Two time solution to quantum measurement paradoxes

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May 5, 2018

Abstract

It is hypothesized that the Langevin time of stochastic quantum quantization is a physical time over which quantum fields at all values of space and coordinate time fluctuate. The average over paths becomes a time average as opposed to an ensemble average. It is further hypothesized that the Langevin time also paces the motion of particles through coordinate time and is equal to the coordinate time of the present hypersurface in the frame of the Hubble expansion. Despite having a preferred frame, special relativity continues to hold in this formulation as a dynamical symmetry due to the presumed Lorentz invariance of interactions. The measurement process becomes an integral part of the theory and is realized as a process of spontaneous symmetry breaking. The continuously fluctuating history of fields, characteristic of having two times, and the switch from ensemble averages to time averages allows for logical and straightforward explanations of many quantum measurement paradoxes. The fluctuating history also evades hidden-variable prohibitions allowing an essentially classical system to underlie quantum mechanics. These changes to the stochastic quantization paradigm makes this stochastic classical system differ somewhat from standard quantum mechanics, so, in principle, distinguishable from it.
1 Introduction

Simulations of quantum field theory using Monte Carlo, molecular dynamics or Langevin methods all have a second time over which configurations are generated. This “Langevin time” or “Monte Carlo time” is usually thought of as simply a part of the technique, with no physical significance. It is used to generate field configurations that are then used in ensemble averages. However, to the extent these techniques generate correct answers, for which much evidence exists, one is led to the possibility that the physical world is described more directly by these equations than the original quantum field theory from which they were developed. As Langevin time advances, fields at all values of space and coordinate time fluctuate. If one additionally hypothesizes some connection between the Langevin time and the compelled motion of particles through coordinate time, where the Langevin time in some sense paces the motion through coordinate time, then one obtains a system that has a lot in common with quantum systems but differs in some useful aspects. It is possible these differences, though in principle observable, are so small as not to have been observed. In this case the real world may more closely resemble the two-time Langevin system than it does standard quantum mechanics, so it is worth considering it as an alternative. In fact, it seems to have many advantages over standard quantum mechanics in that the measurement process is easily incorporated into the theory itself, and most quantum “paradoxes” involving superpositions and entanglement appear to have simple non-mysterious explanations.

These are classical but stochastic systems that fluctuate in the Langevin time from random inputs. Expectation values become time averages of these rapidly varying classical configurations, which have definite values at any actual instant of Langevin time. The idea is to replace the ensemble averages of quantum mechanics with time averages over fluctuating classical systems.
These are not exactly the same, because the time average is only over the
time of an observation, rather than an infinite time, so it is a truncation
from the full ensemble average, which could have observable differences, for
instance for rapidly sequenced observations. This scenario also allows one to
understand how spontaneous symmetry breaking can practically take place
in a finite system as an historical event and how measurements happen in
quantum mechanics through this process of spontaneous symmetry breaking.

The fact that the past continues to exist and is still fluctuating allows one
to explain systems such as the double slit, EPR experiment, entanglement,
and Schrödinger’s cat with simple logical explanations that are no longer
mysterious. The measurement process is brought completely within quan-
tum mechanics with no additional hypotheses or interpretations required.
There is also no conflict with relativity so long as the Lagrangian is Lorentz
invariant, although relativity from this point of view is more a consequence
of dynamics than kinematics.

Although usually the above methods are performed in Euclidean space,
the Langevin approach to stochastic quantization can at least in principle
be taken directly in Minkowski space which is the version one would need
if the simulation were to be directly equivalenced to reality. This scenario
still leaves open the source of fluctuations, which are simply postulated
to be random variables located at each spacetime point that interact with
the fields. It also leaves out the sticky question of “the present” and what
determines it, and why we seem to be compelled to move through coordinate
time. This problem it shares, of course, with ordinary quantum field theory.
Physicists are divided on whether the lack of a physics explanation for the
existence of “the present” is a flaw in present-day theories.

