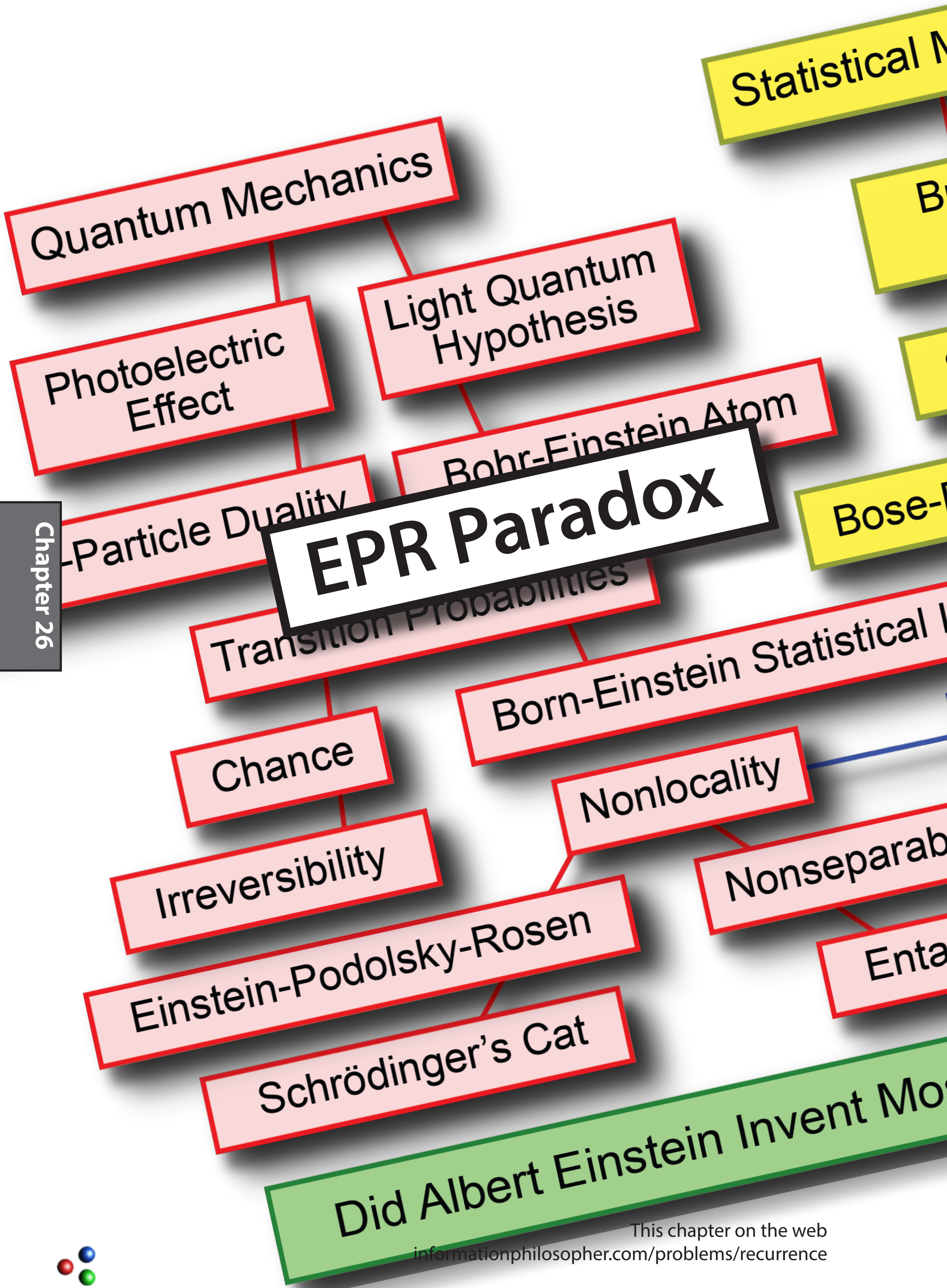

Chapter 26

This chapter on the web
informationphilosopher.com/problems/recurrence

Einstein-Podolsky-Rosen

The 1935 paper, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" by Albert Einstein, Boris Podolsky, and Nathan Rosen (and known by their initials as EPR) was originally proposed to exhibit internal contradictions in the new quantum physics.

Einstein hoped to show that quantum theory could not describe certain "*elements of reality*" and thus was either *incomplete* or, as some think he may have hoped, demonstrably incorrect.

