Energy

Unit: Energy, Work & Power

NGSS Standards/MA Curriculum Frameworks (2016): HS-PS3-1

AP® Physics 1 Learning Objectives/Essential Knowledge (2024): 3.1.A, 3.1.A.1, 3.1.A.2, 3.1.A.3, 3.3.A, 3.3.A.1, 3.3.A.2, 3.3.A.3, 3.3.A.4, 3.3.A.4.i, 3.3.A.4.ii, 3.3.A.4.iii, 3.3.A.5

Mastery Objective(s): (Students will be able to…)

- Calculate the gravitational potential energy of an object.
- Calculate the kinetic energy of an object.

Success Criteria:

- Correct equation(s) are chosen for the situation.
- Variables are correctly identified and substituted correctly into equation(s).
- Algebra is correct and rounding to appropriate number of significant figures is reasonable.

Language Objectives:

- Explain when & why an object has potential energy.
- Explain when & why an object has kinetic energy.

Tier 2 Vocabulary: work, energy

Labs, Activities & Demonstrations:

- "Happy" and "sad" balls.
- Popper.

Notes:

energy: the ability to cause macroscopic objects or microscopic particles to increase their velocity; or their ability to increase their velocity due to the effects of a force field.

If we apply mechanical energy to a physical object, the object will either move faster (think of pushing a cart), heat up, or have the ability to suddenly move when we let go of it (think of stretching a rubber band).

Energy is a scalar quantity, meaning that it does not have a direction. Energy can be transferred from one object (or collection of objects) to another.

Energy is a "conserved" quantity in physics, which means it cannot be created or destroyed, only changed in form.*

Energy is measured in joules (J):

$$1\,\text{J} \equiv 1\,\text{N}\cdot\text{m} \equiv 1\,\frac{\text{kg}\cdot\text{m}^2}{\text{s}^2}$$

* More properly, the combination of mass and energy is conserved. Einstein's equation states the equivalence between mass and energy: $E = mc^2$.

Kinetic Energy

Because energy is a conserved quantity, if energy is used to cause a macroscopic object to increase its velocity, that energy is then contained within the moving object. We call this energy "kinetic energy", and the amount of kinetic energy that an object has is related to its mass and velocity. An object has translational kinetic energy (the kinetic energy of an object or system that is moving in the *xy* plane or *xyz* space) if its center of mass is moving. Translational kinetic energy is given by the equation:*

$$K = \frac{1}{2} m v^2$$

Note that a single object can have kinetic energy. An entire system can also have kinetic energy if the center of mass of the system is moving (has nonzero mass and nonzero velocity).

The above equation is for translational kinetic energy only. Kinetic energy also exists in rotating systems; an object can have rotational kinetic energy whether or not its center of mass is moving. *Rotational Kinetic Energy* will be discussed in a later topic, starting on page 445.

Potential Energy

Potential energy is "stored" energy due to an object's position, properties, and/or forces acting on the object that have the ability to cause it to move. Potential energy is also energy that is available to be turned into some other form, such as kinetic energy, internal (thermal) energy, *etc.*

Potential Energy from Force Fields

Potential energy can be caused by the action of a force field. (Recall that a force field is a region in which an object experiences a force because of some property of that object.) Some fields that can cause an object to have potential energy include:

- gravitational field (or "gravity field"): a force field in which an object experiences a force because of (and proportional to) its mass. (See page 278 for more information.)
- electric field: a force field in which an object experiences a force because of (and proportional to) its electric charge.

* In these notes, K without a subscript is assumed to be translational kinetic energy. In problems involving both translational and rotational kinetic energy, translational kinetic energy will be denoted as K_t and rotational kinetic energy as K_r.

Potential Energy from Forces that are not Fields

Potential energy can also come from non-field-related sources. Some examples include:

- gravitational force: two (or more) objects that exert gravitational attraction on each other are separated. When the objects are released and allowed to come together, the potential energy due to the separation becomes kinetic energy of one or more of the objects.
- springs: an object that is attached to a spring that has been stretched or compressed has potential energy. When the spring is released and allowed to move, the potential energy stored in the spring becomes the kinetic energy of the object.
- chemical potential: chemicals have the potential to release energy by forming chemical bonds. When these bonds are formed, the chemical potential energy is released, usually in the form of heat.
- electric potential: the energy that causes electrons to move through an object that has electrical resistance.