A more radical two-time approach that solves these problems while also
explaining the source of fluctuations is the Phase Boundary Universe pro-
posal. This is a classical model that has four spatial dimensions and one
Newtonian universal time. The space is filled with a supercooled liquid at a certain temperature which undergoes ordinary thermal fluctuations. A nucleation event starts a crystal growing which is the big bang. Our 3-d universe is located at the surface of the crystal - the growing phase boundary, which we view as “the present.” The fourth spatial dimension that the crystal is growing into is interpreted by us as a time coordinate because we are compelled to move through it due to the growth of the crystal, which creates the Hubble expansion. Here the source of fluctuations are simply the ordinary thermal fluctuations of the 4-d substance (crystal + liquid) which take place in universal (Langevin) time. Elementary fermions might arise as crystal dislocations and bosons as phonon-like excitations confined to the surface, and perhaps even gravity as a surface tension effect. Special relativity arises from the dynamics. This universe is not based on a vacuum solution for the background space but rather on a non-equilibrium dynamic phase front with reduced symmetry, the symmetry of our universe. There is a preferred frame, the co-moving frame of the expansion, but it is not detectable until inverse momenta are small enough to approach the crystal spacing. A “world-crystal” model for the universe with some similarities to this has also been proposed by Kleinert and Zaanen[5]. Unfortunately a satisfactory model resembling our universe is still a long way off in the phase boundary approach. It may be required to replace the crystal with something more exotic such as a liquid crystal or one of the phases found in He-3[6]. Nevertheless, solving the mystery of the present (also addressed in [3]) and how it differs from past and future, explaining quantum fluctuations as thermal fluctuations, giving a reason for the big bang and Hubble expansion, and very possibly reconciling quantum mechanics with gravity are compelling reasons to work within this framework. Due to the two times, the quantum measurement ideas presented here also hold in the phase boundary universe model, in fact that is their origin. However, because the quantum
measurement results are simply a consequence of the two times, this paper is more generally cast for any theory that achieves stochastic quantization with a second time. The one which presents the least radical departure from standard quantum field theory is the Langevin scenario depicted above, so that is the system that will be mostly considered here.

2 Quantum measurement process as spontaneous symmetry breaking

The quantum measurement process has always been a chink in the armor of quantum mechanics. The Von Neumann wave function collapse that occurs in the standard Copenhagen interpretation is a process beyond the operation of the Schrödinger equation, and although mechanisms that involve added interactions have been suggested\[7\], there is no widely agreed upon equation that describes how it takes place. In addition, there is no agreed-upon definition of what constitutes a measuring device or a clear operational distinction between a quantum object which can exist in a superposition and a measuring device which presumably cannot. The measurement process has a close similarity to the process of spontaneous symmetry breaking(\textit{SSB}). When a quantum system undergoes SSB one always ends up in a single definite ground state with a specific value of the order parameter, never in a superposition of several ground states. Although that would seem to be possible from normal quantum evolution it is ruled out by superselection rules or similar arguments forbidding it. This looks very much like wave-function collapse. For instance at the electroweak symmetry breaking in the early universe when the Higgs particle gains a mass, one can think of the universe in a sense measuring itself for the Higgs field to fall into a specific vacuum. Superselection rules can come and go at a symmetry breaking. For instance, normally there is a superselection rule prohibiting the super-
position of states of different electric charge, however if the electromagnetic symmetry breaks spontaneously, as in the abelian Higgs model, the vacuum itself has this property. The usual argument for existence of a superselection operator is if there is no interaction connecting the states, there is no way to ever produce the superposition. This is usually a result of symmetry. In a classical statistical mechanical system operating in time (e.g. microcanonical) undergoes SSB, due to a lowering temperature for instance, then it is clear how it gets stuck in a particular sub-ensemble simply by accident by virtue of the particular state it was in when the temperature fell below the transition temperature. Providing the system is infinite, it will never make the transition to another sector - they are no longer ergodically connected. The situation is less clear in the canonical ensemble where all configurations are still counted, however adding a small external field allows one to choose a ground state in this formalism. For a finite system, there is technically no SSB. It still occurs for all practical purposes in finite systems if the tunneling times between different ground states becomes long compared to the observation time (such as the age of the universe). Thus there are significant differences between the canonical ensemble where all configurations are used and the time-series of states of a single system, averaged over a large but finite time. This can be either a microcanonical or Langevin evolution.

