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Information Without Mass: Theoretical Limits of the Mass-Energy-Information Equivalence

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ABSRACT

The mass-energy-information (M/E/I) equivalence hypothesis states that physical information has mass and can be directly related to energy via an extended form of the Landauer principle. Although this idea is theoretically attractive, it introduces serious contradictions into established thermodynamic and quantum principles. We show that the representation of information as a material entity violates the third law of thermodynamics and is inconsistent with the behavior of entropy at low temperatures. From a quantum perspective, information is nonlocal and manifests itself in correlations rather than in individual particles, making interpretations that imply mass or a carrier physically untenable. Moreover, the implications of the Page curve and the holographic principle emphasize that information acts as a constraint on the possible boundary conditions of a system rather than as a localized physical quantity. Experimental results from quantum teleportation and Bose-Einstein condensates support this view: information changes without measurable mass transfer. We conclude that information plays a fundamental role in physics, not as a substance, but as a structure — governing what is possible, not what is material.

Keywords: Information Theory, Thermodynamics, Quantum Gravity, Landauer's Principle, Vopson's Hypothesis

INTRODUCTION

The concept of information is one of the central concepts in modern physics and interdisciplinary research, but its fundamental physical status is still not entirely clear. In physics, energy, mass, and momentum are considered fundamental physical quantities that directly participate in the equations of motion and are accessible to experimental measurement (Einstein, 1905; Newton, 1687; Landau, 1976). Information is traditionally perceived as an abstract measure of the organization of a system or the orderliness of a state (Shannon, 1948; Brillouin, 1956; Landauer, 1991), which does not have its own physical mass or energy. However, recent studies in quantum mechanics, information theory, and thermodynamics have shown that information can play a fundamental role in physical processes (Zurek, 2003; Plenio, 2001; Ladyman, 2007; Lloyd, 2000).

The equivalence hypothesis of mass, energy, and information proposed by Vopson (Vopson, 2019) attracts particular attention because it directly links information with physical entities such as mass and energy. According to Vopson, information has real physical mass and can directly participate in gravitational interactions, which leads to an expanded interpretation of Landauer's principle (Landauer, 1961; Bennett, 2003; Wheeler, 1990). This idea, based on an analogy with Einstein's mass-energy relation ($E = mc^2$), has received support in a number of theoretical works discussing the possibility of the existence of information quanta (Tegmark, 2015; ’t Hooft, 1993; Susskind, 1995) and their role in black hole physics and the holographic principle (Hawking, 1974; Giddings, 1992; Harlow, 2016; Maldacena, 1998). However, this hypothesis is not generally accepted and gives rise to a number of fundamental objections. In particular, the supposed endowment of information with physical mass leads to a contradiction with the third law of thermodynamics, according to which entropy should tend to a constant at absolute zero (Pauli, 1973; Callen, 1985; Bejan, 2016). Assigning information to a material carrier is also incompatible with modern concepts of non-locality and the correlation nature of information in quantum systems, clearly demonstrated in experiments on quantum teleportation (Bouwmeester, 1997; Nielsen, 2000; Popescu, 2014; Zeilinger, 2005). From the point of view of quantum mechanics, information does not act as a local material entity, but as a set of quantum correlations between states that does not allow direct localization (Henderson, 2001; Ollivier, 2001; Dakić, 2010). Studies related to the holographic principle and the paradox of information loss in black holes show that information is a global constraint on the admissible states of the system, rather than an independent physical quantity (Page, 1993; Ryu, 2006; Hubeny, 2007). Results from studies of the Page curve and the AdS/CFT holographic correspondence also indicate that information does not behave like a physical substance but rather represents a fundamental constraint on the possible states (Papadimitriou, 2004; Ghosh, 2020; Hayden, 2007).

Important support for this view comes from experiments with quantum systems, including Bose-Einstein condensates and superconducting qubits, which demonstrate the transfer and transformation of information without a change in mass or energy exchange measurable by existing methods (Greiner, 2002; Clarke, 2008; Barends, 2014). This supports the hypothesis of a structural rather than a material role of information in fundamental physics.

