Gravitational Interaction, Inertia and Mass

Imre Kuczmann
Budapest, Hungary. E-mail: kuczmann.imre@mte.eu; kuczmann@zoznam.sk

The article discusses the mechanism of gravitational interaction and inertia. The proposed mechanism is inseparable from the novel approach to the carrier medium (vacuum). The existence of the substance of the vacuum is based on the wave nature of quanta, but not on zero-point energies, but on the absence of infinitely deep potential wells. Accordingly, the wave field of quanta can be infinitely extensive. The carrier medium consists of the quanta themselves and the parts of the quanta where their amplitude decreases exponentially. This is the basis of Mach's principle. The vacuum is the part of space where only the exponentially decreasing part of the bound quanta is present. The gravitational and inertial force is induced by the inhomogeneities of the carrier medium (in the simplest case, vacuum), through the dependence of the phase velocity on the energy density. The location-dependent energy density is determined everywhere by the material of the cosmic environment, but bodies accelerating relative to the inertial frame also perceive inhomogeneities due to acceleration. Acceleration is also relative, not just velocity, there is no absolute frame of reference. The two types of inhomogeneity cannot be distinguished from each other, the equivalence principle is valid. The concept of mass is filled with content by forces.

1 Introduction

Under terrestrial conditions, almost all gravitational phenomena can be described with sufficient accuracy by Newton's law of gravitation. Einstein's general theory of relativity (1915) represents a significant advance in that it eliminates instantaneous action at a distance and binds the concepts of space and time even more closely to matter than does special relativity. The increased precision is a prerequisite for the operation of the Global Positioning System (GPS) and allows the explanation of gravitational light deflection, gravitational redshift, and the perihelion shift of planetary orbits.

The relationship between gravity and the Standard Model, which describes the phenomena of the microscopic world, remains unresolved. The discovery of the Higgs boson in 2011 indicates the presence of a field responsible for explaining the inertia of quanta, yet the model does not explain gravity. In this situation, various attempts have emerged to formulate a quantum description of gravity. This is not the direction we are aiming for below. We do not think that the vacuum between gravitationally interacting objects is permeated by a gravitational field composed of quanta.

Motion in a gravitational field can be described on the basis of Einstein's field equations; however, this provides only a description of the phenomenon, not its mechanism. One must ask which properties of matter give rise to the presence of a gravitational field in the surroundings of bodies and, conversely, by what mechanism the gravitational field acts on those bodies. In Chapter 7.7 of his well-known lecture series, Richard P. Feynman explicitly writes about the absence of such a mechanism [1]. The need to resolve this problem also appears in later works [2].

In the following, the proposed answer to these questions is based on the wave nature of quanta. At the centre of the discussion is a novel interpretation of the carrier medium (vacuum) and the dependence of phase velocity on energy density. The proposed model of the vacuum (ether) makes it possible to treat gravity and inertia on common foundations while leaving the known formulas of relativity theory and quantum theory untouched. Forces are associated with inhomogeneities of the carrier medium.

Section 2 derives the concept of the carrier medium from the wave nature of quanta. In the discussion, we almost everywhere speak of "elementary quantum" or "quantum" for short instead of "elementary particle", emphasizing that the building elements of matter are waves under all circumstances. It is easy to see that the appearance of "particles" with identical parameters (mass, charge, spin) cannot be explained by a naive particle approach. This quantization can only be understood from the wave nature and is far from the classical particle approach. This is also shown by basic knowledge about atoms. One important conclusion of the present study is that since there are no infinitely deep potential wells, the energy of quanta must be accounted for in the entire space. This provides the basis for Mach's principle.

Section 3 presents the mechanism of the gravitational force and the gravitational potential based on the proposed model of the vacuum. It defines the status of local and distant observers, which is already necessary even in the potential field of an isolated celestial body.

Section 4 discusses the fundamental concepts of general relativity and places the conclusions of the previous two chapters into context.

Section 5 shows that in reference frames accelerating relative to inertial frames, the inhomogeneity of the carrier medium appears as a relativistic effect.

The calculation of the density of the vacuum in Section 6 is based on the concept of the refractive index. The well-known densities of materials represent density surpluses relative to the density of the vacuum.

Section 7 explains the concept of mass through the gravitational and inertial effects of matter, distinguishing between the active and passive manifestations of mass. The discussion of the direction of the gravitational force between particles and antiparticles corresponds to the assumption that quanta possess positive or possibly negative energy density not in an absolute sense but relative to the energy density of the vacuum.

The discussion also briefly refers to several additional phenomena (more or less well understood), including quantum entanglement, the probabilistic character of quantum theory, the issue of fluctuations, the Casimir effect, the predominance of matter over antimatter, and the rotation curves of galaxies.

2 The wave nature of micro-objects and their carrier medium

Elementary quanta in their rest frame are three-dimensional standing waves (oscillators). Their existence as individual units (their countability, quantization) is ensured by their indivisible intrinsic dynamics. The rest frequency f_{CP} (Compton frequency) can be considered a threshold frequency below which the given dynamics does not exist. The role of the propagation velocity of matter waves is played by the invariant speed of light c, which also serves as the limiting velocity, according to

$$\lambda_{CP} = \frac{hc}{m_0 c^2} = \frac{hc}{h f_{CP}} = \frac{c}{f_{CP}}\,, \tag{1}$$

where m_0 is the invariant mass, λ_{CP} is the Compton wavelength, and h is Planck's constant. In a standing wave, changes associated with the intrinsic dynamics occur simultaneously at different spatial locations. The Lorentz transformation converts the standing wave into a de Broglie wave with wavelength

$$\lambda_{dB} = \frac{h}{m_0 c^2}\sqrt{1-\frac{V^2}{c^2}}\,\frac{c^2}{V} = \frac{h}{E}\frac{c^2}{V} = \frac{h}{mV} = \frac{h}{p}\,, \tag{2}$$

where V is the *group velocity*, E the energy, and p the momentum [3].

