Solenoid valve – electromagnetism

Topic areas

Electrical and electronic engineering:

- The solenoid
- Magnetic flux, Φ
- Magnetic flux density, B
- Magnetomotive force, F_m
- Field strength, H
- Permeability, μ_0 and μ_r

Prerequisites

None.

Problem statement

Many engineering applications involve the transport and control of fluids, especially in areas such as chemical engineering and petrochemical plants.

Fluids are generally transported through a series of pipes and flow is controlled using valves that either allow or block the flow. A simple and familiar example of a valve is a kitchen or bathroom tap.

However, it is impractical to use a manually controlled valve on a large plant, so instead, remotely operated solenoid valves are used. What is a solenoid valve, and how are they designed and controlled?

Above: A solenoid valve controlling flow in a chemical engineering plant

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Activity 1 – Discussion

An electromagnet is a type of magnet that produces a magnetic field when a current flows through it. The magnetic field produced by an electromagnet behaves exactly the same as a magnetic field produced by a permanent magnet:

- It has a north and south pole.
- It attracts certain types of metals, especially iron and alloys of iron.

However, an electromagnet has the advantage over a permanent magnet in that the magnetic field can be turned off by turning off the current.

The resource **Solenoidvalve.html** can be used to demonstrate a practical design for a normally closed solenoid valve – no fluid flows unless action is taken. When the solenoid is powered, the metal plunger is pulled upwards allowing fluid to flow.

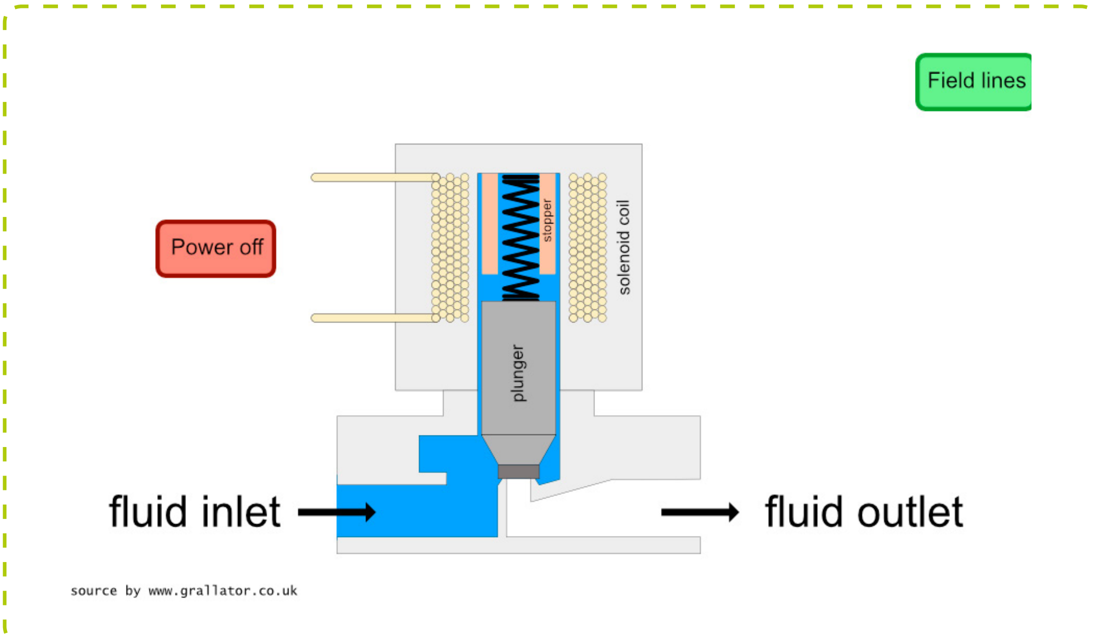
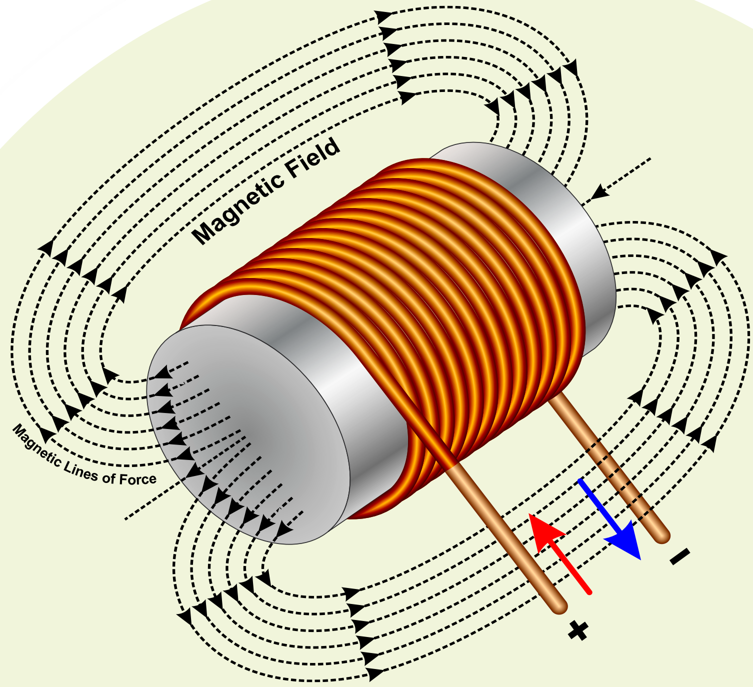


