School of Electronic and Electrical Engineering

Semester 1, 2018

ELEC1900 laboratory session

A Simple brushless DC motor

Student details (please print clearly)			
Name:		**SSID:**	
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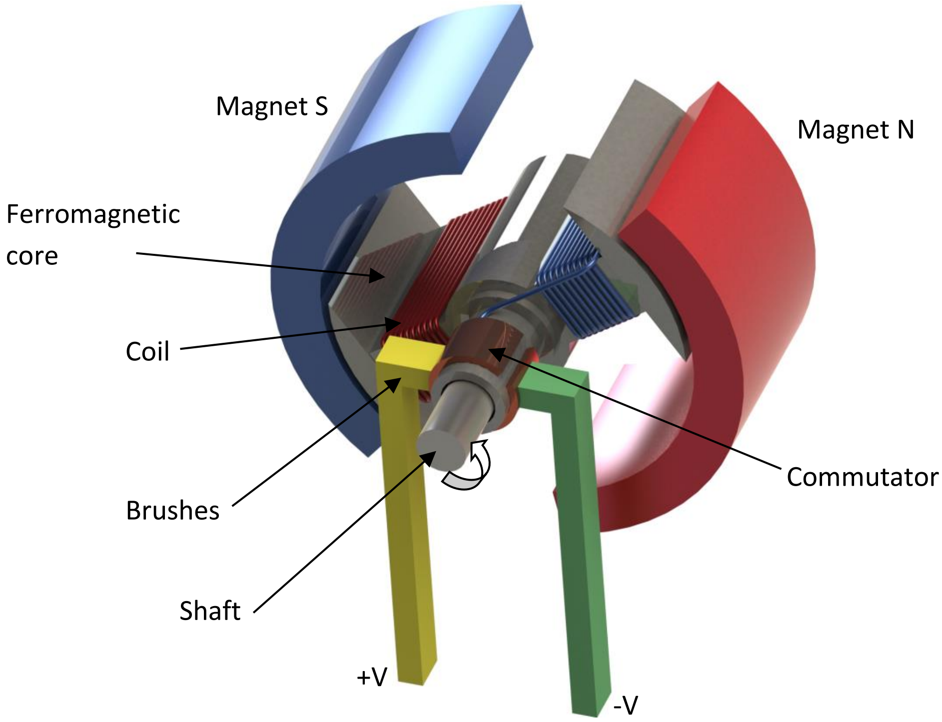
A simple electric motor

Introduction

A motor is a device designed to convert electrical signals into mechanical rotary motion (or vice versa), in the presence of a magnetic field. The aim of this laboratory is to (re)introduce you to the basic operation of a DC motor, alongside various techniques for controlling the motor operation. A schematic of a brushed DC (BDC) motor is given below:



In its simplest form, the BDC motor consists of several integral parts, typically:

- **Stator:** this does not move, and generally contains static, permanent magnets.
- **Rotor / armature:** produces the rotational motion, and often contains current-carrying wire wrapped around a ferromagnetic core.
- **Commutator**: allows the current direction in the wire to be changed as the rotor rotates.
- **Brushes:** form an electrical connection between the moving commutator and external circuitry.
- **Shaft**: allows the rotary motion to be transferred to an external object.

The motor you will build in this laboratory is a deconstructed, brushless DC motor – brushless means that you do not need mechanical contact to the rotating part. You will use several types of switch to interrupt the DC power supply (replacing the function of a commutator), and measure the motor operation using an oscilloscope. This will provide you with valuable experience of circuit development, troubleshooting and data interpretation, which will help you with the rest of your undergraduate project work.

Your pack includes:

1 x transistor	1 x elastic band	1 x iron core with tape	3 x plastic posts
1 x Hall sensor	1 x reed switch	1 cylindrical wooden spacer	2 x domed hubs
1 x long pin	1 x short pin	2 x sequin spacers	
1 x reel transformer wire	4 x magnets	1 x faceted plastic tube	

You can obtain the following from laboratory supplies:

Solid core wire	1 x diode (1N4001)	Superglue	4.7 kΩ resistor
1 x (4x4) piece of veroboard	1 x white breadboard		

Some general advice

In order to obtain high marks, to improve your learning experience and to maximise your enjoyment of this (and any other) practical laboratory session, a few suggestions are provided below.