As you have probably noticed, gravitational forces are listed above, both under Fields and Not Fields. That is because gravitational potential energy can be viewed as an interaction between an object and the Earth's gravitational field or an interaction between two objects with mass. Either of these ways of looking at the interaction is correct and yields the same results.

Gravitational Potential Energy (GPE) for Objects Close to the Earth

We can think of gravitational potential energy (GPE) as the action of the gravitational force in a way that can increase an object's kinetic energy. Because acceleration due to gravity on Earth is approximately $\vec{g} = 10\,\frac{\text{m}}{\text{s}^2}$ near the surface of the Earth, this means that the acceleration caused by the gravitational force is:

$$\vec{F}_g = m\vec{a} = m\vec{g}$$

Because kinetic energy is $K = \frac{1}{2}mv^2$ and $v^2 - v_o^2 = 2ad$, if an object starts from rest $(v_o = 0)$, and is only accelerated by the gravitational force, then:

$$v^2 = 2ad \quad \text{and} \quad \Delta K = \tfrac{1}{2}m(2ad) = mad$$

Remember that $\vec{a} = \vec{g}$. If the distance is vertical, we usually call it height, and we use the variable *h* instead of *d*, which means $\Delta K = mgh$. Therefore, the GPE (U_g) is the amount of kinetic energy that could be added by the object falling from a height:

$$U_g = mgh$$

Deriving Potential Energy from the Gravitational Force as a Force Field

A discussed earlier, we think of the gravitational force as the force caused by a gravitational force field—a region (near a massive object like the Earth) in which a gravitational force acts on all objects that have mass (*m*). If the strength of the gravitational fied is $\vec{g}$ (approximately $10\,\frac{\text{N}}{\text{kg}}$ near the surface of the Earth), then the force is $\vec{F}_g = m\vec{g}$. Using the reasoning above, this gives the same equation, $U_g = mgh$.

GPE between Objects that are Far Apart Compared with Their Size

Considering the gravitational force as a force field of constant strength does not work when the objects are very far apart. In that case, we need to consider GPE as the result of a gravitational force between two objects.

As we saw in the section on *Universal Gravitation*, starting on page 400, when two objects with mass (m_1 and m_2) objects are separated, the gravitational force between them is given by:

$$F_g = \frac{Gm_1m_2}{r^2}$$

If *r* is the distance between the objects' centers of mass, then we can apply the same reasoning as above, but using *r* instead of *h* as the distance between the objects. Thus, $U_g = mgh$ becomes $U_g = mgr$, which means:

$$U_g = F_g h = \frac{Gm_1m_2}{r^2} \cdot r = \frac{Gm_1m_2}{r}$$

Potential Energy of a Spring

As mentioned above, potential energy can be stored in a spring that is either stretched or compressed (and is therefore exerting a spring force).

The elastic potential energy of an ideal spring is given by the equation:

$$U_s = \tfrac{1}{2}k(\Delta x)^2$$

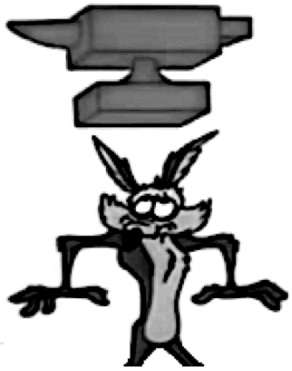
where:

- U_s = potential energy of the spring-object system (J)
- k = spring constant ($\frac{\text{N}}{\text{m}}$)
- Δx = displacement of the object from the spring's equilibrium position (m)

Systems and Potential Energy

Recall that a <u>*system*</u> is a collection of objects for the purpose of describing the interaction of objects within *vs.* outside of that collection. The <u>surroundings</u> is all of the objects outside of the system ("everything else"). (Systems are explained in more detail on page 264.)

Potential energy is an energy relationship between two objects within a system. A single, isolated object cannot have potential energy.



