Imperial College London

Lecture 15

Drive

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In this lecture, we will look at the theme of DRIVE. Mostly we will consider motors and actuators.

We will consider four types of motors:

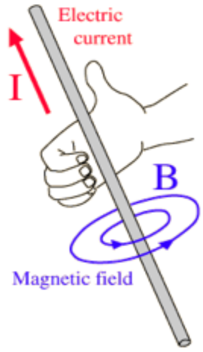
1. Simple DC motors as used in the Lab and project.
2. Brushless DC motors as used in portable Dyson vacuum cleaner.
3. Stepper motors as used in ink-jet and 3D printers.
4. Servo motors as used in radio-controller boats or planes.

Electromagnetism – the foundation for motors

- **Electromagnetism** has two different facets: Electricity and magnetism
  1. a moving electric charge produces magnetic fields
  2. changing magnetic fields move electric charges
- Theories developed by: Faraday, Maxwell, Lenz
- A static distribution of **charges** produces an **electric field**
- **Charges in motion** (i.e. an electrical current) produce a **magnetic field**.

Right-hand rule:

Wrap your right hand around a conductor with thumb pointing in direction of current flow, your fingers curl in the direction of the field.



Curl your fingers in the direction of the current, your thumb points toward the north.

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In the domain of sensors as we considered in the last lecture, resistances and capacitances dominate. In the topic of DRIVES, inductances domain.

The foundation of motors is based on electromagnetism, which is about the relationship between electric charge or current and magnetic field.

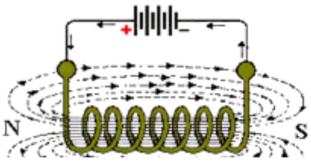
The most important scientists who created the field are: Maxwell, Faraday and Lenz.

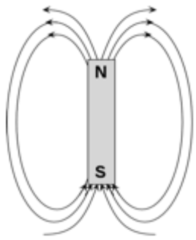
You would have come across at least Michael Faraday, who developed his famous motor experiment at the Royal Institution (RI) in London. In fact there is a free permanent exhibition there that is open to the public.

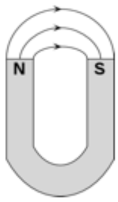
At high school physics, you would also have learned the Right-Hand Rule as depicted above, in order to determine the direction of magnetic field given the direction of current flow, or vice versa.

Electromagnets

- Arranging wire in a coil and running a current through produces a magnetic field that looks a lot like a bar permanent magnet:
  - This is called an **electromagnet**
- Putting an iron or steel rod inside the coil makes the electromagnet stronger – the iron is magnetic, it concentrates and amplifies the magnetic field created by the current in the coil.
- Putting a permanent magnet inside, one can move the magnet back and forth depending on current direction: called a solenoid.
- A **solenoid** is a simple device illustrating how the **interaction** between the magnetic field from a permanent magnet interacts with the magnetic field produced by an electromagnet to produce force.







If we wind a coil of wire around a tube, and then pass current through the coil, we have an electromagnet that behaves like a permanent magnetic with a north and a south pole. Removing the current, this is just a coil of wire – all the magnetic filed will disappear. This is called an electromagnet.

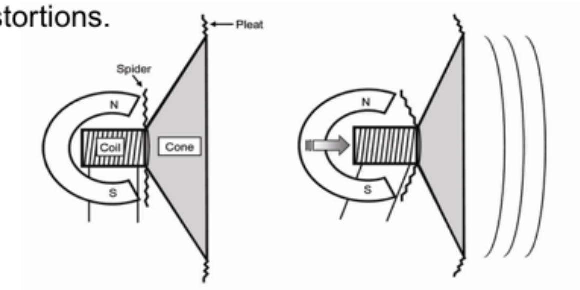
It is important to remember that an electromagnet is also an inductor when you consider it as an electrical component. The current through the coil cannot change instantaneously. Furthermore, the voltage across it = L di/dt.

An electromagnet normally has an iron or steel core in the centre of the coil. This has the effect of amplifying the magnetic field and make the electromagnet behaves like a really strong magnet.

If you put a permanent magnet in the centre, the central rod will move in either direction depending on the direction of current flow. This is called a Solenoid. I have a number of solenoid in the Design Engineering Store (kept by me) which you may or may not want to use to build your “kicker” for the Team Project.