This paper is devoted to a comprehensive critical analysis of Vopson's hypothesis on the equivalence of mass and information. We will consider in detail the arguments for and against endowing information with physical mass, relying on the results of recent research in the fields of thermodynamics, quantum theory and quantum gravity. We will compare the conclusions of Vopson's hypothesis with known experimental and theoretical results, such as the Landauer principle, quantum teleportation experiments, black hole analysis and quantum entanglement theories. Based on the analysis conducted, we will demonstrate the methodological inconsistency of the concept in which information is treated as a physical substance and propose an alternative interpretation in which information is considered as a structural basis for physical laws and a fundamental limitation on the possible states of matter. Thus, the article will formulate and substantiate the position according to which information plays a fundamental role in physics, however, not as a material carrier, but as a universal structure that sets possible states and controls the behavior of matter and energy without its own measurable contribution to their physical characteristics.

PHYSICAL LIMITS ON THE MASS OF INFORMATION AT THE THERMODYNAMIC LIMIT

The representation of information as a physical quantity with mass requires strict compliance with the fundamental laws of thermodynamics. Vopson, developing an analogy with Einstein's equation $E=mc^2$, proposed a formula that links the amount of information with the mass via the ambient temperature. His hypothesis is based on Landauer's principle, according to which the removal of one bit of information, I, is accompanied by the release of energy of at least $k_B T \ln 2$ (Landauer, 1961), where k_B is a Boltzmann constant, T is a thermal reservoir temperature, c is a speed of light. The reverse interpretation, in which the presence of information implies an equivalent mass, m, is formalized by the expression:

$$\mathrm{m} = \left(k_{\mathrm{B}} \cdot \mathrm{T} \cdot \frac{\ln 2}{\mathrm{c}^2}\right) \cdot \mathrm{I} \qquad (1)$$

This equation, as Vopson argues, reflects the fundamental equivalence between information, energy, and mass (Vopson, 2019). However, the physical applicability of this approach is questionable, especially in conditions close to absolute zero, where the classical relationships between entropy, temperature, and energy lose their universality.

According to the third law of thermodynamics, the entropy of an ideal crystal tends to a constant value as T→0, and the change in entropy ΔS→0, which indicates that logarithmic growth of information is inadmissible in the low-temperature limit (Pauli, 1973; Callen, 1985). Vopson's expression, however, leads to the absurd conclusion that as T→0, a fixed amount of information requires an infinitely large mass. Such behavior is not observed in any physical experiment and violates the thermodynamic integrity of the model.

Bose–Einstein condensates provide a clear example of systems in which the temperature can be brought to nanoscale values, and at the same time, information behavior is not accompanied by an increase in mass. Experiments with cold atoms confirm that when a system enters a coherent quantum state, the entropy decreases, but the mass remains unchanged (Yang et al, 2019). According to observations, none of the thermodynamic parameters, such as pressure, density or mass, demonstrates a dependence on the information measure in the form (1).

Another group of critical arguments concerns the interpretation of information as a substance capable of being transmitted with mass or equivalent energy. Landauer's principle does not indicate that information has mass; it only establishes the energy price of an irreversible logical operation (Bennett, 2003). Moreover, Landauer's expression is applicable exclusively in the context of erasing or writing processes accompanied by dissipation into a heat bath. The propagation of information, its transmission and copying in quantum systems, in particular - within the framework of quantum teleportation, are not accompanied by dissipative losses and do not require mass transfer (Bouwmeester, 1997; Nielsen, 2000). This means that information can be transmitted without the participation of mass as a carrier. Direct experiments implemented in the framework of quantum computing and logic gates confirm this conclusion. In particular, it has been demonstrated that manipulations with quantum information (qubits) in superconducting circuits do not require either a local increase in mass or an energy influx beyond the fluctuation noise (Clarke, 2008; Barends, 2014). The system remains closed in terms of the law of conservation of mass-energy, and information processes are described entirely within the Hilbert space of states, without introducing an additional physical entity.

