INDUCTANCE AND ELECTROMAGNETISM

CP4976

Inspiring The Next Generation Of Engineers

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Contents

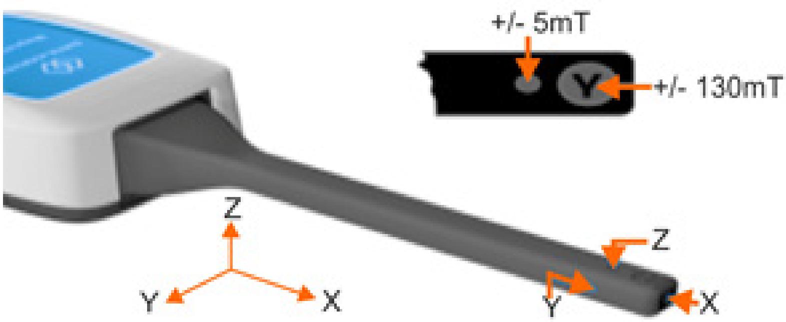
Introduction

The Electromagnetism kit comes complete with three Data Harvest sensors:

- A magnetic field sensor;
- Two 'Voltage-Current' sensors, able to measure both voltage and current.

Data Harvest magnetic field sensor:
The Smart Wireless Magnetic field sensor can be used to explore both the magnitude and direction of a magnetic field in three dimensions, X, Y and Z.

It has two ranges, ±5 or ±130 mT and is both USB and Bluetooth compatible.



The sensor uses two 3D Hall sensing devices positioned near the end of the wand.

The ±5 mT device is positioned directly behind the dot on the end cover.

The ±130 mT device is located directly behind the letter 'Y'.

Data Harvest 'Voltage-Current' sensor:

The kit comes with two sensors, one capable of reading voltages up to ±20V and currents of ±1A, the other reading ±5V and ±0.1A These ranges are printed on the labels on the sensors.

Introduction

Connecting the sensors:

- Launch the ‘EasySense2’ software, which is available from the Data Harvest website at https://store.data-harvest.co.uk/easysense2.

- **Connecting using Bluetooth:**

- Press the button on the base of the sensor to start the connection process. When the link is established, a green LED on the sensor flashes on and off.

- In the Devices tab on the App, find and connect to the magnetic field sensor.(When a number of groups are using sensors, the 6-digit number printed on the label can be used to identify a particular sensor.)

- **Connecting using USB:**

- Link the sensor to the PC or tablet running the ‘EasySense2’ software.

WORKSHEETS

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Worksheet 1 - Measuring the Earth's Magnetic Field

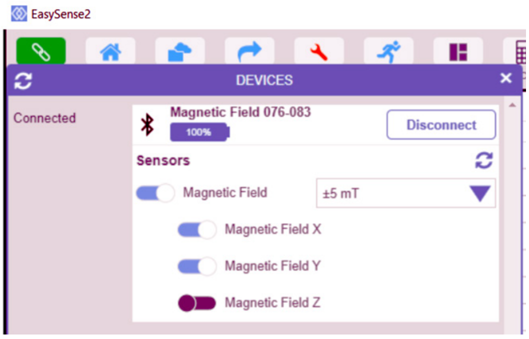
The Earth is surrounded by a magnetic field with magnetic poles currently near the north and south geographic poles.

It is a result of convection currents in a mixture of molten iron and nickel in Earth's outer core.

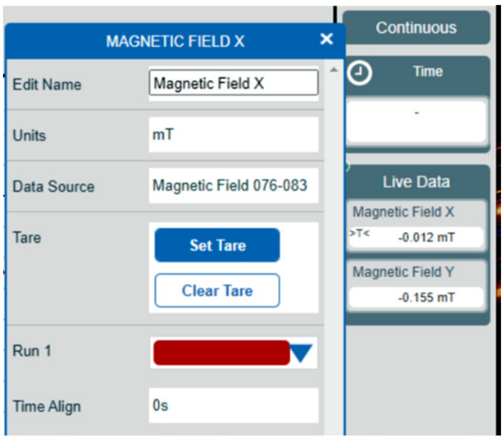
It deflects most of the solar wind, charged particles ejected from the Sun protecting the ozone layer that protects the Earth from harmful ultraviolet radiation. The field is far from uniform and varies across the surface of the globe.

Over to you:

- Start the 'EasySense2' software and choose a Graph experiment.
- Connect to the magnetic sensor and select the ±5mT range and check that both the X and Y fields (but not Z) are enabled.



- Hold the sensor horizontal in mid-air, away from magnetic materials such as steel-framed furniture.
- Click on the 'Live Data' fields at the right of the screen to set a tare ('zero') for both X and Y. Notice that the two directions have to be 'tared' individually.



- Click the 'Start' button at the bottom of the screen.
- Rotate the sensor through one full turn clockwise while keeping it horizontal.
- Once a full rotation is completed, click the 'Stop' button to halt the recording.

So What?

- The graph approximates to two sine waves displaced by around 90^0 relative to each other. The X sensor gives maximum and minimum values when pointing North / South whereas the Y sensor does so when pointing East / West.
- By default, the y-axis of the graph shows the full range of the sensor. Click on the y-axis labels to bring up the 'Y-AXIS' dialog box and replace 'Default Range' with either 'Min to Max' or 'User Range' to make the measured data more visible.
- The total field strength measured for each axis is the difference between the maximum and minimum readings, calculated for you using the 'Stats' function, in the 'tools' tab.
- Try using the 'Smoothing' tool to improve the appearance of the traces.
- When you are happy with the graph, either save it, in '.es2' format, via the 'File' tab, or capture a screen dump of it and save it in the Student Handout using an image-editing app.
- Use the graph to estimate the total field strength for each axis.
- Record your answers in the Student Handout.
- Compare your answers with those found on the internet, for example by the British Geological Survey.

Challenges

1. Use the magnetic field sensor to find the direction of magnetic north for your location. (It might be easier to use the 'Numbers' option for experiment type.) Remember that magnetic north is the direction indicated by the north end of a compass needle. Since opposite poles attract, this means that magnetic north is in fact the south pole of the Earth's magnetic field. Thus, the field sensor gives a maximum reading when pointing south and a minimum when pointing north. Verify your result by comparing it with the behaviour of a compass or by hanging a bar magnet from a length of cotton to see in which direction it settles.

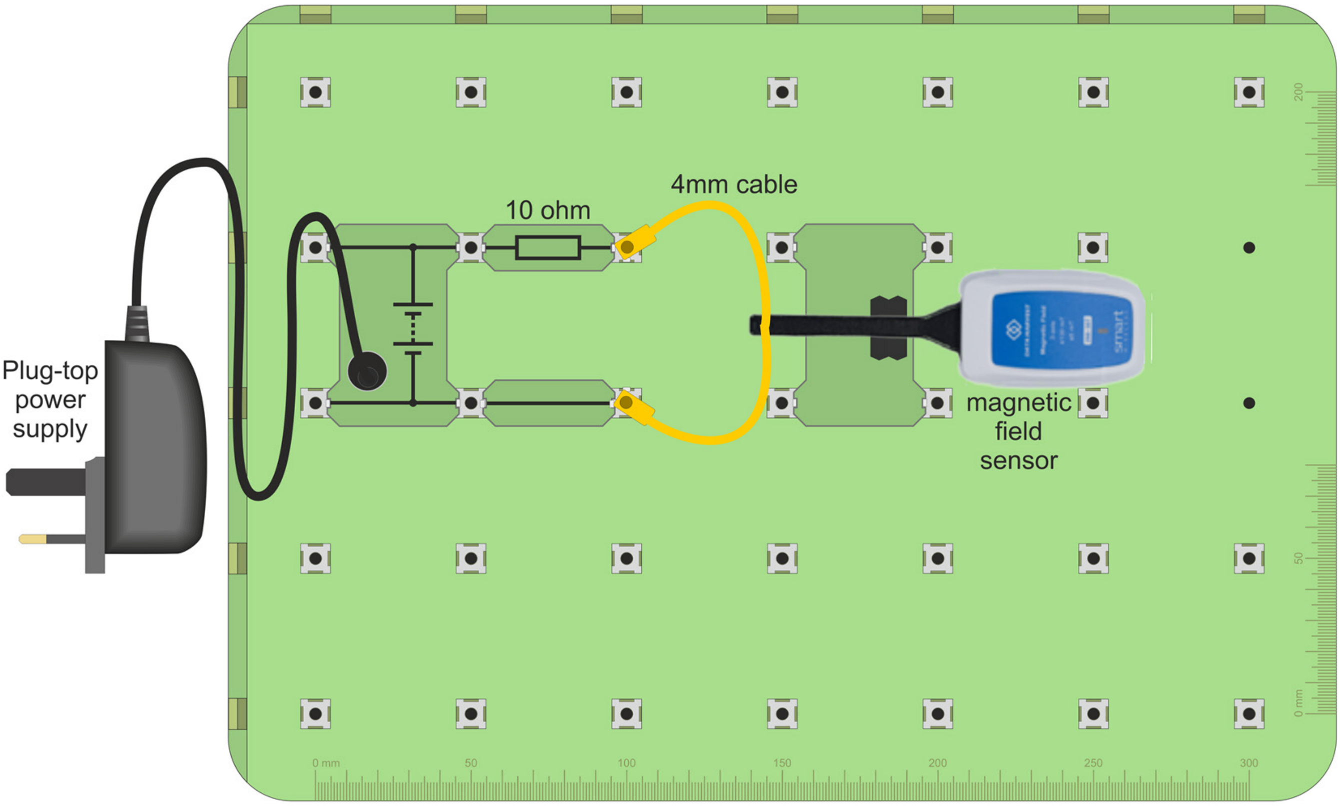
Worksheet 2 - Measuring an Electromagnetic Field

A magnetic field is created whenever electric current flows in a conductor. Its origin is in the behaviour of the electrons that make up the current.

