Is Gravitation Physical Interaction or just Curved-Spacetime Geometry?

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Abstract

As there have still been attempts to regard gravity, a 100 years after Einstein's general relativity, not as a manifestation of the non-Euclidean geometry of spacetime, but as a physical field (and therefore as a force), it is high time to face the ultimate judge – the experimental evidence – to settle this issue once and for all. Two rulings of the ultimate judge are reminded – (i) the experimental fact that falling particles do not resist their fall rules out the option that gravity may be a force, and (ii) the experiments that confirmed the relativistic effects are impossible in a three-dimensional world, which also implies that gravity is indeed manifestation of the geometry of the *real* spacetime. It is also stressed that not only are attempts to impose a kind of scientific democracy in physics doomed to failure (because the question of what the external world is, is not necessarily determined by what the majority of physicists claim), but such attempts might, in the end, hamper the advancement of fundamental physics.

Keywords Gravitation, spacetime, non-Euclidean geometry, geodesic hypothesis, inertial motion, inertial force, inertial energy, gravitational field, gravitational force, gravitational energy, gravitational waves

> *Gravitation as a separate agency becomes unnecessary*
> Arthur S. Eddington [1]

> *An electromagnetic field is a "thing;" gravitational field is not, Einstein's theory having shown that it is nothing more than the manifestation of the metric*
> Arthur S. Eddington [2]

1 Introduction

Despite that for centuries physicists have known well that there is no democracy in science, there have been attempts in recent years to get rid of the tyranny of experiment and to introduce the "values" of democracy in physics too – to sideline the scientific method silently as an undemocratic method of doing physics and to replace it with purely unscientific "criteria" such as beauty and elegance[1] of the mathematical formalism of proposed theories, ambiguous virtues such as explanatory power, and the core of scientific democracy (which has being implicitly promoted) – if a proposed theory is supported by sufficient number of researchers and a great number of MSc and PhD theses on this theory have been defended, the theory should have the democratic right to be treated equally with the established theories.

Not only may allowing any degree of scientific democracy in physics not lead to scientific progress, but it almost certainly may hamper the advancement of fundamental physics and may even have disastrous consequences for the public image of science. Here are two groups of examples of what I think are manifestations of attempted scientific democracy some of which might have held back the progress in fundamental physics (just imagine the funds and the number of researchers involved in the research on string theory, if it turns out that it contradicts the *existing* experimental evidence, especially if that contradiction could have been discovered years earlier):

Proposed theories: In recent years there has been a growing dissatisfaction among physicists with the attempts to regard theories (such as string theory and the multiverse cosmology), which have not been experimentally confirmed, on equal footing with the already accepted physical theories. In December 2014 George Ellis and Joe Silk published in *Nature* the article "Scientific method: Defend the integrity of physics," whose beginning openly expressed that dissatisfaction and alarm [3]: "This year, debates in physics circles took a worrying turn. Faced with difficulties in applying fundamental theories to the observed Universe, some researchers called for a change in how theoretical physics is done. They began to argue – explicitly – that if a theory is sufficiently elegant and explanatory, it need not be tested experimentally, breaking with centuries of philosophical tradition of defining scientific knowledge as empirical."

While the multiverse cosmology does not seem to make any testable predictions (which excludes it from the realm of physics), string theory needs especially rigorous and impartial scrutiny because I think it contradicts the already existing experimental evidence.[2]

Alternative interpretations: I will give two examples of interpretations based on misconceptions in spacetime physics.

The first is a growing fashion to claim that the notion of relativistic mass (that mass increases with velocity) is a misconception.[3] In fact, it is the claim that mass does not

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[1] Such "criteria" worried both Einstein and Eddington almost a 100 years ago: "I cannot avoid the suspicion that the mathematical elegance is obtained by a short cut which does not lead along the direct route of real physical progress. From a recent conversation with Einstein I learn that he is of much the same opinion" [2, p. 269].

[2] String theory contradicts the experimental fact that the hydrogen atom does not possess a dipole moment in its ground state – if the electron were a miniature string (according to string theory) it would be localized in an area much smaller than 10^{-18} m somewhere above the proton and the charges of the electron and the proton would inescapably form a dipole (in contradiction with experiment). Unlike quantum mechanics, string theory makes a clear claim about what an electron, for example, is – a miniature string. Because of this explicit claim string theory contradicts the experimental evidence. Quantum mechanics avoids such a contradiction, because it deals with the states of the electron, not directly with the electron itself (there is no spacetime model of the electron in quantum mechanics, that is, quantum mechanics tells us nothing about what quantum objects themselves are).

[3] The notion of relativistic mass could not be a misconception, because it is an *experimental fact* – a particle's mass increases as its speed increases, because an increasing force should be applied to overcome the particle's *increasing resistance* as its speed increases, which means the force should overcome the particle's increasing mass (because mass is the measure of a particle's resistance to its acceleration).

increase with velocity that is an unfortunate and embarrassing misconception, which becomes immediately obvious when two facts are taken explicitly into account:

- the very definition of mass (mass is defined as the measure of the resistance a particle offers to its acceleration)
- that in relativity acceleration is different in different reference frames.