In the Lorentz transformation formula for time, $V_{ph} = c^2/V$ represents the *phase velocity*. Energy is given by the partial time derivative of the wave, while momentum corresponds to the spatial derivative of the wave. The phase velocity connects these derivatives in the wave equations. The relativistic relation

$$E^2 - p^2c^2 = m_0^2 c^4 \tag{3}$$

applies to all quanta. For quanta with zero rest mass $m_0 = 0$, one has $p = E/c$. Such quanta have no rest frame; in vacuum their phase velocity and group velocity are both equal to c. For $V \neq 0$,

$$f_{dB} = \frac{f_{CP}}{\sqrt{1-\dfrac{V^2}{c^2}}} \tag{4}$$

is the de Broglie frequency. The relation $V_{ph} = \lambda_{dB} \cdot f_{dB}$ follows directly from the above expressions. In the rest frame the phase velocity and the de Broglie wavelength are infinite. No energy or information propagates with the phase velocity. If the group velocity V is nonzero, the phase velocity becomes finite but remains greater than the speed of light.

The energy, momentum, angular momentum, and other parameters of a quantum reflect the influence of the entire wave field. The wave nature of quanta also plays a key role in the explanation of quantum entanglement.

Quanta possess intrinsic rotational states (spin). The quantization of spin follows from the fact that a quantum cannot be transformed into a reference frame rotating with an arbitrary angular velocity, due to the cyclic constraint on the phase [4]. Spin can therefore be interpreted only in terms of wave concepts.

The motion of quanta is nothing other than a change in the distribution of their amplitudes within a carrier medium. Clearly, no object can move faster than the propagation speed of the quanta that constitute it. The result of the Michelson-Morley experiment follows naturally from the wave nature of matter.

A finite wave can be imagined only in an infinitely deep potential well, but such wells do not exist in nature. This has far-reaching consequences. We must accept that at any point in the world, inside bodies, in the space between stars and galaxies, every quantum is present with at least a small amplitude, for which the time elapsed since its creation and the limiting speed c do not preclude this. Elementary quanta may therefore be spatially unbounded; correspondingly, they have no own volume, surface, or shape. In a bound state, only the major portion of their energy is concentrated in a declared region of space, such as an atom or body; Outside of the given parts of space, there is always an exponentially decreasing part of the wave field of the quanta, along with the energy contained in it. This energy must be considered at any point in space. Put succinctly, there are no quanta without the possibility of their amplitude extending to infinity in at least an exponentially decreasing manner.

This exponential decrease is so rapid that the quanta forming macroscopic bodies appear with unimaginably small amplitudes at macroscopic distances from those bodies. Contributions from individual sources form an extremely delicate wave field in which averaging makes the energy density almost perfectly homogeneous and isotropic over small spatial regions. The Casimir effect appears in the transitional region close to the "surface" of macroscopic objects. The vacuum is the region of space in which only the exponentially decreasing parts of the quanta are present. On large scales the energy density is not homogeneous; its inhomogeneities correspond to the macroscopic distribution of matter. These inhomogeneities play a role in gravitational interaction.

We consider the continuous material field described above as the carrier medium for quanta. The quanta thus form a carrier medium for each other. In this concept, different types of quanta are waves of energy density with different eigendynamics. The eigendynamics is formed by the interplay of the spatial partial derivatives and temporal partial derivatives of the energy density along the x, y, and z axes (see *Dirac equation*). More complex eigendynamics means a higher spin quantum. Different parameters of the quanta can be related to different characteristics of the wave field. The more the energy density carried by a quantum differs from the energy density of vacuum, the greater the mass of the quantum. The electric charge of the quanta and the value of other physical parameters are determined at this level.

Relative motion of objects, energy flows, and radiation maintain continuous changes in the energy density of the carrier medium. These changes propagate with the invariant speed c, according to relation (1). This is the propagation speed of gravitational effects. All fluctuations observed in the vacuum energy density are the apparently random superposition of influences arriving from an effectively untraceable number of objects affecting the given locality.

The mutual dependence of the carrier medium and quanta further refines the insight of special relativity that matter exists within the space and time shaped by itself. These relations express the connection between the micro- and macroscopic worlds. The question of why matter exists at all lies beyond the scope of physics.

The energy density of the vacuum is everywhere determined by the matter of the cosmic environment. In a certain sense the entire matter content of the universe contributes to it, since every quantum — or some predecessor of it — exists everywhere with some amplitude. This leads naturally to *Mach's principle*. The existence of the carrier medium cannot be justified by zero-point energies, because only existing oscillators can possess zero-point energy. Zeropoint energies over the full spectrum lead to divergences. The vacuum as a carrier medium is quantized only insofar as the matter that forms it is quantized.