For example, in the coyote-anvil system pictured to the right, both Wile E. Coyote and the anvil have negligible potential energy. (There is a tiny amount of gravitational attraction between them—assuming the anvil has a mass of 200 kg and the coyote has a mass of 20 kg, the gravitational attraction between them would be 3×10^{-7} N.) However, the Earth can attract the entire coyote-anvil system toward itself.

In the coyote-anvil-Earth system, the anvil and the coyote each have GPE with respect to the Earth. As the coyote and anvil both fall toward the Earth, that GPE changes to kinetic energy for both objects, causing both the coyote and the anvil to fall faster and faster…

Remember that potential energy requires:

- Two objects that exert some sort of attractive or repulsive force on each other. (In the case of GPE, this is the gravitational force, which is attractive.)
- A distance between the two objects over which at least one of the objects can move. (In the case of gravitational potential energy, this is the height above the ground.)

This means that a single, isolated object cannot have potential energy.

This also means that regardless of whether we consider gravitational potential energy to be caused by an object and the Earth attracting each other or by the Earth's gravitational field, ***gravitational potential energy can exist only in a system that contains the Earth*** (or other planet/star that has enough mass to exert a significant gravitational force).

Mechanical Energy

Mechanical energy is gravitational potential energy (GPE) plus kinetic energy. Because GPE and kinetic energy are easily interconverted, it is convenient to have a term that represents the combination of the two. There is no single variable for mechanical energy; in this text, we will sometimes use the abbreviation *TME*:

$$TME = U_g + K$$

Internal (Thermal) Energy

Kinetic energy is both a macroscopic property of a large object (*i.e.,* something that is at least large enough to see), and a microscopic property of the individual particles (atoms or molecules) that make up an object. Internal (thermal) energy is the aggregate microscopic energy that an object (often an enclosed sample of a gas) has due to the combined kinetic energies of its individual particles. (Heat is thermal energy added to or removed from a system.)

As we will see when we study thermal physics, temperature is the average of the microscopic kinetic energies of the individual particles that an object is made of. Kinetic energy can be converted to internal energy if the kinetic energy of a macroscopic object is turned into the individual kinetic energies of the particles of that object and/or some other object. Processes that can convert kinetic energy to internal energy include friction and collisions.

Chemical Potential Energy

Chemical potential energy comes from the ability of atoms to react by forming chemical bonds. This energy comes from the electromagnetic forces that attract the atoms in these bonds. When the bonds form, the energy that is released often causes an increase in the kinetic energy of the molecules, which we observe as a rise in temperature. When this happens, some of the thermal energy is released into the surroundings as heat. The chemical potential energy that is turned into heat is called the enthalpy of formation and is specific to each chemical compound.

However, chemical potential energy is more complicated than just thermal energy. Chemical potential energy can also be turned into thermal energy that is spread out into a very large number of separate microscopic energy states. Thermal energy that is spread in this manner is called entropy. The combination of enthalpy and entropy is called free energy, and the total amount of chemical potential energy that can be released when a compound is formed is called the free energy of formation.

The study of the energy released in chemical reactions is called chemical thermodynamics, which is beyond the scope of this course, and is studied in detail in AP® Chemistry.

Electric Potential Energy

Electric potential is the energy that causes electrically charged particles to move through an electric circuit. The energy for this ultimately comes from some other source, such as chemical potential energy (*i.e.,* a battery), mechanical energy (*i.e.,* a generator), *etc.* The difference in electric potential energy between two locations is called the electric potential difference, or more commonly the voltage. Electricity and electric potential energy are studied in detail in Physics 2.

Homework Problems

1. **(M)** Calculate the kinetic energy of a car with a mass of 1200 kg moving at a velocity of $15\,\frac{m}{s}$.

   Answer: 135 000 J

2. **(M)** Calculate the gravitational potential energy of a person with a mass of 60. kg at the top of a 10. m flight of stairs.

   Answer: 6 000 J

3. **(M)** Calculate the gravitational potential energy between the Earth and the moon. (You will need to use information from *Table T. Planetary Data* and *Table U. Sun & Moon Data* on page 580.)

   Answer: 7.62×10^{28} J