Voice Coil and Loudspeaker

- The speaker converts electrical energy into sound (kinetic) energy.
- **Alternating electrical** (AC) current causes the **voice coil** to move in relation to a permanent magnet.
- Movements in the coil are transferred to a diaphragm or cone, which create movements in air molecules and sound.
- Speaker impedance must be matched closely to the amplifier's output impedance to avoid damaging the amplifier, and to increase system efficiency.
- As speaker impedance drops, current flow increases, causing overheating of the amplifier components or distortions.



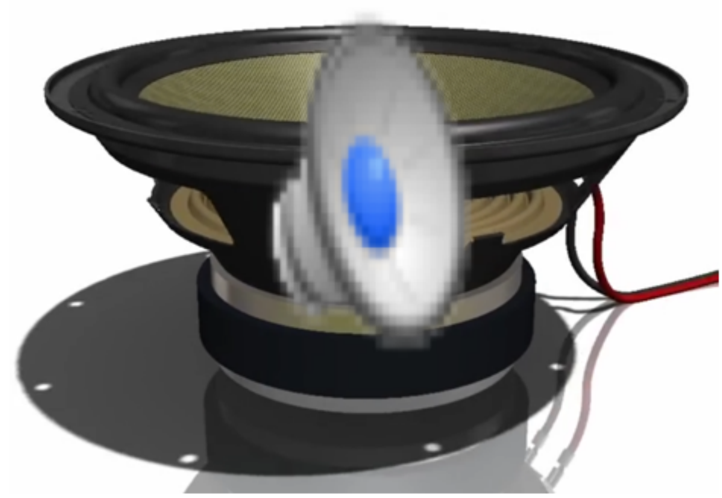
An other good example of application of electromagnet is the loudspeaker.

The key to a loudspeaker is the voice coil. This is no more than an electromagnet – a permanent magnet interacting with a coil of wire. The coil is linked to a cone to amplify the movement of the coil. As you pass the music or speech signal (which is AC) to the coil, it moves forwards and backwards. This causes the cone to move and thus moving the air around it. Sound is then produced.

It is worth noting this principle is similar to that found in piezoelectric crystal from the last lecture, which is a common materials to make a microphone sensor. If you squeeze (move) the piezoelectric crystal, an electrical voltage is produced. That's how a mic works. However, a piezoelectric crystal can also found a small speaker (tweeter) and produce sound by sending to it an AC voltage.

A loudspeaker produces sound. It also can be designed to respond to sound pressure and produces an electric current proportional to the sound, i.e. a microphone.

An Animation of a Speaker working (1 min)



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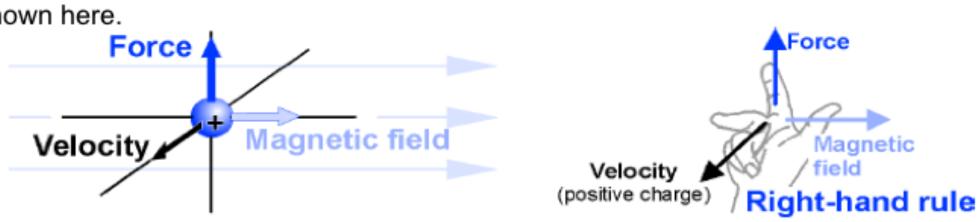
This video can be found on:

https://www.youtube.com/watch?v=3ZQqCyRQFB4

Electromagnetic Force

- The **magnetic force** on a wire is due to force acting on moving charges in the wire.
- When an electric charge moves in a magnetic field, a force **perpendicular to both** the magnetic field and to the direction of motion of the charge is produced as shown here.



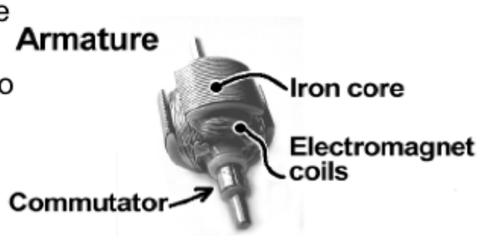
- A charge moving perpendicular to a magnetic field moves in a circular orbit.
- A charge moving at an angle to a magnetic field moves in a spiral.

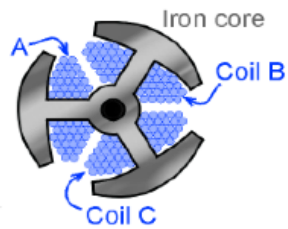
If you have a current carrying conductor moving through a magnetic field, or moving a magnet near to a current carrying conductor, a force is produced. The direction of the force is perpendicular to BOTH the magnetic field and the electric current, as governed by the Right-Hand Rule shown above. (You probably have done this in high school physics.)

