

# Energy

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## Key Concepts

- Although energy may be most familiar in the form of mechanical work and heat transfer, the field of classical mechanics recognizes two types of energy: kinetic and potential.
- All physical processes involve either an exchange of energy or conversion of one form of energy to another.
- The unit of energy in SI units is the joule (J), defined as the force of one newton acting in the direction of the force through a distance of 1 m.
- The law of conservation of energy states that the total energy of a closed, isolated system is always constant.
- Types of energy include kinetic energy, elastic energy, surface-tension energy, potential energy, binding energy, atomic cohesive energy, nuclear energy, and electrical energy.
- Common misconceptions about energy include confusion over the nature of kinetic and potential energy, and misapplication of the concept of energy conversion.

**One of the two fundamental constituents of the universe; it is interconvertible with matter, which is the other constituent.** All physical processes involve exchange of energy, or conversion from one of its named forms (including relativistic mass-energy) into another. The total energy (including mass) of a closed system is a conserved quantity. *See also:* MATTER (PHYSICS).

## Intuitive notions

On the human scale, energy is most familiar in the form of mechanical work and transfer of heat. The word “energy” is derived from Greek meaning “inner work.” This is intuitively reasonable from the everyday notion of doing work because physical labor expends the body’s energy.

The causal relationships among energy, force, work, power, kinetic energy, potential energy, heat, and temperature are also intuitive. A person pushing a rock up a slope applies the force of his or her muscles. While the rock is in motion, it has kinetic energy (relative to the ground) that could, for example, dent a tree trunk that

might be in the rock's path. The amount of work done on the rock and on the person's body increases proportionally with the distance the rock is moved. It results in a reduction of the person's internal energy resources; hence the notion that work done and energy spent are somehow equivalent. To push the rock faster, the person must apply more power, or energy per unit time. The work done on the rock is converted into an increase of gravitational potential energy, because the rock is now higher up on the slope, and into heat energy, resulting from friction, that raises the temperature of the rock and proximate ground. The potential energy of the rock is so-named because it has the potential to be converted into other forms of energy such as kinetic energy in the event that the rock should be allowed to roll freely downhill. *See also:* FORCE; HEAT; POWER; TEMPERATURE; WORK.

## Formal and quantitative concepts

The intuitive notions of energy and its related parameters were first quantified with Newton's three laws of motion. Classical mechanics recognizes two types of energies:

1. Kinetic energy: energy due to relative motion. A mass  $m$  moving with speed  $v$  relative to an observer has kinetic energy  $T = \frac{1}{2}mv^2$ .
2. Potential energy: energy that is stored in restraining motion against forces. For example, lifting a mass  $m$  from ground level to a height  $h$  increases its gravitational potential energy by  $\Delta U = mgh$ , where  $g$  is the downward acceleration due to Earth's gravitational field. *See also:* GRAVITATION; NEWTON'S LAWS OF MOTION.

With the development of atomic and subatomic physics came understanding of new types of forces with which potential energies could be associated. The electric and magnetic forces, with their associated potentials, act on electrical charges. In the nineteenth century, they were revealed to be two manifestations of a single field called the electromagnetic field. Twentieth-century research revealed that subatomic particles interact via the so-called weak nuclear force and the strong nuclear force. *See also:* ELECTRIC FIELD; FUNDAMENTAL INTERACTIONS; MAGNETISM; MAXWELL'S EQUATIONS; STRONG NUCLEAR INTERACTIONS; WEAK NUCLEAR INTERACTIONS.

Most force fields of interest, such as gravity and electromagnetic force, are conservative. This means that taking a particle that "feels" that force, and moving it through any round trip starting at rest from any point in the field and ending at rest on the same point will require no net energy input. The particle's potential energy will be unchanged.

## Units of energy

The unit of energy in the International System of measures (SI) is the joule (J), defined as the force of one newton (N) acting in the direction of the force through a distance of 1 m. Power is the time rate of flow of energy and is measured in watts (W): 1 W of power is defined as the rate of energy flow of 1 J per second. Electrical utilities use the kilowatt-hour (kWh), the energy delivered by 1 kW over a period of 1 h; 1 kWh equals exactly  $3.600 \times 10^6$  J.

Energies of chemical interactions are often measured in kilocalories per mole, where one calorie equals 4.187 J. A kilocalorie of heat will raise the temperature of a liter of water by about one degree Celsius. *See also:* METRIC SYSTEM; PHYSICAL MEASUREMENT; UNITS OF MEASUREMENT.