This field is transient - present only as long as current is flowing. Its strength is greatest close to the wire and increases when the current increases.

Over to you:

- Plug the power supply carrier and 10Ω resistor onto the Locktronics board and mount the magnetic field sensor in its holder close by.
- Use a 4mm plug cable to complete the circuit. The Locktronics layout should look like the one below.



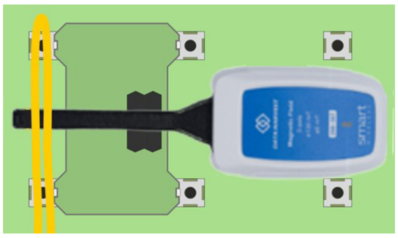
- Set the plug-top power supply to 5V.
- Set up the magnetic field sensor on the ±5mT range with all three sensor axes enabled and 'tared'.
- Start the 'Numbers' option on the EasySense software and place the cable in a straight line across the wand close to the dot embossed on it, as shown in the diagram.
- Switch on the power supply. (Caution - the resistor will get hot!)
- Record the magnetic field strength on each of the three axes.

Over to you:

- Position the cable across the sensor vertically so that it is at right angles to the previous step. Again record the field strength of the three axes.
- Finaly, position the cable along the wand itself, at right angles to the previous two tests. Record the field strengths.
- Try to relate the readings to the shape of the magnetic field.

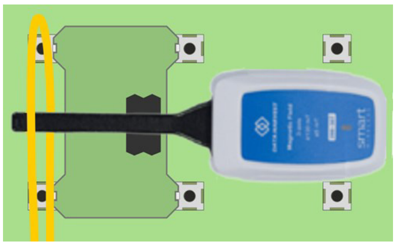
Challenges

1. Different wire shapes:



Fold the cable to form a loop over the top of the sensor, as shown in the diagram opposite.

What happens to the magnetic field readings?



Next, form the cable into a loop, placed around the sensor, as shown opposite.

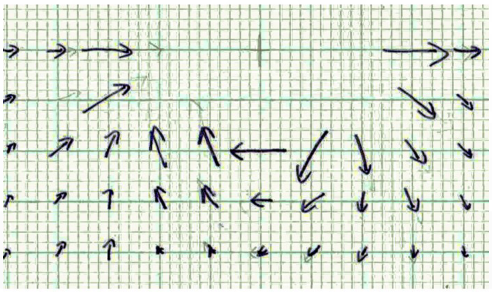
Now compare the magnetic field readings for the two arrangements.

Record your findings in the Student Handout and explain why these two situations produce different results.

2. Magnetic field around a bar magnet:

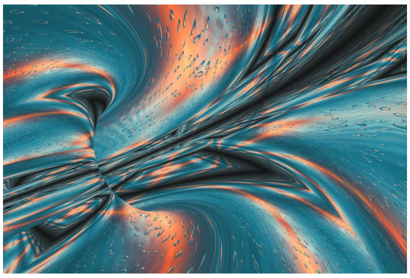
Use the sensor to investigate the magnetic field around a bar magnet.

Suggested procedure:
- Position the magnet in the centre of a sheet of graph paper.
- Select the ±130 mT range and tare (zero) each axis to eliminate effects of the Earth's magnetic field.
- Lower the sensor vertically down onto each corner of the 10mm grid.
- For each position, draw a vector on the paper with length and direction proportional to the magnetic field measurements.



- Typical results are shown opposite.
- Use your results to sketch the flux pattern around a bar magnet in the Student Handout.

Worksheet 3 - Electromagnetic Field Around a Coil

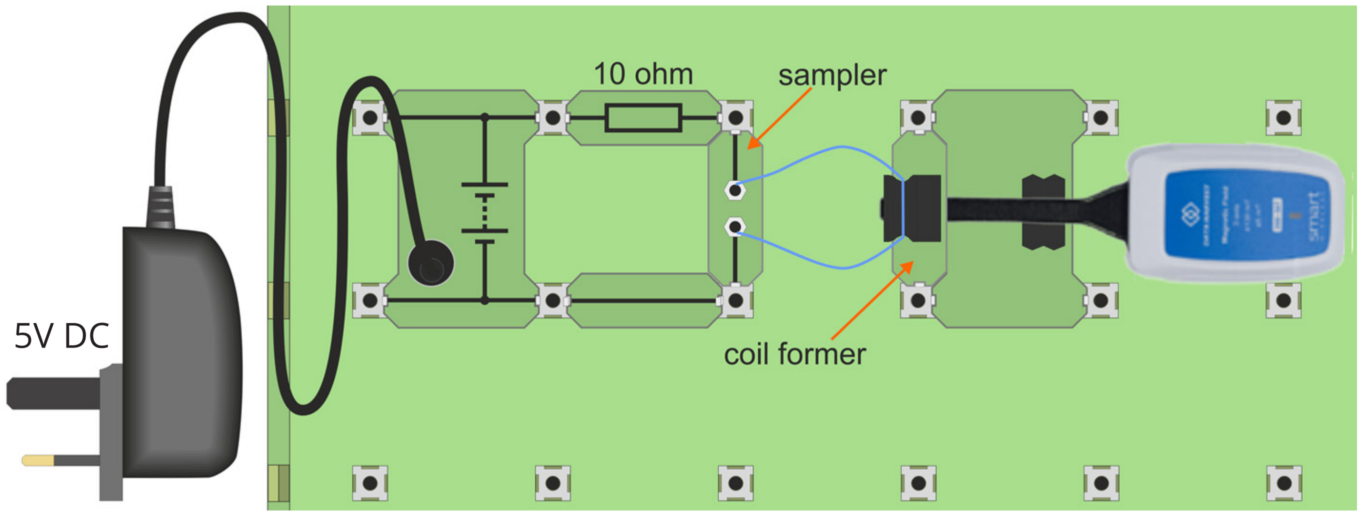


Current-carrying coils are at the heart of a number of common devices, such as electric motors, generators, electromagnets and transformers. In electronic circuits, they become inductors, used to control AC circuits. In medicine, they appear in MRI imaging devices.

1. Number of turns on the coil:

Over to you:

- The Locktronics layout is similar to the previous one except that it includes a coil former having two turns of 0.6mm single core wire wrapped around it and connected to the sampler. (Make a twist in the wire to keep the loops in position.)



- Set up the magnetic field sensor on the ±5mT range with all three sensor axes enabled and 'tared'. Locate it with the tip of the 'wand' inside the coil.
- Start the 'Numbers' option on the EasySense software and switch on the 5V power supply. (Caution - the resistor will get hot!)
- Adjust the position of the sensor inside the coil to give maximum reading.
- Record the magnetic field strength on the three axes in the Student Handout.
- Switch off the power and wrap two more turns of wire around the coil former to give four turns in total.
- Now carry out the same procedure but with coils having more turns of wire. Start with a coil of six turns and increase the number to eight turns and finally ten turns.
- Record the results in the Student Handout.
- Find out what happens when you reverse the current direction by reversing the sampler.
- Comment on your findings in the Student handout.

So What?

The magnetic field at the centre of a coil is given by B = **μ0 N I / D where N** is the number of turns in the coil, I is the current (A) through it and D is its diameter (m). The coil former has a diameter of 15 mm. How do the results compare to the predicted value?

The permeability of free space, **μ0** = $4\pi \times 10^{-7}$ T mA^{-1}.

- Use this formula to calculate the theoretical value of the magnetic field strength at the centre of the coils you used.
- Complete the table in the Student Handout with your results.