A micro-object, owing to its small mass, contributes only slightly to the vacuum energy density, whereas massive bodies produce significant contributions over larger spatial regions. The total energy of space includes kinetic energy, pressure-related potential energy, and energy associated with shear stresses. The energy density associated with the Earth contributes to that of the Solar System; the energy density of the Solar System contributes to that of the Milky Way, and so forth. This structure also leaves its imprint on the "anomalous" motion of stars orbiting at the edges of galaxies. Even in the vicinity of celestial bodies, the cosmic environment plays a decisive role in the resulting energy density. This is illustrated by the behaviour of a pendulum: its plane of oscillation aligns not with the rotating Earth but with the slowly changing cosmic environment.

The structure of the vacuum also plays a key role in the fact that only statistical correlations can be observed between the matter wave and the measurement result. The dispersion becomes larger when the energy of the investigated object is comparable to that of the quanta constituting the vacuum. The probability of interaction is higher at locations where the wave amplitude is larger. Determinism holds in every individual interaction, but it is practically unverifiable.

3 Gravitational interaction and potential

A wave can only be affected by its surroundings through the potential distribution of the carrier medium. The fact that quanta constitute a carrier medium for one another and that their phase velocity depends on the energy density of this medium is what we call gravitational interaction. The existence of force follows from the overlap of waves. The force acts toward regions of higher energy density, that is, toward regions of lower phase velocity. The range of the interaction is infinite, just like the wave field of quanta in the sense described above.

The gravitational force is a real force that arises between real quanta. The law of action and reaction follows from the overlap of wave fields. This is difficult to imagine with gravitons traveling between finite objects. In the interaction, the *active role* of quanta consists in their contribution to the carrier medium, while their *passive role* lies in the fact that the energy density of the carrier medium influences their phase velocity. The gravitational interaction between bodies is realized through the quanta composing them.

During gravitational interaction the energy, momentum, and gravitational potential of the overlapping quanta change continuously. To describe the processes occurring in the overlap region one may employ the concept of virtual gravitons, but these clearly do not contribute to the energy density of space and therefore cannot serve as sources of additional gravitational fields (which would contradict Newton's law of gravitation and lead to divergences). Independent gravitons are only possible in gravitational waves, which contribute to the energy density of space.

The behaviour of quanta in a force field characterized by a potential is well known [5]. In gravitational interaction the relevant potential is determined by the energy density of the carrier medium. Every wave field possesses *energy density*; therefore, every form of matter participates in gravitational interaction. At a given point, each quantum gravitationally affects other objects in proportion to its share of the total energy density at that point. For bodies that are relatively well localized in space, the contribution to the potential in the surrounding points decreases as $1/r$ with distance. (Gauss's law,

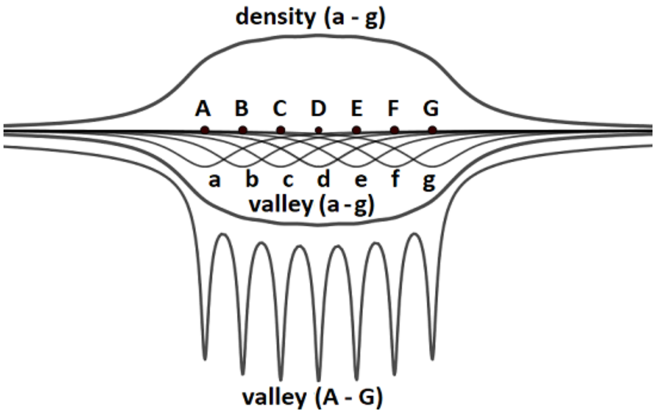

Fig. 1: The "spiky" potential valley of mass points A–G and the potential valley of continuous material distributions a–g (own GeoGebra construction).

Green's function). If the contribution of bound quanta to the vacuum energy density did not decrease according to $1/r$, the mechanism based on the carrier medium and phase velocity could not be a generalization of Newton's law.

The Newtonian gravitational potential

$$\varphi = -\frac{GM}{r} \tag{5}$$

is a function of the excess energy density created by a celestial body of mass M. Here $G = 6.67 \times 10^{-11}\text{m}^3\text{kg}^{-1}\text{s}^{-2}$ is the gravitational constant and r is the distance from the centre of the body. The resulting energy density increases and becomes increasingly spherically symmetric as one approaches the body, while the gravitational potential becomes progressively smaller. The potential is nowhere infinite, since the celestial body is not a point, and relation (5) is not valid inside its volume.

The difference between approaches that allow or disallow point masses is instructive even in one dimension (Fig. 1). The potential $\varphi_A + \varphi_B + \cdots + \varphi_G$ associated with point masses along the line AG is represented by a "spiky" graph along a line close to AG. As the line approaches AG, the spikes increase, but the spike-free part of the curve changes only slightly. Starting from continuous matter distributions, however, the potential never becomes infinite even along the line AG. Its mirror image is the potential valley, which is deepest where the energy density is greatest. The matter distributions a–g drawn in the figure have the form $-1/(x^2+1)$. It is apparent that Mach's principle does not lead to an infinitely dense vacuum even in a universe with infinite total mass, because increasing the cosmic domain and the $1/r$ dependence act in opposite directions.

The use of relation (5) presupposes that the units of length and time can be extended to arbitrary domains. However, gravitational light deflection and the shifts of distant spectra indicate the potential dependence of the units (and of the speed of light), corresponding to *gravitational contraction* and *time dilation*. The recognition of this fact is one of the key results of general relativity, ultimately traceable to relation (1). In such a situation, however, we must always indicate whether the observation is made in the observer's own environment or in a location with a different gravitational potential. Accordingly, an observer examining phenomena in his own environment is called a *local observer*, and an observer examining phenomena in another gravitational potential is called a *distant observer*. The difference between their data increases with the difference in potential (we assume that an observer reads always the instruments located beside them). Relation (5) is exact only if the quantity r is expressed in the units of an observer located far from the celestial body.

