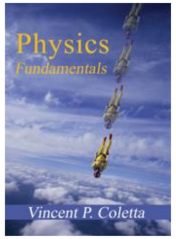
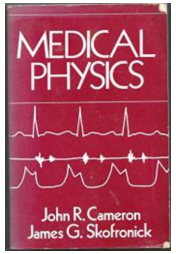
Medical Physics Class

Energy, Work, and Power of Human Body



Physics Fundamentals by Vincent P. Coletta, Ch 7



Medical physics : John R Cameron, Ch5

Learning Goals

Looking forward at …

- The Concept of Energy
- Energy Changes in Human Body
- Oxygen Consumption
- Basal Metabolic Rate (BMR)
- Work and Kinetic Energy
- Potential Energy
- Total mechanical energy
- Power
- Heat Losses From Human Body
- The Energy to Run (Homework)

The Concept of Energy

- All the activities of the body, including thinking, is come from energy conversions **(Oxygen Consumption)**.
- Food is the fuel for the body which is use the released energy to:
  - **Operate its varies organs.**
  - **Maintain the body with constant temperature.**
  - **Do the external work.**
- The energy used to operate the organs appears as body heat.
- Some of this heat is useful in maintaining the body at its normal temperature.

The Concept of Energy

- Other energy source can help maintain body temperature.
  - Radiant solar energy and Heat energy from our surrounding environment.

- Under **resting** conditions about:
  - **25%** of the body's energy is being used by skeletal muscles & the heart.
  - **19%** is being used by the brain.
  - **10%** is being used by the kidneys.
  - **27%** is being used by the liver and spleen.
  - **5%** is being used by the feces and urine.
  - Any energy that is left over is stored as **body fat**.

The Concept of Energy

- The law of conservation of energy.
- This law states that there exists a numerical quantity called **"energy"** that remains fixed in any process that occurs in nature.

- Energy comes in many forms. **Mechanical energy**, **Electrical energy**, **Chemical energy**, **Nuclear energy**, and **Thermal energy**.

- In this lecture we study only the <u>conversion of energy in the body, the work don by and power of the body and how the body loses heat</u>.

The Concept of Energy

- Conservation of Energy in the Body.
- Change in stored energy in the body (i.e. food energy, body fat, and body heat) = Heat lost from the body + Work done.
- This is known as the first law of thermodynamics:

$$\Delta U = \Delta Q - \Delta W$$

- ΔU: is the stored energy.
- ΔQ: is the heat lost or gained.
- ΔW: is the work done by the body in some interval of time.

The Concept of Energy

- A body that is doing no work $(\Delta W = 0)$ and at a constant temperature, continues to lose heat to surrounding environment, i.e., $(\Delta Q = -ve)$. Therefore, ΔU is also $-ve.$, indicating a decrease in stored energy.

- It is useful to consider the change of $\Delta U, \Delta Q, and\ \Delta W$ in a short interval of time Δt.

$$\boldsymbol{\frac{\Delta U}{\Delta t} = \frac{\Delta Q}{\Delta t} - \frac{\Delta W}{\Delta t}}$$

  - $\frac{\Delta U}{\Delta t}$: is the rate of change of stored energy.
  - $\frac{\Delta Q}{\Delta t}$: is the rate of heat loss or gain.
  - $\frac{\Delta W}{\Delta t}$: is the rate of doing work (Mechanical Power).

Energy Changes in Human Body

- Energy of the Human body **is the measure of its ability to do work**.
- Several energy and power **units** are used in relation to the body.
- **Physiologist:**
  - *Kilocalories (kcal)* for food energy.
  - *Calorie (C)* is actually a kilocalorie.
  - *Kilocalories (kcal) per minute* for the rate of heat production
    - diet of 2500 C/day is 2500 kcal/day.

Energy Changes in Human Body

- **Physics**
- Unit for **energy** in $Meter, Kilogram, Second\ (SI)$ system is
  - $Newton.meter\ (N.m)$,or $Joule(J)$
- and in $Centimeter, Gram, Second\ (CGS)$ system is
  - the $erg, (1\ erg = 10^{-7}J)$.
- **Power** is given in (J/s) or Watt (W).

Energy Changes in Human Body

- MET (metabolic equivalents) is a convenient unit for expressing the rate of energy **consumption** of the body.

$$MET = \frac{working\ metabolic\ rate}{resting\ metabolic\ rate}$$

- **Metabolic rate** refers to the **chemical process** by which your body converts food and drinks into **energy**.
- It plays a crucial role in determining how many calories you need to function and how much energy you use for basic and physical activities.

Energy Changes in the Body

- $1MET$ is the energy you spend sitting at rest — your resting or **basal metabolic rate**.
- MET defined as: $50\,kcal/m^2$ of body surface area per hour. For normal person the energy consumption is $1\,MET$ under resting conditions.
- Atypical man has about $1.85m^2$ of surface area (a woman has $1.4\,m^2$), and thus for a typical man $1\,MET$ is about $92\ \ kcal/hr\ or\ 107\,W$.

