Leibniz's principle of indistinguishability

In the years 1715 and 1716, the great German philosopher and mathematician Gottfried Wilhelm Freiherr von Leibniz carried on an extensive correspondence with Samuel Clarke, an English colleague of Isaac Newton, arguing over the nature of good thinking about scientific theories. Leibniz was concerned with the conclusions to draw from the empirical indistinguishability of apparently different physical situations, and, as physicist Robert Spekkens notes in an interesting recent essay (preprint at https://arxiv.org/abs/1909.04628; 2019), he formulated a general principle on the issue.

As Leibniz put it: "If an ontological theory implies the existence of two scenarios that are empirically indistinguishable in principle but ontologically distinct ... then the ontological theory should be rejected and replaced with one relative to which the two scenarios are ontologically identical."

In other words, if a theory describes two situations as being distinct, and yet also implies that there is no conceivable way, empirically, to tell them apart, then that theory contains some superfluous and arbitrary elements that ought to be removed.

Leibniz's prescription is, of course, widely accepted by most physicists today. The idea exerted a powerful influence over later thinkers, including Poincaré and Einstein, and helped lead to the theories of special and general relativity. And this idea, Spekkens suggests, may still hold further value for questions at the frontiers of today's physics.

Leibniz's correspondent Clarke objected to his view, suggesting an exception. A man riding inside a boat, he argued, may not detect its motion, yet that motion is obviously real enough. Leibniz countered that such motion is real because it can be detected by someone, even if it isn't actually detected in some particular case. "Motion does not indeed depend upon being observed," he wrote, "but it does depend upon being possible to be observed ... when there is no change that can be observed, there is no change at all."

In this, Leibniz was arguing against prevailing ideas of the time, and against Newton, who conceived of space and time in absolute terms. "I have said more than once," Leibniz wrote, "that I hold space to be something merely relative."

Einstein, of course, followed Leibniz's principle when he noticed that the equations of electricity and magnetism make no reference to any absolute sense of motion, but only to relative motion. A conducting wire moving through the field of a magnet seems like a distinct situation from a magnet moving past a stationary wire. Yet the two situations are in fact empirically identical, and should, Einstein concluded, be considered as such. Demanding as much leads to the Lorentz transformation as the proper way to link descriptions in reference frames in relative motion. From this, one finds a host of highly counter-intuitive effects, including time dilation.

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Einstein again followed Leibniz on his way to general relativity. In this case, the indistinguishability of two distinct situations — a body at rest in the absence of a gravitational field, or in free fall within a field — implied the impossibility of referring to any concept of absolute acceleration. In a 1922 lecture, Einstein recalled the moment of his discovery: "The breakthrough came suddenly one day. I was sitting on a chair in my patent office in Bern. Suddenly the thought struck me: If a man falls freely, he would not feel his own weight. I was taken aback. This simple thought experiment made a deep impression on me. This led me to the theory of gravity."

Leibniz now mostly inhabits scientific history books, his ideas receiving scant attention in actual research. And yet, Spekkens argues, Leibniz's principle concerning indistinguishability may be as useful as ever, especially when confronting foundational issues in physics. Consider the interpretation of quantum theory, where theorists remain separated into two opposing groups, loosely associated with the terms realism and empiricism. Although Leibniz's principle can't offer any way to unify the two groups, Spekkens argues, it might help them focus their attention on the most important issues dividing them, where progress might be made.

For example, one particular interpretation comes in the form of so-called pilot-wave theories, in which electrons and other particles follow precise but highly non-classical trajectories under the influence of a quantum potential, which produces the wave-like nature of quantum dynamics. These theories demonstrate by explicit example that nothing in quantum physics prohibits thinking about particles moving along well-defined trajectories. But the theory does require the existence of some absolute rest frame, while also implying that this frame can never be detected. Many other aspects of such theories also remain unconstrained by empirical data. Hence, one might take Leibniz's principle as coming down against such theories.

On the other hand, Spekkens points out, Leibniz's principle demands that distinct states be, in Leibniz's own words, "empirically indistinguishable in principle," and achieving such certainty is not easy. If several states appear indistinguishable now, future experiments might turn up measurable differences between them. So a proponent of the pilot-wave approach might agree with Leibniz's principle, but still reject its application just yet. The aim of research, from this point of view, ought to be to seek out such evidence, or at least envision the conditions under which it might be obtained.

And in this sense, Spekkens notes, Leibniz's principle also offers some criticism of theorists from the empirical school, who object to pilot-wave or other realist interpretations of quantum theory for containing unmeasurable quantities. It implies, as he puts it, that the empiricists' "set of mental tools is too impoverished." After all, progress in physics often requires imagination, and creative exploration of possible distinguishing features that have not yet been measured, or even thought to exist. Progress requires scientists to "entertain ontological hypotheses, expressed with concepts that are not defined purely in terms of empirical phenomena."

Science thrives on the essential tension existing at the boundary between empirical observation and unconstrained imagination. Incredibly, Leibniz perceived that more than 300 years ago. ❐

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