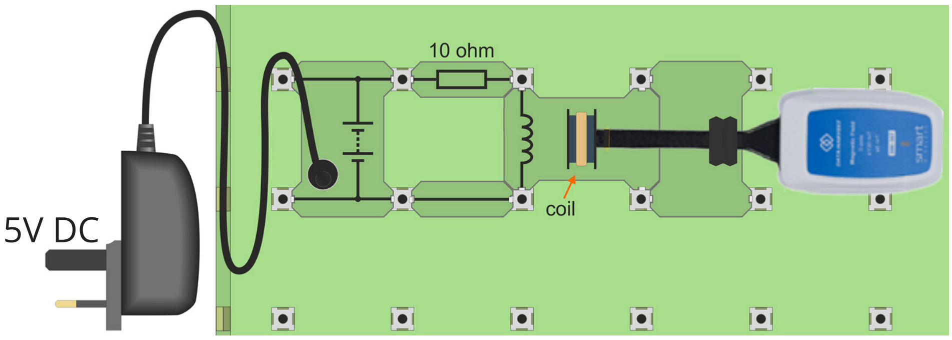
Challenge

- Test the other coils provided in the kit in the same way.
- Record your results in the Student Handout.

2. Distance from the coil:

Over to you:

- The Locktronics layout is similar to the earlier one, except that it includes a ready-made coil.



- Locate magnetic field sensor with the tip of the 'wand' inside the coil.
- Start the 'Numbers' option on the EasySense software and switch on the 5V power supply.
- Adjust the position of the sensor inside the coil to give maximum reading.
- Record the magnetic field strength on the three axes in the Student Handout.
- Position a ruler alongside the body of the sensor.
- Withdraw the sensor from the coil by 1cm and measure the magnetic field again.
- Repeat this for distances of 2cm, 3cm and 4cm.
- Record the results in the Student Handout.
- Use these results to plot a graph of magnetic field strength against distance from the coil.

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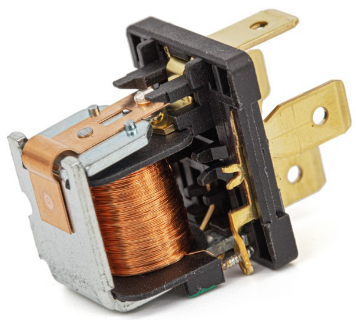
Worksheet 4 - Ferromagnetic Materials



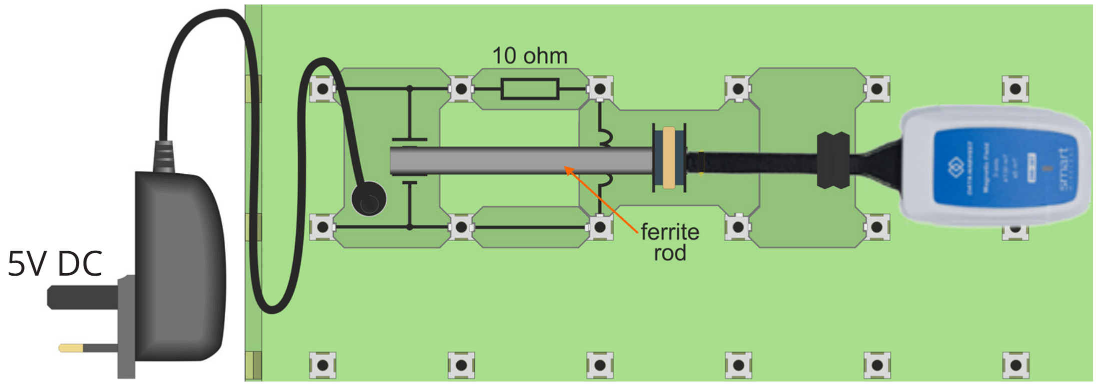
A small number of materials interact with a magnetic field, to intensify the field, leading to many applications.

These materials become magnetised and experience a force due to the magnetic field.

Depending on the nature of the material, it can become permanently magnetised, or may lose its magnetisation once it leaves the magnetic field.

Over to you:

- The Locktronics layout is identical to that used in worksheet 3 part 2, except for the addition of the ferrite rod.
- This is inserted into the coil and pushed up to the tip of the sensor wand.



- The magnetic field sensor is set up in the same way as previously.
- Start the 'Numbers' option on the EasySense software and switch on the power supply.
- Repeat the same investigation as in worksheet 3 part 2, measuring the magnetic field strength at distances of 1cm, 2cm, 3cm and 4cm from the coil.
- Record the magnetic field strength on the three axes in the Student Handout and use this data to plot a graph of magnetic field strength against distance from the coil again.
- Compare this with the previous graph (without the ferrite core present) and comment on the comparison in the Student Handout.

Challenge

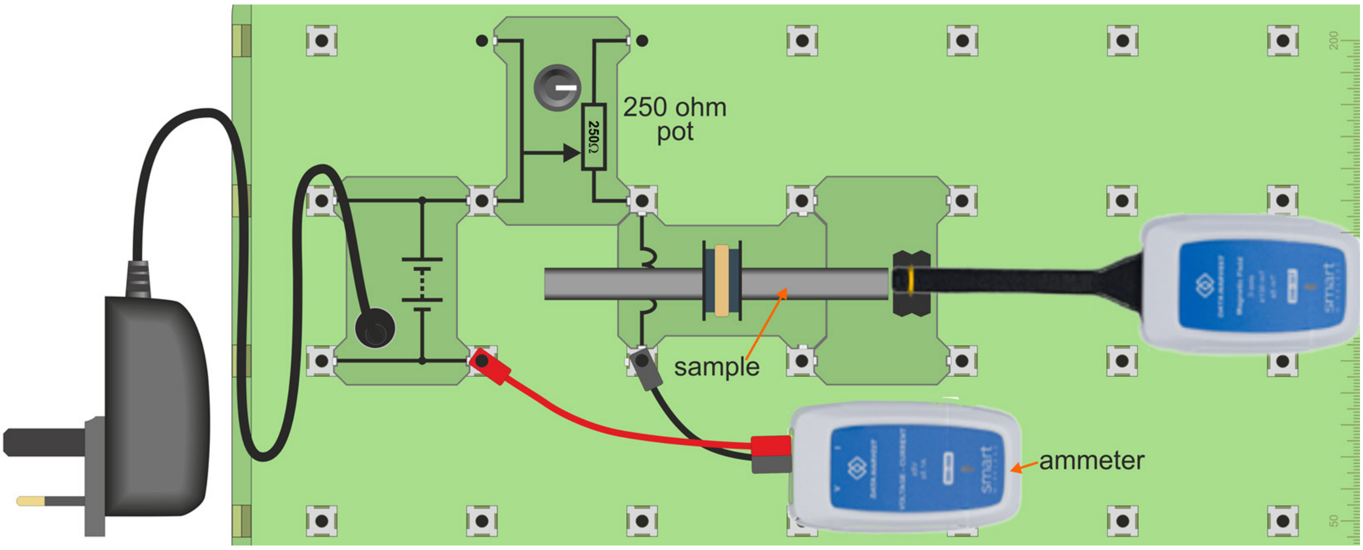
- Keep the magnetic field sensor at 4cm from the coil.
- Replace the ferrite rod with a range of other objects, such as steel scissors, copper wire, a steel screwdriver, a nail etc. and measure the field strength produced for each.
- Record your results in the Student Handout.

It's a bit like **gravity and weight! Gravity** is a force field created by chunks of matter. There are strong and weak gravitational fields. **Gravitational field strength** measures their strength. In the presence of matter, this field produces the effect we call **weight.**

A magnetic field, created by permanent magnets or current-carrying wires, is measured by **magnetic field strength**. In the presence of magnetic material, it causes magnetisation - creates a magnet - whose strength is measured by its **magnetic flux density.**

Over to you:

- Build the Locktronics layout shown below. It includes a 12VDC power supply, a 250Ω potentiometer, connected as a variable resistor and the Data Harvest current sensor.
- To begin with, use the ferrite rod as the sample, inserted into the coil as before and pushed up to the tip of the magnetic field sensor wand.



- Set the plug-top power supply to deliver 12V, but do not switch it on.
- The magnetic field sensor is set up with only the X-axis sensor active, on the +/- 5mT range.
- Turn the 'pot' to give maximum resistance.
- Connect the EasySense2 software to both the X-axis of the magnetic field sensor and the current axis of the 'Voltage - Current' sensor.
- Click on the time-axis label of the graph and change from 'time' to 'current'.

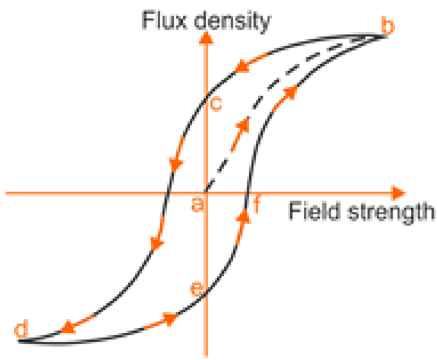
Over to you:

- Start the recording and then switch on the power supply.
- Slowly turn the 'pot' to decrease its resistance and thus increase current.
- Now, slowly turn the 'pot' back to give minimum current.
- Next, reverse the polarity of the power supply by removing the power supply carrier, rotating it 1800 and replacing it. Again turn the potentiometer to adjust the current from minimum to maximum and back to minimum. Next remove the power and stop the recording.
- When you are happy with the graph, either save it in '.es2' format, via the 'File' tab, or capture a screen dump of it and save it in the Student Handout, using an image-editing app.