In high-energy physics, subatomic-particle interactions frequently involve mass changing to quanta of radiant energy, and vice versa. Therefore, it is more convenient to express both energy and mass by the same unit of measure, the electronvolt (eV): the change in potential energy of one electron when moved through an electrical potential difference of 1 V; 1 eV equals  $1.602 \times 10^{-19}$  J. *See also:* ELECTRONVOLT.

## Law of conservation of energy

The law of conservation of energy, also known as the first law of thermodynamics, is one of the most important laws of physics. It states that the total energy of closed, isolated systems is always constant. (For relativistic velocities and nuclear reactions we speak of the conservation of mass and energy jointly.) This law is a result (according to Nöther's theorem) of the homogeneity of the universe with respect to time; that is, with all else being equal, the outcome of any experiment is independent of when it is performed. *See also:* CONSERVATION LAWS (PHYSICS); CONSERVATION OF ENERGY; SYMMETRY LAWS (PHYSICS).

Many periodic phenomena are due to the cyclic interchange between potential energy and kinetic energy, with their sum always constant. The classical example is a swinging pendulum whose potential energy is maximum at the highest part of its swing, its kinetic energy at the lowest. *See also:* PENDULUM.

## Energy and special relativity

Albert Einstein's special theory of relativity introduced the notion of mass-energy  $E = mc^2$ , where  $c$  is the speed of light. In the mass's own frame of reference, within which the mass is stationary, this formula gives the rest-mass energy. For small (nonrelativistic) velocities, the total energy approximately equals the rest-mass energy plus the term  $\frac{1}{2}mv^2$ , which is exactly the classical formula for kinetic energy. *See also:* REST MASS.

When velocities are routinely relativistic, as in high-energy physics, it is convenient to express universally true physical relations as four-vectors. The momentum four-vector, also known as the momenergy, embodies the conservation laws of both energy and momentum for all moving observers. *See also:* CONSERVATION OF MOMENTUM; MOMENTUM; RELATIVITY.

## Energy in quantum mechanics

Quantum mechanics, and its offshoot quantum field theory, are founded on the principle of the quantum, the smallest amount of energy exchangeable in a given interaction. (Linear momentum, angular momentum, and mass are also quantized.) *See also:* QUANTUM FIELD THEORY; QUANTUM MECHANICS.

One interesting property of quanta of electromagnetic radiation is that they cannot have energies of zero even in empty space. This nonzero energy is called the zero-point energy and is experimentally confirmed by the Casimir effect: two parallel, closely spaced, uncharged conducting plates in empty space will attract each other.

Mechanical energy can be observed to be quantized: vibrational energy propagating through periodic media, such as silicon crystals, does so in quanta called phonons; essentially, these are quanta of sound energy. *See also:* LATTICE VIBRATIONS; PHONON.

A second principle of quantum mechanics, Heisenberg's uncertainty principle, limits the accuracy with which energy (as well as length, velocity, time, and position) may be measured. The error  $\Delta E$  in measuring energy over a time interval  $\Delta t$  is related by the inequality  $\Delta E \Delta t \geq h/(2\pi)$ , where  $h$  is Planck's constant. One consequence is that as masses (which, of course, are equivalent to energies) are examined at ever-shorter time scales, the uncertainties in the measured values increase. For short-enough particle interactions, particle physicists can invoke virtual particles that exist only briefly during the transformation of colliding particles into postcollision products. During their putative existence, they are allowed to violate the law of conservation of energy, a paradox resolved by the fact that they are never directly observed. *See also:* PLANCK'S CONSTANT; UNCERTAINTY PRINCIPLE.

## System evolution, entropy, and the second law of thermodynamics

In a closed, isolated system with a certain distribution of energy within it there are many (usually practically uncountable) ways the energy could be redistributed. The second law of thermodynamics indicates what the ultimate distribution of energy within the system will be after a long time. It invokes the concept of entropy, a measure of the disorder within the system. Because the number of ways the water molecules can be arranged in a steam vessel is larger than the ways they can be arranged to form ice, a given quantity of water has a lower entropy as ice crystals than as steam. The second law states that a closed, isolated system will evolve over time so as to maximize the entropy. Thus, heat energy flows (if allowed) from hotter regions to colder ones, eventually equalizing the temperature. This maximizes the entropy; it also serves as an indicator of the flow of time (specifically, thermodynamic time). *See also:* ARROW OF TIME; ENTROPY; THERMODYNAMIC PRINCIPLES.

All natural processes that locally decrease the entropy increase it elsewhere. When sodium and chlorine atoms migrate in aqueous solution to form a salt crystal, their entropy is decreased. However, the heat of crystallization that is released warms the solution, thereby increasing its entropy. Similarly, the biological processes of life create order but at the expense of the surroundings: consuming food creates highly ordered tissue but increases disorder via waste products and heat.