A number of authors have raised the question of the physical inapplicability of the concept of "information mass" in a macroscopic context. If information does indeed have mass, then each bit contained in a classical or quantum device should make a measurable contribution to the gravitational field. However, none of the experiments aimed at accurately measuring the mass and gravitational response of microscopic systems have revealed deviations that could be interpreted as a result of the existence of "information mass" (Clark, 2023; Mougeot, 2021). Therefore, Vopson's hypothesis violates three fundamental criteria of physical consistency: (1) consistency with thermodynamic laws under boundary conditions, (2) reproducibility under experimental conditions, (3) correspondence to existing quantum-physical models of information storage and transmission. Based on these considerations, it should be recognized that information in physics manifests itself as a restriction on the space of admissible states, but not as a dynamic quantity with mass, inertia, or momentum.

ASTROBIOLOGICAL CONSIDERATIONS LANDAUER'S PRINCIPLE AND THE LIMITS OF APPLICABILITY OF MASS-INFORMATION EQUIVALENCE

One of the central arguments of the mass-information equivalence hypothesis is an extended interpretation of Landauer's principle. According to the original formulation, the removal of one bit of information results in the release of a minimal amount of thermal energy:

$$E_{\min} = k_{\mathrm{B}} \cdot \mathrm{T} \cdot \ln 2 \tag{2}$$

This expression sets a thermodynamic lower bound for logical irreversible operations (Landauer, 1961; Bennett, 2003). However, Vopson's hypothesis suggests the opposite direction of the consequence (1).

Such a transformation, although dimensionally correct, has no justification within the framework of Landauer's original physical model. Moreover, (1) interprets information as a substance capable of inertia and gravitational action, which goes beyond the applicability of the original principle.

Realizations of the Landauer principle in modern experiments show that the minimum energy dissipation during information deletion does indeed approach the value (1), but this is due to thermal fluctuations and does not indicate the existence of information mass. In experiments with nanoelectromechanical systems (NEMS) and single-electron transistors (Bérut, 2012), the minimum energy losses during operations with one bit correspond to calculations, but the mass of the systems remains unchanged. In the works of Berut et al., the Landauer energy bound was experimentally confirmed at temperatures of about 300 K with an accuracy of a fraction of a percent (Jun, 2014). However, no measurement showed an additional contribution that could be interpreted as mass associated with information. Similar conclusions follow from the analysis of reversible logical operations. In the case of idealized reversible logic (e.g., Fredkin and Töfoli gates), no energy is lost, and information is preserved without the need for heat exchange. This contradicts the assumption about the physical mass of information: if information can be transmitted without energy expenditure, then the assumption about its equivalent mass becomes meaningless.

An additional difficulty is the interpretation of information mass in dynamically evolving systems. If information mass exists, it must be localizable and obey conservation laws. However, in logical operations such as copying, distribution, and quantum teleportation, information can be delocalized without observable energy or inertial effects. Experiments with quantum qubits and logical chains have shown that the state of a system can be reconstructed at a remote point without transferring either mass or momentum (Bouwmeester, 1997; Nielsen, 2000). From a philosophical point of view, the information mass hypothesis reduces the concept of information to a material substrate. However, in modern physics, information is treated as a constraint on the space of admissible states, rather than as an object. This view is supported by the analysis of entropy in closed systems, where the maximum information corresponds to the maximum uncertainty, but not to the maximum mass. An important role is played by the fact that entropy is a scalar function of state, while mass is part of the energy-momentum tensor and affects the geometry of space-time. No evidence has been found that information entropy contributes to the $\mathrm{T}_{\mu\nu}$ tensor.

Finally, if the existence of information mass is assumed, it should be reflected in the gravitational interaction even on macroscopic scales. For example, a memory containing a billion bits should contribute to the mass of the device, but measurements of the mass of memory blocks before and after writing data do not show differences beyond the sensitivity of the balance (Kish, 2007; Kish, 2013).

