# 4 ENERGY & FIELDS

H2 Physics 9749

**Content** **Page**



**Learning Outcomes**

Candidates should be able to:

(a) show an understanding that physical systems can store energy, and that energy can be transferred from one store to another.

(b) give examples of different energy stores and energy transfers, and apply the principle of conservation of energy to solve problems.

(c) show an understanding that work is a mechanical transfer of energy, and define and use work done by a force as the product of the force and displacement in the direction of the force.

(d) derive, from the definition of work done by a force and the equations for uniformly accelerated motion in a straight line, the equation $E_K = \frac{1}{2}mv^2$.

(e) recall and use the equation $E_K = \frac{1}{2}mv^2$ to solve problems.

(f) show an understanding of the concept of a field as a region of space in which bodies may experience a force associated with the field.

(g) define gravitational field strength at a point as the gravitational force per unit mass on a mass placed at that point, and define electric field strength at a point as the electric force per unit charge on a positive charge placed at that point.

(h) represent gravitational fields and electric fields by means of field lines (e.g. for uniform and radial field patterns), and show an understanding of the relationship between equipotential surfaces and field lines. **[Equipotential surfaces not in H1 syllabus]**

(i) show an understanding that the force on a mass in a gravitational field (or the force on a charge in an electric field) acts along the field lines, and the work done by the field in moving the mass (or charge) is equal to the negative of the change in potential energy.

(j) distinguish between gravitational potential energy, electric potential energy and elastic potential energy.

(k) recall that the elastic potential energy stored in a deformed material is given by the area under its force-extension graph and use this to solve problems.

(l) define power as the rate of energy transfer.

(m) show an understanding that mechanical power is the product of a force and velocity in the direction of the force.

(n) show an appreciation for the implications of energy losses in practical devices, and solve problems using the concept of efficiency of an energy transfer as the ratio of useful energy output to total energy input.

## 1.1 Introduction

Now that we have learnt about the basics of forces and its relationship with motion, it is time to turn our attention towards another important concept in Physics – energy.

Using energy to analyse the motion of systems can be very powerful, because while forces often deal with analysing how each component of a system behaves at each instant, energy often uses a "big picture" approach to analyse a complex system.

We will begin by defining some broad terms relating to systems, before introducing different energy stores and transfers, and how these are all tied together by a very important and fundamental concept in Physics – the principle of conservation of energy.

## 1.2 Systems

In Physics, we often use the word "system" to describe a collection of objects that we would like to focus our analysis on.

As an example, when trying to understand how the planets move, we could call our entire Solar System a "system". However, we could also choose to focus only on the "system" consisting of the Sun and our Earth, leaving everything else (the Moon, the other planets…) outside of our "system".

### ❖ Types of systems

Systems can be broadly categorised into three different types, based on their ability to interact with their surroundings.

1. Open systems are systems that are able to exchange both energy and matter with their surroundings.

2. Closed systems are systems that are able to exchange energy, but not matter, with their surroundings.
3. Isolated systems are systems that are unable to exchange energy nor matter with their surroundings.

For example, a container of gas with a hole in its walls is an open system, since it is able to exchange both energy and matter (i.e. the gas particles) with the surroundings freely.

On the other hand, a sealed container of gas is a closed system. This is because although matter exchange with the surroundings is no longer possible, its walls are not insulated to prevent exchange of thermal energy with the surroundings. Therefore, for example, if the temperature of the gas in the container is higher than the surroundings, thermal energy will be able to flow from the gas to the surroundings.

Finally, an isolated system can be represented by a sealed container of gas with perfectly insulated walls, such that both matter and energy exchange with the surroundings are impossible.

Note that there should also not be any net external force doing work on an isolated system, because as we will soon learn, work done is actually a process of energy transfer in and out of systems. Hence, for isolated systems to have no energy exchange between itself and its surroundings, there must also be no work done on the system.

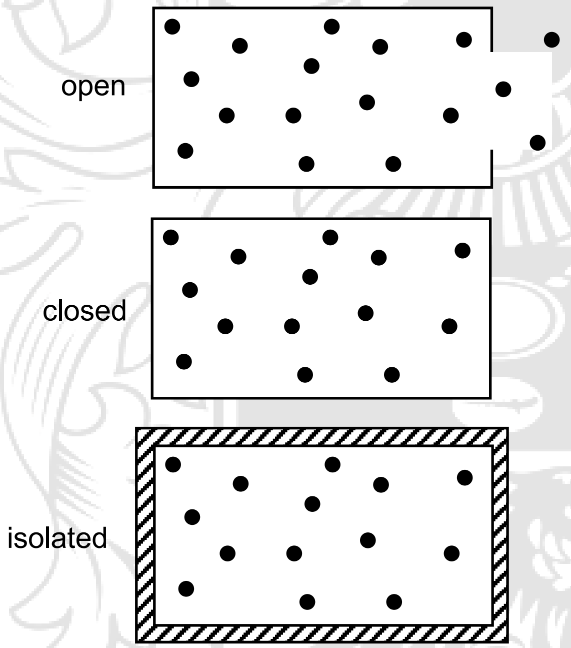



**Fig. 4.1**

### 1.3 Energy Stores & Transfers

From your previous studies in Physics, you would have learnt about energy as the capacity to do work. It is a quantity measured in Joules (J) as its SI unit.

You would also have learnt about the energy of a system being present in different stores, and how systems can transfer energy from one store to another. We are now going to expand on your previous knowledge of energy, energy stores and energy transfers with some new concepts.

### ❖ Energy stores

There are eight different types of energy stores in which systems store energy. They are:

| | |
|---|---|
| Kinetic energy | Magnetic potential energy † |
| Gravitational potential energy | Electric potential energy |
| Chemical potential energy | Nuclear energy |
| Elastic potential energy | Internal energy * |

†: Not covered in H1 / H2 Physics syllabus

*Note: You might have previously learnt and referred to this as thermal energy. However, in later topics within H2 Physics, we will learn to distinguish between internal energy and thermal energy.

A simple mnemonic device you can use to help you remember all eight is to visualise a group of men carrying a 1 kg block of ice (in Fig. 4.2):


**Fig. 4.2**

Remembering the words "MEN", "KG" and "ICE" should help you recall the eight energy stores, because it stands for Magnetic potential, Electric Potential, Nuclear, Kinetic, Gravitational potential, Internal, Chemical potential, Elastic potential.

