Constraints on an external reality under the simulation hypothesis

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Abstract

Whether or not we are living in a simulation has become the subject of much lighthearted conjecture. Despite it being often considered an unfalsifiable question, here I present an argument that places strong contraints on the nature of any universe that contains ours as a "simulation," and I argue that these constraints are so strict that the most likely conclusion is that we are not living in a simulation. The crux of the idea is that almost any external world-simulation interface allows for Lorentz violations, and that these cannot be remedied in a simulation that implements quantum mechanics as we observe it. These arguments do not preclude all possibility that we are living in a simulation, but they impose significant constraints on what such a thing could mean or how the physics of the "external" universe must work.

1 Assumptions

The analysis that follows requires making three key assumptions.

Assumption C. The state of a valid universe must be internally consistent at all times.

Consistency is an essential property of any mathematically-describable physics; when we discover contradiction implied by our mathematics, we know that something must be wrong. (Indeed, for one example of this reasoning, the Einstein-Podolsky-Rosen "paradox" was originally phrased as a challenge to the correctness of quantum mechanics, which turned out be a powerful illustration of quantum mechanics's validity when entanglement was discovered and did not result in paradoxes.) It is difficult to formalize this simple idea in a sufficiently general way since here we are not only concerned with our own universe, but the space of all possible universes that might be simulated or which could contain a simulation.

For our universe, we might say that if we take a measurement of a quantum state $|\psi\rangle$ at some time t and a certain eigenvalue $|1\rangle$ is observed, there is no possible other measurement that produces a conflicting value. (Put differently, without getting into interpretational issues, histories must be consistent.)

It's worth briefly noting that while our current understanding of physics doesn't inherently prohibit paradoxes *in principle* there are strong suggestions that they may nevertheless be disallowed, at least for all practical purposes.[1–3]

Assumption A. A simulation should be somehow accessible to its creators.

Similarly, this is difficult to formalize fully generally, but for a quantum mechanical universe like ours with Hermitian observables, we can say something like the space of positive operator-valued measures available to the creators of the simulation is not empty; that is, they have some way to measure things. (You might say: but the creators have privileged access and do not need to measure things like we do. This idea has challenges that will be addressed later.)

We can refine A into *weak accessibility* and *strong accessibility*. Weak accessibility means that an agent external to the simulation is capable of making observations of its state at least at some non-zero set of times. Strong accessibility means that an agent external to the universe is capable of influencing its evolution beyond merely setting its initial conditions; that is, it can inject information, either in limited or arbitrary ways.

If the simulation's creators can't at least *see* their creation, for some appropriate meaning of "see," what's the point? It's unclear why such a thing would have any resources dedicated to making it, and even the meaning of it being a "simulation" seems to lose sense.

Finally, to keep the analysis rooted in something concrete, we need to bound how different we imagine the "external" universe, the one that would contain our simulation, is from our own.

Assumption R. The physics of the universe external to our simulation exhibits general covariance.

That is, it is roughly relativistic. This *seems* like a fairly light constraint: we don't need to assume anything about the external universe's geometry, or the nature of its matter or energy, just that it acts the same to all observers, for all frames of reference.

R is probably the most questionable of our assumptions. We have no real basis to be making it. It can almost be considered as a straw man, with interesting questions arising from considering where it fails. But, without making *some* statement about the nature of a potential "containing reality" we lose the precision required to have any kind of meaningful discussion. At the very end I will briefly mention some possibilities that follow from relaxing this assumption.

2 Accessibility by multiple external agents implies violations of Lorentz invariance

When constructing a simulation, we are confronted by the question of how to represent the passage of time. The naïve approach of handling time implicitly as a series of state changes provides no explicit representation at all; instead, it mimics the effect of time using some global clock.[4]

However, this is problematic as it creates a single global reference frame: no matter how you choose the observers' spatial coordinate systems, there is always only a single clock available.

This is not an issue if the observers are entirely contained within the simulated world and have no possible link to an "outside" world. It is easy to simulate relativity for observers created by the simulation and who only exist within it and are happy to take the software's accounting of their timeline at face value.

However, if the observer has any existence external to the simulation, it must provide its own accounting of time that is invariant over choice of reference frame within that simulation. This is fine if there is only one possible external agent observing the simulation, but becomes a problem if there are two or more external agents making simultaneous (to them) observations of the simulation using different reference frames (in the simulation).

To understand why this is an issue, consider two events $\mathcal{A}$ and $\mathcal{B}$ with $\xi = \mathcal{A} - \mathcal{B}$. If $\mathcal{A}$ is observed by o_1 relative to $\mathcal{A}(\tau) - \mathcal{O}_A$ and $\mathcal{B}$ is observed by o_2 relative to $\mathcal{B}(\tau) - \mathcal{O}_B$, there is a reference frame external to the simulation available in which $\mathcal{A} - \mathcal{B} = \xi + \alpha$. The mapping between the external universe and the simulation effectively deforms the simulated spacetime in a way that may violate its metric and therefore allow consistency violations. Each external observer has two simultaneously valid frames of reference — one in their external reality and one in the simulation — which need not be reconciled.