Energy Changes in the Body

- $1\ kcal = 4184\ J$
- $1\ J = 10^7\ erg$
- $1\ kcal/\text{min} = 69.7\ W = 0.094\ hp$ (horsepower)
- $100\ W = 1.43\ kcal\ /\ \text{min}$
- $1\ hp = 642\ kcal\ /\ hr = 746\ W$
- $1\ MET = 50\ kcal/m2.hr = 58\ W/m2$
- $1\ kcal\ /\ hr = 1.162\ W$

Oxygen Consumption

- Food oxidation
- The oxidation occurs in the **cell of the body** which increased during the process of digestion.
- In the oxidation process by **combustion**, heat is released as an energy of metabolism.
- The **rate of oxidation** is called **metabolic rate.**

- The oxidation equation for $\mathbf{1\ mole\ (180\ g)}$ of glucose $(C_6H_{12}O_6)$ in common intravenous feeding is:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6H_2O + 6CO_2 + 686\ kcal$$

(heat energy)

Oxygen Consumption

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6H_2O + 6CO_2 + 686\ kcal$$

(heat energy)

- 1 $mole$ of gas has a volume of 22.4 $litter$
  - (at constant temperature & pressure).
- Kilocalories of energy released per gram of fuel $=$
  $686 / 180 = 3.8 kcal/g$
- Kilocalories released per liter of O_2 used $=$
  $686 / (6 \times 22.4) = 5.1 kcal/l$
- Liters of O_2 used per gram of fuel = $6 \times 22.4 / 180 = 0.75 l/g$
- Liters of CO_2 produced per gram of fuel = $6 \times 22.4 / 180 = 0.75 l/g$

Oxygen Consumption

- The various types of food gives various energy released per liter of oxygen consumed.
- Therefore, by measuring the oxygen consume by the body we can get a good estimate of the energy released.
- Stored energy (at constant temp.) = Extracting energy from food + Body fat.

- Note: Not all of this energy is available to the body because part is lost in incomplete combustion (feces, urine, and gas)

Basal Metabolic Rate (BMR).

- At rest, the typical person consumes energy at a rate of about 92 kcal/hr (107 W or 1 met). This lowest rate of energy consumption, called **Basal Metabolic Rate (BMR).**
- **BMR** defined as the amount of energy needed to perform minimal body function such as
  - breathing and
  - pumping the blood through the arteries under resting conditions.
- Clinically BMR compared to normal values for a person of the same sex, age, height, and weight.

Basal Metabolic Rate (BMR).

- **BMR depends primarily upon:**

1) Thyroid function, a person with an **overactive thyroid** has a higher BMR than a person with normal thyroid function.
2) Temperature of the body, a small change in temperature can produce a large change in chemical reactions. Every $1^{\circ}C$ change cause 10% change in BMR.
3) BMR change fast with surface area.
4) BMR is proportional to mass of the body.

Basal Metabolic Rate (BMR).

- Weight loss through dieting and physical exercise discussed in following example:
- **<u>Example 1</u>**: Suppose you wish to lose $4.54\ kg$ either through physical activity or by dieting.

a) How long would you have to work at an activity of $15\ kcal/\min$ to lose $4.54\ kg$ of fat?

Basal Metabolic Rate (BMR).

Fats the maximum rate of energy $9.3\ kcal/g$.

If you worked for $T\ minutes$, then

$$T\ \text{min} \times\ 15\ kcal\ /\ \text{min} =\ 4.54\ \times\ 10^3\ g\ \times\ 9.3\ kcal\ /\ g$$

$$=\ 4.2\ \times\ 10^4\ kcal$$

$$T\ =\ 2810\ \text{min} =\ 47\ hr$$

Note that a great deal of exercise is needed to lose a few kg.

Basal Metabolic Rate (BMR).

It is usually much easier to lose weight by reducing your food intake. If you normally use $2500\ kcal/day$, how long must you diet at $2000\ kcal/day$ to lose $4.54\ kg$ of fat?

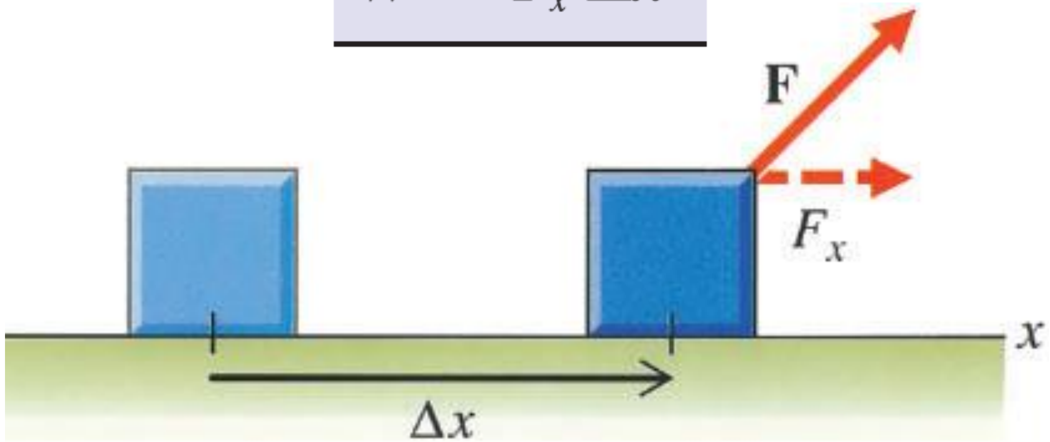
$$T = energy\ of\ 4.54\ kg\ fat\ /\ energy\ deficit\ per\ day$$
$$T = 4.2 \times 10^4 (kcal)\ /\ 5 \times 10^2 (kcal\ /\ day) = 84\ day$$

- Note: From the oxygen consumption:
  - BMR is sometimes determined when resting.
  - We can estimate the food energy used in various physical activities.