Challenge

- If a laboratory power supply with a constant current function is available, use it to plot curves for currents up to 1A. (This should be done quickly as the coil will get warm during the test.)
- Record the resulting graph as before.

So What?



As field strength is increased on an unmagnetised sample, flux density also increases (from points '**a**' to '**b**').

The curve flattens as the sample reaches saturation.

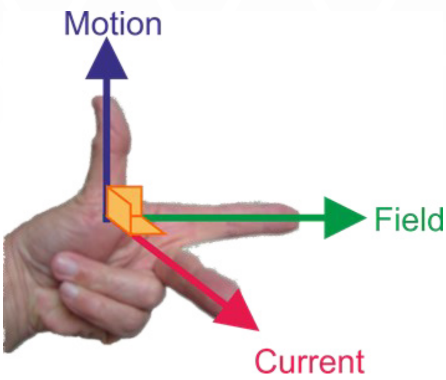
When field strength is reduced, the sample's residual magnetism causes the graph to follow the curve from points '**b**' to '**c**'.

Reversing the magnetising force rearranges the molecular structure. Eventually, the sample is unmagnetised again, at point '**c**'. Beyond that, the sample becomes magnetised in the opposite direction. Increasing this magnetisation further will cause the sample to reach saturation point but in the opposite direction, point '**d**' on the curve, a point symmetrical to point '**b**'.

If magnetising is reduced again to zero, the residual magnetism present in the core will be equal to the previous value, but in reverse, at point '**e**'.

As field strength is increased in the positive direction again, the magnetic flux density will reach zero, at point '**f**' before returning to saturation at point '**a**' .

Worksheet 6 - Fleming's Left-Hand (Motor) Rule



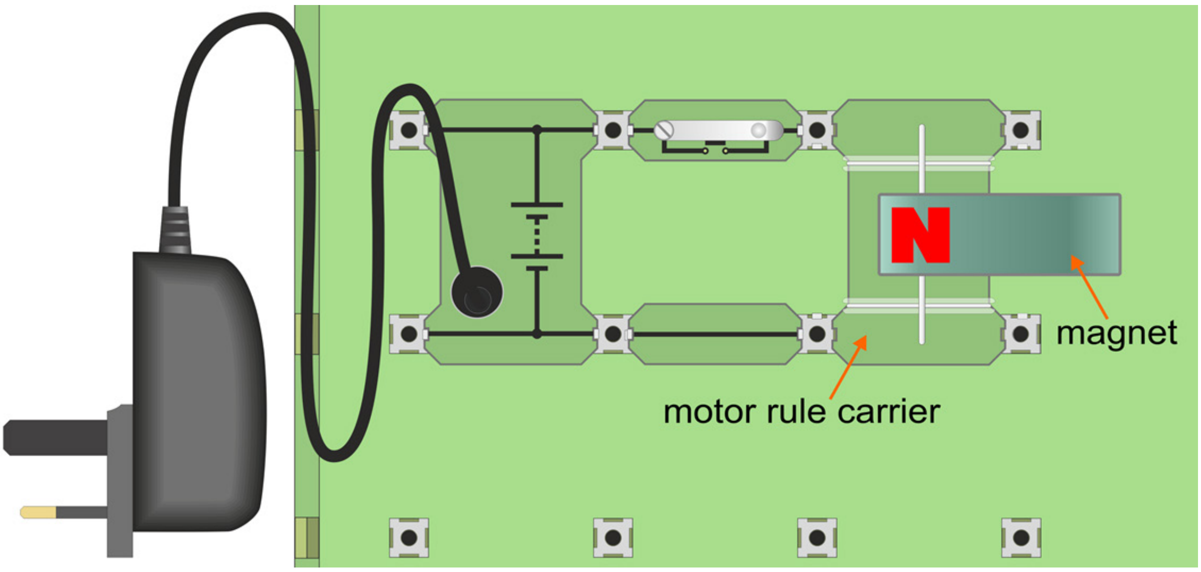
When two magnets are placed near each other, it is likely that they will move, either towards each other or away from each other.

An electric current always produces a magnetic field. When there is another magnet nearby, it is likely that motion will take place.

The unusual issue is the direction in which the motion occurs. That's where Fleming's left-hand rule helps!

Over to you:

- Build the system shown below. For clarity, the magnet has not been pushed right over the metal rod. Push it right across, so that the moveable rod sits in the middle of the magnetic field.



- The power supply is set to 3V.
- Press the push switch, and notice what happens.
- Next, flip the magnet over so that the South pole is on top.
- Press the push switch again. What is the difference?
- Reverse the current direction by rotating the power supply carrier so that the negative end (short line on the symbol) is at the top.
- What happens now when you press the push switch?
- Increase the power supply voltage to 12V to increase the current flowing through the rod.
- Can you see any difference when you close the push switch?
- Record your findings in the Student Handout.

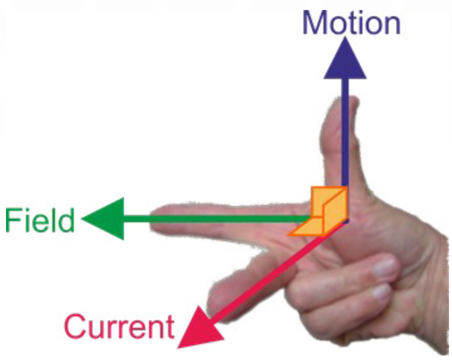
So What?

The poles of the magnet in the apparatus create a field between them. When current flows through the metal bar, it generates circular lines of magnetic flux around the conductor. These reinforce the magnetic field on one side of the bar and reduce it on the other side. This imbalance causes the force that moves the bar.

This is the principle behind all electric motors. In a practical motor, the metal bar would be either copper or aluminium wire. It would be part of a bundle of wires all carrying current to increase the force produced. It would also be part of the armature, producing rotary rather than linear motion.

Challenge

- Complete the template given in the Student Handout by adding lines to represent the lines of magnetic flux. Referring to this, explain why reversing the current reverses the direction of movement.



The last worksheet illustrated the workings of Fleming's left-hand rule: "field plus current produces movement".

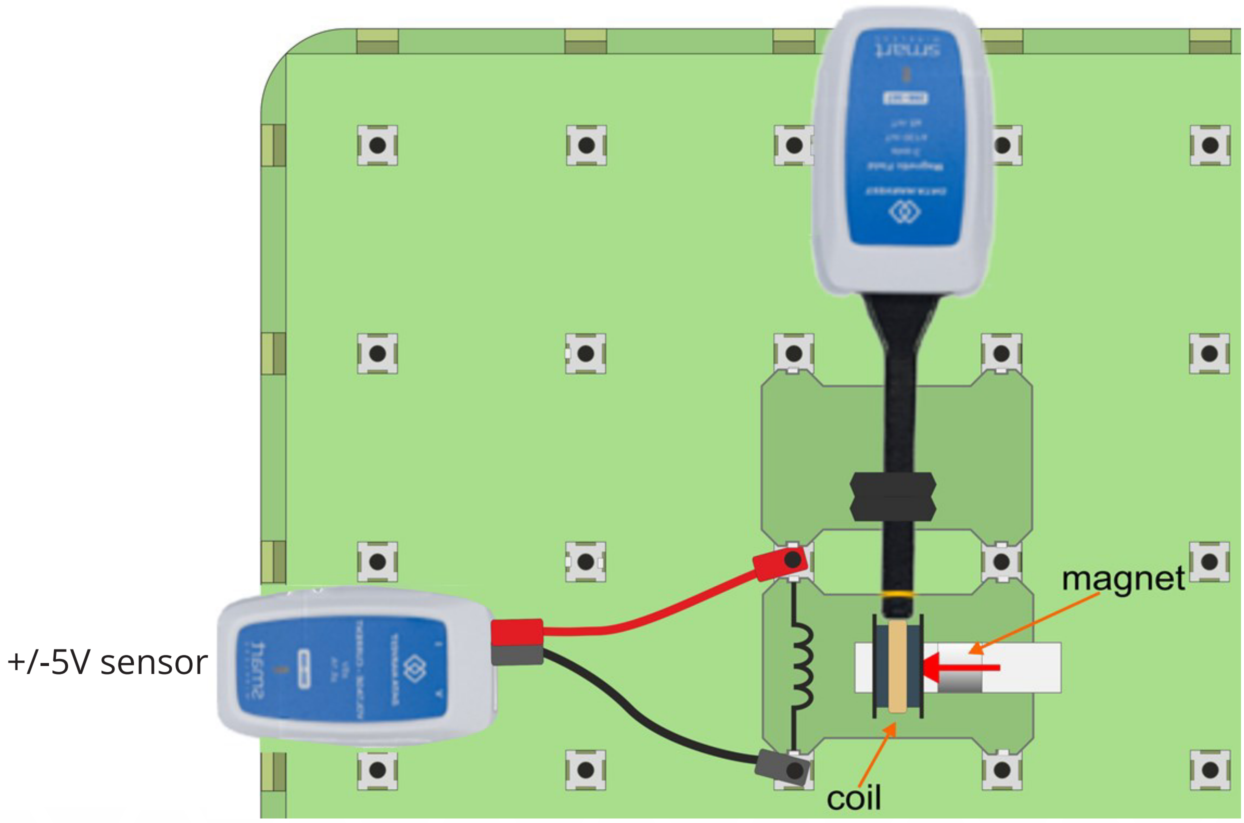
Fleming had two hands, of course! His right-hand rule is a guide to a different effect:

When a conductor and a magnetic field move relative to each other, an electric current is induced in the conductor. The same three quantities but different inputs and output - "field plus movement produces current".

