SLE123 Physics for the Life Sciences

Week 4

Energy and Work

DEAKIN COLLEGE
in association with
DEAKIN UNIVERSITY

Looking Ahead

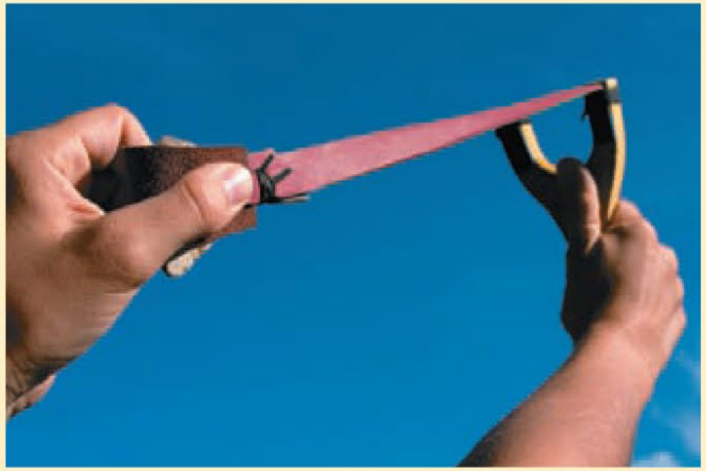
Forms of Energy

This dolphin has lots of **kinetic energy** as it leaves the water. At its highest point its energy is mostly **potential energy.**

You'll learn about several of the most important forms of energy—kinetic, potential, and thermal.

Work and Energy

As the band is stretched, energy is *transferred* to it as **work.** This energy is then *transformed* into kinetic energy of the rock.



You'll learn how to calculate the work done by a force, and how this work is related to the *change* in a system's energy.

Conservation of Energy

As they slide, their potential energy decreases and their kinetic energy increases, but their total energy is unchanged: It is **conserved.**

How fast will they be moving when they reach the bottom? You'll use a new before-and-after analysis to find out.

The forms of energy

- ***Kinetic energy (K)*: the energy of motion**

The forms of energy

- ***Gravitational potential energy (U_g)*: stored energy due to height in a gravitational potential field**

The forms of energy

- ***Thermal energy*** **(E_{th}): a statistical measure of the individual microscopic kinetic and potential energies of particles comprising a system**

The forms of energy

- ***Elastic (spring) potential energy (U_s)*: stored energy due to the deformation from equilibrium of an elastic system**

The forms of energy

- ***Chemical potential energy (E_{ch})*: energy stored in the bonds that maintain the chemical structure of molecules and other aggregates of matter**

Chemical energy derives from changes in electro-magnetic potential energy that occur when the chemical structure of matter is altered

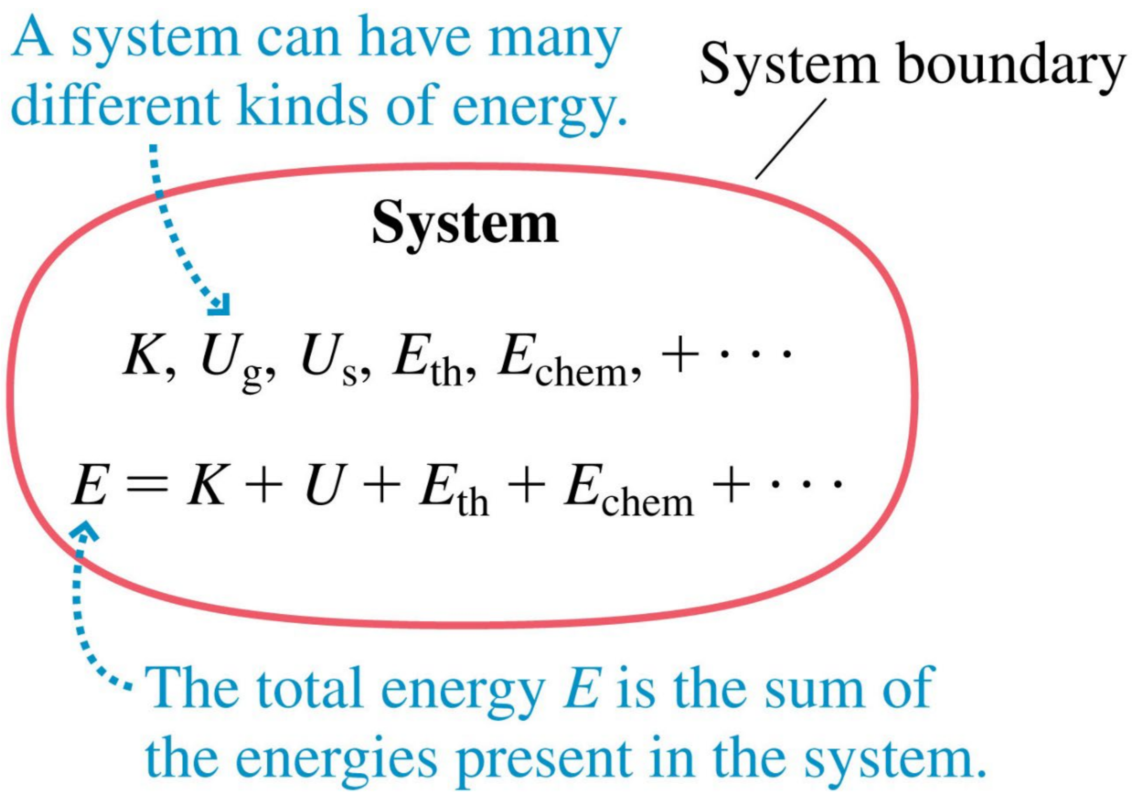
The forms of energy

- ***Nuclear potential energy (E_n)***: **energy stored in the nuclei of atoms**

This energy was may be released in fission and fusion processes and escapes as electromagnetic radiation (flow of EM energy) or heat

The Basic Energy Model

- Every system in nature has a quantity we call its **total energy** E.