Given the close similarity of wave-function collapse in measurement and choice of ground state in SSB, it is tempting to try to model all measurements as a process of SSB. Measuring devices may be pictured as machines that can exist in two phases, one spontaneously broken and one not, with a knob that can be turned that adjusts the parameter that causes the symmetry to break. The device is then coupled to the property of a quantum system one wishes to measure, and then the symmetry breaking knob is activated, carrying both the measuring device and the quantum system, now strongly coupled to it, into a single broken state. However, one is again
faced with problems in the canonical formulation if the measuring device is not infinite, because then the ensembles are not fully bifurcated, superselection operators not exact and the normal problem of the measuring device itself ending up in a superposition ensues. Cosmological symmetry breaking in a finite universe suffers from the same problem. Both are solved if one switches to a stochastic system that varies over (Langevin) time, taking time averages instead of ensemble averages. In this case symmetry breaking does take place in a finite system for all practical purposes, just as it does in a finite piece of a crystal or magnet, because one is not going to observe it for an infinite time.

There are some statements in the literature that decoherence removes the need for wave function collapse\textsuperscript{[10]}, but many others feel that this is only a partial solution\textsuperscript{[11]}. It does not seem to help with the cosmological phase transition, for instance. Here I take the point of view that wave function collapse is a necessary feature of quantum mechanics which requires an explanation.

3 Double slits and interferometers

Let us consider the electron double slit experiment from this perspective. In the usual picture, the fact that an interference pattern is still created if electrons are sent at the slits one at a time, leads to the conclusion that each electron passes through both slits. The complementarity principle allows us to accept this, because, as has been shown many times, if one observes which slit the electron goes through the pattern is then destroyed. Nevertheless it is unsettling to imagine an electron in vacuum actually splitting in two and going through both slits, considering it has proven to be impossible to split an electron in half by force even given the huge energies available in particle accelerators. If it is not “exactly” splitting in two then how “ex-
actly” is it going through both slits? In a two-time theory, past values of the fields continuously fluctuate in Langevin time. For a single electron propagating the field has non-zero occupation number only for present and past, since there is no electron yet in this vicinity in the future. This means that the electron world-line drifts around as it is also extended — history is constantly being rewritten as time progresses (the coordinate time of the particle’s and observer’s present and Langevin time being linked). At one instant the electron “has” passed through one slit, perhaps just having arrived near the screen and wandering around (not yet having been absorbed). An instant later the electron world-line trajectory wanders to the second slit which is able to reconnect with the world line on the other side (perhaps similar to magnetic reconnection). We are still considering that the electron has a phase factor associated with it, i.e. a wavelike nature. As the electron is hitting the screen, still many instants of Langevin time occur before it is absorbed. Thus it wanders around from spot to spot on the screen, undergoing phase angle changes as well, due to path length differences, sometimes going through one slit and sometimes the other. Say it is a photographic screen which will initiate an irreversible chemical reaction if a certain activation energy is deposited. This energy must be built up over some time. Each time the electron returns to that spot if the phase angle is close to the same as before the effect will add, if opposite it will subtract from the previous interaction and possibly cancel it. These effects are averaged over a certain time scale characteristic of the absorber, possibly short on the human scale, but long on the Langevin scale. Once actually absorbed the electron is captured in a molecule and that end of the trajectory is then tied down. This is because so many degrees of freedom have taken place in the irreversible reaction that the transverse translation symmetry the electron had is now spontaneously broken. Its position at the final time is nearly definite, the remaining fluctuations being much smaller due to the
large numbers of coupled degrees of freedom, and the dissipation of energy. This is also what happens if one monitors the slits. Coupling large numbers of degrees of freedom to the electron at the position of the slit breaks the translation symmetry there preventing fluctuations from “rewriting history” to the extent of switching slits. Now the fluctuations at the screen don’t include the drift to the other slit, so of course the pattern seen is different.