Therefore the mass of a particle cannot be the same in all frames in relative motion. Proper or rest mass (which is an invariant) and relativistic mass (which is frame-dependent) are exactly like proper time (which is an invariant) and relativistic or coordinate time (which is frame-dependent), and, to some extent, like proper and relativistic length.

The second example deals with attempts not to regard gravitational phenomena as actually being manifestations of the non-Euclidean geometry of spacetime (viewing the geometrical presentation of general relativity as pure mathematics), but as caused by a gravitational field (and therefore by a gravitational force). As such attempts still exist a 100 years after the creation of Einstein's theory of general relativity, the purpose of this paper is to stress it as strongly as possible that such an interpretation of Einstein's general relativity is ruled out by the experimental evidence as will be shown in Section 2. It will be also shown in this section that the experiments that confirmed the kinematic relativistic effects would be impossible if spacetime were a mathematical notion not representing a real four-dimensional world. The logically unavoidable implication from (i) the non-existence of gravitational force and (ii) the reality of spacetime that gravitational phenomena are fully explained by the non-Euclidean geometry of spacetime, without the assumption of gravitational interaction, is outlined in Section 3. An Appendix demonstrates that it is almost self-evident that what is traditionally called kinetic energy is in fact inertial energy; it is this energy (not gravitational energy) that is involved in gravitational phenomena.

2 Gravitational force does not exist, spacetime does exist

> *In relativity there is no such thing as the force of gravity,*
> *for gravity is built into the structure of space-time, and*
> *exhibit itself in the curvature of space-time, i.e. in the*
> *non-vanishing of the Riemann tensor* R_{ijkm}
> John L. Synge [7]

It is generally believed that Einstein identified gravitation with the non-Euclidean geometry of spacetime. However, contrary to common belief, as Lehmkuhl showed [4], Einstein himself did not believe that general relativity geometrized gravitation: "I do not agree with the idea that the general theory of relativity is geometrizing Physics or the gravitational field" [5]. Although this explicit view of Einstein against identifying gravity with geometry is not widely known, Einstein had certainly and greatly influenced the present rather confused understanding not only of the nature of gravitational phenomena, but also of what the physical meaning of his general relativity is. We will see in the next section that although Einstein made perhaps the greatest revolution in physics by linking gravitation with the geometry of spacetime, it seems the revolution was so great that even he did not fully realize its huge implications (which to a great extent is known but not entirely, because most of Einstein's improper interpretations of his own theory are still accepted today).

In addition to Einstein's role for not taking seriously the physical meaning of general relativity at face value ("gravitational field ... is nothing more than the manifestation of the metric" [2]) the decades of failed attempts to create a theory of quantum gravity have significantly contributed to the attempts to regard gravity, implicitly, as a physical field (i.e., as a force) in the framework in general relativity. Weinberg [6] argued almost explicitly that "too great an emphasis on geometry can only obscure the deep connections between gravitation and the rest of physics" and that "Riemannian geometry appears only as a mathematical tool for the exploitation of the Principle of Equivalence, and not as a fundamental basis for the theory of gravitation."

It seems the pressure from the unsuccessful attempts to arrive at a theory of quantum gravity on Weinberg had been so strong that he ignored Synge's call to abandon the use of the Principle of Equivalence in modern physics:

"I have never been able to understand this Principle ... Does it mean that the effects of a gravitational field are indistinguishable from the effects of an observers acceleration? If so, it is false. In Einsteins theory, either there is a gravitational field or there is none, according as the Riemann tensor does not or does vanish. This is an absolute property; it has nothing to do with any observers world-line. Spacetime is either flat or curved ... The Principle of Equivalence performed the essential office of midwife at the birth of general relativity, but, as Einstein remarked, the infant would never have got beyond its long-clothes had it not been for Minkowskis concept. I suggest that the midwife be now buried with appropriate honours and the facts of absolute space-time faced" [7, pp. ix-x].

We will see in Section 3 that not only the phenomena captured in the principle (or rather the postulate) of equivalence but also the very nature of gravitational phenomena find natural *explanation* when two facts are explicitly taken into account:

- The experimental fact that gravitational force does not exist.
- The fact that the *true reality* – what Hermann Minkowski called the World (or what we call spacetime) – is a four-dimensional world with time as the fourth dimension.

Before discussing these two facts let me say how I think Minkowski, had he lived longer, might have dealt with Einstein's principle of equivalence. I guess he would have almost certainly reformulated Einstein's general relativity (exactly like he reformulated Einstein's special relativity in terms of spacetime) and would have explained the principle of equivalence (exactly like he explained the principle of relativity).

Einstein's approach to physics was rather to postulate things, whereas Minkowski strived to explain phenomena. Einstein postulated:

- The equivalence of the time of a "stationary" observer and the different time of a moving observer (formally introduced as an auxiliary mathematical notion by Lorentz).
- The experimental impossibility to detect absolute motion (captured in the relativity postulate).
- The equivalence of some inertial and gravitational phenomena such as the equivalence of inertial mass and force and gravitational mass and force; Einstein called this experimental fact the equivalence postulate (or principle).

