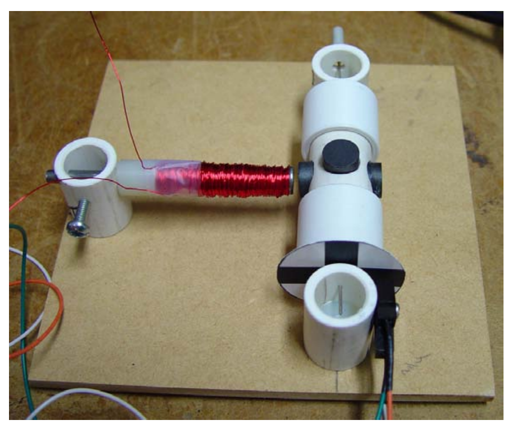
Lab 5

Electric Motors and Transistors

Introduction

In this lab you will build a circuit using a transistor, and build a simple electric motor.

- The motor only has 1 driving magnet, so you will need a transistor and an optical detector to turn its driving coil on.



Before we can build this motor, we need to understand:

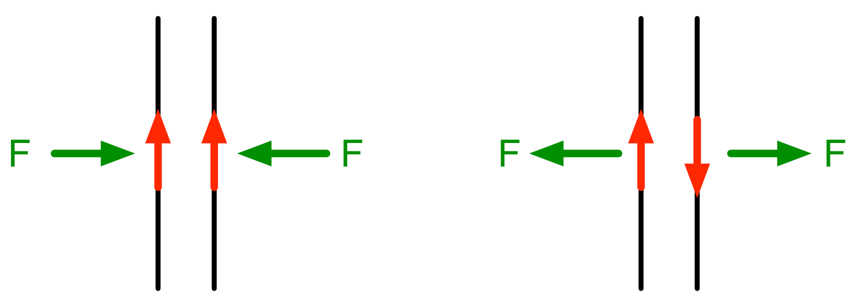
- How does this simple motor work.
- How do electromagnets work.
- How do transistors work.
- Some history about motors.

The Electromagnet

Force Between Parallel Conductors

Earlier we learnt that in 1820 the French physicist and mathematician André-Marie Ampère demonstrated:

- That parallel wires carrying currents moving in the same direction attract each other.
- And if the currents move in opposite directions the wires repel each other.



Current flowing in the same direction

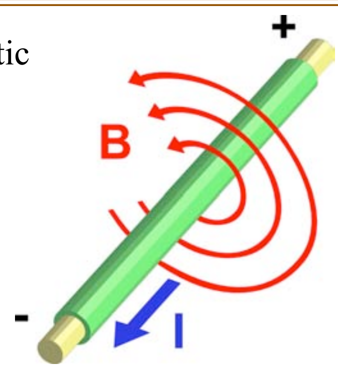
Current flowing in the opposite direction

Why does this happen?

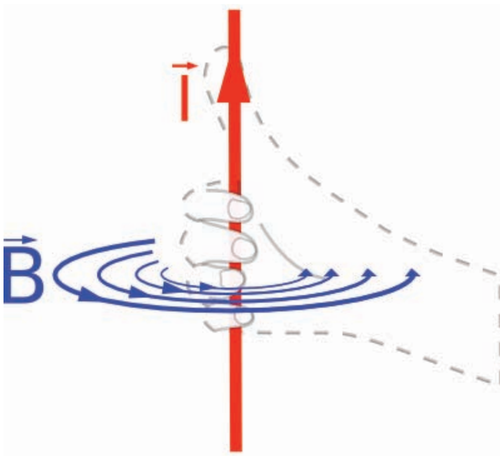
Force Between Conductors - Explanation

Ørsted showed us that an electric current produces a magnetic field as it flows through a wire.

- The strength of the field is proportional to the current.



Picture from Wikipedia



The direction of the magnetic field around the wire (clockwise or counterclockwise) can be found using the "right hand rule".

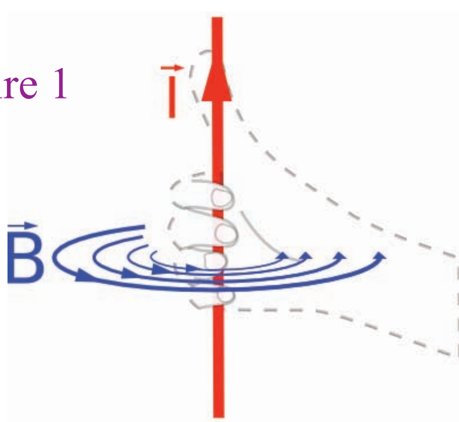
- With your thumb pointing in the direction of the current, your fingers show the direction of the magnetic field.

Force Between Conductors - Explanation

Let's consider two parallel wires carrying currents moving in the same direction.

