The physical meaning of the fundamental concepts of physics

3. The physical nature of 'work' and 'kinetic energy' (i)

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Abstract

The principle of conservation of 'energy' is the ultimate building stone of physics. The problem is that we don't have a tight description of what 'energy' really is and how and where it is physically stored.
On the basis of the conclusion of my paper Part 2: "The true physical nature of force" in which I have demonstrated that 'force' is a mathematical expression of the rate at which congruent translational motion is transferred, I will in this paper give a real physical definition of the true nature of 'work', which is in the present textbooks mathematically defined as the product of a force times its displacement and of the true physical nature of 'kinetic energy' of a moving body, which is in the present textbooks mathematically defined as the product of its mass times half the square of its velocity.

1. The indistinct nature of the concept of 'energy'

The principle of conservation of 'energy' is the ultimate building stone of physics. It implies the transformation of different forms of 'energy' into one another while the total amount of 'energy' remains constant.
The problem thereby is that, although the textbooks of physics give exact mathematical definitions for the different forms of 'energy' – kinetic energy, potential energy, gravitational energy, electromagnetic energy, field energy, radiant energy, thermal energy, etc. - one cannot find an accurate definition of the physical nature of 'energy' as such.
In fact, most textbooks simply don't give a definition of 'energy' at all, and in those cases that they do, it is rather woolly.
In Wikipedia for instance, 'energy' is defined as "*the ability to do work*".
This 'definition' agrees with the definition of professor Atkins of the University of Oxford, who writes [1] that 'energy' is "*a measure of the capacity of a system to do work*".
It is however clear that the definition of something as an 'ability', a 'capacity' or a 'potentiality' doesn't exactly tell us what that something is and how and where it is physically present.
In his "Lectures on Physics" Noble prize winner Richard Feynman blames this vagueness with regard to 'energy' on a fundamental ignorance of its real nature [2]: *"It is important to realize that in physics today, we have no knowledge of what energy is. We do not have a picture that energy comes in little blobs of a definite amount. It is not that way. However, there are formulas for calculating some numerical quantity, and when we add it all together it gives always the same number. It is an abstract thing in that it does not tell us the mechanism or the reasons for the various formulas."*

(i) The physical nature of 'potential' energy will be analyzed in my paper "The physical nature of potential energy".

In my successive papers I will reveal the true nature of energy and I will give the reasons and the mechanisms for its conservation. To do so we first have to deepen our insight in the laws of motion, making thereby a clear distinction between the real physical data on the one hand and the numerical results of their mathematical processing on the other hand.

2. The vagueness of the present definitions of 'work' and 'kinetic energy'

In my paper part 1 "The true nature of linear momentum", I have demonstrated that Newton's laws of motion led to the concept of 'the quantity of motion', which is nowadays known as the 'linear momentum' of an object and which is mathematically defined as the product of its mass 'm' and velocity '**v**':

$$\mathbf{p} = m\mathbf{v}$$

Another consequence of Newton's laws of motion is the so-called 'moving energy' [3] of an object with mass 'm' and speed 'v', which is nowadays called the 'kinetic energy' and which is mathematically defined as the quantity:

$$K = mv^2/2$$

The problem is that this definition of 'kinetic energy' is a purely mathematical definition of which the physical meaning is not as clear as it seems at first sight.
In the present textbooks 'kinetic energy' is physically defined as "*something that an object possesses by virtue of having work done on it*" or as "*the capacity of an object to do work by virtue of its speed*". 'Work' on its turn is defined as "*something that is done on an object by a force as the object is displaced and which is equal to the change of kinetic energy*".
These definitions of 'work' and 'kinetic energy' are however mathematical equations that are put into words instead of mathematical symbols and that don't give any added value to the mathematical equations.
There are thereby based on a circular reasoning because it follows automatically from the mathematical equation of kinetic energy, that the work done by a force on a body when that body is displaced, and the transfer of 'kinetic energy' to that body, are just two different expressions of one and the same thing.

$$W = \int \mathbf{F}.d\mathbf{s} = \int m.\mathbf{a}.d\mathbf{s} = \int m.d\mathbf{v}.d\mathbf{s}/dt = \int m.\mathbf{v}.d\mathbf{v} = m.v^2/2 - m.v_0^2/2 = K - K_0 = \Delta K$$

But this still doesn't tell us at all what this 'something' is and how and where it is physically present. This means that we are turning in circles and that we badly need to clarify these fundamental concepts once and for all.

