Mass, Energy, and the Metaphysics of Circularity

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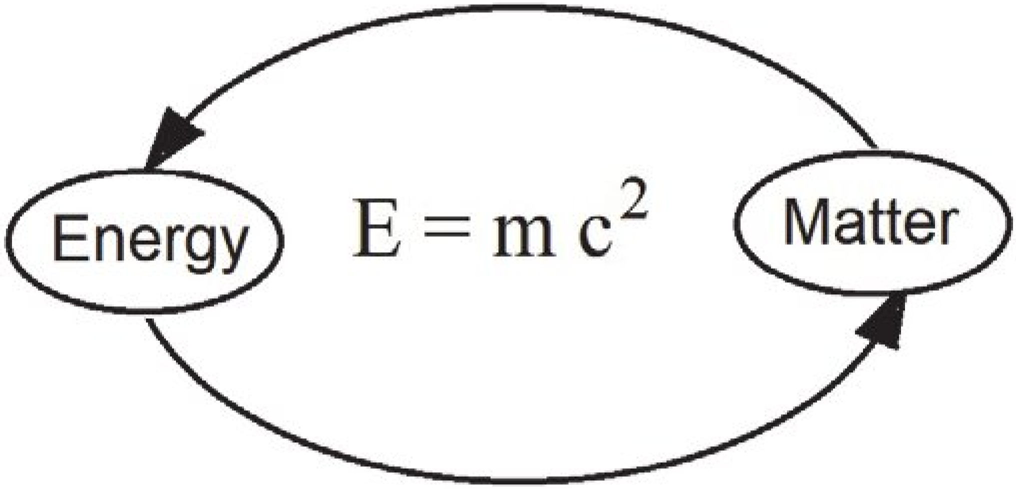

(Gieras, 2024)

1. Introduction

Mass and energy are typically presented as fundamental physical properties, unified by Einstein's celebrated equation $E = mc^2$, i.e., energy equals mass times the speed of light squared. Yet closer inspection reveals that both concepts are defined only operationally and circularly, via their roles in mathematical relations rather than by independent physical content. In this essay, we argue that modern physics does not explain what mass or energy *are*, but instead only how certain numerical invariants transform across formal systems. Consequently, mass–energy equivalence expresses not an ontological identity, but a conversion rule within a closed network of measurement conventions. This undermines realist interpretations of physical quantities and strengthens a structural-skeptical view of theoretical physics.

2. The Hidden Circularities of Physical Definition

Introductory physics textbooks present mass as the measure of inertia — resistance to acceleration under applied force. Force, in turn, is defined as that which produces acceleration: $F = ma$, i.e., force equals mass times acceleration. Acceleration is change in velocity over time, velocity is change in position, and work is force applied over distance ($W = Fd \cos \theta$). Energy is then defined as the capacity to do work. Each term is introduced as fundamental, yet none is intelligible without reference to the others.

This is not a defect of pedagogy but a structural feature of modern physics. These quantities are not grounded in prior concepts but implicitly defined together by their roles in equations. As Percy Bridgman famously argued, physical quantities acquire meaning only through operations of measurement—not through independent conceptual analysis (Bridgman, 1927). Mass means "whatever must appear in $F = ma$ for the equation to track experimental outcomes." Energy means "whatever is conserved under time-translation symmetry," as codified by Noether's theorem (Noether, 1918).

But this functionalism comes along with a significant philosophical cost. We are no longer told what mass or energy *are*, but rather only what they *do* inside formal systems. Physics becomes a theory of transformations between symbols constrained by invariance principles, not a theory of substances.

3. Mass and Energy as Operational Placeholders

Consider mass. In Newtonian mechanics, mass plays three roles: inertial mass, gravitational mass, and passive gravitational response. Empirically these coincide, but nothing in the formalism explains why (Mach, 1883; Jammer, 1961). In relativity, rest mass becomes frame-dependent energy, and in quantum field theory, mass becomes a parameter in Lagrangians whose value is fixed by renormalisation procedures rather than conceptual necessity (Weinberg, 1995).