- Write clearly. If your assessor cannot read your writing, you will not be given marks for that section. Please use capitals or print if required.
- When asked to draw a graph, **LABEL EVERYTHING CLEARLY.** This includes axis labels and features of interest on your graph (e.g. maximum values, minimum values, the zero position etc.).
- When assembling a circuit, particularly on a prototype board, keep it tidy! If troubleshooting is required it does nobody any good if the first 20 minutes is spent working out where your wires go. Colour coding helps – red for positive, black for negative etc.
- Read and re-read any information given and any questions asked to avoid silly mistakes.

Building the motor

You will work in pairs for this laboratory, so please ensure that you distribute the tasks equally between you. However, you will **both** need to complete your own lab sheet! The lab begins by winding the coil for your motor. The coil, formed using enamel coated wire, has a soft-iron nail located at its core. The coil winding is straightforward but requires some time and *patience* – a key attribute for an engineer! An equally valuable trait for an engineer is finding the balance between productivity and performance – whilst it is true that a perfectly wound coil will produce the best performance, if you take more than 1 hour to complete the wind then this is too long!

As shown in Figure 1, tape is fixed to the nail to allow you to secure one end of the wire – leave ~ 20 cm overhang. This will anchor the wire as you begin to wind the coil, beginning from the taped end of the nail and moving away in ***either*** a clockwise ***or*** anticlockwise direction – maintain one direction for all of your winding! Student 1 should wind **4 passes** of the coil (see Figure 1) making the coil as tight and uniform as is practical. When finished, pass the wire underneath the tape again and cut a second ~ 20 cm overhang. You have now created a weak electromagnet. Use the small piece of sandpaper to clean the enamel off each **end** of coil you have wound, to expose the copper core (*you only need to clean off ~5 – 10 mm of enamel from each end, but you need to do it thoroughly*). Apply a 1V DC bias across your coil using your power

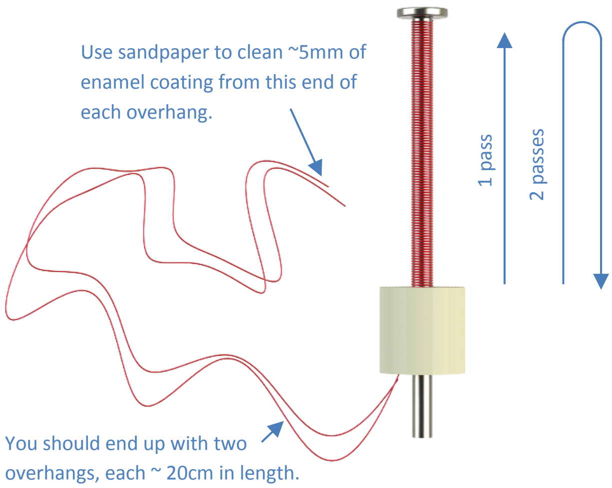


Figure 1: coil winding

supply. You should be able to feel the force exerted on one of the permanent magnets supplied with your kit.

Student two should repeat this process with a new winding (on top of the previous one). Continue to wind a further 4 passes. If you finish at the far end of the core, a loose winding to reach the tape, whilst retaining a ~20 cm overhang at the end, will suffice. *Hint: It helps if you secure each pair of wires, two from each winding, to opposite sides of the tape.* Use a multimeter to check the continuity of each of your two coils.

Show your winding to a demonstrator for assessment.

Winding marked for uniformity and completion. (*max. 2 marks*)	Assessor signature: Total marks awarded:

Thought: Why are we using enamelled wire instead of normal, polymer-coated wire which will be used in the rest of our circuit?

Insert the end of the core into the plastic pillar provided. This coil now constitutes a large inductor, with which you will drive your motor. An inductor is a device which opposes sudden changes in current by producing a back-EMF (electro-motive force) and ideally would have zero resistance. However, zero resistance is not achievable in real life and all motor coils can therefore be represented as a resistor in series with an ideal inductor, as shown in Figure 2.

