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Article

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Abstract

The principle of conservation of energy is often demonstrated by means of free fall. In mechanics, states of a body with potential and kinetic energy are energetically compared. Based on the mass concept of relativistic mechanics, energy conservation is considered to be linked with mass conservation. We show that the process of free fall can be interpreted more thoroughly, if the cause-effect principle and the mass concept of thermodynamics are applied. For the first time in the history of physics, the mechanism of energy conversion in free fall can be shown, which is valid for any object, whether body or elementary particle. The phenomenon of falling confirms the following facts to be valid of on a fundamental level: i) The principle of conservation of energy, ii) The equivalence of inertial and gravitational mass, iii) The real mass increase of any object with its velocity, and iv) The continuousness of space and time. At the end of the article we explain why the theory of general relativity is unsuitable to demonstrate the conservation of energy during free fall.

Keywords: free fall, mechanics, thermodynamics, energy conservation, equivalence of inertial and gravitational mass, continuous space and time, general relativity.

1. Introduction

The free fall, i.e. the uniformly accelerated rectilinear motion of an object in the Earth's gravitational field without friction, is often cited as the simplest example for the valid principle of energy conservation. To demonstrate the conservation of energy, one equates the potential and kinetic energy of a body that is in two different states. Here one uses equations and concepts of force suggested by Isaac Newton and Gustav Robert Kirchhoff in the 17th and 19th centuries [1,2]. According to $E = mc^2$, the equality of the energy amounts of the states is assumed to be linked with mass conservation [3,4]. Since states of a body are considered, the process for transforming one state into the other remains unknown. We call this the *state thinking* of mechanics.

In this paper, we exemplify the consistent application of thermodynamics to the free fall of any object such as a body or a quantum object like an electron or photon. Thermodynamics not only extends mechanics by a more realistic description of matter far from idealizing point masses, it is also based on *process thinking* that is characterized by an uncompromising cause-effect principle [5,6]. Instead of comparing states, we describe the free fall as a coupled process, in which two extensive state variables change simultaneously. In doing so, the mechanism of energy conversion during free fall becomes obvious and the validity of energy conservation can be explained on a principal level.

A main goal of this paper is to substantiate the mass and time concepts of thermodynamics [7–10] as a conceptual basis of fundamental theoretical physics. If one applies the process equations and the energy-mass relation $E = mc^2 + E_{\text{pot}}$ of thermodynamics, the equivalence of inertial and gravitational mass can be *explained* and proved as a law of nature. This approach is superior to the idealizing ideas of mechanics and special relativity. Even the thought experiments of general relativity, e.g. in elevators, only allow to *state* the equivalence of inertial and gravitational mass.

Furthermore, free fall demonstrates that the experimentally confirmed real mass increase of any accelerated object is an explicable law of nature and not an apparent effect that depends on the chosen reference system. The additional fact that the phenomenon of the fall of any object is only compatible with continuous, i.e. *not-quantizable* time and space deepens our insights into reality and sets criteria for the exclusion of unrealistic theories.

In this context, it is noteworthy that the conservation of energy in free fall cannot be demonstrated with the basic theories of modern theoretical physics such as special and general relativity or quantum field theories. Either they are not applicable or they lead to logical paradoxes, as discussed at the end of the paper.

2. The state thinking of mechanics

One of the first statements that pupils learn in mechanics is that mechanical potential energy E_{pot} of a body and kinetic energy E_{kin} of a body can be converted into each other.

Usually, two states at the times t_1 and t_2 are compared (cf. **Figure 1**):

- state 1 without initial velocity ($v = 0$) at the height h with E_{pot} , and
- state 2 at the height $h = 0$ with the velocity v and thus with E_{kin} .

Figure 1. The state thinking of mechanics and the mass concept of relativistic mechanics.

By equating the energy amounts E_{pot} of a body and E_{kin} of the body at t_1 and t_2 , one obtains the well-known equation:

$$m/2 \cdot v^2 = mgh. \quad (1)$$

The mass m in Equation (1) can be reduced without hesitation, although the inertial mass m_i is on the left and the gravitational mass m_g on the right. This calculation step contains the experimentally confirmed assumption, already made by Newton, that gravitational and inertial mass are equal. One obtains the equation $v = \sqrt{2gh}$ that is used to calculate v shortly before hitting the Earth, when E_{pot} is “fully” converted into E_{kin} . A free-falling body is mostly described as having one force acting on it: its weight force $F_g = mg$ that causes acceleration.

