

Preferred Observers in Quantum Gravity

What happens to us after we die? Will there be sumptuous feasts and bebies of virgins, or will there be walls of furious fires and three headed serpents? From the inside, each of us will know for ourselves. From the outside, we can only speculate, though it doesn't seem to matter that no one can ever be sure.

It is quite remarkable that questions we ask about life and death have close parallels in the context of gravity, and these questions are even forced upon us when we consider quantum effects. As we watch from afar, we might see a star burn up its nuclear fuel to eventually undergo gravitational collapse. If the star were to collapse within a critical radius, it would become a black hole with a horizon at the critical radius. However, we will never actually “see” the formation of a black hole as the collapsing star will appear to freeze in its motion just outside the black hole horizon. When we include quantum effects in our calculations of gravitational collapse, the collapsing star slowly leaks off energy, and its mass depletes during collapse. For an “asymptotic” observer, an observer far away from the star, gravitational collapse leads to a “frozen star” or “black star” which evaporates by quantum effects¹. Since the evaporation occurs at a steady rate, all the initial mass of the star gets depleted even as the collapsing matter is frozen just outside the black hole horizon. There is no object like a black hole, only a black star that continues to collapse and evaporate [1-5].

On the other hand, what does an observer who falls into the collapsing object experience? Classical General Relativity suggests that the observer does not notice anything unusual all the way through a black hole horizon, and the observer's journey can continue smoothly until it finally terminates at a black hole singularity. Quantum considerations also suggest the alternate possibility: an infalling observer encounters a hot bath of destructive quantum fluctuations near the horizon [6]. Yet, from afar, like the matter of the collapsing star, the infalling observer will appear to hover just outside the black hole horizon and slowly evaporate; and just as death is viewed from the outside world, so does the asymptotic onlooker observe the demise of the infalling observer. This is not to say anything about what the infalling observer will feel; after all how do we know what the dying feel until we ourselves go through the experience? The story from afar is consistent and complete; the story from the infalling point of view is open to speculation. But does the viewpoint of the infalling observer matter for a description of the physical world? Are there sumptuous feasts, bebies of virgins, furious fires, and three headed serpents, awaiting the arrival of the infalling observer?

Cultures differ in their descriptions of after-life. However, we expect a single coherent description of black holes from physics. To study the properties of black holes, researchers often consider “eternal” black holes – black holes that have existed for an infinite amount of time. Given that black holes are known to evaporate, this does not seem like the correct approach. The

¹ The word “frozen” suggests a static configuration and misses out on the fact that the star continues to collapse, as is evidenced by an increasing redshift of any emitted light. For this reason, the “black star” terminology is more suitable.

only unambiguous way to obtain a valid description of black holes is to start with initial conditions that we fully understand, one without black holes, and then to study the fate of gravitational collapse and the possible formation of a black hole. These calculations of gravitational collapse are difficult and it is necessary to make simplifying assumptions along the way. In particular, the backreaction (*i.e.* recoil) of quantum evaporation on the spacetime evolution is notoriously difficult to include [7]. Yet a large variety of approaches all seem to point to the same conclusion from the viewpoint of the asymptotic observer – collapse and evaporation are concurrent, and since the collapse can never proceed through the horizon, as this is a surface where dynamics completely freezes, the collapsing matter evaporates before a black hole is formed. Even without a full analysis, the key point remains that there is a complete and consistent description of quantum gravitational collapse from the outside². For the purposes of a physical theory, it is sufficient to describe gravitational collapse from the external point of view, just as we are able to describe our physical world regardless of Heaven or Hell. The infalling observer's description is irrelevant for a physical theory; the asymptotic observer is a preferred observer.