3. The true nature of 'work' and 'kinetic energy'

3.1 The total amount of momentum flow

In section 2.2 of my paper Part 2: "The true physical nature of force" I have shown that the momentum flow '$\mathbf{Q_p}$' of a body with mass 'm' and velocity 'v' indicates the amount of linear momentum that moves across a given section per unit time:

$$\mathbf{F} = \mathbf{Q_p} = (m_1.\mathbf{v}).(N\mathbf{v}/\mathbf{L})$$

This expression can also be written as:

$$\mathbf{F} = \mathbf{Q_p} = (Nm_1\mathbf{v})/(\mathbf{v}/\mathbf{L}) = (m\mathbf{v}/\mathbf{L}).\mathbf{v} = (\mathbf{p}/\mathbf{L}).\mathbf{v}$$

In this expression the linear momentum per unit time, is expressed as the linear momentum per unit length '**p**/**L**', multiplied by the number of unit lengths per unit time '**v**'.

If the momentum flow '$\mathbf{Q_p}$' of a particle system with mass 'm' that is moving with a velocity '**v**', is equal to linear momentum that is present in a unit length multiplied by its velocity, then the 'total amount/capacity of momentum flow' ($Q_{p\,L}$) of the whole particle system must be equal to the linear momentum that is present in its whole length (m**v**) multiplied by its velocity (**v**):

$$Q_{pL} = \mathbf{F}.\mathbf{L} = \mathbf{Q_p}.\mathbf{L} = \mathbf{p}.\mathbf{v} = m.v^2 \quad \text{(expressed in N.m = J)}$$

This means that 'mv²' is a mathematical expression of the total amount of momentum flow of a particle system with mass 'm' that is moving with a velocity '**v**'.

It is important to notice that this expression corresponds to the extreme case in which the total amount of motion is transferable in one strike and all the particles to which this amount of motion is are at once moving congruently with the same invariable speed 'v'.
This corresponds to the specific situation of light particles (photons) that all move effectively with the same speed 'c' and in that case the total amount of kinetic energy is indeed equal to Einstein's mass-energy equation: $E = mc^2$ (ii).

3.2 The total amount of reversibly transferable momentum flow

The in section 3.1 described way of transferring momentum flow may be okay for photons and for theoretical, perfectly elastic billiard balls that act like one big, monolithic particle, but for real material composite macro structures, the accelerations and the consecutive impulsive forces are much too high and will cause a breakdown of those structures.
In section 5.2 of my paper Part 2 "The true physical nature of force", I have demonstrated that in order to accelerate real physical structures, we have to use a steady driving force '$\mathbf{F_d}$' that consists of a large number of very small successive impulses that produce a steady transfer of momentum flow '$\Delta\mathbf{Q_p}$', from the 'force' particle system to the body:

$$\mathbf{F_d} = \Delta\mathbf{Q_p} = \Delta\mathbf{p_1}.f = (m_1.\mathbf{v})(N\mathbf{v}/2\mathbf{L}) = (Nm_1)v^2/2\mathbf{L} = m.v^2/2\mathbf{L} = \mathbf{Q_p}/2$$

This means that we have to maintain a steady transfer of momentum flow '$\Delta\mathbf{Q_M}$' that is equal to half the momentum flow '$\mathbf{Q_p}$' of that body when it steadily proceeds with that same velocity '**v**'.
The former equation of the driving force can also be written as:

$$\mathbf{F_d} = \Delta\mathbf{Q_p} = \Delta\mathbf{p_1}.f = (Nm_1.\Delta\mathbf{v}).(\mathbf{v}/2\mathbf{L}) = (m.\Delta\mathbf{v}/\mathbf{L}).(\mathbf{v}/2) = (\Delta\mathbf{p}/\mathbf{L}).\mathbf{v_{av}}$$

which allows us to reveal the true physical nature of the 'work' done by a driving force on a free body: if the linear momentum that is transferred by the particles that are present in a unit length of the force particle system multiplied by their average velocity level is equal to the

(ii) This will be analyzed in my paper "The physical nature of mass".