A brief description of the nature of the energy in each store can be found in the table below.

| Energy stores | Description |
|---|---|
| Kinetic | Energy due to the motion of an object |
| Gravitational potential | Energy due to the position of a mass in an external gravitational field |
| Elastic potential | Energy due to the physical deformation of an object (e.g. compressing or stretching a spring) |
| Internal | Consists of two components: energy due to the random motion of atoms / molecules in a system (internal kinetic energy) and energy due to interatomic / intermolecular forces (internal potential energy) |

| | |
|---|---|
| Chemical potential | Energy due to the structural arrangement of atoms / molecules in a substance |
| Electric potential | Energy due to the position of a charge in an external electric field |
| Magnetic potential | Energy due to the orientation of a magnetic dipole to an external magnetic field† |
| Nuclear | Energy stored in atomic nuclei – released during fusion or fission processes |

†: Not covered in H1 / H2 Physics syllabus

### 1.4 Energy Transfers & Work Done

❖ **Energy Transfers**

Energy can be transferred from one store to another.

For example, when you drop a ball from rest, it falls to the ground – this process transfers energy from the ball's gravitational potential energy to its kinetic energy, since it gains speed as it travels towards the ground.

We can now ask ourselves the question: how does this energy transfer process even happen in the first place? What causes the energy to be transferred from the gravitational potential energy to the kinetic energy?

In this case, the answer is a concept you might be familiar with: there is work done by the gravitational force acting on the ball.

In general, there are four pathways for energy to be transferred from one store to another:

| Energy transfer pathways | Examples |
|---|---|
| Mechanical | Work done (by a force acting over a distance on a system) |
| Electrical | Energy transferred by an electric current |
| Heating | Energy transferred due to a temperature difference between two systems |
| Wave propagation | Mechanical waves (e.g. sound) or electromagnetic waves (e.g. light) |

We are now going to explore the first pathway, which is the concept of work done. We will be looking at how work done can be seen as a process of mechanical energy transfer between stores and even between systems.

❖ **Work done by a constant force**

In scientific terms, work is done by a force on an object when the object is moved in the direction of the force.

For example, a constant force $F$ acts on a box at an angle $\theta$ to the horizontal, and displaces it by $s$ horizontally to the right, as shown in Fig. 1.1.

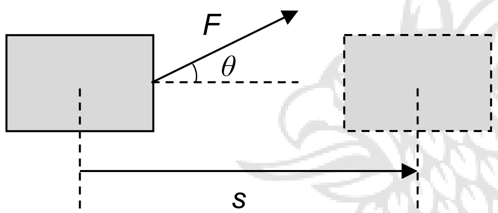



**Fig. 1.1**

The work done on the box by the constant force $F$ is given by

$$W = (F\cos\theta)s = Fs\cos\theta$$

where $F\cos\theta$ is the component of the force in the direction of the displacement.

> **Definition 1**
>
> Work done by a constant force is the product of the force and the displacement in the direction of the force.

Things to note:

- When the component $F\cos\theta$ is in the same direction as the displacement, the work done by the force is positive because $\cos\theta > 0$.
- When the component $F\cos\theta$ is in the opposite direction to the displacement, the work done by the force is now negative because $\cos\theta < 0$.
- The component $F\sin\theta$ of the force is perpendicular to the displacement, hence no work is done by this component.

Work done is a scalar quantity and its S.I. unit is the joule (J).

> **Definition 2**
>
> 1 J is the work done on an object by a force of 1 N when the object is displaced by 1 m in the direction of the force.

### ❖ Work done & Energy Transfers

Now, we have learnt before that the positive and negative sign for a vector quantity indicates its direction in space. (For example, a car with a velocity of 5 $ms^{-1}$ will be moving in the opposite direction to another car with a velocity of – 5 $ms^{-1}$.)

However, since work done is a scalar quantity, what would positive work done and negative work done mean then? What does it mean to do 5 J of work, as compared to – 5 J of work?

Consider an object moving to the right with a velocity $u$. If a force $F$ were exerted on the object towards the right (as shown in Fig. 4.3), intuitively we would agree that the object must accelerate and move faster as a result, which means its kinetic energy increases.

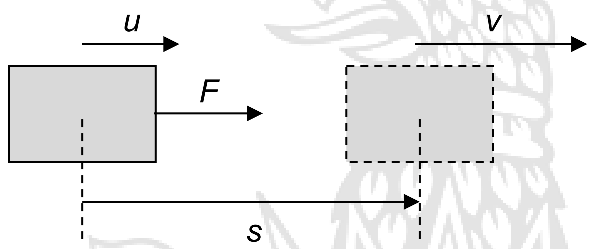



**Fig. 4.3**

At the same time, the work done on the object must be positive since the force $F$ and the object's displacement $s$ are in the same direction.

Hence, using this example, we can see that when the work done on an object (or a system) is positive, it results in an increase in the energy of the system. In other words, positive work done on the object results in a transfer of energy to the object.

Similarly, if a force $F$ were exerted on the same object, but towards the left (opposite to its velocity, as shown in Fig. 4.4), we would agree that the object will begin to decelerate and slow down, which means its kinetic energy decreases.

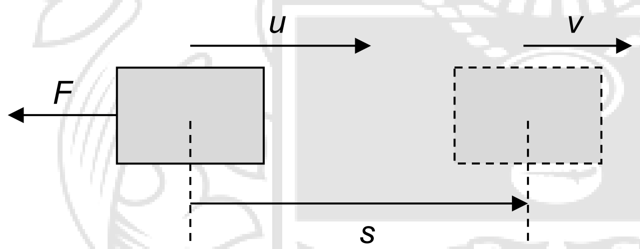



**Fig. 4.4**

In this case, the work done on the object is negative since $F$ and $s$ are in opposite directions – which implies that when the work done on an object is negative, there is a decrease of energy of the system, and there is a transfer of energy out of the system.