Minkowski explained (see Minkowski's paper [8] and also [9] and Section 3):

- The equivalence of the times of observers in relative motion – *why* such observers have different times.
- The relativity postulate – *why* absolute motion (with constant velocity) cannot be detected or its modern formulation – *why* the laws of physics are the same in all inertial reference frames.
- Almost certainly, had he lived longer, Minkowski would have explained the equivalence postulate (as we will see in Section 3) – e.g. *why* inertial mass and force are equivalent to gravitational mass and force.

Let us now see why the two facts, listed above – gravitational force does not exist, whereas spacetime does exist – are indeed facts.

1. There is no gravitational force in Nature. This is proved by the experimental fact[4] that particles falling toward the Earth's surface do not resist their fall (i.e. their apparent acceleration), which means that no gravitational force is causing their fall (and therefore they move by inertia).

It should be emphasized as strongly as possible that the experimental fact that falling particles do not resist their fall proves that no gravitational force is acting on the particles – *a gravitational force would be required to accelerate particles downwards if and only if the particles* ***resisted*** *their acceleration, because only then a gravitational force would be needed to* ***overcome*** *that resistance.*[5]

It is difficult to explain how Einstein could deny that general relativity geometrized gravitation given the fact that it was him who first had the insight that falling bodies do not resist their fall. Einstein called this insight the "happiest thought" of his life (most probably in November 1907):

> I was sitting in a chair in the patent office at Bern when all of a sudden a thought occurred to me [10]:
>
> "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 might have believed that the gravitational force acting on a particle, causing its fall, is somehow compensated by the inertial force with which the particle resists its downward acceleration (in line with his equivalence principle). However, that would not explain his "happiest thought" that a falling person "will not feel his own weight," because if there were a gravitational force acting on the person, his fall would not be non-resistant – his body will resist the gravitational force which accelerates it downwards (exactly like a particle

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[4] A falling accelerometer, an example of real experiments, does prove that no gravitational force is acting on the accelerometer: the absolute (frame-independent) fact is that the accelerometer reads zero acceleration, that is, zero resistance to its fall and therefore zero gravitational force acting on it. The accelerometer's apparent acceleration is not true acceleration (which is an absolute, i.e., frame-independent, property in both special and general relativity).

[5] As experiments do not contradict one another, this is the *final proof* that gravitational force does not exist; no future experiments can contradict this experimental fact.

accelerated by a force in open space resists its acceleration); the very physical meaning of the inertial force is that it is a *resistance* force, with which a particle resists its acceleration.

It seems Einstein had misinterpreted his "happiest thought" but, fortunately, that did not prevent him from arriving at the correct mathematical formalism demonstrating that gravity is a manifestation of the non-Euclidean geometry of spacetime. Indeed, in general relativity a falling particle is represented by a geodesic worldline which is the curved-spacetime analogue of a flat-spacetime straight worldline, and as a straight (undeformed) worldline in flat spacetime represents a particle moving non-resistantly (by inertia) a geodesic in curved spacetime (which is undeformed) represents a particle moving non-resistantly, i.e., by inertia. Regardless of what Einstein thought, the fact that in general relativity geodesic worldlines represent free particles which move non-resistantly (by inertia) has been regarded as "a natural generalization of Newton's first law" [7, p. 110], that is, "a mere extension of Galileo's law of inertia to curved spacetime" [11]. Sometimes this fact is called the *geodesic hypothesis*, which might be misleading because it is not a hypothesis that a geodesic worldline represents a falling particle which offers no resistance to its fall – it reflects the experimental fact that particles fall toward the Earth non-resistantly.

To understand fully not only the physical meaning of the experimental fact that there is no gravitational force in Nature, but also the nature of gravitational phenomena, one has to realize fully another experimental fact – that reality is a four-dimensional world as Minkowski first pointed out.

2. The true reality is a four-dimensional world with time as the fourth dimension.

The issue of the reality of spacetime (Minkowski's four-dimensional world) constitutes an unprecedented situation in fundamental physics. It seems many physicists, including relativists, simply refuse to see the double experimental proof of the reality of spacetime. The first experimental proof is the set of all experiments (including the Michelson-Morley experiment) that failed to detect absolute uniform motion and that gave rise to the relativity postulate. It is these experiments whose hidden profound message was successfully decoded by Minkowski – absolute (uniform) motion cannot be detected because such a thing does not exist in Nature; absolute motion presupposes absolute (i.e. single) space, but those experiments imply that observers in relative motion have different times and spaces, which in turn implies that the world is four-dimensional world.

On September 21, 1908 Minkowski explained how he decoded the profound message hidden in the failed experiments to discover absolute motion in his famous lecture *Space and Time* and announced the revolutionary view of space and time, which he deduced from those experiments [8, p.111]:

> The views of space and time which I want to present to you arose from the domain of experimental physics, and therein lies their strength. Their tendency is radical. From now onwards space by itself and time by itself will recede completely to become mere shadows and only a type of union of the two will still stand independently on its own.

