The Ultimate Physics Experiment

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I. INTRODUCTION

It may be that there is a simple, elegant, set of equations – constrained by equally elegant boundary conditions – that govern everything that happens in our universe. But even so, it is possible that the discovery of such an ultimate explanation would not qualify as physics. That is because physics is fundamentally an experimental science; if any theoretical explanation had aspects that could not be physically confirmed – *at least in principle* – then such a discovery would be more accurately classified as metaphysics or philosophy.

The central importance of experiments in physics is easy to forget while immersed in the latest cutting-edge theoretical research, which has typically far outstripped current experimental capabilities. But buried in every single line of theoretical physics research – no matter how abstract – is the implication that eventually the theory may be tested by experiment. Without this future possibility, such research would be like counting angels on the head of a pin – ultimately untestable, and therefore outside the domain of the scientific method itself.

Consider a discovery trumpeted in future physics journals as "Ultimate Theory B", the obvious replacement for some old and clunky "Ultimate Theory A". The older theory A may not have been simple, elegant, or even correct. Theory B might extend its explanatory power into alternate universes or hidden dimensions unimagined by A. But so long as A and B made exactly consistent predictions for what might be observed in our accessible 4D universe, there would be no way to physically distinguish the two theories. The discovery of B would not technically be a physics advance at all – *even if B correctly described the rules that governed our universe.*[1]

So when confronted with the question of what is ultimately possible in physics, one need only consider what is ultimately possible in *experimental* physics. Any theoretical proposal that ventures beyond the ultimate experimental limit might be useful in its own way, but shouldn't be given the label of "physics" – or even "science". This essay is an attempt to deduce those experimental limits from a few basic principles. Of course, choosing the starting principles is hardly straightforward, and my choices may raise immediate complaints. Fortunately, the results from this analysis can be "tested", comparing the deduced experimental limits to widely-accepted experimental limits (for instance, Heisenberg's uncertainty principle). Such comparisons will lend some credence to this entire chain of reasoning, including a general description of the ultimate physics experiment – the limit to what any ultimate physical theory can purport to explain.

[1] "Ultimate Theory B" would certainly be a great philosophical advance, and most working physicists might quickly adopt B over A, but that still doesn't mean there is a physical distinction between the two theories.

II. THE FRAMEWORK

A. Variational Principles Taken Seriously

Although this essay explores fundamental limits on experiments, it won't describe any particular experimental approach. The *ultimate* experimental limit, after all, might involve measurement devices built from every atom in every nearby galaxy, or microscopic black holes capable of probing space and time on unimaginably small scales. A discussion of the largest conceivable particle accelerator would miss the point, steering us into a mindset where the energy density was more important than precision detectors. The ultimate experiment will have both.

To analyze experimental limits *in general*, one needs some guiding principles as to how our universe generally fits together. The problem is that modern physics is built upon two incompatible sets of guiding principles: one from relativity, and another from quantum theory. Fortunately there is some overlap; notably, both can be neatly formulated using variational principles (VPs). A variational principle is a way of doing physics that doesn't seem natural to most people, but still works remarkably well. The basic idea is that instead of starting with initial conditions and solving some set of equations, VPs utilize partial initial conditions and partial final conditions, and then minimize some global function S (known as the action) that describes what happens inbetween.[2] The fact that all known fundamental physics can be done using VPs will serve as this essay's lodestar.

Now, most books on VPs will stress that such variational analysis is identical with the "ordinary" way of doing physics, because you can derive the usual equations that describe the evolution of the physical system, and these equations can then be used in the "ordinary" manner (i.e. plugging in initial boundary conditions and solving). But this argument is incorrect; it implies physics is nothing more than the equations, with boundary conditions (BCs) as an unimportant detail. In fact, physics equations are pretty much useless without BCs, as any experimentalist can tell you. For example, try using the equations of motion for a pendulum to determine where it will be in one second, without using any information concerning the initial position and velocity! It's true that if you were in possession of the initial position, the initial velocity, and the final position, you could solve this problem using either "ordinary" physics or VPs, but we'll soon see that we never actually have such an overabundance of information before we solve the equations.

The central premise is simply this: **The results of external measurements on some space-time region are exactly the external constraints to be used in action minimization for that region**. One alternative to such a premise is that some things happen for no reason at all – or that the BCs on a system are just random. I would allow that some events might be unconstrained by any BC, but I draw the line at treating those events as BCs in their own right. Also, the analysis from the introduction implies that events unconstrained by every measurement in the universe aren't even in the domain of physics – so this essay needn't be concerned with them. Given this premise, we have almost all the tools we need to answer the original question.

