The Universe Is Unknowable From Within It
Is This My Spacetime Or Yours?

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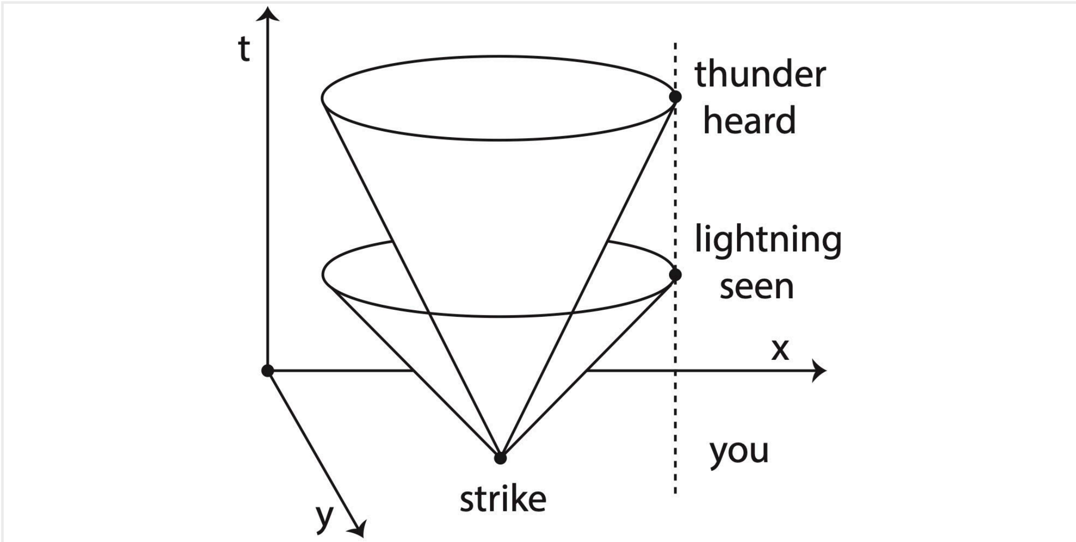
It is well known that the region beyond the 'observable universe' is unknowable. What is less well known is this: even if one were somehow able to observe this unobservable region, the universe would remain unknowable. Indeed, the puzzling state of affairs would persist even if one were given an all-access pass to every possible observation at every possible place and time -- here, there, past, present, and future.

In what follows, I will argue that there is a sense in which the universe is fundamentally unknowable via any number of observations made from within it. This claim amounts to a theorem of Einstein's general theory of relativity and the argument amounts to a simple proof sketch of this theorem. Only a few key definitions will be needed to state the theorem and sketch the proof.

Let's start with the notion of a four-dimensional spacetime. This is a model of general relativity that represents a possible universe compatible within the theory. One can think of a spacetime as a collection of events with some additional structure that specifies how the events are related. One's birth and one's death are events. A first kiss is an event. The moon landing is also an event. But July 20, 1969 is not an event. And the moon is not an event.

Experience seems to tell us that any event can be characterized by four numbers: one temporal coordinate t and three spatial coordinates x,y,z. Accordingly, the local structure of spacetime resembles a four-dimensional Cartesian coordinate system. Diagrams can help us 'see' this spacetime structure. Consider the spacetime diagram of a lightning strike for example.