Energy fares no better. It is introduced as "capacity to do work," but work itself is defined in terms of force and displacement, both already implicated in mass. Alternatively, energy is defined as the conserved quantity associated with time symmetry, but this too presupposes a mathematical framework rather than providing ontological insight (Noether, 1918; Lange, 2001, 2002).

Thus, both mass and energy function as structural placeholders: abstract invariants whose meaning consists entirely in how they transform across equations and experiments. They are not descriptions of intrinsic properties of matter, but nodes in a closed inferential network.

This aligns closely with the structural realist thesis that physics captures only relational form, not underlying nature (Worrall, 1989; Ladyman, 1998). But the problem here is deeper: even the *relations themselves* rest on mutually circular definitions, making the entire conceptual scheme self-supporting but metaphysically opaque.

4. What Does $E = mc^2$ Actually Assert?

Einstein's mass–energy equivalence is widely taken to express a profound metaphysical truth: that mass *is* energy. But if both quantities lack independent conceptual grounding, what could such an identity amount to?

Operationally, $E = mc^2$ tells us that when systems undergo certain transformations—nuclear decay, particle–antiparticle annihilation, and high-energy collisions—the numerical quantity previously tracked as "mass" can be re-expressed as the numerical quantity previously tracked as "energy," up to a constant factor. What it does not tell us is what mass or energy *are in themselves*.

The equation therefore asserts not identity of substances but instead the equivalence of bookkeeping measures across transformation regimes. It says: whatever you were measuring with kilograms in one context can be measured with joules in another, provided you multiply by c^2. This is a symmetry principle inside a formal calculus, not a revelation about the metaphysical furniture of the world.

Put bluntly: $E = mc^2$ does not explain what mass or energy are; it only explains how one set of symbols can replace another without loss of predictive power.

This mirrors the fate of other celebrated identities in physics. The equivalence of gravitational and inertial mass, for example, is experimentally exact but conceptually unexplained (Einstein, 1920; Jammer, 1961). It is treated as a postulate, not a derivation. Likewise, the mass–energy equivalence is an invariant constraint, not an ontological disclosure.

This interpretation is independently supported by Flores, who surveys six major philosophical readings of the mass–energy equivalence, and finds that all but one fail minimal adequacy conditions (Flores, 2005). The only viable interpretation, he argues, treats mass and energy as distinct physical quantities linked by a systematic transformation rule, rather than as identical properties or interchangeable substances. On this view, $E = mc^2$ functions only as a conversion principle governing how conserved quantities are re-expressed across interaction regimes, not as a metaphysical identification of kinds. Flores's analysis thus reinforces the conclusion that the mass–energy equivalence expresses structural invariance rather than ontological unity.

Jammer further argues that the standard derivations of the mass–energy equivalence—including Einstein's original 1905 radiation argument—tacitly presuppose the very equivalence they purport to establish (Jammer, 1961). Conservation principles and relativistic transformation laws embedding energy–

momentum relations are introduced prior to the conclusion, rendering the derivations conceptually circular. Even where mathematically valid, such derivations function as consistency proofs internal to an already interdependent formal framework rather than as explanations of what mass or energy are.

Jammer begins where we have: inertial mass is classically defined as the proportionality constant in $F = ma$, but force is routinely defined via the acceleration it produces on a mass. Textbook authors who stipulate the existence of "mass-independent" (nongravitational) force commit the sin of smuggling mass back in, yielding either circularity or explaining the unknown by appealing to the unknown: *ignotum per ignotius*. Attempts to ground mass in density (volume × density) merely defer the problem—density presupposes mass. Jammer traces this definitional quagmire through centuries: no non-circular, logically independent anchor exists.