❖ **Work done by a variable force**

If the force $F$ acting on the object varies with displacement $s$, then the work done by the variable force $F$ over a displacement $s_1$ to $s_2$ can be determined by finding the area under the force – displacement graph, as shown in Fig. 4.5:

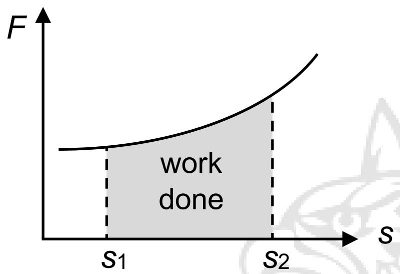



**Fig. 4.5**

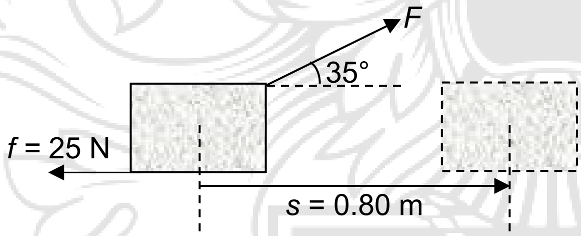
Hence, the work done can be calculated by applying:

$$W = \int_{s_1}^{s_2} F \, ds$$

(Note: *F* and *s* are parallel.)

**Example 1**

A force *F* of 50 N is applied on a box of mass 4.0 kg at an angle of 35° to the horizontal for a displacement *s* of 0.80 m horizontally. A constant frictional force *f* of 25 N acts on the box.




Calculate the work done on the box, by the

a) applied force *F*,

b) frictional force *f*, and

c) normal force *N* from the ground.

## 1.5 Kinetic Energy

We were previously talking about how doing work can lead to a change in the system's kinetic energy. Now, let us mathematically derive an expression for the kinetic energy of a moving body.

- **Derivation of kinetic energy**

Consider a body of mass *m* that is moving with an initial velocity *u*. It is acted on by a constant resultant force *F* which is parallel to *u*. The body accelerates with a uniform acceleration *a* to a final velocity *v* over a displacement s, as shown in Fig. 4.6.

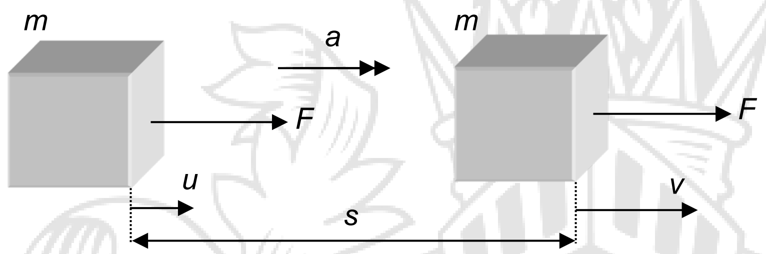



**Fig. 4.6**

Since the displacement of the body is in the same direction as the applied force,

$$W = Fs = (ma)s \quad ..... \quad (1)$$

From $v^2 = u^2 + 2as$

$$s = \frac{v^2 - u^2}{2a} \quad ..... \quad (2)$$

Substituting equation (2) into (1),

$$W = (ma)\left(\frac{v^2 - u^2}{2a}\right)$$

$$= \boxed{\frac{1}{2}mv^2 - \frac{1}{2}mu^2} \quad ..... \quad (3)$$

Thus, the work done *W* is equal to the change in the quantity $\frac{1}{2}m(\text{velocity})^2$, which is termed the kinetic energy, $E_K$.

In general, the kinetic energy $E_K$ of a body of mass *m* moving with speed *v* can be expressed as

$$\boxed{E_K = \frac{1}{2}mv^2}$$

Note that this is also known as the translational kinetic energy as it is the energy due to an object moving along a straight path.

## 1.6 Elastic Potential Energy

Another broad category of energy stores are the potential energy stores, which refers to the energy stored due to either an object's shape or its position in a field of force.

We are going to start our exploration of potential energy with one that falls in the former category – elastic potential energy. It will be explored within the context of the energy due to the stretching and compressing of a spring.

### ❖ Hooke's Law

The external force $F$ needed to produce an extension or compression $x$ in a spring that obeys Hooke's Law is $F = kx$, where $k$ is the spring constant. This force is a variable force as its magnitude depends on the extension or compression of the spring.

Therefore, suppose we stretch a spring by a displacement $x$ to the right by applying a force $F$ to the right. The (positive) work done on this spring system results in an increase in the energy of the system – in this case, energy is transferred to the system's elastic potential store. This energy is therefore stored as elastic potential energy.

Recalling that the work done is the area under the force-displacement graph, we can use the force-extension graph for the spring to find:

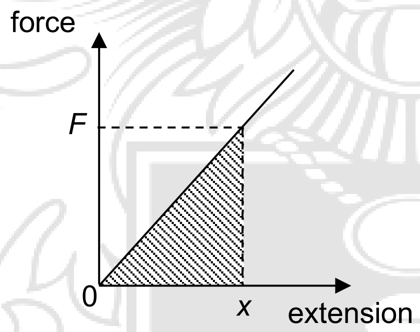



**Fig. 4.7**

Work done in stretching spring by $x$

= area under force-extension graph

$$= \frac{1}{2}Fx$$

Since $F = kx$,

$$W = \frac{1}{2}(kx)x = \frac{1}{2}kx^2$$

Note that the above expression can also be used when the spring is being compressed by a distance $x$.

And since this work done is equivalent to the increase in elastic potential energy stored in the spring, the elastic potential energy $U_E$ can be expressed as

$$\boxed{U_E = \frac{1}{2}kx^2}$$

Note that when the spring is at its natural length, $x$ = 0, and $U_E$ is zero.

❖ **Elastic potential energy & the elastic limit**

As shown above, the elastic potential energy stored in a spring when it is stretched is given by the area under its force-extension graph. The expression $\frac{1}{2}kx^2$ comes from an application of Hooke's Law for the stretched spring.

However, in real springs, the expression $\frac{1}{2}kx^2$ only applies when the stretched spring is below what is known as its proportionality limit.

On a force-extension graph, the spring being stretched beyond its proportionality limit is indicated by a departure from a linear graph (i.e. no longer obeying $F = kx$), as shown in curve A in Fig 4.8.

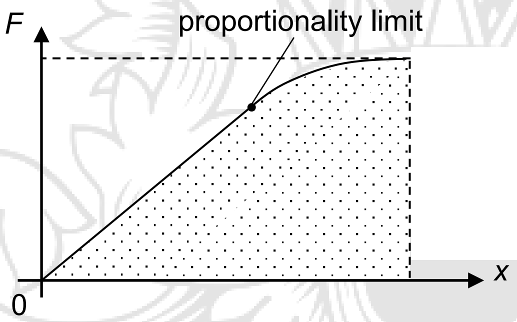



**Fig. 4.8**

While the elastic potential energy of such a spring cannot be found using the expression of $\frac{1}{2}kx^2$, it can still be found by finding the area under the graph (as shaded in Fig. 4.8).

