

Energy: A Conserved Account, Not a Substance

IDE-001 · Fundamental Ideas

Concept essays for The Universe and Its Observers

Author: Juan Segurolo

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Article Abstract

Energy is one of science's most powerful unifying quantities, but everyday language easily turns it into a misleading substance. This essay examines what physicists and chemists actually mean by energy: a calculable property of a specified system whose changes can be tracked through motion, configuration, radiation, internal degrees of freedom and mass. It distinguishes stored state quantities from transfers such as work and heat, explains why conservation depends on drawing the system boundary correctly, and shows how Noether's theorem links conserved energy to time-translation symmetry. It then marks two important limits. Conserved energy does not imply that all energy is equally available for useful change, and general relativity does not supply a unique, universally applicable global energy for arbitrary spacetimes. The result is a concept that unifies many descriptions without becoming a material fluid or a universal substance.

In 60 Seconds

Energy is not a stuff that hides inside objects and flows as identical little parcels. It is a physical quantity that different theories calculate in different but mutually compatible ways. A moving object can contribute kinetic energy; a system's configuration can contribute potential energy; matter has internal energy; radiation carries energy; mass itself contributes to relativistic energy. Work and heat are better treated as ways energy crosses a chosen system boundary, not as substances stored inside it. The conservation law works only after the system and its interactions are specified. Mechanical energy alone can decrease through friction while the broader energy account remains balanced because internal energy rises. Noether's theorem gives a deeper structural reason for conservation in many physical theories: invariance under shifts in time is associated with a conserved energy. But the slogan has boundaries. Entropy constrains how energy can be used, and in curved, evolving spacetime a single

global total energy need not be definable. Energy is therefore a disciplined accounting concept with extraordinary reach, not a universal fluid.

Why This Question Matters

Energy appears in almost every scientific story: falling stones, chemical reactions, stars, batteries, metabolism and the expansion of the Universe. That breadth makes it tempting to treat the word as if it named one hidden material. Doing so creates persistent confusions: heat becomes something an object 'contains', friction seems to destroy energy, ATP becomes an energy packet, and cosmological redshift looks like energy disappearing into nowhere. A careful definition does more than tidy vocabulary. It tells us what must be measured, which boundary has been chosen, what quantity is conserved, and when the familiar conservation slogan needs qualification.

1. A number that survives change

Energy earns its importance by surviving transformations in a precisely constrained sense. In elementary mechanics, kinetic and potential terms can trade against one another. In thermodynamics, internal energy changes when energy crosses a boundary by heat or work. In electromagnetic and quantum descriptions, fields and quanta carry energy. Relativity links a body's mass to its energy content. These are not rival definitions attached to unrelated substances. They are domain-specific ways of calculating contributions to a common accounting structure.[1,7-9]

That is why the familiar list of 'forms of energy' can mislead. The useful idea is not that energy repeatedly changes costume while remaining a microscopic material. The useful idea is that different state variables and dynamical terms contribute to a quantity whose changes obey exact relations. Feynman's famous block analogy captures the bookkeeping but also its limitation: the conserved number is real as a physical constraint even when no single picture shows what all its contributions 'look like'.[1,7]

The SI reinforces this abstraction. Energy, work and amount of heat are measured in joules, the coherent derived unit $\text{kg m}^2 \text{s}^{-2}$. [5] Sharing a unit does not make them the same kind of concept. A state quantity can describe a system at an instant; a transfer quantity describes a process across a boundary. The equation and the experimental procedure decide which is meant, not the unit alone.