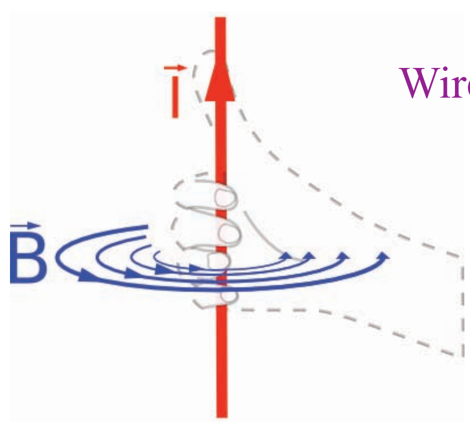
- We can see that each wire sees the magnetic field created by the other wire pointing in the opposite direction.
- Therefore, the magnetic field that each wire sees is opposite in polarity (North - South), and opposite magnetic poles attract each other.

Wire 1



Wire 1 sees the field from wire 2 pointing out of the page.

Wire 2

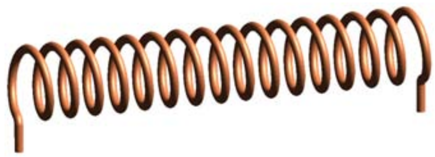


Wire 2 sees the field from wire 1 pointing into the page.

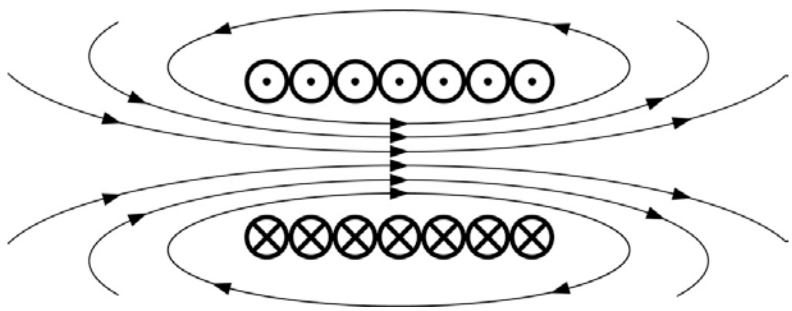
A Wire Coil

A cylindrical coil of wire has a magnetic field who’s north and south polarity comes out of the ends of the coil.

- A coil wrapped in a cylinder shape is called a solenoid.



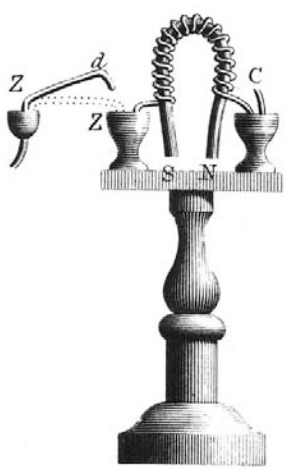
Think about the right hand rule giving magnetic field direction, and you can see why the field from each wire adds together.



Wire Coil Electromagnet

You probably have seen or built simple electromagnets made by wrapping a wire around a steel (iron) nail.

- The iron in the nail magnifies the magnetic field (1000’s of times) more than if only air was surrounded by the coil.



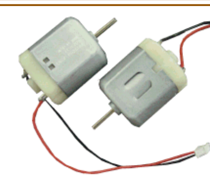
In 1824, the electromagnet was invented by the British physicist William Sturgeon (1783 - 1850).

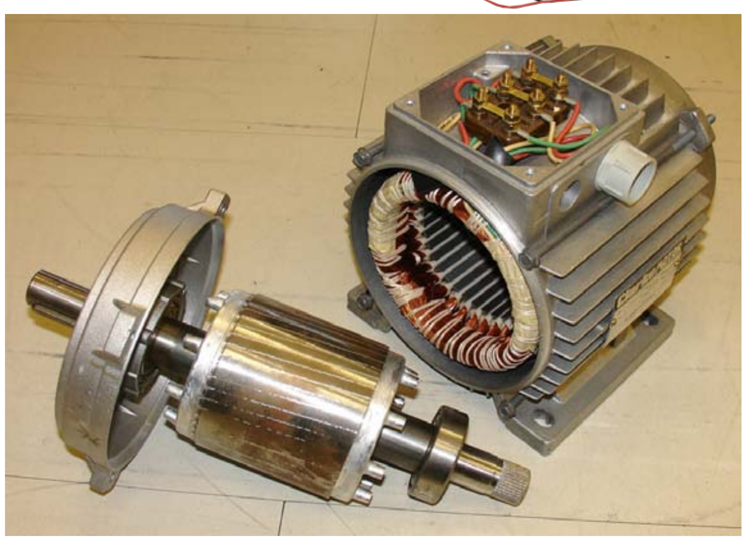
He apprenticed to shoemaker in childhood. However, he later taught himself mathematics and physics.

Electric Motors

Electric Motors

An electric motor converts electrical energy into mechanical energy.





There are two main parts of an electric motor.

- The rotor is the spinning shaft in the middle.
- The stator is the area surrounding the rotor.

Electric motors consume about $^2/_3$ of the electric power used in a typical industrial facility.