The universal speed of light is defined by $c = d\varrho/d\tau$ and its value ($c = 2.998 \times 10^8$ m/s) can be determined anywhere using the locally measured length ϱ and time τ. The fact that the units of length and time are most naturally defined through the properties of light propagating in vacuum is precisely what is established by general relativity. The definition of the second since 1967 and of the meter since 1983 reflects this viewpoint.

In the vicinity of a celestial body of mass M, the test body exists in a carrier medium whose energy density is also contributed by distant objects. Its potential energy relative to these objects is advisable to consider together. The total energy of a test body of mass m is mc^2, representing the work required to create it. The gravitational potential generated by the entire universe is

$$\Phi = c^2 \tag{6}$$

and from the viewpoint of a distant observer the body of mass M reduces this potential according to

$$\Phi(r) = c^2 - \frac{GM}{r}\,. \tag{7}$$

The function $\Phi(r)$ is smooth everywhere, always *positive*, and far from the celestial body it approaches not zero but c^2. If the potential were defined as $\Phi(r) = -c^2$ [7], these conditions would not be satisfied. Increasing r requires work.

The ratio of the potentials (6) and (7)

$$\frac{\Phi(r)}{\Phi} = \frac{c^2 - \frac{GM}{r}}{c^2} = 1 - \frac{GM}{rc^2} \tag{8}$$

equals the ratio of the energy densities (or densities). In general relativity this ratio is used to transform the measurements of local and distant observers into one another. At the surface of the Earth its value differs from unity only at the level of about 10^{-9}, because the Earth's mass is itself only a tiny fraction of the mass of the relevant cosmic environment.

The calculation of the vacuum density in Eq. (19) assumes that the square of the propagation velocity is inversely proportional to the energy density of the carrier medium. This relationship can be studied particularly well in gases (see the Gladstone-Dale relation).

The derivative of Eq. (5) with respect to r gives the gravitational field strength

$$g(r) = \frac{GM}{r^2}\,. \tag{9}$$

Where the energy density does not depend on position, the field strength is zero. The independence of the free-fall acceleration from mass follows from the fact that relation (9) does not contain the mass m of the test body and that the phase velocity of quanta does not depend on mass. The independence of the acceleration from the type of matter, as well as the concept of mass itself, suggests that all quanta exist in the same universal vacuum. Potential energy may be accompanied by kinetic energy. The potential (5) is related to the final velocity of a test body falling from infinity with zero initial velocity (the escape velocity v). During the fall a test body of mass m loses potential energy $m \cdot \Phi(r)$, and at least this amount of kinetic energy must be supplied to escape from the potential well. For a distant observer the square of the escape velocity, starting from the relativistic expression for kinetic energy, is

$$v^2 = c^2 - \frac{c^2}{\left(1 + \frac{GM}{rc^2}\right)^2}\,, \tag{10}$$

while from the nonrelativistic expression one obtains

$$v^2 = \frac{2GM}{r}. \tag{11}$$

4 General relativity

General relativity describes events using the concept of spacetime, similarly to special relativity, in which spatial and temporal quantities are interrelated; that is, they do not transform independently when passing to another reference frame. The fundamental reason for this is the wave nature of matter and the finite propagation speed of matter waves. In spacetime, an event is characterized by three spatial coordinates and one time coordinate. The distance between events is given by the arc length s, whose calculation is determined by the metric. Specifying the metric not only determines the transformation rules of spatial and temporal coordinates but also indirectly fixes the transformation rules of all physical quantities.

Around a spherical, isolated, non-rotating celestial body, the relation between the time τ and length ϱ measured by local observers and the time t and length r used by distant observers is, according to (8),

$$d\tau(r) = \left(1 - \frac{GM}{rc^2}\right)dt \quad \text{and} \quad d\varrho(r) = \left(1 - \frac{GM}{rc^2}\right)^{-1} dr. \tag{12}$$

The quantities measured by local and distant observers differ more strongly as r becomes smaller, that is, the deeper the quantities τ and ϱ are taken from within the gravitational field of the celestial body.

The relation $d\tau < dt$ means that the duration of a given process is shorter according to a clock located closer to the celestial body than according to distant clocks, because the clock nearer to the body runs more slowly (this also means that the unit of time used closer to the celestial body is larger). The relation $d\varrho > dr$ means that the size of a given object appears longer when measured by a meter rod located near the celestial body, because that rod is shorter than a distant meter rod.

In general relativity, the ratio between the lengths and time intervals measured by local and distant observers, as well as the position dependence of the propagation speed of light, is embodied in the metric. The *Schwarzschild metric* expresses the squared spacetime interval between infinitesimally close events in the gravitational field of an isolated, spherically symmetric, non-rotating body of mass M:

$$\begin{aligned} ds^2 = \left(1 - \frac{GM}{rc^2}\right)^2 c^2dt^2 - \left(1 - \frac{GM}{rc^2}\right)^{-2} dr^2 - \\ - r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)\,. \end{aligned} \tag{13}$$

In the Schwarzschild metric, a point in spacetime is specified by the spherical coordinates r, θ, φ of the distant observer. Because of the approximation $(1 - x)^2 \approx (1 - 2x)$ for $x \ll 1$ equation (13) has the approximate form

$$\begin{aligned} ds^2 = \left(1 - \frac{2GM}{rc^2}\right)c^2dt^2 - \left(1 - \frac{2GM}{rc^2}\right)^{-1} dr^2 - \\ - r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)\,. \end{aligned} \tag{14}$$

If the distance r increases, the gravitational influence of the body of mass M decreases, and (13) gradually approaches the Euclidean metric

$$ds^2 = c^2dt^2 - dr^2 - r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)\,. \tag{15}$$

This is the metric of special relativity.