Over to you:

This effect can be demonstrated by moving a magnet through a coil.

- Build the system shown below. The tube containing the neodymium magnet is placed so that it can slide easily into the coil.

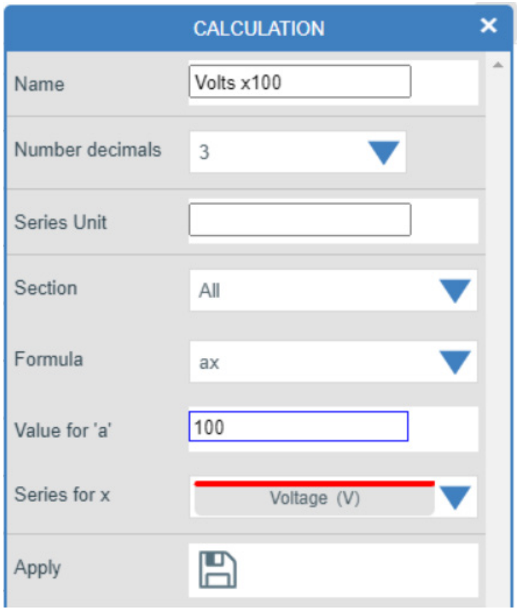


- Connect the coil to the Data Harvest voltage sensor.
- In the EasySense software, connect to both the ±5V voltage-current sensor and the magnetic field sensor. Select the X axis of the field sensor and set it to the 130mT range. Select the voltage trace of the voltage-current sensor.
- Click the "Setup" icon at the bottom left of the window and change the recording interval to 10ms.

Over to you:

- On a graph of voltage versus the magnetic field, it is not easy to see the voltage as the measurements are so small. One solution is to multiply the voltage measurements to make them of comparable size to the magnetic field measurements.

To do so, click the ‘Calculate’ button to add a math trace to the EasySense software. Display the voltage x 100. (Formula = “ax”, Value for a = 100, x = Voltage).



- Click the software ‘Start’ button and slide the magnet through the coil.
- Click the ‘Stop’ button to halt the recording
- The graph shows a double spike as first one pole then the other passes through the coil.
- When you are happy with the graph, either save it in ‘.es2’ format, via the ‘File’ tab, or capture a screen dump of it and save it in the Student Handout using an image-editing app.
- Notice the effect of speed on the voltage produced. The peak voltage depends on the speed. The faster the magnet is moving, the greater the voltage produced.

So What?

As the magnet comes closer to the coil, the magnetic field intensity increases. Then, as the magnet passes through the coil, a field of the opposite polarity is observed.

The changing field induces a voltage in the coil, measured by the voltage-current sensor. When the movement is slow, the induced voltage is around 100 mV. More rapid movement can generate around 1.0 V.

The principle shown here is the basis of all electromechanical generators. In practical generators rotary rather than reciprocating motion is generally used and it is more common for the coil to rotate while the magnet is stationary.

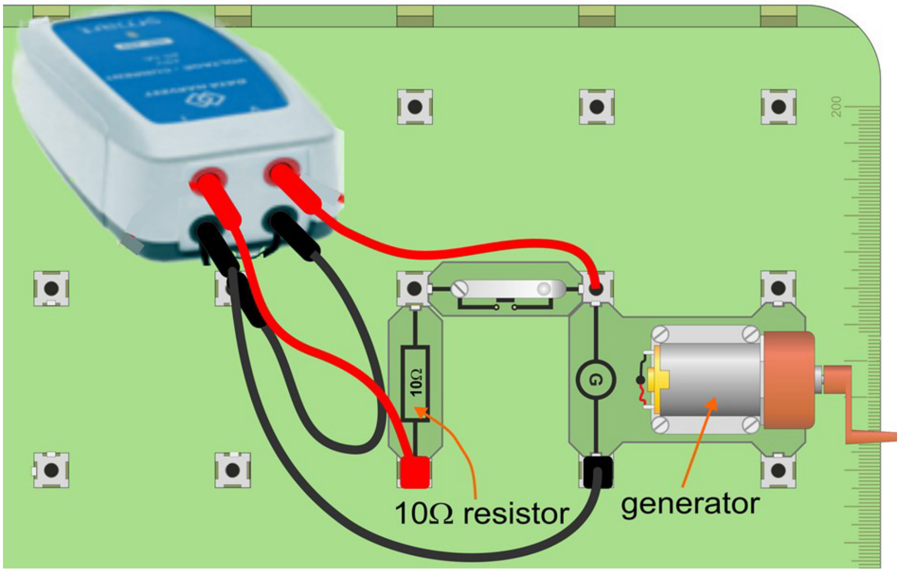
Generating electricity by passing a magnet through a coil is not very useful in the real world. Most practical generators convert rotary motion into electricity.

The rotary generator is constructed in much the same way as a motor. In fact the Locktronics generator component is a DC motor with a crank handle attached to it!

Over to you:

- Build the system shown below. The ±20V / ±1A voltage-current sensor is connected so that the voltage inputs are connected to measure the voltage across the generator and the current inputs measure the current flowing through the 10 resistor and the generator when the switch is pressed.

±20V/±1A sensor



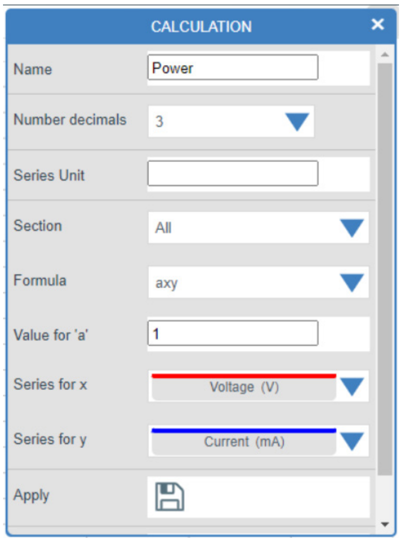
- Start the EasySense software recording.
- Turn the generator handle. The voltage will increase with speed of rotation. (This experiment ideally requires two hands, one to turn the generator and the other to prevent it from jumping out position.
- Press the switch to connect the resistor into the circuit and then release it.
- Click the ‘Stop’ button to halt the recording
- Record what you see (and feel) as you do so in the Student Handout.
- Add two math functions to the EasySense graph:

(i) The ‘Power’ calculation, voltage x current, gives the power delivered in mW .

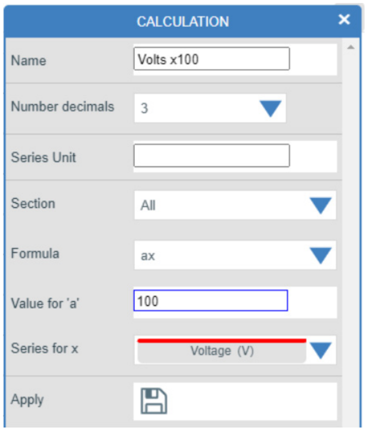
(ii) The ‘Volts x 100’ calculation scales the voltage so that the traces are all easily viewable on the same axes.

Over to you:

Maths functions: (i)



(ii)



- When you are happy with the graph, either save it in '.es2' format, via the 'File' tab, or capture a screen dump of it and save it in the Student Handout using an image-editing app.

So What?

The motor contains a commutator, connecting the generator contacts to the coil that is in the magnetic field at that time. The result - a DC output voltage.

(An AC generator would use slip rings rather than the commutator. Each coil drives current in first one direction and then the other as it passes through the magnetic field.)

Three distinct sections are visible on the graph, depending on the state of the switch.

1. The switch is not pressed.
- The generator is easy to spin and the voltage rises as the speed increases.
- There is no power developed since no current flows through the open switch.
- The voltage varies because it is difficult to turn the generator at a steady speed.