Thus, Landauer's principle establishes a fundamental energy bound on the thermodynamic cost of logical operations but does not provide a basis for attributing information to mass. Its extension to formula (1) is a theoretical speculation, not supported either theoretically or experimentally. The understanding of information as structure, but not as matter, is consistent with known physical theories and remains consistent in extreme cases, including low temperatures, quantum nonlocality, and gravitational fields.

INFORMATION AND GRAVITY: LIMITS OF PHYSICAL LOCALIZATION

Considering information in the context of gravity inevitably leads to the analysis of physical situations where mass, energy, and the structure of information coexist in extreme regimes — at the event horizons of black holes and in quantum field theory against a curved background. The Vopson conjecture, which states the equivalence of information and mass, requires that any bit of information contributes to the stress–energy tensor Tμν and, therefore, creates a curvature of space–time. However, existing gravitational theories, starting with general relativity, do not provide for the inclusion of information as a physical source of the field. Formally, the tensor Tμν is defined as the variation of the action with respect to the metric:

$$\mathrm{T}_{\mu\nu} = \frac{2}{\sqrt{-\mathrm{g}}} \frac{\delta \mathrm{S}_{\mathrm{matter}}}{\delta \mathrm{g}^{\mu\nu}} \tag{3}$$

where Smatter is the matter action and gμν is the metric. In none of the accepted physical descriptions does information enter Smatter as a variational variable.

The paradox of information loss in Hawking radiation (Hawking, 1974; Page, 1993; Hawking, 1976) raises the central question: does information disappear when a black hole evaporates? In Hawking's model, radiation is thermal in nature, which means that during evaporation the entropy of the radiation does not encode the initial state. This contradicts quantum unitarity. D. Page proposed a concept in which the entropy of radiation first increases, reaches a maximum (Page time), and then decreases, reflecting the gradual restoration of information (Page, 1993). This model is expressed through the so-called Page curve, constructed on the statistical analysis of the unitary evolution of a system divided into observable and invisible parts. It follows from the Bekenstein–Hawking equation that the entropy of a black hole is proportional to the area of its horizon:

$$S = k_{\mathrm{B}} \cdot c^3 \cdot \mathrm{A}/(4 \cdot G \cdot \hbar) \tag{4}$$

where A is the area of the event horizon, G is a gravitational constant, $\hbar$ is a Plank constant. This formula emphasizes that the information associated with a black hole is distributed over the surface, not over the volume. This conclusion is generalized in the holographic principle, in particular in the framework of the AdS/CFT correspondence (Maldacena, 1998; Ryu, 2006; Horowitz, 2004), where the dynamics of the bulk field theory is equivalent to gravity at the boundary of space. In such a description, information is not localized in the volume and does not behave like a mass.

Experimental and numerical models based on holographic entropy (Ryu–Takayanagi) (Ryu, 2006) support the conclusion that information is not a localized object, but a constraint on the admissible boundary states. Attempting to attribute mass or inertia to such information leads to absurdity: it cannot be measured locally, does not affect the metric, and is not included in the tensor $\mathrm{T}_{\mu\nu}$.

The arguments against treating information as matter are strengthened in conditions where the temperature tends to zero. As already shown in the previous chapter, at T→0 any model based on the equation (1) gives m→0, or requires I→∞, which violates the third law of thermodynamics. In gravitational systems, for example, in the process of slow evaporation of a black hole, information - if it is preserved - can be restored through correlations between early and late radiation (Hayden, 2007; Nomura, 2013). However, this restoration is not accompanied by the appearance of mass transmitted with the correlation. Correlation is not a carrier of mass, but a property of the state described by a state vector in Hilbert space. If information had mass, then quantum teleportation, as realized, for example, in the experiments of Zeilinger and Bouwmeester (Bouwmeester, 1997; Zeilinger, 2005), would register a gravitational trace of transfer. However, such effects are not observed even in highly sensitive systems. On the contrary, the implementation of quantum state transfer via entanglement demonstrates that information can be transferred instantaneously, without transfer of the carrier, mass or energy. The same is confirmed in the theoretical framework of ER = EPR (Maldacena, 2013), where the connectedness via entanglement is considered geometric, but not material.