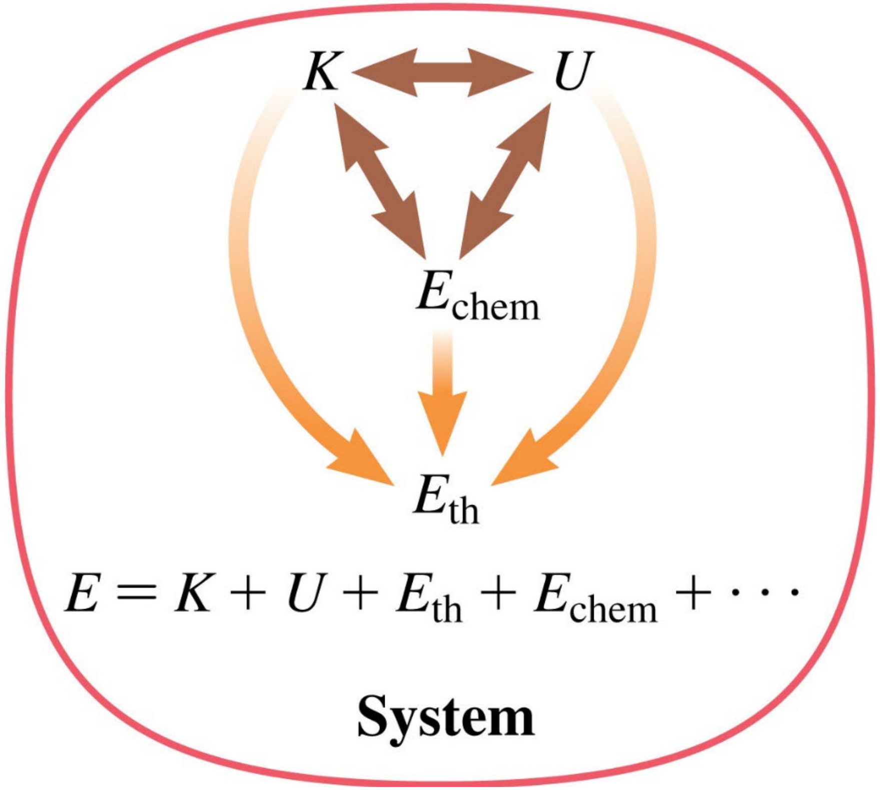


Forms of Energy

- Some important forms of energy are
  - *Kinetic energy* K: energy of motion.
  - *Gravitational potential energy* U_{g}: stored energy associated with an object’s height above the ground.
  - *Elastic or spring potential energy* U_{s}: energy stored when a spring or other elastic object is stretched.
  - *Thermal energy* E_{th}: the sum of the kinetic and potential energies of all the molecules in an object.
  - *Chemical energy* E_{chem}: energy stored in the bonds between molecules.
  - *Nuclear energy* E_{nuclear}: energy stored in the mass of the nucleus of an atom.

Energy Transformations

- Energy of one kind can be *transformed* into energy of another kind within a system.

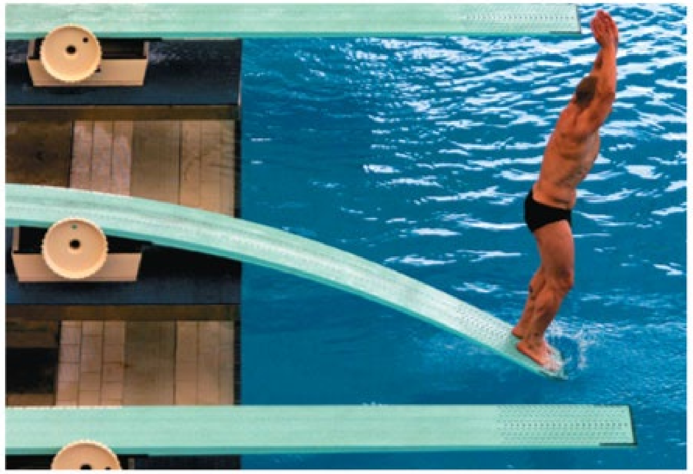


Energy Transformations

- We witness energy transformations around us every day.
- Indeed, without them, life would not exist.
- Our bodies convert chemical energy and electrical energy into mechanical energy to enable us to move, grow and live.
- Nearly all of the energy available on Earth has been derived from our Sun, or from the stars that existed in our region of space prior to our sun (and from which our solar system formed).
- Here are some examples of energy transformations…

Energy Transformations

The weightlifter converts chemical energy in her body into gravitational potential energy of the barbell.



Elastic potential energy of the springboard is converted into kinetic energy. As the diver rises into the air, this kinetic energy is transformed into gravitational potential energy.

Energy Transformations

This campfire shows the large amount of chemical energy in the wood being combined chemically with oxygen in the air to produce significant amounts of thermal energy in the hot gases and embers. We also see electromagnetic radiation (energy) being emitted as the hot gases release the energy they have gained.

Energy Transformations

It is relatively easier to convert kinetic, chemical and potential (both gravitational and elastic) energies into thermal energy.

Unfortunately it is not so easy to convert **thermal energy** back to these other forms.

We will see why later… for now, let’s formalise the total energy of a closed (isolated) system.

Law of Conservation of Energy

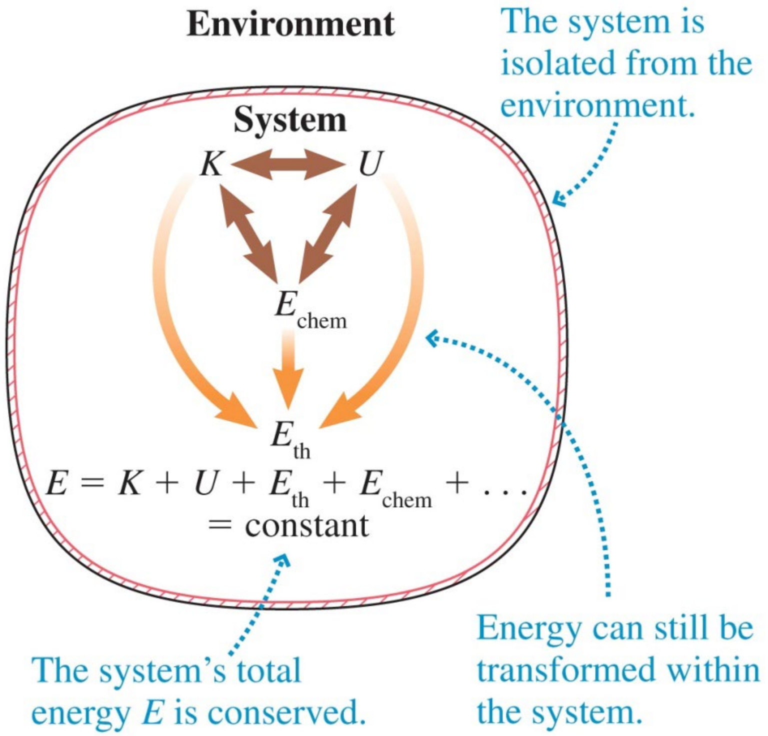
If a system is isolated then the total energy within the system remains constant and is the sum of the forms of energy present