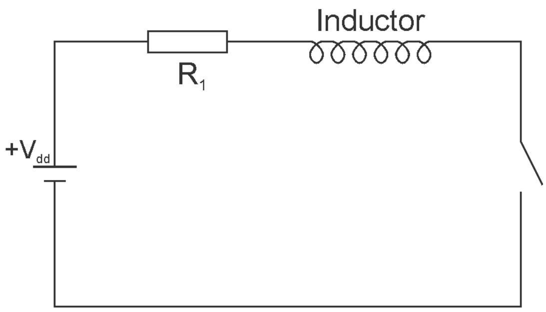


Figure 2: Equivalent circuit for a non-ideal inductor

Question 1: Imagine that the switch in the circuit is closed suddenly, allowing current to flow. As a function of time from t = 0 seconds until a stable state has been reached, sketch three graphs: 1) the voltage drop you would expect across the inductor, 2) the voltage drop across the resistor, and 3) the total current in the circuit.
(Hint: it may help to recall that, if no current is flowing in the circuit, the voltage drop across the resistive part of the circuit will be zero, so all the voltage must drop across the ideal inductor at t = 0).

Graph 1	Graph 2	Graph 3	
			(*Max. 4 marks*)

Connect one of your coils across the positive and negative terminals of your power supply. Set the DC bias to 0.5 V and switch on the output. What current do you read? What, therefore, is the resistance of your coil? Repeat with the second coil. *(If you need to use a lower voltage, make certain you note this below!)*

Current 1: Resistance 1:	Current 2: Resistance 2:	(*Max. 1 mark*)

Next, use superglue to adhere your magnets to the flat sides of the plastic section, as shown in Figure 3. Make certain that the magnets are facing in the same direction with the South pole (labelled 'S') facing outwards. Please note, these magnets are strong – if you do not hold them in place until the glue sets, they **WILL** jump onto any other nearby magnets / metal surfaces and the glue will then inevitably set and prevent their future use. **Take particular care not to get glue on any instrumentation.** Insert the long and short pins into either cap, slide the wooden spacer into one end and then assemble the full section as shown below (see Figure 3). Take care not to bend the long pin – it is essential that this remains as straight as possible.

Figure 3: Exploded view of your rotor assembly

There are two pillars which will act as the support mounts for this section of the rotor. The pillar with one small hole will hold the short pin, and the pillar with one small and one larger hole will support the long pin. Insert the sequins onto the short pin and then gently locate the pin in the appropriate pillar – this is **END ONE**. Place the long pin through the **<u>smaller hole</u>** of the second pillar – this is **END TWO**. The whole section should now stand by itself. Hold the two ends and make certain you can spin the rotor freely – if it is stiff, adjust your pillar position until free movement is achieved. If it is still stiff, you've probably put your long pin through the large hole instead of the small hole in the support pillar!

On the wooden board provided with your kit, some stars have been positioned, each with a line drawn through them, to aid alignment. Align **END ONE** with the star closer to the centre of the board – try to ensure that the marks on either side of the pillar align with the line drawn on the board, and glue it in place. The exact location of the second pillar is now critical – the marks on the board are **guides only**, designed to aid you with initial positioning. Without using glue, align the second pillar to a position which allows for easiest rotation of the motor. The long needle should hang over the edge of the board. The key points are 1) to ensure that the axis of the rotor is straight to minimise axial strain, and 2) to leave ~1 – 2 mm gap at either end between the rotor hub and the pillars, to allow free rotation. Once you are satisfied, glue the second pillar in place. You have now assembled the rotor part of your motor (see Figure 4).

Align your wound coil perpendicularly to the magnets on your rotor. Position the end of the core as close to the magnets as possible whilst ensuring that the rotor can rotate freely without the magnets hitting the coil. Glue the coil pillar in this position, taking care that it does not move before the glue sets. Check free rotation again afterwards. If the magnets impact the coil during rotation, you will have to force the coil off the base and try to re-seat it with a new application of glue**. This can get messy, so care is advised the first time!** This is your stator – the total assembly should look similar to Figure 4 on the next page.