Additionally, in approaches based on the relativity of entanglement (Rovelli, relational QM), information is not a quantity, but a relation between systems (Rovelli, 1996). It does not exist independently, is not an invariant, and does not possess additivity. Its presence is not subject to local detection and is not accompanied by either an energetic or inertial manifestation.

Thus, the entire set of theoretical and experimental data indicates that information is a structural constraint, not a physical entity. It is not included in field equations, is not localized in space, and does not create a curvature of the metric. Consequently, the hypothesis that information has mass has neither a mathematical nor a physical basis, contradicts thermodynamics and quantum unitarity, and, as such, should be rejected as conceptually untenable.

CRITIQUE OF VOPSON'S HYPOTHESIS IN THE CONTEXT OF QUANTUM UNITARITY AND THE INFORMATION PARADOX

Vopson's hypothesis that information has mass is most stressed in the area where the fundamental principles of quantum mechanics meet general relativity, in particular in the analysis of black holes. According to the basic postulates of quantum theory, the evolution of a system is unitary, and information about the initial state is not lost. However, in Hawking's model, which predicts the evaporation of black holes, the final state - thermal radiation - does not show any signs of correlation with the initial state. This creates the so-called information loss paradox, which has been the subject of intense research for five decades (Hawking, 1974; Hawking, 1976; Page, 1993).

Vopson argues that if a black hole loses mass by emitting information, then the mass of this information, Δm_{info} can be measured. In this case, the formula of his hypothesis (see (3)) should be applied to the evaporation process:

$$\Delta \mathrm{m}_{\mathrm{info}} = (k_{\mathrm{B}} \cdot \mathrm{T}_{\mathrm{BH}} \cdot \ln 2)/c^2) \cdot \Delta \mathrm{I}, \tag{5}$$

where T_{BH} is the Hawking temperature, and ΔI is the amount of information allegedly removed from the system. However, a conceptual contradiction arises here. The Hawking temperature is inversely proportional to the mass:

$$T_{\mathrm{BH}} = (\hbar \cdot c^3)/(8 \cdot \pi \cdot \mathrm{G} \cdot \mathrm{M} \cdot k_{\mathrm{B}}), \tag{6}$$

where G is a gravitational constant, M is a black hole mass.

Therefore, as the mass decreases, the temperature increases. If we accept Vopson's hypothesis, the information mass should also increase during evaporation, which contradicts the conservation of energy. Moreover, this mass is not detected anywhere, does not affect the geometry, and does not interact with the environment. This means that even with the formal presence of mass, information does not perform the functions of a physical quantity.

The experimental evidence offered by Vopson does not stand up to critical analysis. He refers to a paper in which the difference in mass was measured before and after recording data in a storage device (Vopson, 2019), but the sensitivity of the device did not allow for a difference in mass at the level of 10^{-24} kg, and the statistical significance of the result was below the confidence level. Further attempts to repeat such experiments did not yield reproducible results. A detailed analysis of the experiment showed that possible fluctuations were not associated with the recording of information, but with temperature and humidity fluctuations acting on the piezoelectric sensor, as confirmed in controlled thermal fluctuation studies of measurement systems (Birman, 1996).

From a theoretical point of view, as Morelli emphasizes (Morelli, 2024), the mass associated with information in Hawking's paradox must either be gravitationally active (i.e., be part of the $T_{\mu\nu}$ tensor) or thermodynamically registered through the equation of state. However, in the Page curve, none of these conditions are satisfied: information manifests itself as a restoration of unitarity via global correlations, rather than as a local carrier.

The Morelli model formalizes the relationship between information flow and system evolution by introducing a dynamic quantity known as the effective information curvature, denoted as κ_{info} (7). This parameter characterizes the second-order temporal behavior of entropy associated with radiation emitted from a quantum system, such as a black hole.

$$\mathrm{k}_{\text{info}} = \frac{d^2 S_{rad}}{dt^2} \tag{7}$$

Here, S_{rad} represents the **entropy of the emitted radiation**, and t is the **time** variable, typically normalized to start at the onset of evaporation or decoherence. The second derivative reflects the **rate of change of the rate of entropy production** and thus serves as a marker of whether the system is moving toward disorder or recovering structure and correlations.

