### ELECTROMAGNETISM - GRADE 11\*

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#### 1 Introduction

Electromagnetism describes between charges, currents and the electric and magnetic fields which they give rise to. An electric current creates a magnetic field and a changing magnetic field will create a flow of charge. This relationship between electricity and magnetism has resulted in the invention of many devices which are useful to humans.

#### 2 Magnetic field associated with a current

If you hold a compass near a wire through which current is flowing, the needle on the compass will be deflected.

Since compasses work by pointing along magnetic field lines, this means that there must be a magnetic field near the wire through which the current is flowing.

NOTE: The discovery of the relationship between magnetism and electricity was, like so many other scientific discoveries, stumbled upon almost by accident. The Danish physicist Hans Christian Oersted was lecturing one day in 1820 on the possibility of electricity and magnetism being related to one another, and in the process demonstrated it conclusively by experiment in front of his whole class. By passing an electric current through a metal wire suspended above a magnetic compass, Oersted was able to produce a definite motion of the compass needle in response to the current. What began as a guess at the start of the class session was confirmed as fact at the end. Needless to say, Oersted had to revise his lecture notes for future classes. His discovery paved the way for a whole new branch of science - electromagnetism.

The magnetic field produced by an electric current is always oriented perpendicular to the direction of the current flow. When we are drawing directions of magnetic fields and currents, we use the symbols  $\odot$  and  $\otimes$ . The symbol

 $\odot$  (1)

<sup>\*</sup>Version 1.3: Jul 1, 2011 7:07 am -0500

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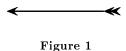
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represents an arrow that is coming out of the page and the symbol

$$\otimes$$
 (2)

represents an arrow that is going into the page.

It is easy to remember the meanings of the symbols if you think of an arrow with a head and a tail.



When the arrow is coming out of the page, you see the point of the arrow  $(\odot)$ . When the arrow is going into the page, you see the tail of the arrow  $(\otimes)$ .

The direction of the magnetic field around the current carrying conductor is shown in Figure 2.



Figure 2: Magnetic field around a conductor when you look at the conductor from one end. (a) Current flows out of the page and the magnetic field is counter clockwise. (b) Current flows into the page and the magnetic field is clockwise.

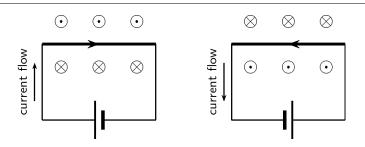


Figure 3: Magnetic fields around a conductor looking down on the conductor. (a) Current flows clockwise. (b) current flows counter clockwise.

#### 2.1 Case Study: Direction of a magnetic field

Using the directions given in Figure 2 and Figure 3 try to find a rule that easily tells you the direction of the magnetic field.

Hint: Use your fingers. Hold the wire in your hands and try to find a link between the direction of your thumb and the direction in which your fingers curl.

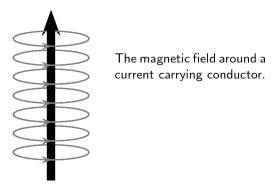
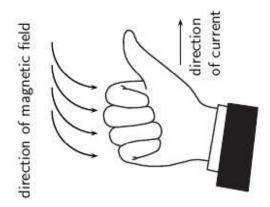


Figure 4

There is a simple method of finding the relationship between the direction of the current flowing in a conductor and the direction of the magnetic field around the same conductor. The method is called the Right Hand Rule. Simply stated, the right hand rule says that the magnetic field lines produced by a current-carrying wire will be oriented in the same direction as the curled fingers of a person's right hand (in the "hitchhiking" position), with the thumb pointing in the direction of the current flow.



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#### 2.2 Case Study: The Right Hand Rule

Use the Right Hand Rule to draw in the directions of the magnetic fields for the following conductors with the currents flowing in the directions shown by the arrows. The first problem has been completed for you.