Equation (1) demonstrates the conservation of energy with the total energy E of a body:

$$E = E_{\text{pot}} + E_{\text{kin}} = \text{const.} \quad (2)$$

Energy conservation is considered to be linked with mass conservation. This interpretation goes back to Albert Einstein’s statement within his theory of special relativity (SR) that any kind of energy, including gravitational energy E_{pot} , is ponderable:

The mass of a body is a measure of its energy content. [4], p. 641

Thus, any energy in the gravitational field has energy of position which corresponds to the energy of position of a “ponderable” mass of magnitude E/c^2 . [11], p. 462

Einstein interpreted the *rest energy* E_0 of a body as equivalent to its *rest mass* m_0 and the total energy E of a body as equivalent to its Lorentz-transformed mass $m(v)$ measured by an observer in a moved inertial system:

$$E_0 = m_0 c^2, \quad (3)$$

$$E = m_0 c^2 + E_{\text{kin}} = m(v) c^2. \quad (4)$$

Although SR describes moving point masses or bodies consisting of point masses with $E_{\text{pot}} = 0$ in empty space, E_{pot} was heuristically included as being ponderable:

The so satisfying result of the theory of relativity, according to which the conservation of mass is merged with the conservation of energy [...]. [12], p. 900

This reading is still used today, e.g. in popular textbooks:

The theory of relativity shows [...] that a given energy always has a given mass. This relationship is called **energy-mass equivalence** and has become the most famous formula in physics. [13], p. 643

or by the 2020 Nobel Laureate in physics Roger Penrose:

Imagine two planets [...]. If (a) they are far apart, then the (Newtonian) negative potential energy contribution is not so great as (b) when they are close together. Thus the total energy (and hence the total mass of the whole system) is larger in case (a) than in case (b) [...]. [14], p. 465

In order to fulfill both the principle of energy conservation and the postulate $E = mc^2$ of SR, the energy and the mass of a falling object are interpreted as being constant (cf. Figure 1):

$$E = \text{const.}; \quad m = \text{const.} \quad (5)$$

The above equations and interpretations are common and applicable at low velocities, but hide methodological and logical weaknesses:

1. Energy amounts are equated, i.e. states are compared without being able to describe the process to transform one state into the other during free fall. In this way, the mechanism of energy conversion must remain unknown.
2. The statement that the weight force F_g represents the driving force for acceleration should be used with caution. Given the omnipresence of this interpretation, this objection may be surprising, but there is no mechanical process equation containing a *force* F_g and an *effect* Δv .
3. The conservation of mass is not demonstrated, but m is *set* constant. In Equation (5), one applies the energy-mass relation $E = mc^2$ of SR. Special relativity explicitly excludes E_{pot} and acceleration in its assumptions, while the free fall is characterized by dynamic processes involving E_{pot} and accelerated motion. General relativity (GR) extends SR by introducing E_{pot} and acceleration, but plays no role here because the claimed mass conservation in Equation (5) is based merely on SR, and $E = mc^2$ is also used in GR. Since $m = \text{const.}$ originates from a theory that is not applicable to accelerated motion, dynamic processes and free fall, it represents an unproven assertion.
4. If $E = mc^2$ of SR is applied to free fall, it remains unclear which mass is to be used in Equation (1). At t_1 ($v = 0$), the rest mass m_0 can be used to calculate mgh . And yet, at t_2 if we calculate $E_{\text{kin}} = m/2 \cdot v^2$ from the velocity and the mass of a body, we have to ask: Should we use the *rest mass* m_0 or the velocity-dependent mass $m(v)$? The astonishing result of the history of physics of the last 100 years is that this question is still debated today. Although SR describes an increase in mass with velocity:

$$m(v) = m_0 / \sqrt{1 - (v^2/c^2)} = \gamma m_0 \geq m_0 \quad (6)$$

with $\gamma \geq 1$, it has remained unresolved whether the observer-dependent mass $m(v)$ is *real* or *apparent* [15,16]. Various answers exist in the literature [7], p. 39. If the experimentally

confirmed mass increase in particle accelerators is considered, $m(v)$ is interpreted as *real* mass. If instead priority is given to the kinematic nature of observations, $m(v)$ is called *apparent*. Then, the rest mass m_0 is used in Equation (1): “Mass as a direct measure of quantity of matter must be independent of the coordinate system.” [17], p. 53 The sobering fact is that simple processes like acceleration work or the free fall cannot be imagined today without ambiguities.

3. The process thinking of thermodynamics

Instead of looking at states, thermodynamics describes processes and the associated changes in energy of a system like a body. The reasons for this are that the absolute content of energy in a real system cannot be specified and that nature is characterized by processes.

Each natural process represents a coupled process, where at least two extensive state variables X_i of a system change simultaneously. By considering reversible processes and avoiding side processes, the study of isolated processes is sometimes possible.

In the following, we present the cause-effect principle and the mass concept of TD and show what follows from their application to the process of free fall.

3.1 The cause-effect principle of TD

Thermodynamics (TD) is characterized by an uncompromising process thinking that is based on the empirically confirmed 1th and 2nd laws of TD and can include an indication of the direction of processes. In classical equilibrium TD, each individual abstracted process equation provides information on *how* the energy of a system is changed:

$$Y = \Delta E = \int_{X_{i,1}}^{X_{i,2}} \xi_i dX_i = \int_{X_{i,1}}^{X_{i,2}} \left(\frac{\partial E}{\partial X_i} \right)_{X_j \neq X_i} dX_i; \quad \delta Y [J] = \xi_i [J/a] dX_i [a]. \quad (7)$$

Y denotes the relevant abstracted exchange process, which always represents an energy transfer and accordingly exhibits the unit of energy Joule. The local gradient of the *intensive* state variable ξ_i denotes the thermodynamic force as the *cause* of Y , while the temporal change of the *extensive* state variable X_i denotes the *effect* of Y . ξ_i and X_i in one process equation are so-called *energetically conjugated* variables.

