The role of the rotating frame thought experiment in the genesis of general relativity

By: Jonathan Everett

Friedman, in *Synthetic History Reconsidered*, argues that the light postulate and the equivalence principle are constitutive of general relativity in the sense that they both played a crucial historical role in the development of the central empirical tenet of the theory: i.e., the action of gravity could be represented by a variably curved four dimensional geometry (2010, p.663).

The light postulate and the equivalence principle make such a geometry possible through their role in Einstein's rotating frame thought experiment. As such Friedman's interpretation of the rotating frame thought experiment is entirely central to his project as a whole, a fact he clearly acknowledges in contrasting his own understanding of the principle of equivalence with DiSalle's (see Friedman 2010, p. 663 and p. 725).

The three-dimensional geometry of the rotating frame is known to be non-Euclidean on the basis of the behaviour of rods within the frame. Ideal clocks within the frame read off time at a slower rate the further away they are from the centre of the frame. These two considerations, Friedman claims, led Einstein to see that he needed to appeal to a non-flat generalisation of the four-dimensional Minkowski metric in order to describe this sort of situation. The equivalence principle—understood as the claim that gravitational effects and inertial effects are of essentially the same kind—plays a crucial role on Friedman's view in motivating Einstein to use a non-flat Minkowski metric to describe gravitation as well.

In this paper, I argue that Friedman's interpretation of the rotating disk thought experiment in the development of general relativity faces two problems:

1. The rotating frame is first referred to in Einstein's published papers in 1912. Einstein here does not treat the rotating frame as making four-dimensional variably curved geometry possible; he treats it as posing a problem for taking coordinate systems to have direct physical significance.

2. Friedman's understanding of the role of the rotating frame requires us to assign to Einstein a logical-empiricist-style epistemology about the role of rigid rods in 1912. This allows us to treat the light postulate as constitutive of general relativity in Friedman's sense, but it is less clear that it secures a similar status for the equivalence principle.

Problem 1: the rotating frame and the physical significance of coordinates

The first problem with taking the rotating frame to have played the historical role that Friedman assigns to it, is that there is little evidence in Einstein's published papers or correspondence between 1912-13 that supports the claim that Einstein took the thought experiment to suggest the physical possibility of four-dimensional space-time. Instead, I suggest, the evidence from this period and later recollections suggest that Einstein viewed the rotating frame as a reason to doubt that coordinate systems have direct physical significance. (See (Einstein 1912, pp.95-6) for the context in which the rotating frame is introduced and (Einstein 1949, p.63) for emphasis on the difficulty in coming to understand coordinate systems as representative).

Prior to 1912 Einstein had considered reference frames to be measured out by rigid rods between which the laws of Euclidean geometry hold. In 1912, when Einstein first mentions the problems posed by a rotating frame of reference, it is in terms of a potential test for precisely this physical hypothesis.

This interpretation explains the role of this thought experiment in the development of general relativity quite differently. It marks the culmination of a series of concerns that Einstein had about the physical meaning of coordinate systems in physics. Eventually assigning coordinate systems direct physical significance came to be so problematic that Einstein abandoned the idea and sought instead for generally covariant field equations, which found their natural expression in four-dimensional tensor calculus.

Problem 2:

While the above understanding of the rotating frame in Einstein's thought seems, to me, plausible, there is evidence to be mustered in defence of Friedman's reading. Friedman places much emphasis on Einstein's mention of the rotating disk thought experiment in his 1921 lecture Geometry and Experience (see Friedman's 2010, pp.661- 3, discussion of Einstein 1921, pp.33-4). In this work, Einstein seems to be claiming that the transition to generally covariant field equations was dependent on two factors: his distinctive view on geometry, and the admission of non-inertial frames of reference on an equal footing to inertial frames.

Einstein's understanding of geometry, as outlined in his (1921, pp.30-1), was a distinctively logical empiricist one. He separated geometry into mathematical geometry and physical geometry: mathematical geometry is based upon the axiomatic approach of Hilbert in which key terms, such as 'line' are intrinsically defined, whereas physical geometry requires the coordination of 'lines' to 'rigid rods'. Friedman emphasises the influence of Helmholtz in Einstein's geometry, but, I suggest, it is really the logical empiricist influence that Einstein took to be crucial to the rotating frame thought experiment.

There are three reasons for this. First, the only philosopher mentioned by Einstein prior to the quote above in Geometry and Experience, is Moritz Schlick. Second, the lecture itself was delivered in the context of an epistemological dispute between Weyl and Reichenbach about mathematical and physical geometries and the role of rigid rods in connecting the two. Einstein, I suggest, is best understood as taking Reichenbach's side in this dispute. Finally the discussion of Helmholtz and Poincaré comes only after the above quote. Einstein here treats Poincaré as objecting to physical geometry on the grounds that there are no rigid rods; Einstein agrees, but argues that, based on practical considerations one may, in the manner of Helmholtz, appeal to rigid rods to determine geometry.

Nevertheless, I argue that if we view Einstein in 1912 as having a proto-logical empiricist epistemology, then much of Friedman's account can be rendered plausible. In particular, by linking the rotating frame thought experiment to a logical empiricist epistemology, I think there is a clear sense in which we can see Einstein as coming to the conclusion that physical geometry need not be Euclidean.

The price to pay for this reconciliatory interpretation, however, is that the equivalence principle is ill-suited to playing the same sort of role in the thought experiment as the light postulate. Prior to Einstein's (1912) he had only stated the equivalence principle as an extension of the relativity principle: the physical laws take the same form in uniformly accelerated frame of reference as they do in a stationary frame of reference in a homogeneous gravitational field. Since uniform rotation is not tantamount to uniform acceleration, it is not clear that this form of the equivalence principle can be seen as doing any work here. Furthermore, the physics of a relativistically rotating frame are so complex that it is difficult to make sense of how even modern formulations of the equivalence principle might apply to it.

Given this, I argue that there is insufficient motivation for describing the equivalence principle as constitutive—in Friedman's historicised sense—of general relativity. I conclude by suggesting instead that if we wish to assign any role to the equivalence principle in this thought experiment, it is preferable to treat it as playing a heuristic role: it convinced Einstein that taking coordinate systems to have direct physical significance would be a general problem for theories of gravitation.

Bibliography:

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