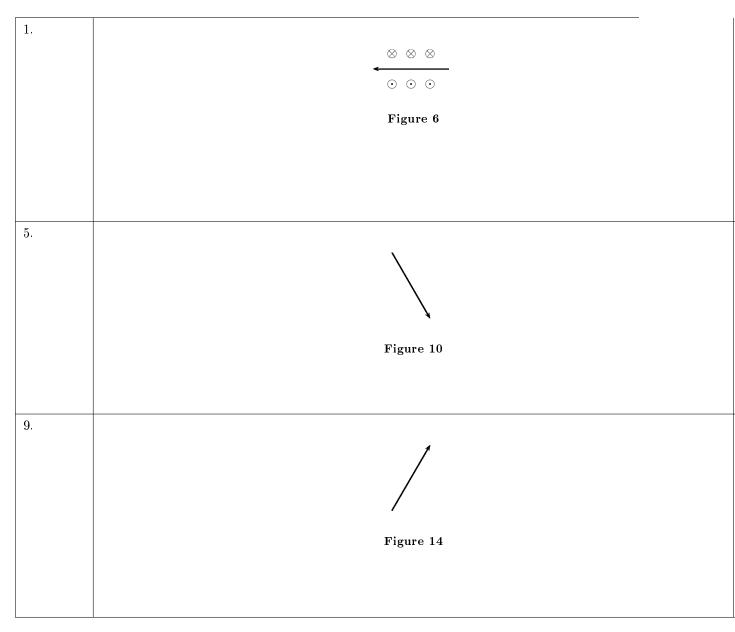


Table 1

## 2.3 Experiment: Magnetic field around a current carrying conductor Apparatus:

1. one 9V battery with holder

Connexions module: m32837 6

- 2. two hookup wires with alligator clips
- 3. compass
- 4. stop watch

#### Method:

1. Connect your wires to the battery leaving one end of each wire unconnected so that the circuit is not closed.

- 2. One student should be in charge of limiting the current flow to 10 seconds. This is to preserve battery life as well as to prevent overheating of the wires and battery contacts.
- 3. Place the compass close to the wire.
- 4. Close the circuit and observe what happens to the compass.
- 5. Reverse the polarity of the battery and close the circuit. Observe what happens to the compass.

#### Conclusions:

Use your observations to answer the following questions:

- 1. Does a current flowing in a wire generate a magnetic field?
- 2. Is the magnetic field present when the current is not flowing?
- 3. Does the direction of the magnetic field produced by a current in a wire depend on the direction of the current flow?
- 4. How does the direction of the current affect the magnetic field?

#### 2.4 Case Study: Magnetic field around a loop of conductor

Consider two loops made from a conducting material, which carry currents (in opposite directions) and are placed in the plane of the page. By using the Right Hand Rule, draw what you think the magnetic field would look like at different points around each of the two loops. Loop 1 has the current flowing in a counter-clockwise direction, while loop 2 has the current flowing in a clockwise direction.

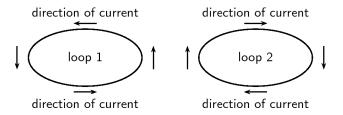
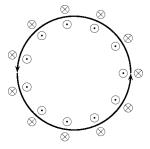


Figure 18

If you make a loop of current carrying conductor, then the direction of the magnetic field is obtained by applying the Right Hand Rule to different points in the loop.



The directions of the magnetic field around a loop of current carrying conductor with the current flowing in a counter-clockwise direction is shown.

Figure 19

If we now add another loop with the current in the same direction, then the magnetic field around each loop can be added together to create a stronger magnetic field. A coil of many such loops is called a *solenoid*. The magnetic field pattern around a solenoid is similar to the magnetic field pattern around the bar magnet that you studied in Grade 10, which had a definite north and south pole.

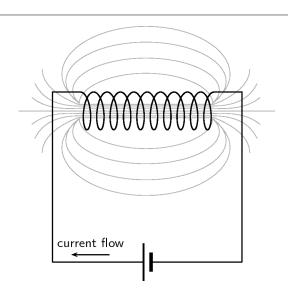


Figure 20: Magnetic field around a solenoid.