transferred momentum flow '$\Delta\mathbf{Q_p}$', then the total amount of linear momentum ($\Delta\mathbf{p}$) that is transferred by the particles that are present in the whole length '**L**' multiplied by their average velocity, represents the 'total amount of transferred momentum flow' (ΔQ_{ML}):

$$W = \Delta Q_{pL} = \mathbf{F_d}.\mathbf{L} = \Delta\mathbf{Q_p}.\mathbf{L} = \Delta\mathbf{p_1}.f.\mathbf{L} = (Nm_1.\Delta\mathbf{v}).(\mathbf{v}/2\mathbf{L})\mathbf{L} = (m.\Delta\mathbf{v}).(\mathbf{v}/2) = \Delta\mathbf{p}.\mathbf{v_{av}}$$

This demonstrates that 'work', which is classically defined as the product of a force times its displacement ($W = \mathbf{F}.\mathbf{L}$), is in fact a mathematical expression of the total amount of momentum flow 'ΔQ_{pL}' that is reversibly transferred by a 'force particles system' with a length '**L**' in its direction of motion, to a free body and which can also be expressed as the total amount of transferred linear momentum ($\Delta\mathbf{p} = m.\Delta\mathbf{v}$) multiplied by the average velocity level ($\mathbf{v_{av}} = \mathbf{v}/2$) at which this linear momentum is transferred.

$$W = \Delta Q_{pL} = \mathbf{F_d}.\mathbf{L} = = \Delta\mathbf{p}.\mathbf{v_{av}} = Q_{pL}/2$$

This means that the total amount of reversibly transferable momentum flow 'ΔQ_{pL}' is equal to half the total amount/capacity of momentum flow of the moving force particle system 'Q_{pL}'. It is hereby important to stress the fact that in the classic definition of work, the factor '**L**' stands for the displacement of the force (together with the body), whereas in our physical analysis of work, '**L**' stands for the total active length of the force particle system in its direction of motion, which are mathematically however one and the same.

3.3 The true physical nature of work

The true physical meaning of 'work' as the total amount of reversibly transferred momentum flow, can still be revealed more clearly by analyzing the physical meaning of a reversibility with regard to the velocity increase. If we want to increase the velocity of a real physical body in a reversible way, we have to do that with the smallest possible increasing momentum transfers. In mathematics this is symbolized by so-called 'infinitesimal' velocity increase '$d\mathbf{v}$', so that:

$$W = \int \mathbf{F} d\mathbf{L} = m\int \mathbf{v} d\mathbf{v} = mv^2/2$$

This is however a purely mathematical concept. Physically spoken, it means that we have to fire consecutive particles with e.g. the same mass as the body but with the smallest possible velocity increases When we take this "smallest possible velocity increase" as the natural velocity unit, this means that we have to fire mass particles with increasing velocities from '1' up to 'v'. It is clear that in this system of extremely small natural velocity units, 'v' must represents an incredibly large number ($v >> 1$).

The total amount of linear momentum or i.e. the total amount of congruent translational motion, that has to be transferred to increase the velocity of the body in a reversible way from '0' (the initial speed of the body) to 'v' (the final speed of the body) is then equal to the sum of the linear momentums of all the successively fired particles:

$$\Delta p_{tot} = m(1 + 2 + 3 + \ldots + v)$$

$$= m[v(1 + v)/2]$$

which for $v >> 1$ gives us:

$\Delta p_{tot} = mv^2/2$

This physical reasoning demonstrates that the numerical value of the performed 'work', or i.e. of the total amount of reversibly transferred amount of congruent translational motion, represents in fact the sum of all the linear momentums at all the intermediary velocity levels. Since I have demonstrated in my paper Part 1 that 'linear momentum' is a mathematical expression of the total amount of congruent translational velocity/motion, this means that 'work' is a mathematical expression of the total amount of reversibly transferred congruent translational velocity/motion at all the intermediary velocity levels.

In this way we have revealed the true physical nature of 'work' as a mathematical expression of the total amount of congruent translational motion that is reversibly transferred between particle systems at different velocity levels. This conclusion follows also logically from the fact that a 'constant' force on a free body means that we have to transmit a steady stream of impulses at increasingly higher velocities.