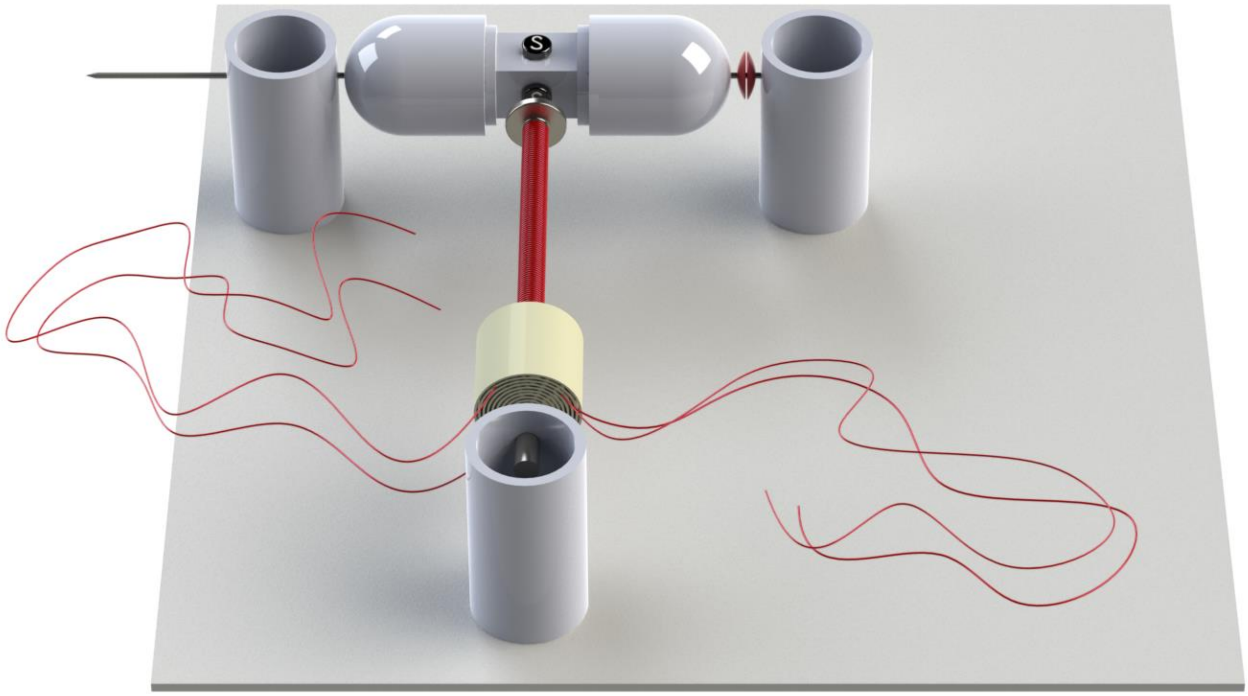


Figure 4: Assembled stator and rotor

Ensure that the current limit on your power supply is set to 2A (where possible). Connect either end of **one** coil to the power supply and set the output to 2V. Ensure that the magnet is **repelled** by your electromagnetic coil, and note which coil-wire is connected to the positive and negative terminals of the power supply (you may mark the wire if necessary). Repeat this process with your second coil. The basic motor construction is now complete. Show it to a demonstrator for assessment, and demonstrate that you can repel the static magnets with your coils.

<table>
<tr><td>Rotor rotates freely
(1 mark)</td><td>Yes / No</td><td rowspan="4">Assessor signature:

Total marks awarded:</td></tr>
<tr><td>Magnets are clear of coil
(1 mark)</td><td>Yes / No</td></tr>
<tr><td>Rotor and stator are in correct orientation
(1 mark)</td><td>Yes / No</td></tr>
<tr><td>Magnets are repelled when bias applied to coil.
(2 marks)</td><td>Yes / No</td></tr>
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Building the driving circuits

In this section, you will construct three variations of possible driving circuits, sequentially. For this exercise, you will use a breadboard to allow quick changing of connections, and will probe voltage waveforms using an oscilloscope (some sections will require two probe leads).

Please ensure that you wire your circuit logically and neatly – if you encounter problems, this will ensure that your cheerful, helpful demonstrators remain both cheerful and helpful.