The cause-effect principle is repeated in TD of irreversible processes, where the fundamental equation describes the entropy production density σ_s that accompanies every irreversible system-internal process α :

$$\sigma_s \equiv \frac{1}{V} \frac{d_i S}{dt} = \sum_{\alpha} F_{\alpha} J_{\alpha}, \quad \alpha = 1, 2, 3, \dots, k. \quad (8)$$

The generalized thermodynamic *force* F_{α} is the local gradient of an *intensive* state quantity ξ_i , while the thermodynamic *flux* J_{α} is the temporal transport of an *extensive* state quantity X_i as effect. In equilibrium, F_{α} and J_{α} are zero.

Let us discuss the state variables in Equation (7) and (8) in a little more detail because their understanding is crucial for the analysis of free fall (cf. **Table 1**):

Table 1: Main differences between intensive and extensive state variables.

	Intensive state variable ξ_i	Extensive state variables X_i
Describes	Conditions within a system, Grade of intensity	The system as a whole
Measure of the	Quality	Quantity
Answers the Question	how strong, how intense	how much
Examples	T, p, c, μ , each kind of density X_i/V	S, V, A, n, m , momentum mv , energy E
Role in process	Generalized Force local gradient $d\xi_i/dx$	Generalized Flux temporal change dX_i/dt
Causality	Cause	Effect

An intensive state variable ξ_i such as temperature T , pressure p , concentration c , chemical potential μ , or density ρ describes the conditions within a system, i.e. its *quality*. ξ_i answers the question: *how strong?*, and does not depend on the size of a system. A local gradient of ξ_i within a system, i.e. the thermodynamic force $F_\alpha = d\xi_i/dx$ in equation (8), can cause an *internal process*, while $d\xi_i/dx$ between the system and its surroundings can cause an *exchange process*. Equation (7) does not explicitly state $d\xi_i/dx$ because equilibrium processes are described, which proceed infinitely slowly in infinitely small steps. However, $d\xi_i/dx > 0$ is implicitly included. $d\xi_i/dx = 0$ defines the equilibrium, e.g. between two phases a and b with $T_a = T_b$, $p_a = p_b$, $\mu_a = \mu_b$, while a real exchange process only takes place if $d\xi_i/dx \neq 0$. Intensive state variables ξ_i can be formed from the quotient or differential quotient of two extensive state variables X_i , e.g. $c = n/V$, $\mu = dG/dn$, mass density $\rho_m = m/V$, energy density $\rho_E = E/V$.

An extensive state variable X_i such as entropy S , volume V , interface area A , amount of substance n , mass m or momentum mv in turn describes the system as a whole, its *quantity*. X_i answers the question: *how much?*, and depends on the size of the system. X_i applies only to the entire system, i.e. there can be no local gradient of X_i within the system. dX_i/dx between system and surroundings is just as logically impossible because there is no spatial intensity grade, no gradation of X_i . If, for example, a volume $V_1 = 4$ ml is adjacent to $V_2 = 5$ l, there is no local gradient and accordingly no force. If a volume V is specified, nothing is said about the conditions in V . This concerns also other extensive state variables X_i like mass m , entropy S or energy E . Values like $m = 2$ kg, $S = 2$ J/K or $E = 5$ J say nothing about the spatial distribution of the relevant amounts within the system. Thus, extensive state variables X_i cannot exhibit spatial gradients, which is why they can never act as force. Spatial gradients within a system and across its boundaries can only be specified by means of ξ_i .

Instead, an extensive state variable X_i can be changed as a temporal effect of a process. If there is, for example, a local concentration gradient within a system, a substance transport by diffusion can be initiated ($dn/dt = D \nabla c$). Or the local pressure gradient between system and surroundings can cause that the volume V of the system is changed with time. While $d\xi_i/dx$ is the initiator of the process and cannot add up, the infinitesimally small temporal effects dX_i/dt in Equation (7) add up with time. Here, the value of X_i after the process is a measure of

the new energetic state of a system. dX_i/dt is accompanied by a decrease of the local gradient $d\xi_i/dx$, i.e. the force, up to equilibrium.

Thinking in terms such as quantity and quality can be traced back to Aristotle and was systematized by Immanuel Kant, who already described *intensive* state variables as the cause of a process [18], p. 210.

The following guidelines apply in line with the cause-effect principle:

- i) An intensive state variable ξ_i may have a local gradient $d\xi_i/dx$ that causes a flow dX_i/dt , i.e. an exchange or transfer process in time.
- ii) An extensive state variable X_i cannot have a local gradient nor play the role of a force.
- iii) The temporal change of X_i is always the effect of a process.
- iv) dX_i/dt can be accompanied by simultaneous changes in ξ_i because state variables of a system are interconnected by equations of state.