> the following requirement for a complete theory seems to be a necessary one: every element of the physical reality must have a counterpart in the physical theory. We shall call this the condition of completeness.
>
> We shall be satisfied with the following criterion, which we regard as reasonable. *If, without in any way disturbing a system, we can predict with certainty {i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.*[1]

Using Werner Heisenberg's uncertainty principle, Einstein wrote in the EPR paper, "when the momentum of a particle is known, its coordinate has no physical reality." But if both momentum and position had simultaneous reality—and thus definite values—"these values would enter into the complete description, according to the condition of completeness."[2]

Despite Einstein's very clear definition of incompleteness, Niels Bohr and his Copenhageners took "incompleteness" as just one more of Einstein's criticisms of quantum mechanics, especially its uncertainty principle.

There is a lot in the paper that looks like a failed attempt to get around the uncertainty principle. Einstein's concern about incompleteness was the inability of quantum mechanics to provide exact and simultaneous values for position and momentum.

Einstein gave an "objectively real" example of incompleteness that even a third grader can understand. Imagine you have two

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1 Einstein, Podolsky, Rosen, 1935, p.777

2 *ibid*. p.778

boxes, in one of which there is a ball. The other is empty. An *incomplete* statistical theory like quantum mechanics says, "the probability is one-half that the ball is in the first box." An example of a *complete* theory is "the ball *is* in the first box."

But Einstein's fundamental concern in the EPR paper was not incompleteness. It was *nonlocality*, which had been on Einstein's mind for many years. Nonlocality challenged his special relativity and his claims about the *impossibility of simultaneity*.

Nonlocality in 1905 and 1927 involved only one particle and the mysterious influence of the probability wave. But now Einstein showed nonlocal effects between *two* separated particles.

Einstein's basic concern was that particles now very far apart may still share some common information, so that looking at one tells us something about the other.

His other colleague Nathan Rosen made use of Einstein's argument that measuring a particle here would give us information about a particle far away, without a direct measurement, if in the past they had interacted. Rosen mistakenly claimed he could get simultaneous accurate values for both distant momentum and position, a clumsy attempt to circumvent the uncertainty principle, which Einstein himself had stopped attempting years earlier.

This was probably because Einstein actually thought that an individual "objectively real" particle can have simultaneous values for position and momentum even if quantum measurements, being statistical, can only estimate values as averages over many measurements. The statistical deviations Δp and Δx around the mean values give us the uncertainty principle $\Delta p \Delta x = h/2\pi$.

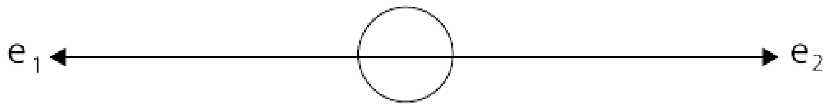
Just before Einstein left Europe forever in 1933, he attended a lecture on quantum electrodynamics by Leon Rosenfeld.[3] After the talk, he asked Rosenfeld, "What do you think of this situation?"

> Suppose two particles are set in motion towards each other with the same, very large, momentum, and they interact with each other for a very short time when they pass at known positions. Consider now an observer who gets hold of one of the particles, far away from the region of interaction, and measures its momentum: then, from the conditions of the experiment, he will obviously be able to deduce the momentum of the other particle. If, however, he chooses to

3 Lahti and Mittelstaedt, 1985, p.136

measure the position of the first particle, he will be able tell where the other particle is.

We can diagram a simple case of Einstein's question as follows.



Two particles moving with equal and opposite momentum leave the circle of interaction (later "entanglement") in the center. Given the position of one particle, the position of the second particle must be exactly the same distance on the other side of the center.

Measuring one particle tells you something about the other particle, now assumed to be at a large spacelike separation. Does that knowledge require information to travel faster than light? No.

But Einstein thought this was "paradoxical." He asked Rosenfeld, "How can the final state of the second particle be influenced by a measurement performed on the first after all interaction has ceased between them?" This was the germ of the EPR paradox, and ultimately the problem of two-particle entanglement.

He later called nonlocality "*spukhaft Fernwirkung*" or "*spooky action-at-a-distance*."[4] But calculating and predicting the position and momentum of a distant particle based on conservation principles is better described as "*knowledge-at-a-distance*."

This idea of something measured in one place "influencing" measurements far away challenged what Einstein thought of as "local reality." These "influences" *appear* to be nonlocal.

What did Einstein see? What was Einstein worried about? We have been arguing that it challenged the *impossibility of simultaneity* implied by his theory of special relativity.

Note that Einstein knew nothing of the simultaneous spin or polarization measurements by Alice and Bob that constitute modern entanglement experiments. But Einstein's insight into the guiding field of the probability wave function can be applied to both entanglement and the two-slit experiment, in which case it might solve two mysteries with one explanation.

It will show Einstein was wrong about the "impossibility" of simultaneity, but like many of his mistakes, gives us a deep truth.

4 Born, 1971, p.155