Every field at each spacetime point changes with each instant of Langevin time. Whether the process is continuous or not is largely irrelevant. Symmetries and conservation laws as well as the presence of broken symmetries provide some order in this chaos (one could argue the only order). Whatever the exact mechanism of evolution in Langevin time, it must be possible for large changes to happen quickly because in some cases the possible paths the electron could be on are widely separated, such as in the Stern-Gerlach experiment or Mach-Zehnder interferometer. So long as symmetry and conservation laws allow it, we are picturing that the system has a way of moving quickly between allowed configurations that may be widely separated, provided the number of degrees of freedom that are changing is still small, such as the fields along a single electron’s world-line. Fields along the world line at adjacent time coordinates are highly correlated, so do not count as fully separate degrees of freedom (they must fluctuate together). This lepton number conservation keeps the number of degrees of freedom along an electron’s world-line in the relatively small category. Collective degrees of freedom involving many elementary fields, so long as the collective degrees of freedom themselves are few in number can in principle evolve quickly in a stochastic system.
4 Schrödingers cat and quantum entanglement

What is being proposed here is essentially Feynman’s sum over histories, but with the histories being presented one by one ordered by the Langevin time. This likely gives different results than a complete sum over histories, because not all histories will be visited in a finite time. The time for an observation to take place is the relevant time over which the histories are effectively summed. If a large number of moderately-coupled degrees of freedom exist in a broken-symmetry state, separated from other such states by an energy or entropy barrier, then there will likely be insufficient time to bridge these barriers, and the system will be essentially frozen in this state. This allows for symmetry breaking to take place in finite systems and effectively prevents measuring instruments that rely on broken symmetries from existing in superpositions. This is the mechanism’s explanation of the Schrödinger’s Cat paradox. The radioactive decay effects too many degrees of freedom to be able to fluctuate back to the undecayed state in a reasonable Langevin time. Needless to say, adding the cat’s degrees of freedom makes this even less likely. Tunneling times generally increase exponentially with system size. So although there will be a range of mesoscopic systems which will fluctuate slowly and perhaps observably, as the number of degrees of freedom is raised one quickly moves from a regime of extremely rapid tunneling to one with extremely rare, essentially nonexistent tunneling as the number of moderately-coupled degrees of freedom is increased. The idea of moderate coupling is an important one in that it involves counting the effective degrees of freedom. Two degrees of freedom that are so strongly coupled that they must fluctuate together are essentially only one degree of freedom. One can in principle have rather large systems that still have relatively few degrees of freedom, such as for instance a Josephen junction, which can still display entanglement.
Fluctuating histories also give an explanation of quantum entanglement in the Einstein-Podolsky-Rosen\textsuperscript{[12]} gedankenexperiment. Here a spin-0 particle decays into two spin 1/2 particles moving in opposite directions, the spins of which are perfectly oppositely correlated, the two particle wavefunction being $(1/\sqrt{2})|\uparrow\downarrow> + (1/\sqrt{2})|\downarrow\uparrow>$. If the one particle’s spin is measured along a particular axis, giving a result of $\pm \frac{1}{2}\hbar$, then one knows immediately the spin component of the other particle along the same axis. Bell’s inequality\textsuperscript{[13]} violation, confirmed by experiment\textsuperscript{[14]}, shows that the result is not predetermined as it would in a classical hidden-variable theory, but rather follows the predictions of quantum mechanics. The oddity of this example is that the fact that one particle is measured seems to instantaneously affect the other particle, which may be far away. It does appear to be impossible to use this to send a superluminal message\textsuperscript{[15]}, so it is not really a paradox, but still, as described by Einstein, a “spooky action at a distance.” In the two-time interpretation, the spins of the two particles along their entire historical world lines drift in concert with each other in order to preserve angular momentum conservation. This “fluctuating history” avoids the difficulties of the classical hidden variable model, which can be traced to the fixed definite (but simply unknown) history assumed there. When one particle’s spin is measured its spin stops fluctuating, because it is now highly correlated with the large numbers of d.f. of the measuring device. This fixes the particle’s history and also stops the other particle from fluctuating, instantaneously in the Langevin time, because it too is correlated with the distant measuring device. Because both spins at all times are updated at every moment of Langevin time, their fluctuations only limited by conservation laws and SSB, this behavior seems rather straightforward.