Picture from Wikipedia

Types of Electric Motors

There are many types of electric motors.

Some are:

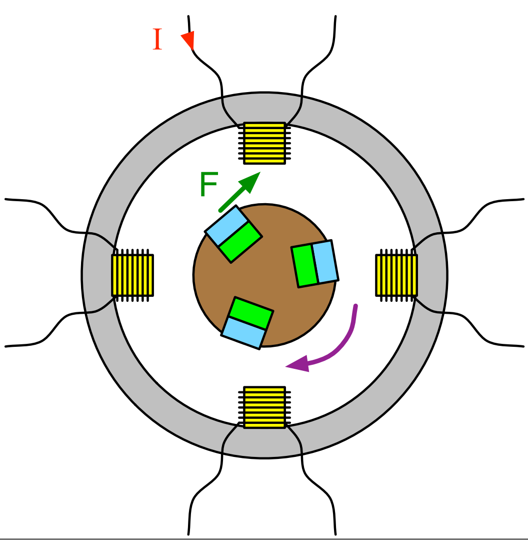
- Stepper motors
- DC motors (brushed)
- Brushless DC motors
- AC induction motors
- AC synchronous motors

Magnetic force forms the basis of operation all electric motors. We will investigate the stepper motor first, since it is easy to understand.

Simple "Stepper" Motor Concept

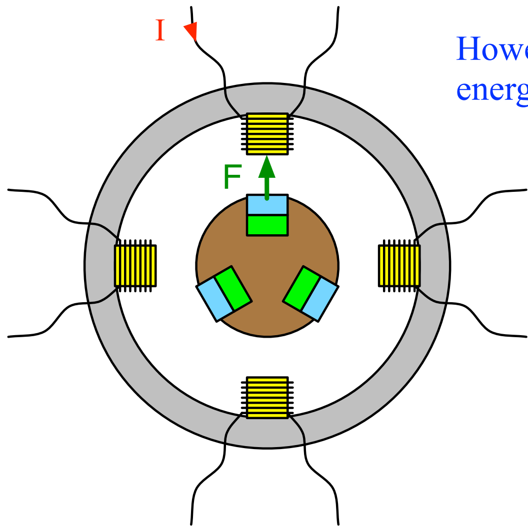
In the below picture, the stator has wire coils on it, and the rotor has permanent magnets attached to it.

- When current flows through the top stator coil, a magnetic field is created.
- If the created magnetic field is opposite in polarity to a nearby rotor magnet, the rotor will feel a force pulling it towards the energized stator coil.

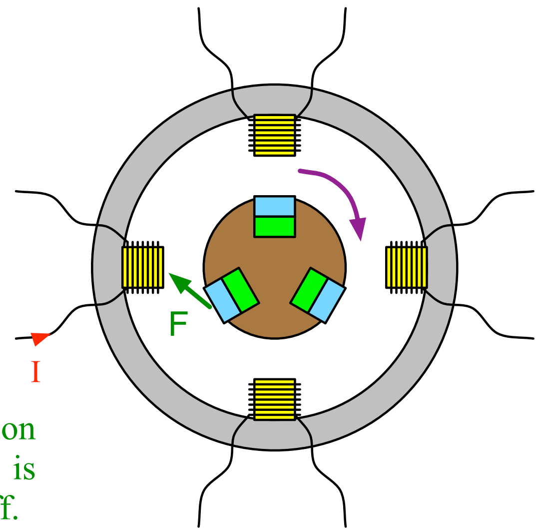


Note: You don't need permanent magnets on the rotor. You can use coil electromagnets or appropriately shaped rotors.

Simple “Stepper” Motor Concept



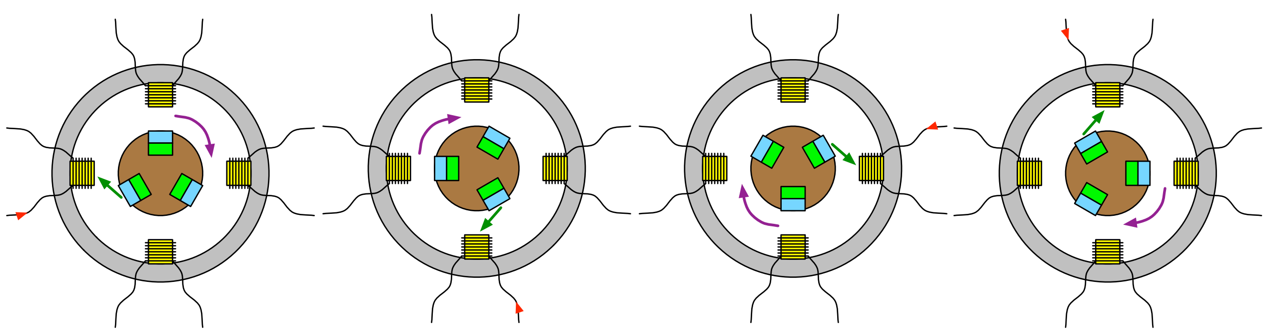
However, once the rotor has reached the energized stator coil, the rotation stops.



