_{\geq 0}$, where $\mathcal{X}_0 \equiv 0$ and $\mathcal{X}_K \equiv \sum_{k=1}^{K} \xi_k$, $K \geq 1$;

(B) There exists a $M \gg 1$ an a sequence $\{\zeta_1, \zeta_2, \ldots\}$ of i.i.d. geometrically-distributed random variables with $E[\zeta_k] = M$, such that $w_{\mathcal{X}_{\mathcal{Z}_K}+1} = w_{\mathcal{X}_{\mathcal{Z}_K}+2} = \ldots = w_{\mathcal{X}_{\mathcal{Z}_{K+1}}}$ $\forall K \in \mathbb{Z}_{\geq 0}$, where $\mathcal{Z}_0 \equiv 0$ and $\mathcal{Z}_K \equiv \sum_{k=1}^{K} \zeta_k$, $K \geq 1$;

(C) For each $K \in \mathbb{Z}_{\geq 0}$, the sequences $\{c'_{\mathcal{X}_K+1}, c'_{\mathcal{X}_K+2}, \ldots, c'_{\mathcal{X}_K+\xi_k}\}$ and $\{c_{\mathcal{X}_K+1}, c_{\mathcal{X}_K+2}, \ldots, c_{\mathcal{X}_K+\xi_k}\}$ uniformly sample $C'_{\mathcal{X}_{K+1}}$ and C, respectively;

(D) The sequences $\{c'_{\mathcal{X}_K+1}, c'_{\mathcal{X}_K+2}, \ldots, c'_{\mathcal{X}_K+\xi_k}\}$ and $\{c_{\mathcal{X}_K+1}, c_{\mathcal{X}_K+2}, \ldots, c_{\mathcal{X}_K+\xi_k}\}$ are statistically independent;

(E) The sequences $\{w'_{\mathcal{X}_1}, w'_{\mathcal{X}_2}, \ldots\}$ and $\{w_{\mathcal{X}_{\mathcal{Z}_1}}, w_{\mathcal{X}_{\mathcal{Z}_2}}, \ldots\}$ are mixing, and uniformly sample Ω and Ω' respectively.

Following these assumptions, we may compute:

$$\begin{aligned}
\frac{\mathcal{A}'_{\mathcal{Z}_K}}{\theta N \sqrt{M}} &= \frac{1}{\theta N \sqrt{M}} \sum_{k=0}^{K-1} \sum_{m=\mathcal{Z}_k}^{\mathcal{Z}_{k+1}-1} \sum_{n=\mathcal{X}_m+1}^{\mathcal{X}_{m+1}} e^{iS(c_n)+S(c_n')} \\
&\approx \frac{|\Omega||\Omega'|}{\theta\sqrt{M}|C||C'|} \sum_{k=0}^{K-1} \sum_{m=\mathcal{Z}_k}^{\mathcal{Z}_{k+1}-1} \frac{\xi_{m+1}}{N} \psi(w_{\mathcal{X}_{m+1}}) \phi(w'_{\mathcal{X}_{m+1}}) \qquad (14) \\
&= \frac{|\Omega||\Omega'|}{\theta|C||C'|} \sum_{k=0}^{K-1} \left(\psi(w_{\mathcal{X}_{\mathcal{Z}_{k+1}}}) \cdot \frac{1}{\sqrt{M}} \sum_{m=\mathcal{Z}_k}^{\mathcal{Z}_{k+1}-1} \frac{\xi_{m+1}}{N} \phi(w'_{\mathcal{X}_{m+1}}) \right) \\
&= \frac{|\Omega||\Omega'|}{\theta|C||C'|} \sum_{k=1}^{K} \left(\psi(w_{\mathcal{X}_{\mathcal{Z}_k}}) \cdot \frac{1}{\sqrt{\zeta_k}} \sum_{m=1}^{\zeta_k} \eta_{m,k} \right), \qquad (15)
\end{aligned}$$

where the approximation holds for large N and

$$\eta_{m,k} \equiv \sqrt{\frac{\zeta_k}{M}} \left(\frac{\xi_{\mathcal{Z}_{k-1}+m}}{N} \right) \phi \left(w'_{\mathcal{X}_{\mathcal{Z}_{k-1}+m}} \right). \tag{16}$$

Notice the similarity between (9) and (15). Instead of a summation over M, there is a summation over ζ_k, which has expectation M. Within this summation, instead of the mean-zero i.i.d. random variables $\{\eta_k\}$, we now have $\{\eta_{k,m}\}$ given by the complicated expression (16). By assumption, the variables ζ_k/M and $\xi_{\mathcal{Z}_{k-1}+m}/N$ are independent, and have expectation 1; while the additional complex factor $\phi \left(w'_{\mathcal{X}_{\mathcal{Z}_{k-1}+m}} \right)$ will vary randomly with mean zero as the process evolves. If we assume that $\{\eta_{k,m}\}$ are (approximately) i.i.d. mean-zero random variables, then (15) and (9) are virtually identical, except that ζ_k in (15) replaces M in (9). However, $E[\zeta_k] = M$; and conditioning on the different possible values of ζ_k, we may obtain the same result that the probability density for w_{K_Θ} is given by $|\psi(w)|^2$.