Work and Kinetic Energy

- Energy stored in the body is converted into external mechanical work.
- When a force acts through a distance, we say, "The force does work."
- More precisely, the work $\boldsymbol{W}$ done by a constant force $\boldsymbol{F}$ acting on a body moving in a straight line is defined to be the product of the force component F_x in the direction of motion times the distance Δx the body moves:

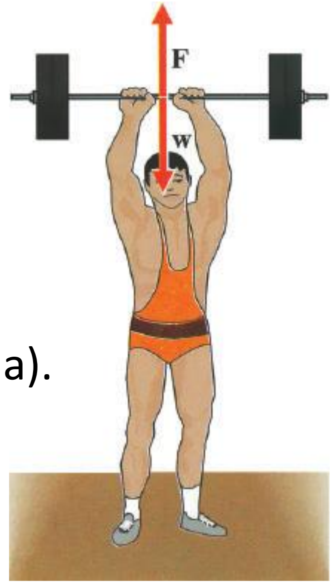
$$W = F_x \Delta x$$



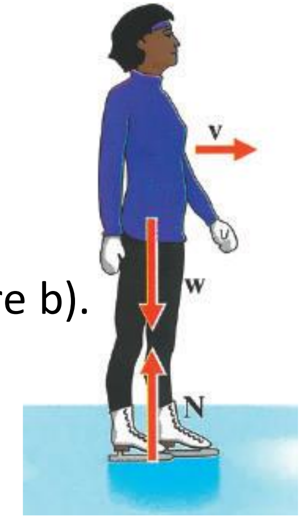
Work and Kinetic Energy

- If a body does not move, $\Delta x = \mathbf{0}$, and so, even though forces may act on the body, no work is done by those forces (Figure a).
- no work is done on a moving body by any force that is perpendicular to the direction of the body's motion (Figure b), since such a force has a zero component in the direction of motion.

(Figure a).



(Figure b).



Work and Kinetic Energy

- The unit of work is the unit of force times the unit of distance the Nm in SI. This unit is given the name "joule" (abbreviated J), in honor of James Joule, who demonstrated by numerous experiments in the nineteenth century that heat is a form of energy:

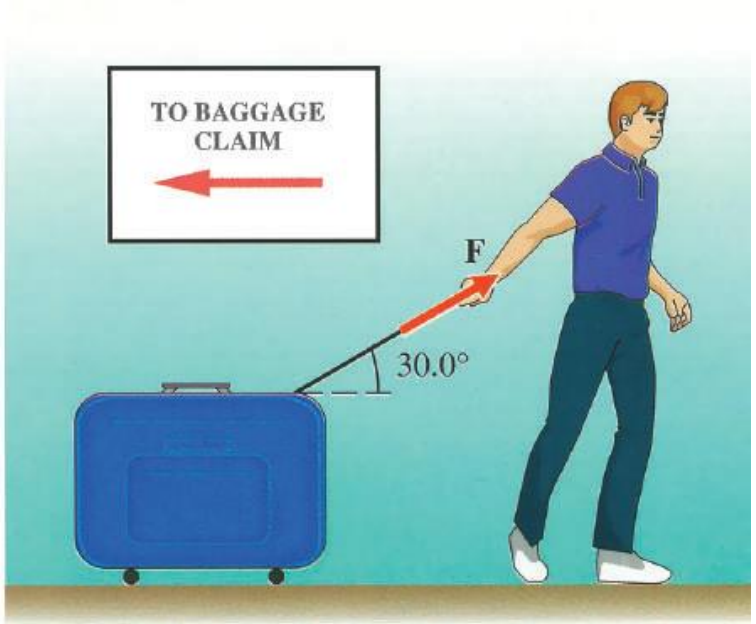
$$1 \text{ joule} = 1 \text{ N-m} = 1 \text{ kg-m}^2/\text{s}^2$$

- In the cgs system the unit of work is the *erg,* defined as a dyne-cm. Since $1\ N = 10^5\ dyne$ and $1\ m = 10^2\ cm$, $1\ N - m\ \ 10^7\ dyne - cm$ or

$$1 \text{ J} = 10^7 \text{ erg}$$

Work and Kinetic Energy

- **EXAMPLE 1 Pulling a Suitcase**
- An airline passenger pulls his suitcase a horizontal distance of 40.0 m, exerting a force **F** of magnitude 25.0 N, directed 30.0° above the horizontal. Find the work done by the force **F**.