Regardless of where in the simulated universe the two observers are, or what reference frame each is using, they might be sitting right next to each other in the "real world" and able to compare observations and act on them.

Explicitly modeling four-dimensional spacetime, with simulated observers as cursors within it, has the same problem while avoiding a global clock. This reinforces that the problem really stems from the observational mapping between universes rather than any choice of time dimension in the simulation.

We arrive at a conclusion that simulated realities in which multiple external observers can have causal influence must not implement Lorentz (much less Poincaré) symmetry. This immediately implies nonlocality: the speed of light (information) becomes infinite as change propagates instantaneously. An implication of this is that the time must be discrete, since there is no mechanism for continuous evolution. (In each moment, light fills the whole universe instantaneously.) Were this not true, two observers could coordinate in their external reality to transmit information superluminally. For example, the observers in the "future" could communicate events in an in-world market to the observer in the "past". Though a game can obviously simulate travel through space, it is impossible to simulate travel through time with multiple players in a way that has any meaningful consequences so long as they can communicate effectively superluminally.

It's not enough to say there is a different, but still finite, speed of light, because we have to follow a new postulate of relativity:

Theorem 1 *For a simulation influenced by multiple external agents that share a common sense of time, its physics must be invariant over arbitrary informational connectivity.*

This arises spontaneously from our assumption of consistency under strong accessibility. It is difficult to imagine a universe that allows internal inconsistency but is otherwise comprehensible. Classical nonlocality of this form is clearly incompatible with the observed physics of our universe.

There is a clear relationship between the independence of the clocks of the observers and the degree to which it can resemble a relativistic universe like ours.

3 Observation requires interaction

Theories of quantum mechanics that preserve a concept of an underlying "objective reality" that is merely revealed through measurement require "hidden variables" which describe the inaccessible state. Hidden variables have been extensively ruled out through experiment by Bell-type inequality violations.[5,6]

Quantum measurement requires physical interaction: a quantum system cannot be observed without perturbing its state[7,8], and quantum mechanics is believed to have universal validity[9]. (All systems are quantum systems: it describes both subatomic particles as well as large-scale cosmological features, and everything in between.)

At first glance, it might seem possible to recover quantum measurement under weak accessibility in some interpretations of QM, like Rovelli's Relational Quantum Mechanics[8] or Fuch's QBism[10,11]. However, observation without interaction implies the possibility of measurement in excess of the limits imposed by Heisenberg uncertainty, in any interpretation.

You might say that while complementarity limits *our* ability to measure, there's no reason to believe that this constrains external observers. But the problem is deeper than that: the uncertainty principle arises naturally from Fourier duality and is inherent in its mathematical structure. If it were possible to gain a tight estimates of complementary variables simultaneously (e.g., $\sigma_x\sigma_p \leq \frac{\hbar}{2}$), this would imply at a minimum that $[\hat{x}, \hat{p}] \neq i\hbar$. But more broadly, the existence of simultaneously bandlimited and timelimited signals would challenge the conception of conjugate variables as Fourier duals, which implies deep conceptual problems in our construction of physics.

Like projective measurement, uncertainty is an important principle that prevents an infinite amount of information from being embedded in a finite amount of energy[12]; if a magical "universe debugger" attached to our simulation can exceed Heisenberg uncertainty, we have misunderstood something significant about either thermodynamics or the Fourier transform.

Thus, weak accessibility is not enough to observe our universe: a quantum mechanical universe requires strong accessibility to observe and we have already seen that strong accessibility imposes the altered principle of general covariance described in theorem 1. This is clearly incompatible with the observed physics of our universe.

Theorem 2 *To the extent that we are living in a simulation, the state of our relativistic, quantum mechanical universe must not be observable to agents that exist outside of the simulation.*

4 Conclusion

If we are living in a simulation and the external universe is even vaguely similar to our own, either it appears as a black hole to external observers, or we can infer that the nature of the interface is such that it presents only a single possible agent from our perspective.

Importantly, this analysis does not hinge on any assumptions about available or required computational power, and possessing arbitrarily great compute capability does not alter our results. On this basis, we can refute Bostrom's simulation argument[13] for the case in which there is more than one simultaneous external observer.

The only-one-observer limitation imposes bandwith constraints between an external universe and a simulation; further analysis could be directed towards elucidating these limits and whether they impose significant constraints on what a set of external observers can learn from a simulation.

To close, we can consider the implications of relaxing R: it is possible to imagine that theorem 1 is inverted and instead describes an external universe with a profoundly different sense of time capable of simulating our general covariance for multiple external observers. (Note that simply having a non-de Sitter metric is not sufficient so long as it still includes any space-time connection.)

The case where the external universe contains, at least to us, only a single agent also allows R relaxation, since the whole concept of general covariance loses meaning in a universe with only one possible observer.

Further thought is required to play out the full implications of these possibilities. One line of attack might be to consider a graph-coloring problem of physics capable of simulating other physics, though of course this depends on essential unsolved problems from complexity theory. It would be especially interesting if a k-color bound could be shown over a sufficiently broad space of possible physics subject to a requirement of internal consistency.

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