Here is Minkowski's most general proof that the world is four-dimensional. To explain the experiment of Michelson-Morley, which failed to detect the Earth's absolute motion, Lorentz suggested that observers on Earth can formally use a time that is different from the true time of an observer at absolute rest. Einstein postulated that the times of different observers in relative motion are equally good, that is, each observer has his own time, and that for Einstein meant that time is relative.

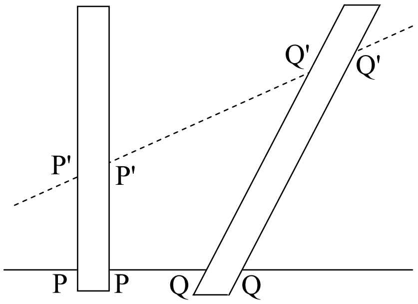
Minkowski demonstrated that as observers in relative motion have different equally real times, they inescapably have *different spaces* as well, because space is defined as a set of simultaneous events, and different times imply different simultaneity, i.e., different spaces (or simply – different times imply different spaces because space is perpendicular to time) [8, p. 114]:

> "Hereafter we would then have in the world no more *the* space, but an infinite number of spaces analogously as there is an infinite number of planes in three-dimensional space. Three-dimensional geometry becomes a chapter in four-dimensional physics. You see why I said at the beginning that space and time will recede completely to become mere shadows and only a world in itself will exist."

Therefore the experimental failure to detect absolute motion has indeed a profound physical meaning – that there exists not a single (and therefore absolute) space, but many spaces (and many times). As many spaces are possible in a four-dimensional world, Minkowski's irrefutable proof that the world is four-dimensional becomes self-evident:

If the real world were three-dimensional, there would exist a ***single*** *space, i.e. a single class of simultaneous events (a single time), which would mean that simultaneity and time would be absolute in contradiction with both the theory of relativity and, most importantly, with the experiments which failed to detect absolute motion.*

The second experimental proof of the reality of spacetime are all experiments that confirmed the kinematic relativistic effects. How these experiments would be *impossible* if the world were *not* four-dimensional (i.e., if spacetime were just a mathematical space) is immediately seen in Minkowski's own explanation of length contraction (which is the accepted explanation) – as length contraction (along with time dilation) is a specific manifestation of relativity of simultaneity, an assumption that reality is *not* a four-dimensional world directly leads (as in the above paragraph) to absolute simultaneity (and to the impossibility of length contraction [13]) in contradiction with relativity and the experiments that confirmed length contraction; one of the experimental tests of length contraction (along with time dilation) is the muon experiment – "in the muon's reference frame, we reconcile the theoretical and experimental results by use of the length contraction effect, and the experiment serves as a verification of this effect" [14].



The right half of Figure 1 of Minkowski's paper *Space and Time*

To see exactly how length contraction would be impossible if reality were a three-dimensional world, consider Minkowski's explanation whose essence is that length contraction of a body is a manifestation of the reality of the body's worldtube. Minkowski considered two bodies in uniform relative motion represented by their worldtubes in the figure above (see Figure 1 of Minkowski's paper [8]). Consider only the body represented by the vertical worldtube to understand why the worldtube of a body must be real in order that length contraction be possible. The three-dimensional cross-section PP, resulting from the intersection of the body's worldtube and the space (represented by the horizontal line in the figure) of an observer at rest with respect to the body, is the body's proper length. The three-dimensional cross-section $P'P'$, resulting from the intersection of the body's worldtube and the space (represented by the inclined dashed line) of an observer at rest with respect to the second body (represented by the inclined worldtube), is the relativistically contracted length of the body measured by that observer (one should always keep in mind that the cross-section $P'P'$ only looks longer than PP because a fact of the pseudo-Euclidean geometry of spacetime is represented on the Euclidean surface of the page).

Now assume that the worldtube of the body did not exist as a four-dimensional object and were merely an abstract geometrical construction. Then, what would exist would be a single three-dimensional body, represented by the proper cross-section PP, and both observers would measure the *same* three-dimensional body PP of the *same* length. Therefore, not only would length contraction be *impossible*, but relativity of simultaneity would be also impossible since a spatially extended three-dimensional object is defined in terms of *simultaneity* – as all parts of a body taken *simultaneously* at a given moment.[6] Because both observers in relative motion would measure the same three-dimensional body (represented by the cross-section PP) they would share the *same* class of simultaneous events (therefore simultaneity would turn out to be absolute) in contradiction with relativity and with the experiments that confirmed the specific manifestations of relativity of simultaneity – length contraction and time dilation.

All experiments that confirmed time dilation and the twin paradox effect are also impossible in a three-dimensional world [12]. For example, it is an experimental fact, used every second by the GPS, that observers in relative motion have different times, which is impossible in a three-dimensional world [12].

I think the unprecedented situation in fundamental physics – ignoring the fact that the relativistic experiments and the theory of relativity itself are impossible in a three-dimensional world[7] – should be faced and addressed because this situation prevents a proper understanding of the physical meaning of general relativity as revealing that gravitational phenomena are nothing more than a manifestation of the curvature of spacetime; such a deep understanding of the nature of gravity may have important implications for the research on quantum gravity and on gravitational waves.