$$W = F_x \Delta x = F \cos 30.0^\circ \, \Delta x$$

$$= (25.0 \text{ N})(\cos 30.0^\circ)(40.0 \text{ m})$$

$$= 866 \text{ J}$$

Work and Kinetic Energy

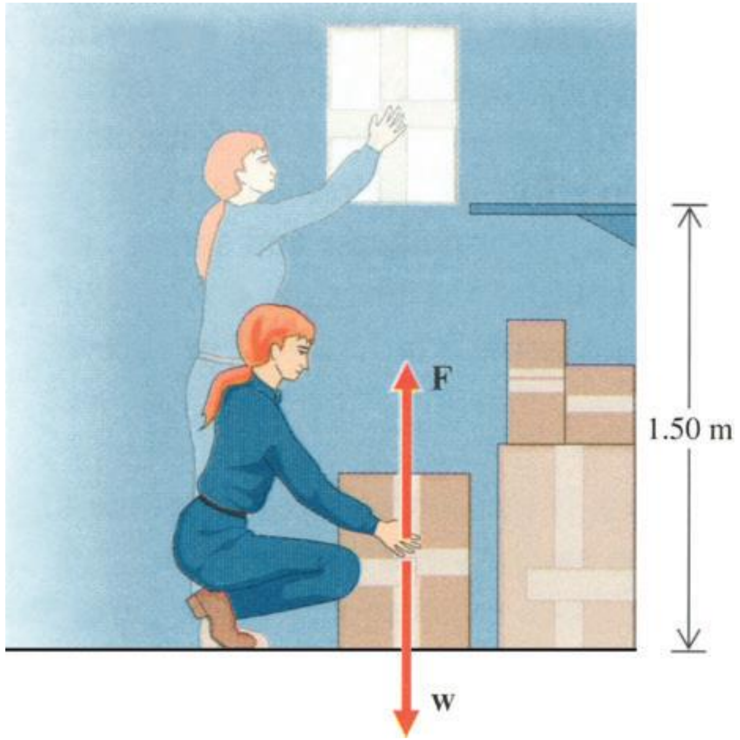
- **EXAMPLE 2 Lifting a Box**

A woman slowly lifts a box weighing 40.0 N from the floor to a shelf 1.50 m above

(a) Find the work done by the force F the woman exerts on the box.

(b) Find the work done on the box by its weight w.

(c) Find the net work done on the box.



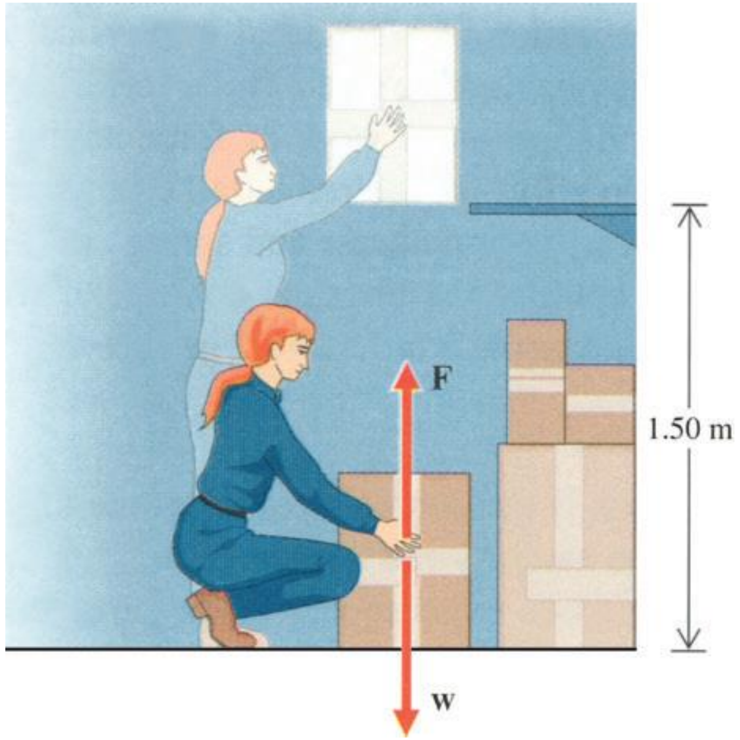
(a)

$$W_F = F_x \Delta x = F\,\Delta x = (40.0\text{ N})(1.50\text{ m}) = 60.0\text{ J}$$

Work and Kinetic Energy

(b)

$$W_w = w_x\,\Delta x = -w\,\Delta x = -(40.0\text{ N})(1.50\text{ m})$$
$$= -60.0\text{ J}$$



(c) The net work done on the box is the sum of the work done by each of the forces acting on the box. Net work equals zero:

$$W_{net} = \sum W = W_F + W_w = +60\text{ J} - 60\text{ J} = 0$$

Work and Kinetic Energy

- **Kinetic Energy**
- A body's **kinetic energy** K is defined to be half its mass m times the square of its speed v.