[2] This is not a physical "testing out" of each possibility; only the minimum value of S corresponds to what actually happens.

B. The Local Block Universe

Two additional principles from general relativity (GR) will provide additional guidance: 1) local interactions, and 2) a single "block universe". I've written a comparable essay about the block universe [1], and won't dwell on the motivating arguments here. Still, I'd like to clearly introduce the concept (without getting deep into jargon about differential manifolds and diffeomorphism invariance), so consider a universe that has only two spatial dimensions, along with the usual time dimension. If you think about our universe as a succession of instants, each "instant" would be a two-dimensional snapshot. Now imagine stacking the snapshots that represent successive instants on top of each other, a stack extending into a third spatial dimension. This additional dimension represents time, of course, but in the resulting 3D "block", time is represented as a spatial dimension for purposes of conceptual clarity. A 4D block universe that corresponds to our three spatial dimensions (plus time) is more difficult to imagine, but it's the same basic idea; a 4D structure that spatially encodes every event that has ever happened, or will ever happen.

For example, your bodily existence takes up some four-dimensional volume (or 4-volume for short) in this block universe representation. At each instant you only physically extend into a 3-volume, but stacking successive instants on top of each other into a 4th dimension extends all of your 3-volumes into a single, lifelong, 4-volume. In this essay I'll refer to such a 4-volume of an extended object as a "worldtube".

The block universe is just a picture, of course, but it's a useful one – and arguably the only proper picture to carefully think about time and space on an logically equal footing. The key point is that nothing can *change* in a block universe, because change requires ordinary time, and the block universe has already represented time as a spatial coordinate (there's no "additional" time that is not included in the block). The static nature of the block universe enables us to bypass our usual intuitions that tell us that time and space are different, naturally putting us into a GR-friendly mindset where space and time are inherently interrelated. For instance, once you have a single 4D block, there are many angles at which can slice it up again into 3D "snapshots", and GR tells us that all of these different slicings are perfectly valid ways to view our 4D universe. This "relativity of simultaneity" is a difficult concept for new physics students, defying ordinary common sense, but it appears natural once you think of the universe as a single, static, 4D structure.

The other starting point for the below analysis is the principle of locality. This is a widely-respected principle (at least outside of quantum theory), which effectively forbids the behavior of events at one location in the block universe from directly interacting with events somewhere (or somewhen) else. This is not to say that information can't be shared between different parts of our universe – after all, you're reading an essay written at a different time and place – but there is a continuous chain of local interactions to allow that to happen.

III. MEASUREMENT IN A LOCAL BLOCK UNIVERSE

So what sort of generic measurement conclusions can one draw from the framework described above?[3] Remarkably, one can immediately deduce a weak form of the so-called "holographic

[3] For those worried that this "local, realistic" framework is incompatible with quantum mechanics (*i.e.* violations of Bell's inequality), this issue is addressed in Section VI.

principle", as extended to four dimensions. This "principle" is the speculative notion that all of the information in an ordinary 3-volume can be encoded on its 2-surface.[4] But in a local block universe, a similar principle naturally falls out of some basic analysis: if all interactions are local, then all *externally accessible* information from any spacetime region must also be accessible on that region's 3-surface. In other words, the only external measurements you can make on an arbitrary 4-volume are measurements on the closed 3-surface that encloses the measured region.

The concept of closed 3-surfaces (aka hypersurfaces) can be made less abstract via a concrete example. Consider the spacetime 4-volume that coincides with your own home for exactly one hour, starting now. (Picture it in the block universe framework, where that hour is represented by a 4th spatial dimension; you'll probably have to drop one of the spatial dimensions to picture this, as shown in Figure 1.) The boundary of this 4-volume is a 3-surface, and is made up of three parts: A) the initial state of everything in the home's 3-volume (right now), B) the ordinary 2-surface of the home, stretching out into the time direction for one hour, and C) the final state of everything in the home's 3-volume (one hour from now). Each of these three components is a 3D structure; A and C comprise 3 spatial dimensions at an instant, and B comprises a 2D spatial surface over a 1D time. (Physicists call A and C "space-like surfaces" and B a "time-like surface"; I'll refer to these basic components A,B, and C more generally throughout the essay.) Together the three parts form a closed 3-surface: the boundary of the enclosed 4-volume.