## Types of energy

There are many types of energy that are involved in physical processes. A few of these are listed below.

Heat became understood, with the development of the atomic theory in the nineteenth century, as a manifestation of the collective kinetic energy of atoms in bulk materials. Temperature is a measure of their average kinetic energy. In solids, the motions are confined to vibrations of the atoms about equilibrium positions. In gases, the energy is equally partitioned into linear flight (between collisions), rotations, and vibration modes of the molecules. *See also:* KINETIC THEORY OF MATTER; STATISTICAL MECHANICS.

Elastic energy is potential energy stored when solids are deformed by various kinds of strains, such as compression or torsion. It is due to dislocation of the constituent atoms of the solid from their “relaxed” minimum-energy configurations. *See also:* ELASTICITY.

Surface-tension energy, which is responsible for the spherical shape of droplets, is the potential energy stored in the tangential cohesive forces between molecules at the surface of a liquid. *See also:* SURFACE TENSION.

The field of chemistry involves various kinds of forces, often expressed in terms of potential energies. Some are the ion-ion force, the van der Waals force, and the dipole-dipole force. The binding energy of a covalent or other bond between two atoms of a molecule is the energy required to pull them apart. Atomic cohesive energy is the energy required to separate the atoms of a solid far enough that they no longer feel cohesive forces. *See also:* CHEMICAL BONDING; COHESION (PHYSICS); DIPOLE-DIPOLE INTERACTION; INTERMOLECULAR FORCES.

Burning is a process of oxidation that converts fuel plus oxygen into combustion products. The total binding energy of the fuel plus air is larger than of smoke plus ash, and the difference is emitted as light and heat. Energy to power biological processes is stored in the binding energies of biomolecules such as adenosine triphosphate (ATP). This energy is also released through oxidation processes such as the Krebs cycle. *See also:* ADENOSINE TRIPHOSPHATE (ATP); BIOLOGICAL OXIDATION; CITRIC ACID CYCLE; COMBUSTION; METABOLISM.

Bending, stretching, and twisting of molecular bonds store and release energy. Analysis of molecules by infrared spectroscopy uses the fact that the various distortions of the bonds have telltale resonance frequencies. *See also:* INFRARED SPECTROSCOPY; MOLECULAR STRUCTURE AND SPECTRA.

The shapes that molecules assume are those that minimize the total potential energy due to the forces among their constituent atoms. This simple driving principle yields surprisingly complex configurations in proteins. Deoxyribonucleic acid (DNA) codes for the one-dimensional sequence of amino acids, sometimes thousands of units long. These spontaneously crumple, by shedding potential energy, into precise and unique three-dimensional configurations that determine their highly specific biological functions. Predicting the ultimate shape of a given amino-acid chain is called the protein-folding problem, which has not yet been solved. *See also:* DEOXYRIBONUCLEIC ACID (DNA); PROTEIN; PROTEIN FOLDING.

Nuclear energy results from release of binding energies of atomic nuclei, orders of magnitude larger than the binding energies among molecules. For example, solar nuclear fusion combines pairs of deuterium nuclei into single nuclei of helium having a smaller binding energy and the difference is released as heat. The binding-energy

differences are large enough to be evident as a conversion of mass to energy. Much of the mass of nucleons is due to the binding energies confining the quarks that comprise them. Chemical reactions, too, result in changes of mass, but generally too small in magnitude to be measurable. *See also:* ELEMENTARY PARTICLE; NUCLEAR BINDING ENERGY; NUCLEAR FUSION; PROTON-PROTON CHAIN; QUARKS.

## Energy as a commodity

The production of electricity and its consumption illustrate how energy can go through many forms.

The energy in the coal burned in a power plant originated during the Earth's Carboniferous Period, 300 million years ago. Various plants' chlorophyll used the Sun's energy to convert rainwater and airborne carbon dioxide (CO<sub>2</sub>) to produce plant tissue, mainly cellulose and other polysaccharides. The Sun's radiation also powered the meteorological processes that brought water from the oceans to growth regions. Over subsequent eons, the energies of geological processes, such as the folding of tectonic plates, concentrated the carbon content through prolonged heat and pressure. This resulted in the fossil fuels, of which coal has the highest carbon content. *See also:* CARBONIFEROUS; CHLOROPHYLL; COAL; FOSSIL FUEL; PHOTOSYNTHESIS.

In one type of power plant, coal is burned to heat water in boilers (thereby also sending the carbon back into the atmosphere as CO<sub>2</sub>). The heat converts water to high-pressure steam that is passed to steam turbines where the potential energy of steam pressure is converted to kinetic energy of the turbines. They are coupled mechanically to the electric generators in which conductive metal windings are moved relative to a magnetic field. This results in electromotive force (emf) that results in electrical power flowing out of the generators. The electrical energy is passed to the power grid, which distributes it to the power plant's customers. *See also:* ELECTRIC POWER GENERATION; ELECTRIC POWER SYSTEMS; ELECTROMOTIVE FORCE (EMF); GENERATOR.