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

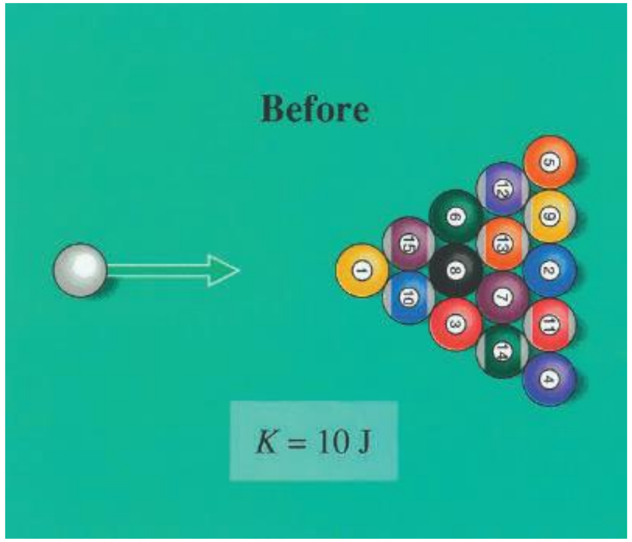
From its definition, kinetic energy must have units equal to mass units times velocity units squared—SI units of kg-$(m/s)^2$. Since 1 N = 1 kg-m/s^2, the SI unit of kinetic energy is N-m, or J, the same as the unit of work.

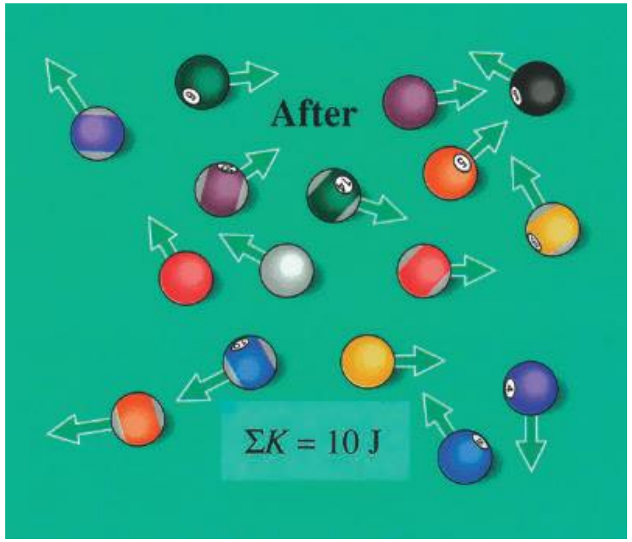
Work and Kinetic Energy

- Kinetic energy is conserved. A more interesting example of **conservation of kinetic energy** occurs in the game of pool.
- ball has a mass of $0.2\ kg$ and is initially moving at $10\ m/s$, its initial kinetic energy

$$K = \tfrac{1}{2}mv^2 = \tfrac{1}{2}(0.2\ \text{kg})(10\ \text{m/s})^2 = 10\ \text{J}$$

- The other balls are initially at rest and so have no kinetic energy.
- Just after the collision, the kinetic energy of $10\ J$ is shared among all balls





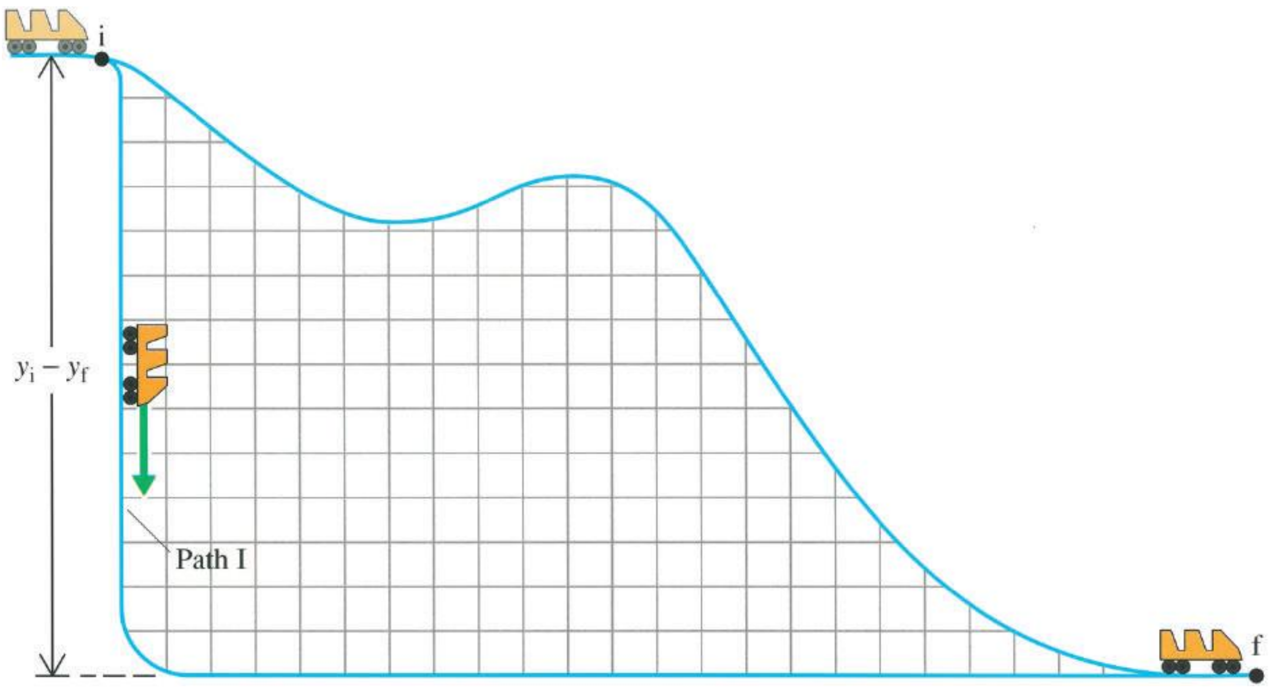
Work and Potential Energy

- Constant Gravitational Force
- The work done on a body on or near the earth's surface by the constant force of gravity.
- work always equals the decrease in a quantity called "gravitational potential energy," which depends on the body's elevation.
- when gravity is the only force doing work on a body, the sum of the body's kinetic energy plus its gravitational potential energy is conserved.