Figure 1
Screen shot of interactive resource

1 Sketch an outline design for a valve that is normally open, but closes to prevent flow when the electromagnet is turned on.



Background – how strong is a magnet?

In order to attract the metal plunger in a solenoid valve, the magnetic force must be sufficient to overcome the force of the spring, and in the case of the example valve shown in **Solenoidvalve.html**, the force of gravity pulling the plunger down. Further, the attraction between a magnet and metal object depends on the object's distance to a pole and its position relative to the magnet's axis.

The magnetic flux, Φ, is a measure of the intrinsic strength of a magnet. It is measured in units of weber (Wb). It is conceptually helpful to think of flux lines emanating from the north pole of a magnet and closing again at the south pole (magnetic flux lines are always closed).

The strength of a magnetic field at a given point is given by the magnetic flux density, B (see **Figure 2**). It is a measure of how closely packed the magnetic field lines are through a given area and is measured in units of Wb m^{-2} or, equivalently, tesla (T). In equation form, the flux density is given by:

$$B = \frac{\Phi}{A}$$

The resource **magneticfields.html** shows a bar magnet. The slider lets you change the magnetic flux, while the button option "Flux density" draws three unit areas in different locations. The number of flux lines that pass through an area gives the flux density at a point at the centre of the circle.

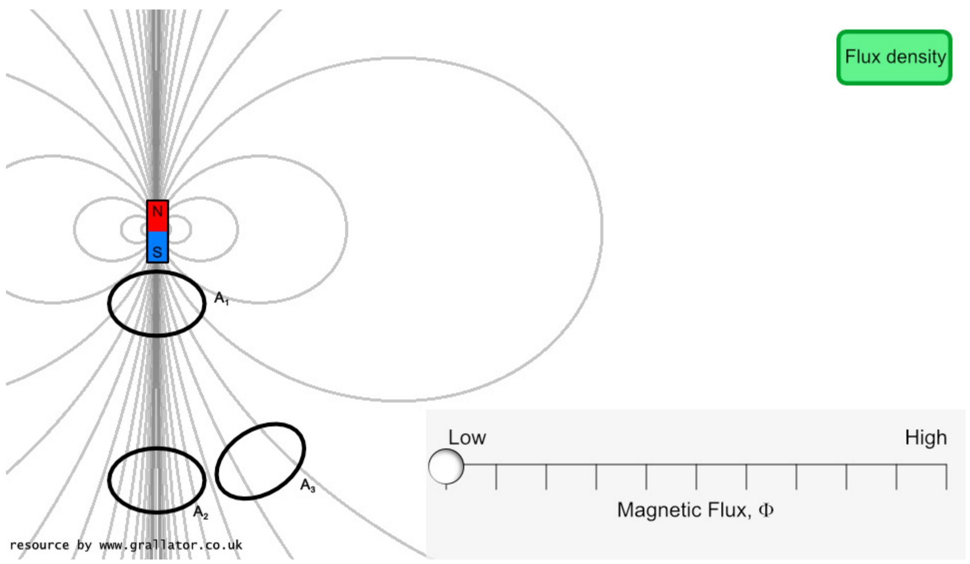


Figure 2
Screen shot of interactive resource

In **Figure 2**, the magnetic flux density is highest at A_1, followed by A_2 then A_3. A metal object will feel the strongest attraction where the flux density is the highest. Increasing the total flux by moving the slider increases the flux density at each point. When increased enough, a strong magnet will have the same flux density at, for example A_2, as a weaker one would at A_1. Metal objects at these two locations for the two different strength magnets would feel the same attractive force.

Activity 2 – current in a wire and making a solenoid

When a current flows in a wire it produces a circular magnetic field around the wire, as shown in **Figure 3(a)**. The direction of the field is anticlockwise for a current flowing upwards. For a current flowing in the opposite direction, the magnetic field would be clockwise. To remember the relationship between the direction of the magnetic field lines and the current, imagine holding the wire in your right hand and curling your fingers in the direction of the magnetic field, B. The thumb of your right hand will point in the direction of the current.

In the case where the wire is curved into a loop, the magnetic field produced by the upwards flowing current adds to the magnetic field produced by the downwards flowing current to produce a stronger overall field, see **Figure 3(b)**.

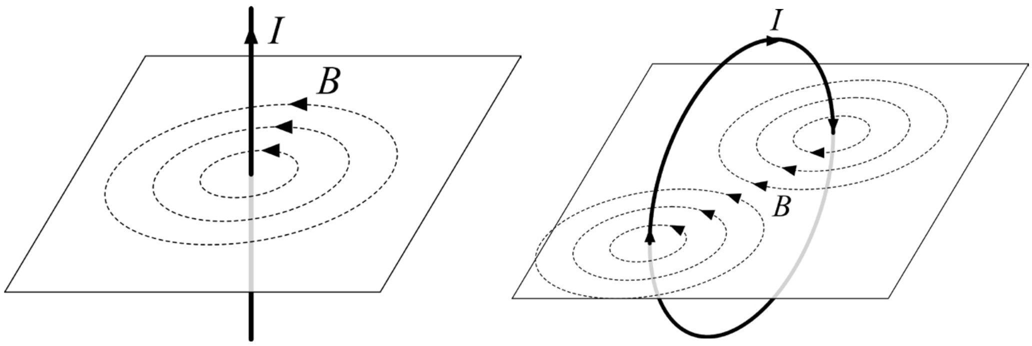


Figure 3(a) magnetic field produced by a wire carrying a current and (b) by a loop of wire carrying a current

Extending the coil by adding more loops to the wire further increases the additive effect, increasing the strength of the overall magnetic field, see **Figure 4**. This coil is called a solenoid.

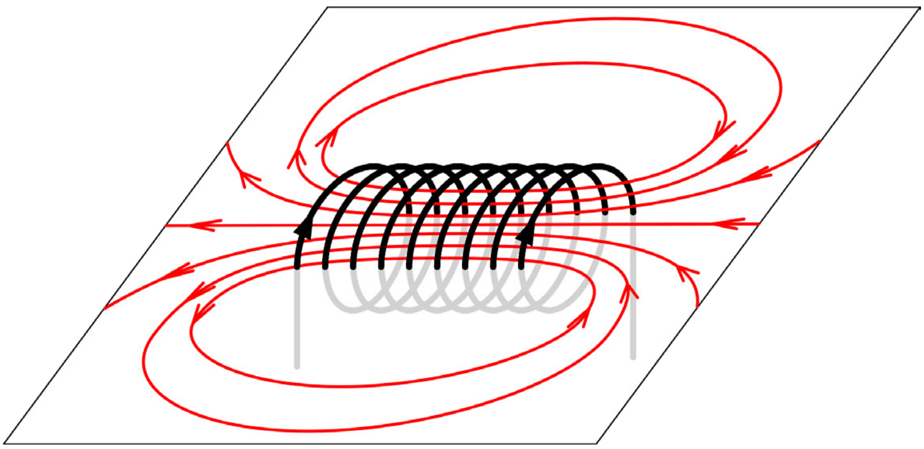


Figure 4 A solenoid

1 Discuss what features will affect the strength of the magnetic field that a solenoid constructed of a number of turns of wire carrying a current will produce.