2. The switch is pressed.
- Current flows through the closed switch, delivering power to the resistor.
- It becomes distinctly harder to turn the generator. It slows down and the voltage drops.

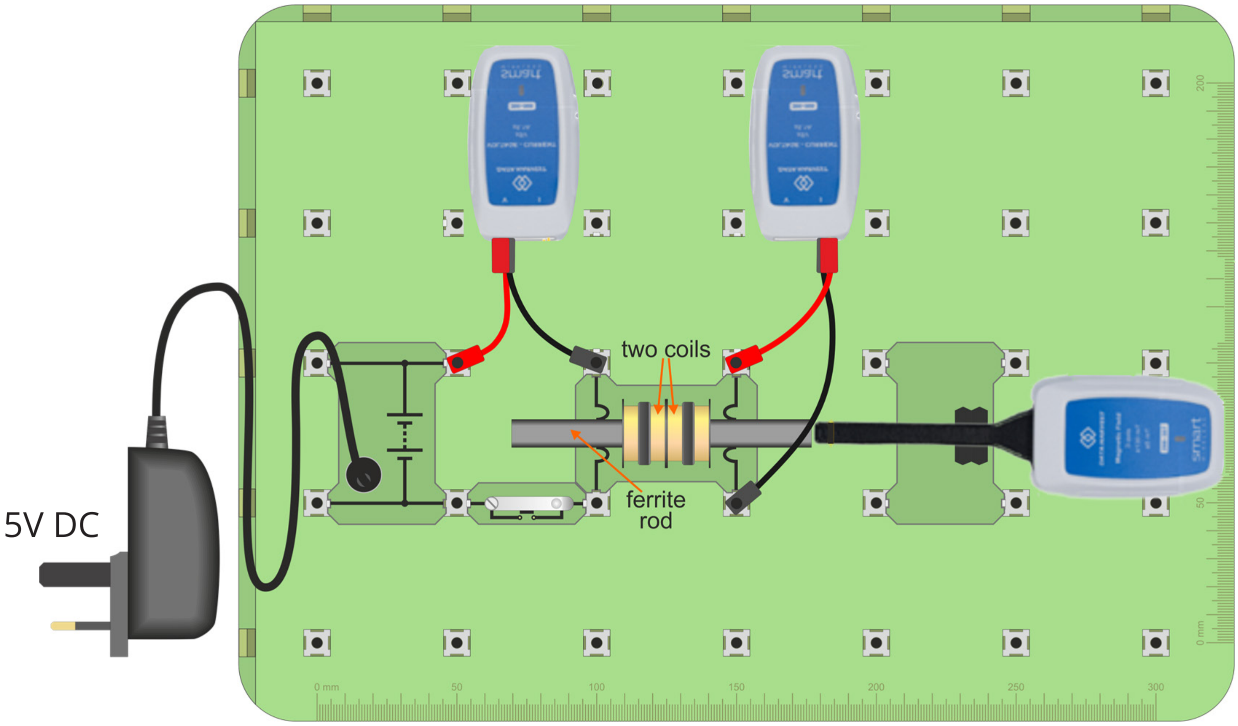
3. The switch is released.
- Current falls to zero. The generator is easier to turn and the voltage increases.

Instead of physically moving a magnet in order to create a moving magnetic field and generate electricity, it is more common to use an electrically-generated moving magnetic field.

Ignition coils in cars, power transformers, cooker induction hobs all use this principle. The photograph shows a smartphone charging pad which uses this approach to charge the battery.

Over to you:

- Build the system shown below. One voltage-current sensor is set up to measure the current delivered to the left-hand coil. The other is set up to measure the voltage generated in the right-hand coil.



Step 1 - Show that current in the left-hand coil produces a magnetic field:

- Connect the EasySense software to the current sensor and the magnetic field sensor. Ignore the voltage sensor for the moment.
- Remove the ferrite rod and position the field sensor so that it is in the centre of the two coils. Add a math trace to the EasySense graph with the name “Current / 100” and the formula “ax”. Use the value 0.01 for ‘a’ and the current (mA) measurement for ‘x’. The graph should plot current x100 and magnetic field strength against time.

Over to you:

- Switch on the 5V power supply.
- Start the graph and press the switch. Make a note of the measurements for current and field strength when the switch is pressed.
- Withdraw the probe from the coils and insert the ferrite rod. Position the probe so that it touches the end of the rod and repeat the experiment.

Step 2 - Show that a current in the left-hand coil induces a voltage in the other coil:

- Start a new EasySense graph and connect the software to both the current sensor and the voltage sensor.
- This time, we do not use the magnetic field sensor. (The EasySense software is constrained to the speed of the slowest device and the magnetic field sensor is too slow to capture the effect that we are studying here.)
- Add a math trace to the graph with the name “Current / 1000” and the formula “ax”. Use the value 0.001 for ‘a’ and the current (mA) measurement for ‘x’. Show voltage and current / 1000 on the graph, (rather than the raw current measurement.)
- Click on the settings icon at the bottom of the graph and set the measurement interval to 1 ms.
- Start the graph and press and release the switch. Try this with and without the ferrite rod in place.

Step 3 - Show that the moving magnetic field induces a voltage.

- Start a new EasySense graph and press the switch.
- Holding the switch down, move the ferrite rod in and out of the coil.
- Observe the results on the graph.
- Try moving at different speeds.

So What?

When current flows in the left-hand coil, it produces a magnetic field, which increases from zero and then remains constant. This field permeates the second coil. While it is changing (initially increasing,) it induces a voltage across the second coil.

Introducing the ferrite rod intensifies the magnetic field, coupling the coils.

Moving the ferrite rod in and out of the coils greatly increases the induced voltage.

It is the change in flux, not the flux itself, that induces the voltage. When the magnetic field is static it does not induce a voltage.

Worksheet 10 - Self-Inductance

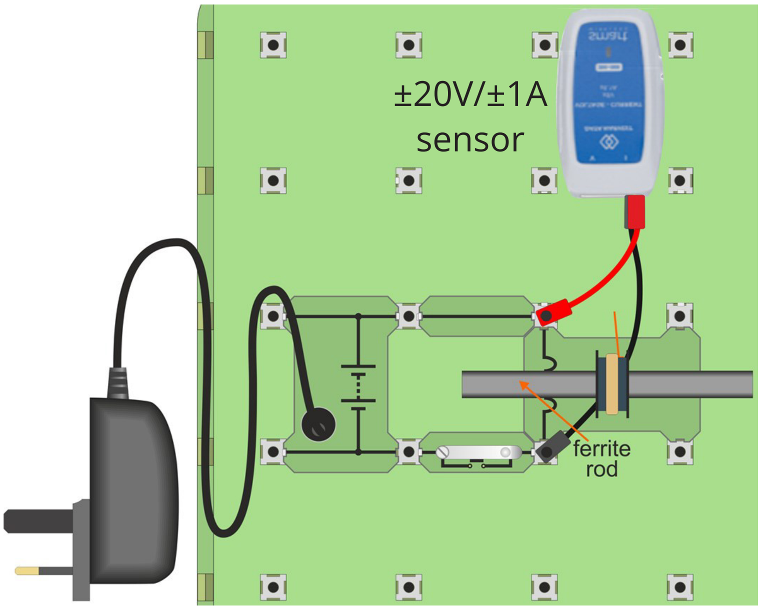
A changing magnetic field in a coil will induce a voltage in a neighbouring coil.

The coil creating a magnetic field is itself inside that field.

The question is, does the coil induce a voltage in itself?

Over to you:

- Build the system shown opposite.



This experiment is trying to catch a transient event. To do so requires a trigger in the EasySense software. Click on the 'Setup' button that is underneath the graph.

- Configure the following:
- Recording interval - 100µs;
- Start condition - 'Higher than 1V', (when the 'Start' button is pressed, the software waits for a voltage above 1V before recording data on the graph);
- Pre-trigger time - 100ms, (the graph shows events from 100ms before the trigger occurs)
- Duration - 1s, (the recording stops 1s after the trigger occurs.)

Over to you:

- Press the 'Start' button on the EasySense graph. It will show the message "Waiting for Trigger".
- Press and quickly release the switch to capture the waveform.
- When you are happy with the graph, either save it in '.es2' format, via the 'File' tab, or capture a screen dump of it and save it in the Student Handout using an image-editing app.

So What?

When current flows in the coil, it generates a magnetic field. When current is switched off, the field collapses to nothing. Since the coil is inside the magnetic field as this change occurs, a voltage is induced in it.

The practical result of this is that a voltage is induced whenever a changing current flows through a conductor. This voltage always opposes any change in the current.

This effect is known as inductance. All conductors exhibit inductance but the effect can be magnified by arranging conductors into a coil and by the presence of a ferromagnetic core passing through it.