Therefore, in order to keep rotation going, the stator coil on the left side is energized and the top coil is turned off.

Simple “Stepper” Motor Concept

The rotation of the rotor can be made to be continuous, by successively turning on and off stator coils in front of the moving rotor magnets.



A stepper motor benefit:

- The fact that a stepper motor rotor can controllably stop (or be held) at a coil position can be useful.
- Sometimes you want to turn a motor a precise rotation angle, or a certain number of rotations.

DC Electric Motor

Turning off the stator coil when a rotor pole reaches it is a disadvantage, since the motor loses power from that coil. In a DC motor, the stator current is reversed instead.

- By reversing the current flow, the stator coil's magnetic pole reverses. And so the rotor pole is pushed away from the stator pole, continuing the rotation.
- This can be done mechanically using a commutator, or by using electronic circuitry to reverse the voltage on the stator coil.

In 1827, Ányos Jedlik (1800 - 1895) a Hungarian physicist, engineer, and Benedictine priest, demonstrated the first device which contained a stator, rotor, and commutator.

- Both the stator and rotor were electromagnetic. There were no permanent magnets.

Picture from Wikipedia

Motors and Generators

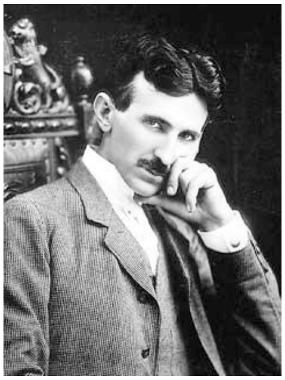
Motors and generators are duals of each other.

- In a motor, electricity is used to generate magnetic fields between stator and rotor magnetic poles, which causes the rotor to turn.
- In a generator, mechanical energy (steam turbine, water flow, wind power, etc.) is used to turn the rotor, which causes current to flow in stator coils due to induction, giving electrical energy.

This duality was discovered accidentally in 1873. The Belgian electrical engineer Zénobe Théophile Gramme (1826 - 1901) was demonstrating his dynamo (a DC generator with a commutator) during an industrial exhibition in Vienna.

- A technician incorrectly connected the terminals of one dynamo to another one which was producing electricity, and its shaft began to turn.

AC Induction Motor



AC induction motors are a preferred choice for industrial motors due to their rugged construction.

- They operate from AC voltages, and don't need permanent magnets.
- The induction motor was invented by Nikola Tesla in 1882.

The induction motor is more complex to understand, and you don't need to know it for this course. But briefly:

- The stator coils are energized by an AC voltage, which induces currents in the rotor conductors through electromagnetic induction.
- The stator coils are arranged so that the time varying AC voltage creates a rotating magnetic field that sweeps past the rotor, creating torque on the rotor.

Electric Motors in Vehicles

Electric Vehicles

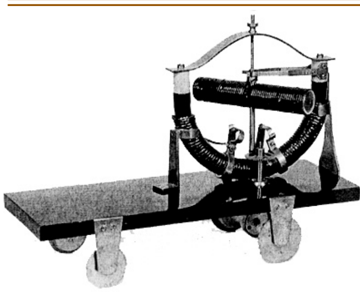
Electric vehicles are not a new idea. In fact, electric cars were very popular in the late 1800's and early 1900's.

- They did not have the vibration, noise, or smell associated with petroleum powered cars. They did not require gear changes or need a hand crank to start.
- At the turn of the 20th century, 40% of american cars were powered by steam, 38% by electricity, and 22% by gasoline. 33,842 electric cars were registered in the US.

An electric car from 1913.

Picture from Wikipedia

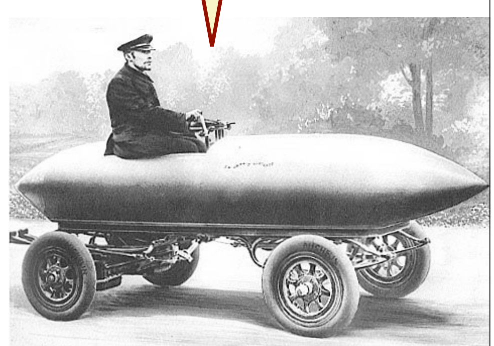
Notable Early Electric Vehicles

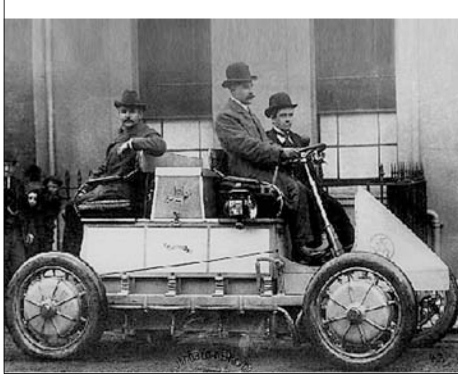


In 1828, Ányos Jedlik created this tiny model car powered by his electric motor.