Work and Potential Energy

Work is done by the gravitational force

$$W_G = mg(y_i - y_f)$$
$$W_G = mgy_i - mgy_f$$



gravitational potential energy

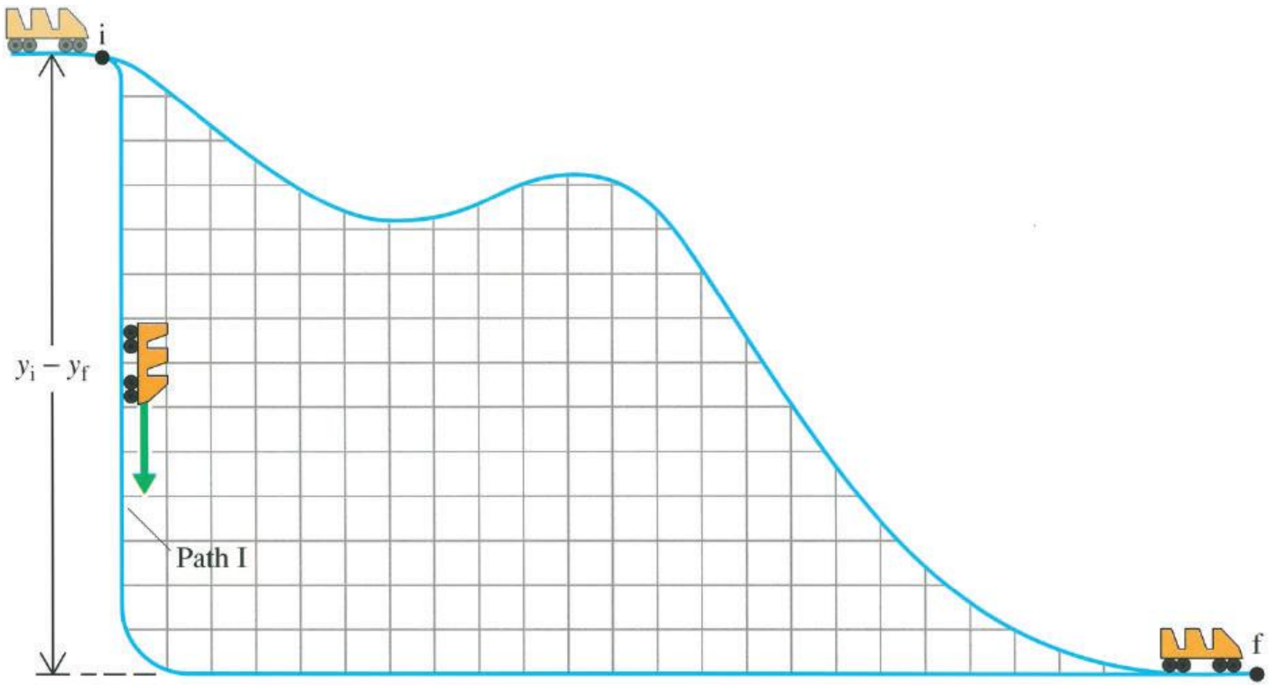
$$U_G = mgy$$

the work equals the difference in the values of the gravitational potential energy

$$W_G = U_{G,i} - U_{G,f}$$

Work Potential Energy

For example, suppose a roller coaster weighing $10^4\ N$ starts at an elevation of $40\ m$, where its potential energy $mgy = 4 \times 10^5\ J$, and falls to an elevation of $10\ m$, where its potential energy $mgy = 10^5 J$. No matter what path the roller coaster follows, the gravitational force does work on it equal to its decrease in potential energy of $3 \times 10^5\ J$