We may write this as:

$$K + U_g + U_s + E_{th} + E_{ch} + \ldots$$
$$= E = \text{constant}$$

An alternative form states that any increase in one form of energy is balanced by a decrease in one or more other forms of energy. Thus,

$$\Delta K + \Delta U_g + \Delta U_s + \Delta E_{th} + \Delta E_{ch} + \ldots = 0$$



Energy Transfers

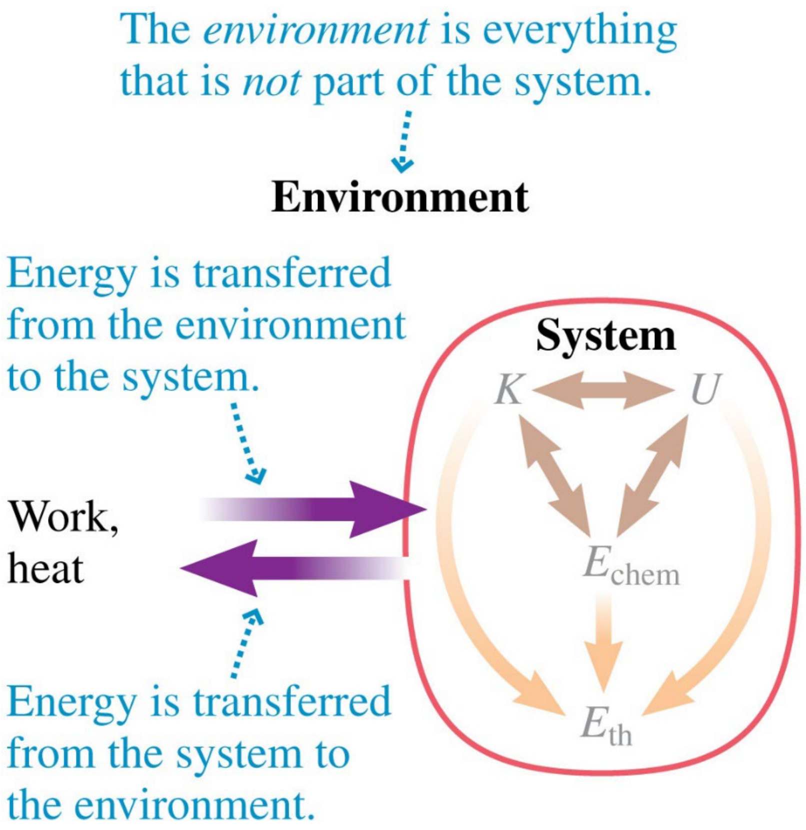
For systems that are not isolated we must consider the exchange of energy between the environment and the system.

Such exchanges are termed *energy transfers.*

There are two primary energy transfer processes: *work* and *heat.*

Energy Transfers and Work

- Energy can be *transferred* between a system and its environment through work and heat.
- **Work** is the mechanical transfer of energy to or from a system by pushing or pulling on it.
- **Heat** is the nonmechanical transfer of energy between a system and the environment due to a temperature difference between the two.



Energy Transfers and Work

- The athlete does **work** on the shot, giving it kinetic energy, K.

The hand does **work** on the match, giving it thermal energy, E_{th}.

The boy does **work** on the slingshot, giving it elastic potential energy, U_s.

The Work-Energy Equation

- Work represents energy that is transferred into or out of a system.
- The total energy of a system changes by the amount of work done on it.

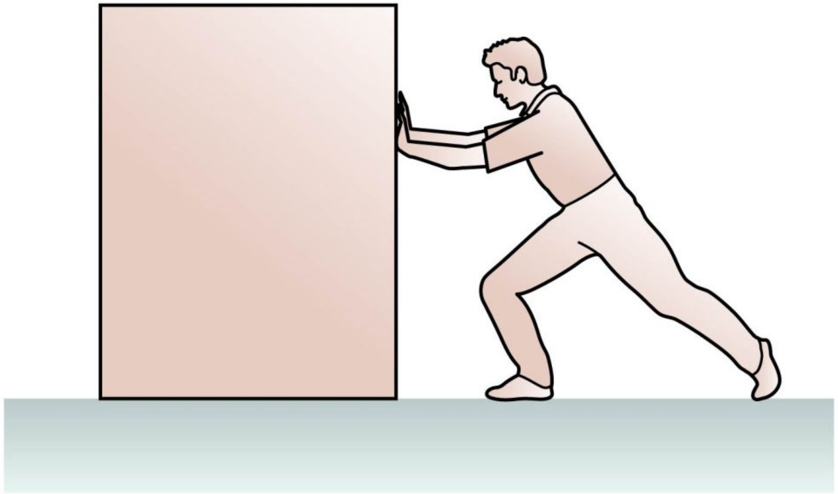
- Work can increase or decrease the energy of a system.
- If no energy is transferred into or out of a system, that is an **isolated system**.

$$\Delta E = \Delta K + \Delta U_g + \Delta U_s + \Delta E_{th} + \Delta E_{chem} + \cdots = W$$

QuickCheck 10.2

- Robert pushes the box to the left at constant speed. In doing so, Robert does _______ work on the box.