Oddly, the driver was not included in the streamlining.

In 1899, "La Jamais Contente" was the first vehicle to exceed 100 km/h.





In 1901, Ferdinand Porsche (1875-1951) built the first gasoline-electric hybrid car. It was a series hybrid. Electric motors drove the wheels, and a gasoline motor powered a generator and recharged batteries.

Regenerative Braking

The duality between electric motors and generators is often used in electric vehicles for regenerative braking.

- During acceleration, the batteries run the electric motors to turn the wheels.
- During deceleration, the car's inertia turns the wheels, which spins the electric motor's rotor, enabling the motor to operate as a generator. The power produced recharges the batteries.

This idea is not new.

- Regenerative braking was used in this electric landaulet, built in 1906 by Louis Antoine Krieger (1868 - 1951). It was driven by electric motors on the front wheels.

Picture from http://www.shorpy.com/

Electric vs. Petroleum Vehicles

Petroleum powered cars started to dominate in the early 1900's. Some reasons are:

- Fuel became inexpensive, and improved highways resulted in people wanting to travel between cities.
- Noise was reduced by using mufflers, invented in 1897 by Hiram Percy Maxim, in parallel with his invention of the silencer for firearms.

He was the son of Sir Hiram Stevens Maxim, the inventor of the Maxim Machine Gun.

- The need for hand crank starting was eliminated with the development of a reliable electric starter motor in 1912 by Charles Kettering.

He later became the head of research for General Motors.

1927 Ford Model T

Picture from Wikipedia

Some Modern Hybrid-Electric Cars

The Toyota Prius is a series-parallel hybrid. Both the battery and gasoline motor can drive the wheels.

The Chevrolet Volt is a series hybrid. The electric motor drives the wheels, with the gasoline engine used to recharge batteries if extra range is needed.

Some Modern Electric Vehicles

The Nissan Leaf started selling in North America in 2010.

The Tesla Roadster can accelerate from 0 to 60 mph in 3.7 seconds.

Unlike internal combustion engines, electric motors have high torque values at low speeds.

A quiet electric sports car might not be as "satisfying".

Electric vehicles are very quiet, making this electric ATV an ideal way to experience the outdoors. Electrical and Computer Engineering at U of M helped built it.

Transistors

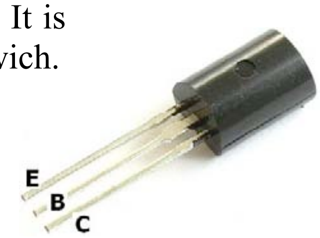
Transistors

A transistor is a semiconducting device that is used to amplify or switch electronic signals.

- The transistor is the key active component in almost all modern electronics.
- Without it, modern electronics would not exist.
- It is one of the most significant inventions of the 20th century.

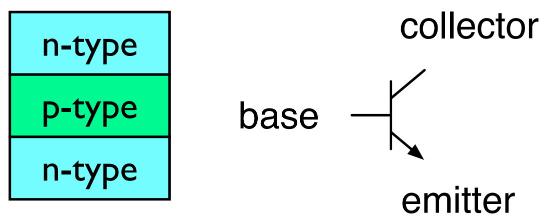
Bipolar Junction Transistor (BJT)

A common type of transistor is the bipolar junction transistor. It is made from 3 layers of doped semiconductor material in a sandwich.

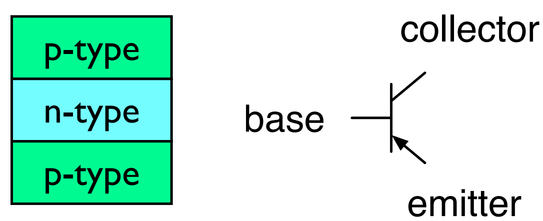


- The 3 parts are called the collector, base, and emitter.

npn transistor

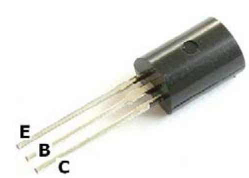


pnp transistor

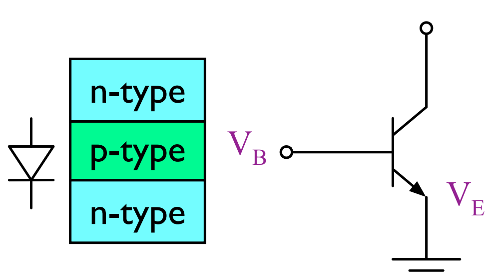


Operating the BJT as a Switch

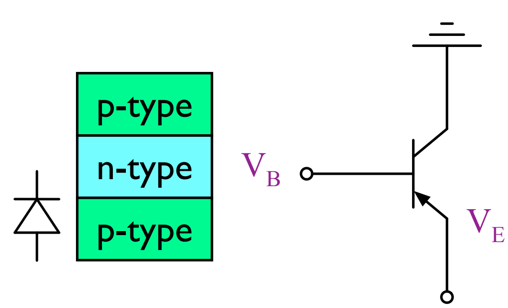
When operating the BJT as a switch, we want to switch the current flow between the collector and the emitter on and off.