## 1.7 Fields

As mentioned previously, certain types of potential energies arise from the position of an object in a field of force.

In this section, we will be looking at two different potential energies that fall in this category – gravitational potential energy, and electric potential energy.

However, before we begin, let's take a look at the concept of a field in Physics and how it can be represented visually.

❖ **Fields & Forces**

**Definition 3**

A **field** is a region of space in which an object placed in that region, with certain properties, will experience a force associated with the field.

The concept of a field is particularly useful for explaining what are known as “action-at-a-distance” forces. These are types of forces that result even when the two interacting objects are not in physical contact with each other, yet are able to exert a push or pull despite their physical separation. The region in which each point is affected by such a force is called a field.

For example, a gravitational field is a region of space in which an object with mass experiences a gravitational force. Objects fall to the ground because they are affected by the force of Earth’s gravitational field.

Similarly, an electric field (which we will explore later on) is a region of space in which an object with charge experiences an electric force. An electric field surrounds an electric charge; when another charged particle is placed in that region, it experiences an electric force that either attracts or repels it.

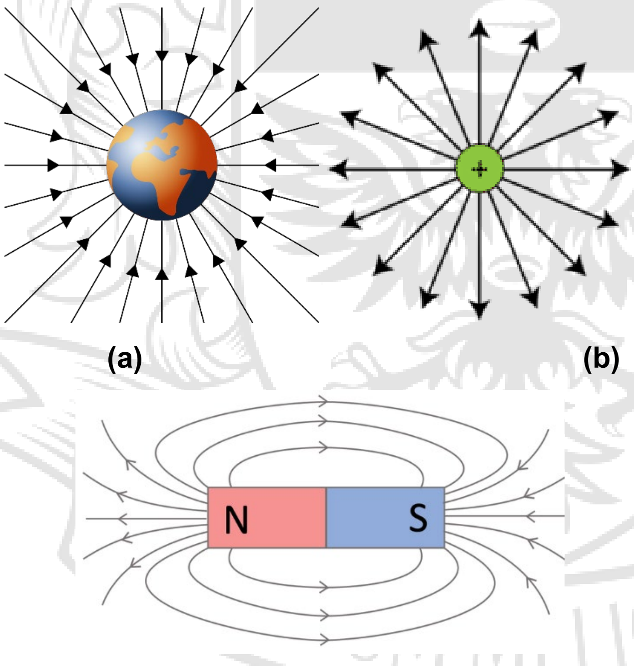
## ❖ Representation of fields

A field can be visualised as consisting of an array of imaginary field lines. The force on an object placed at a point on a field line acts along the tangent at that point.

Notes:

- The direction of the field lines indicates the direction of the field.
- The density of the field lines (i.e. how closely spaced they are) indicates the strength of the field.
- Field lines do not cross each other.
- For a point source or a uniform spherical source, its field lines are all along the radial direction, either pointing towards or away from the centre of the source.

Fig. 4.9 (a), (b) and (c) shows examples of field lines for gravitational fields, electric fields and magnetic fields respectively.




(c)

**Fig. 4.9 (a)(b)(c)**

## 1.8 Gravitational Potential Energy

### ❖ Gravitational field strength

**Definition 4**

The **gravitational field strength *g*** at a point in space is defined as the gravitational force $F_G$ experienced per unit mass *m* at that point.

$$g = \frac{F_G}{m}$$

From the above definition, we can see that

$$F_G = mg$$

which shows that the gravitational force $F_G$ experienced by an object placed at a point in a gravitational field increases proportionately with the mass *m* of the object.

Fig. 4.10(a) shows the gravitational field lines around Earth, directed towards its centre. The direction of gravitational field lines represent the direction of the gravitational force acting on a small mass placed at that point in the field – hence, gravitational forces are always attractive, and directed towards the centre of the source (e.g. Earth).

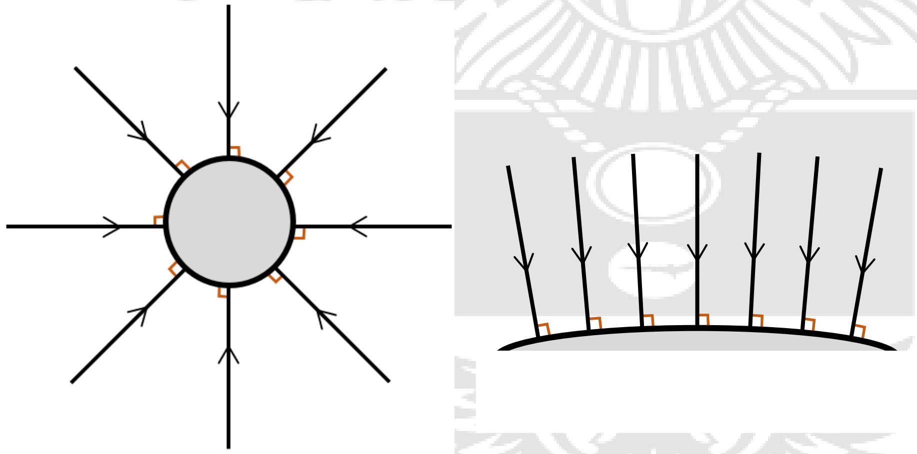


**Fig. 4.10(a)** **Fig. 4.10(b)**

Zooming into a region near the surface of Earth, the field lines seem to be parallel to each other and evenly spaced as shown in Fig. 4.10(b).

Hence, near the surface of the Earth, we can consider the gravitational field to be approximately uniform. On top of that, since the field lines are downwards, objects with mass in such a field will experience a gravitational force (i.e. weight) acting downwards.

## ❖ Gravitational Fields & Gravitational Potential Energy

How are these gravitational fields linked to the concept of gravitational potential energy?

Let us look at the simple case of the gravitational field near the suface of Earth, which can be considered to be uniform. An object of mass $m$, initially on the ground, is brought upwards at a constant velocity $u$ for a displacement $h$, as shown in Fig. 4.11.

