Lecture 24
Einstein on General Relativity

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Scientific Thought II
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Introduction

Previous classes

- We were discussing a paper Einstein published in 1905.
- *Principle of relativity:* If one coordinate system is in uniform translational motion with respect to another then all physical laws are the same in both systems.

Today

- We'll discuss a paper Einstein published in 1916.
- Calls the 1905 principle of relativity *the special principle*, because it is restricted to uniform translational motion and doesn't cover non-uniform motion (accelerated motion).
- Defends *the general principle of relativity:* Physical laws are the same in all coordinate systems.

Epistemological argument for general relativity

Einstein's question (148)

Two fluid bodies of the same size and nature hover freely in space at so great a distance from each other and from all other masses that only those gravitational forces need be taken into account which arise from the interaction of the different parts of the same body. Let the distance between the two bodies be invariable, and in neither of the bodies let there be any relative movements of the parts with respect to one another. But let either mass, as judged by an observer at rest relatively to the other mass, rotate with constant angular velocity about the line joining the masses . . . Let the surface of S_1 *prove to be a sphere, and that of* S_2 *an ellipsoid of revolution. Thereupon we put the question—What is the reason for this difference in the two bodies?*

Observability requirement (148–49)

No answer can be admitted as epistemologically satisfactory, unless the reason given is an observable fact of experience. The law of causality has not the significance of a statement as to the world of experience, except when observable facts ultimately appear as causes and effects.

Criticism of Newton's answer (149)

Newtonian mechanics . . . pronounces as follows: The laws of mechanics apply to the space R_1, in which S_1 is at rest, but not to the space R_2, in which S_2 is at rest. But the privileged space R_1 of Galileo, thus introduced, is only a fictitious cause, not something observable. It is therefore clear that Newton's mechanics does not really satisfy the requirement of causality in the case under consideration, but only appears to do so, since it makes the fictitious cause R_1 responsible for the observed difference in the bodies S_1 and S_2.

Einstein's conclusion (149)

Of all imaginable spaces R_1, R_2, etc., in any kind of motion relatively to one another, there is none which we may look upon as privileged a priori without reviving the above-mentioned epistemological objection. The laws of physics must be of such a nature that they apply to systems of reference in any kind of motion. Along this road we arrive at an extension of the postulate of relativity.

My criticism

- We can have knowledge of unobservable causes.
  - There was good reason to believe germs cause diseases before germs were observable.
  - We know beliefs and desires cause actions, though nobody can observe a belief or desire.
- How this is possible: Hypotheses about unobservable causes can be confirmed by testing their observable consequences.

Einstein changed his mind

- His epistemological argument came from Ernst Mach (1838–1916), who said science is only about sensory experiences. Mach denied the existence of atoms.
- Einstein later wrote (1949, 21):
  In my younger years . . . Mach's epistemological position . . . influenced me very greatly, a position which today appears to me to be essentially untenable. For he did not place in the correct light the essentially constructive and speculative nature of thought and more especially of scientific thought.

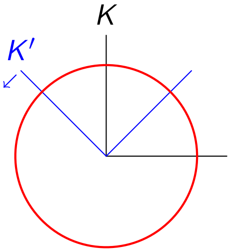
Physical argument for general relativity (150)

- Let K be a coordinate system in which Newton's laws of motion hold and let K' be another system that is uniformly **accelerated** relative to K.
- *Relatively to K', a mass sufficiently distant from other masses would have an acceleration and direction of acceleration that are independent of the material composition … of the mass.*
- *Does this permit an observer at rest relatively to K' to infer that he is on a "really" accelerated system of reference? The answer is in the negative; for the above-mentioned relation of freely movable masses to K' may be interpreted equally well in the following way. The system of reference K' is unaccelerated but the space-time territory in question is under the sway of a gravitational field.*
- This is possible because gravitation accelerates all bodies at the same rate.

My example

- You are in a plane about to take off. The pilot opens the throttle, the engines roar, you get pushed back in your seat, everything out the window moves faster and faster to the rear.
- Einstein said you can adopt a coordinate system in which you are at rest and the world outside is accelerating backwards. The laws of physics shouldn't be any different.
- In this coordinate system:
  - The ground is accelerating backwards because there is a gravitational field behind the plane.
  - The plane is stationary because the engines are counteracting the gravitational force.
  - You are being pushed back in your seat by the gravitational force.

Violation of Euclidean geometry (151–52)



- K is a coordinate system in which Newton's laws hold with no gravitational field (called a Galilean system).
- K' is a coordinate system, with the same origin as K, rotating relative to K.
- The circle center is at the origin of K & K'.

- If the circle circumference and diameter are measured with a measuring rod at rest in K, circumference/diameter $= \pi$.
- A measuring rod at rest in K' will (relative to K) be contracted when along the circumference but not when along the diameter (why?). Therefore, measurement in K' gives circumference/diameter $> \pi$.
- General relativity says all laws of physics hold in any coordinate system. So we must reject Euclidean geometry.

Theory of general relativity

- Einstein developed a theory based on the general principle of relativity, making the laws of physics the same in all coordinate systems.
- As we've seen, the laws of Euclidean geometry don't hold in this theory.
- The theory has made empirical predictions that have been verified.
  - The orbit of mercury precesses more than can be accounted for in Newton's gravitational theory. Einstein's general theory implies the observed amount of precession.
  - General relativity implies that the path of light in a gravitational field bends twice as much as Newton's theory says. Observations confirmed this.
- Euclid's geometry, which was taken to be certainly true for more than 2,000 years, is now found not to be a correct description of the world we live in.

Questions

1. What is Einstein's general principle of relativity? How does it differ from the special principle?
2. Let S_1 and S_2 be two fluid bodies, each far from all other bodies and each rotating in a coordinate system in which the other is at rest. Suppose the surface of S_1 is a sphere and the surface of S_2 is an ellipsoid. How would Newton's mechanics explain this difference? What was Einstein's epistemological objection to Newton's explanation? Is the objection correct? Justify your answer to the latter question.
3. Let K be a coordinate system in which Newton's laws of motion hold and let K' be another system that is uniformly *accelerated* relative to K. Why might it seem that Newton's laws don't hold in K'? What was Einstein's method for avoiding this apparent counterexample to general relativity?
4. Explain Einstein's argument that, if we accept the general principle of relativity, then we must reject Euclidean geometry.

Reference

Albert Einstein.
The foundation of the general theory of relativity.
English translation of article published in German in 1916.
Online edition. Numbers in parentheses are page numbers of this edition if no year is given.
I have improved the translation in places.

Albert Einstein.
Autobiographical notes.
In *Albert Einstein: Philosopher–Scientist*. Library of Living Philosophers, 1949.