- The current flowing between the collector and emitter is controlled by the voltage between the base and the emitter.
- Think of the base-emitter as a diode controlling the transistor.
- This diode must be "on" (forward biased) to enable significant current to flow between the collector and the emitter.



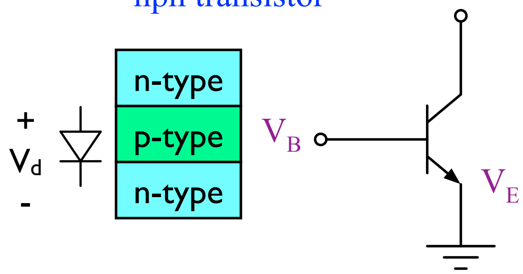
npn transistor



pnp transistor

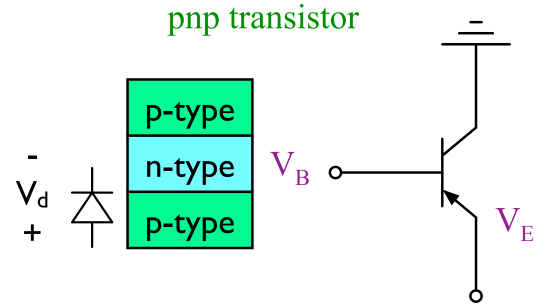
Forward Biasing the Base-Emitter

npn transistor



The base-emitter is in forward bias if: $V_B \approx V_E + 1$

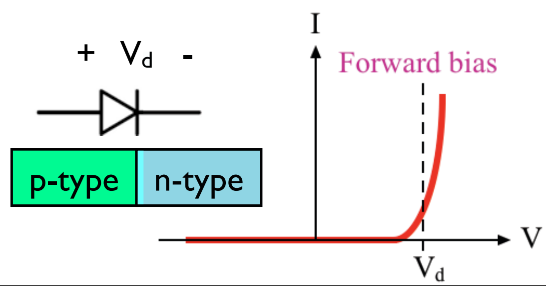
pnp transistor



The base-emitter is in forward bias if: $V_B \approx V_E - 1$

Recall from Lab 4:

- To forward bias a diode, the voltage on the p-type side needs to be higher than the voltage on the n-type side.



Advanced BJT Operational Concepts

What happens if the base-emitter diode is not fully on?

What happens if you vary the voltage between the collector and emitter?

These questions are answered when you study your electronics courses in Electrical and Computer Engineering.

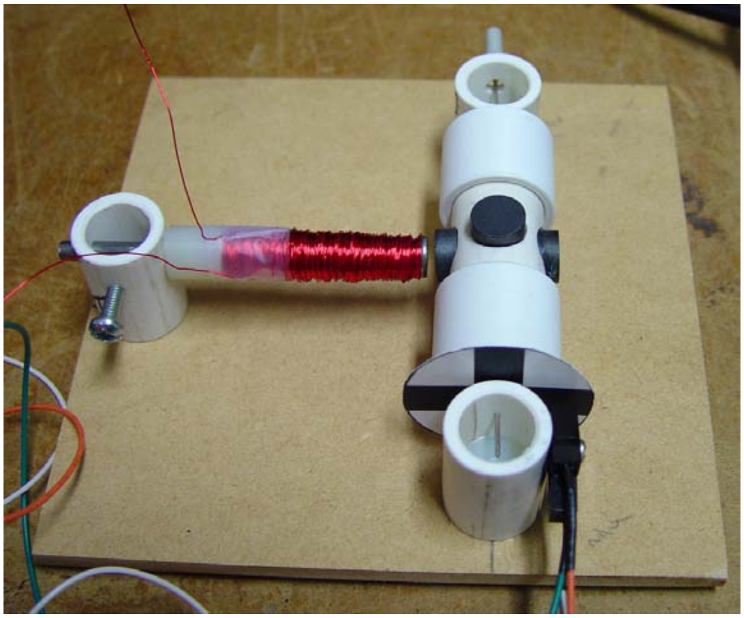
- You will learn how to use the transistor as a switch, amplifier, current or voltage regulator, or use them to make logic circuits.

Today’s Lab

Simple DC Motor

The simple DC motor that you will build is shown here.

- The rotor has 4 poles, and the stator has only 1.
- Therefore, in order to keep continuous rotation of the rotor, the stator coil has to be turned off once each rotor pole reaches it.