Simple logic reveals that any external measurement of anything in a 4-volume is actually a measurement on its 3-surface; in other words, if you leave home for that hour, you can't find out anything that happens there unless the information is locally accessible on either A, B, or C. Looking through the windows at the half-hour mark is just measuring the electromagnetic radiation at the window pane itself, which is part of B. Your knowledge of how the furniture is (initially) arranged comes from A. And if there's an unnetworked video camera running in your home for that hour, you can't access the recording until you get that information on C. If you were to find out anything about the internal configuration of the 4-volume *without* that information passing through the 3-surface, it would necessarily involve a non-local interaction.

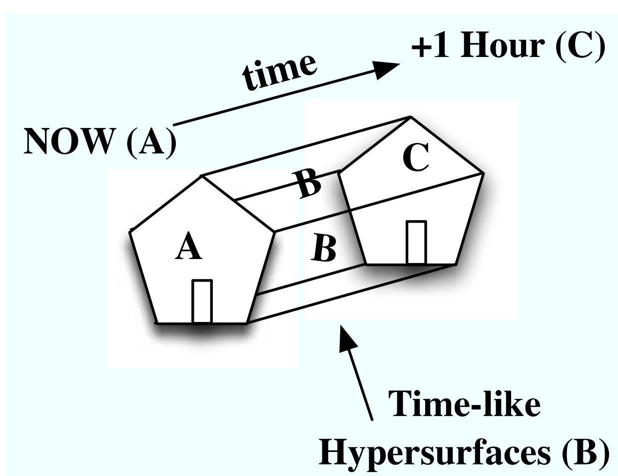

FIG. 1: The 4-volume of a house for one hour, with one spatial dimension suppressed. "A" is the initial 3D house, "B" is a time-like 3-surface, and "C" is the final 3D house.

[4] A surface is one dimension less than the enclosed volume, so ordinary surfaces are two-dimensional, or 2-surfaces.

My claim that you can't make measurements inside a 4-volume may not sound quite right. After all, there's nothing stopping you from walking into your home after half an hour and taking all the measurements you want. The problem then is that the house's 4-volume now includes part of your own world-tube, and a good case can be made that nothing can measure itself. So now you're limited to measuring a subset of your home's 4-volume (minus your own world-tube), and sure enough, all the measurements still occur on that subset's 3-surface (including the walls of your world-tube).

IV. HOW MUCH MEASUREMENT IS ENOUGH?

Given that one can't measure throughout 4D volumes, but only on 3D hypersurfaces, it's not obvious how much of a given boundary needs to be measured in order to fully ascertain the parameters that describe the enclosed spacetime region. In classical physics, one can ideally measure physical values on a hypersurface (like particle positions) and simultaneously measure the rate of change of those values perpendicular to the hypersurface (like particle velocities); together I'll refer to these two quantities as "Cauchy data". If you can measure all the Cauchy data on a given surface, classical physics tells us we can describe a 4-volume from measurements on the initial space-like surface (A) and on all the time-like surfaces (B).

But there are two problems with this in real life. First, quantum physics tells us that we can't measure all the Cauchy data on a surface; we're limited (for example) by Heisenberg-style uncertainty to measuring position *or* measuring velocity, not both. (I'll call such measurable quantities "half-Cauchy data".) This continues to be true for things like classical electric and magnetic fields, which together comprise 6 real values at every point in space – of these 6, actual measurements can only determine 3. Nevertheless, quantum physics is still built around the premise that you still only need to measure half-Cauchy data on A and B to get a complete description of the 4-volume surrounded by A, B, and C. Quantum theorists often insist upon this classical structure, despite the fact that the values on C predicted from data on A and B almost never match the actual measured values on C! Instead, the match between predicted and measured values on C yields a probability that I'll discuss further in the next section.

Another problem comes from general relativity, as it's the curvature of spacetime that determines whether a given hypersurface is time-like or space-like in the first place. But GR relates curvature to the distribution of energy, so now one can't determine the division lines between A, B, and C until one measures them in the first place – and then, the available half-Cauchy data simply isn't enough for this purpose. So even if the data on A and B were enough to predict C, you can't determine where B ends and C begins without using the measurement results from C, making any "prediction" an exercise in circular logic.