Some time ago Ne’eman envisioned the two EPR particles being connected through a rigid connection that traced the two world lines through their source, something akin to a differential gear that allowed them to fluctu-
ate only in a correlated manner[16]. Our fluctuating history that respects conservation laws essentially implements this vision.

5 Interaction free measurements

Interaction free measurements are another area where quantum mechanics seems to have a non-classical and surprising result. At first glance one might think the stochastic approach presented here might run into trouble in such a system, but in fact the two-time model again has no difficulty explaining it. A famous case is the Elitzur-Vaidman bomb-testing scenario[17]. It is supposed that one has some bombs that have hair-trigger detonators each attached to a mirror. Some of the bombs have their hair triggers jammed (duds). By placing these mirror triggers in one leg of a Mach-Zehnder interferometer one can some of the time detect active bombs without setting them off. The interferometer is arranged so that the recombined beams always exit the final beamsplitter in one of two possible directions (say A). However, this requires a rigid mirror (dud) so that each photon can go through both legs without being detected, interfering constructively in direction A and destructively in direction B. However, if a live bomb is in place then that will measure which leg the photon went through by either exploding if the photon hit it or not, in which case the photon took the opposite leg. But now there is no interference because there is no second beam and the exiting photon can take either path at the final beamsplitter. If it takes path B then one knows a bomb is present even without having interacted with it. In the two-time model, as coordinate time progresses the photon worldline rapidly cycles between the two interferometer legs as it is extended. If it hits a fixed mirror the path is extended beyond the mirror. For the dud bomb case eventually the paths come together and interfere by the rapid fluctuation between paths mechanism, averaging over time, with destructive interfer-
ence along one route (B) and constructive along the other (A). Finally it is
detected along the A-leg of the beamsplitter output where the interference
is constructive. If a bomb is present, then there are two possibilities. If
the beam happens to be on the bomb side when it reaches the mirror, it
may well transfer enough momentum to it to trigger the bomb. This will
correlate the photon with the many degrees of freedom of the moving mir-
ror and exploding bomb preventing the history to fluctuate back, and the
beam will never be able to switch to the other side again. However this
goes both ways. If the beam was on the non-bomb side when it hits that
mirror, it can no longer fluctuate back to the bomb side where it would
have passed the bomb mirror. This would require moving the bomb mirror
forward to accommodate the required history of the photon, but this would
be too many degrees of freedom to move simply through fluctuation. So the
non-measurement is a just as definite fix to the history as a measurement
would have been, given only two possibilities. The photon on the non-bomb
side can never fluctuate back to the bomb side after this because there is no
longer a history on that side consistent with momentum conservation etc.,
which involves changing only a few degrees of freedom.

6 Modifying stochastic quantization to implement
the two-time relationship

Stochastic quantization of quantum systems and field theory has been ex-
plored with a number of somewhat different formalisms [18, 19, 20, 21]
mostly based on the Parisi-Wu ideas[1]. An earlier attempt by Nelson [22]
differs somewhat in using only a single time coordinate over which parti-
cles move and fields fluctuate. In a sense the approach here bridges the
difference between the Nelson approach and later approaches by using a
second (Langevin) time, but still relating the growth of coordinate time to
it (developed further below). Clearly our approach differs from all of these approaches, in that the modern approaches to stochastic quantization, which are believed to be fully equivalent to quantum mechanics, use a Langevin time wholly separate from the coordinate time. However there is one ingredient missing from these modern approaches to stochastic quantization - one way in which these classical stochastic systems are not fully equivalent to the quantum systems they model, and that is a lack of measurement process or theory. The quantum measurement theory must still be applied to results obtained with stochastic simulations. As succinctly stated by Haba and Kleinert, “It remains to solve the open problem of finding a classical origin of the second important ingredient of quantum theory: the theory of quantum measurement associated with a stochastically evolving wavefunction[20].”

As outlined above, relating the two times allows the measurement theory to become a part of the stochastic system evolution. Beyond being a possibly more accurate description of nature than quantum mechanics itself (the two theories being only approximately the same), this also opens the possibility of obtaining the speed of algorithms promised by a quantum computer to be obtained by a classical computer with stochastic inputs. Already quantum systems have been successfully modeled by stochastic analog computers utilizing noise generators[23]. By simulating measurement processes as well, it seems possible that such a system could fully simulate, i.e. replace, a quantum computer. The problems of decoherence and scaling would likely be much less of a factor with such an approach.