Where That Leaves Us

Energy is best treated as a calculable quantity constrained across transformations, not as a material ingredient. Different theories expose different contributions, while the joule provides a common unit. The next step is therefore not to ask where energy 'really sits', but to ask which system has been defined and which terms belong in its account.[1,5,7,8]

2. The system boundary does the hidden work

Conservation statements are always statements about a system. Drop a ball through air and its mechanical energy does not remain exactly constant: drag reduces the ball's kinetic-plus-gravitational-potential account. Enlarge the system to include the air, the ball and their microscopic degrees of freedom, and the apparent loss reappears chiefly as internal energy and motion in the surroundings. Nothing mystical was recovered. The bookkeeping changed because the boundary changed.[8]

This is one reason 'potential energy belongs to the object' is often a poor sentence. Gravitational potential energy near Earth is naturally assigned to the configuration of the Earth-object system; elastic potential energy belongs to a deformed system; electrostatic potential energy belongs to a configuration of charges and fields. In many calculations we assign terms to a convenient subsystem, but the assignment is partly a modelling choice. Observable predictions remain invariant when the bookkeeping is transformed consistently.[14]

The same discipline matters in chemistry and biology. A reaction vessel, a cell and an ecosystem exchange matter and energy with their surroundings in different ways. Before saying energy was produced, consumed, stored or wasted, the analyst must declare the boundary and the variables retained. Many verbal paradoxes disappear at that point.[8]

Where That Leaves Us

An energy balance is never boundary-free. Apparent creation or destruction often signals that the chosen account omitted a transfer, an interaction or internal degrees of freedom. This makes system definition part of the physics rather than clerical setup, and it prepares the distinction between energy a system has and energy that crosses its boundary.[8]

3. Heat and work are transfers, not stored fluids

Thermodynamics sharpens the distinction. Internal energy is a state function: once the thermodynamic state is fixed, its value does not depend on the path by which the state was reached. Heat and work, by contrast, describe transfers during a process. IUPAC defines heat as energy transferred because of a temperature difference, while mechanical work can be represented by the force-displacement integral.[3,4] A body can have internal energy; it is usually misleading to say that it 'contains heat' in the same technical sense.

The first law connects them. With the sign convention in which work done on the system is positive, $\Delta U = q + w$. Other disciplines sometimes adopt the opposite sign for work, so the sign convention must be stated. What does not change is the structural claim: a change in the system's stored energy is related to energy transferred across its boundary.[2]

This vocabulary also clarifies friction. Friction does not violate energy conservation.[8] It redirects organized mechanical energy into less organized microscopic motion and other internal degrees of freedom. That distinction becomes crucial when we ask not merely how much energy exists but how much can drive a specified change.

Where That Leaves Us

Internal energy characterizes a state; heat and work characterize transfers. Conflating them creates the false image of heat as a substance and makes friction look destructive. Once state and transfer are separated, the first law becomes an accounting relation rather than a story about invisible fluids. That distinction prepares the next question: why should such balances be conserved at all?[2]

4. Conservation is deeper than a useful trick

In many physical theories, energy conservation is tied to a symmetry. Noether's first theorem shows that continuous symmetries of an action correspond to conserved quantities. When the laws governing a closed system do not change under a shift of the time coordinate, the associated

conserved quantity is energy. Spatial translation is similarly associated with momentum, and rotational symmetry with angular momentum.[6]

This result does not mean that every school-level statement of energy conservation requires solving a variational problem. It explains why conservation laws are structurally embedded in large classes of modern theories. It also prevents a common overstatement: 'energy is conserved because time exists'. The relevant condition is not the mere existence of time but a specific invariance of the dynamics under time translations.[6]

The theorem also reveals why defining the system still matters. If an explicitly time-dependent external influence acts on a subsystem, that subsystem's energy need not be conserved. The larger theory may possess a conserved quantity once the external degrees of freedom are included, but conservation does not license us to ignore what we have left outside the model.

Where That Leaves Us

Noether's theorem links energy conservation to time-translation symmetry in variational theories.[6] That is stronger and more precise than saying energy is conserved 'by definition'. It also exposes the boundary of the claim: an open or explicitly time-dependent subsystem need not carry a conserved energy by itself. The next step is to see how that structure survives when relativity and quanta enlarge the account.

5. Mass, light and the widening of the account

Special relativity enlarged the classical energy account. A massive body at rest has rest energy $E_0 = mc^2$, while its total relativistic energy includes motion as well.[1] This does not mean mass is a separate substance that can be poured into energy. Mass and energy are related properties of a physical system,[9] and changes in binding energy can alter the mass of a composite system.