Figure 2 shows results of simulations of the refined model specified in (A)-(E). A system with 31 discrete states was simulated, and the states' probabilities were chosen according to the sinusoidal wavefunction shown in the picture. The transition between states w was determined according to a Markov chain that produced a mean dwell time of M, followed by a transition to one of the four nearest-neighbor states with equal probability 1/4. Parameters used were $M = 625$ and $\theta = 10$. The figure shows very close agreement between quantum-theoretic probabilities and those obtained from simulation. Deviations are shown in more detail in Figure 3 for different values of M and θ. Small $|\psi|^2$'s are consistently overestimated, and large $|\psi|^2$'s are underestimated. Deviations between simulation and quantum theory decrease with increasing M and θ, so that the model probabilities apparently converges to quantum-theoretic values as $M, \theta \to \infty$.

4. Proposed Experimental Test

In the above model, quantum probabilities are generated by an accumulative process which essentially performs a stochastic approximation to the quantum path integrals. In the previous section we showed that finite values of θ and M introduced deviations from quantum-theoretical probabilities. In both cases, the deviations are positive for small probabilities, but negative for large probabilities.

Another possible source of numerical error, which we did not model in the simulation, results from the approximation

$$\frac{1}{\xi_m} \sum_{n=\mathcal{X}_m+1}^{\mathcal{X}_m+\xi_m} e^{iS(c_n)} \approx \psi(w_{\mathcal{X}_{m+1}}), \tag{17}$$

which was used in (14). If we suppose there is a random error of constant variance ϵ^2 in this approximation, then by carrying through the computations it can be shown

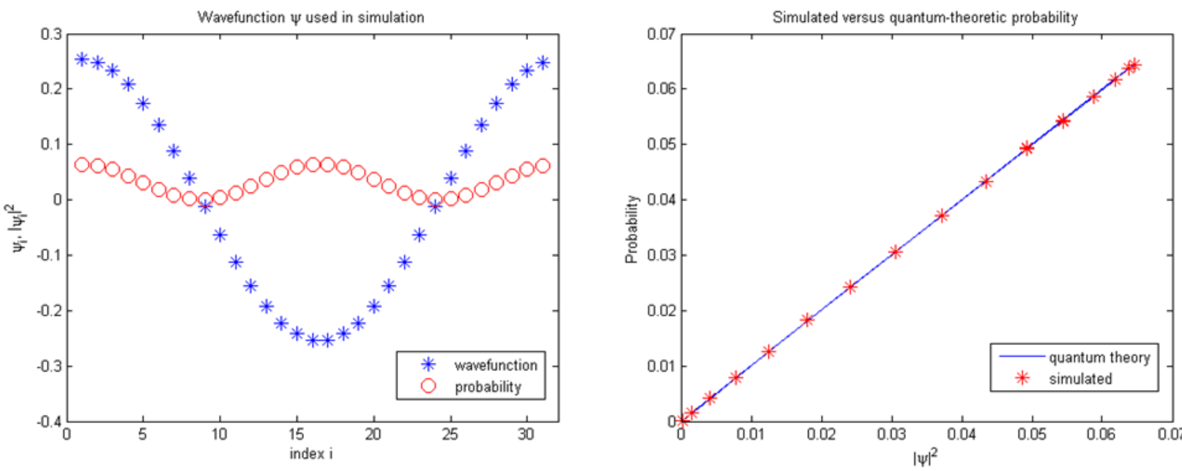

Figure 2. (Left) Sinusoidal "wavefunction" used in simulation. 31 configurations were used with probabilities as shown. (Right) Simulation results compared to theory for $\theta = 10, M = 625$. Computed probabilities are based on 10 million repetitions.