  - positive
  - negative
  - zero



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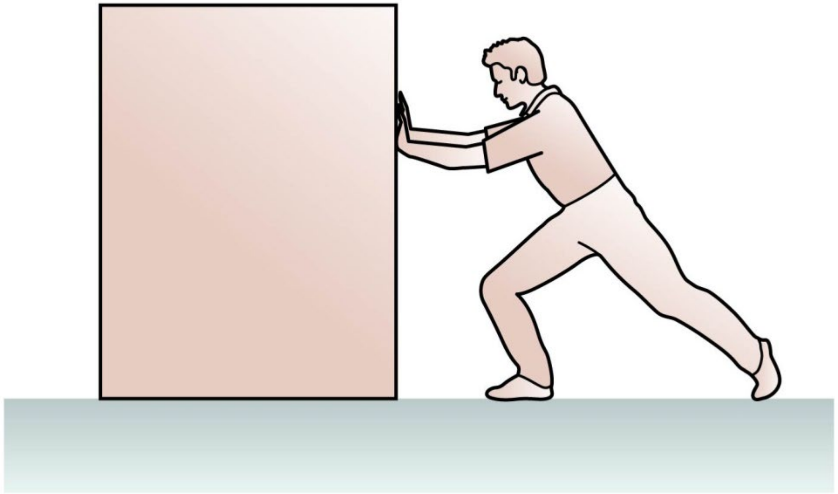


Force is in the direction of displacement $\Rightarrow$ positive work

Work

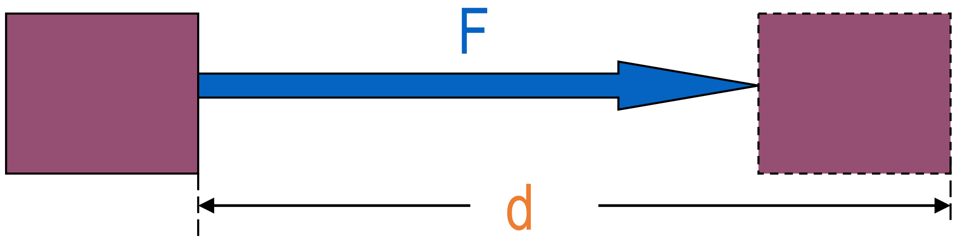
Work done on an object is defined in physics as the product (multiplication) of the applied force and the distance through which the object is moved.

$$\text{Work}(W) = \text{Force}(F) \times \text{Distance}(d)$$

$$W = F \times d$$

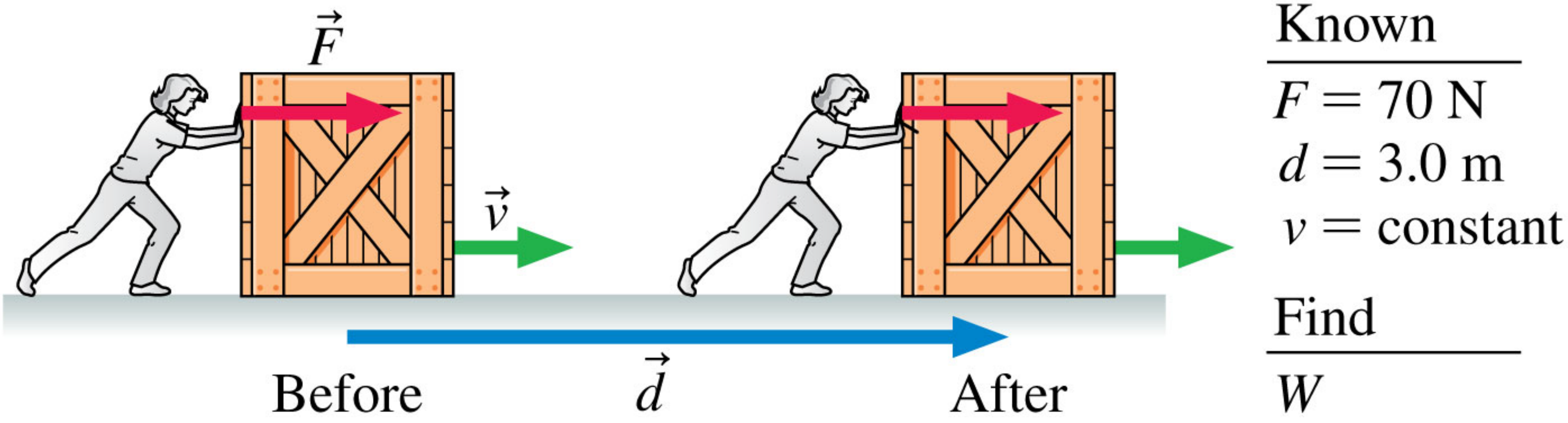
The unit of work (and energy) is:

$$1\ \text{joule} = 1\ \text{J} = 1\ \text{N} \cdot \text{m}$$



Example 10.1 Work done in pushing a crate

- Sarah pushes a heavy crate 3.0 m along the floor at a constant speed. She pushes with a constant horizontal force of magnitude 70 N. How much work does Sarah do on the crate?

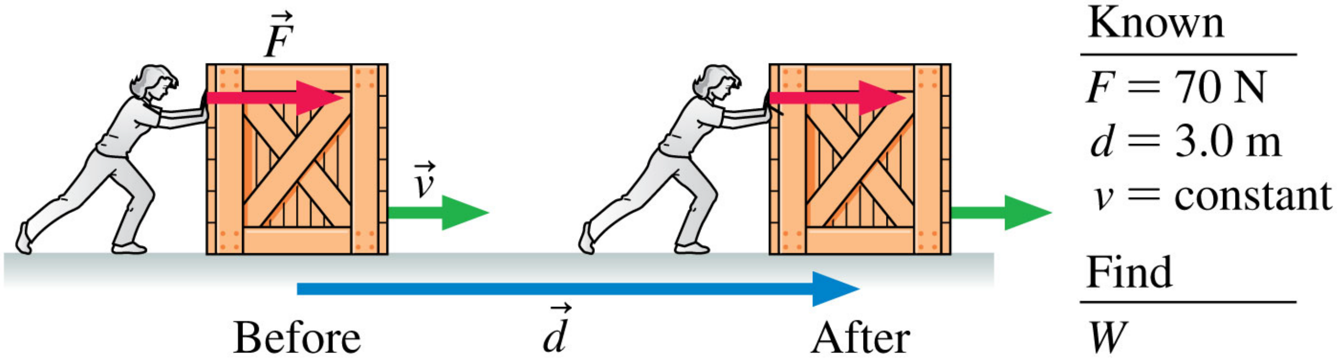


Example 10.1 Work done in pushing a crate (cont.)