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[6] The fact that an extended three-dimensional body is defined in terms of simultaneity confirms Minkowski's interpretation of the cross-sections PP and $P'P'$ as two three-dimensional bodies – while measuring the *same* body, the two observers measure *two* three-dimensional bodies represented by the two cross-sections. This relativistic situation only looks paradoxical at first sight because what is meant by "the same body" is the body's worldtube; the cross-sections PP and $P'P'$ represent the two three-dimensional bodies measured by the two observers.

[7] It appears to be a real problem in physics that some physicists regard issues such as the reality of spacetime as belonging to philosophy, which is *physics at its worst* - the issue of the dimensionality of the world is pure physics.

3 Is Gravitation Physical Interaction?

After Minkowski explained in his lecture *Space and Time* that the true reality is a four-dimensional world in which all ordinarily perceived three-dimensional particles are a forever given web of worldlines, he outlined his ground-breaking idea of regarding physics as spacetime geometry [8, p. 112]:

> 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 started to implement his program by explaining that inertial motion is represented by a timelike *straight* worldline, after which he pointed out that [8, p. 115]:

> With appropriate setting of space and time the substance existing at any world-point can always be regarded as being at rest.

In this way he explained not only why the times of inertial observers are equivalent (their times can be chosen along their timelike worldlines and all straight timelike worldlines in spacetime are equivalent) but also the physical meaning of the relativity principle – the physical laws are the same for all inertial observers (inertial reference frames), i.e. all physical phenomena look exactly the same for all inertial observers, because every observer describes them in his own space (in which he is at rest) and uses his own time. For example the speed of light is the same for all observers because each observer measures it in its own space using his own time.

Then Minkowski explained that accelerated motion is represented by a *curved* or, more precisely, *deformed* worldline and noticed that "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 as Galileo first demonstrated), 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 deformed (curved) worldlines, respectively.

The realization that an accelerated particle (which resists its acceleration) is a deformed worldtube in spacetime would have allowed Minkowski (had he lived longer) to notice two virtually obvious implications of this spacetime fact [12]:

- The acceleration of a particle is absolute not because it accelerates with respect to some absolute space, but because its worldtube is deformed, which is an absolute geometrical and physical fact.

- The resistance a particle offers to its acceleration (i.e. its inertia) originates from a four-dimensional stress in its deformed worldtube. That is, the inertial force with which the particle resists its acceleration turns out to be a static restoring force arising in the deformed worldtube of the accelerated particle. I guess Minkowski might have been particularly thrilled by this implication of his program to regard physics as spacetime

> geometry because inertia happens to be another manifestation of the fact that reality is a four-dimensional world.

Unfortunately, we will never know whether Minkowski might have discovered general relativity (surely under another name) before or independently of Einstein had he lived longer. Let me summarize a scenario involving a logical possibility that might have been available to Minkowski after his lecture *Space and Time* in 1908 [15].

This scenario demonstrates the enormous potential of Minkowski's program of geometrizing physics and assumes that Minkowski had read Galileo's works, particularly Galileo's analysis demonstrating that heavy and light bodies fall at the *same* rate [16]. 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.

If Minkowski had lived longer but did not discover general relativity, I believe he would have certainly reformulated it. Minkowski would have regarded general relativity, taking its mathematical formalism at face value, as a triumph of his program to present physics as a spacetime geometry.

As Minkowski would have regarded spacetime (or as he called it the World) as real, then it becomes virtually obvious that gravitational phenomena are fully explained as manifestation of the non-Euclidean geometry of spacetime with no need to assume the existence of gravitational interaction. Indeed, particles fall toward the Earth's surface and planets orbit the Sun not due to a gravitational force or interaction, but because they move by inertia; expressed in correct spacetime language, the falling particles and planets are geodesic worldlines (or rather worldtubes) in spacetime.

Minkowski would have easily explained the force acting on a particle on the Earth's surface, i.e. the particle's weight. The worldtube of a particle falling toward the ground is geodesic, which, in ordinary language, means that the particle moves by inertia (non-resistantly) in full agreement with the experimental evidence. When the particle lands on the ground it is prevented from moving by inertia and it resists the change of its inertial motion by exerting an inertial force on the ground. Like in flat spacetime the inertial force originates from the deformed worldtube of the particle which is at rest on the ground. So the weight of the particle that has been traditionally called gravitational force turns out to be inertial force, which naturally explains the observed equivalence of inertial and gravitational forces. While the particle is on the ground its worldtube is deformed (due to the curvature of spacetime), which means that the particle is being constantly subjected to a curved-spacetime acceleration (keep in mind that acceleration means deformed worldtube!); the particle resists its acceleration through the inertial force and the measure of the resistance the particle offers to its acceleration is its inertial mass, which traditionally has been called (passive) gravitational mass. This fact naturally explains the equivalence between a particle's inertial and gravitational masses, which turned out to be the same thing.

In this way, Minkowski would have explained Einstein's equivalence postulate exactly like he explained Einstein's relativity postulate.

Despite that taken at face value general relativity fully explains gravitational phenomena without assuming that there exists gravitational interaction, there have been continuing attempts (initiated by Einstein) to smuggle the concept of gravitational interaction into the framework and mathematical formalism of general relativity. Let me address these attempts in a bit more detail.