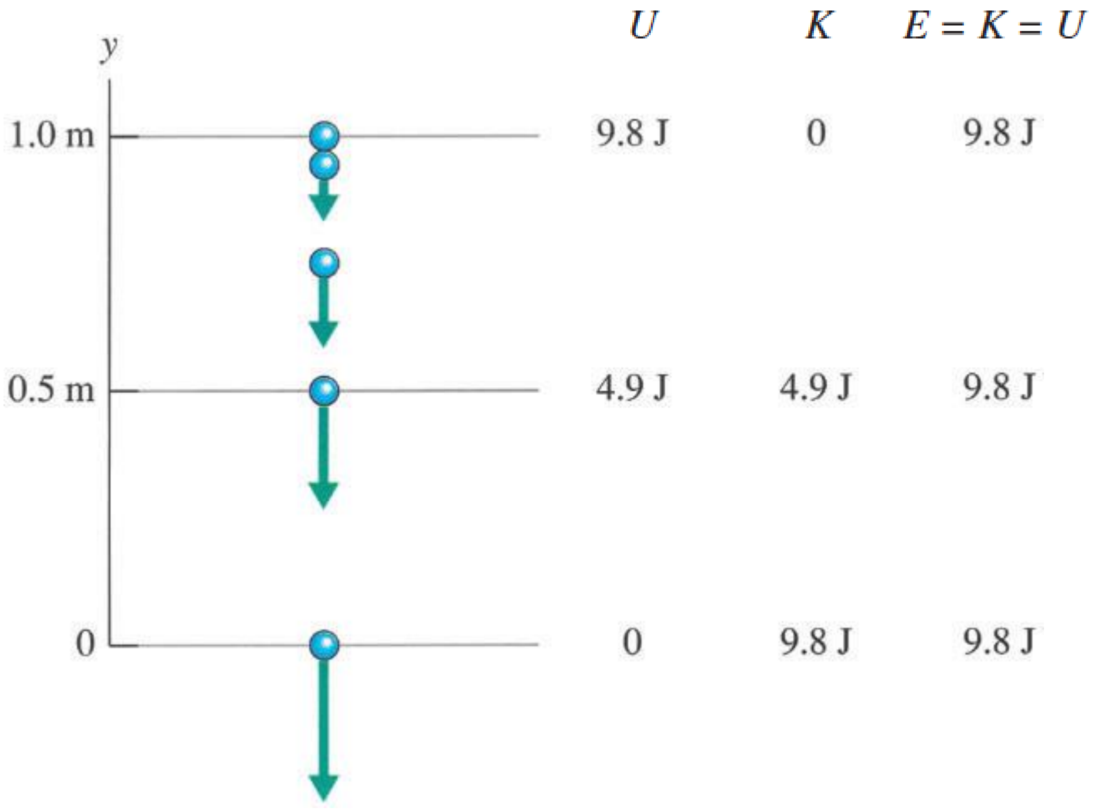


Total mechanical energy

- We define the total mechanical energy E to be the sum of the kinetic and gravitational potential energies:

$$E = K + U_G$$

- As a simple example of conservation of mechanical energy, consider a body in free fall.
- As a body falls, its speed increases. Its kinetic energy increases while its potential energy decreases, so that the sum of the two the total mechanical energy remains constant.
- This is illustrated in Fig. for a 1 kg body falling from rest through a distance of 1 m.



Power

- The rate at which work is performed by a force is defined to be the power output of the force. The average power, denoted by $\bar{P}$, is the work divided by the time Δt over which the work is performed.

$$\bar{P} = \frac{W}{\Delta t} \qquad \text{(average power)}$$

- The SI unit of power is the J/s, which is called the "$watt$" (abbreviated W), in honor of James Watt, the inventor of the steam engine.

$$1\ \text{W} = 1\ \text{J/s}$$

Heat Losses From Human Body

- The normal body contains stored heat and constant temperature $37^{\circ}C$. The body should have certain mechanism to keep this temperature constant despite of fluctuations in the environment temperature. These mechanisms are:

  - Radiation
  - Convection
  - Perspiration
  - Respiration

Heat Losses From Human Body

- **Radiation**

Body emit electromagnetic radiation of energy proportional to the fourth power of absolute temperature. This given by **Stefan Boltzmann Law**:

$$P = e\,\sigma\,T^4$$

$$Where\ \sigma = 5.7 \times 10^{-12}\ W/cm^2\ {}^{o}k^4$$

The emissivity e in the infrared region is independent of the color of the skin and is very nearly equal to 1.

Heat Losses From Human Body

- The body receives radiant energy from surroundings objects. The approximate difference between the heat radiated by the body and the heat absorbed from surroundings can be given by:

$$H_r = Kr\, A_r\, e\, (Ts - Tw)$$

H_r: the rate of energy loss (or gain) due to radiation.

A_r: effective area of the body emitting radiation.

T_s: skin temperature.

T_w: wall surrounding temperature.

K_r : radiation coefficient or constant that depends upon various physical parameters = 5 kcal/m^2. hr. ͦC.

Heat Losses From Human Body

- The heat loss due to convection (H_c) can be given by:

$$H_c = K_c A_C (T_s - T_a)$$

- H_c: Heat loss due to convection.
- K_c: convection coefficient or constant that depends upon the movement of the air and equal to 2.3 kcal /m2. hr. ̊C when the body is resting and there is no apparent wind.
- A_c: the effective surface area.
- T_s: the temperature of the skin.
- T_a: the temperature of the air.

Heat Losses From Human Body

- The previous mechanisms of losing heat depends upon:
  - Temperature.
  - Humidity.
  - Motion of the air.
  - Physical activity of the body.
  - The amount of body exposed.
  - The amount of insulation of body (clothes and fat).
- The hypothalamus of the brain contains the body' s thermostat. For example, if the core temperature rises, the hypothalamus initiates sweating and vasodilatation, which increases the skin temperature

The End

Do not forget to do your homework

The Energy to Run

- Why is it so much harder to run than to ride a bicycle at the same speed?
- When you ride a bicycle, it is after all your own body that produces your motion, just as when you run. And yet cycling requires much less effort than running. After 30 minutes or an hour of running along a level road at a moderate pace, even a well conditioned runner may tire, whereas a cyclist can keep the same pace with little effort.