PREPARE We begin with the before-and-after visual overview in FIGURE 10.6. Sarah pushes with a constant force in the direction of the crate's motion, so we can use Equation 10.5 to find the work done.

SOLVE The work done by Sarah is

$$W = Fd = (70\text{ N})(3.0\text{ m}) = 210\text{ J}$$



By pushing on the crate Sarah increases its kinetic energy, so it makes sense that the work done is positive.

Problem task 1

Calculate the work done on an object by a force

Kinetic Energy (Energy of Motion)

In the absence of drag and friction the result of doing work on a system is a displacement and a change in its kinetic energy

It can be readily shown that

$$W = \Delta K = \frac{1}{2} m\left(v_f^2 - v_i^2\right)$$

and from this it follows that

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

K has units of kg $(m/s)^2$ = (kg m/s^2) m = N m = Joules

Kinetic energy is a scalar quantity, not a vector.

Problem task 2, 3

Calculate kinetic energy

Potential Energy

Interaction forces that store energy are called conservative forces.

Other interaction forces that do not store energy, such as friction, are termed non-conservative forces.

We will look more closely at the two mechanical forms of potential energy: *gravitational potential energy* and *elastic (spring) potential energy.*

Gravitational Potential Energy

The mass *m* held a distance *h* above the stake has the potential to do work on the stake if the mass is dropped.
The GPE of the mass is transferred into KE of motion, this KE is in turn transformed into work on the stake, a force acting through a distance.

$$W = \Delta U_g = mg\Delta y$$

$$U_g = mgh$$

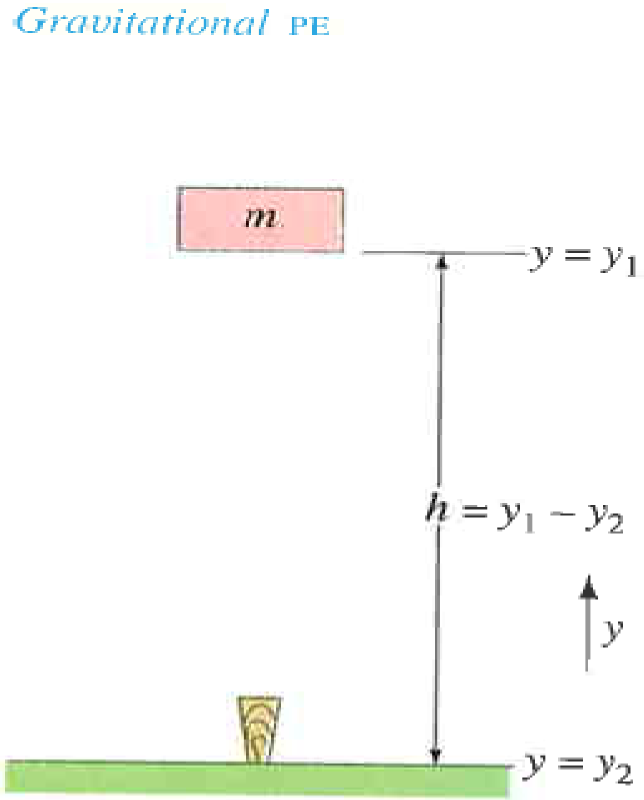


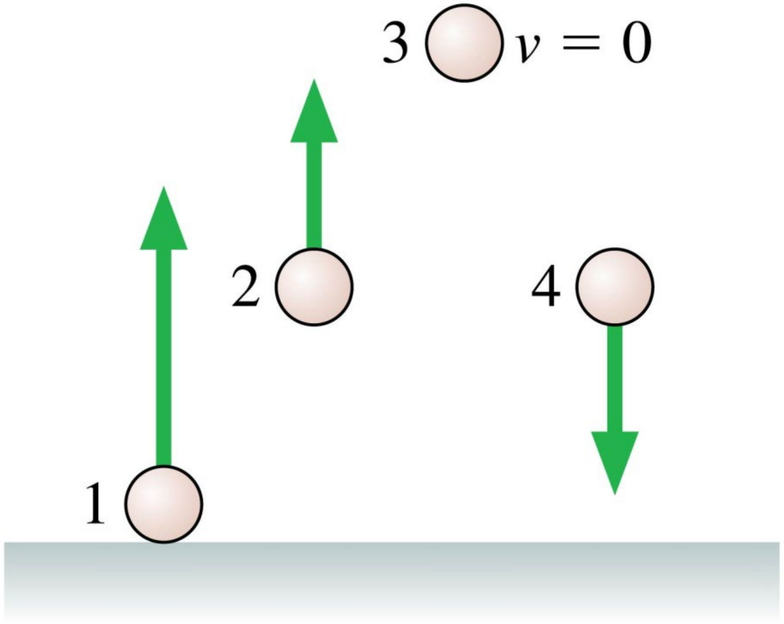
FIGURE 6–8 An object of mass m at height h above the ground can do an amount of work $W = mgh$ when it falls.

(Giancoli, chap. 6)

QuickCheck 10.3

Rank in order, from largest to smallest, the gravitational potential energies of the balls.