This is not the first time in the history of physics that a preferred set of observers is being advocated. In Newtonian theory, the first law defines “inertial” observers. The idea behind the first law is that there is a preferred set of observers who only see forces that have known agents. Observers who are “non-inertial” see bizarre forces that they cannot attribute to known agencies. In Einstein's classical theory of General Relativity, all observers are treated equally, and it is a fundamental assumption that there should be consistency between the viewpoints of infalling and asymptotic observers. However, the asymptotic and infalling pictures appear confusingly different when we dig deeper into specific systems such as black holes, and the fundamental assumption of observer equivalence has to be questioned. The tension is further heightened with the inclusion of quantum effects that, at least in the standard treatment [9], seem to show that black holes must evaporate into thermal radiation that is featureless. The danger is that objects that were initially outside the black hole and in our description of physical reality may disappear into the black hole. Those objects would leave no trace of their existence for the external observer's reality but remain within the reality of the inside observer. Even after the black hole has evaporated, the external observer cannot recover any objects that had fallen in, and all signs of what originally went into the black hole are lost (“information loss”) since the emitted radiation is featureless. This violates the physical principle called “unitary evolution” that permits the unambiguous prediction of a final state starting from a definite initial state.

A natural resolution of the conundrum is that not all observers are equal in quantum gravity and some observers are preferred over others. A key difference between asymptotic and infalling observers is that asymptotic observers can communicate universally, but infalling observers, once they cross over behind the horizon, cannot send signals to asymptotic observers. How meaningful are observers who do not, or cannot, communicate their observations to others?

² Some of the views expressed in this essay are tightly aligned with those advocated by L. Susskind (*e.g.* [8]).

A set of preferred observers can also fit within the framework of quantum mechanics where a measurement can project a quantum state onto a definite eigenstate (“collapse of the wavefunction”). It seems consistent to postulate that observers who cannot communicate the results of their experiments, or even that an experiment was done, can make no difference to the quantum state and are irrelevant for quantum evolution. While this statement seems very reasonable, quantum considerations can be very subtle as may be seen in an Einstein-Podolsky-Rosen (EPR) thought experiment.

In the EPR setup, independent experiments performed on certain quantum systems at distant locations give results that have non-trivial correlations. The choice of experiment and the result of the experiment at one location seemingly influences the outcome of the experiment at the second location. Remarkably, this occurs even though the distance between locations is so large that no signals could have possibly communicated the setup or the results of one experiment to the second location prior to the second experiment [10]. Now let us imagine one set of experimentalists to be inside a pre-existing black hole and another set of experimentalists to be outside the black hole. The experimentalists inside the black hole can perform certain experiments and they can check that their results are correlated with the experiments done by the experimentalists outside. However, since the experimentalists outside do not have access to the data from within the black hole, they cannot check these correlations, and the existence of another set of experiments inside the black hole makes no difference to their physical world. If instead of a pre-existing black hole, we consider gravitational collapse, then the external experimentalists will only see a black star, and the infalling experimentalists will never cross into a black hole horizon, and the EPR setup will never even be realized. Thus life goes on in a self-consistent and complete manner for the external experimentalists without the need to even think about observers hidden inside black holes.

Just as Newton’s first law defines inertial frames, and the second law only applies in these inertial frames, to eliminate fictitious constructs in quantum gravity we also need a “first law”. A precise formulation of the first law should define spacetimes that are fully “networked”, *i.e.* they allow for a network of observers who can mutually communicate. Then the dynamical equations will define evolution within this subset of spacetimes. At present, General Relativity describes all spacetimes, whether they are networked or not. The situation is similar to positing Newton’s second law without first restricting it to frames defined by the first law.

Black holes are not the only context in which we are confronted with puzzling questions due to the occurrence of horizons. Similar questions also arise in the cosmological context where horizons play a prominent role in our understanding of the universe. With the discovery of dark energy, which is looking more and more like a cosmological constant as observations improve [11], observers beyond a horizon distance cannot communicate with each other. One can then ask if Heaven and Hell exist just beyond our cosmological horizon?