Since Einstein it has been taken for granted that gravity is a physical interaction and gravitational energy and momentum do exist, but it is admitted that there is some annoying difficulty to represent them in a proper mathematical form. However, an analysis of the mathematical formalism of general relativity (following Minkowski's example of analysing the mathematical formalism of Newtonian mechanics that led him to revealing the true physical nature of Einstein's special relativity as a theory of flat spacetime) demonstrates that there is no room for gravitational energy and momentum in general relativity:

- There is no proper tensorial expression (which represents a real physical quantity) for gravitational energy and momentum; for a 100 years no one has managed to find such an expression.

- As indicated above gravitational phenomena are fully explained in general relativity as mere effects of the non-Euclidean geometry of spacetime and no additional hypothesis of gravitational interaction (and therefore of gravitational energy and momentum) is necessary. In general relativity, a particle, whose worldline is geodesic, is a free particle moving by inertia; therefore the motion of bodies falling toward the Earth's surface and of planets orbiting the Sun (whose worldlines are geodesic) is inertial, i.e., interaction-free, because the very essence of inertial motion is motion which does not involve any interaction (and any exchange of energy momentum) whatsoever.

- If changing the shape of a free body's geodesic worldtube (from straight geodesic to curved geodesic) by the spacetime curvature induced, say, by the Earth's mass (which causes the body's fall toward the Earth's surface) constituted gravitational interaction, that would imply some exchange of gravitational energy and momentum between the Earth and the body, but such an exchange does not seem to occur because the Earth's mass curves spacetime regardless of whether or not there are other bodies in the Earths vicinity (which means that, if other bodies are present in the Earth's vicinity, no additional energy-momentum is required to change the shape of the geodesic worldtubes of these bodies and therefore no gravitational energy-momentum is exchanged with those bodies). In other words, the Earth's mass changes the geometry of spacetime around the Earth's worldtube and it does not matter whether the geodesics (which are no longer straight in the new spacetime geometry) around the Earth are "empty" or "occupied" by particles of different mass, that is, in general relativity "a geodesic is particle independent" [11].

- The fact that "in relativity there is no such thing as the force of gravity" [7] implies that there is no gravitational energy either since such energy is defined as the work done by gravitational forces. Whether or not gravitational energy is regarded as local does not affect the very definition of energy.

Despite the above facts, the prevailing view among relativists is that there exists indirect astrophysical evidence for the existence of gravitational energy – coming from the interpretation of the decrease of the orbital period of the binary pulsar system PSR 1913+16 discovered by Hulse and Taylor in 1974 [17] (and other such systems discovered after that), which is believed to be caused by the loss of energy due to gravitational waves emitted by the system (which carry away gravitational energy).

This interpretation that gravitational waves carry gravitational energy should be carefully scrutinized (especially after the recent detection of gravitational waves) by taking into account the above arguments against the existence of gravitational energy and momentum and especially the fact that there does not exist a rigorous (analytic, proper general-relativistic) solution for the two body problem in general relativity. I think the present interpretation of the decrease of the orbital period of binary systems contradicts general relativity, particularly the geodesic hypothesis and the experimental evidence which confirmed it, because by the geodesic hypothesis the neutron stars, whose worldlines had been regarded as exact geodesics (since the stars had been modelled dynamically as a pair of orbiting *point* masses), *move by inertia without losing energy since the very essence of inertial motion is motion without any loss of energy.* For this reason no energy can be carried away by the gravitational waves emitted by the binary pulsar system. Let me stress it as strongly as possible: the geodesic hypothesis and the assertion that bodies, whose worldlines are geodesic, emit gravitational energy (carried away by gravitational waves), cannot be both correct.

In fact, it is the very assumption that the binary system emits gravitational waves which contradicts general relativity in the first place, because motion by inertia does not generate gravitational waves in general relativity. The inspiralling neutron stars in the binary system were modelled (by Hulse and Taylor) as *point* masses and therefore their worldlines are exact geodesics, which means that the stars move by inertia and no emission of gravitational radiation is involved; if the stars were modelled as extended bodies, then and only then they would be subject to tidal effects and energy would be involved, but that energy would be negligibly small (see next paragraph) and would not be gravitational (see the explanation of the origin and nature of energy in the sticky bead argument below). So, the assertion that the inspiralling neutron stars in the binary system PSR 1913+16 generate gravitational waves is incorrect because it contradicts general relativity.