- 1 > 2 = 4 > 3
- 1 > 2 > 3 > 4
- 3 > 2 > 4 > 1
- 3 > 2 = 4 > 1



QuickCheck 10.3

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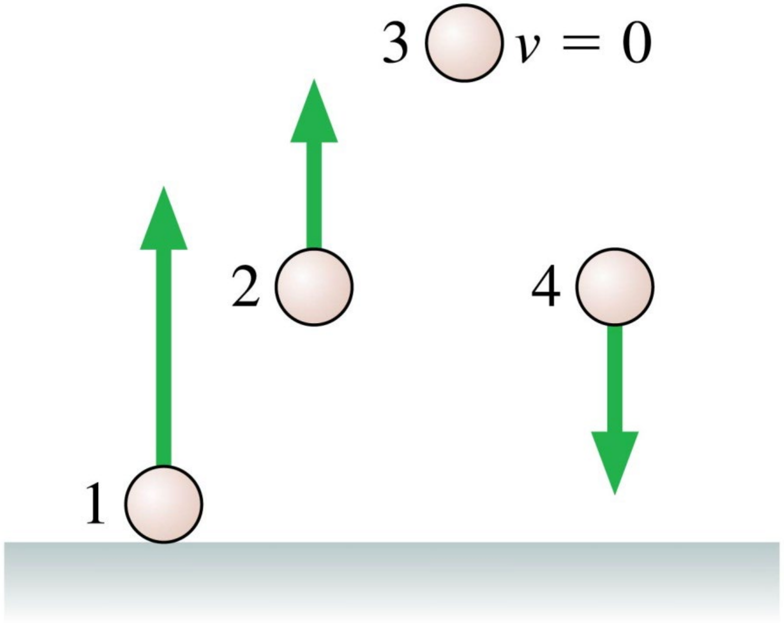


Problem task 4,5

Calculate gravitational potential energy

Conservation of Energy-example

$$mg\Delta h \Rightarrow \tfrac{1}{2}mv^2$$

Conservation of Energy-example: Roller Coaster

Kinetic Energy

A 2.0 g desert locust can achieve a takeoff speed of 3.6 m/s (comparable to the best human jumpers) by using energy stored in an internal "spring" near the knee joint.

- When the locust jumps, what energy transformation takes place?
- If 50% of the initial kinetic energy is transformed to thermal energy because of air resistance, how high will the locust jump?

Kinetic Energy

A 2.0 g desert locust can achieve a takeoff speed of 3.6 m/s (comparable to the best human jumpers) by using energy stored in an internal “spring” near the knee joint.

When the locust jumps, what energy transformation takes place?

If 50% of the initial kinetic energy is transformed to thermal energy because of air resistance, how high will the locust jump?

When the locust jumps, spring potential energy is transformed into kinetic energy.

$$\text{initial KE} = \frac{1}{2}\text{mv}^2 = \tfrac{1}{2}(0.002\,\text{kg})(3.6\,\text{m/s})^2 = 1.296\times10^{-2}\,\text{J}$$

$$\text{Energy transformed into GPE} = \frac{1.296\times10^{-2}\,\text{J}}{2} = 0.648\times10^{-2}\,\text{J}$$

$$\text{GPE} = mg(\Delta h)$$

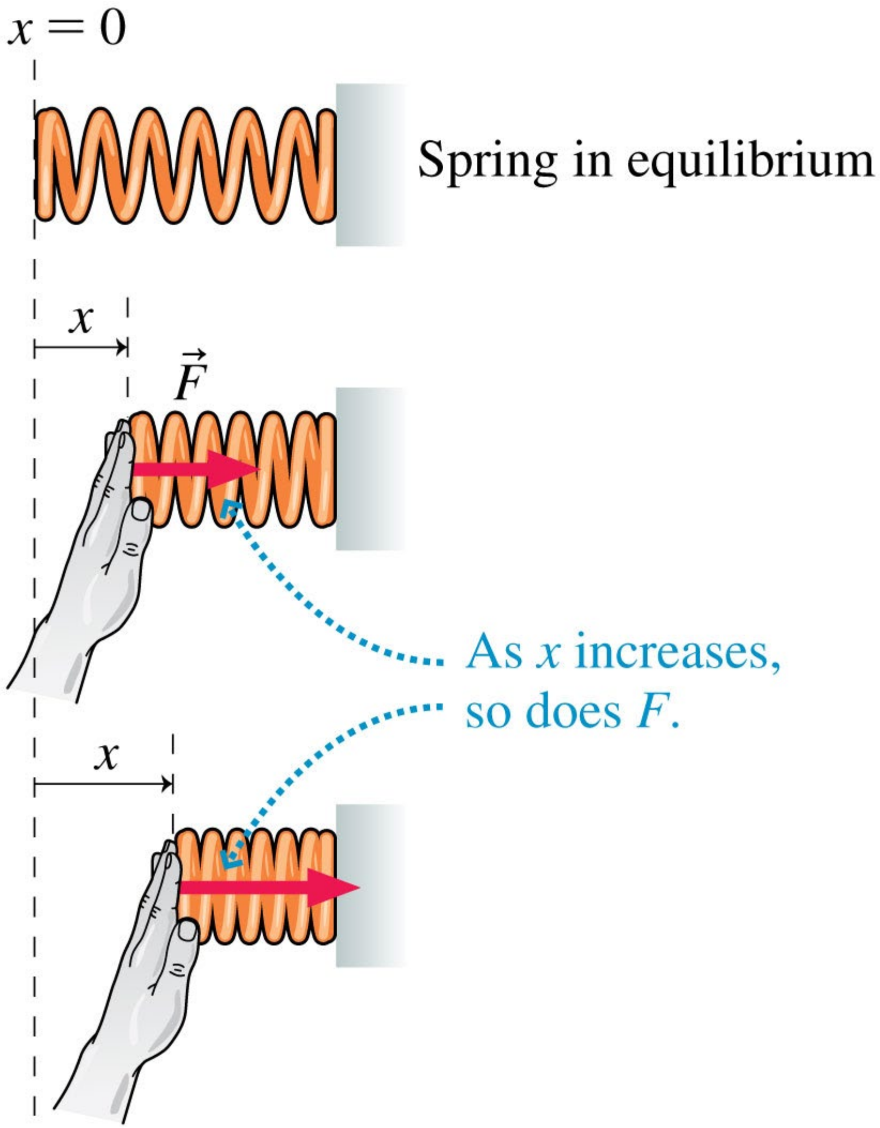
$$\Delta h = \frac{\text{GPE}}{mg}$$

$$\Delta h = \frac{0.648\times10^{-2}\,\text{J}}{(0.002\text{kg})(9.8\text{m/s}^2)} = 0.33\,\text{m} = 33\text{cm}$$

Elastic Potential Energy

Elastic (or spring) potential energy is stored when a force compresses a spring.

Hooke’s law describes the force required to compress a spring.