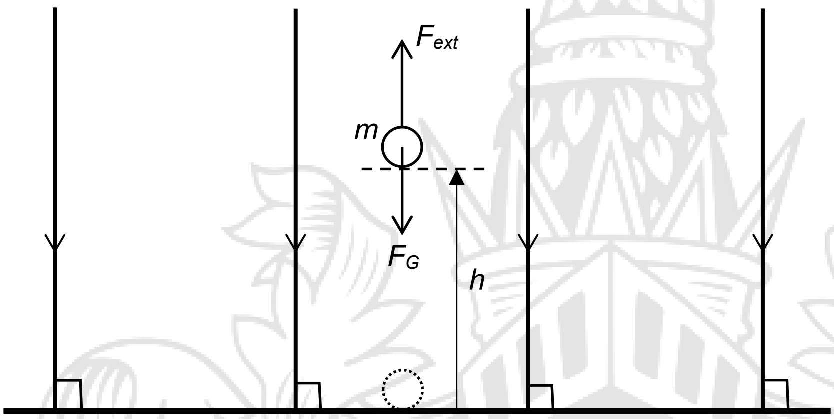



**Fig. 4.11**

During its displacement upwards, a constant gravitational force $F_G = mg$ is acting downwards on the mass. This is known as the weight of the object.

(Note: This gravitational force is, of course, due to the gravitational field. Since the gravitational field is uniform, the gravitational force is constant.)

An external force $F_{ext}$ is also exerted on the object in order to lift it up. Since the object is moving with a constant velocity, we can also conclude that magnitude-wise, $F_G = F_{ext} = mg$.

Since the object is displaced upwards, the work done $W_{ext}$ by the external force $F_{ext}$ is given by

$$\begin{aligned} W_{ext} &= (F_{ext})h\cos\theta \\ &= (mg)h\cos(0°) = mgh \end{aligned}$$

Although $F_{ext}$ does work on the object, there is no change in its kinetic energy since it is moving at constant velocity. So, where did the energy transferred due to the work done $W_{ext}$ go to?

To answer the above question, we simply have to release the object at a height $h$ above the ground.

From our kinematics equations, we can find the speed $v$ of the object just before it hits the ground to be

$$\begin{aligned} v^2 &= u^2 + 2as \\ &= u^2 + 2gh \end{aligned}$$

By rearranging and multiplying both sides by $\frac{1}{2}m$, we see that

$$\frac{1}{2}mv^2 - \frac{1}{2}mu^2 = mgh$$

This shows that the increase in kinetic energy of the object as it falls back down to to the ground by a displacement $h$ is equal to $mgh$, which is the work done by the external force $W_{ext}$.

We can therefore conclude that $W_{ext}$ is not lost, but is in fact stored by the object, and that this energy from $W_{ext}$ is recoverable as kinetic energy.

We can now define this stored energy due to the work done by the external force against the gravitational force as the object's gravitational potential energy, $U$, where the change in the object's gravitational potential energy $\Delta U$ is given by

$$\Delta U = W_{ext} = mgh$$

The absolute value of gravitational potential energy $U$ holds little significance, since it can be changed by simply choosing a different point of reference for $h$. Hence, the change in the gravitational potential energy $\Delta U$ arising from a change in position of the body in the gravitational field is the more important quantity.

The point where gravitational potential energy is taken to be zero is arbitrary. Therefore, if the Earth's surface is taken as the reference level with zero gravitational potential energy, an object raised to a height $h$ above the Earth's surface acquires a gravitational potential energy $U$ given by

$$\boxed{U = mgh}$$

Note:

- The zero potential energy level can be assigned to any point that is convenient.
- The acceleration of free fall $g$ is assumed to be constant near the Earth's surface.

On the other hand, we note that the gravitational field also does work on the object as it exerts a force $F_G$ downwards on the object as it is being displaced upwards by $h$.

The work done $W_G$ by the gravitational force $F_G$ is given by

$$\begin{aligned} W_G &= (F_G)h\cos\theta \\ &= (mg)h\cos(180°) = -mgh \end{aligned}$$

Note that the work done is negative because the gravitational force and displacement are in opposite directions.

Hence, by comparing $W_G$ and $\Delta U$, we can see that there is a simple relationship between the work done by the gravitational field and the change in the object's gravitational potential energy, which is

$$W_G = -\Delta U$$

In fact, this is a general relationship that links a field, its associated force, and its associated potential energy.

**Definition 5**

The work done $W$ by the field in moving the object in the field is equal to the negative of the change in its potential energy $U$.

$$W = -\Delta U$$

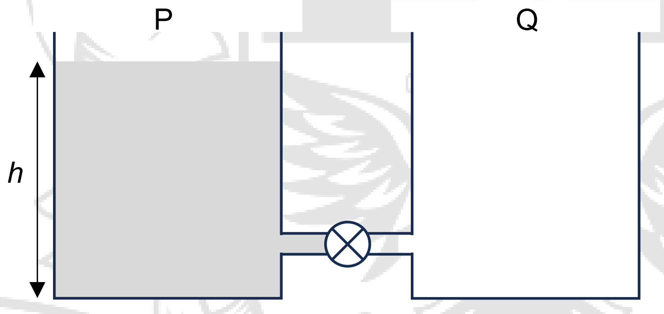
**Example 2**

A 2.0 kg box is released from the top of a frictionless slope. It slides a distance of 3.0 m down the slope, which is inclined at an angle of 30° to the horizontal.

a) Find the work done by gravitational force on the box.
b) Find the change in gravitational potential energy of the box.

**Example 3**

The diagram shows two identical containers P and Q connected by a short pipe with a tap. Initially, P is filled with water of mass $m$ to a depth $h$, and Q is empty.




When the tap is opened, water flows from P to Q until the water level in both containers is the same.

How much potential energy is lost by the water?

### ❖ Force & Potential Energy

We now need to consider the relationship $W = -\Delta U$ in a more general case, where the force associated with the field doing the work is not constant. Recalling our definition for work done for a varying force, we see that

$$W = \int F \text{ ds} = -\Delta U$$

Using the fundamental theorem of calculus, which links integration with differentiation, we can conclude that

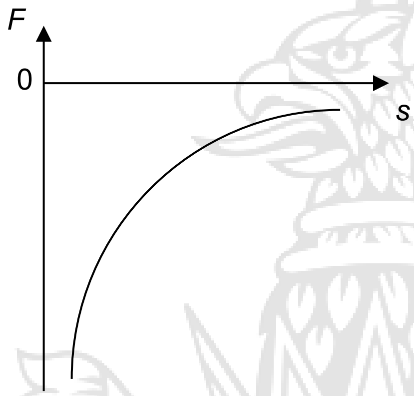
$$\boxed{F = -\frac{dU}{ds}}$$

This expression provides a relationship between the field's force and its associated potential energy. It shows that the magnitude of the force is equal to the potential energy gradient, and acts in the opposite direction to this gradient (i.e. the force acts in the direction of decreasing potential energy).