#### 2.5 Real-world applications

#### 2.5.1 Electromagnets

An electromagnet is a piece of wire intended to generate a magnetic field with the passage of electric current through it. Though all current-carrying conductors produce magnetic fields, an electromagnet is usually constructed in such a way as to maximize the strength of the magnetic field it produces for a special purpose.

Electromagnets are commonly used in research, industry, medical, and consumer products. An example of a commonly used electromagnet is in security doors, e.g. on shop doors which open automatically.

As an electrically-controllable magnet, electromagnets form part of a wide variety of "electromechanical" devices: machines that produce a mechanical force or motion through electrical power. Perhaps the most obvious example of such a machine is the *electric motor* which will be described in detail in Grade 12. Other examples of the use of electromagnets are electric bells, relays, loudspeakers and scrapyard cranes.

#### 2.5.1.1 Experiment: Electromagnets

#### Aim:

A magnetic field is created when an electric current flows through a wire. A single wire does not produce a strong magnetic field, but a wire coiled around an iron core does. We will investigate this behaviour.

#### Apparatus:

- 1. a battery and holder
- 2. a length of wire
- 3. a compass
- 4. a few nails

#### Method:

- 1. If you have not done the previous experiment in this chapter do it now.
- 2. Bend the wire into a series of coils before attaching it to the battery. Observe what happens to the deflection of the needle on the compass. Has the deflection of the compass grown stronger?
- 3. Repeat the experiment by changing the number and size of the coils in the wire. Observe what happens to the deflection on the compass.
- 4. Coil the wire around an iron nail and then attach the coil to the battery. Observe what happens to the deflection of the compass needle.

#### **Conclusions:**

- 1. Does the number of coils affect the strength of the magnetic field?
- 2. Does the iron nail increase or decrease the strength of the magnetic field?

#### 2.5.1.2 Magnetic Fields

- 1. Give evidence for the existence of a magnetic field near a current carrying wire.
- 2. Describe how you would use your right hand to determine the direction of a magnetic field around a current carrying conductor.
- 3. Use the Right Hand Rule to determine the direction of the magnetic field for the following situations:

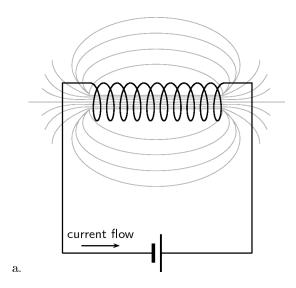
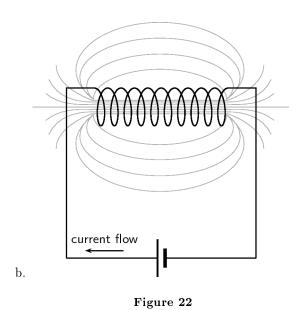
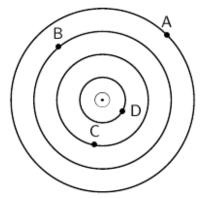
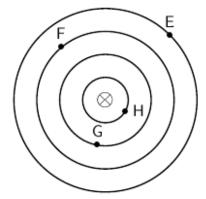


Figure 21



4. Use the Right Hand Rule to find the direction of the magnetic fields at each of the points labelled A - H in the following diagrams.





#### 3 Current induced by a changing magnetic field

While Oersted's surprising discovery of electromagnetism paved the way for more practical applications of electricity, it was Michael Faraday who gave us the key to the practical generation of electricity: **electromagnetic induction**.

Faraday discovered that a voltage was generated across a length of wire while moving a magnet nearby, such that the distance between the two changed. This meant that the wire was exposed to a magnetic field flux of changing intensity. Furthermore, the voltage also depended on the orientation of the magnet; this is easily understood again in terms of the magnetic flux. The flux will be at its maximum as the magnet is aligned perpendicular to the wire. The magnitude of the changing flux and the voltage are linked. In fact, if the lines of flux are parallel to the wire, there will be no induced voltage.

