What is Non-locality?

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April 20, 2023

Outline

What is a local theory (or process)?

- The path between cause and effect can be traced from one point in spacetime to another.
- There is a continuous path between the cause and the effect, with no "breaks."
- This also holds for space alone, and time alone.
- For example, a cause at one time can't have an effect later (at the "same place") unless there are effects at every time in between.
- The *propagation* element is crucial here. A local theory explains how this happens at each individual point in space and time.
- Example: Newton's 2nd law. Knowing that the acceleration equals the force divided by the mass tells us how the velocity of an objects changes at each point along its path. This allows us to construct the complete path out of the individual points.
- What is a *non-local* theory or process? Simply anything that does not correspond to the preceding definition. Anything that is not local.

Action at a distance

- The first kind of non-locality we'll look at is *action at a distance.* I think the phrase is fairly self explanatory. You have a cause at one place (or time) and an effect at another place (or time) without anything happening in-between.
- For example, Newton's theory of gravitation is typically construed as involving action at a distance. A body exerts a gravitational force directly on another body without any intervening effects.

  It's not clear whether Newton himself actually believed this, but we won't go into that here.
- If Alice and Bob separately measure their entangled particles, you might imagine that a message passes from one of them to the other, telling how the receiving particle should behave. This would be a local process.
- Or, you might imagine that when Alice does her measurement, it directly affects Bob's particle, without anything passing between them. This would be action at a distance.
- These days action at a distance is definitely frowned upon in physical theories. But who really knows for sure?

The whole is not the sum of the parts

- Here's another kind of non-locality. We drop the assumption that a single entity must be localized in space. You might think of this as a failure of "geographic reductionism" or that the whole is not the sum of the parts.
- *Asides (maybe):*
  - *Different kinds of reductionism*
  - *the "sum" is really a product*
  - *Cartesian vs tensor product spaces.*
- So, although it may violate our intuitions about how things work, if the entangled pair is really a *single thing* then perhaps this could provide an explanation for the correlations. Our theory certainly treats the pair as a single entity. There is a single joint state, but the individual particles do not have states.

State does not precede correlation

- Suppose I make a statement like "My shirt is the same color as John's." Then, even though we don't know the color involved, I think we normally assume that I'm actually referring to some specific color, and that both my shirt and John's shirt each individually are of that color.
- In other words, claims about correlations are really just claims about underlying states.
- But what if this intuition turns out to be wrong? What if correlation can underly states? Does it seem like entanglement might be hinting at something like this?
- Michael Esfeld's paper Do relations require underlying intrinsic properties?, for example, explores this possibility.

Different formulations of classical laws

- Let's switch gears for a moment and talk about different ways that the laws of classical physics are typically framed.

- Equations of motion vs. conservation laws

  (1) Newton's 2nd law: $F = ma$

  (2) Momentum and kinetic energy are conserved over space and time.

  A simple collision can be analyzed using either formulation.

- Local dynamics vs. extremal laws.

  (1) Snell's law†: $\frac{\theta_1}{\theta_2} = \frac{n_2}{n_1}$

  (2) Fermat's principle: Light travels the path which takes the least time.

  Both govern a "light ray" traveling a path through several different substances.

- In both cases (1) above, the laws themselves refer to local conditions. But in the cases (2) the laws are global. Classically, it is always possible to believe that the global laws are actually underwritten by the local dynamics. Perhaps that's not so in quantum theory.

† For a given pair of media, the ratio of the sines of the angle of incidence (θ_1) and the angle of refraction (θ_2) is equal to the ratio of the refractive indices of the two media (n2/n1).

Laws on spacetime

- So perhaps what quantum theory is telling us is that the global laws were really the primary ones all along. We simply have “laws on spacetime” rather than laws governing local dynamics. When we look closely enough (at the microscopic level) we see that sometimes there are *only* these global laws.

- An example, for those already familiar with the Pilot Wave interpretation. Perhaps this concept can be used to get around the “action at a distance” objection. Perhaps we’re talking about a fundamental law that’s framed globally.

- Sheldon Goldstein, Nino Zanghì, and Detlef Dürr have proposed something like this in the following papers:

  Bohmian Mechanics and the Meaning of the Wave Function

  Reality and the Role of the Wavefunction in Quantum Theory

Configuration space

- TBD (maybe)

Summary

- What is non-locality? There are a number of different ways that we could view the world as having non-local elements and/or processes. Some (all?) of these ways overlap in some respects, and the boundaries between them are arguable.
- We've seen previously that quantum theory *could* be interpreted as implying some sort of non-locality in the world. (Some people claim it *must* be interpreted that way.)
- Often the non-locality claim is phrased in terms of action at a distance. But there are other possibilities.
- At the end of the day, to what extent are these other possibilities truly and fundamentally different? What do you think?
- Do you find any of the other possibilities more palatable than action at a distance?