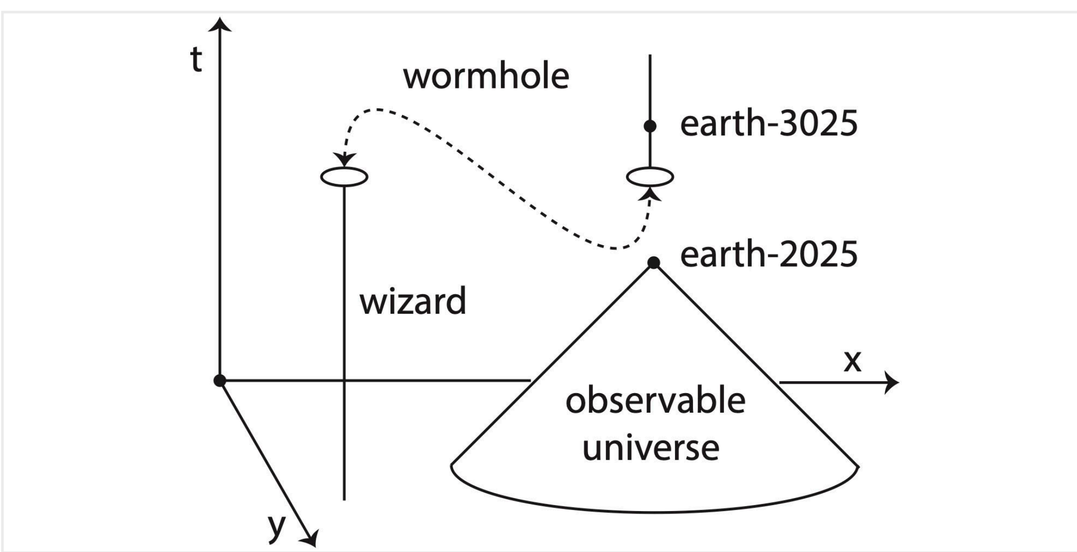
Following a long tradition, the time axis t is vertical with the up arrow pointing in the future direction. Two spatial dimensions x and y are also depicted with the z dimension suppressed. Just after the event of the strike, light propagates radially outward in all spatial directions. The uniform speed of light has the effect of producing a cone shape in the future direction of spacetime. The thundering sound of the strike creates a similar structure. The future 'sound cone' fits inside the future 'light cone' because the speed of light is so much faster than that of sound. Suppose you are standing nearby. At any particular time, you are located at a particular point in space. When all of the you-at-a-time points are stacked together, the resulting 'world-line' is a smooth curve in spacetime: the four-dimensional you. Naturally, you will see the lightning before hearing the thunder. How much time passes between these two events will depend on how far away you are from the strike; the further away, the more time will separate the two events.

Spacetime diagrams take some getting used to. But with a little practice, one can develop the ability to view the universe and its happenings from a different angle. Consider another example: what is the spacetime diagram of the entire human race? After a bit of thought, it becomes clear that it must look something like an enormous tree. The world-line of each person is a little branch of the tree that is joined to some other branch -- the world-line of the person's biological mother -- at the event of the person's birth. At any given time, humanity is a collection of disconnected bodies in three-dimensional space. In four-dimensional spacetime, however, humanity is a single entity. From this perspective, the aphorism "we are all connected, man" is not a mere metaphor!

Central to general relativity is the idea that nothing can travel faster than light. Returning to the lightning strike example, this means that there is no way to know that the strike has happened before its future light cone reaches you. Let's explore this idea a bit more. Given any event in spacetime, we say a second event is in the future light cone of the first if it is possible to travel (or send a signal) from the first to the second while never exceeding the speed of light. The past light cone of a given spacetime event is defined analogously. Because time has a direction, there is an empirical asymmetry with respect to past and future light cones. The region of spacetime that is observable from a given event is represented by the former and not the latter. Because of the cosmic 'speed limit' of light, there is just no way for a local observer to empirically access the region outside of her past light cone. For this reason, what is often called the 'observable universe' is just the past light cone of the spacetime event we might call earth-2025.

The universe is much, much larger than the observable universe. Consider a metaphor due to the cosmologist George Ellis: "The situation is like that of an ant surveying the world from the top of a sand dune in the Sahara desert. Her world model will be a world composed only of sand dunes -- despite the existence of cities, oceans, forests, tundra, mountains, and so on beyond her horizon'' [1]

Just as it would be a mistake to conclude that the earth is flat simply because it seems to be that way in one's immediate vicinity, so too would it be a mistake to conclude that the local structure of the universe mirrors its global structure. For this reason, general relativity can be quite permissive with respect to physical possibility. For example, the theory allows for a wide variety of global shapes so long as the four-dimensional Cartesian coordinate system is preserved locally. Perhaps spacetime is shaped like a type of cylinder: a cross between spherical space and linear time. General relativity allows for such possibilities. Even pathologies such as 'time travel' and spacetime 'holes' of various kinds are not ruled out a priori. Let's now explore some of the strangeness of the theory.



Consider a spacetime diagram of a 'wormhole' outside the past light cone of

Earth-2025. Beyond the observable universe, an otherworldly wizard travels along one trajectory until the wormhole transports him to Earth-3025. This possible universe counts as a model of general relativity. One constructs such a model by cutting a pair of slits from an otherwise well behaved spacetime and identifying the top edge of one slit with the bottom edge of the other and vice versa. From the diagram, we see that the wormhole is unknowable for any observer at the event Earth-2025 since it is not contained in the past light cone of the event, i.e. the observable universe. Of course the wormhole can be known to the wizard once he passes through it at the later event Earth-3025.