#### Definition 1: Faraday's Law

The emf,  $\varepsilon$ , produced around a loop of conductor is proportional to the rate of change of the magnetic flux,  $\phi$ , through the area, A, of the loop. This can be stated mathematically as:

$$\varepsilon = -N \frac{\Delta \phi}{\Delta t} \tag{3}$$

where  $\phi = B \cdot A$  and B is the strength of the magnetic field.

Faraday's Law relates induced emf to the rate of change of flux, which is the product of the magnetic field and the cross-sectional area the field lines pass through.

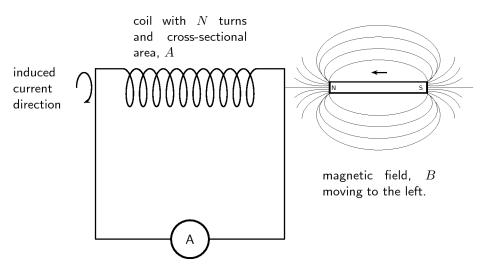


Figure 24

When the north pole of a magnet is pushed into a solenoid, the flux in the solenoid increases so the induced current will have an associated magnetic field pointing out of the solenoid (opposite to the magnet's field). When the north pole is pulled out, the flux decreases, so the induced current will have an associated magnetic field pointing into the solenoid (same direction as the magnet's field) to try to oppose the change. The directions of currents and associated magnetic fields can all be found using only the Right Hand Rule. When the fingers of the right hand are pointed in the direction of the magnetic field, the thumb points in the direction of the current. When the thumb is pointed in the direction of the magnetic field, the fingers point in the direction of the current.

TIP: An easy way to create a magnetic field of changing intensity is to move a permanent magnet next to a wire or coil of wire. The magnetic field must increase or decrease in intensity perpendicular to the wire (so that the magnetic field lines "cut across" the conductor), or else no voltage will be induced.

TIP: Finding the direction of the induced current

The induced current generates a magnetic field. The induced magnetic field is in a direction that tends to cancel out the change in the magnetic field in the loop of wire. So, you can use the Right Hand Rule to find the direction of the induced current by remembering that the induced magnetic field is opposite in direction to the change in the magnetic field.

Electromagnetic induction is put into practical use in the construction of electrical generators, which use mechanical power to move a magnetic field past coils of wire to generate voltage. However, this is by no means the only practical use for this principle.

If we recall that the magnetic field produced by a current-carrying wire is always perpendicular to the wire, and that the flux intensity of this magnetic field varies with the amount of current which passes through it, we can see that a wire is capable of inducing a voltage along its own length if the current is changing. This effect is called self-induction. Self-induction is when a changing magnetic field is produced by changes in current through a wire, inducing a voltage along the length of that same wire.

If the magnetic flux is enhanced by bending the wire into the shape of a coil, and/or wrapping that coil around a material of high permeability, this effect of self-induced voltage will be more intense. A device constructed to take advantage of this effect is called an *inductor*, and will be discussed in greater detail in the next chapter.

#### 3.1 Lenz's Law

The induced current will create a magnetic field that opposes the change in the magnetic flux.

#### Exercise 1: Faraday's Law

(Solution on p. 21.)

Consider a flat square coil with 5 turns. The coil is 0,50 m on each side, and has a magnetic field of 0,5 T passing through it. The plane of the coil is perpendicular to the magnetic field: the field points out of the page. Use Faraday's Law to calculate the induced emf, if the magnetic field is increases uniformly from 0,5 T to 1 T in 10 s. Determine the direction of the induced current.

#### 3.2 Real-life applications

The following devices use Faraday's Law in their operation.

- induction stoves
- tape players
- metal detectors
- transformers

#### 3.2.1 Research Project: Real-life applications of Faraday's Law

Choose one of the following devices and do some research on the internet or in a library how your device works. You will need to refer to Faraday's Law in your explanation.