Here, equations of state as *momentary snapshots* are to be distinguished from process equations that describe a *temporal development* and always have the same causality structure. There must be a local gradient, a spatial contradiction quasi, for a process to occur. If one ignores the cause-effect principle as described in Equation (7) and (8), one negates the laws of TD as its basis.

3.2 Application of the cause-effect principle of TD

Since a body is a macroscopic system, thermodynamics is applicable to a falling body. If we exclude side processes like heat exchange or volume work, we can describe the reversible *free fall*. Even in doing so, the free fall represents a coupled or combined process, where two extensive state variables X_i change simultaneously. Accordingly, two individual abstracted process equations have to be considered.

We interpret the process equations in line with equation (7), where ξ_i and X_i are energetically linked (cf. **Figure 2**).

Figure 2. The process thinking and the mass concept of thermodynamics.

The individual abstracted process equation, where E_{kin} of an object is changed, is:

$$W_P = \Delta E_{\text{kin}} = \int_{P_1}^{P_2} v dP = \int_{P_1}^{P_2} v d(mv) \quad (9)$$

with the *intensive* state variable velocity v , and the temporal change of the *extensive* state variable momentum P as the energetic effect of the process. Equation (9) is a mandatory consequence of equation (7).

The local gradient of v represents the *force*, i.e. the cause of W_P . If dv/dx applies, a temporal change dP/dt in momentum P occurs. This interpretation is quite analogous to the interpretation of Newtonian friction work, where the local gradient dv/dx or ∇v (shear rate) causes dP/dt , i.e. the temporal transfer of the extensive state variable P . In case of $v_1 = v_2$, no dynamic exchange process is initiated between adjacent bodies or molecules, even if they have different masses m .

The temporal change $d(mv)$ represents the *effect* of the process. Here, it is imperative that with v also m changes with time. If m would remain constant, one would have to write $mv \, dv$. However, $X_i d\zeta_i$ represents a logical impossibility. An extensive state variable X_i like the momentum $P = mv$ cannot have a local gradient and can therefore never act as force of a process. Furthermore, no *extensive* state variable X_i would change as effect of equation (9), which contradicts the cause-effect principle. Since the momentum mv is changed, not only v , we do not refer to this process equation as *acceleration work*, but as *momentum work* W_P . It becomes obvious that no displacement of an object is described by W_P .

The individual abstracted process equation, where E_{pot} of an object is changed, is called lifting work W_h . It represents a special kind of displacement work described by:

$$W_h = \Delta E_{\text{pot}} = \int_{h_1}^{h_2} F_g \, dh; \quad F_g = \dot{P} = \frac{d(mv)}{dt} \quad (10)$$

with the intensive state variable weight force F_g , and the change of the extensive state variable height h as the energetic effect of the process. F_g is expressed as *momentum flow*.

$F = \dot{P}$ that was already suggested by Newton in 1687 [1] is well established in continuum mechanics [19–21] and allows a vivid interpretation of F [22,23]. It was not until 1876 that Gustav Kirchhoff, in his mathematical treatment of a moving “material point”, introduced mass as a constant coefficient and thus coined the interpretation $F = ma$ [2]. This pragmatic definition of force as the product of constant mass and acceleration was also expressed by Ernst Mach and Gustav Hertz, accepted by Henri Poincaré and has been shown to be useful for describing motion [24]. To justify a world view, however, the definition is not sufficient, the more so as in particle accelerators no constant masses are measured. Furthermore, $F = \dot{P}$ corresponds to the thermodynamic approach that extensive state variables X_i are transferred in time and to Equation (9), where P is transferred as temporal effect. In Equation (10), the momentum P is a more elementary quantity than F_g .

In case of *free fall*, where the momentum P and the height h of a body change simultaneously, we are obliged to combine Equation (9) and (10). With the convention $\Delta h = h_2 - h_1 < 0$ as well as $dh < 0$ of TD, it follows (cf. Figure 2):

$$\delta W_P = -\delta W_h; \quad v \, dP = -F_g \, dh; \quad S, V, n = \text{const.} \quad (11)$$

The thermodynamic interpretation of W_P and W_h is listed in **Table 2** and supplemented, in order to show the analogy, by two further kinds of displacement work. It becomes obvious that each process Y has its own force and effect.

Table 2: The thermodynamic forces ξ_i and effects ΔX_i of four mechanical processes.