This is the basis of electric motors. All motors work by having current flowing through a magnetic field, and those produces force and motion.

The principle of simple DC motor

- An electric motor uses electromagnets to convert electrical energy into mechanical energy.
- DC motors motors have three key components:
  1. A rotating element (**rotor**) with magnets.
  2. A stationary magnet that surrounds the rotor (**stator**).
  3. A **commutator** that switches the electromagnets from north to south at the right place to keep the rotor spinning.
- The magnets in the rotor and stator could be permanent magnets or electromagnets (but at least one of them have to be electromagnets).
- The rotating part of the motor, including the electromagnets, is also called the armature.





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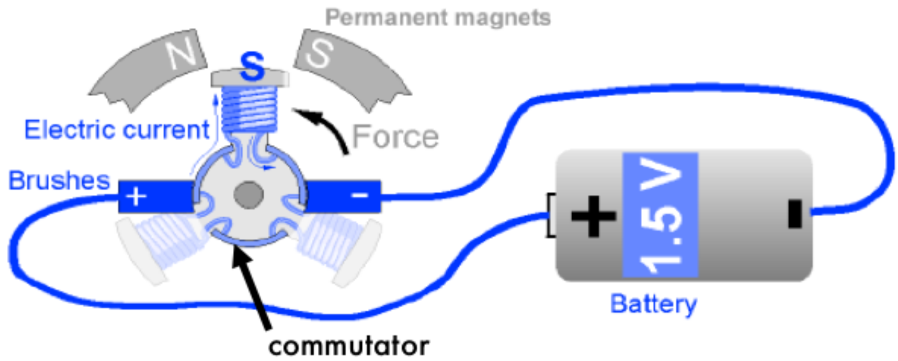
This is the simple DC motor that we use in the Lab and the Team Project. Most motors have a moving part – called the rotor, and a stationary outer shell called a stator. There is a third component called a commutator. This is effectively a contact ring that is split into segments. It is attached to the coils A, B and C, and is making contact with the DC supply voltage source. As the rotor turns, each coil is supplied with the current at the right time and flowing in the right direction for a force to be developed.

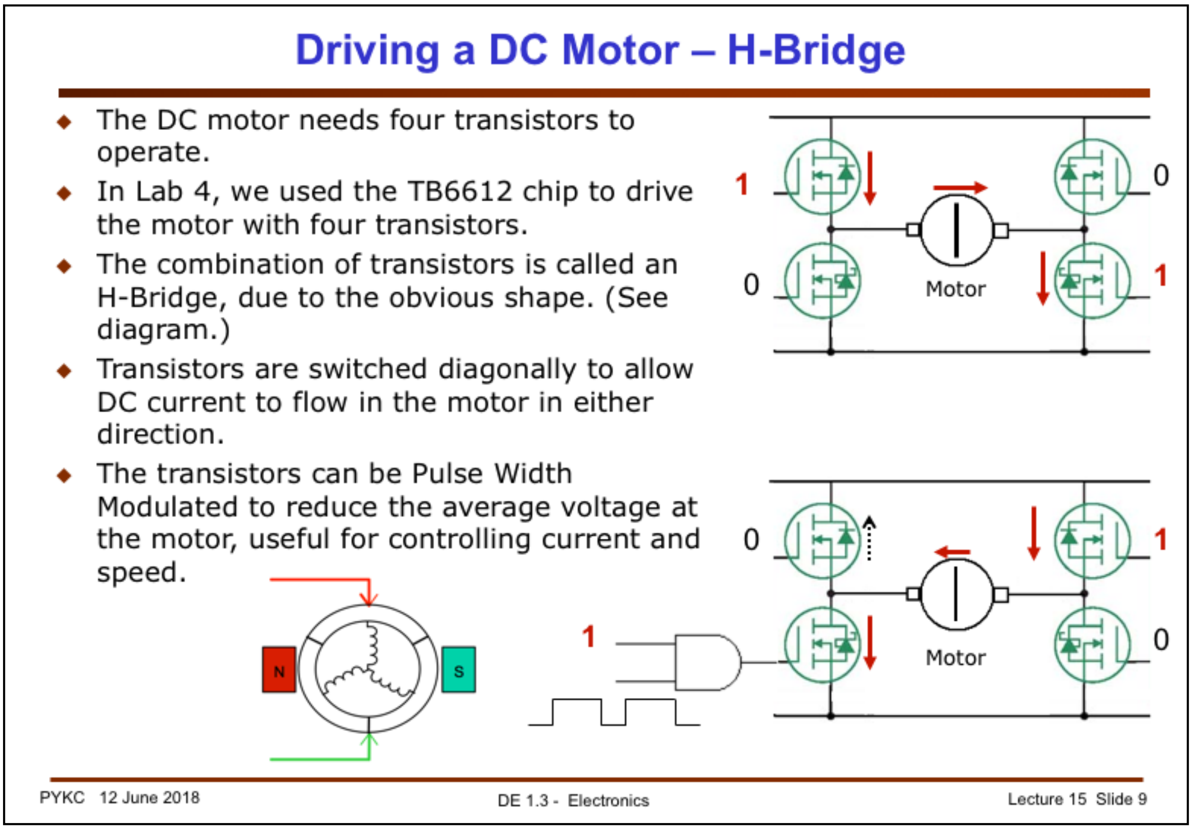
Because of the use of this commutator where electrical contacts are made using carbon (or copper) brushes, such a DC motor is called a brushed DC motor.