- induction stoves
- tape players
- metal detectors
- transformers

#### 3.2.2 Faraday's Law

- 1. State Faraday's Law in words and write down a mathematical relationship.
- 2. Describe what happens when a bar magnet is pushed into or pulled out of a solenoid connected to an ammeter. Draw pictures to support your description.
- 3. Use the Right Hand Rule to determine the direction of the induced current in the solenoid below.

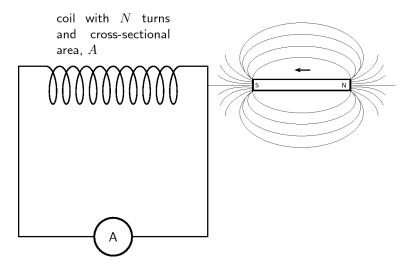


Figure 25

#### 4 Transformers

One of the real-world applications of Faraday's Law is in a transformer.

Eskom generates electricity at around 22 000 V. When you plug in a toaster, the mains voltage is 220 V. A transformer is used to *step-down* the high voltage to the lower voltage that is used as mains voltage.

#### **Definition 2: Transformer**

A transformer is an electrical device that uses the principle of induction between the primary coil and the secondary coil to either step-up or step-down the voltage.

The essential features of a transformer are two coils of wire, called the primary coil and the secondary coil, which are wound around different sections of the same iron core.

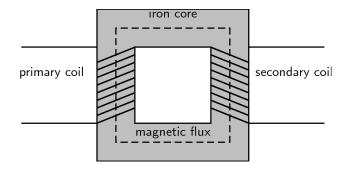


Figure 26

When an alternating voltage is applied to the primary coil it creates an alternating current in that coil, which induces an alternating magnetic field in the iron core. The changing magnetic flux through the secondary coil induces an emf, which creates a current in this secondary coil.

The circuit symbol for a transformer is:

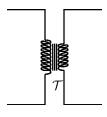


Figure 27

By choosing the number of coils in the secondary solenoid relative to the number of coils in the primary solenoid, we can choose how much bigger or smaller the induced secondary current is by comparison to the current in the primary solenoid (so by how much the current is stepped up or down.)

This ability to transform voltage and current levels according to a simple ratio, determined by the ratio of input and output coil turns is a very useful property of transformers and accounts for the name. We can derive a mathematical relationship by using Faraday's law.

Assume that an alternating voltage  $V_p$  is applied to the primary coil (which has  $N_p$  turns) of a transformer. The current that results from this voltage generates a changing magnetic flux  $\phi_p$ . We can then describe the emf in the primary coil by:

$$V_p = N_p \frac{\Delta \phi_p}{\Delta t} \tag{4}$$

Similarly, for the secondary coil,

$$V_s = N_s \frac{\Delta \phi_s}{\Delta t} \tag{5}$$

If we assume that the primary and secondary windings are perfectly coupled, then:

$$\phi_p = \phi_s \tag{6}$$

which means that:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \tag{7}$$

#### Exercise 2: Transformer specifications

(Solution on p. 21.)

Calculate the voltage on the secondary coil if the voltage on the primary coil is 120 V and the ratio of primary windings to secondary windings is 10:1.

A transformer designed to output more voltage than it takes in across the input coil is called a *step-up* transformer. A step-up transformer has more windings on the secondary coil than on the primary coil. This means that:

$$N_s > N_p \tag{8}$$

Similarly, a transformer designed to output less than it takes in across the input coil is called a *step-down* transformer. A step-down transformer has more windings on the primary coil than on the primary coil. This means that:

$$N_p > N_s \tag{9}$$

We use a step-up transformer to increase the voltage from the primary coil to the secondary coil. It is used at power stations to increase the voltage for the transmission lines. A step-down transformer decreases the voltage from the primary coil to the secondary coil. It is particularly used to decrease the voltage from the transmission lines to a voltage which can be used in factories and in homes.