Process	Thermodynamic force <i>Local gradient of an intensive state variable ξ_i</i>	Thermodynamic effect <i>Temporal change of an extensive state variable X_i</i>
Momentum work W_P	velocity v	change in momentum dP
Lifting work W_h	gravitational force $F_g = \dot{P}$	change in height dh
Volume work W_V	pressure $p = \dot{P}/A$	change in volume dV
Interfacial work W_A	interface tension $\sigma = \dot{P}/L$	change in interface area dA

3.3 The mass concept $E = mc^2 + E_{\text{pot}}$ of TD

The mass concept of thermodynamics (TD) differs from that of special relativity (SR). Instead of $E = mc^2$, the first law of TD is only compatible with $E = mc^2 + E_{\text{pot}}$. This was again demonstrated by the analysis of process equations [8].

SR and TD are both understood today as an extension of mechanics. SR intends to extend mechanics in a special way at high velocities. From the energetic point of view, however, SR represents an extreme limitation of mechanics because in its assumptions E_{pot} is excluded and only uniform motion is allowed. TD in turn extends mechanics by a more realistic description of matter far from point masses and an uncompromising process thinking that includes an indication of the direction of processes.

In our previous work [7–10], we studied different mechanical, thermodynamic and quantum processes, among them isolated processes, where only E_{pot} of a body is changed e.g. by lifting, volume or spring tensioning work. Here only the relevant *spatial* extensive state variable X_i is changed reversibly, i.e. infinitely slowly, while all others $X_i \neq X_j$ are kept constant. The result of the comprehensive analysis is that mechanical potential energy E_{pot} is not ponderable. Only the following integral equations are valid for the internal energy U and the total energy E of a system:

$$U = E_0 + E_{\text{pot}} = m_0 c^2(n, S) + E_{\text{pot}}(h, V, A, \dots), \quad (12)$$

$$E = E_0(n, S) + E_{\text{kin}}(P) + E_{\text{pot}} = \underbrace{mc^2 + E_{\text{pot}}}_{\text{matter}}. \quad (13)$$

Here, the ponderable energy amounts E_0 and E_{kin} are functions of the amount of substance n , the entropy S and the momentum P . The *non-ponderable* mechanical potential energy E_{pot} , by contrast, is a function of *spatial* variables X_i such as height h in a gravitational field, volume V , and interface area A . Since more properties of matter are energetically relevant than mass, this was called *energy-matter equivalence* [8]. If this result suggests that SR undervalues the energetic relevance of *spatial* state variables X_i in addition to mass, one should keep in mind that $E = mc^2$ was concluded from a theory that excludes E_{pot} a priori.

3.4 Application of $E = mc^2 + E_{\text{pot}}$

Considering Equation (9), the momentum P , not only v , is changed in momentum work W_P , where E_{kin} is added. This is consistent with the experimental fact that elementary particles such as electrons or protons change their mass *in real terms* in particle accelerators. Accordingly, the mass m of any object increases in real terms by means of W_P :

$$E = f(P); \quad E_{\text{kin},2} > E_{\text{kin},1}; \quad \Delta m = m_2 - m_1 > 0. \quad (14)$$

Considering Equation (10), F_g causes lifting work W_h . The energetic effect of the decreasing potential energy E_{pot} , however, manifests itself in Δh . Since E_{pot} is only released, if the extensive *spatial* state variable h decreases, h represents an independent energetic property of an object in addition to m . If we consider merely the change in E_{pot} by lifting work, it follows:

$$E = f(h); \quad E_{\text{pot},2} < E_{\text{pot},1}; \quad m \neq f(h); \quad m = \text{const.} \quad (15)$$

In case of free fall, where W_h and W_P are coupled, we have to combine the relations (14) and (15). On the one hand, m increases in real terms as effect of W_P . On the other hand, m does not change as effect of W_h . Thus, the total energy E of a falling object remains constant, while its mass m shows a real increase (see Figure 2):

$$E = f(h, P); \quad \Delta E = 0; \quad \Delta m > 0. \quad (16)$$

This means that the conservation of energy in free fall is *not* linked with mass conservation.

3.5 The mechanism of energy conversion in free fall

In the following, we discuss the coupled process of free fall in more detail and show that it makes a large difference whether one analyses energetic states or process equations.

Indicating the direction of change of the four relevant intensive and extensive state variables in the course of free fall, Equation (11) reads as:

$$\begin{array}{c} \uparrow \quad \uparrow \quad \uparrow \quad \downarrow \\ v \quad dP = -F_g \quad dh. \end{array} \quad (17)$$

The thermodynamic forces ζ_i , i.e. v and F_g , each increase in the progressive free fall, but do not change as *effect* of W_h and W_P . The temporal changes of the extensive state variables X_i , i.e. P and h , in contrast, are energy-relevant effects. h decreases in favor of the increasing P . In contrast to equation (1), where energies are equated, it is impossible to simply eliminate m in Equation (17). This does not mean that the equivalence of inertial mass m_i and gravitational mass m_g is denied. On the contrary: Equation (17) provides a logical explanation of why m_i and m_g *have to be equal* what we are going to show below.