Here the proposed method will be demonstrated with a scalar field theory. A scalar field $\phi(x,t)$ with action $S(\phi)$ is described by a Langevin equation

$$\frac{\partial \phi(x,t,t')}{{\partial t'}} = i \left. \frac{\partial S(\phi(x,t))}{\partial \phi(x,t)} \right|_{\phi(x,t)=\phi(x,t,t')} + \eta(x,t,t') - \epsilon \phi(x,t,t'), \quad (1)$$
where $\eta(x, t, t')$ is a random Markov noise characterized by

$$< \eta(x, t, t') > = 0, < \eta(x_1, t_1, t'_1) \eta(x_2, t_2, t'_2) > = 2\hbar \delta^n(x_2-x_1) \delta(t_2-t_1) \delta(t'_2-t'_1).$$

(2)

Here $t$ is coordinate time, $x$ is the spatial coordinate ($n = 1$-3 dimensions), and $t'$ is the separate Langevin time. This is the Minkowski space version with the $\epsilon$ term added for convergence. In the standard stochastic quantization method correlation functions are given by averages over different noise sets $\eta(x, t, t')$ and with the Langevin time taken to infinity. Alternatively by the ergodic theorem one can just average correlation functions over the Langevin time once a sufficiently long time has passed for the probability distribution to achieve its limiting form. The modification being suggested here is to equate the Langevin time to the coordinate time of the present hypersurface in a frame to be discussed below. The simulation is run for a sufficient time before the experiment takes place to have equilibrated. Then a measurement when $t' = t_1$ (i.e. when $t_1$ is the present time or “at time $t_1$”) prepares the initial state. The simulation continues in $t'$ and a second measurement takes place when $t' = t_2$ shortly after which the simulation is terminated. Note that the entire history of the events that took place subsequent to the final measurement is still fluctuating during the second measurement because all fields at all times fluctuate over the Langevin time. This allows the constructive and destructive interference to appear through the time average of fluctuating fields over the characteristic time of the second measuring device, as envisioned above. The limit of taking the Langevin time to infinity is not taken, because the measurement will be read shortly after taking it and one purposely does not want to wait a very long time over which the measuring device could eventually fluctuate to a different state, since it is a finite size. This avoids the measuring device from itself “entering a superposition.” Instead the Langevin time in principle starts at
negative infinity - in practice a sufficiently early time so as to forget the very initial state. A single run of the simulation is all the universe itself is doing, of course. However in order to build up a probability distribution of possible results, the average over different noise sets would also be performed, but this is at the level of probability and not probability amplitude because it is a post-measurement average.

The modeling of specific measurements as part of the quantum calculation seems unusual, but that is exactly what is needed if the measurement process is to be brought into quantum mechanics. If specific measuring devices are not being modeled, as is more normally the case in quantum mechanical calculations, one can simulate their effect by averaging the correlation functions measured with the simulation over the expected characteristic time of a measurement, $\Delta$. For each Langevin simulation run one would compute the expectation value of a correlation function using

$$\int_{t_2-\Delta/2}^{t_2+\Delta/2} \phi(0, t_1, t')\phi(x, t', t)dt'$$

(3)

This allows for the “in-time” superposition or cancellation referred to above to take place. Then these results are further averaged over different noise sets $\eta(x, t, t')$ only after a probability quantity is computed (such as by squaring) to then obtain the full probability distribution.

The theory presented here, therefore, differs in two important ways from standard quantum field theory under stochastic quantization. The first is relating the Langevin time to the coordinate time, with the Langevin time being the coordinate time of the present hypersurface. The second difference is that the sum over paths that creates interference is limited to those that are visited in the relatively short time $\Delta$ over which a measurement takes place. The results of the measurements from different runs of the simulation may then be gathered to form a probability distribution. Whether this theory will be easy to distinguish from quantum mechanics depends on
the ratio of times between the characteristic measurement time $\Delta$ and the characteristic time of quantum fluctuations themselves, $\delta$ over which fields change their values significantly. Simulations with toy models are planned. It is conceivable that differences from standard quantum mechanics could be seen from rapidly repeated measurements or possibly a series of weak measurements.