The lengths and time intervals measured by a local observer are called *proper length* and *proper time*, whereas the distances and time intervals measured by a distant observer are called *coordinate length* and *coordinate time*. The distant observer measures a speed of light smaller than c in regions of higher energy density and greater than c in regions of lower energy density. For such an observer, regions of lower energy density act as gravitational diverging lenses, while regions of higher energy density act as gravitational converging lenses. All this is also supported by astronomical observations.

For the distant observer, the position dependence of the speed of light expressed by the ratio $c(r) = dr/dt$ follows from (12):

$$c(r) = c\left(1 - \frac{GM}{rc^2}\right)^2, \tag{16}$$

where $c = d\varrho/d\tau$ is the definition of the universal speed of light [6]. The approximate form is

$$c(r) = c\left(1 - \frac{2GM}{rc^2}\right). \tag{17}$$

Because the units themselves depend on the gravitational potential, the description of events is possible only within the framework of *Riemannian geometry*, which is more general than Euclidean geometry. The calculations are correspondingly more complex, similar to when geometry is performed not on a plane but on curved surfaces. Where the gravitational potential is independent of position (which holds only approximately in small regions of space), spacetime is practically "flat"; otherwise it is "curved". The metric (13) expresses a "curved" spacetime, since the ratio of local and global quantities depends on r both in space and in time; see relation (12). In gravitational light deflection, both gravitational time dilation and length contraction contribute; each of these only explains half of the deviation [6].

Albert Einstein did not consider it sufficient to identify gravity purely with mathematical curvature. In a lecture delivered at the University of Leiden in May 1920, he pointed out that Mach's idea finds full expression in the ether of general relativity. He argued that the variability of the metric properties of spacetime implies that space is neither homogeneous nor isotropic, which excludes the possibility of empty space. Referring to the scientific understanding of the time, he described elementary particles as "condensations" of the electromagnetic field and indicated that he would regard it as a major advance if the "gravitational ether" and the electromagnetic field could be understood as manifestations of some unified structural basis ("conformation") [8].

Arthur Stanley Eddington explained the gravitational deflection of light in the vicinity of celestial bodies by the presence of a surrounding "medium" [9].

In 2001, James Evans, Paul M. Alsing, Stefano Giorgetti, and Kamal Kanti Nandi discussed motion in a gravitational field in terms of a medium characterized by a refractive index, not only for light but for all forms of matter [10]. However, they did not address the question of the physical nature of this medium.

Dennis W. Sciama regarded Mach's principle as an indispensable element of gravitational theory and maintained that inertia can only be explained by a field-like space [11]. George F. R. Ellis, professor at the University of Cape Town, in evaluating Sciama's work, classified the issue of Mach's principle among the open questions [12].

In the present study, quanta are interpreted as excitations of a *universal carrier medium* (a new type of ether, or vacuum). The existence and movement of quanta is determined by the dependence of the phase velocity on the energy density. The possibility of this follows from the wave nature of quanta and from the absence of infinitely deep potential wells. The material background of the metric is constituted by the quanta themselves; curvature is only one of the parameters characterizing the distribution of energy. The proposed carrier medium fully reflects the spirit of Mach's principle and provides a "unified structural basis" in which the electromagnetic field and the various types of elementary quanta are merely waveforms with different intrinsic dynamics. In this structural basis, the most general phenomena are the gravitational and inertial phenomena related to energy density.

5 Inertia

The inertial force is a consequence of the inhomogeneity of the carrier medium that accelerating bodies perceive during the period of acceleration. The analysis of an accelerating observer can also be carried out using the tools of special relativity [13].

The example of an accelerating rod (segment AB on Fig. 2) remains within the framework of the standard Lorentz transformation. In the Minkowski diagram, the origin of the system K', moving along the x-axis, coincides with the origin of the inertial system K at the instant $t = t' = 0$. The endpoints of the rod at this instant are the points A and B. In the system K the t-axis is horizontal and the x-axis vertical so that velocity and acceleration can be obtained by simple differentiation. The event $(t,\, x)$ is transformed into the event $(t',\, x')$ by an *active transformation* [14]; that is, the result is again plotted with respect to the axes of the system K. The systems K' are the successive instantaneous rest frames of the rod moving with variable velocity $V(t)$ (with axes t' and x'). The instantaneous velocity of the points is the transformation velocity $V(t)$. Since the Lorentz transformation preserves the interval $x^2 - t^2$ (here $c = 1$), the points A' and B' describe hyperbolas

$$x^2 - t^2 = const \tag{18}$$

as $V(t)$ varies. These are the worldlines of the points A and B (the time axis is horizontal). The motion represented is called *hyperbolic motion*. The points A' and B' shown correspond to the velocity $V(t) = 0.4\,c$; the slope of the hyperbolas at these points is 0.4. The proper acceleration of hyperbolic motion is constant, but the proper acceleration associated with point A is smaller than that with point B [15].