Besides, we're interested in the ultimate experimental measurement – so why should we limit ourselves by ignoring the measurement on C when determining the behavior of a physical system bounded (in part) by C? No good reason that I can imagine; such an omission would be like an analysis of a sporting event that didn't mention the final score.

In fact, the main premise from section II tells us that measurement information on C is *required* to provide a complete description of the full 4-volume; that's how variational principles (VPs) work in four dimensions. To reiterate this important point, VPs take partial information on the entire hypersurface boundary (A+B+C), and then deduces the missing information on that boundary (as well as parameters throughout the 4-volume) by minimizing a global value S known as the "action". In such an approach it's the information on the *entire* boundary that determines the physics, further implying that one shouldn't treat the line between B and C in any realistic manner.

Another notable feature of VPs is that they *expect* to only have partial information on each part of the boundary, exactly in tune with what quantum uncertainty tells us that we can measure. After all, in classical physics, specifying all possible information (say, particle positions and velocities) on A, B, and C would completely overconstrain the problem; typically one implements variational principles on particles by only specifying positions, not velocities. So knowing only the "half-Cauchy data" on a closed hypersurface is actually what you expect when using VPs. This implies that the ultimate experiment on a spacetime region will be a measurement on the *entirety* of a closed hypersurface.

V. PREDICTIONS AND PROBABILITY

The preceding discussion of what's going on inside a 4-volume is actually somewhat beside the point. If a 4-volume is defined by its measured boundary, then there's no direct experimental access to the interior of that 4-volume − by definition − and therefore any description of that interior isn't physics. (The claim that we *could* measure it, if we chose to, is not useful; it would then be a different system, just as walking into a house to take measurements would change the interior of the house.) Physics can at most explain experimental results, and if measurements occur on hypersurfaces, then any discussion of what happens inside those hypersurfaces is outside the domain of the scientific method.

This seems to leave the role of physics in a bind. Classically, everything would still be okay; physics would simply predict what happens on C given measurements on A and B. But this only works if one can get enough information on A and B to make the prediction. As we saw in the previous section, that's not generally possible in the real world; there is information on C that isn't accessible on A and B. And once you take the results on C into account, it seems that there's nothing left to predict.

But there's still a classical answer to this dilemma. Whenever one has insufficient information to make a perfect prediction, one is reduced to using *probabilities.* Indeed, a lack of knowledge is the *only* time one uses probabilities in a classical framework, and gaining new information requires one to instantaneously update your probabilistic assessments. (Sound a little like quantum theory?) So even with imperfect information on A and B, generating a probabilistic prediction about what might happen on C is still a perfectly valid role for physics.

Still, how can one use probability in a block-universe framework? The block never changes, so we shouldn't resort to mystic talk about potentialities collapsing into certainty or any related nonsense. Instead, as in classical physics, we simply need to condition all probabilities on what we do (and don't) know. Conditional probabilities shouldn't be viewed as objective truths; just subjective statements. For example $P(Q_0|R_0)$ is the probability of Q_0 given R_0, but this may be different from $P(Q_0|R_0, S_0)$, the probability of Q_0 given R_0 and S_0. So in general an observer that knows about both R_0 and S_0 will end up with different probabilities than an observer who only knows about R_0.

What is needed is an objective way to build up these subjective (conditional) probabilities. The natural solution in a VP-block-universe framework is to assign objective status to something called *joint probability distributions*, or JPDs. This sort of probability tells you the joint likelihood of two (or more) things both happening; so $P'(Q_0, R_0, S_0)$ is the likelihood that Q_0, R_0 and S_0 all happen. You can build up any conditional probability from JPDs; for example

$$P(Q_0|R_0) = \frac{\sum_n P'(Q_0, R_0, S_n)}{\sum_{m,n} P'(Q_m, R_0, S_n)}, \tag{1}$$

where the upper sum is over everything you don't know, and the lower sum is also over all possible outcomes for Q that may (or may not) have happened instead. You can use the same JPB to build up any conditional probability at all. To take the other example above,

$$P(Q_0|R_0, S_0) = \frac{P'(Q_0, R_0, S_0)}{\sum_n P'(Q_n, R_0, S_0)}. \tag{2}$$

In this view, theoretical physics needs to do only two things: 1) Provide a two-way map between physical measurements and mathematical boundary conditions, and 2) generate a JPD of the form $P'(A, B, C)$ for all possible boundary conditions on a closed hypersurface. With the JPD in hand, you could conditionalize on any subset of the boundary you like – generating, for example, $P(C|A, B)$ as is traditional – but now the "division line" between B and C is purely arbitrary; a different division would simply produce a different conditional probability from the same objective JPD.