7 Conflict with Relativity?

The concept of “the present” is generally not considered to have a physical reality because observers in different Lorentz frames have different present hypersurfaces in special relativity. Nevertheless the present seems like quite a special time to us which can be seemingly be distinguished from past and future. Philosophers have struggled with the notion that we exist at the present and are compelled to move through time. Some have postulated a second time to pace our motion through time [21]. A “growing block” theory of time is discussed by some philosophers, which closely resembles a growing phase boundary [25]. Whitehead invented the term “concrescence,” a process through which a formless future becomes a concrete reality at the present, to form a fixed past [26]. These ideas are also explored in the already mentioned book by Muller [3], who envisions new space and time being created at the edge of the Hubble expansion. In the Phase Boundary Universe proposal, the present is the physical surface of the growing crystal - the phase boundary itself. This is a simultaneous surface in the frame of the Hubble expansion. It is in this frame that the coordinate time of the present hypersurface tracks exactly the Langevin (Newtonian) time.

Ascribing reality to the present clearly requires choosing such a preferred frame, an anathema to anyone trained in relativity. Nevertheless it is possible to have a preferred frame and still get most if not all of what relativity
provides. This will happen if interactions in the Lagrangian of the theory are all Lorentz invariant. Measuring rods and clocks built from matter that obeys these Lorentz invariant interactions will necessarily behave as predicted by the Lorentz transformation when moving. In other words they will obey Lorentz contraction and time dilation. An example of this is the Lorentz contraction (relative to the speed of sound) of the displacement field surrounding a moving screw dislocation \[27\]. This is a dynamical realization of the Lorentz symmetry as opposed to our usual kinematical formulation of an empty Minkowski space to which particles are added. The moving observer using these physical clocks and rods will see special relativity as fully reciprocal, simply due to the property that the inverse Lorentz transformation is also a Lorentz transformation. Despite being reciprocal, the \textit{reasons} that moving rods shrink and clocks run slow are different in the preferred frame and other frames. From the preferred frame this is a physical effect of the dynamics of particle interactions. From another frame looking back at the preferred frame it is more of an illusion based on the moving frame’s use of slowed clocks and shrunken rods for measurement, along with the different clock synchronization scheme that results from their use. In the early days of relativity Lorentz and others still clung to the ether as a preferred frame, even though unobservable\[28\], with moving rods and clocks shrinking and slowing due to their interactions with the ether. This point of view could not be proven wrong because it is equivalent to special relativity, but the ether eventually fell to Occam’s razor as an unnecessary element.

So having a preferred frame in a theory does not necessarily violate special relativity. This has been emphasized by Bell\[29\] and discussed by numerous authors\[30\]. For a theory in which the Lorentz symmetry arises dynamically, the preferred frame may be the most logical to calculate within, even if not experimentally distinguishable. It may simply be a calculation aid similar to gauge fixing or choosing a coordinate system in general relativity.
Nevertheless one must also keep aware of possible frame dependence in the measurement process. A measuring device has its own frame in which it is simultaneously sensitized, and this needs to be taken into account if the device is moving relative to the preferred frame. Measuring devices on Earth, however, are moving only about 0.0012c relative to the Hubble expansion as measured by cosmic background radiation[^31], so the frame difference of most Earthbound experiments from the Hubble frame is actually rather slight and may not be of practical importance.

It is unclear whether giving the preferred frame of the Hubble expansion a role in quantum evolution, as in this paper, makes it observable or not. That is a subject of further study. In the Phase Boundary Universe there is an additional feature that does make the preferred frame detectable at high energies. If the solid phase is crystalline, the continuous translation symmetry is spontaneously broken to a discrete one. For inverse momenta close to the lattice spacing, the photon dispersion relation should become phonon-like which will only be spherically symmetric in the Hubble frame. Lorentz symmetry is only approximate in this theory. A preferred frame of this sort also opens the door a crack to possible faster than light (FTL) communication or interaction, just as a bullet can break the sound barrier. The reason is that causality is arbitrated by the Langevin time which is equivalent to the coordinate time only in the preferred frame, so causality-based arguments against FTL are removed. Nevertheless, it still could be the case that there simply are no interactions that break light speed.

