Aspects of Time in Physics

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Time, the most common English noun, has mystified thinkers at least since Saint Augustine (354–430). Humans have long recognized regularities in nature that have to do with time, particularly in astronomy, such as the length of the tropical year, determined to be 365.2422 days by Omar Khayyam (1048–1131).

In Newtonian mechanics, absolute time is a fixed background for Newton’s three laws of motion. In special relativity, time by itself is not absolute, but related to space. Although space and time are separately not absolute, their union into Minkowski spacetime was still viewed as an absolute background for all events, not affected by the events themselves. In general relativity, spacetime itself is not absolute in the sense of being a background structure unaffected by the events within it, but is instead a dynamical structure evolving in interaction with the matter. General relativity implies that in many situations spacetime has a singular boundary or edge where space or (more usually) time begins or ends.

Newtonian mechanics, special relativity, and general relativity are all classical theories, in which particles and fields have histories, but in quantum mechanics, there are not definite particle histories, but instead a quantum state $|\Psi\rangle$ that in a simple background evolves deterministically by the Schrödinger equation for all time $t$, so there is no limit to time in either the past or future.

However, the situation is more uncertain in quantum gravity, in which one also applies quantum theory to the spacetime itself. Canonical quantum gravity for a closed universe gives a quantum state that has no dependence on time and obeys $\hat{H}|\Psi\rangle = 0$, which is the Hamiltonian constraint equation for quantum cosmology (the Wheeler-DeWitt equation). Then how do we get the observed time evolution of the universe?

DNP and William Wootters, “Evolution without Evolution: Dynamics Described by Stationary Observables,” Phys. Rev. D27 (12), 2885-2892 (1983), showed that because the time parameter in the Schrödinger equation is not observable, energy apparently obeys a superselection rule in the same sense that change does. That is, observables must all commute with the Hamiltonian and hence be stationary. This means that even without considering canonical quantum gravity, it is consistent with all observations to assume that any closed system such as the Universe is in a stationary state. The observed dynamical evolution of a system can be described entirely in terms of stationary observables as a dependence upon internal clock readings, given by the conditional expectation value

$$E(A|\tau) = \frac{\langle P_\tau AP_\tau \rangle}{\langle P_\tau \rangle} = \frac{\text{tr}(P_\tau AP_\tau \rho)}{\text{tr}(P_\tau \rho)}.$$