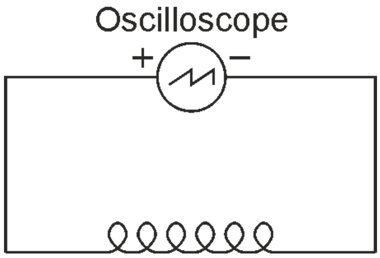

Figure 5: Oscilloscope connected across coil

Exercise: Before you construct the first circuit, we will first test your understanding of inductors. Connect your oscilloscope probe leads across the coil, as shown in Figure 5 below. Spin the rotor by hand – what do you see on the oscilloscope? *Hint: If you see nothing, then alter the time base and/or sensitivity of your oscilloscope until you do!*

Using your knowledge of electromagnetism, describe this effect *(ask a demonstrator if you require help setting up the oscilloscope)*.

Marks awarded *(Max. 2 marks)*:

Circuit 1: The Reed switch

The reed switch is the simplest control circuit you will build, and consists of a mechanical switch which is operated by the permanent magnets on your rotor.

Cut two ~ 30cm long lengths of enamelled wire. Remove ~10 mm of enamel from each end using the sand paper provided (as you did for your coil), and solder one wire to each side of the reed switch. A pillar is provided on which to mount the reed switch. Pass the enamelled wire through the small holes on the pillar, crossing them in the centre and passing them out of the far side. Pull the wire tight and twist several times to hold the reed switch in place – note that the reed switch should be positioned off-centre on the pillar. **Do not cut the wire** – it is needed to connect to your breadboard. Use the elastic band provided for extra support for the reed switch if required. Glue the pillar in place (note the correct orientation of the pillar in Figure 6) and, using your breadboard, build the circuit in Figure 7, using **one** of your wound coils.

Connect the positive terminal of your DC power supply to the top rail, and the negative terminal to the bottom rail of the breadboard using the cable provided. Set the power supply to 6V and switch on the output. If your motor does not rotate, it may be stalled – check the output current on the power supply - a stalled motor may draw the full 2A limited current. The coil will get hot if left in this state, so gently spin the motor with your hand to get it going. Allow it to reach a steady state. For an ideal motor in this

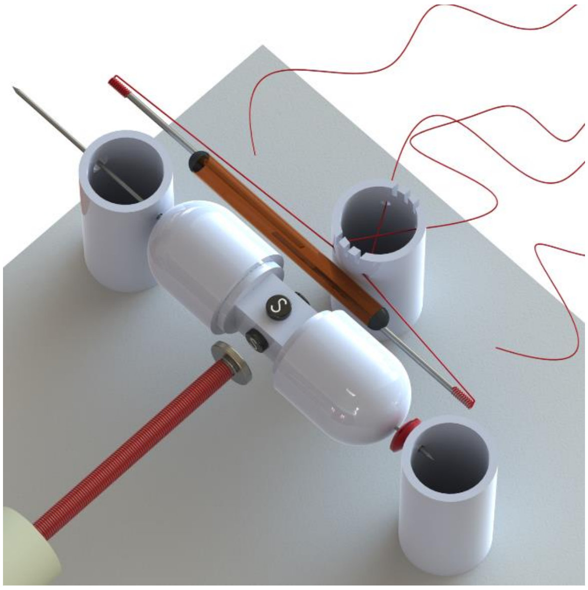

Figure 6: Reed switch arranged next to rotor.

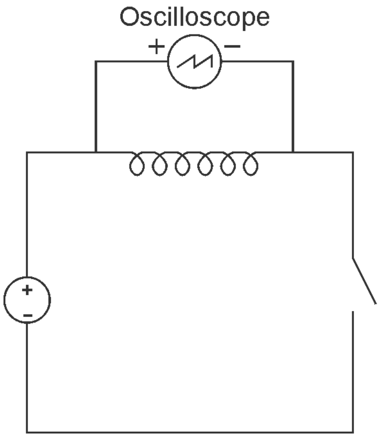

Figure 7: Oscilloscope connections across coil

configuration, you would expect to see a perfect square wave, in which the 'on' state (reed switch closed) is at the DC supply voltage, and the 'off' state is 0V (reed switch open), as shown in Figure 8.