This infects energy too. Defined as "capacity to do work," work loops back through force and displacement, both mass-implicated. Noether's theorem elevates energy to the conserved quantity under time-translation invariance; but the symmetry framework itself presupposes the dynamical laws containing mass. The entire edifice is self-supporting but self-referential: mass and energy derive meaning solely from mutual interrelations and measurement protocols (Bridgman operationalism). Jammer stresses that even "effective mass" in condensed matter or QFT—arising from particle-medium interactions (Higgs field couplings and vacuum fluctuations)—renders mass relational and context-dependent, not intrinsic. "Bare mass" becomes a hypothetical, unobservable artifact; what we measure is always dressed up by environment.

Jammer hammers the weak equivalence principle (inertial ≈ gravitational mass) as empirically impeccable yet conceptually opaque—a postulate Einstein elevated to axiom in GRT, not derived. Why these masses coincide remains unexplained; it's simply a brute fact layered beneath $E=mc^2$. In relativity, rest mass becomes frame-dependent energy, but Jammer questions whether relativistic mass is even legitimate or if rest mass retains classical primacy. The equation inherits these unresolved equivalences: it builds atop unexplained coincidences, not resolving them.

Jammer's most lethal argument lies in his critical dissection of mass-energy derivations, especially in Einstein's 1905 paper ("Does the Inertia of a Body Depend Upon Its Energy Content?"). Echoing Herbert Ives and others, Jammer argues the original thought experiment—radiation emission from a body at rest—suffers circular reasoning: kinematic transformations and energy-momentum relations implicitly embed the very equivalence the derivation claims to prove (Ives, 1952). Einstein assumes conservation laws and relativistic postulates that already presuppose mass-energy links, then "derives" what was smuggled in. Ives called it *petitio principii*; and

Jammer reiterates the logical flaw, noting Einstein's setup introduces relations tantamount to $L/(m - m')c^2 = 1$—precisely what needs proving.

Later proofs (full relativity, and Noether-based) avoid vicious circularity but inherit the operational circularity: they formalize transformations within the interdependent framework without independent grounding. Jammer analyzes conflicting interpretations—$E=mc^2$ as ontological identity vs. mere conversion rule—and finds neither metaphysically satisfying. The equation predicts nuclear yields spectacularly, but its derivations rest on assumptions critics deem question-begging or incomplete: for example, Newtonian limits for extended bodies, and velocity dependencies.

In Quantum Field Theory and beyond, mass emerges dynamically, as per the Higgs mechanism: interaction energies, not intrinsic stuff. In GRT, global energy-mass isn't conserved due to spacetime curvature—no universal time-translation. At Planck scales, classical notions likely evaporate. Jammer's critical analysis of "effective" vs. "bare" mass underscores the point that observable inertia is always contaminated by fields/vacuum; intrinsic mass is theoretical fiction. $E=mc^2$ holds in its own domain as a powerful constraint, but offers zero insight where foundations fracture.

5. Against the Ontology of Quantities

The deeper issue is that modern physics has abandoned ontological definition in favour of implicit axiomatisation. As Hilbert showed in geometry, one can define "point," "line," and "plane" entirely by their relations without specifying what they actually are (Hilbert, 1899). Physics has followed the same path: mass, energy, force, and momentum are defined solely by their algebraic interrelations and experimental roles. But unlike geometry, physics is often misread as describing real properties rather than formal invariants. This encourages a Rylean category mistake: treating operational placeholders as metaphysical substances.

From a skeptical perspective, this is unwarranted. What physics gives us is not ontology but constraint structure—rules governing how measurement outcomes covary under transformations. That this structure supports astonishingly accurate prediction does not license the inference that its primitives correspond to intelligible physical essences.

Indeed, the circularity of physical definitions suggests the opposite. If mass is defined via force, force via acceleration, acceleration via motion, motion via time, and time via dynamical laws containing mass, then the system has no conceptual anchor outside itself. It is self-consistent, but also strictly self-referential.

