Might have Minkowski discovered the cause of gravity before Einstein?

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On January 12, 1909 only several months after his Cologne lecture *Space and Time* at the age of 44 Hermann Minkowski untimely left this world. We will never know how physics would have developed had he lived longer.

What seems undeniable is that the discovery of the true cause of gravitation – the non-Euclidean geometry of spacetime – might have been different from what actually happened. On the one hand, Einstein's way of thinking based on conceptual analyses and thought experiments now seems to be the only way powerful enough to decode the unimaginable nature of gravitation. However, on the other hand, after Minkowski had written his three papers on relativity, he (had he lived longer) and his friend David Hilbert might have formed an unbeatable team in theoretical physics and might have discovered general relativity (surely under another name) before Einstein.

As there is no way to reconstruct what might have happened in the period 1909-1915 I will outline here what steps had been logically available to Minkowski on the basis of his results. Then I will briefly discuss whether their implications would lead to the modern theory of gravitation – Einstein's general relativity.

In 1907 (most probably in November) Einstein had already been well ahead of Minkowski when he made a gigantic step towards the new theory of gravity:[1]

> I was sitting in a chair in the patent office at Bern when all of a sudden a thought occurred to me: "If a person falls freely he will not feel his own weight." I was startled. This simple thought made a deep impression on me. It impelled me toward a theory of gravitation.

Einstein had been so impressed by this insight that he called it the "happiest thought" of his life.[2] And indeed this is a crucial point – at that time Einstein had been the only human who realized that no gravitational force acted on a falling body. Then he struggled eight years to come up with a theory – his general relativity – according to which gravity is not a force but a manifestation of the curvature of spacetime.

Here I will stress particularly the core of general relativity which reflects Einstein's "happiest thought" – the geodesic hypothesis according to which a falling particle is not subject to a gravitational force. In other words, the geodesic hypothesis in general relativity assumes that the worldline of a free particle is a timelike *geodesic* in spacetime. The geodesic hypothesis is regarded as "a natural generalization of Newton's first law,"[3] that is, "a mere extension of

[1] Quoted from: A. Pais, *Subtle Is the Lord: The Science and the Life of Albert Einstein* (Oxford University Press, Oxford 2005) p. 179.

[2] A. Pais, Ibid.

[3] J. L. Synge, *Relativity: the general theory.* (Nord-Holand, Amsterdam 1960) p. 110.

Galileo's law of inertia to curved spacetime."[4] This means that *in general relativity a particle, whose worldline is geodesic, is a free particle which moves by inertia.*

The geodesic hypothesis has been *confirmed* by the experimental fact that particles falling towards the Earth's surface *offer no resistance to their fall* – a falling accelerometer, for example, reads zero resistance (i.e. zero acceleration; the observed *apparent* acceleration of the accelerometer is caused by the spacetime curvature caused by the Earth). The experimental fact that particles do not resist their fall (i.e. their apparent acceleration) means that they move by inertia and therefore no gravitational force is causing their fall. It should be emphasized that a gravitational force would be required to accelerate particles downwards *only if* the particles *resisted* their acceleration, because *only then* a gravitational force would be needed to *overcome* that resistance.

In his famous lecture *Space and Time* Minkowski outlined his profound idea of regarding physics as spacetime geometry:[5] "The whole world presents itself as resolved into such worldlines, and I want to say in advance, that in my understanding the laws of physics can find their most complete expression as interrelations between these worldlines." Then he explained the difference between inertial motion (represented by a *straight* worldline) and accelerated motion (represented by a *curved* or rather *deformed* worldline) and remarked: "Especially the concept of *acceleration* acquires a sharply prominent character."

As Minkowski knew that a particle moving by inertia offers no resistance to its motion with constant velocity (which explains why inertial motion cannot be detected experimentally), whereas the accelerated motion of a particle can be discovered experimentally since the particle *resists* its acceleration, he might have very probably linked the sharp physical distinction between inertial (non-resistant) and accelerated (resistant) motion with the sharp geometrical distinction between inertial and accelerated motion (represented by straight and curved / deformed worldlines, respectively).

Then Minkowski would have had many logical possibilities to implement his program of geometrization of physics. For example, absolute acceleration is a manifestation of the absolute geometrical feature (*deformation*) of the worldline of an accelerating particle and *does not imply some absolute space with respect to which the particle accelerates.* As an accelerating particle is represented by a curved (deformed) worldline Minkowski might have realized that inertia – the *resistance* a particle offers to its acceleration – could be regarded as arising from a four-dimensional stress[6] in the deformed worldline, or rather worldtube, of an accelerating particle.

To demonstrate the enormous potential of Minkowski's criteria for inertial and accelerated motion I will discuss two scenarios in the talk. Here I will outline the first in which it is assumed that Minkowski had read Galileo's works, particularly Galileo's analysis demonstrating that heavy and light bodies fall at the *same* rate.[7] In this analysis Galileo practically came to the conclusion that a falling body does not resist its fall.

Then the path to the idea that gravitational phenomena are manifestations of the curvature of spacetime would have been open to Minkowski – the experimental fact that a falling particle accelerates (which means that its worldtube is curved), but offers no resistance to its acceleration (which means that its worldtube is not deformed) can be explained only if the worldtube of a falling particle is *both curved and not deformed*, which is impossible in the flat Minkowski spacetime where a curved worldtube is always deformed. Such a worldtube can exist only in a non-Euclidean spacetime whose geodesics are naturally curved due to the spacetime curvature, but are not deformed.

[4] W. Rindler, *Relativity: Special, General, and Cosmological* (Oxford University Press, Oxford 2001) p. 178.

[5] H. Minkowski, *Space and Time: Minkowski's Papers on Relativity*, edited by V. Petkov (Minkowski Institute Press, Montreal 2012) p. 112.

[6] V. Petkov, *Relativity and the Nature of Spacetime*, 2nd ed. (Springer, Heidelberg 2009) Chap. 9.

[7] Galileo, *Dialogues Concerning Two Sciences.* In: S. Hawking (ed.), *On The Shoulders Of Giants*, (Running Press, Philadelphia 2002) pp. 399-626, p. 447.