For example, the gravitational force due to a gravitational field near the surface of Earth acts downwards, which is the direction of decreasing gravitational potential energy.

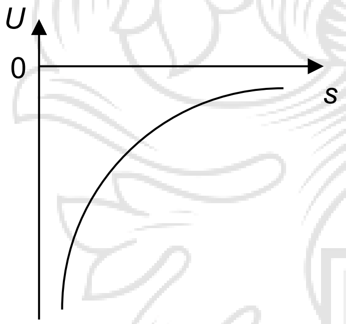
**Example 4**

The graph below shows the variation with displacement *s* of the force *F* on an object in a field.

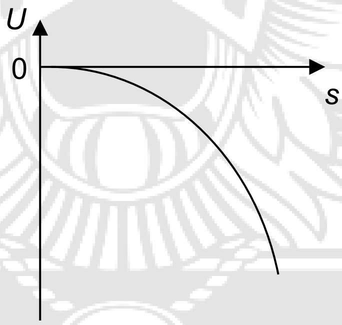



Which graph best represents the variation with displacement *s* of the potential energy *U* of the object?

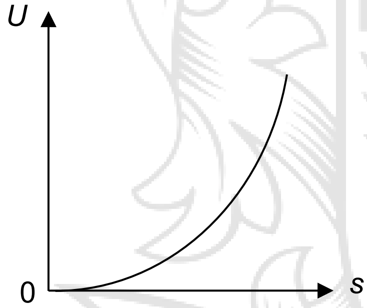
**A**



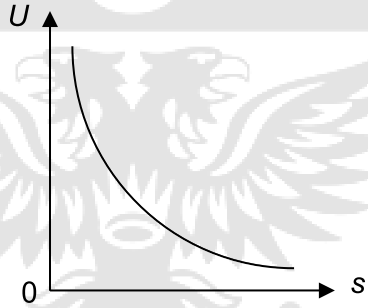

**B**




**C**




**D**



## 1.9 Electric Potential Energy

We are now going to turn our attention towards another common type of potential energy, which is electric potential energy. We are going to look at both its similarities and differences with gravitational potential energy.

### ❖ Electric Field Strength

**Definition 6**

The **electric field strength *E*** at a point in space is defined as the electric force $F_E$ experienced per unit positive charge at that point.

$$E = \frac{F_E}{q}$$

From the above definition, in a similar way to gravitational field strength, we can see that

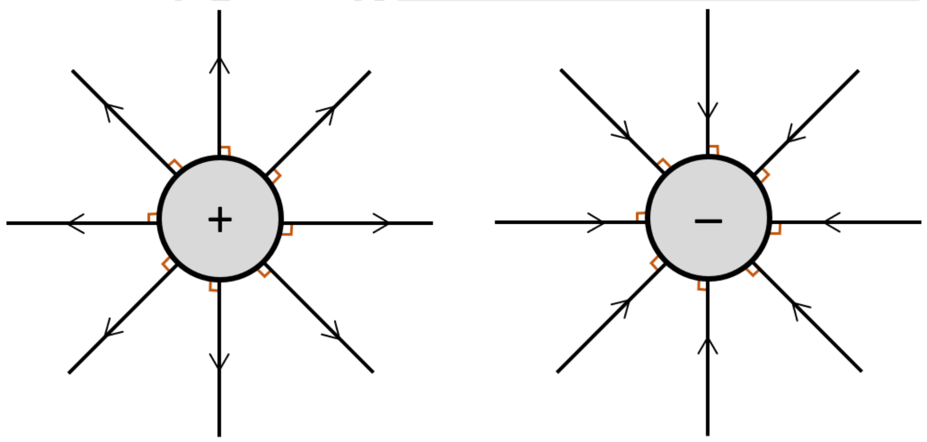
$$F_E = qE$$

which shows that the electric force $F_E$ experienced by a charged object placed at a point in an electric field increases proportionately with the charge $q$ of the object.

However, when it comes to representing electric fields with field lines, there is an important difference between electric and gravitational fields.

Firstly, unlike gravitational field lines which are always pointing inwards and towards its source, electric field lines can be pointing either inwards or outwards, depending on the sign of the charge of the source.

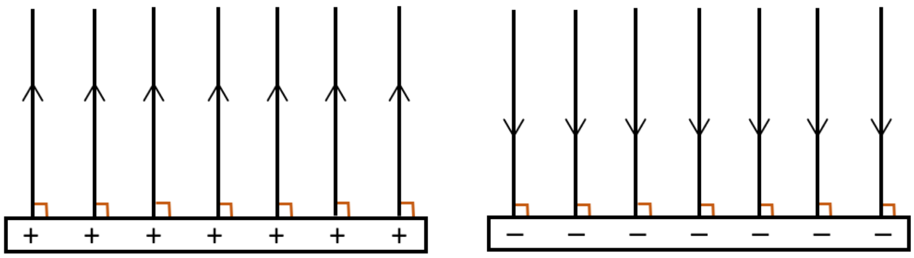
Positive point or spherical charges produce electric fields that point outwards, while negative point or spherical charges produce electric fields that point inwards, as shown in Fig. 4.13.




(a) (b)

**Fig. 4.13**

An electrically charged plate produces a uniform electric field with equally spaced field lines, much like the gravitational field near the surface of the Earth. This is shown in Fig. 4.14.




**(a)** **(b)**

**Fig. 4.14**

A positively charged plate produces electric fields pointing away from it, while a negatively charged plate produces electric fields pointing towards it.

The direction of these field lines indicate the direction of the electric force experienced by a small positive test charge placed at that point in the field. A small negative test charge will experience an electric force in the opposite direction to the field lines.

Hence, as an example, a positive charge placed in the electric field of another positive charge will feel an outward repulsive force, while a negative charge will feel an inward attractive force towards the positive charge. This is shown in Fig. 4.15.