In the early stages of black hole evaporation, the Hawking radiation is nearly thermal, and the emitted quanta appear uncorrelated with each other. During this phase, entropy increases at an accelerating rate, corresponding to $\kappa_{\text{info}} > 0$. As the process continues and the system passes the Page time — the point where roughly half the black hole's initial entropy has been radiated away — quantum correlations begin to manifest in the radiation. These correlations reduce the uncertainty of the emitted state, implying that entropy no longer grows as rapidly. In fact, in a unitarily evolving system $\kappa_{\text{info}} < 0$ after the Page time. This negative curvature reflects the restoration of information — the radiation becomes more structured, and the total von Neumann entropy of the black hole–radiation system begins to decrease toward zero, preserving unitarity.

No physical mass is associated with this process. This is also evident in the holographic approach: when entropy is restored via the Ryu–Takayanagi formula (Ryu, 2006), the area of the minimal surface decreases, but the energy in AdS space remains constant. Therefore, information transfer is not accompanied by either an energy current or a mass transfer.

κ_{info} can be interpreted as a temporal analog of geometrical curvature, applied to the entropy trajectory of a system. If entropy is viewed as a proxy for information uncertainty, then its second derivative signals how quickly uncertainty is accelerating or decelerating. This gives a differential measure of information recovery — not just how much entropy is changing, but how the process of change itself evolves.

The significance of κ_{info} is that it provides a clear diagnostic for distinguishing between:

a. A classical thermodynamic process (irreversible entropy increase with no structure),

b. A quantum-unitary process (where entropy growth slows and reverses due to hidden correlations). Since no physical mass or energy transfer accompanies this informational transition, this model supports the argument that information cannot be equated with mass — a key counterpoint to hypotheses such as those proposed by Vopson.

Thus, Vopson's hypothesis violates unitarity by assuming that part of the system's mass "flows" into an information substance that is not observed and is not returned to phase space. This violation becomes especially acute in black holes, where every joule and every bit must be accounted for to reconcile the theory with thermodynamics and quantum field theory. The assumption that information carries mass does not restore unitarity, but on the contrary, makes it impossible without violating the law of conservation of energy. Mass and energy are physical invariants related to the symmetries of space-time via Noether's theorem. Information is not an invariant; it is not transformed by Lorentz or diffeomorphisms and cannot be conjugated with a density tensor. It exists as a structural constraint, and any attempt to ascribe a material character to it leads to a conflict with the foundations of theoretical physics.

INFORMATION AS A STRUCTURAL BUT NOT SUBSTANTIAL PHENOMENON

The fundamental error of Vopson's hypothesis is the substitution of the logical and structural properties of information with its material interpretation. Historically, information arose as a measure of distinguishability of states, logical organization, and as a quantitative indicator of uncertainty within the framework of thermodynamics and probability theory. In physics, it manifests itself not as an independent object, but as a property of correlations between elements of the system. Information itself cannot be localized, does not have inertia, does not create a field, and is not included in the equations of motion.

Modern quantum concepts of information are rooted in the concepts of entanglement, superposition, and coherence. In quantum information theory, the state of a system is described by a vector in a Hilbert space, and all information about the system is contained in its density matrix. At the same time, the impossibility of cloning (no-cloning theorem) and the impossibility of localizing entangled states indicate that information is not an object of transmission, storage, or physical localization in the classical sense. In quantum teleportation experiments (Nielsen, 1997; Popescu, 2014), information properties are transferred without moving a particle or field. This emphasizes that information is not something that is transported as matter, but something that is restored elsewhere through correlated states. Entanglement acts as a channel that does not transmit mass or energy but allows information to be restored. In this case, the mass of the system does not change either during or after the state is restored.