Background – the magnetomotive force and field strength of a solenoid

The total potential to produce a magnetic field is called the magnetomotive force (mmf, denoted F_m), given mathematically as:

$$F_m = NI$$

where N is the number of turns in the solenoid and I is the current it carries. The value of F_m increases with the number of turns, as the field produced by each turn adds to the total field to produce a stronger field.

The spacing of the coils in a simple design consisting of a single coil determines the length of the solenoid. However, more complex designs layer turns over each other so a simple spacing measurement cannot be used. To account for this, it is useful to consider the number of turns per unit length instead of coil separation. Using this, and the magnetomotive force, gives the following expression for the magnetic field strength (H), consisting of N turns of wire carrying a current I over solenoid of length ℓ:

$$H = \frac{NI}{\ell}$$

Note, the field strength *H* is not the same as the magnetic flux density *B*. It has a different unit; it measured in units of *A* m^{-1}, not T. The magnitude of *H* determines how large the magnetising field produced by the solenoid is. It is not necessarily the same as the actual field produced by the solenoid, as the magnetising field can interact with matter near the solenoid – this is discussed below.

Background – converting between *H* and *B*

The units of the field strength produced by a solenoid, H, are *A* m^{-1}, which are not equivalent to tesla, the units used for the magnetic flux density of a magnet. A conversion factor is required to convert between H and B. This is given by the permeability, μ, such that:

$$B = \mu H$$

The units of μ are T m *A* m^{-1}, or more commonly henry per metre (H m^{-1}). (Note, the henry is a unit of *inductance*, which is not covered in this example.)

The magnetic field produced by the solenoid (the magnetising field) can interact with the material in the vicinity of the solenoid, and in particular material inside the coils (the solenoid core). The interaction can either reduce the field (a diamagnetic material), which is usually a weak effect in all materials except superconductors, or it can interact to strengthen the field (paramagnetic).

In a vacuum, there is no material to influence so the magnetic flux density and the magnetic field strength are the same when measured in the same units. The permeability in this case is called the permeability of free space and is denoted μ_0, where:

$$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{Hm^{-1}}$$

The relative permeability, μ_r, of a material is a measure of whether the material in a solenoid interacts with the magnetic field produced by the current to strengthen or weaken the overall solenoid magnetic flux density relative to the case of a solenoid in a vacuum. In this case:

$$B = \mu_0 \mu_r H$$

If $\mu_r < 1$ the material is diamagnetic and the total flux density is lower than the solenoid magnetic field. If $\mu_r > 1$ the material is paramagnetic and the total flux density is higher than the solenoid magnetic field. For air, $\mu_r \approx 1$, so is very close to the vacuum value. For iron, a typical value could be $\mu_r = 5000$, which represents a 5000-fold increase in magnetic flux density compared with a solenoid with an air core. Water is weakly diamagnetic and has a relative permeability of $\mu_r = 0.999992$.

Activity 3 – Solenoid design and use in a solenoid valve

The resource **Solenoid.html** allows an engineer to explore how the various factors affect the magnetic field strength, H, and the resulting magnetic flux density, B, of a single coil layer solenoid. Experiment with the sliders and note how H and B are related to each other and the design variables available.