If we express the forces F_g and v as temporal changes and apply the convention $dh < 0$ in both process equations, we obtain the following differential and integral forms of Equation (17):

$$\frac{dh}{dt} dP = \frac{dP}{dt} dh; \quad \frac{dh}{dt} (P_2 - P_1) = \frac{dP}{dt} (h_2 - h_1). \quad (18)$$

From the differential form in Equation (18) it becomes evident: At any given moment, the temporal effect dX_i of the one process corresponds as *local gradient* to the force of the other process. In δW_h und δW_P , the *same* state variables stand – only in different functions, which is hidden in Equation (1). The integral form shows that the structure of process equations excludes to simply reduce one variable against the other. However, the reciprocity of the forces and effects in the differential form reveals *how* energy conversion works and in which role the respective state variables act. Now it becomes obvious what energy conservation means: While both h and P *must* change with time, energy is conserved – an expression of the ever-changing *quality* of energy, while its quantity remains constant [9].

We rewrite the differential form in Equation (18) in terms of mass:

$$\boxed{\frac{dh}{dt}d(mv) = \frac{d(mv)}{dt}dh} \quad (19)$$

and realize that all state variables on the left and right sides *have to be identical at any moment*. There is only one object falling. It is logically excluded that one and the same object has different heights h or velocities v at the same moment. This means that the masses m on the left and right sides *have to be identical* at any moment, too. Since on the right stands F_g , the cause-effect-principle proves the identity of inertial and gravitational mass.

Furthermore, Equation (19) justifies an increase in mass in real terms with increasing velocity v , not an apparent one from the point of view of observers in moving inertial systems. In the progressive fall from t_1 to t_4 (cf. **Figure 3**), the mass $m(v)$ of an object increases *continuously* with time just like v increases and h decreases *continuously* with time. h , v , and m are emergent properties of matter. Matter changes its properties, while energy is conserved.

Figure 3. Continuous mass increase of an object during free fall.

Since the use of process equations in free fall reveals the dual role of state variables and shows how forces and effects of two process equations are interrelated, we can reinforce the implications of the thermodynamic view in line with energy conservation. The experimental evidence of the omnipresent phenomenon of fall confirms the following laws of nature:

1. The equivalence of inertial and gravitational mass

The equivalence of m_i and m_g is just as evident as the equality of the height h or the velocity v of *one* object on the two sides of Equation (19). During the free fall, m_i and m_g represent the same state variable m , i.e. they *must be equal*. Here, m_i and m_g are not “two different kinds of mass”, but there is only *one mass* that acts in two different roles: once it represents a part of a temporal effect, once a part of a local gradient, i.e. of a force.

2. The increase in mass with E_{kin} and the dependency of m on v

Each of the state variables in equation (19) changes with time. The process equations show that m and v are connected in both the effect of W_P and the force of W_h . If v changes, also m changes. Only if v remains constant, m remains constant, too. Mass is linked to velocity, i.e. motion.

3. The continuousness of length and time

If W_p and W_h proceed *simultaneously*, energy conversion must happen *continuously*. The double role of m , v and h in free fall requires that both the increase of m and v and the decrease of h happen *continuously*. This means that h and t cannot be quantized without violating the energy conservation:

However, to move means: to be at this place and at the same time not to be at this place; this is the continuity of space and time, - and this is what makes the movement possible at all. [25], p. 322

Energy conservation and the statements 1–3 apply to any object, even at the quantum level. Electrons not only change their mass in particle accelerators. Also, during the free fall, the mass of an electron increases *continuously* with time, whereas its total energy remains constant. In case of a falling photon ν , its energy remains constant, whereas its dynamic mass $m_\nu = h\nu/c^2$ increases *continuously* with time because the photon is *continuously* blue-shifted in real terms. The famous Pound-Rebka experiments with the effects of gravity on gamma radiation [26] thus confirm the above derived laws.

At this point it should be added that the *free* fall is still an idealization. In reality, not only two but further extensive state variables X_i of an object can change simultaneously during falling, what has to be described by further coupled process equations. In case of bodies, deformation work, compression work, interfacial work, and last but not least *heat exchange* can be abstracted, where the 2nd law of thermodynamics needs to be considered. Also, in case of elementary particles, which do not represent “material points” but spatially extended entities, further properties beside h , v and m change during falling.

The kinematic thought experiments of special relativity (SR) have led to the idea of ignoring the 1st and 2nd laws of TD at quantum level and also at cosmological level. For instance, in quantum mechanics, violations of the conservation of energy are considered allowed for the very short-term quantum fluctuations from the vacuum. General relativity (GR) conflicts with energy conservation (see next section) and contains no notion of irreversibility, although GR is a macroscopic theory. These readings are tolerated today because mechanics is assumed to be more fundamental than thermodynamics and became the basis of the worldview, at least since the acceptance of SR.

4. **Difficulties to demonstrate energy conservation in free fall with other theories**

In physics textbooks, the conservation of energy in free fall is demonstrated by means of $m/2 \cdot v^2 = mgh$. The application of Newtonian mechanics is well-tried, but hides the underlying laws of nature and the fact that the principle of energy conservation cannot be demonstrated with the theories that are considered fundamental in theoretical physics and on which the standard models are based.