Figure 8: Example of an ideal square wave

a) Draw below the signal seen on the oscilloscope, including the maximum and minimum voltages of the square wave, and any extra features *(Hint: if the oscilloscope cannot trigger correctly, press the 'single scan' button to freeze the image)*
b) Referring the waveform you have drawn for part a), what do you notice when your motor is in the 'off' state (i.e. when the switch opens)? How do you explain this?
c) Again referring to your waveform, what do you notice when your motor is in the 'on' state (i.e. when the switch closes)? What causes this? *(Hint: it may help to zoom in on this region of the trace)*
d) What do you notice happening inside the reed switch as the motor rotates? Why?

a)   *Max. 4 marks*
b)   *Max. 2 marks*

c)   *Max. 4 marks*
d)   *Max. 2 marks*
Marks awarded *(Max 10 marks)*:

Make a note of the speed of rotation of your motor. *(Hint: using the 'auto-set' button on your oscilloscope will not work owing to the poor signal quality. Use 'single scan' when your motor is rotating at its fastest to catch a trace, and then calculate the speed based on the signal shown and the time-base of your oscilloscope).* **MOTOR SPEED:**

Now connect your second coil in parallel with your first coil. You motor should increase in speed as you are increasing the strength of your electromagnet. **NEW MOTOR SPEED:**

Thought: If you were to connect the second coil in reverse polarity to the first, what do you think would happen?

Circuit 2: The Reed switch with transistor

Now adjust the drive circuit to match Figure 9a below, using the BJT transistor provided. The correct orientation of the pins is provided in Figure 9b. You may recall from your Elec1130 laboratories that, when measuring a single component of a multi-component circuit, using a single channel from the oscilloscope (as you did for the previous questions) may not work, as the ground connection may inadvertently ground parts of the circuit which otherwise would have a potential. Using two probes, one on Ch1 and one on Ch2, connect the scope as shown in Figure 9a), and set the 'Math' function to Ch1 – Ch2. **All subsequent questions refer to the 'Math' trace.** Turn on the power supply and start the motor rotating.

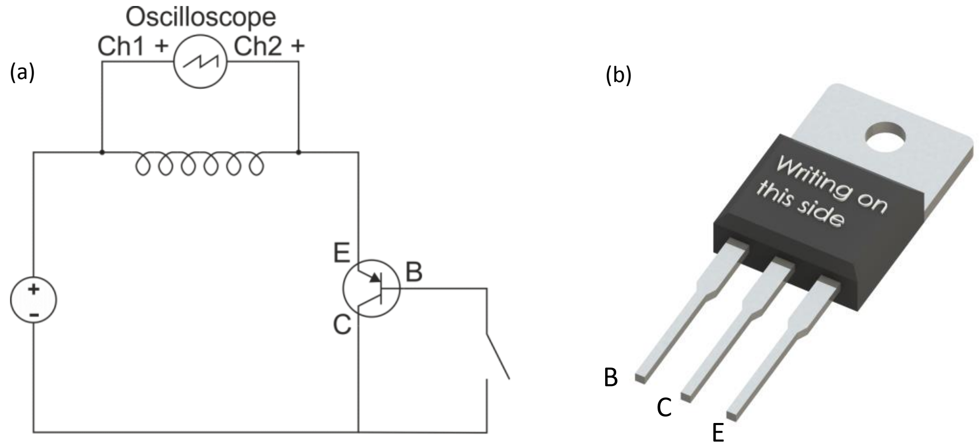

Figure 9: a) Circuit diagram of a transistor integrated with your reed switch, and b) pin-out diagram for the BJT transistor.

What do you notice about the signal on the oscilloscope in comparison with your previous measurement? Draw the trace below, and note the main differences from your previous measurement.

Max. 4 marks

What is happening inside the reed switch and why?