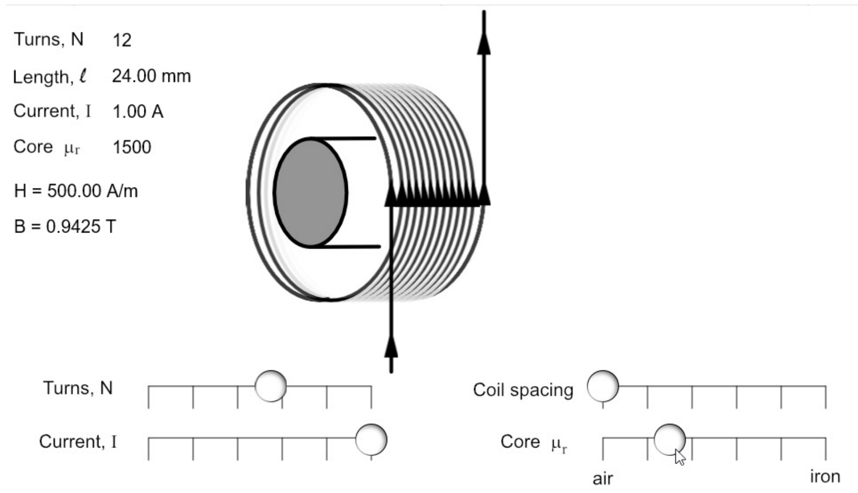


Figure 5
Screen shot of interactive resource

1 The attractive force experienced by a metal object near the solenoid is related to the magnetic flux density, B. What design features make for an effective and efficient solenoid for use in a solenoid valve?

The resource **Solenoidvalve.html** was used earlier to demonstrate a practical design for a normally closed solenoid valve. In addition to this, there is also an option to show field lines that indicate the field produced when the solenoid is energised.