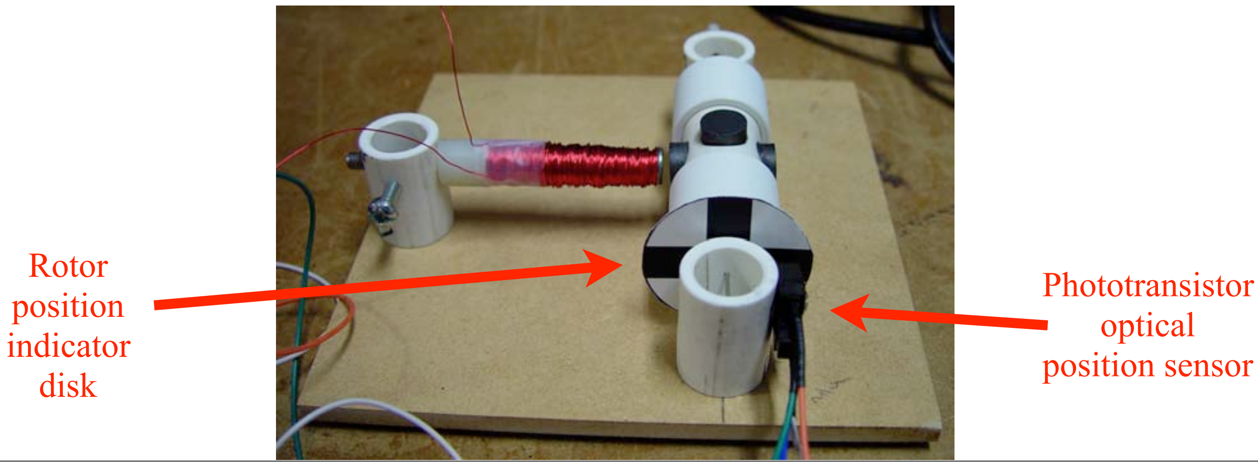


How do we know when a rotor magnet has reached the stator coil, and how do we turn off the power to the stator coil?

Rotor Position Indicator

The rotor position is known by using an optical position sensor to read a coloured disk attached to the spinning rotor.

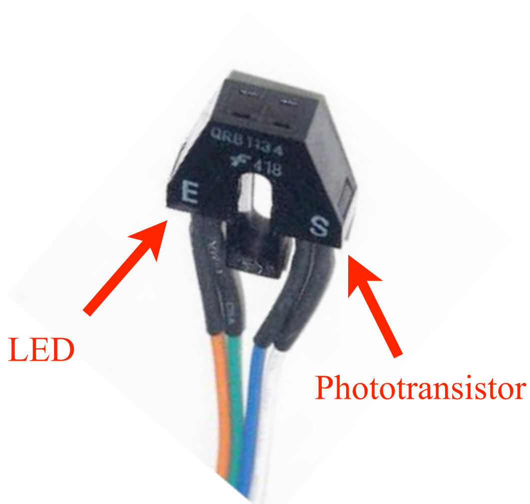
- The optical position sensor gives a “high” voltage when it sees white colour, and a zero voltage when it sees black colour.
- Since the motor you are building turns fairly fast (~ 1000 rpm), you need a fast optical detection circuit. Therefore, you will use a phototransistor optical detector in this circuit.

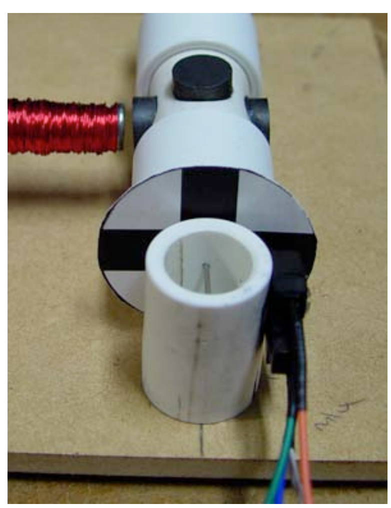


Phototransistor Optical Position Sensor

The optical position sensor has two parts.

- An LED that emits infra-red (IR) light. The IR light is reflected from the white colour of the rotor position indicator disk, and is absorbed by the black colour.
- An IR light detector (a phototransistor).





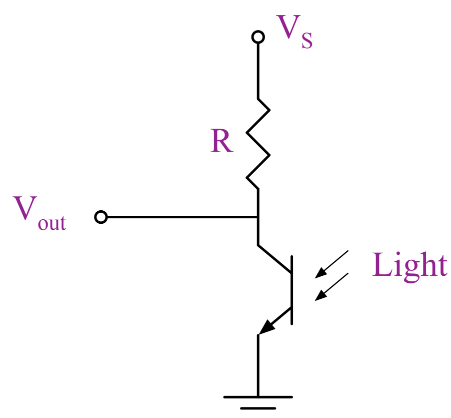
Optical Detector Circuit

In a phototransistor, light can hit the base region through a small window.

- When photons of sufficient energy strike the base, the energy absorbed releases electrons, causing current to flow in the base, and so between the collector and emitter.