Due to its restrictive assumptions, special relativity (SR) is a priori not applicable to free fall. Today, one grants a great deal of confidence credit to a kinematic thought experiment if one considers the heuristic statement $E = mc^2$ and the relative, symmetric time of SR as valid for free fall. One gives preference to

- i) the mass concept of SR that contradicts the 1th law of TD and has led to a “confusion which surrounds the definition of the key term in dynamics – mass” [15], and
- ii) the time concept of SR that contradicts the 2nd law of TD (absolute, asymmetric time) and has led to “the confusion of different meanings of the word time.” [27], p. 83

In the following, we discuss that also the theory of general relativity (GR) [28,29] is unsuitable for demonstrating the conservation of energy during free fall. Before we begin in concrete terms, let us make a few general remarks to GR, which today is considered the leading theory of gravity and is often attested beauty and elegance. We would like to note that beautiful equations and symmetry principles can miss reality if they are combined with idealizing and ambiguous concepts. On the one hand, it is correct that in GR a curved spacetime was added in order to abandon the assumption of empty space within SR and to substitute the classic gravitational field. On the other hand, spacetime was inserted afterwards and by maintaining ideas of SR such as $E = mc^2$, point masses, complete separability, and relative time (each of which contradicts thermodynamics).

The result is that general relativity is an indeterminate theory, open to interpretation, which does not commit itself and, because of its conceptual ambiguities, cannot be committed. Just as SR is conceptually vague because, as a kinematic theory, it claims to be able to describe dynamic changes of matter, the concept of spacetime is vague. Spacetime can be interpreted purely metric/geometric, purely substantial or with many gradations between these two extremes, where all variants coexist today without being able to prefer one of them [30,31]:

The fusion of relativity theory and quantum mechanics resulted in a new world view in which matter has lost its central role. Its place is now taken by principles of symmetry, some of which, in the present state of the universe, are beyond our sight. [32]

“Imagine the Earth as if it were immersed in honey. As the planet rotated its axis and orbited the Sun, the honey around it would warp and swirl, and it's the same with space and time”, said Francis Everitt, a Stanford physicist and principal investigator for Gravity Probe B. [33]

From the interpretational openness of the energy-momentum tensor $T_{\alpha\beta}$ in GR and the multiplicity of the possible energy and symmetry conditions result the many different representations of $T_{\alpha\beta}$ in the textbooks, which again are all allowed to coexist without a unique solution of Einstein’s equations being found so far [34,35]. It is well-known that scientists have been fiddling about how to deal with E_{pot} in the GR for more than 100 years. The common approaches exclude that $T_{\alpha\beta}$, which is interpreted as “Source of Gravity” [35], includes gravitational energy E_{pot} , as has been widely debated by Richard Feynman, Roger Penrose, and others:

Let us return to the question of the mass/energy in the gravitational field itself. Although there is no room for such a thing in the energy–momentum tensor T , it is clear that there are situations where a “disembodied” gravitational energy is actually playing a physical role. [14], p. 464

[...] it does not describe the energy-momentum of the gravitational field itself, a more mysterious and elusive quantity [35], p. 198

[...] within GRT, there is no tensor characteristics of the energy-momentum for the gravity field [36], p. 7

In attempting to pin down general relativity to unambiguous statements, we will limit our discussion of the conservation of energy in free fall to the following simple conceptional statements of GR on energy and mass:

- i) GR is a *field theory* that postulates a field/spacetime next to moved masses. The separation of matter (moving masses) and field/spacetime becomes clear e.g. in animations when spacetime is deformed by masses. Furthermore, only this separation allows the idea to quantize spacetime by gravitons, which represent energy (gauge bosons) *beside* the matter particles.
- ii) The field is assumed to possess its own gravitational field energy E_{pot} . The gravitational energy E_{pot} is interpreted as “disembodied” and cannot be included in the energy-momentum tensor $T_{\alpha\beta}$ of GR, even if this was tried [14,34–36].
- iii) The gravitational field energy E_{pot} is assumed to be ponderable according to $E = mc^2$ just like any kind of energy, as is today unanimously accepted in the whole modern physics and like Roger Penrose describes:

Imagine two planets [...]. If (a) they are far apart, then the (Newtonian) negative potential energy contribution is not so great as (b) when they are close together. Thus the total energy (and hence the total mass of the whole system) is larger in case (a) than in case (b) [...]. [14], p. 465

Summarizing these statements, we describe the ponderable disembodied gravitational field energy by:

$$E_{\text{pot}} = m_{\text{field}} c^2 \quad (20)$$

and discuss on basis of equation (20) the free fall of a body as illustrated in **Figure 4**.

Figure 4. Disembodied ponderable gravitational field energy E_{pot} in GR.

We consider a two-body system consisting of the Earth with mass M and a body with mass m . The meaning of positional energy E_{pot} *that a body has* is abandoned. Instead, disembodied ponderable E_{pot} is located between the Earth and the body.