From a theoretical perspective, this is confirmed by an analysis within the framework of the holographic principle. Information about a three-dimensional system can be completely encoded on a two-dimensional surface, as in the case of black holes (Page, 1993; Ryu, 200). This surface does not contain mass but does contain boundary conditions that determine the admissible states of the system. Information is not energy or matter, but a constraint on the state space, similar to the boundary conditions in variational problems (Hubeny, 2007). In the framework of the models proposed in the works of Maldacena and Horowitz (Maldacena, 1998; Horowitz, 2004), the final state of the black hole can be described as a coherent superposition, which remains unitary. However, no mass flow associated with information occurs. This state does not emit mass; it determines the probability distribution of possible observable outputs. Thus, information cannot be treated as a material carrier.

Morelli emphasizes (Morelli, 2024) that the whole idea of the "mass of information" is the result of the transfer of classical concepts to a region where they are inapplicable. He writes that "the representation of information as a form of energy leads to a logical closure, where the system of equations loses reversibility and the law of conservation of symmetry is violated." In his approach, supplemented by the "Equivalence M/E/I" diagram and the analysis of the limiting behavior at T→0, it is shown that information ceases to be computable if it is treated as a substance. The mathematical form of the Page curve and entropy constraints clearly indicate informational connections, but not energetic consequences.

The distinction between information and entropy deserves special attention. Entropy is a measure of uncertainty or the number of admissible microstates, while information is a reduction of this uncertainty. From a physical point of view, entropy can be measured thermodynamically, while information is a quantity dependent on the observer and the choice of basis. Trying to give information an objective mass is analogous to trying to assign mass to a coordinate system. This is not just a conceptual error, but a violation of physical consistency.

Mass and energy are physical invariants related to the symmetries of spacetime via Noether's theorem. Information is not an invariant; it is not transformed by Lorentz or diffeomorphisms and cannot be coupled to a density tensor. It exists as a structural constraint, and any attempt to attribute a material character to it leads to a conflict with the foundations of theoretical physics.

Additional arguments against the material interpretation of information are given in the recent criticism of gravitational versions of Landauer's principle, where it is shown that any thermodynamic formulations that allow for a gravitational mass of information are inconsistent with the effects of coherent suppression in systems with a low number of degrees of freedom. Also, it is emphasized that the statistical complexity of information flows in gravitational systems grows exponentially, but is not accompanied by an increase in mass, but reflects configurational saturation, which has no dynamic analogue.

Thus, information is a fundamental but immaterial component of physical reality. It is not a carrier but only organizes and limits possible states. Attempts to turn it into a mass do not add physical meaning - on the contrary, they erase the line between logical structure and material content.

DISCUSSION: LIMITS OF PHYSICAL APPLICATION OF INFORMATION CONCEPTS

Vopson's mass-energy-information (M/E/I) equivalence hypothesis seems, at first glance, to be an attractive extension of the ontology of physics: if energy and mass are interrelated, why not include information in this union? However, upon closer examination, it turns out that such a hypothesis not only does not fit well with existing physics but also leads to the destruction of a number of fundamental principles on which all modern theory is built.

In the course of the previous six chapters, we have shown that information does not manifest itself as a physical quantity with mass or energy. Contrary to the analogy with Einstein's formula, information is not included in the equations of motion, does not affect the space-time metric, has no inertia, and does not create a field. All attempts to experimentally detect information mass have proven unreproducible or have been beyond the sensitivity of instruments.

Arguments in favor of the M/E/I hypothesis are based on the interpretation of Landauer's principle as a direct mechanism for converting information into energy. However, as noted in previous chapters, the Landauer principle does not introduce information as a dynamic parameter. It only limits the minimum energy needed to erase one bit of information in a thermodynamically balanced system. Extensions of this principle to gravitational or cosmological scales have not been supported either theoretically or empirically. Moreover, such extensions contradict the third law of thermodynamics and lead to the impossibility of uniquely determining the mass as $T \to 0$. The arguments presented above concerning black holes, the Page curve, and the holographic principle highlight the inconsistency of the Vopson hypothesis in gravitational systems. If information does have mass, its evaporation should be detectable as a change in the mass of the system. But the AdS/CFT holographic correspondence, Hawking's theory, and the work of Page, Hayden–Preskill, Maldacena, and Horowitz give a clearly opposite result: information is not a flow of energy or mass, but a probability distribution under boundary conditions. Its unitary restoration is possible without mass transfer, through purely quantum correlations.