The optical detector circuit you will build:

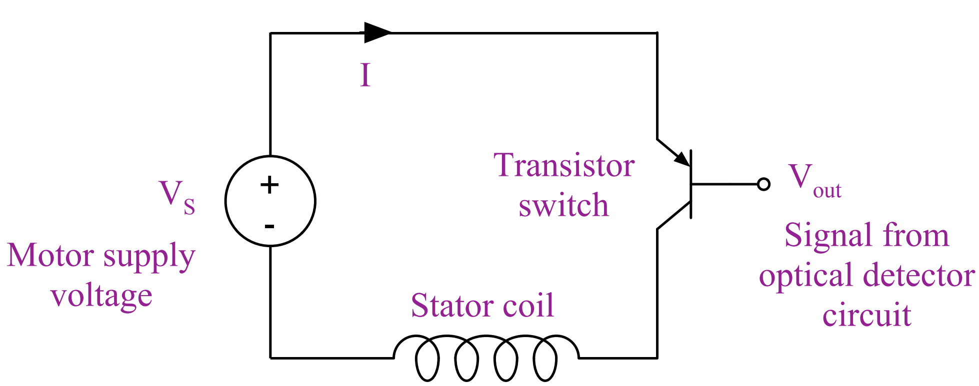
- When there is light, the transistor is on, and so $V_{out} \approx 0$ volts.
- When there is no light, the transistor is off, and so $V_{out} = V_S$.



Stator Coil Current Control

Switching the power on and off to the stator coil is achieved by connecting the optical detector circuit to a transistor acting as a switch, which is connected in series with the stator coil.

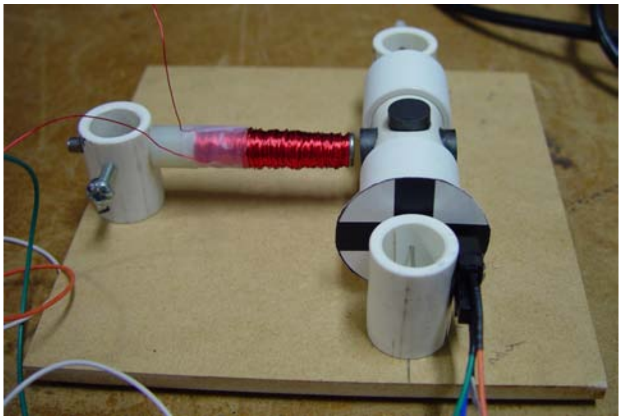
- When the phototransistor sees a white colour on the position indicator disk, V_{out} is a low voltage, which turns the Transistor Switch on.
- When the phototransistor sees a black colour on the position indicator disk, V_{out} is a high voltage, which turns the Transistor Switch off.



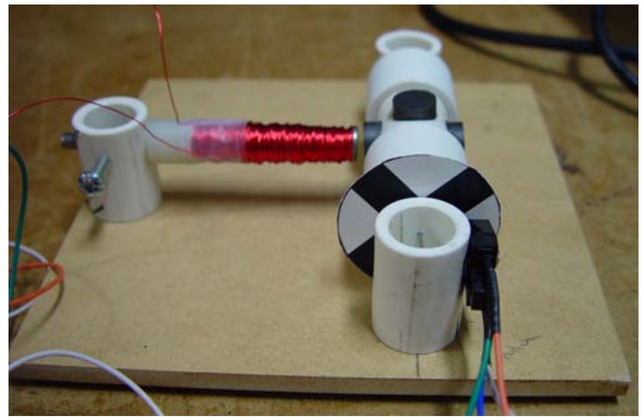
Stator Magnetization Timing

Since we have only 1 stator pole, if we want to maintain continuous rotation, we need to keep this coil turned off for a short period after the rotor has rotated past it.

- This is achieved by adjusting the rotor position indicator disk to be a small angle (timing angle) misaligned from the rotor magnet positions.



Position indicator aligned with rotor magnets



Position indicator mis-aligned with rotor magnets

Optimum Timing Angle Offset

The highest motor speed is achieved when the stator coil is turned on and off at the "best times" with respect to the rotor magnet positions.

- But, the stator coil takes a finite amount of time to turn on and off.
- Therefore, the highest motor speed is achieved at an optimum timing angle offset for the rotor position indicator disk.
- Also, since the stator coil takes a finite amount of time to turn on and off, the optimum timing angle offset varies with motor speed.

The concept of timing angle advance or retardation is also used in gasoline engines.

- Spark plug firing timing is adjusted to account for the finite amount of time the fuel takes to burn, and for air to enter or leave the moving pistons.
- This varies with engine speed. Many modern cars have variable valve timing to optimize power and efficiency at different engine speeds.

Important Things To Remember

Important Points

The direction of the magnetic field around a wire (clockwise or counterclockwise) can be found using the “right hand rule”.

A cylindrical coil of wire (solenoid) has a magnetic field who’s north and south polarity come out of the ends of the coil.

Stepper motors can be controllably stopped and held at a specific position.

Electric motors and generators are the dual of each other.

A BJT transistor is controlled by the voltage applied between the base and emitter.