The principle of brushed DC motor

- The permanent magnets are on the outside, and they stay fixed in place.
- The wires from each of the three coils are attached to three metal plates (commutator) at the end of the armature.
- As the rotor spins, the three plates come into contact with the positive and negative brushes.
- Electric current flows through the brushes into the coils.



This slide shows how a DC voltage source is applied to different coils to produce an electromagnet in the rotor. This electromagnet interface with the permanent magnets in the stator – thus producing rotational motion.



Since motor coils are essentially inductors, they have low DC impedances (resistance of the wiring). Hence when driving motors, we need to use special driver chips.

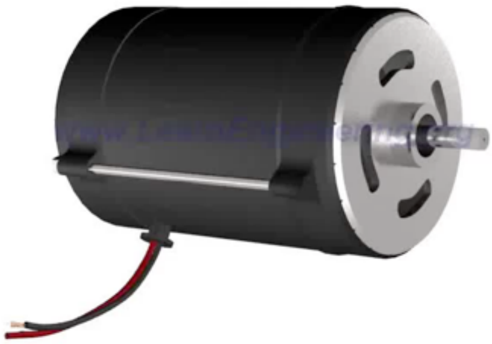
The driver chip you used in Lab 4 (the TB6612) is often called the H-Bridge Driver. Shown here is the simplified block diagram. There are four transistors connected to the supply rail and ground. (It doesn’t matter which is which because the circuit is symmetrical.) The motor is connected in the middle forming the horizontal link of the H. The transistors are MOSFETs (metal oxide silicon field effect transistors) which is acting like a voltage controlled switch. When a ‘1’ or high voltage is applied to the gate control terminal, the transistor turns ON and conduct electricity. If a ‘0’ or low voltage is applied, the transistor is OFF. So the top diagram shows a configuration that results in the supply voltage being applied to the left terminal of the motor. The right terminal of the motor is grounded, and the motor turns in one direction. Reversing the control to the transistors results in the motor turning in the other direction.

If you use an AND gate at the control input, you can also add a PWM signal to control the speed of the motor.

Basically the ‘1’ and ‘0’ control signals are the A0 and A1 signals on the TB6612. The PWM signal is what you apply to the input of the AND gate.

Now you know how the TB6612 works.

A video on how brushed DC motor works



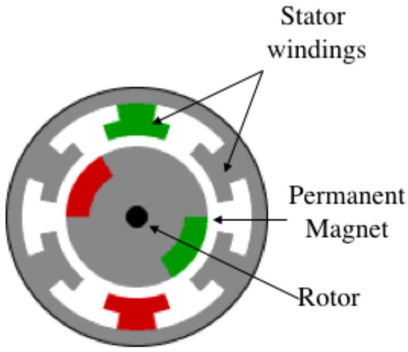
www.LearnEngineering.org

You can find this video on:

https://www.youtube.com/watch?v=LAtPHANEfQo

The principle of brushless DC motor (BLDC)

- Brushed DC motor needs commutators and brushes for electrical contacts.
- Causes sparks and source of failure – not good for reliability and longevity.
- Brushless DC motor eliminates commutator by:
  1. Putting permanent magnet in the rotor
  2. Fixed windings in the stator
  3. Use electronic circuits to perform commutation, and thus eliminating mechanical commutator
- Advantages:
  - No brushes or commutators – no sparks
  - More efficient than brushed DC motors
  - Higher speed
  - Higher power density



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Brushed DC motors are cheap to make and simple to use – apply a DC voltage, such as connecting it to a battery, or drive it with PWM, you are ready to go.

