Conceptual Problems in Quantum Gravity

Why is quantum gravity hard? There are a lot of particular answers, but most, if not all, of them, have the same root. According to general relativity, gravity is a characteristic of the structure of spacetime, so quantum gravity means quantizing spacetime itself. In a very basic sense, we have no idea what this means. For instance:

1. As a probabilistic theory, quantum mechanics gives time a special role: we would like to say, for example, that an electron has a total probability of one of being somewhere in the Universe at a given time. But if spacetime is quantized, we don't know what "at a given time" means.

2. We can try to define time as "the reading of a clock." But any quantum mechanical clock made of ordinary matter has a finite (though small) probability of occasionally running backwards.

3. We would like to require that causes precede effects; this is, in fact, a basic axiom in the construction of quantum field theories. But if spacetime is subject to quantum fluctuations, the notion of "preceding" gets smeared out, and we no longer know how to make sense of causality. We can't say "A comes before B" any more; the best we seem to be able to do is to say "A probably comes before B."

4. Typical observables in quantum theories are things like "the field at a given point x." But if spacetime is quantized, we no longer know what it means to talk about "a given point." It is probably true that all, or almost all, observables in quantum gravity are nonlocal, and we know very little about how to deal with such objects.

5. It's likely that the structure of spacetime itself at very small distances is quite different from what we're used to. For instance, there are variations on the uncertainty principle that seem to imply that there is a minimum observable length. (Observing small distances requires high momenta, which then curve spacetime and distort the distances.) Other hints suggest that spacetime loses dimensions at very short distances, perhaps becoming effectively two-dimensional. But we don't know what to replace our ordinary picture of spacetime with.

6. Typically, quantum field theories can't be solved exactly, and must be approached with systematic approximation methods, or "perturbation theory." For quantum gravity, ordinary perturbative methods start with flat spacetime and treat curvature as a small distortion. But there is no reason to believe that flat spacetime -- or any simple, smooth manifold at all -- is a good approximate solution to quantum gravity.

I should stress that people who work on quantum gravity don't, for the most part, spend much time thinking about such
problems in the abstract. Rather, they try various approaches that work elsewhere, run into some difficulty that's rooted in these conceptual problems, and try to solve it in a concrete instance; or they look for ways to reformulate general relativity or quantum mechanics to make these issues less important; or they look for simpler models in which some of these problems occur but may be solvable. There are lots of vague ideas about what quantum gravity might look like; the hard part is in getting any of them to actually work in detail.

(For a nice review paper by Chris Isham on some of the conceptual issues in quantum gravity, go here.)

Contributors and Attributions

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