### 8 Application to Non-Relativistic Quantum Theory

Relativistic quantum field theory is the most correct quantum theory we have, so it is really only necessary to describe how it is to be modified...
to incorporate measurement, eqns. 1-3 above. Nevertheless it would also be useful to have a similarly-modified version of ordinary first-quantized non-relativistic quantum mechanics, since many systems are more easily described and studied within that theory. Non-relativistic quantum mechanics has been shown to be equivalent to a stochastic model in a number of different but probably equivalent ways. The most straightforward approach, however, has essentially a single time with a stochastic trajectory \( x(t) \) following the Langevin equation

\[
\dot{x} = -\frac{\partial W(x)}{\partial x} + \eta(t) \tag{4}
\]

\( W(x) \) is related to usual the quantum potential by a Ricati equation.

\[
V = \frac{1}{2\sigma} \left[ \frac{\partial W}{\partial x} \right]^2 - \frac{1}{2} \frac{\partial^2 W}{\partial x^2} \tag{5}
\]

(the above is the Euclidean version). This approach which is more like the Nelson approach has even been modeled using a classical analog computer with a noise input. Although this scheme gives correct results for quantum mechanics when averaged over noise histories, each trajectory considered has a fixed history. The two-time approach advocated above, however, requires a fluctuating history within each trajectory. One needs a model where the entire history functional \( x(t) \) fluctuates in the second time \( t' \). This may be achieved through the path integral approach, which is the same as the field theory approach given above with \( \phi(x,t) \) replaced with \( x(t) \). The associated Langevin equation is

\[
\frac{\partial x(t,t')}{\partial t'} = i \frac{\partial S(x)}{\partial x} \bigg|_{x=x(t,t')} + \eta(t,t') - \epsilon x(t,t') \tag{6}
\]

Since the particle’s worldline does not exist beyond the present hypersurface, new variables \( x(t = t') \) must be introduced as \( t' \) evolves. In other words the path ends at the present, \( t = t' \). This feature is quite different from the standard treatment in which the Langevin time has no relationship
to the coordinate time. Measurement is either modeled explicitly as with the field-theory case, or paths for the propagator \( \langle x(t_1)x(t_2) \rangle \) are averaged over a measurement time \( \Delta \) as in Eqn. 3. For a fixed initial condition, \( x(t_1) \) would not vary with \( t' \), but all other \( x(t) \) would. Further averaging over different noise histories would be done with the squared propagator or whatever probability was being calculated, because a measurement process is being modeled and each measurement terminates an experiment. Multiple experiments generate a probability distribution as in ordinary statistics. Simulations with simple quantum systems are planned to explore the differences between this proposal and standard quantum mechanics.

### 9 Conclusion

The hypothesis presented in this paper is that the Langevin time of stochastic quantum quantization is a physical time over which quantum fluctuations take place and also by which particles move through both space and coordinate time. This allows quantum measurements to be modeled as a process of spontaneous symmetry breaking, even in a finite system. Quantum fluctuations are averaged over time during the measurement process which effectively implements quantum superposition. One advantage of this approach is that measurement is built into the theory - no separate measurement process need be added on. This makes resolution of quantum paradoxes particularly straightforward. Because of its close relationship to standard stochastic quantization, this theory is expected to closely mimic standard quantum theory, although some differences could exist. These will be explored in future work with simple test systems. Since the measurement process is built in, the potential to construct computational engines with the power of a quantum computer seems possible using such a noisy classical system with one added dimension (the second time). To have multiple bits
at least a 2-d array of noise generators is needed. However, this could also just end up reproducing a known algorithm such as simulated annealing applied to a system resembling to a spin glass. The analog version of simulated annealing would be annealing itself. In this case “thermal computing” would rival quantum computing. A better understanding of the relationship of quantum systems to noisy classical systems will likely generate insights into both the capabilities and limitations of quantum computers.

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