An observer in an accelerating universe such as ours will see distant galaxies fade away from view but never quite disappear, similar to the way that asymptotic observers see objects fall towards a black hole horizon but never pass through it. Like we see a black star in the case of black holes, we will see a “black sky” in the cosmological case. So it would appear that observers can obtain a complete and consistent picture of the universe by just considering their

own horizons and there is no need to speculate about what other observers might see. Yet one cannot help feel dissatisfied with this viewpoint because it puts each observer at the center of their own universe and this egocentric view disagrees with the homogeneity and isotropy that we observe, and it also undermines the success our models have had in predicting cosmological dynamics. It seems more natural that the cosmological horizon is due to the limitations of the observer, rather than a fundamental limitation of spacetime dynamics, in contrast to what we have argued for the black hole. A different treatment of black hole and cosmological horizons may be reconciled by looking more closely at the nature of these horizons. A black hole horizon is a trapped surface and observers inside this surface can, in principle, make measurements to check that they are within a trapped region. On the other hand, the cosmological horizon is an anti-trapped surface as objects beyond the horizon recede faster than the speed of light. When we include quantum effects, the black hole horizon shrinks due to evaporation, while no such effect is known for the cosmological horizon. Thus there are crucial differences in the nature of black hole and cosmological horizons, and the purpose of the first law may be to give preference to the viewpoint of observers who are not trapped.

Our hypothesis of preferred observers will impose additional constraints on the solutions permitted in gravitational physics and will play a role in cosmological model building. For example, an essential element of inflationary cosmology is that the universe is eternally inflating with an infinite number of bubbling universes. In such a picture, observers living in distant universes are incommunicado. Baby universe creation in the scenario is viewed from the outside as black hole formation [12], and so our earlier discussion of black holes suggests that baby universe creation should not appear in the spectrum of possibilities in quantum gravity and cosmology.

If baby universes are not admissible, how was our universe created? One possible resolution is in the spirit of quantum cosmology, whereby space and time and the laws governing evolution are all created simultaneously. Then “creation from nothing” is possible wherein any meaningful questions (do observers exist?) can only be asked post-creation. Another possible resolution is that the universe is eternal and is empty except for a cosmological constant. Occasionally there are large quantum fluctuations that create islands of matter that can be inhabited, and we live on one such island [13]. In this scenario, we do not attempt to explain the existence of spacetime as it is assumed to be always there as a background. The big bang corresponds to the creation of matter in this background spacetime.

In physics the bottom line is always provided by experiments and observations. If a theory cannot be tested, we can never be sure if the ingredients and assumptions we have used to obtain the theory are viable. If dark matter is not directly detected, there will always be some doubt that it is really there. In the absence of scalar fields with suitably flat potentials, inflationary cosmology will remain a paradigm. If experiments do not show that fundamental particles have an extended linear size, we cannot be sure if string theory is the correct description of Nature. What experiments can we do to check if there are preferred observers in quantum gravity?

The best bet for any test seems to be in the context of black holes. If black holes exist, assuming that they were formed in gravitational collapse, it would suggest that matter has fallen through the horizon, and this would violate the proposed first law that implies we should only see black

stars that gradually evaporate. Now to show that black holes exist is very difficult. Astronomers do see a number of objects that are candidate black holes, *e.g.* Sagittarius A* at the center of the Milky Way. It has to be realized, however, that “astrophysical black holes”, in contrast to “General Relativistic black holes”, may simply be very compact objects and, in fact, may very well be black stars. Can we tell that Sgr A* and other candidates are black holes and not black stars?

If two black holes collide, they probe each other as if they are infalling observers, and their merger will lead to gravitational wave emission. More crucially, since the space around a General Relativistic black hole is completely empty, there will be gravitational radiation but *no other kind of radiation*. On the other hand, if two black stars collide and merge to form a single black star, the matter that is frozen at the horizon and gradually evaporating also has to collide and relax during the merger, causing the radiation of photons, neutrinos and other particles. Thus the collision and merger of two candidate black holes can distinguish between genuine black holes and black stars, and so test the hypothesis that the viewpoint of the un-trapped observers is preferred, even when the black objects are probed from close-up.

The experimental hurdles to determine whether the objects astronomers see are black holes or black stars seem daunting because the fraction of energy emitted as photons from colliding black stars is likely to be tiny, and also because astrophysical objects are situated in very messy environments. Yet there are heroic ongoing efforts to probe deeper and deeper into known black hole candidates [14], and to seek black hole binary systems and mergers by their gravitational wave signals [15]. Possibly we will see experimental resolution in the not too distant future. The results will be invaluable in our quest for the principles of quantum gravity.

*Tanmay Vachaspati
Physics Department
Arizona State University
Tempe, AZ 85287, USA.*

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