Max. 2 marks

Marks awarded *(Max. 6 marks)*:

You should notice that the on state does not reach the DC supply voltage, and is not flat during the on-time of the motor. With the DC power supply switched off connect probe 1 of your oscilloscope probe to the emitter, and probe 2 to the collector of your transistor. Switch on the motor and ensure it is turning. Sketch what you see below, labelling important values:

Marks awarded *(Max. 4 marks)*:

Does this account for all the losses in your signal? Turn off your supply and, using a multimeter, measure the DC resistance of the wires you use to connect the DC power supply to the motor.

a) How does this value compare with your inductor resistance?
b) Accounting for the voltage drop measured across your transistor, what maximum voltage would you therefore expect across your coil? Does this agree with your oscilloscope measurement?

a) *Max. 2 marks*
b) *Max. 2 marks*
Marks awarded *(Max 4 marks)*:

The key points to take from this exercise so far are:

- When designing a circuit, you cannot ignore the fact that the parts you use are not ideal. Each component you add will have a resistive, capacitive or inductive component -or often, a combination thereof.
- You must always remember that wires contribute losses to your circuit. This is particularly important for high power applications, or in applications in which your load resistance is close to that of your wires.
- Mechanical switches are generally best avoided where possible. There are often better alternatives available.

Make a note of the speed of rotation of your motor. **MOTOR SPEED:**

Thought: Why is this speed lower than for the previous circuit which did not include a transistor?

Circuit 3: The Hall Effect sensor and transistor

The final circuit you will construct consists of a Hall-effect sensor in place of the reed switch. In a few words, describe the Hall-effect below, and how you think this can therefore be used as a sensor:

Marks awarded *(Max. 2 marks)*:

Note the orientation of the leads, as shown in Figure 10a, and connect the Hall sensor into the circuit of Figure 10b. Make certain to leave sufficient length on the wires to reach the bread board. Use the small (3 x 3) section of veroboard to solder the positive, negative and signal wires of the Hall sensor. Next, connect three lengths of wire (shown respectively as red, black and yellow in the diagram on the next page), long enough to reach your breadboard, to the veroboard - you will have to bend the wires such that the Hall-effect sensor is suspended above your rotor. The writing on the Hall sensor must face downward assuming your magnetic south poles are facing outward from the rotor, as instructed. The grooves in the pillar will help you secure the wires in place.

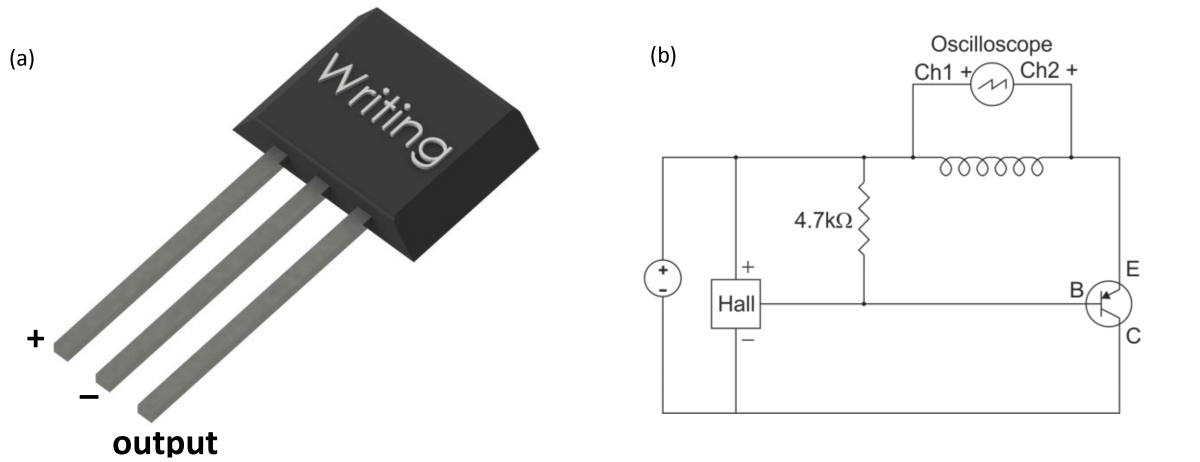

Figure 10: a) a pin-out diagram for the Hall sensor, and b) a circuit diagram of a Hall-sensor integrated with your motor circuit.

Your assembled motor and Hall sensor should look similar to the illustration given in Figure 11 on the next page. The slots in the support pillar can be used to guide your wiring, which will provide support for your sensor.