This echoes the finitist critique of real analysis in mathematics: consistency and applicability do not entail ontological grounding (Wildberger, 2005). Just as real numbers function impeccably inside calculus despite lacking coherent construction, so too mass and energy function impeccably inside physics despite lacking independently intelligible definition.

6. Structural Success Without Ontological Clarity

None of this undermines the predictive success of physics. But it does undermine a common philosophical narrative: that modern physics has revealed the deep nature of matter by identifying mass with energy, matter with spacetime curvature, and particles with field excitations.

What it has revealed instead is something subtler and more austere: a web of transformation laws linking measurement outcomes across experimental contexts. The power of physics lies not in what it says things *are*, but in what it says quantities *must do* if the equations are to hold.

Seen this way, mass–energy equivalence is not a metaphysical discovery but a conversion theorem: two conserved measures previously treated as distinct can be exchanged without disturbing the formal structure of the theory.

This is not realism about physical properties; it is realism about equations.

7. Conclusion: Equal to What?

If mass and energy are circularly defined operational quantities, then the question "What are they?" admits no substantive answer beyond "whatever satisfies these equations." And if so, then $E = mc^2$ does not assert an identity between intelligible physical properties but an equivalence between formal invariants.

Equal to what?

Equal to each other—and to nothing beyond the system of relations that defines them.

Modern physics, on this view, is not wrong. It is simply not metaphysics. It delivers structure without substance, invariance without essence, and astonishing predictive power without ontological disclosure. Whether that is a feature or a limitation depends on whether one expects science to describe the world—or merely to calculate it.

REFERENCES

(Bridgman, 1927). Bridgman, P. W. *The Logic of Modern Physics*. New York: Macmillan.

(Einstein, 1920). Einstein, A. *Relativity: The Special and General Theory*. New York: Henry Holt.

(Flores, 2005). Flores, F. "Interpretations of Einstein's Equation $E = mc^2$." *International Studies in the Philosophy of Science* 19, 3: 245-260.

(Gieras, 2024). Gieras, J.F. "Equations of Physics That Have Most Important Impact on Electromechanical Engineering." *PRZEGLĄD ELEKTROTECHNICZNY* 1, 1: 3-10. Figure 4. Available online at URL = <https://www.researchgate.net/publication/377864620_Equations_of_physics_that_have_most_important_impact_on_electromechanical_engineering>.

(Hilbert, 1899). Hilbert, D. *Grundlagen der Geometrie*. Leipzig: Teubner.

(Ives, 1952). Ives, H.E. "Derivation of the Mass-Energy Relation." *Journal of the Optical Society of America* 42, 8: 540–543.

(Jammer, 1961). Jammer, M. *Concepts of Mass in Classical and Modern Physics*. Cambridge MA: Harvard Univ. Press.

(Ladyman, 1998). Ladyman, J. "What is Structural Realism?" *Studies in History and Philosophy of Science* 29, 3: 409–424.

(Lange, 2001). Lange, M. "The Most Famous Equation." *Journal of Philosophy* 98: 219-238.

(Lange, 2002). Lange, M. *An Introduction to the Philosophy of Physics: Locality, Fields, Energy, and Mass*. Oxford: Blackwell.

(Mach, 1883). Mach, E. *Die Mechanik in ihrer Entwicklung historisch-kritisch dargestellt*. Leipzig: Brockhaus.

(Noether, 1918). Noether, E. "Invariante Variationsprobleme." *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen*. Pp. 235–257.

(Weinberg, 1995). Weinberg, S. *The Quantum Theory of Fields, Vol. I*. Cambridge: Cambridge Univ. Press.

(Wildberger, 2005). Wildberger, N.J. *Divine Proportions: Rational Trigonometry to Universal Geometry*. Sydney: Wild Egg Books.

(Worrall, 1989). Worrall, J. “Structural Realism: The Best of Both Worlds?” *Dialectica* 43, 1–2: 99–124.