The use of 'cut-and-paste' constructions like the one just considered was pioneered by Roger Penrose, Stephen Hawking, and others and has proved invaluable in helping us better understand general relativity [2, 3]. It turns out that one can use a cut-and-paste construction to show a general sense of cosmic underdetermination: one cannot know which universe one inhabits even if one were able to access every possible observation at every possible spacetime event. Let's now clarify this statement and sketch an argument for why it must be true.

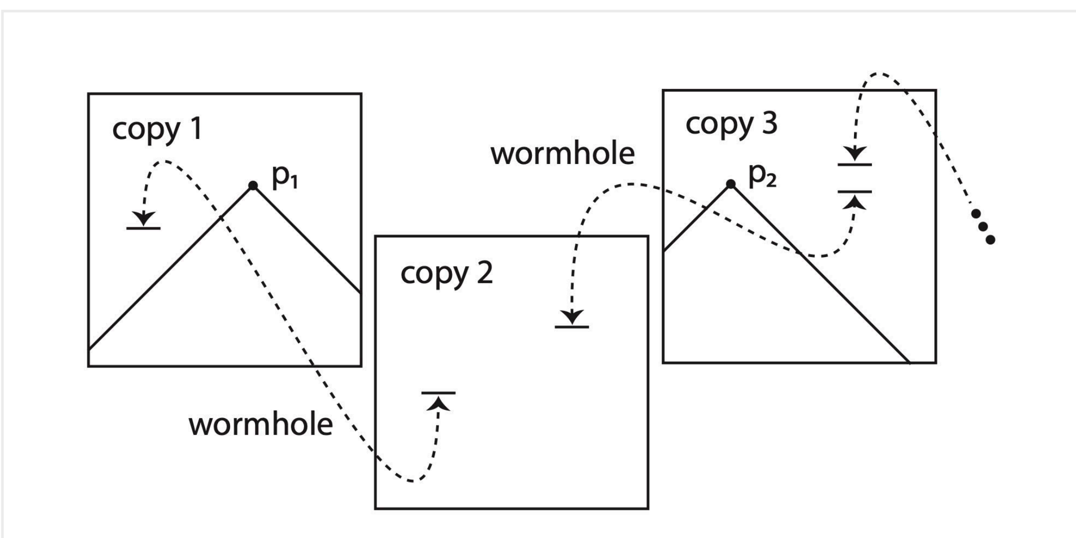
Consider a simple definition due to the philosopher David Malament [4]: a given spacetime is observationally indistinguishable from a second spacetime if, for each event in the first spacetime, there is a corresponding event in the second spacetime such that the past light cones of the two events have the same structure.

Suppose a spacetime is observationally indistinguishable from some other spacetime. From the definition, we see that any light cone in the first spacetime is reproduced somewhere in the second. Now consider an observer, Alice, at some spacetime event in the first. Since Alice only has empirical access to the region within her past light cone, and since this past light cone is reproduced somewhere in the second spacetime, it follows that Alice cannot distinguish between the two spacetimes. But this argument applies not only to Alice but to every other possible observer at every other possible event in the same universe -- Betty, Cher, Daisy and so on. So a radical type of cosmic underdetermination holds: the collective data set gathered by all possible observers in the first spacetime is not sufficient to distinguish between the two models.

Let's now introduce a final definition. We say that a spacetime has a God point if there is an event whose past light cone is the totality of spacetime. From a God point, the entire universe can be observed from a single spacetime event. Because general relativity is so permissive, there are models that admit God points -- the Gödel universe is one famous example. But such models are quite extraordinary in that they necessarily allow for 'time travel' of a certain kind. This follows since the future light cone of any God point must, by definition, fit inside its past light cone. From here on out, let's restrict attention to models of general relativity that do not have a God point. Within this context, Malament conjectured that any relativistic spacetime must have an observationally indistinguishable counterpart different from itself. The conjecture eventually turned out to be true [5].

To see why, consider any spacetime without a God point. Call it A. One can show that all of spacetime A can be observed from some infinite number of events p1, p2, p3, and so on. It follows that any past light cone fits inside the past light cone of one of these events. Consider an infinite number of copies of spacetime A. We will now link all of these copies together via certain wormholes to create a 'chain' spacetime B.