Gravitational waves are emitted only when the stars' timelike worldlines are not geodesic,[8] that is, when the stars are subject to an absolute (curved-spacetime) acceleration (associated with the absolute feature that a worldline is not geodesic), not a relative (apparent) acceleration between the stars caused by the geodesic deviation of their worldlines. For example, in general relativity the stars are subject to an absolute acceleration when they collide (because their worldlines are no longer geodesic); therefore gravitational waves – carrying no gravitational energy-momentum – are emitted only when the stars of a binary system collide

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[8] The original prediction of gravitational wave emission, obtained by Einstein (*Berlin. Sitzungsberichte*, 1916, p. 688; 1918, p. 154), correctly identified the source of such waves – a spinning rod, or any rotating material bound together by cohesive force. None of the particles of such rotating material (except the centre of rotation) are geodesic worldlines in spacetime and, naturally, such particles will emit gravitational waves. This is not the case with double stars; as the stars are modelled as point masses, their worldliness are exact geodesics (which means that the stars are regarded as moving by inertia) and no gravitational waves are emitted. If the stars are regarded as extended bodies their worldtubes will still be geodesic, but their motion will not be entirely non-resistant, because of the tidal friction within the stars (caused by the fact that the worldlines of the stars' constituents are not congruent due to geodesic deviation).

and merge into one, that is, "Inspiral gravitational waves are generated during the end-of-life stage of binary systems where the two objects merge into one" [18].

Let me repeat it: when the stars follow their orbits in the binary system, they do not emit gravitational waves since they move by inertia according to general relativity (their worldlines are geodesic and no absolute acceleration is involved); even if the stars were modelled as extended bodies, the worldlines of the stars constituents would not be geodesic (but slightly deviated from the geodesic shape) which will cause tidal friction in the stars, but the gravitational waves generated by the very small absolute accelerations of the stars' constituents will be negligibly weak compared to the gravitational waves believed to be emitted from the spiralling stars of the binary system (that belief arises from using not the correct general-relativistic notion of acceleration ($a^\mu = d^2x^\mu/d\tau^2 + \Gamma^\mu_{\alpha\beta}(dx^\alpha/d\tau)(dx^\beta/d\tau)$), but the Newtonian one).

The famous sticky bead argument has been regarded as a decisive argument in the debate on whether or not gravitational waves transmit gravitational energy because it has been perceived to demonstrate that gravitational waves do carry gravitational energy which was converted through friction into heat energy [19]:

> The thought experiment was first described by Feynman (under the pseudonym "Mr. Smith") in 1957, at a conference at Chapel Hill, North Carolina. His insight was that a passing gravitational wave should, in principle, cause a bead which is free to slide along a stick to move back and forth, when the stick is held transversely to the wave's direction of propagation. The wave generates tidal forces about the midpoint of the stick. These produce alternating, longitudinal tensile and compressive stresses in the material of the stick; but the bead, being free to slide, moves along the stick in response to the tidal forces. If contact between the bead and stick is 'sticky,' then heating of both parts will occur due to friction. This heating, said Feynman, showed that the wave did indeed impart energy to the bead and rod system, so it must indeed transport energy.

However, a careful examination of this argument reveals that kinetic, not gravitational, energy is converted into heat because a gravitational wave changes the shape of the geodesic worldline of the bead and the stick prevents the bead from following its changed geodesic worldline, i.e., prevents the bead from moving by inertia; as a result the bead resists and exerts an *inertial* force on the stick (exactly like when a particle away from gravitating masses moving by inertia is prevented from its inertial motion, it exerts an inertial force on the obstacle and the kinetic energy of the particle is converted into heat).

It appears more adequate if one talks about *inertial*, not kinetic, energy, because what is converted into heat (as in the sticky bead argument) is the energy corresponding to the work done by the inertial force (and it turns out that that energy, originating from the inertial force, is equal to the kinetic energy [20]; see Appendix). The need to talk about the adequate inertial, not kinetic, energy is clearly seen in the explanation of the sticky bead argument above – initially (before the arrival of the gravitational wave) the bead is at rest and does not possess kinetic energy; when the gravitational wave arrives, the bead starts to move but by inertia (non-resistantly) since the shape of its geodesic worldline is changed by the wave into another geodesic worldline (which means that the bead goes from one inertial state – rest – into another inertial state, i.e., without any transfer of energy from the gravitational wave; transferring energy to the bead would occur if and only if the gravitational wave changed the state of the bead from inertial to non-inertial), and when the stick tries to prevent the bead from moving by inertia, the bead resists and exerts an inertial force on the stick (that is why, what converts into heat through friction is inertial energy).

Finally, it is a fact in the rigorous structure of general relativity that gravitational waves do not carry gravitational energy,[9] which, however, had been inexplicably ignored, despite that Eddington explained it clearly in his comprehensive treatise on the mathematical foundations of general relativity *The Mathematical Theory of Relativity* [2, p. 260]: "The gravitational waves constitute a genuine disturbance of space-time, but their energy, represented by the pseudo-tensor t_μ^ν, is regarded as an analytical fiction" (it cannot be regarded as an energy of any kind for the well-known reason that "It is not a tensor-density and it can be made to vanish at any point by suitably choosing the coordinates; we do not associate it with any absolute feature of world-structure," *ibid*, p. 136).

Conclusion

Taken at face value general relativity implies that gravitational phenomena are not caused by gravitational interaction and are mere manifestation of the non-Euclidean geometry of spacetime. Although the very thought that gravitation might not be a physical interaction may be regarded by many physicists as too heretical, it should be examined carefully for one simple reason. The failures so far to create a theory of quantum gravity may have a simple but unexpected explanation – it might turn ot that gravitation is not a physical interaction and therefore there is nothing to quantize.