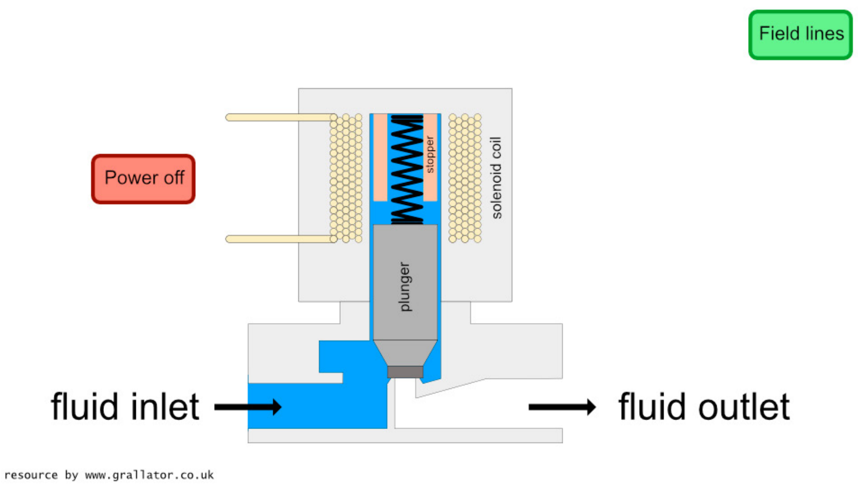


Figure 6
Screen shot of interactive resource

Stretch and challenge activity

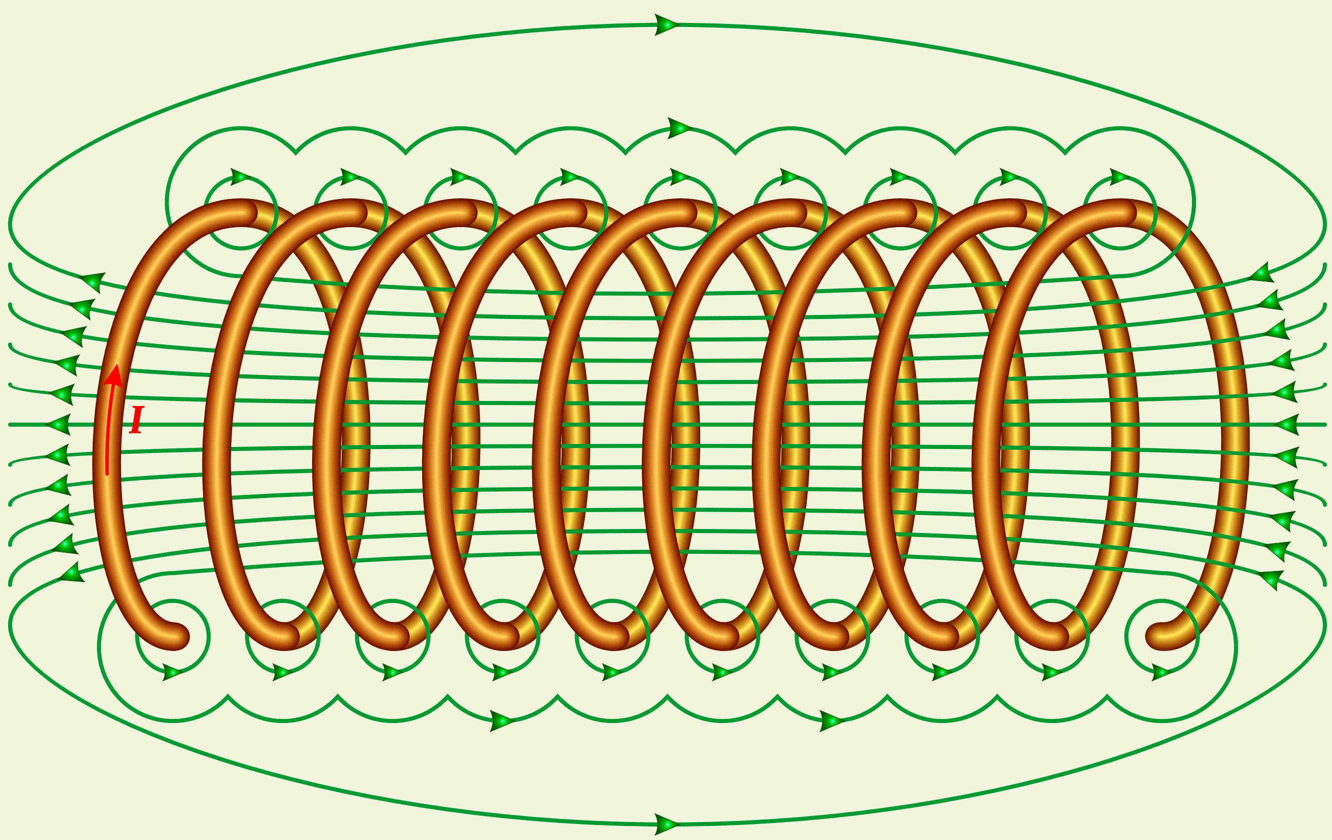
The solenoid to be used for an example solenoid valve has the following design:

Maximum current	0.5 A
Length	4 cm
Number of turns	500

1. Calculate the magnetic field strength, H of the solenoid (this is the value at the centre).

2. Calculate the magnetic flux density, B, in the case where the core of the solenoid is water ($\mu_r \approx 1$).

3. In order to operate the valve, the magnetic flux density, B, should have a magnitude of at least 1.2 T. Calculate the relative permeability of the core that is required to achieve this. Give your answer to the nearest whole number.