The Energy to Run

- We say that “running burns calories” or that “running uses a lot of energy.”
- To understand the physical basis of such expressions, to see why running requires so much energy and is so much less energy efficient than bicycle riding, we shall apply concepts of work and energy to the human body.
- also extend concepts of work and energy to systems of particles such as human bodies and machines.
- in general, how energy is used by the body when muscles contract and specifically how that energy is used in running and cycling.

The Energy to Run

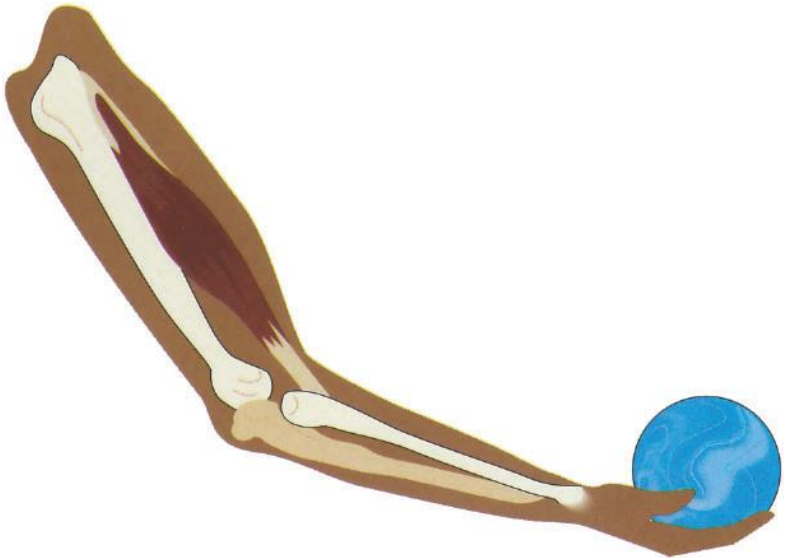
- The following are some general properties of work and energy associated with muscular exertion:

1. Work Done by Muscles

- Muscles consist of bundles of muscle fibers. Under tension, these fibers can shorten, or “contract,” as protein filaments within the fibers slide over each other.
- Contraction of a muscle fiber means that a force (the tension in the muscle fiber) acts through a distance (the distance the fiber contracts).
- The direct effect of a muscle’s contraction may be to move one of the body’s limbs.

The Energy to Run

- For example, if you hold a weight in your hand and contract the biceps muscle in your arm, your hand and forearm swing upward, raising the weight. The work done by your biceps muscle is approximately equal to the work done by the force your hand exerts on the weight.
- The effect of this work is to increase the weight's gravitational potential energy.



The Energy to Run

2. Heat Generated by the Body When Muscles Contract

- Heat, a disordered form of energy, is generated whenever muscles do work.
- Typically the quantity of heat generated when muscles contract is about three times as great as the work done by the muscles.
- When your muscles do very much work, you can usually feel the heat generated by your body.
- You may begin to sweat, which is a way the body gets rid of excess heat.

The Energy to Run

3. Internal Energy of the Body

- The body's internal energy is the total energy of all the particles within the body.
- Chemical reactions within the body provide the energy necessary to produce muscle contraction. The energy released by these chemical reactions produces the work and heat associated with muscle contraction.
- Conservation of energy implies that the body's loss of internal energy equals the sum of the work and heat generated.

Loss of internal energy = Work done by muscles + Heat generated

- When your body loses much internal energy in a short time interval, you tend to feel tired. Your body's internal energy is replenished by the consumption of food.

The Energy to Run

- Now we can use these basic concepts of work and energy to understand why cycling requires less energy than running.
- Suppose you ride a bicycle with, well-inflated tires and very little friction in its moving parts. Riding over flat, level pavement at 10 km/h, requires little effort.
- Once moving, both the kinetic energy and the gravitational potential energy of the bicycle and your body stay constant with just a little pedaling required.
- Consequently, only a little work needs to be done by your legs as they push against the pedals and your body loses little internal energy in producing this small amount of work. The work that is done by your legs is needed to compensate for the small negative work done by friction and air resistance. If you did not pedal at all, your bike would gradually slow down.

The Energy to Run

- In contrast to riding a bike, when you run on a flat, level surface, your kinetic energy and gravitational potential energy can never be exactly constant.
- Watch a runner and you will see that the runner's head moves up and down somewhat, an indication of some change in elevation of the runner's center of mass. This means that the runner's gravitational potential energy is not constant.
- Some of that energy is lost each time the runner's body moves downward, and this energy must then be supplied as the body moves up - ward again.
- More efficient runners, bob up and down less than average runners do and there by use less energy.

The Energy to Run

- A runner's center-of-mass kinetic energy also necessarily varies somewhat, again in contrast to that of a cyclist.
- this effect is more difficult to see, a runner's center of mass continually alternates between speeding up and slowing down with each stride.
- the variation in center-of-mass speed is slight, it does require a significant amount of work for the legs to increase the center of mass kinetic energy from the minimum value to the maximum value during each stride.