Transformer technology has made long-range electric power distribution practical. Without the ability to efficiently step voltage up and down, it would be cost-prohibitive to construct power systems for anything but close-range (within a few kilometres) use.

As useful as transformers are, they only work with AC, not DC. This is because the phenomenon of mutual inductance relies on *changing* magnetic fields, and direct current (DC) can only produce steady magnetic fields, transformers simply will not work with direct current.

Of course, direct current may be interrupted (pulsed) through the primary winding of a transformer to create a changing magnetic field (as is done in automotive ignition systems to produce high-voltage spark plug power from a low-voltage DC battery), but pulsed DC is not that different from AC. Perhaps more than any other reason, this is why AC finds such widespread application in power systems.

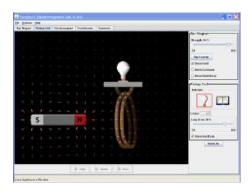


Figure 28

run demo<sup>1</sup>

#### 4.1 Real-world applications

Transformers are very important in the supply of electricity nationally. In order to reduce energy losses due to heating, electrical energy is transported from power stations along power lines at high voltage and low current. Transformers are used to step the voltage up from the power station to the power lines, and step it down from the power lines to buildings where it is needed.

#### 4.1.1 Transformers

- 1. Draw a sketch of the main features of a transformer
- 2. Use Faraday's Law to explain how a transformer works in words and pictures.
- 3. Use the equation for Faraday's Law to derive an expression involving the ratios of the voltages and the number of windings in the primary and secondary coils.
- 4. If we have  $N_p = 100$  and  $N_s = 50$ , and we connect the primary winding to a 230 V, 50Hz supply, then calculate the voltage on the secondary winding.
- 5. State the difference between a step-up and a step-down transformer in both structure and function.
- 6. Give an example of the use of transformers.

#### 5 Motion of a charged particle in a magnetic field

When a charged particle moves through a magnetic field it experiences a force. For a particle that is moving at right angles to the magnetic field, the force is given by:

$$F = qvB \tag{10}$$

where q is the charge on the particle, v is the velocity of the particle and B is the magnetic field through which the particle is moving. This force is called the Lorentz force.

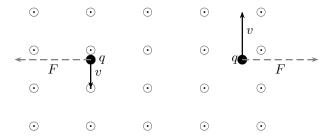


Figure 29

Exercise 3: Charged particle moving in a magnetic field (Solution on p. 21.) An electron travels at  $150m.s^{-1}$  at right angles to a magnetic field of 80 000 T. What force is exerted on the electron?

<sup>&</sup>lt;sup>1</sup> http://phet.colorado.edu/sims/faraday/faraday en.jnlp

TIP: The direction of the force exerted on a charged particle moving through a magnetic field is determined by using the Right Hand Rule. Point your first finger (index finger) in the direction of the velocity of the charge, your second finger (middle finger) in the direction of the magnetic field and then your thumb will point in the direction of the force exerted on the charge. If the charge is negative, the direction of the force will be opposite to the direction of your thumb.

#### 5.1 Real-world applications

The following devices use the movement of charge in a magnetic field

- old televisions (cathode ray tubes)
- oscilloscope

#### 5.1.1 Research Project: Real-life applications of charges moving in a magnetic field

Choose one of the following devices and do some research on the internet or in a library how your device works.

- oscilloscope
- television

#### 5.1.2 Lorentz Force

- 1. What happens to a charged particle when it moves through a magnetic field?
- 2. Explain how you would use the Right Hand Rule to determine the direction of the force experienced by a charged particle as it moves in a magnetic field.