In the first copy of spacetime A, find a region outside the past light cone of p1. We know such a region exists because A does not have a God point. Cut a slit in this region in both of the first two copies of A. Identify the top edge of one slit with the bottom edge of the other and vice versa to create a wormhole as shown in the diagram (two spatial dimensions are suppressed). This connects up the first two links in the chain. In the third copy of A, find a region outside the past light cone of p2. Again, we know this can be done since A does not have a God point. Cut a slit in this region in both the second and third copies of A and identify the slits to create another wormhole. This connects up the second and third links in the chain. Carry on in this way to link up all of the copies of A. Let the resulting chain spacetime be called B.



Due to the infinite number of wormholes, the chain spacetime is clearly different from the spacetime we started with. And because any past light cone in spacetime A fits inside the past light cone of one of the events p1, p2, p3, etc, we see that any past light cone in A has a corresponding past light cone in one of the links in the chain spacetime B. Indeed, the wormholes were carefully chosen so as to preserve the structure of such past light cones in the odd links of the chain.

Meanwhile, the even links of the chain act as a type of spacetime buffer in which cutting and pasting can be done wherever needed.

Stepping back, we see that the original spacetime A is observationally indistinguishable from the chain spacetime B. The collective data set gathered by all observers in A is not sufficient to distinguish between these two spacetimes. This is the sense in which the universe is unknowable from within it -- no matter how many observations are made.

This result is surprising. Returning to the metaphor from above, one might have expected that although the ant in the Sahara desert cannot know what lies beyond the sand dune, if an army of ants were stationed in every possible location -- cities, oceans, forests, tundra, mountains, and so on -- they could collectively determine the structure of their world. This is not so. We see that some other 'chain world' must exist that reproduces all the possible observations of cities, oceans, forests, tundra, mountains in a different way.

Let's now consider a few common objections to the cosmic underdetermination result just presented. The argument presupposes the standard formulation of general relativity. But how can an observer within the universe be in position to know for sure that such a theory is true? She can't. But she also cannot rule out, with absolute certainty, any number of wild conspiracy theories concerning the universe. As noted by the philosopher Bertrand Russell: "There is no logical impossibility in the hypothesis that the world sprang into existence five minutes ago, exactly as it then was, with a population that 'remembered' a wholly unreal past'' [6].

Russell goes on to emphasize that such skeptical 'theories' of spacetime are entirely uninteresting from a scientific point of view. In contrast, the argument for cosmic underdetermination sketched above is of some interest precisely because it proceeds from within the context of our best large-scale physical theory: general relativity. It is curious that even within the strict confines of such a theory, no amount of empirical observation can determine the structure of the universe. Moreover, the result seems to hold within the context of any spacetime theory whose models do not have God points (e.g. any future theory of quantum gravity). The predicament is not unique to general relativity.

One might object that the cut-and-paste chain spacetime is artificial in some sense. Fine. But it is essential to keep in mind the following: "The spacetimes which result from these constructions are, in almost every case, physically unrealistic for various reasons. The point of the construction, however, is not normally to construct physically realistic cosmological models, but rather to demonstrate by means of some example that a certain assertion is false, or that a certain line of argument cannot work'' [7]. In the present context, the line of argument that cannot work is this: the collection of all possible observations in a given universe is sufficient to determine the global structure of that universe.

Perhaps the predicament can be avoided by restricting attention to spacetimes with certain 'physically reasonable' properties. For example, one might insist that spacetime satisfy any number of 'energy conditions' which constrain the local distribution and flow of matter. This amounts to a mild form of induction in which "the normal physical laws we determine in our spacetime vicinity are applicable at all other spacetime points'' [8]. But one can show that the cosmic underdetermination theorem is maintained under any such local induction; the cut-and-paste construction outlined above preserves all local spacetime properties.

In light of the situation, one might insist that spacetime have certain global properties instead. But what justifies this move? Given the theorem, we know this justification cannot be due to any observational data we have collected -- even after allowing for any local induction on such data. Perhaps one could appeal to some strong form of global induction. For example, the Copernican principle could be invoked which seems to modestly deny us a special status in the cosmos: the observable universe is presumed to be representative of the entirety of spacetime. But as the philosopher John Earman has aptly remarked, "this seeming modesty is belied by the immodest use to which the principle is put in justifying an inductive extrapolation'' [9]. Indeed, induction on such vast scales would seem to be suspect given that we are able to observe only the tiniest fraction of the universe [10]. Remember the ants!

References

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