The diagram represents the entire motion. During the period $t < 0$ the rod approaches the origin with decreasing velocity, while for $t > 0$ it moves away with increasing velocity. The acceleration always points in the positive direction of the x-axis. It is essential that although in the system K the points A and B reach the velocity $V = 0$ simultaneously, these events are not simultaneous when viewed from the various systems K'. Conversely, the events A' and B', which are simultaneous in the systems K' ($t' = 0$ for both), correspond to different instants $t_{A'}$ and $t_{B'}$ in the system K.

From the system K it can be read that during the interval $t < 0$ the velocity of the point B of the rod, which has the

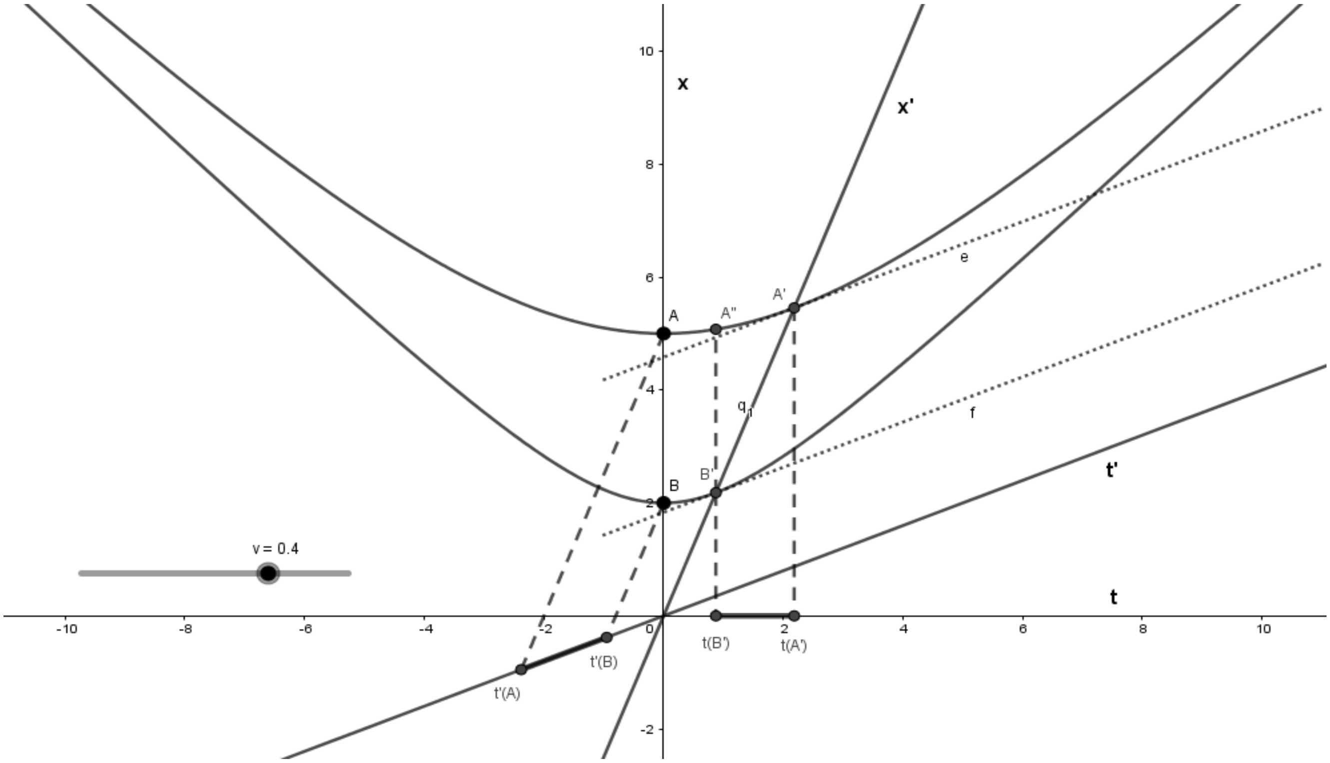

Fig. 2: Worldlines of the endpoints A and B of an accelerating rod in the systems K and K' (the time axis is horizontal) (own GeoGebra construction).

smaller x-coordinate (the "front" point), decreases later to a chosen value, whereas for $t > 0$ it is again the point B, now with the smaller x-coordinate (the "rear" point), whose velocity increases earlier to a chosen value. This means that at every instant the point B moves with a greater velocity relative to the inertial system than point A.

By the nature of the de Broglie wavelength, this implies that during the period of acceleration the point B of the rod perceives the quantum at rest in the inertial system as having a shorter wavelength and higher energy density than does point A. Such a perception of the energy density in the system K produces, for the quanta of the rod, a force directed toward the negative direction of the x-axis. This force is the inertial force. In the reverse viewpoint, the quanta of the rod exert a force in the opposite direction on the quanta of the carrier medium.

The inertial force appears as the interaction of real waves; therefore, it is not fictitious. Since the vacuum is constituted by the matter of the cosmic environment (in the sense indicated above, the total matter of the universe), Mach's principle is realized. The inertial force is a force that confirms the physical reality of the vacuum.

If only two quanta of equal mass existed in the universe and they accelerated relative to one another, it would be impossible to ask which one is "truly" accelerating. From this it follows that *acceleration is also relative*, not only velocity. In inertial systems the inhomogeneity arising from the presence of celestial bodies and the inhomogeneity arising from acceleration (within a finite region of space) compensate each other.