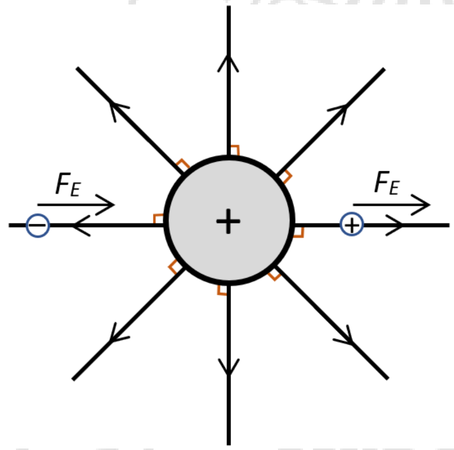



**Fig. 4.15**

❖ **Electric Fields & Electric Potential Energy**

Analagous to gravitational fields, the work done *W* by the electric field in moving a charge in the field is equal to the negative of the change in the electric potential energy $U_E$.

$$W_E = -\Delta U_E$$

The difference, however, is that the direction of the electric force that does the work can change depending on the relative charges of the objects involved.

For example, a positively charged particle $+q$ is moved a displacement $x$ away from a positively charged plate at a constant velocity.

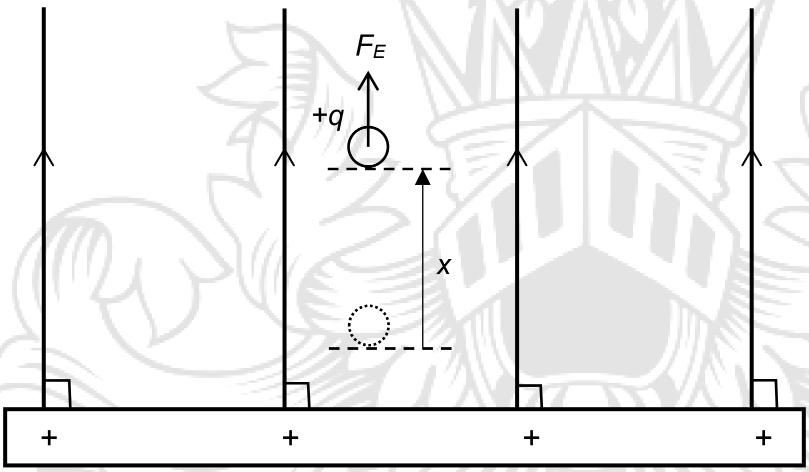



**Fig. 4.16**

In the uniform electric field, the particle experiences a constant electric force $F_E$ acting away from the plate.

Since the electric force and the displacement are in the same direction, the work done $W_E$ by the field on the particle is positive. Hence, for $W_E = -\Delta U_E$ to hold true, $\Delta U_E < 0$.

In other words, the electric potential energy of the charged particle has decreased.

Let's look at another example. A negatively charged particle $-q$ is moved a displacement $x$ away from a positively charged plate at a constant velocity.

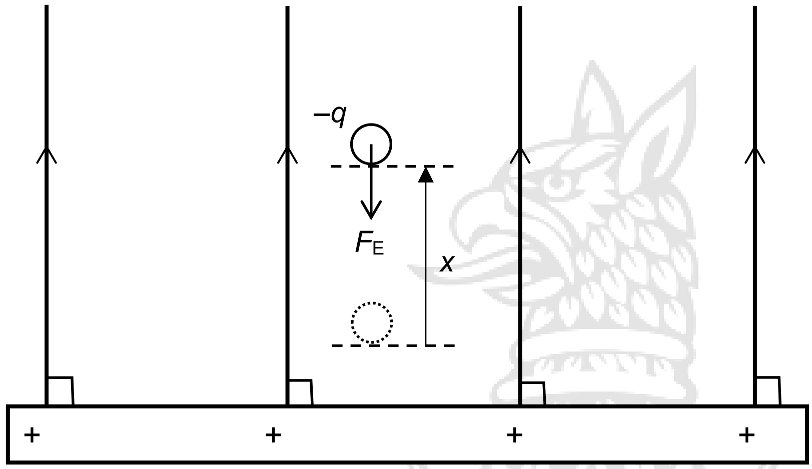



**Fig. 4.17**

In this example, the particle experiences a constant electric force $F_E$ towards the plate.

Since the electric force and the displacement are in opposite directions, the work done $W_E$ by the field on the particle is negative. Hence, for $W_E = -\Delta U_E$ to hold true, $\Delta U_E > 0$.

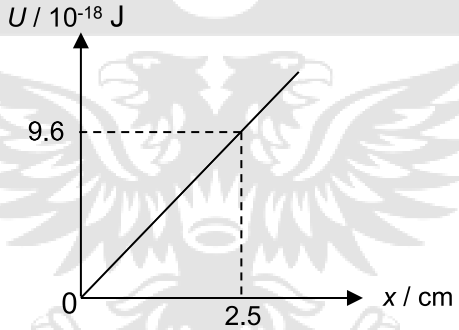
In other words, the electric potential energy of the charged particle has increased.

Note that the relationship $F = -\dfrac{dU}{ds}$ still applies to the electric force $F_E$ and the electric potential energy – the electric force always acts in the direction of decreasing electric potential energy.

**Example 5**

The graph shows the variation with distance $x$ of the electric potential energy $U$ of an electron in a uniform electric field.

Find the electric force acting on the electron.



## 1.10 The Principle of Conservation of Energy

You should be familiar with the principle of conservation of energy. It is, after all, one of the most fundamental cornerstone principles in Physics.

**Definition 7**

The principle of conservation of energy states that energy cannot be created or destroyed. It can only be transferred or transformed from one form to another.

Recall what we have learnt about an isolated system in section 1.2: since they do not exchange matter or energy with its surroundings, and they do not have any net work done on them, the energy in an isolated system can only be transferred from one store to another – this keeps the total energy of the system constant.

For an isolated system, the principle of conservation of energy can be written as a simple energy equation:

$$E_{initial} = E_{final}$$

where $E_{initial}$ and $E_{final}$ are the initial and final energies of the system.