Currently, the best guess we have for how to generate such JPDs comes from the Standard Model, which tells us how to generate an extremized classical action S from a boundary on a closed hypersurface. ("Classical", meaning it's the same action as in classical field theory; the "quantum" aspects can all be traced to step 1 in the previous paragraph, not step 2.) In this case, the JPD on the entire boundary simply becomes $P' = |e^{iS}|^2$. This can't be the final story, however, in large part because gravity's action isn't included in S (it could be, but this confounds the usual quantum procedure in step 1). The ultimate physical theory will somehow find a way to get around these problems, but at the end of the day, it looks like it's still going to be a recipe for producing JPDs from an arbitrary closed-hypersurface boundary condition.

VI. FIRST ORDER IMPLICATIONS

So how much physics will we be able to extract from such an ultimate theory? Cutting-edge physics measurements, of course, are made with other systems that act as an intermediary between our own world tube and the system of interest. We interact with the measurement device on one boundary, while the device interacts with the system of interest on another boundary.

What's interesting is that such a framework proves that there's no way to avoid uncertainty, even with a clever measurement device. That's because an initial measurement on a system – measuring A, or even A and B – is never going to be enough information to solve a variational problem. Sure, a measurement device could surround an entire 4-volume to get a complete description of that volume's surface (subject to global phase issues I'll mention below). But this measurement device must *also* take up a 4-volume in spacetime, and in order for us to get all of the information out of that device, something else (such as our world-tube) has to also completely surround the device. And you can't surround something in 4D spacetime without a final measurement, after everything of interest has already happened. This means that any full measurement won't be *pre*-dictive. Even an ultimate theory will have to resort to merely making probabilistic correlations.

Another interesting feature that results from JPDs is that there's no reason to expect the generated conditional probability $P(C|A,B)$ to be independent of the type of measurement performed on C. Indeed, different boundary conditions on C will necessarily lead to different extremized actions, so S is a global function dependent (in part) on the final measurement at the temporal end of the 4-volume. The resulting conditional probabilities would then be expected to have strange, "spooky" correlations, because such a system behaves differently in the past depending on what measurement would be made on it in the future. Indeed, such correlations really exist – and are so "spooky" that they have convinced many physicists to give up the principle of locality. In fact, one can keep the principle of local interactions if the JPD of the entire closed boundary is derived from a constrained global action.

Note that this picture naturally extends to the whole universe, where one simply replaces the measurement data with cosmological boundary conditions (CBCs). Sure, those CBCs aren't known (except for the Big Bang to some limited extent), but this only implies that we can't predict the future with perfect accuracy. Indeed, some strange observational features may be naturally explained in this way, such as how different regions in the universe (that apparently have never *had* a common cause) turn out to have almost exactly the same temperature.[5] If there is a regular CBC not just at the Big Bang, but also continuing as an asymptotic spatial boundary condition with a nice, uniform structure, this may explain these correlations in the same way one explains the spooky quantum correlations.

VII. TOWARDS THE ULTIMATE MEASUREMENT

The above framework hints at how measurements on physical systems can be improved – as well as how they should be thought of in the first place. The first myth to dispel is that the ultimate measurement is merely a full experimental accounting of everything at some instant. Instead, such a measurement is merely a *part* of a full experiment; without prior or subsequent measurements, one can't do any physics. An experiment necessarily has a time duration.

Another myth is the typical quantum-theorist view of measurements as dismebodied mathematical operations that occur out of nowhere. Measurements are physical events, that occur to physical measurement systems, and those systems have to exist somewhere, over some time duration. And yes, those measurement devices have their own set of boundary conditions, with the chain of causality extending all the way to the CBCs

Still, expanding ones concept of an experiment to "two consecutive, complete measurements" isn't enough, either. That's pretty much what quantum field theory ordinarily does; taking the above A-B-C hypersurface and stretching it out so that B ends up so far away that you can ignore it. Meanwhile, A and C are assumed to be "space-like" hypersurfaces, even before the measurements confirm what spacetime looks like. Recently there's been a push to expand classical and quantum field theory to general-shaped hypersurfaces, including time-like surfaces [2–4], but most people still aren't thinking in these terms.