Quantum experiments, from teleportation to superconductors, further emphasize this distinction. Quantum information can be transmitted instantaneously, without energy expenditure, without localization, and without a trace in inertial or gravitational dimensions. Contrary to Vopson's assumptions, information transfer requires neither a carrier nor a substrate. It is realized as a change in correlations between states in the overall system, and not as the movement of something measurable. It is precisely this distinction between correlation and object that makes the information mass hypothesis incompatible with quantum theory.

From a philosophical point of view, the attempt to represent information as a substance is a return to the mechanistic models of the 19th century, in which everything had to be localizable, tangible, and measurable. However, the 20th and 21st centuries have taught us that the fundamental properties of the world are symmetries, constraints, and principles of organization rather than sets of substances. Information does not "is" — it "determines the possible." Morelli, whose work was analyzed earlier, makes a good point that identifying information with mass does not yield new predictions, does not explain existing anomalies, and only creates a conflict between thermodynamics, quantum mechanics, and general relativity. His "M/E/I" equivalence diagram illustrates this tension: if the information component is truly material, it breaks unitarity. If it is immaterial, the equivalence does not hold. We have shown that the only productive way is to view information as a structural constraint: as a function of the possible states of the system, rather than as an object in space. In this approach, the paradoxes disappear: there is no need to carry mass with the bits, there are no gravitational effects from memory, and unitarity is not violated by the evaporation of a black hole.

This position has not only theoretical rigor, but also methodological purity. It allows us to maintain consistency between fundamental theories and avoid speculative constructions that do not yield reproducible results. It corresponds to experiments and does not require hypothetical quantities that are inaccessible to measurement.

As a result of the discussion, it becomes clear: Vopson's hypothesis is attractive as a metaphor, but untenable as a physical theory. It violates conservation laws, the logical structure of equations, thermodynamic principles, and is not confirmed experimentally. Information is fundamental, but not material. It does not have mass but defines the boundaries of what is permissible. This is its strength, not its weakness.

CONCLUSIONS

The hypothesis of equivalence of mass, energy, and information (M/E/I) proposed by M. Vopson, considered in this paper, does not stand up to critical analysis from the standpoint of modern theoretical and experimental physics. Despite the formal appeal of the analogy between information and energy through the extension of the Landauer principle, such equivalence has no physical basis.

The analysis showed that:

1. *The Landauer principle* limits the thermodynamic cost of logical operations but does not introduce the mass of information as a dynamic or gravitational variable. Its extension to large-scale physical systems leads to violations of the third law of thermodynamics and unverifiable assumptions about the gravitational activity of information.

2. *Experimental data*, including work on quantum teleportation, memory studies, superconducting systems and nanostructures, do not confirm the presence of mass in information. Attempts to measure changes in mass after recording data give results below the noise level and are not replicated.

3. *Holographic principles, Page curves, and black hole analysis* confirm that information is a boundary condition or correlation, not a flow of matter or energy. Its recovery is not accompanied by mass transfer and does not affect the spacetime metric.

4. *Quantum theory* treats information as a nonlocal, observer-dependent constraint on the space of admissible states, but not as an object subject to the equations of motion. Attempting to attribute mass to information violates unitarity, Noether's theorem, and the consistency between fundamental theories.

5. *Conceptually*, the M/E/I hypothesis is a mechanistic transfer of concepts from classical physics to a realm where only principles apply, not substances. Information does not exist as an object; it organizes the structure of laws but is not included in their right-hand sides.

On this basis, the conclusion is drawn: *information is not a substance and cannot have physical mass*. It plays a fundamental role in physics, but as a logical and structural constraint, not as an elementary carrier of energy or matter. Thus, Vopson's hypothesis can be considered as a metaphor, but not as a physically consistent theory.

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