3.4 The true nature of 'kinetic energy'

For an initial zero velocity, '$\Delta\mathbf{v} = \mathbf{v}$' so that in that case, the 'work' or i.e. the total amount of reversibly transferred congruent translational motion is equal to:

$$W = \Delta Q_{pL} = \Delta\mathbf{Q_p}.\mathbf{L} = \mathbf{F_d}.\mathbf{L} = (m.v^2/2\mathbf{L}).\mathbf{L} = m.v^2/2 = Q_{pL}/2 = \Delta K$$

Which is the equation of the 'kinetic energy' of a mass 'm' that moves with a speed 'v'.
In this way, it is clear that the 'kinetic energy' of a moving mass is in fact a mathematical expression of its total amount/capacity of reversibly transferable congruent translational motion at a given speed level with regard to any free body that is initially at rest in that same reference frame.

It follows from this that the work 'W' on a body with a mass 'm' that is propelled from a velocity 'v' to a velocity 'v + Δv' is equal to the difference between of the kinetic energies of this mass at both velocity levels:

$$W = \int m\mathbf{v}d\mathbf{v} = m(\mathbf{v} + \Delta\mathbf{v})^2/2 - mv^2/2 = \Delta K$$

and

$$\Delta K = m(\mathbf{v} + \Delta\mathbf{v})^2/2 - m.v^2/2 = m.\mathbf{v}.\Delta\mathbf{v} + m.\Delta v^2/2 = m.\Delta\mathbf{v}(\mathbf{v} + \Delta\mathbf{v})/2 = m.\Delta\mathbf{v}.\mathbf{v}_{av} = \Delta\mathbf{p}.\mathbf{v}_{av}$$

This demonstrates that the work done by a driving force on a body that is free to move, and the transfer of kinetic energy to that body while exerting that force, are evidently one and the same thing.

In this way I have revealed that the '**kinetic energy of congruent/bulk motion**' of a moving body is **a mathematical expression of its total amount/capacity of reversibly transferable congruent translational motion at its given velocity level in regard to any free body that is at rest in the same reference frame**.
This definition of the kinetic energy of a moving body is generally considered as a relative datum because it depends on a fortuitously chosen reference frame. But it was already

demonstrated in 1669 by Christiaan Huygens [4] that this so-called 'relative' velocity in regard to any other physical body that moves in the same reference frame is an absolute, physical datum (iii).

3.5 The direct link between 'force' and 'kinetic energy' of congruent/bulk motion

It follows from the former definitions of kinetic energy of bulk motion that 'force', which is classically defined as the transfer of linear momentum per unit time, can also be defined as the transfer of kinetic energy (or i.e. of the total amount of momentum flow) per running meter:

$$\mathbf{F} = \Delta\mathbf{p}/\Delta t = K/\mathbf{L} = Q_{pL}/\mathbf{L} = \mathbf{Q_p}$$

As I have mentioned in my paper part 2 'The true nature of force', this direct link between 'force' and 'energy' by means of the concept of momentum flow was already indirectly demonstrated by Andrea diSessa, who proposed in his paper "Momentum flow as an alternative perspective in elementary mechanics" [5] to use the notion of 'momentum flow' instead of 'force', because momentum flow analysis provides a better appreciation for the distribution mechanism of the 'forces' in static structures involving real bodies. To demonstrate this he worked out a number of examples: He consecutively analyzed (A) the momentum flow while holding an apple in one's hand, (B) the breaking force of a rope pulled by two elephants, (C) the stress in the legs of a racehorse, (D) the stress in a pressure tank, and (F) the stress in a spinning rim. But in example 'E' he gives a derivation of Bernouilli's law, which as he writes himself, is clearly a question of energy.

This illustrates that the intuitive link between 'force' and 'kinetic energy' that was made by diSessa was an evident link, because from the standpoint of momentum flow, 'force' is nothing else than the transferred (kinetic) energy per running meter.

This similarity between 'force' and 'energy' has however led to a non proper use of both concepts in the 19th century. The reason therefore is that originally 'mv^2' was referred to as the 'living force' (vis-viva) which was widely used by physiologists to explain the motion of biological bodies at that time [6]. This explains why the first paper that established the conservation of energy: "On the quantitative and qualitative determination of forces", that was published in 1841 by Julius Robert von Mayer (1814 – 1878), used the word 'force' instead of 'energy'. In that same period, Hermann von Helmholtz (1821 – 1894), also used the word 'force' instead of 'energy' in his paper "On the conservation of force", which shows that the two concepts were poorly differentiated at that time.