Light carries energy even though photons have zero rest mass. For a photon, $E = h\nu$, so frequency is directly related to energy. Radiation can therefore transfer energy and momentum, heat matter, drive transitions and exert pressure. The classical image in which energy must belong to massive particles is too narrow.[1,15]

The broader lesson is methodological. Each extension of physics preserved the accounting role while changing which terms had to be included. Conservation survived by becoming more comprehensive, not by forcing new phenomena into an old mechanical picture.[1,7,9,15]

Where That Leaves Us

Relativity and quantum physics did not abolish energy; they enlarged what counts in the balance. Rest mass contributes energy, while massless radiation carries energy through its frequency. The durable feature is the conservation structure, not any one classical picture of what the contributing terms must be. That widening raises a different question: even when total energy balances, how much remains available to do useful work?[1,15]

6. Conserved does not mean available

If energy is conserved, why can a battery run down, a hot drink cool, or a machine become unable to do further work? Because the amount of energy and the capacity to drive a particular process

are different questions.[7] The second law of thermodynamics constrains spontaneous change through entropy, the quantity whose change IUPAC defines as the heat brought to a system in a reversible process at constant temperature, divided by that temperature.[12] Thermodynamic potentials such as Gibbs energy, defined as enthalpy minus the product of thermodynamic temperature and entropy,[13] are constructed for specified environmental constraints.

A room-temperature ocean contains immense internal energy, but a device in equilibrium with that same ocean cannot turn all of it into directed work without other changes.[7] Conversely, a modest energy difference maintained across a gradient can be highly effective because it is organized relative to the process that can exploit it. This is the point at which the language of 'high-energy' and 'low-energy' becomes context dependent.

The article stops short of a full treatment of entropy. The essential boundary here is simply that conservation answers how an energy account balances, whereas thermodynamics asks which transformations are possible, in which direction, and with what available driving capacity.

Where That Leaves Us

Energy conservation does not guarantee usefulness. Entropy and thermodynamic constraints determine how readily energy differences can drive change. This prevents a major conceptual error: a process can conserve total energy perfectly while irreversibly reducing the fraction that can be converted into a desired form of work. The final boundary is geometric: what becomes of the slogan when spacetime itself is dynamical?[7]

7. The cosmological boundary of the slogan

The strongest caution arrives in general relativity. Matter is described by a stress-energy tensor whose covariant divergence vanishes, expressing a local conservation structure. But curved spacetime complicates the idea of a unique gravitational energy density, and a single globally conserved total energy is not available in every spacetime. Global energy definitions work cleanly only under additional geometric conditions, such as appropriate symmetries or asymptotic structure.[10,11]

This matters in cosmology. In an expanding Friedmann-Lemaître-Robertson-Walker universe, photon wavelengths stretch and their measured energies decrease. Asking 'where did that energy go?' assumes in advance that the whole evolving universe possesses the same kind of global conserved scalar familiar from time-translation-invariant laboratory systems. General relativity does not generally provide that object.[10,11] The local equations remain consistent; the global bookkeeping intuition has been pushed beyond its domain.

This is not evidence that energy conservation is approximate or optional. It is evidence that conservation laws have mathematical conditions. A slogan learned from isolated systems in nearly flat spacetime should not be promoted into a stronger theorem than the theory itself supplies.
[10,11]

Where That Leaves Us

General relativity preserves local energy-momentum structure but does not guarantee a unique globally conserved energy for arbitrary spacetimes.[10,11] Cosmological redshift therefore cannot be understood

safely by demanding a missing global energy reservoir. The boundary condition is part of the law, not an embarrassment added after the fact. That boundary sets the final synthesis: separate the robust accounting principle from the conditions under which global conservation can be stated.