There's a case to be made that by assuming there's no information on B, theorists are missing out on some opportunities to make new experimental predictions. For example, in quantum

[5] This mystery is "solved" by the inflationary universe, but this is unproven physics that arguably raises more questions than it answers.

measurement theory, every measurement on A or C is only complete to within an overall phase; you can measure relative phases between different parts of the system, but not the overall phase. Although this limitation is generally assumed to apply to measurements on A and C independently, once you throw B into the mix (connecting A and C), this simply isn't true any more. If an experimentalist was able to keep track of the quantum phase along a continuous time-like surface B, then the relative quantum phase between A and C could be experimentally determined – possibly even leading to new predictions.

In fact, when thinking about the 4-volume taken up by a typical detector at a particle physics experiment, it becomes clear that such measurements *actually occur on a time-like surface*. (The detector doesn't move in space.) Quantum theory is singularly ill-equipped to handle measurements on time-like surfaces, and the mathematical framework of representing measurements with instantaneous "operators" just perpetuates this asymmetry between time and space. Indeed, this point is exactly why there's no quantum "time measurement operator" to correspond to the "position measurement operator"; operators are designed to only function on space-like hypersurfaces, while a "time operator" would have to exist on a time-like surface. The ultimate measurement theory will be able to handle this issue as well.

VIII. CONCLUSION

So what will the ultimate physics experiment look like? It will be an experiment on some region Q of space-time, a region containing many fundamental particles/fields of such large energy density that the spacetime itself is curved and warped in an interesting fashion. The measurement devices will completely surround Q in spacetime, and manage to provide astonishingly detailed data of Q's external hypersurface (both before, during, and after Q). This data will include (partial) gravitational information.

The ultimate physical theory will then take those data and construct corresponding mathematical boundary conditions to constrain the global action S of Q. A mathematical minimization process will then solve for the actual value of S, along with a corresponding joint probability distribution for everything on Q's surface. At this point, one would be able to calculate the shape of Q in spacetime (maybe it would be something unexpected, like a torus). By performing many, many, many such experiments, with different settings of the measurement devices, one can test those theoretical probability distributions against experiment. The ultimate limit of physics will be reached if all those experiments can be correctly explained in this manner. At that point the theory could be used to make probabilistic assessments about future systems.

That's just about it, I'm afraid. Physics won't yield certainty about general outcomes (except in certain special cases), won't provide instant communication over large distances, won't give us insight into the hard problem of human consciousness. The metaphysicists and philosophers will hopefully take over from there and construct more beautiful theories, based upon aesthetics and simplicity – maybe they'll even hit upon the right answer. Or maybe the ultimate physics theory will happen to *already be* the right answer.

But there is one last thing that physics might be able to provide. And that's the special case of when the system Q is the whole universe. In this case, the BCs on Q aren't measurements, but rather cosmological boundary conditions (CBCs). We can see evidence for some of those CBCs (looking into the past), and might possibly get additional evidence for other portions as described in section VI. And there's reason to believe that the CBCs that we can see will be simple. Indeed, the low-entropy (ordered) CBC at the Big Bang is the reason that we see a strong arrow of time in this portion of the universe, and the fact that distant, causally-disconnected regions seem to be very similar tells us that any asymptotic CBC is likely to be quite ordered as well.

At that point, I think I would bend my strict experimental-based picture to allow physics a little speculation for one last prediction, extending any pattern observed on the initial CBC to the entire CBC, all the way to the end of the universe (or temporal asymptotic infinity). Then we could use the same theory to make statistical predictions on the universe itself, not only weighting the likelihood of different CBCs, but also our cosmological destiny. We could treat the entire universe as a single experiment, and predict the likelihood of different outcomes. Indeed, on an infinite time-scale, such a prediction would even be testable. This would be the ultimate experiment, and the ultimate limit of physics, in every meaningful sense.

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[1] Ken Wharton, "Lessons from the Block Universe," Spring 2008 FQXi Essay Contest.

[2] Oeckl, R., "States on timelike hypersurfaces in quantum field theory", arXiv:hep-th/0505267.

[3] K.B. Wharton, "A novel interpretation of the Klein-Gordon equation", arXiv:0706.4075.

[4] K.B. Wharton, "Extending Hamilton's Principle to quantize classical fields", arXiv:0906.5409.