3.6 The difference between 'kinetic energy of bulk motion' and 'linear momentum'

Already in the Newton's time there was a considerable controversy about the relative significance of the 'quantity of motion' (nowadays called the 'linear momentum') and the quantity then called the "living force" that was related to what we now call 'moving' or 'kinetic' energy [7] and the great European physicists, Descartes, Leibnitz and D'Alembert had long discussions [8] whether 'kinetic energy' or 'linear momentum' was the true property that is considered by the conservation laws.

(iii) This will be analyzed in my papers "The conservation of kinetic energy in elastic collisions" , "The physical nature of temperature and thermal energy" and "The physical nature of velocity".

Our unveiling of the true physical natures of 'linear momentum' and 'kinetic energy of bulk motion' allows us to put things clear once and for all and to underline the difference between both physical concepts.
In section 3 of my paper "Part 1: The true nature of linear momentum" I have demonstrated that the principle of the conservation of "linear momentum" or i.e. of the amount/capacity of 'common' or 'congruent' translational motion of a particle system at a given velocity level, is a mathematical expression of the physical fact that the particles of a particle system cannot change their 'congruent' velocity component, by their own.
This is completely different with the nature of 'kinetic energy' of bulk/congruent motion which, as we have demonstrated in this paper, is a mathematical expression of the amount/capacity of the reversible transfer of congruent translational motion between the velocity level of the considered body and the velocity level of a body at rest in the same reference frame.
To demonstrate this, we first consider the case in which we push a free body with mass 'm' gradually from an initial zero velocity to a velocity 'Δv'. In that case:

- the increase of the linear momentum is equal to the mass times the velocity increase:
  $\mathbf{p} = m.\Delta\mathbf{v}$

- the total transferred momentum at all the intermediary velocity levels or i.e. the increase of kinetic energy, is equal to the transferred linear momentum times the average velocity at which this momentum is transferred:
  $W = Q_{pL} = \mathbf{p}.\mathbf{v_{av}} = (m.\Delta\mathbf{v}).(\Delta\mathbf{v}/2) = m.\Delta v^2/2$

Then we consider the case in which we push the same body gradually from an initial velocity '$\mathbf{v}$' to a velocity '$\mathbf{v} + \Delta\mathbf{v}$'. In that case:

- the increase of the linear momentum is equal to the mass times the velocity increase:
  $\mathbf{p} = m.\Delta\mathbf{v}$
  Which means that the transfer of linear momentum depends only on the increase of the momentum and is independent of the velocity level at which this increase takes place.

- the total transferred momentum at all the intermediary velocity levels or i.e. the increase of kinetic energy is equal to the transferred linear momentum times the average velocity at which this momentum is transferred:
  $W = Q_{pL} = \Delta\mathbf{p}.\mathbf{v_{av}} = (m.\Delta\mathbf{v}).[\mathbf{v} + (\mathbf{v} + \Delta\mathbf{v})]/2 = (m.\Delta\mathbf{v}).(\mathbf{v} + \Delta\mathbf{v}/2)$
  This equation tells us that in order to give a body with a mass 'm' and a velocity '$\mathbf{v}$' a velocity increase '$\Delta\mathbf{v}$', we must add a linear momentum 'm.$\Delta\mathbf{v}$' at a velocity level '$\mathbf{v} + \Delta\mathbf{v}/2$', so that:
  $W = Q_{pL} = \Delta\mathbf{p}.\mathbf{v_{av}} = m.\Delta\mathbf{v}.\mathbf{v} + m.\Delta v^2/2$
  This equation tells us that in order to increase the velocity of a body in a reversible way, we must first make sure that the force particle system finds itself at the same velocity level as the body. So the first term of this equation represents the amount of linear momentum 'm.$\Delta\mathbf{v}$' at the velocity level '$\mathbf{v}$' and the second term represents the momentum flow that corresponds to the transfer of the necessary amount of linear momentum 'm.$\Delta\mathbf{v}$' from velocity level '$\mathbf{v}$' to level '$\mathbf{v} + \Delta\mathbf{v}$'.