Elastic Potential Energy

The spring force is,

$$F = -k\Delta x$$

The elastic potential energy stored in a spring is determined by the average force required to compress the spring from its equilibrium length.

$$U_s = \frac{1}{2}kx^2$$

Elastic potential energy of a spring displaced a distance x from equilibrium (assuming $U_s = 0$ when the end of the spring is at $x = 0$)

Slingshots

$$\frac{1}{2}kx^2 \Rightarrow \frac{1}{2}mv^2$$

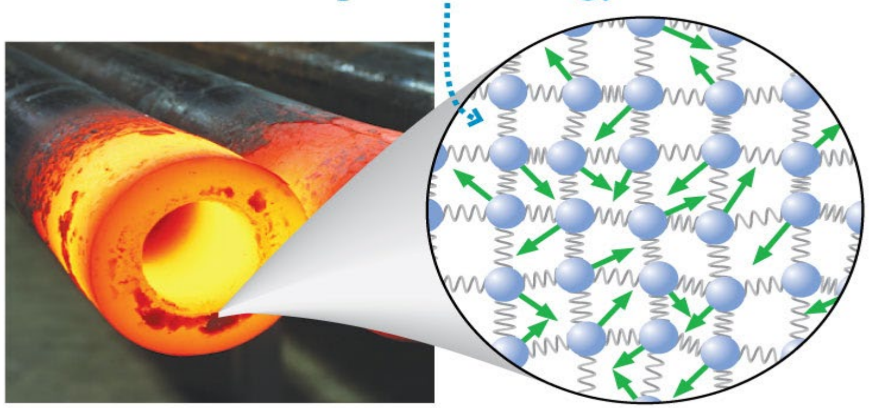
Problem task 6,7

Force and energy in springs

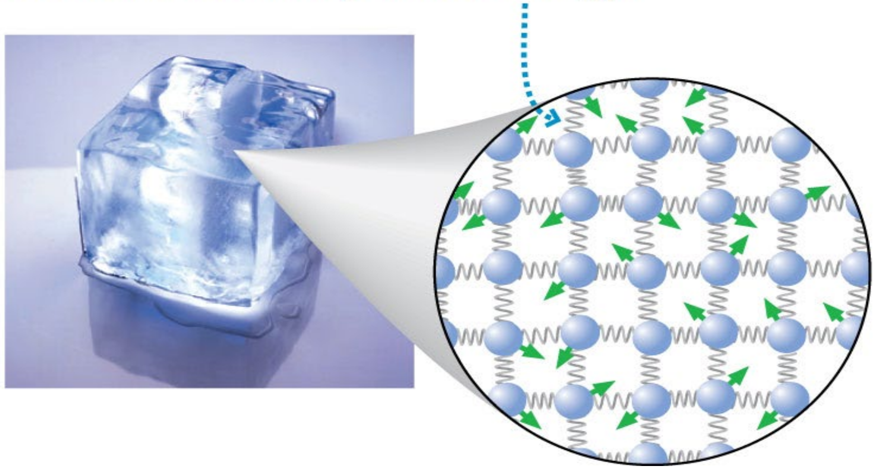
Thermal Energy

Thermal energy is the sum of the kinetic energy of atoms and molecules in a substance and the elastic potential energy stored in the molecular bonds between atoms.

Hot object: Fast-moving molecules have lots of kinetic and elastic potential energy.

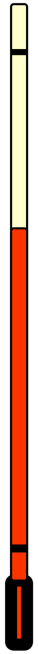


Cold object: Slow-moving molecules have little kinetic and elastic potential energy.



Temperature Scales

Anders Celsius (Centigrade Thermometer)



100 °C Boiling point of Water

Based upon the Boiling & Freezing Points of water at 1 atmospheric pressure.

0 °C Freezing Point of Water

Kelvin Scale K

The Kelvin Scale is based upon Energy.

Celsius to Kelvin - Add 273 to the °C

Where 0 K is the lowest possible temperature absolute zero and corresponds to –273 °C on the Celsius scale.

The units of degrees are the same for Celsius.

K is the SI unit for Temperature (not °K)

Fahrenheit Scale

The other most commonly used temperature scale.

32ºF is the freezing point of water.

212ºF is the boiling point of water.

The zero was set, at a temperature which was attained by mixing water, ice & salt in equal parts.

Power

Same mass...
Both reach 110 kph...

Same final kinetic energy, but **different times mean different powers.**

$$\text{power} = \frac{\text{work}}{\text{time}} = \frac{\text{energy}}{\text{time}}$$

units = joules/seconds = watts

Power examples calculation

The loaded cab of an elevator has a mass of 3000 kg and moves 210 m up the shaft in 23 seconds, at constant speed. What is the power?

$$P = G.P.E. / time = (3000 \times 9.8 \times 210) / 23 = 268 \text{ kW}$$

Energy from food

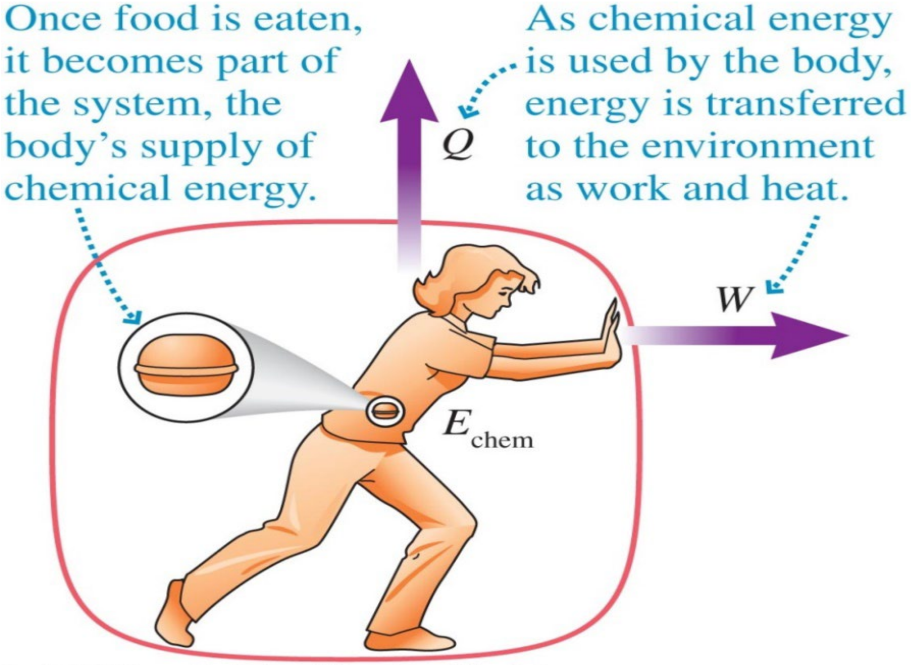
Glucose from the digestion of food combines with oxygen that is breathed in to produce… …carbon dioxide, which is exhaled; water, which can be used by the body; and energy.