What We Know, and How

- Energy is a quantitatively defined property used across mechanics, thermodynamics, electromagnetism, quantum physics and relativity.[1,5,7]
- Experiments and theory support exact balance relations when the system and relevant transfers are specified.[8]
- Heat and work are process quantities; internal energy is a state quantity.
- Noether's theorem connects time-translation invariance with a conserved energy in variational theories.[6]
- Special relativity requires rest energy and relativistic contributions to be included, and radiation carries energy.[1,15]
- Conservation alone does not determine how much energy is available for useful work.[7]
- General relativity preserves local energy-momentum structure but does not provide one unique global energy in every spacetime.[10,11]

What We Still Don't Know

- How best to define gravitational energy quasi-locally in general relativity, and which of the available definitions is most useful in a given spacetime.[10,11]
- How future quantum-gravity frameworks will connect their conserved quantities to the familiar low-energy descriptions.
- None of this is an unresolved empirical question about whether ordinary closed-system energy balances work within their tested domains. These questions do not weaken the laboratory conservation laws; they mark where the concept meets the structure of spacetime itself.[10,11]

What Could Change Our Minds

- A reproducible failure of energy accounting in a genuinely isolated system, after all known particles, fields, radiation and boundary transfers were included, would force a major revision.[6]
- Evidence that a time-translation-invariant fundamental theory systematically lacked the corresponding conserved quantity, under conditions where Noether's assumptions apply, would do the same.[6]
- In gravitation, a new fundamental framework could change which global or quasi-local energy definitions are preferred, but it would have to recover the extremely successful local and weak-gravity limits already measured.[10,11]

If You Remember Only One Thing

Energy is a conserved accounting quantity whose meaning depends on the system and theory; it is not a substance, and global conservation has geometric limits.

Related Articles

- IDE-003 — Entropy
- IDE-005 — Symmetry
- IDE-022 — Mass

References

- [1] International Union of Pure and Applied Chemistry. Energy. Gold Book, 5th ed. (2025). DOI 10.1351/goldbook.E02101.
- [2] International Union of Pure and Applied Chemistry. Internal energy. Gold Book, 5th ed. (2025). DOI 10.1351/goldbook.I03103.
- [3] International Union of Pure and Applied Chemistry. Heat. Gold Book, 5th ed. (2025). DOI 10.1351/goldbook.H02752.
- [4] International Union of Pure and Applied Chemistry. Work. Gold Book, 5th ed. (2025). DOI 10.1351/goldbook.W06684.
- [5] Bureau International des Poids et Mesures. The International System of Units (SI), 9th edition, updated 2026. DOI 10.59161/AUEZ1291.
- [6] Emmy Noether. Invariant Variation Problems. English translation by M. A. Tavel. Transport Theory and Statistical Physics 1, 186-207 (1971). DOI 10.1080/00411457108231446.
- [7] Richard P. Feynman; Robert B. Leighton; Matthew Sands. The Feynman Lectures on Physics, New Millennium Edition, Vol. I, chapter 4 (Conservation of Energy). Basic Books, ISBN 978-0-465-02414-8.
- [8] William Moebs; Samuel J. Ling; Jeff Sanny. University Physics Volume 1, section 8.3 (conservation of energy). OpenStax (2016).
- [9] Albert Einstein. Does the Inertia of a Body Depend Upon Its Energy-Content? Annalen der Physik 18, 639-641 (1905). DOI 10.1002/andp.19053231314.
- [10] László B. Szabados. Quasi-Local Energy-Momentum and Angular Momentum in General Relativity. Living Reviews in Relativity 12, 4 (2009). DOI 10.12942/lrr-2009-4.
- [11] Patrick M. Dürr. Fantastic Beasts and where (not) to find them: Local gravitational energy and energy conservation in general relativity. Studies in History and Philosophy of Modern Physics 65, 1-14 (2019). DOI 10.1016/j.shpsb.2018.07.002.
- [12] International Union of Pure and Applied Chemistry. Entropy. Gold Book, 5th ed. (2025). DOI 10.1351/goldbook.E02149.
- [13] International Union of Pure and Applied Chemistry. Gibbs energy. Gold Book, 5th ed. (2025). DOI 10.1351/goldbook.G02629.
- [14] William Moebs; Samuel J. Ling; Jeff Sanny. University Physics Volume 1, section 8.1 (potential energy of a system). OpenStax (2016).
- [15] International Union of Pure and Applied Chemistry. Photon. Gold Book, 5th ed. (2025). DOI 10.1351/goldbook.P04627.