Induction hobs are increasingly common in kitchens. Coils of copper wire sit beneath a glass plate hob. When an electric current passes through, the coils create a magnetic field. A pan, with a base made from a magnetic metal, placed on the hob, heats up because of electric currents induced in it. The hob and any non-magnetic utensils remain cold.

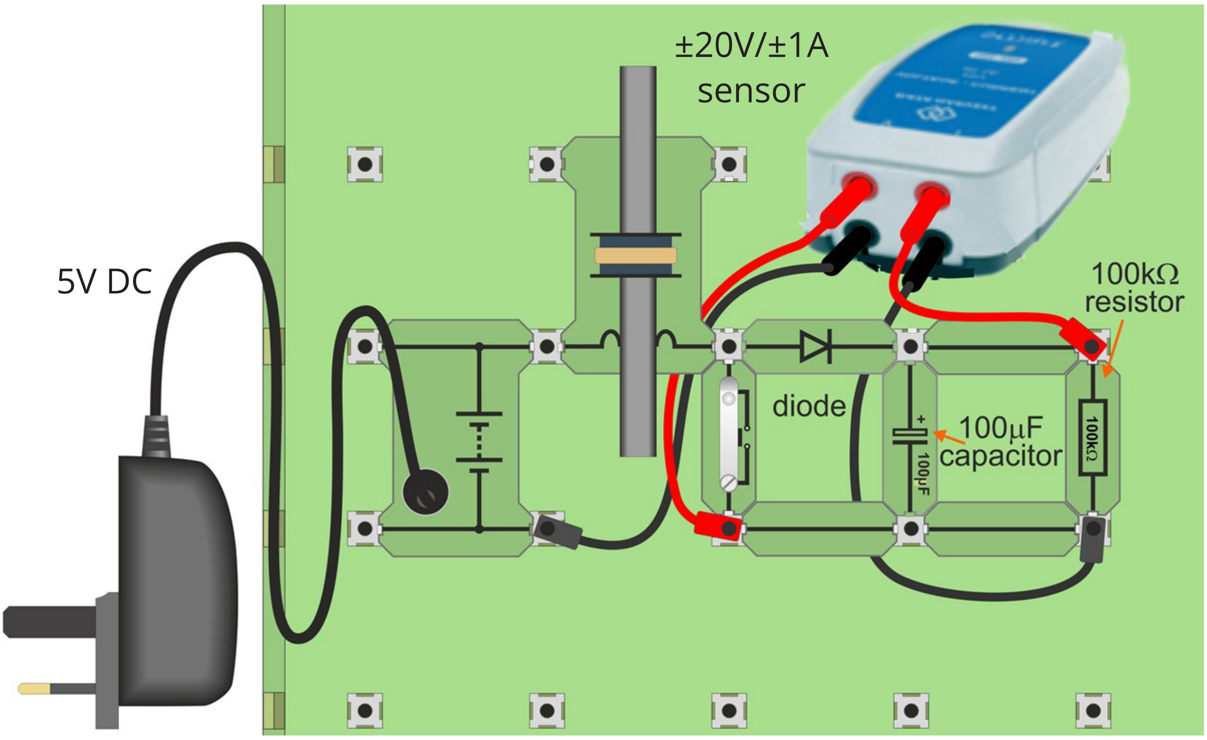
Over to you:

Whenever the current flowing in a conductor changes, there is a change in the magnetic field. This changing magnetic field induces a voltage that opposes that change in current. From an electrical point of view, inductors oppose changes in current.

In this worksheet, we examine a practical application of this.

- Build the system shown below

Notice the orientation of the diode and the polarity of the capacitor.



- The Voltage/Current sensor measures the current delivered by the power supply and also measures the voltage across the 100kΩ resistor.
- Connect the sensor to the EasySense software and configure it to generate a graph, as in previous investigations. The default measurement interval of 50ms is fine for this task.

Over to you:

- Click the ‘Start’ button at the bottom of the screen.
- Switch on the power supply. A small current flows through the coil and the diode and the voltage across the resistor is a little less than 5V.
- Briefly, press and release the switch. The voltage rises and then falls.
- Keep pressing and releasing the switch to see how high the output voltage will go.
- Select an output voltage between 5V and this maximum and see how close you can keep the output to this value by pulsing the switch whenever the voltage begins to fall.
- As before, when you are happy with the graph, either save it in ‘.es2’ format, or save a screen dump of it in the Student Handout.

Challenge

- Investigate what effect removing the ferrite core has.

So What?

This type of circuit is an example of a boost switched mode power supply (SMPS).

An SMPS is a device that regulates the voltage of unregulated power supply using switching. It reduces power consumption and decreases the amount of dissipated heat, in a computer for example.

It relies on the fact that an inductor opposes changes in current. When the switch is pressed, the current in the inductor increases. When it is released, a voltage is generated that tries to maintain the current. The voltage causes current to flow through the diode, into the capacitor. The capacitor can be charged higher than the input voltage because the diode prevents the charge from flowing back into the power supply.

A practical SMPS would have a controller that monitors the output voltage. The controller pulses an electronic switch in order to maintain a steady output voltage.

Traditionally, electricity is generated as alternating current (AC) and transformed and distributed around the country at high voltage. Then, it is transformed back to a voltage suitable for home or industry.

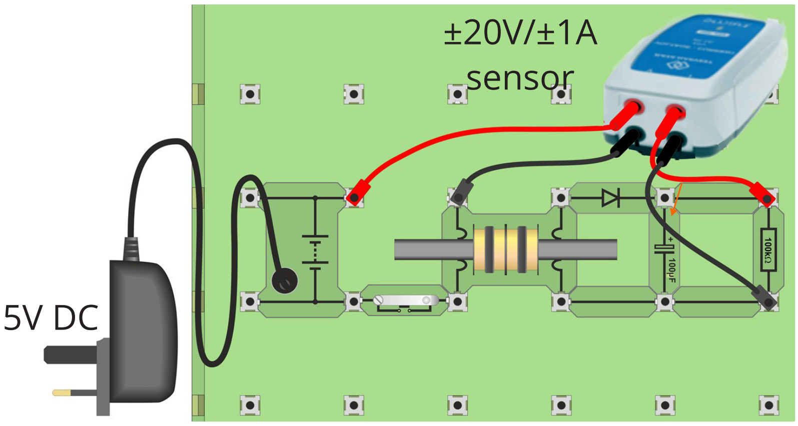
The benefit - higher distribution voltages require lower currents for the same power transfer. Lower currents reduce energy losses caused by the resistance of cables used to transmit the power.

Over to you:

1. The principle:

In this worksheet, we examine another practical application of induction - the transformer.

- Build the system shown below. It is very similar to the one in last worksheet, but uses two coils, electrically separated from each other.



- Set the power supply to 5V and switch on.
- Compare the performance of this circuit to the one with a single coil.
- Once again, see what difference the ferrite core makes.

So What?

This type of SMPS has the advantage that the output is electrically isolated from the input.

However, the output voltage of this SMPS is lower.

In an ideal transformer, all the energy held in the primary coil is transferred to the secondary.

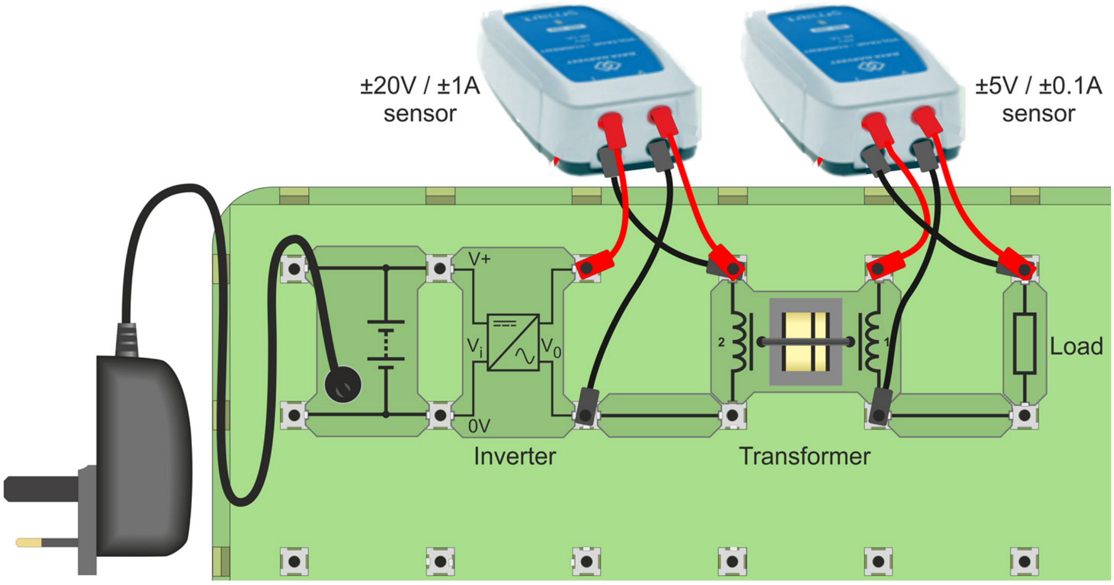
This transformer is not ideal and a significant portion of that energy is wasted.