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#### Figure 30

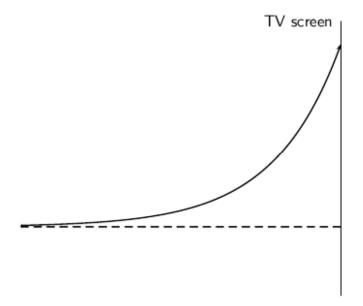
#### 6 Summary

- 1. Electromagnetism is the study of the properties and relationship between electric currents and magnetism
- 2. A current-carrying conductor will produce a magnetic field around the conductor.
- 3. The direction of the magnetic field is found by using the Right Hand Rule.
- 4. Electromagnets are temporary magnets formed by current-carrying conductors.
- 5. Electromagnetic induction occurs when a changing magnetic field induces a voltage in a current-carrying conductor.
- 6. Transformers use electromagnetic induction to alter the voltage.
- 7. A moving charged particle will experience a force in a magnetic field.

#### 7 End of chapter exercises

1. State the Right Hand Rule to determine the direction of a magnetic field around a current carrying wire and the Right Hand Rule to determine the direction of the force experienced by a moving charged particle in a magnetic field.

- 2. What did Hans Oersted discover about the relationship between electricity and magnetism?
- 3. List two uses of electromagnetism.
- 4. Draw a labelled diagram of an electromagnet and show the poles of the electromagnet on your sketch.
- 5. Transformers are useful electrical devices.
  - a. What is a transformer?
  - b. Draw a sketch of a step-down transformer.
  - c. What is the difference between a step-down and step-up transformer?
  - d. When would you use a step-up transformer?
- 6. Calculate the voltage on the secondary coil of a transformer if the voltage on the primary coil is 22 000 V and the ratio of primary windings to secondary windings is 500:1.
- 7. You find a transformer with 1000 windings on the primary coil and 200 windinds on the secondary coil.
  - a. What type of transformer is it?
  - b. What will be the voltage on the secondary coil if the voltage on the primary coil is 400 V?
- 8. An electron moving horizontally in a TV tube enters a region where there is a uniform magnetic field. This causes the electron to move along the path (shown by the solid line) because the magnetic field exerts a constant force on it. What is the direction of this magnetic field?



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- a. upwards (towards the top of the page)
- b. downwards (towards the bottom of the page)
- c. into the page
- d. out of the page

#### Solutions to Exercises in this Module

#### Solution to Exercise (p. 12)

Step 1. We are required to use Faraday's Law to calculate the induced emf.

Step 2.

$$\varepsilon = -N \frac{\Delta \phi}{\Delta t} \tag{11}$$

Step 3.

$$E = -N \frac{\Delta \phi}{\Delta t} 
= -N \frac{\phi_f - \phi_i}{\Delta t} 
= -N \frac{B_f \cdot A - B_i \cdot A}{\Delta t} 
= -N \frac{A(B_f - B_i)}{\Delta t} 
= -(5) \frac{(0.5)^2 (1 - 0.5)}{10} 
= -0.0625 V$$
(12)

The induced current is anti-clockwise as viewed from the direction of the increasing magnetic field.

#### Solution to Exercise (p. 15)

Step 1. Use

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \tag{13}$$

with

- $V_p = 120$   $\frac{N_p}{N_c} = \frac{10}{1}$

Step 2.

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

$$\frac{1}{V_s} = \frac{N_p}{N_s} \frac{1}{V_p}$$

$$\therefore V_s = \frac{1}{\frac{N_p}{N_s}} V_p$$
(14)

Step 3.

$$V_{s} = \frac{1}{\frac{N_{p}}{N_{s}}} V_{p}$$

$$= \frac{1}{\frac{10}{1}} 120$$

$$= 12 V$$

$$(15)$$

#### Solution to Exercise (p. 16)

Step 1. We are required to determine the force on a moving charge in a magnetic field

Step 2. We can use the formula:

$$F = qvB (16)$$

Step 3. We are given

- $q = 1, 6 \times 10^{-19} C$  (The charge on an electron)
- $v = 150m.s^{-1}$

•  $B = 80\ 000T$ 

Step 4.

$$F = qvB$$

$$= (1, 6 \times 10^{-19} C) (150m.s^{-1}) (80\ 000T)$$

$$= 1,92 \times 10^{-12} N$$
(17)