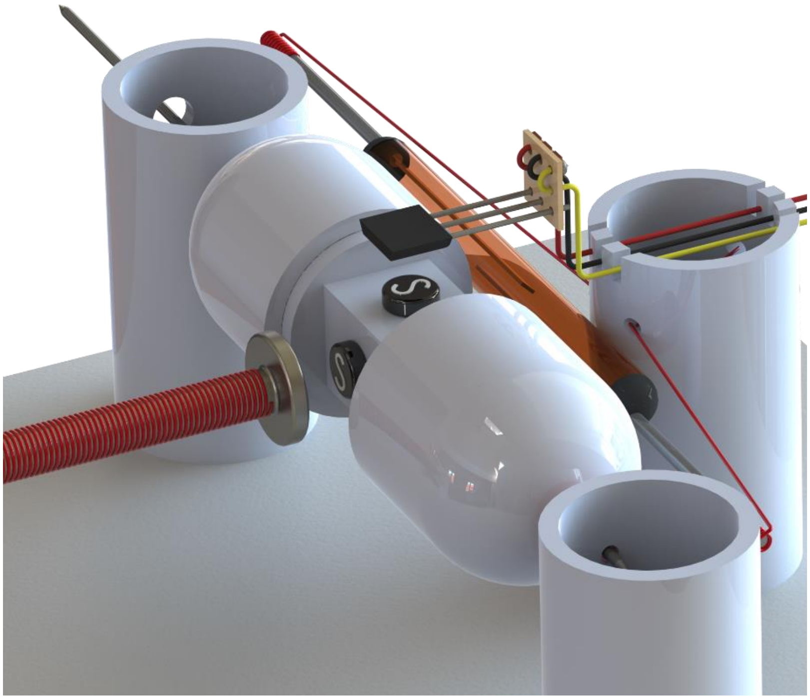

Figure 11: Illustration of the assembled motor, including reed switch and Hall sensor.

Draw the measured oscilloscope signal for this circuit below:

Marks awarded *(Max. 2 marks)*:

The trace should be similar to that obtained for the optical gate. *The large negative spike when the motor switches off is therefore independent of the mechanism used to switch the DC power supply.* Modify your circuit to match Figure 12a, taking care to connect the diode in the correct orientation (Figure 12b):

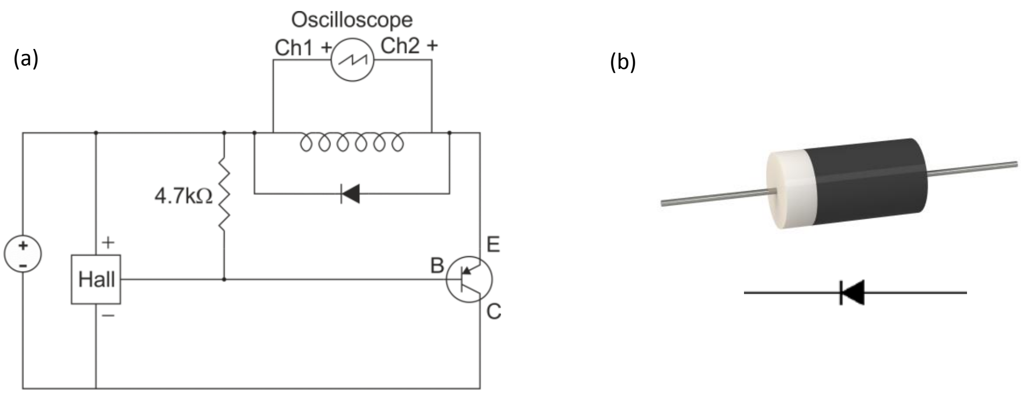

Figure 12: a) Circuit diagram of a diode integrated with your hall-sensor-switched motor, and b) orientation of the diode.

Draw the oscilloscope trace below. What do you notice? How can you explain the difference *(i.e. what role is the diode performing in this circuit)*.

Oscilloscope trace: *(Max.2 marks)*
Observations and explanation of diode: *(Max.2 marks)*
Marks awarded *(Max. 4 marks)*:

Make a note of the speed of rotation of your motor. **MOTOR SPEED:**

This completes your DC motor laboratory sessions. I hope you had fun. If you wish to keep your motor, please ask for some veroboard on which you can solder up the switch of your choice with the transistor.