Over to you:

2. Step-down transformer:
This part of the investigation uses a more efficient transformer which has twice as many turns on the primary coil as on the secondary.

Instead of varying the current by repeatedly pressing and releasing the switch, this circuit uses an inverter to generate AC, with a peak value of around 4V. This voltage generates a continuously varying magnetic field, which in turn produces an AC output voltage.

- Build the circuit shown below. The ±20V sensor is used to measure the voltage across the primary coil and the ±1A sensor measures the current through it. The ±5V sensor measures the voltage across the secondary coil and the ±0.1A sensor measures the output current through the load.



Step 1 - Voltage behaviour:
- Set the power supply to 12V and switch on.
- Connect a 10Ω resistor as the load.
- To begin with, we do not need the current sensors. Under the 'Devices' tab, disable both current sensors.
- With the default interval of 50ms, click 'Start' to produce a graph to show how V_{IN}, the voltage across the primary coil, and V_{OUT}, the voltage across the secondary, vary with time. (You can identify which voltage is which by clicking on the 'Voltage' fields in 'Live Data' on the EasySense software app. It tells you which data source (sensor) is associated with which colour trace.)
- Once you obtain a satisfactory graph, record it and add it in the Student Handout.

Step 2 - Current behaviour:

- This time, we do not need the voltage sensors. Disable both.
- Still using the default interval of 50ms, click 'Start' to produce a graph to show how I_{IN}, the current through the primary coil, and I_{OUT}, the current through the secondary, vary with time.
- Once you obtain a satisfactory graph, record it and add it in the Student Handout.

Step 3 - Power behaviour:

- Enable all sensors.
- Use the app's 'Calculate' function to create a graph of input power and output power against time. Power is equal to voltage times current. Pick the function "axy" and set a = 1, x = voltage and y = current, input current and voltage to generate input power, and output current and voltage to generate output power.
- The graph looks complicated, having six traces on it for current, voltage and power. Click on the y-axis of the graph and remove traces for the voltages and currents.

Challenges

1. Obtain power graphs for different loads, including the open circuit condition, (no load.) (With smaller currents, the current reading might not register for part of the cycle. This may cause the power trace to have gaps in it.)
2. Reverse the transformer, so that the primary coil has fewer turns of wire than the secondary. Comment on its performance.

So What?

Transformers work because of their mutual inductance - a change in the current in one coil induces a voltage in the other.

A step-down transformer is one with more turns of wire in the primary coil than in the secondary.

It 'steps-down' voltage, giving an output voltage lower than the input, but 'steps-up' the current so that the output current is greater.

All transformers are 'lossy', meaning that they have an efficiency less than 100%. The transformer used in this investigation has a high efficiency and manipulates power. However, it always loses some energy.

STUDENT HANDOUT

Worksheet 1 - Measuring the Earth’s magnetic field

Total field strength for N/S axis = ... mT

Total field strength for E/W axis = ... mT

Results from internet search:

Graph obtained in this worksheet:

Student Handout

Worksheet 2 - Measuring an electromagnetic field

Magnetic field measurements for single strand of wire placed **across** the sensor:
X-axis .... Y-axis .... Z-axis ....

Magnetic field measurements for single **vertical** strand of wire:
X-axis .... Y-axis .... Z-axis ....

Magnetic field measurements for single strand of wire running **along** the sensor:
X-axis .... Y-axis .... Z-axis ....

What does this reveal about the shape of the magnetic field around a current-carrying wire?

Challenge 1:

Loop of cable across top of sensor wand:
X-axis .... Y-axis .... Z-axis ....

Loop of cable wrapped around sensor wand:
X-axis .... Y-axis .... Z-axis ....

Why are these results different?

Challenge 2:
Magnetic flux pattern around a bar magnet:

Worksheet 3 - Electromagnetic field around a coil

1. Number of turns on the coil:

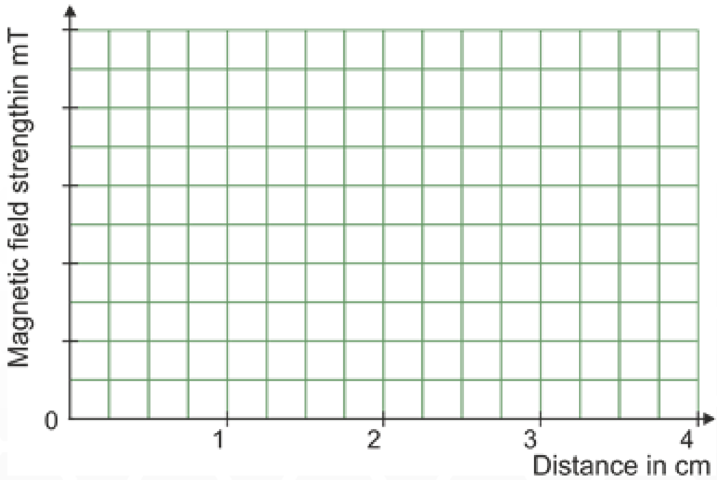
No. of turns of wire	X-axis field in mT	Y-axis field in mT	Z-axis field in mT
2			
4			
6			
8			
10			

Effect of reversing current direction:

2. Distance from the coil:

Distance from coil in cm	X-axis field in mT	Y-axis field in mT	Z-axis field in mT
0			
1			
2			
3			
4			

Graph of magnetic field strength vs distance:



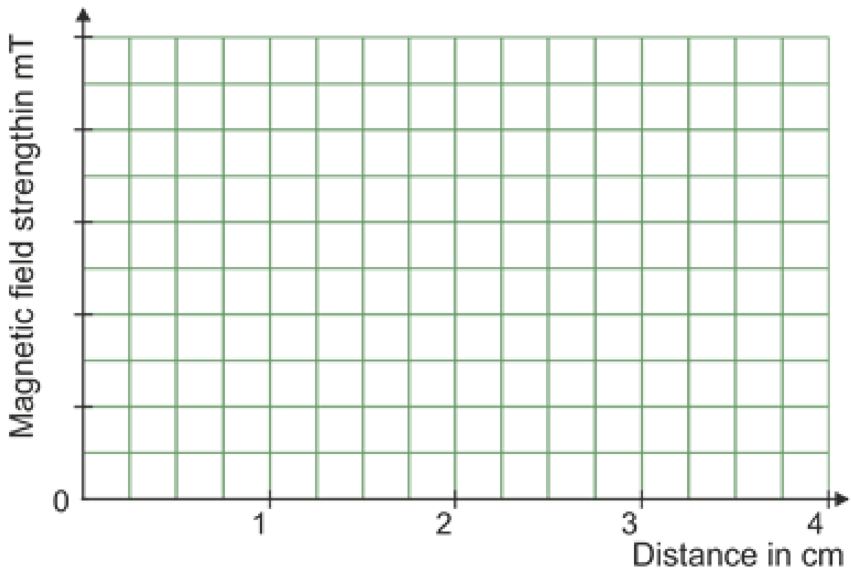
Student Handout

Worksheet 4 - Ferromagnetic materials

Distance from the coil with ferrite core:

Distance from coil in cm	X-axis field in mT	Y-axis field in mT	Z-axis field in mT
0			
1			
2			
3			
4			

Graph of magnetic field strength vs distance with ferrite core in place:



Effect of the ferrite core:

Challenge

Material	Field strength at 4cm in mT

Student Handout

Worksheet 5 - B and H in magnetism

Graph obtained in this worksheet:

Graph (high current) obtained in this worksheet:

Student Handout

Worksheet 6 - Fleming's left-hand motor rule

Effect of reversing magnetic field / current direction / current magnitude:

Magnetic field around the horseshoe magnet:

Referring to this, explain why reversing the current reverses the direction of movement.

Worksheet 7 - Generating electricity

Graph obtained in this worksheet:

Student Handout

Worksheet 8 - Rotary generator

Graph obtained in this worksheet:

Effect of closing and then opening the switch:

Worksheet 9 - Electromagnetism generates electricity

Graph showing that a current in the L.H. coil generates a magnetic field:

Graph showing that a current in the L.H. coil generates a voltage in the R.H. coil:

Graph showing that the moving magnetic field induces a voltage.:

Student Handout

Worksheet 10 - Self-inductance

Graph obtained in this worksheet:

Worksheet 11 - Inductance applications

Graph obtained in this worksheet:

Worksheet 12 - Inductance applications

Graph obtained in this worksheet:

Notes

INDUCTANCE AND ELECTROMAGNETISM

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