On the other hand, I think regarding gravitation as manifestation of curved-spacetime geometry can stimulate the advancement of fundamental physics by, for example, excluding some research directions in gravitational wave physics and identifying what is perhaps the major open question in gravitational physics – how matter curves spacetime.

Appendix: Kinetic Energy is Actually Inertial Energy

As the energy involved in gravitational phenomena is *inertial*, not gravitational, it will be helpful to emphasize what appears to be virtually obvious – that what has been traditionally called kinetic energy is in fact inertial energy because it is related to the work done by inertial forces.

But first let me address a long-standing confusion on the status of inertial forces – physicists usually call them fictitious forces, whereas engineers regard them as real forces. In fact both are correct. To see why, let us imagine an Einstein lift (with transparent walls) moving with constant velocity (by inertia) far away from any masses in the cosmos [21]. Imagine

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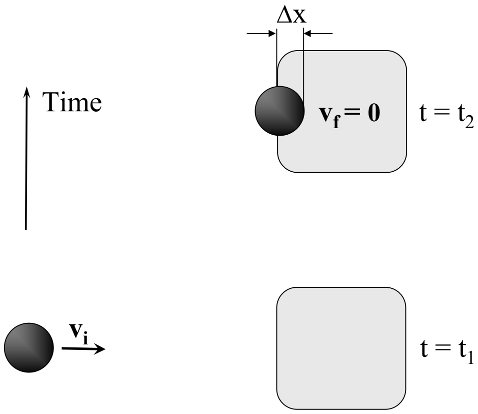
[9] An immediate and misleading reaction "A wave that carries no energy?!" should be resisted, because it is from the old times of three-dimensional thinking – assuming that a wave really travels in the external world. There is no such thing as a propagating wave in spacetime – what is there is a spacetime region whose "wavelike" geometry is interpreted in three-dimensional language as a wave which propagates in space (exactly like a timelike worldline is interpreted in three-dimensional language as a particle which moves in space); also, keep in mind that there is no such thing as space in the external world, because spacetime is not divided into a space and a time.

also that a metal ball is floating in the middle of the elevator. At the moment the lift starts to accelerate an observer A in it sees that the ball starts to fall (accelerate) toward the lift's floor. A would say that a fictitious inertial force is causing the fall of the ball in the lift. That force is indeed fictitious because A knows perfectly well that the inertial state of motion of the ball was not changed (which is confirmed by an outside inertial observer B). However, when the ball hits the lift's floor, or, more precisely, when the lift's floor hits the ball, the ball's inertial motion is disturbed and it resists its acceleration through a *real* inertial force, which (as engineers know well) is quite real, because it does work when it deforms the lift's floor at the spot where the collision occurred.



A massive plastic block is deformed when hit by a ball moving by inertia. Traditionally, it is stated that the ball's kinetic energy converts into a deformation energy. However, a deep physical explanation demonstrates that the ball's energy is inertial energy since the deformation is caused by the work done by the real inertial force with which the ball resists its deceleration

In the above example the deformation on lift's floor (resulting from the collision of the ball and the floor) is caused by the real inertial force with which the ball resists its acceleration. Therefore the work done by the ball's inertial force, which is equal to the ball's inertial energy, converts into a deformation energy and ultimately heat. So far inertial energy has been called kinetic energy. But such a name does not reveal the true nature of the ball's energy responsible for the deformation on the lift's floor – the ball's inertia, i.e. its resistance to the change in its inertial state.

The qualitative argument that kinetic energy is actually inertial energy has a straightforward quantitative counterpart. That inertial energy – the work done by inertial forces – is equal to kinetic energy is easily demonstrated by an example depicted in the figure above. At moment $t = t_1$ a ball travels at constant "initial" velocity v_i towards a huge block of some plastic material; we can imagine that the block is mounted on the steep slope of a mountain. Immediately after that the ball hits the block, deforms it and is decelerated. At moment $t = t_2$ the block stops the ball, that is, the ball's final velocity at t_2 is $v_f = 0$ (the block's mass is effectively equal to the Earth's mass, which ensures that $v_f = 0$). According to the standard explanation it is the ball's kinetic energy $E_k = (1/2)mv_i^2$ which transforms into a deformation energy. But a proper physical explanation demonstrates that the energy of the ball, which is transformed into deformation energy, is its inertial energy E_i, because the ball resists its deceleration a and it is the work $W = F\Delta x$ (equal to E_i) done by the *inertial* force $F = ma$ that is responsible for the deformation of the plastic material.

Using the relation between v_i, v_f, a and the distance Δx in the case of deceleration

$$v_f^2 = v_i^2 - 2a\Delta x$$

and taking into account that $v_f = 0$ we find

$$a = \frac{v_i^2}{2\Delta x}.$$

Then for the ball's inertial energy E_i we have

$$E_i = W = F\Delta x = ma\Delta x = \frac{1}{2}mv_i^2.$$

Therefore the inertial energy of the ball is indeed equal to what has been descriptively (lacking physical depth) called kinetic energy.

The same result is obtained when we consider a falling ball hitting a plastic block on the Earth's surface. In this case v_i will be the instantaneous velocity of the ball at the moment it hits the block and obviously again $v_f = 0$.

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