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{energy} \qquad (11.2)$$

Glucose	Oxygen	Carbon dioxide	Water

TABLE 11.1 Energy in fuels

Fuel	Energy in 1 g of fuel (in kJ)
Hydrogen	121
Gasoline	44
Fat (in food)	38
Coal	27
Carbohydrates (in food)	17
Wood chips	15



Energy from food

TABLE 11.2 Energy content of foods

Food	Energy content in Cal	Energy content in kJ
Fried egg	100	420
Large apple	125	525
Slice of pizza	300	1260
Slice of apple pie	400	1680
Fast-food meal: Burger, fries, drink, large size	1350	5670

1 Cal = 4.2 kJ

Body energy use

TABLE 11.3 Energy usage at rest

Organ	Resting power (W) of 68 kg individual
Liver	26
Brain	19
Heart	7
Kidneys	11
Skeletal muscle	18
Remainder of body	19
Total	**100**

TABLE 11.4 Metabolic power use during activities by a 68 kg (150 lb) individual

Activity	Metabolic power (W) of 68 kg individual
Typing	125
Ballroom dancing	250
Walking at 5 km/hr	380
Cycling at 15 km/hr	480
Swimming at a fast crawl	800
Running at 15 km/hr	1150

Metabolism example question

If a runner eats an energy bar (2000 kJ) before a race and runs at 10 km/hr, how far will he/she run using only the energy from an energy bar? (assume running at 10 km/hr uses 1200 W)

Answer : 4.6 km

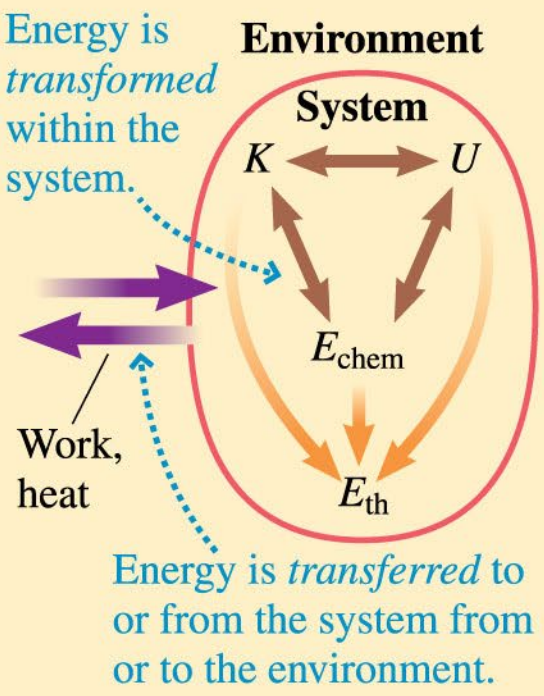
Summary: General Principles

Basic Energy Model

Within a system, energy can be **transformed** between various forms.

Energy can be **transferred** into or out of a system in two basic ways:

- **Work:** The transfer of energy by mechanical forces
- **Heat:** The nonmechanical transfer of energy from a hotter to a colder object



Summary: General Principles

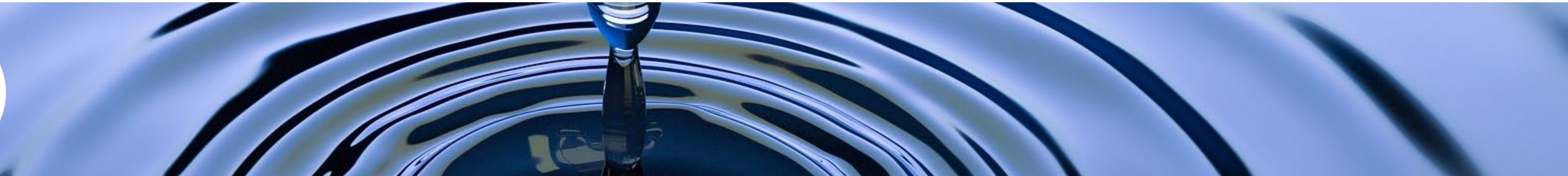
Conservation of Energy

When work W is done on a system, the system's total energy changes by the amount of work done. In mathematical form, this is the **work-energy equation:**

$$\Delta E = \Delta K + \Delta U_g + \Delta U_s + \Delta E_{th} + \Delta E_{chem} + \cdots = W$$

A system is **isolated** when no energy is transferred into or out of the system. This means the work is zero, giving the **law of conservation of energy:**

$$\Delta K + \Delta U_g + \Delta U_s + \Delta E_{th} + \Delta E_{chem} + \cdots = 0$$



Energy and Its Conservation

Kinetic energy is the energy of motion.

$$K = \tfrac{1}{2}mv^2$$

Mass (kg)

Velocity (m/s)

Gravitational potential energy is stored energy associated with an object's height above the ground.

$$U_g = mgy$$

Free-fall acceleration

Mass (kg)

Height (m) above a reference level $y = 0$

Elastic potential energy is stored energy associated with a stretched or compressed spring.

$$U_s = \tfrac{1}{2}kx^2$$

Spring constant (N/m)

Displacement of end of spring from equilibrium (m)

Summary: Applications

Power is the rate at which energy is transformed . . .

$$P = \frac{\Delta E}{\Delta t} \begin{array}{l} \leftarrow \text{Amount of energy transformed} \\ \leftarrow \text{Time required to transform it} \end{array}$$

. . . or at which work is done.

$$P = \frac{W}{\Delta t} \begin{array}{l} \leftarrow \text{Amount of work done} \\ \leftarrow \text{Time required to do work} \end{array}$$