The Standard Model, which describes the phenomena of the microworld, does not discuss gravity and active manifestations of mass. It derives the inertia of quantum particles from their interaction with the Higgs field. This raises the question of how the vacuum based on the exponentially decreasing parts of quanta relates to the Higgs field.

6 Density of the vacuum

There is only one essential difference between the deflection of light occurring along a long path and refraction at the boundary of a medium: near the "surface" of classical bodies the decisive part of the change in direction occurs within a much smaller region with a high gradient of energy density. The propagation speed of light in glass is measured from the position of a distant (external) observer, since we work with meter rods and stopwatches located outside the glass body (see optical path length).

If the squares of the propagation velocities are inversely proportional to the density, which is the sum of the density of the vacuum and the density of the medium (e.g. liquid, gas or solid) contained within it, then a calculation can be made for the density ϱ_0 of the vacuum. For this purpose, one may start from the density and refractive index of non-crystalline materials. The frequency dependence of the refractive index is not considered.

For one type of lead glass the density is and the refractive index is $n = 1.98$ [16]. The refractive index increases with increasing density of the medium (light propagates more slowly in denser materials).

Taking the vacuum density into account, the total density within the glass volume is $\varrho_0 + 6500$ kg/m^3. Based on the relation between propagation velocities and densities,

$$\frac{\varrho_0 + 6500}{\varrho_0} = \frac{c^2}{c^2/1.98^2} = 1.98^2 = n^2 \tag{19}$$

from which $\varrho_0 = 2226$ kg/m^3. This is the vacuum density valid at the location where the refractive index was measured.

Taking the density of air as 1.29 kg/m^3 and its refractive index as 1.0002931, the vacuum density becomes $\varrho_0 = 2201\,\text{kg/m}^3$. The similarity is remarkable considering the large difference between the densities of air and lead glass. Other estimates differ from one another by as much as 120 *orders* of magnitude. Using the data for diamond yields a vacuum density of 721 kg/m^3. A paper published in 2018 [17] reports essentially similar results.

If the refractive index of materials depends measurably on altitude above sea level, then the presence of the energy-density excess surrounding the Earth and the rate of its decrease could also be detected.

7 Mass

Mass is the property of matter by which it influences the energy density of the carrier medium (*active mass*) and by which it is affected by inhomogeneities of the energy density (*passive mass*). The magnitude of the mass of an object depends on how much the energy density within the region occupied by its quanta differs from the energy density of the carrier medium. The equality of active and passive mass follows from the law of action and reaction (conservation of the centre of mass).

When mass is measured by comparison with a unit of mass (weighing) or through the force required for acceleration, we rely on the passive manifestations of mass. In reality, in neither case do we know how much of the measured force is gravitational and how much is inertial. To determine their magnitudes separately, an *absolute reference frame* and *absolute acceleration* would have to exist, but this condition is not fulfilled. We refer to the Earth only on the basis that during the duration of the experiment the cosmic distribution of matter and the state of motion of the Earth are practically constant.

The distinction between the two types of force is also excluded because both gravitational and inertial forces are determined by the dependence of phase velocity on energy density and by the inhomogeneity of the carrier medium. Thus, the *equivalence principle* holds, and it is impossible to speak of separate inertial and gravitational masses.

Two masses could also be compared by measuring whether they exert the same gravitational force on a test body. In this case we would measure mass through its active effects. However, the absence of an absolute reference frame would again play a role, and we would not come closer to distinguishing inertial and gravitational mass. In fact, such a distinction is unnecessary. The above considerations do not exclude determining the masses of distant celestial bodies from the orbital periods of bodies orbiting them.

The mass of quanta is related to their energy content. This relationship is expressed by the Klein-Gordon equation related to equation (3), and in linearized form by the Dirac equation. Particle-antiparticle creation is wave generation, and the energy content is wave property. Paul A. M. Dirac did not regard electrons as point-like entities [18]. The energy of quanta is defined relative to the carrier medium; mass modifies the energy density of the carrier medium.

The energy required for particle-antiparticle pair creation is $2m_0c^2$, so both members of the pair arise through positive work. Since the energy density of the vacuum is not zero, this does not exclude the possibility that an antiparticle decreases the vacuum energy density (in gases, for example, positive work is required to create both denser and rarer regions). This assumption leads to the conclusion that antiparticles attract one another gravitationally just as particles do, whereas a particle and an antiparticle repel each other gravitationally. All this may be completely masked by the electric interaction, which is $10^{36} - 10^{42}$ times stronger (the ratio of the forces is independent of distance). In this hypothetical case the quanta mediating energy deficit (“holes”) are infinitely extended just like the quanta mediating energy-density excess.

In the assumed case one may say that the phase velocity of antiparticles does not decrease but increases when approaching a region of increasing energy density (the group velocity behaves in the opposite way, see the relation $V_{ph} = c^2/V$). Light passing near antimatter concentrations would bend in the opposite direction to light passing near matter concentrations, but this would still correspond to deflection toward higher energy density (see gravitational diverging lens). It should be noted that in the case of photons we do not distinguish between particle and antiparticle.

The fact that the energy of quanta is defined relative to the carrier medium may also imply that the probabilities of particle and antiparticle creation are not exactly equal (cf. the predominance of matter over antimatter), since increasing density does not encounter the same limitation as decreasing density. In a vacuum with positive energy density, the masses of particle-antiparticle pairs may also differ slightly, although the ratio of electric and gravitational forces suggests that the difference would be extremely small.