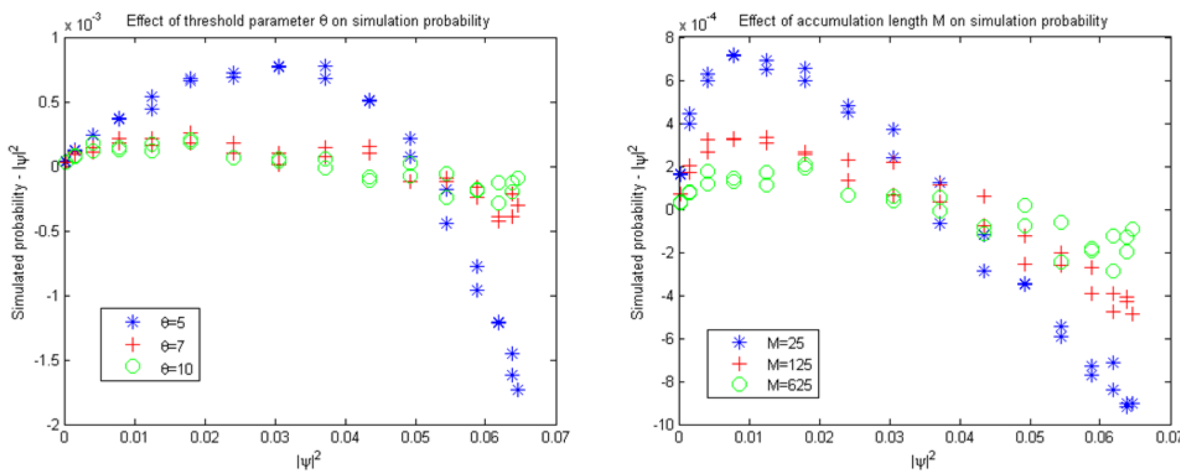

Figure 3. Deviations of computed probabilities from quantum values for simulated adjusted accumulation model, for different values of the accumulation length M and threshold parameter θ (as specified in the figure titles). All computed probabilities are based on 10 million repetitions.

that probabilities turn out to be proportional to $|\psi(w)|^2 + \epsilon^2$ rather than $|\psi(w)|^2$. This produces a deviation from theoretical probabilities that decreases linearly with increasing probability density. So the deviations from quantum-theoretic probabilities due to this effect reinforce the deviations already discussed.

We may conclude that numerical approximation effects should introduce a deviation from quantum-theoretic probabilities that for larger probabilities decreases roughly linearly with increasing probability density. Unfortunately, since the parameters of the process are not directly accessible, it is not possible to predict the size of the deviations.

5. Discussion

The above model provides a conceptually simple solution to many conundrums of quantum theory. It accounts for all quantum paradoxes, since it yields the same probabilities as quantum theory (to a close approximation). It requires no distinction between observer and observed, because the probabilistic significance of the wavefunction is a consequence of the model, rather than an extraneous assumption that is added to match theory with experiment. In particular, the "measurement problem" is no longer a problem: what is perceived as a "collapse of the wavefunction" corresponds to the fact that one particular state of the universe is selected as a result of the thresholding process.

Our model gives a very different perspective on several seemingly "evident" aspects of the universe. Physical causality is atributed to correlation: causes and effects are correlated outcomes of an inaccessible process that occurs outside of spacetime. The Big Bang is not accounted as the "origin" of the universe, because it also is part of the outcome of an extra-dimensional process which produces past, present, and future together as an entirety. (The model thus seems to imply that the universe will have finite duration.) The vacuum is not a "boiling, bubbling brew of virtual particles and fields wildly fluctuating in magnitude,"[8] as quantum field theory seems to imply, but only appears so because of the accumulation process through which the observable universe is actualized.

We mentioned in the introduction that the "pre-space" approach proposed and developed by Bohm, Hiley, and others bears some similarity to our approach. However, our portrayal of pre-space is radically different from that envisioned by Bohm et. al. This difference is clearly seen when we compare the analogies that we use to explain our respective notions of pre-space.

The original inspiration for our model was the example of a cellular phone which accumulates a pilot signal broadcast by a base station as the phone is carried about by the user. When the signal accumulation reaches a certain threshold, a detection is logged. The user's location at the moment of detection is determined by the process of signal accumulation–but no comprehensive record of his past motion may be seen in the final outcome. Still, the outcome reflects the process in that the detection location is more likely to be at a location where the signal is strong. In other words, the legacy of the process of signal accumulation is seen in the probability distribution of the observed outcome.

On the other hand, Bohm in [1] describes an experiment in which a droplet of dye is introduced into a viscous fluid, the fluid is stirred, and the process is repeated several times. When the fluid is stirred in the reverse direction, the droplets reappear one by one. These droplets represent the unfolded order that is evidenced in spacetime events. Fresca and Hiley take this illustration as a jumping-off point in their portrayal of quantum processes in terms of successive enfolding and unfolding. Thus spacetime events are conceived as manifestations of an *ongoing process*. Clearly this is very different from our description of a process from which the entire history of the universe springs full-blown into existence, like Athena emerging from the head of Zeus.