Notes and solutions

Activity 1

A simplified view of the normally closed solenoid valve is shown in **Figure 7**. This will be modified to give a normally open design.

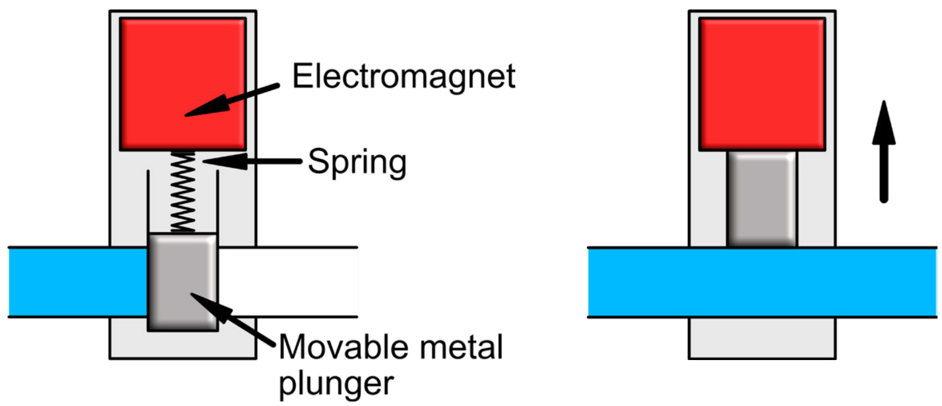


Figure 7
Current is off (a) and current is on (b)

1 One design for a normally open valve could have a fluid flowing around a metal plunger. When the electromagnet is turned on, it attracts the plunger, lifting into a blocking position. A spring is used to ensure that the plunger returns to its non-blocking position when the electromagnet is turned off.