The gravitational behaviour of matter and antimatter can be investigated experimentally. Experiment at CERN aimed at determining the direction of the force — the ALPHA experiment — currently suggest that antihydrogen falls toward the Earth [19]. However, it may be possible to clarify the direction of the force more efficiently through inertia, by rotating or accelerating the tube containing antihydrogen. It is also worth considering the idea that bodies with density lower than that of a fluid move toward one another within the fluid [20].

8 Summary

The proposed model of the vacuum is based on the wave nature of matter and its relativistic properties. The wave nature not only requires the existence of a carrier medium but also enables it. Since quanta are never in an infinitely deep potential well, they penetrate one another and form a carrier medium for each other. Zero-point energies cannot justify the existence of the vacuum as a material entity. Crucially, the energy density represented by quanta is continuously distributed in space, and it must be considered even when the quantum is not localized.

Gravitational interaction and inertia are based on the dependence of wave phase velocity on the energy density of the carrier medium. Interactions describe how overlapping waves modify each other's parameters; there is no need for quanta to move from one interacting object to another. In gravitational interactions, at most, virtual gravitons may be involved, whereas gravitational waves are certainly composed of independent quanta. The model of the carrier medium and the mechanism of interaction also explain Mach's principle. The energy density at every point in space is determined by the matter of the cosmic environment and the state of motion of the test body. The inertial force arises from the inhomogeneity of the carrier medium as perceived by an accelerating test body. Both gravitational and inertial forces are real forces, as they result from interactions of real quanta.

The local value of the gravitational potential correlates with the local energy density, its magnitude expressed in terms of the universal speed of light squared. Units of length and time can be defined through wave concepts (wavelength, period). All of this rests on relation (1).

Mass belongs to those objects that influence the energy density of the carrier medium and are affected by its inhomogeneities. Both the active and passive manifestations of mass are wave properties. The equivalence of inertial and gravitational mass follows from the identical mechanism of the forces and the absence of an absolute reference frame.

The energy of quanta is defined not absolutely but relative to the energy density of the carrier medium (the vacuum). The described mechanism of gravitational interaction and inertia points in the direction that different types of quanta arise in the same universal carrier medium. Differences in the gravitational behaviour of particles and antiparticles may arise because a matter wave can both increase and decrease the energy density of the carrier medium. In the outlined scenario, a gravitational repulsion between particles and antiparticles emerges, which can be largely masked by electromagnetic forces. To clarify in which direction free antiparticles "fall" in the Earth's gravitational field, inertial forces may offer clearer effects. The proposed conception of the carrier medium and quanta concretely illustrates the connection between the microcosm and the macrocosm.

Submitted on April 9, 2026

References

1. Feynman R.P., Leighton R.B., Sands M. The Feynman Lectures on Physics. Vol. I. Addison-Wesley, Reading, MA, 1963, §7-17 – §7-20.
2. Verlinde E. On the origin of gravity and the laws of Newton. arXiv: 1001.0785 (2011).
3. Wignall J.W.G. De Broglie waves and the nature of mass. *Foundations of Physics*, 1985, v. 15, 207.
4. Kuczmann I. A lendület és perdület összefüggése a Lorentz-transzformációval. *Fizikai Szemle*, 2011, v. 71, 126 (*in Hungarian*).
5. Feynman R.P., Leighton R.B., Sands M. The Feynman Lectures on Physics. Vol. III. Addison-Wesley, Reading, MA, 1965, §7-16 – §7-18.
6. Cheng T.-P. A College Course on Relativity and Cosmology. Oxford University Press, Oxford, 2015, 122.
7. Vybíral B. Fyzikálne pole z hľadiska teórie relativity, SPN, Bratislava, 1980, 162 (*in Slovak*).
8. Einstein A. Ether and the Theory of Relativity. An address delivered on May 5th, 1920, in the University of Leyden, Holland. Methuen & Co. Ltd., London, 1922.
9. Eddington A.S. Space, Time and Gravitation: An Outline of the General Relativity Theory. Cambridge University Press, Cambridge, 1920, 99.
10. Evans J., Alsing P.M., Giorgetti S., Nandi K.K. Matter waves in a gravitational field: An index of refraction for massive particles in general relativity. *American Journal of Physics*, 2001, v. 69, 1103.
11. Sciama D.W. The physical structure of General Relativity. *Reviews of Modern Physics* 1964, v. 36, 463.
12. Ellis G.F.R. Cosmology and local physics. *International Journal of Modern Physics A*, 2002, v. 17, no. 20, 2667.
13. Misner C.W., Thorne K.S., Wheeler J.A. Gravitation. W.H. Freeman, San Francisco, 1973, 163–165.
14. Rindler W. Relativity: Special, General, and Cosmological. Oxford University Press, Oxford, 2006, 49.
15. Rindler W. *Ibidem*, 72.
16. Fluegel A. Calculation of the refractive index of glasses (2007). https://www.glassproperties.com/refractive_index
17. Mashkin M.N. Calculation of the density of vacuum matter, the speed of time and the space dimension, *Progress in Physics*, 2018, v. 14, no. 3, 135.
18. Petroni N.C. Vigier J.P. Dirac's aether in relativistic quantum mechanics. *Foundations of Physics*, 1983, v. 13, 253.
19. Horváth D. Mi az antianyag és hová tűnt? *Fizikai Szemle*, 2024, v. 74, 369 (*in Hungarian*).
20. Vybíral B. Fyzikálne pole z hľadiska teórie relativity. SPN, Bratislava, 1980, 38 (*in Slovak*).