Relativity appendix 3: Timelessness in general relativity

Exactly how this works is a complicated story whose details need not concern us. Here's the barest outline. Given an observer and a clock, you can define all the events in the spacetime history that are simultaneous with some reading of that clock. For each reading of the clock—say, noon last Tuesday—these events define a three-dimensional space.

This space has some geometry; it is a complicated, messy, curved three-dimensional space that (together with the positions of all the particles in the geometry) can be thought of as a configuration. You can define the initial conditions, which add to the geometry a measure of how it is changing in the time experienced by the observer. Given that initial data, Einstein's equations can be solved to give the whole spacetime geometry—which is to say, the whole history of the universe. The observer can then tell a story about the world having a three-dimensional geometry that evolves over time, as stars and galaxies move around, black holes form, and gravitational waves are produced and propagate. This is all captured in a path through an enormous configuration space whose points are possible three-dimensional configurations of geometry and matter.

The whole construction starts out with the choice of an observer. The set of events that are so defined as simultaneous are dependent on the choice of observer—where she is and how she moves. Different observers will define different three-dimensional simultaneities and will tell somewhat different stories about how those simultaneities evolve.

Remarkably, the four-dimensional spacetime produced by each observer's story is the same. As in Minkowski spacetime, the viewpoints of all the possible observers fit together into a single structure, which is a single spacetime geometry. What the stories of the observers have in common is the physical processes by which earlier events cause later events.

As in special relativity, no causal influence can travel faster than light. So the history of which events were the causes of which later events is captured, if you know the paths made by light as it travels through the spacetime geometry. This causal structure is the main part of the information captured by the spacetime geometry, which is common to the stories of all observers.

This spacetime geometry is hypothesized to be a solution to a set of mathematical equations. So the whole history of the universe is now hypothesized to correspond to a set of mathematical functions, which represent the solution of the mathematical equations. But mathematical equations do not live in the physical world, they live in the ideal**,** timeless, Platonic world. So must their solutions. Hence the whole history of the universe is hypothesized to correspond to a timeless mathematical object. The whole world we experience unfolding in time has been represented as a complicated geometry that is hypothesized to be nothing but a timeless solution to a timeless equation.

If we take this mathematical representation of the history of the world seriously, it leads to a metaphysical story: the block-universe picture. According to this story, the experience of the flow of time is an illusion. All that is real is the whole history of the universe, laid out at once, timelessly.

Thus we come to one of the biggest arguments for the expulsion of time from our understanding of nature. What is real is not our perception of time or anything having to do with a moment of time. What is real is only the whole history of the universe, existing as a single, timeless unity.

What if you prefer a story of a universe evolving in time? You can have it, just choose your observer and a clock, and she can tell you a story of how events that are simultaneous according to her notion of time define a three-dimensional world that evolves in time. But there are an infinite number of such stories, one for each possible observer. What the stories have in common is the spacetime history.

The problem is that the various observer-dependent stories, in which the universe as a whole is seen to evolve in time, have a lot of information in them that seems to have no physical meaning. Once you fix a notion of time—and hence define a simultaneity involving the whole universe—you're asserting that lots of faraway events that cannot influence one another because they're too far from one another for light to connect them are happening "simultaneously."

These notions of simultaneous events appear mythical for two reasons: (1) they have no relation to physical causality, to the action of real forces or physical influences; and (2) different observers will perceive the order of these faraway unconnected events differently. As these time orders seem to be arbitrary and observer-dependent, they have no real physical meaning.

This conclusion leads us to reject as physically meaningless the picture of the universe evolving in time. We seek instead the real picture, which contains only the physical, causal ordering of events. This picture exists, but it is the spacetime picture in which the universe does not evolve; its history just is. Thus we see how general relativity strengthened the block-universe picture and, in doing so, struck a mighty blow against the idea that time, in the sense of the flow of moments, is fundamental to nature.

Cosmological spacetimes

These solutions are associated with the names of Alexander Friedmann, H. P. Robertson, Arthur Walker, and Georges Lemaître and are called FRWL universes. They are very simple models, in that they assume that the universe is spatially homogeneous. There is a preferred notion of time, which gives rise to a preferred notion of simultaneity. At these moments of simultaneity, each place is the same as every other and the universe looks the same when viewed in any direction.

I should emphasize that the relativity of simultaneity does not prevent some solutions to general relativity from having special time coordinates that reflect symmetries of the model. These time coordinates are properties of the solution, not the theory. But these are very special solutions, useful for realizing only a very rough model of the universe. There are no gravitational waves, no stars, no galaxies, no black holes in these solutions—just a uniform gas. All that such a universe can do is expand or contract, and all that the matter can do is dilute and cool (or increase density and heat up if the universe is contracting.) They are nonetheless useful models, because the universe does appear to be uniform when the distribution of matter is averaged over scales of several hundred million light-years. Within a box this large, there are millions of galaxies. If you observe the universe with a coarse instrument that samples the density of matter only at these large scales, the universe looks roughly the same everywhere.

The FRWL models all behave alike at early times. As you dial the time on the clock of any observer in the universe backward, in a finite amount of time you reach a state in which the density and temperature of matter and the strength of the gravitational field—all the physically observable quantities—approach infinity. At the point when they become infinite, the equations of general relativity, which are being solved to generate the model, break down and stop giving sensible answers. The laws of general relativity simply stop functioning. This kind of behavior is called an initial singularity. It tells you that there is a time before which it makes no sense to continue extrapolating backward.

The singularity theorems

These singularity theorems required only general assumptions:

> (1) There is at least one surface of simultaneity, at which time the universe is expanding, in the sense that the galaxies are everywhere moving apart from one another. This appears to be true of the observable universe.
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> (2) The density of energy is everywhere positive. This is satisfied by all known forms of matter and radiation.
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> (3) The laws of general relativity hold exactly.

Penrose and Hawking proved that any solution to the equations of general relativity that is in agreement with these assumptions will have a moment before which time does not exist. To put it more precisely, they showed that there will be observers whose worldlines cannot continue back before some finite time in the past.

The most likely reason is that there is indeed a time when all physical quantities become infinite and the equations break down, although Penrose and Hawking did not prove this directly. Nonetheless, all the evidence points to a singular moment **[[Q: mean a singularity?]]** being the cause. In all these solutions—which, I must emphasize, agree with all observations of our universe—the universe appears to begin in a singularity where all quantities are infinite. At any later time, the universe is expanding and the densities and temperature are decreasing. This is what is called the Big Bang.

Thus all these solutions describe universes in which time has a beginning. If by "time" we mean a reading on a clock, then there's a limit to how far back we can trace the ticks of any clock before they dissolve in infinite density and temperature. If by "time" we mean a chain of causal relations, then there is a moment before which the chain runs out.