To illustrate this, we take e.g. the case of an object in space with a mass of 'm = 1000 kg' of which we want to increase the speed by 'Δv = 1 m/s'.

- When the object has a velocity of 'v = 0 m/s' with regard to the force particle system:
  - The momentum increase is equal to $\Delta p = m.\Delta v = 1000$ Ns
  - The total momentum flow or 'work' is equal to $W = m.\Delta v^2/2 = 500$ Nm
- When the object has a velocity of 'v = 1 m/s' with regard to the force particle system:
  - The momentum increase is equal to $\Delta p = m.\Delta v = 1000$ Ns
  - The total momentum flow or 'work' is equal to: $W = m.v.\Delta v + m.\Delta v^2/2 = 1000 + 500 = 1500$ Nm

This confirms our conclusion that the kinetic energy of an object with regard to a material body depends on its relative velocity with respect to that body, which means that the magnitudes of relative velocities have an absolute character (iv).

4. Kinetic energy of internal motion

In the case of inelastic collisions, the congruent motions of the colliding bodies will be scattered over all possible directions so that the kinetic energies of congruent bulk motion of both colliding particle systems will be transformed into 'kinetic energy of isotropic/internal motion' or i.e. into 'thermal energy' (v). The advantage of the concept of kinetic energy is that it is a scalar, which means that its use isn't restricted to congruent translational motion but that it can also be used to characterize rotating, vibrating and thermal motion.

Translational motion: $K = mv^2/2$

Rotational motion: $v = R\omega$ so that: $K = mR^2\omega^2/2$

Vibrational motion: $x = x_m \cos(\omega t + \theta)$ and consequently $v = -\omega x_m \sin(\omega t + \theta)$

So that: $K = (m\omega^2/2)x_m^2 \sin^2(\omega t + \theta)$

5. The total amount of kinetic energy

In the former section we have seen that kinetic energy is a scalar that characterizes the total amount of reversibly transferable motion between two velocity levels, which means that it can also be used to express the total amount of motion of a particle system, its congruent as well as its thermal motion. In that way, the conservation of 'energy' means in the total amount of kinetic energy or i.e. the sum of its total amount of congruent and of thermal motion will be conserved.

6. Kinetic energy and Planck's energy equation

In section 3.2 "The total amount of reversible transferable momentum flow", I have

(iv) This will be analyzed in my paper "The physical nature of velocity".
(v) This will be analyzed in my paper "The physical nature of temperature and thermal energy".

demonstrated that the driving force can be expressed as the transfer of linear momentum per impulse '$\Delta\mathbf{p_1}$' times the frequency 'f' of the impulses:

$\mathbf{F_d} = \Delta\mathbf{Q_p} = \Delta\mathbf{p_1}.f$

This means that we can write the equation of 'kinetic energy' as:

$K = \mathbf{F_d}.\mathbf{L} = (\Delta\mathbf{p_1}.\mathbf{L}).f$

Which has a similar form as Planck's formula for the photon energy:

$E = h.f$

Which allows us to conclude that:

$h = \Delta\mathbf{p_1}.\mathbf{L}$

so that for all photons, '$\Delta\mathbf{p_1}.\mathbf{L}$' must have the same constant value.

For rotational motion: $\Delta\mathbf{p_1}.\mathbf{L} = \mathbf{pR} = m\mathbf{vR} = mR^2\omega = I\omega = L$

Which means that the rotational momentum of photons must be invariable (vi).

7. Conclusion

On the basis of the conclusion of my paper Part 2: The true nature of force" in which I have demonstrated that 'force' is a mathematical expression of the rate at which congruent translational motion is transferred, I have in this paper come to the conclusion that 'work', (which is in the present textbooks mathematically defined as the product of a force times its displacement) is a quantitative expression of the total amount of congruent translational motion that is reversibly transferred between particle systems at different velocity levels (in a given reference frame).
In the same way, I have demonstrated that the 'kinetic energy' of a moving body (which is in the present textbooks mathematically defined as the product of its mass times half the square of its velocity) is a quantitative expression of its total amount (capacity) of reversibly transferable congruent translational motion at the given velocity level in regard to any free body that is at rest in the same reference frame.

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(vi) The relationship between Einstein's and Planck's energy equations will be analysed in depth in my paper "The true nature of mass".

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