However, for a non-isolated closed system, where there is work done $W$ by an external force on the system, the energy equation is:

$$E_{initial} + W = E_{final}$$

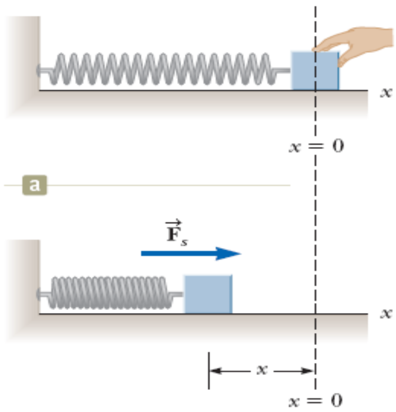
Note that the work done $W$ can be either positive (energy transferring into the system, such as an external force accelerating a cart) or negative (energy transferring out of the system, such as the frictional force declerating a cart).

## Example 6

A block of mass 0.50 kg is pushed against a spring of spring constant $k = 40\ \text{N m}^{-1}$.

The spring is compressed by 10.0 cm and released.

Calculate the maximum speed achieved by the block as it leaves the spring.

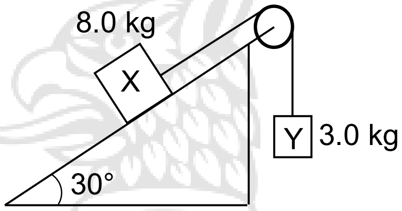


**Example 7**

A system of two bodies X and Y weighing 8.0 kg and 3.0 kg respectively are connected by a light cord that is passed over a light-free running pulley, as shown.

Starting from rest, X moves down a smooth plane inclined at 30° to the horizontal.

When X has travelled 2.0 m along the plane, what is the total kinetic energy of the system?




## 1.11 Power & Efficiency

❖ **Power**

To illustrate the concept of power, consider two different motors which are used to lift the same object to the same height above the ground. The same amount of work can be done by a low-powered motor over a longer duration of time or a high-powered motor in a shorter time.

**Definition 2**

Power is defined as the rate of work done or energy transfer with respect to time.

$$P = \frac{\mathrm{d}W}{\mathrm{d}t}$$

If total work done is $\Delta W$ in a time interval $\Delta t$, the average power is given by $\langle P \rangle = \frac{\Delta W}{\Delta t}$.

The S.I. unit of power is the watt (W). Another common unit of power is horsepower. Note that kilowatt-hour (kWh) is a unit of energy, not of power.

### ❖ Power from a constant force

If a **constant force *F*** is applied on an object, and does work by moving the object a displacement *s* in time *t*, then the power supplied is given by the following derivation:

$$P = \frac{dW}{dt} = \frac{d(Fs)}{dt} = F\frac{ds}{dt}$$

(Note: *F* and *s* are parallel)

Since $v = \frac{ds}{dt}$, where v is the velocity of the object,

$$\boxed{P = Fv}$$

### ❖ Efficiency

When utilizing energy in our daily lives, not all energy input is converted into useful energy output. For example, the work done by friction on a moving car is converted to thermal and sound energy, which are useless for us. In practice, it is common that the useful energy output is less than the energy input due to the presence of dissipative forces such as friction or drag.

Efficiency gives a measure of how much of the total energy may be considered useful and is not "lost". It is given by the expression:

$$\eta = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

When solving efficiency problems, it is important to have a clear idea of what "useful energy output" is. For example, when accelerating a car, the useful energy output is the increase in kinetic energy of the car; when heating a pot of water, the useful energy output is the increase in the internal energy of the water in the pot, as measured by the temperature of the water.

**Example 8**

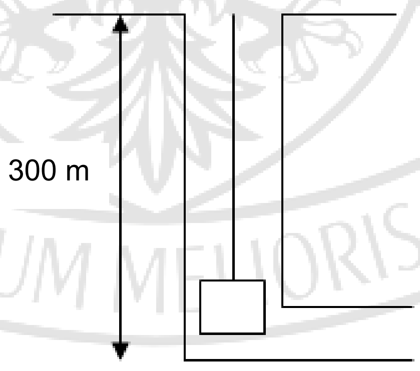
A machine is used to lift coal out of a coal mine.

a) How much work is done by the machine in raising 500 kg of coal out of the mine?

b) If the machine takes 20 minutes to accomplish the lift, what is its average power?

c) Explain why the actual power needed will be greater than that in (b).

d) If the power loss is 3.00 kW, what is the efficiency of this process of lifting coal?



**Example 9**

A car of mass 900 kg has an engine efficiency of 22%. Find the amount of petrol used to accelerate the car from rest to 20 m s$^{-1}$. Assume 1 kg of petrol provides $5.0 \times 10^{7}$ J of energy. Explain the energy conversion of the car.

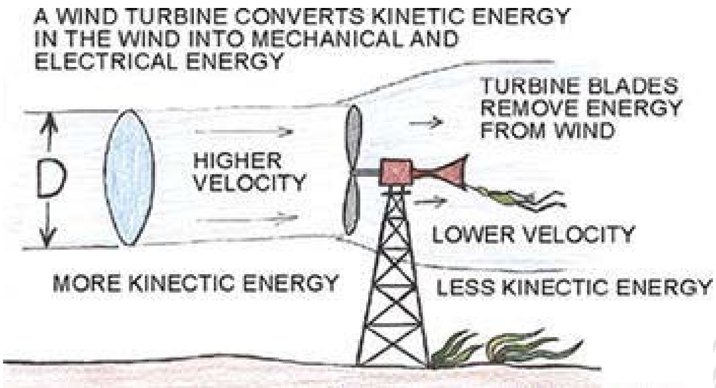
**Example 10**

A locomotive develops a constant power. The locomotive pulls a train of total mass $3.0 \times 10^{5}$ kg against a constant frictional force of $5.0 \times 10^{4}$ N. The acceleration of the train is 0.50 m s$^{-2}$ when travelling at 10 m s$^{-1}$.

What is the maximum speed that the train can achieve on a level track?

**Example 11**

The principle of operation of a wind turbine in which the kinetic energy of the wind is converted into electrical energy is shown below.




One of the world's largest wind turbines has a diameter of 122 m. If at a given time the speed of the wind immediately before and after passing through the blades are 16 m $s^{-1}$ and 14 m $s^{-1}$ respectively, calculate

a) the mass of air per second through the area swept out by the blades, given that the density of air before passing through the blades is 1.3 kg $m^{-3}$,

b) the power output, given that the energy removed from the wind is converted to electrical energy with an efficiency of 70%.