At t_1 and height h , the body ($E_{\text{kin}} = 0$) starts to fall. At t_2 , shortly before hitting the Earth ($h = 0$), E_{kin} becomes maximal and E_{pot} minimal. Already here the problem occurs: E_{kin} belongs to the body and increases during the fall. If E_{pot} would not belong to the body, but would be *disembodied*, the total energy E of the falling body would increase. One might argue that the body may collect or absorb something like “negative” E_{pot} during its fall from the

widely distributed field energy between body and Earth. This idea does not improve the situation and is not free of vagueness und logical breaks:

1. If the body would collect E_{pot} from the outside in order to convert it into E_{kin} , then an *exchange* process would have to be described before the *internal* conversion process. The mechanism of collecting E_{pot} remains completely in the dark. How does the body manage to collect the widely distributed field energy in order to convert it afterwards into E_{kin} ?
2. A transport process of energy E_{pot} from the field into the body needs time. Accordingly, free fall and energy conversion could not happen simultaneously.
3. In $mgh = m/2 \cdot v^2$ of mechanics and in $v \, d(mv) = -F_g \, dh$ of thermodynamics, E_{pot} and the mass m of a body are embodied. Instead in GR, one would have to postulate a conversion of disembodied E_{pot} into embodied E_{kin} according to $m_{\text{field}}c^2 = m/2 \cdot v^2$, i.e. a disembodied mass m_{field} would have to be able to create the whole embodied inertial mass m . This is real logical contradiction, not to mention that then the equivalence of inertial and heavy mass could not be shown.

If E_{pot} does not belong to the body, $E = \text{const.}$ for a falling body can neither be imagined nor demonstrated. Of course, energy conservation can still be *claimed* for the whole two bodies – field system [14], but it cannot be shown by analyzing the process of free fall. One simply says, it is valid in the whole system. This is a helpless excuse because the task is to *show* that energy conversion applies during processes. Because today the different theories of modern physics are not compatible with each other, it has become a pragmatic habit to always apply that theory to a specific problem that fits best. And yet, there is only one nature. Mechanics and thermodynamics are able to show energy conservation in free fall. Should not the leading theory of gravity be able to show it as well?

In line with energy conservation, we can reinforce the implications of the thermodynamic view: Since GR has adopted $E = mc^2$ of SR, which contradicts the 1st law of TD (energy conservation), GR must contradict it, too. There is a reason why the many attempts to include E_{pot} in the energy-momentum tensor $T_{\alpha\beta}$ have failed for 100 years: E_{pot} is not ponderable and not missing in $T_{\alpha\beta}$. Whereas E_{pot} is related to the position, only E_0 and E_{kin} are ponderable and related to the mass (cf. Equation (13)). E_0 and E_{kin} are included in $T_{\alpha\beta}$. This explains why $T_{\alpha\beta}$ works so well: No mass is missing in $T_{\alpha\beta}$, i.e. the force effect towards other bodies can be described quite well. However, just as m , the gravitational energy E_{pot} is embodied and $T_{\alpha\beta}$ describes the *direct* dynamic force effect of massive objects on bodies, light, etc., as already Steven Weinberg assessed:

It simply doesn't matter whether we ascribe these predictions to the physical effect of gravitational fields on the motion of planets and photons or to a curvature of space and time. [37], p. 147

The above implies that also approaches of quantum gravity or quantum field theories with separate field energy are a priori unsuitable to demonstrate the conservation of energy in free fall. Conceptual ambiguities and internal inconsistencies in theories cannot be eliminated by sophisticated mathematics. For historical reasons, the undervaluation of process equations and the overvaluation of equations of state and symmetry principles has led to many acausal and antirealistic theories in higher-dimensional spacetimes. A return to the becoming in nature and

a clarification of the basic concepts would point the way to a causal and realistic physics, which can not only describe the phenomena in the micro- and macrocosm, but also explain them in Euclidean space.

5. Conclusion

Since nature is characterized by processes, process equations are the key to a deeper understanding of reality. Our analysis of free fall shows that a consistent process thinking is superior to the state thinking of mechanics. The application of thermodynamics, i.e. a systematic use of the cause-relation principle in process equations and of the equation $E = mc^2 + E_{\text{pot}}$, allows to reveal the mechanism of energy conversion during free fall.

The free fall demonstrates the following facts to be valid without limitation:

Energy is a conservation quantity.
Inertial and gravitational mass are equivalent.
Mass is linked to velocity. The real mass of any object increases with its velocity.
Time and space are continuous.

This implies that theories violating these statements, even if minimally or at the smallest time scales, do not represent ultimately valid descriptions of nature.

The laws of nature confirmed by free fall are in full agreement with experience, logically consistent and convince by their unambiguity. The confusion concerning the interpretation of the observer-dependent mass $m(v)$ within SR is eliminated. It becomes explainable why the decades-long search for a quantization of the spacetime of GR has to remain in vain. Gravitational energy E_{pot} is *positional energy of an object* in the full sense of the word: E_{pot} is not ponderable and belongs to the object.

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