In the home, the electrical energy undergoes various conversions depending on its use. A few examples are heat energy in electric ranges, radiant energy (light) in lamps, kinetic energy in motorized appliances, and chemical energy in the recharging of batteries. After performing its desired functions, most of the energy will have been dissipated as heat. *See also:* BATTERY; FLUORESCENT LAMP; INCANDESCENT LAMP; MOTOR.

## Potential misconceptions

Some common ways of discussing matters related to energy could be misleading.

Energy utilities are often described as "producing" energy. In fact, they are only converting one form of energy into another.

We speak of an object as "gaining potential energy" when raised from a lower level to a higher one. Thus, a porcelain vase lifted from a tile floor to a tabletop is said to have a certain amount of potential energy. However, this energy does not reside in the vase as the words imply; rather, it resides in the new spatial relationship

between the vase and the Earth's gravitational field. The energy of the configuration of vase plus floor is evident when the vase falls and shatters on the floor.

Similarly, an object's kinetic energy is an attribute not of the object alone but of its mass and the reference frame used. Thus, a speeding car has no kinetic energy relative to the driver, but relative to a pedestrian it has a deadly amount.

## Energy and cosmology

A few minutes after the big bang, the universe was uniformly filled with baryonic matter, mostly hydrogen and helium. Unlike a closed system of gas, however, this configuration did not represent maximum entropy and therefore stability—gravitational attraction among the atoms caused them to clump into stars. Those that exploded as supernovae generated the full range of the natural elements that made planets and life possible. The thermonuclear energy radiating from our Sun is therefore a direct result of gravity, and the Sun's radiated energy powers the entropy-lowering processes of life. *See also:* BIG BANG THEORY; SUPERNOVA.

Observations of star and galaxy dynamics imply that only 4% of the mass of the universe is visible baryonic matter. The other 96% is hypothesized to be composed of invisible dark matter (23%) and dark energy (73%). Since dark matter has mass, it represents a huge part of the universe's total energy budget. *See also:* DARK MATTER.

Dark energy may be partly due to the cosmological constant in Einstein's field equation for gravity that accounts for the expansion of the universe. Such energy could explain the recent evidence that the expansion of the universe is accelerating. Pressure itself, if large enough, can contribute to gravitational force, as occurs when stars collapse into black holes. The dark energy, however, can generate negative pressure, that is, tension, that would account for the acceleration. *See also:* ACCELERATING UNIVERSE; BLACK HOLE; COSMOLOGICAL CONSTANT; COSMOLOGY; DARK ENERGY.

## Search for the “true” nature of energy

Although energy flow and transformations can be accurately measured and calculated, the true nature of energy—its essence, or what it is in the ontological sense—is not known. To define energy in terms of work, as is often done, does not help since work itself is defined in terms of energy transferred.

Understanding of energy's true nature will likely come from a successor to the standard model that will reconcile quantum mechanics with general relativity. In doing so, it will likely have to be valid for all stages of the evolution of the universe, including the very moment of the big bang itself at “time zero” where current theory breaks down. *See also:* STANDARD MODEL.

Interestingly, the two main lines of research to solve this conundrum are founded on the conflicting world views of Isaac Newton and Gottfried Wilhelm Leibniz, archrival founders of classical mechanics. String theory posits

that the superstrings, of which subatomic particles are composed, exist in a fixed frame of time and space (Newton's thesis). In contrast, loop quantum gravity is based on background independence, a concept that does away with absolute space and time (Leibniz's thesis). It also yields the radical implication that spacetime itself must be quantized. *See also:* SUPERSTRING THEORY.

Energy, in the form of fire and the natural forces of nature, baffled and amazed prehistoric peoples. It is remarkable that thousands of years later energy is still a key part of the mystery of existence.

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## Keywords

energy; kinetic energy; potential energy; power; conservation of energy; entropy; heat; elastic energy; dark energy; nuclear energy

## Test Your Understanding

1. What is potential energy? Give an example of a situation in which an object has potential energy.
2. Why is heat energy considered to be a form of kinetic energy?
3. What is entropy? What does the second law of thermodynamics tell us about entropy?
4. Critical Thinking: Suppose a child rides a bicycle near a tree. Why is there a difference in kinetic energy between the bicycle and the tree, but there is no observed kinetic energy difference between the bicycle and rider?
5. Critical Thinking: Describe the main energy conversions that occur during and after a rocket launch.

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