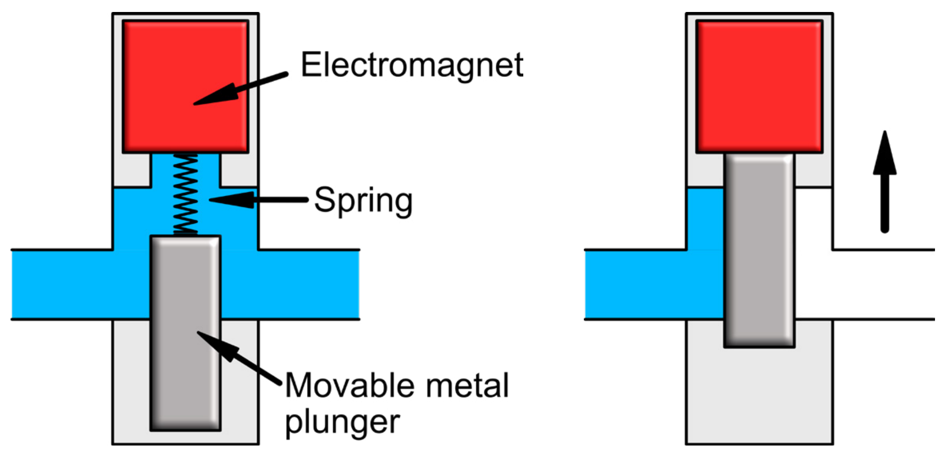


Figure 7
Current is off (a) and current is on (b)

These designs are sketches only.

Activity 2

1) The following three characteristics of the solenoid design determine the strength of the magnetic field it produces.

- The magnitude of the current in the wire, I.
- The number of turns in the solenoid, N. As the field produced by each turn adds to the total field it is reasonable to conclude that more turns will produce a stronger field.
- The spacing between the turns. The strength of the field produced by a coil reduces with distance from the coil. This means that the additive effect between two widely separated loops will be less than that between two loops in close proximity to each other.

Activity 3

1) The following may be considered for an effective and efficient solenoid for use in a solenoid valve. Recall, the discussion in Activity 2 required the flux density to be sufficient to lift the plunger against the force of the spring and gravity.

- The number of turns should be high and the coil length (turns multiplied by spacing) should be low in order to produce as large a field as possible for a given current.
- The current should be as low as possible to produce the desired flux density to reduce power consumption.
- A core with a high a value of relative permeability as possible should be used to give the largest flux density for a given current, number of turns and length.

Stretch and challenge activity

Maximum current	0.5 A
Length	4 cm
Number of turns	500

1) The magnetic field strength is given by:

$$H = \frac{NI}{\ell}$$

$$H = \frac{500 \times 0.5}{0.04}$$

$$H = 6250 \text{ Am}^{-1}$$

2) The magnetic flux density is given by $B = \mu_0 \mu_r H$ with $\mu_0 = 4\pi \times 10^{-7}$ Hm^{-1} and $\mu_r = 0$:

$$B = \mu_0 \mu_r H$$

$$B = 4\pi \times 10^{-7} \times 1 \times 6250$$

$$B = 7.854 \times 10^{-3} \text{ T}$$

3) The required magnetic flux density is 1.2 T and the value of μ_r is required.

$$B = \mu_0 \mu_r H$$

$$1.2 = 4\pi \times 10^{-7} \times \mu_r \times 6250$$

$$\mu_r = \frac{1.2}{4\pi \times 10^{-7} \times 6250}$$

$$\mu_r = \frac{1.2}{7.854 \times 10^{-3}}$$

$$\mu_r = 153 \text{ (nearest whole value)}$$

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