Finally, we consider our proposed model in the context of the overall development of theoretical physics. Physics has historically progressed by means of analogies which have been proposed, explored, and pushed to their limits. For example, Maxwell's equations were originally motivated by an analogy between electromagnetic fields and local displacements within an incompressible fluid medium due to stresses and strains[9]. But as electromagnetic theory developed, the limitations of this analogy became increasingly apparent–to the extent that it is scarcely mentioned in university courses on electromagnetism, and only a few vestiges may be seen in some of the terminology (such as stress tensor). Another important analogy (that has captured the popular imagination) is the idea that gravity bends space. This foundational idea motivated Einstein to look to differential geometry for mathematical formulations of the theory. The inability of general relativity to deal with quantum mechanics shows that the analogy can only go so far. The same could be said for Rutherford's planetary model of the atom. More germane to the subject of this paper, the analogy between the statistical-mechanical partition function and the expression (1) was a key motivation for Euclidean quantum field theory[10].

Historically, the analogies used in theoretical physics have in general been taken from nature, as seen in the above examples. In contrast, our analogy comes from wireless communications technology. We suggest that in view of its explosive development, technology may become a rich new source of analogies for physicists. Conversely, fundamental physics may increasingly suggest technological innovations–not necessarily through direct application of the physics, but rather through analogical similarities between the two regimes.

It is our hope that further exploration of the analogy presented in this paper may lead to additional physical insights. Along these lines, we mention briefly some possibilities suggested by the model we have developed:

- Feynman path integrals are notorious for yielding important physical results despite lacking a mathematical rigorous foundation. Our model suggests making a correspondence between paths and possible states of the universe. This line of attack could lead to a less problematic mathematical characterization of these path integrals.
- Although formula (1) is based on an action, so far we have said nothing about the action, nor the fields that determine its value. Our analogy with signal processing suggests that there may be a relationship between the various types of quantum fields and signal modulations.
- The model is designed to give an account of observed probability distributions for quantum events. However, so far we have not really defined event. Certainly this has something to do with the configuration of the fields involved: and perhaps this also may be understandable in terms of a signal-based representation of the fields.

Although we hope that our model will be a source of insight, we recognize that even in the best case, the analogy that we have suggested will have proscribed limits. Nonetheless, if this conceptual model proves to be accurate, it has profound implications for how we may regard the world around us, and how we regard ourselves as "free agents" within it.

6. Simulation Code

The following Octave/Matlab code was used for the simulation in Figures 2 and 3.

```
% Parameters
clear all;
nsim = 10000000;               % # simulations
nconfig=1;                    % # configs simulated
Theta_fac = 10;              % Theta increment
Theta_fac0=Theta_fac;         % Orig. theta
Ncfg = 31;                    % Number of internal configs
n_acc_mean = 625;            % M interval
max_jump = 2;              % For Markov -- max jump
acc_mean0 = n_acc_mean;       % Orig. M
p = 1/n_acc_mean;
Theta = Theta_fac*sqrt(n_acc_mean); % Rescaled threshold

% Arrays to store results
Counts = zeros(Ncfg,1);
Q = [];

% Create measurable configurations
Psi = cos((0:1:Ncfg-1)/(Ncfg)*2*pi)';
Prob = abs(Psi).^2;
Prob = Prob / sum(Prob);

% Computations
for jj = 1:1:nconfig          % Loop over configurations
for ii = 1:1:nsim             % Perform simulations
    A = 0;
    this_cfg = randi([0,Ncfg-1]);   % Choose current w
    % Accumulate:
    while abs(A) < Theta      % Until threshold is attained
        this_cfg = mod(this_cfg + sign(randn)*randi([1,max_jump]),Ncfg);
        Ptmp = Psi(this_cfg+1);% Amplitude
        while rand() > p
            Rtmp = randn()+1i*randn();
```

```
            A = A + Rtmp*Ptmp;
            if abs(A)>Theta  % If pass threshold, the break and record w
                break
            end
        end
    end
    Counts(this_cfg+1) = Counts(this_cfg+1)+1; % record w
end
Q = [Q Counts/sum(Counts)]   % Summary results for this config
Theta_fac = Theta_fac + Theta_fac0; %Increment theta
Theta = Theta_fac*sqrt(n_acc_mean);
end

Prob = abs(Psi).^2;
Prob = Prob / sum(Prob);     %Normalized, sorted probabilities (for theory)

plot(Prob,Q - Prob*ones(1,nconfig),'*');
```

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