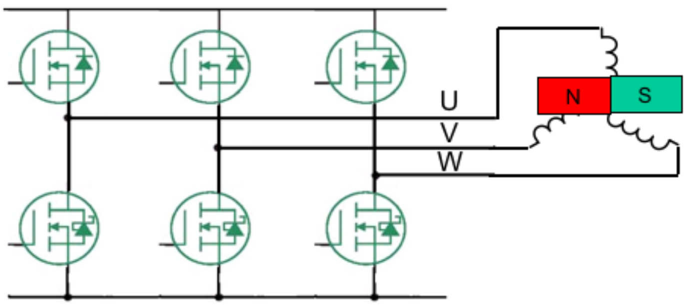
However it is not efficient and is not reliable. The brushes wear off and need replacing. The can be sparks developed when contacts are constantly going through make-break cycles. The rotor with the windings can get hot.

To get a better DC motor, it is helpful to get rid of the commutator. Basically, we put the permanent magnets in the rotor, and the electromagnet coils in the stator. This creates a problem – we still need commutation – i.e. changing the direction of flow of current so that we develop a force in the correct direction to turn the rotor.

This is action of commutation is achieved now by electronic means. With some intelligent electronic circuits (such as using a Pyboard), we can drive the correct stator windings at the right time to develop the rotation force in the right direction.

Three-Phase Bridge to Drive BLDC Motor

- The Brushless DC motor is really a DC motor constructed inside-out, but without the Brushes and Commutators
- The mechanical switches are replaced with transistors
- The windings are moved from the armature, to the stator
- The magnet is moved from the outside to become the rotor



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Here we see the transition from DC to Brushless DC motors. Especially the replacement of the brushes and commutators with the six transistor (three-phase) bridge.

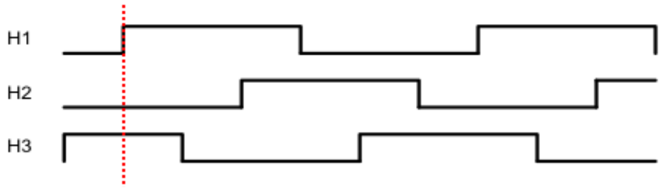
Of course, all these diagrams are extreme simplifications. In real life, the magnetic fields are carried by iron laminations, which close the magnetic loops and keep the air gaps to a minimum. This is necessary for all motors to be most efficient.

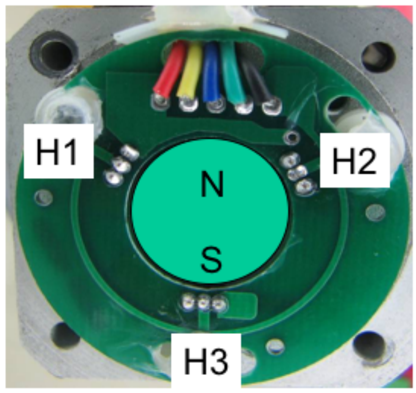
We see the transistors here as MOSFETs, and that is a very popular choice for lower voltages. In higher voltage applications, IGBTs, or Insulated Gate Bipolar Transistors are used. On either case, there must be a diode in parallel with each transistor to handle inductive kick or flyback currents. Let me explain: since the coil is really an inductor, and the voltage across an inductor VL = L di/dt, as we turn OFF a transistor, say, the bottom left transistor, the current through the transistor is suddenly stopped. The voltage at U used to be at GND (the voltage of the lower wire). However, at the moment the transistor is turned OFF, di/dt is large, and VL goes large negative, so as the try to maintain the current through the coil. This is called the flyback current. The diode is there to provide a path for this current to flow. Without the diode, the transistor main break down because the voltage at U may exceed its voltage limit. This flyback diode is built into most devices nowadays. It the diode is not there, you must add one yourself.

You would need similar diode when driving a solenoid or any inductive loads that are switched.

Hall Sensors

- Need to know position of rotor.
- Hall Sensors detect magnetic fields, and can be used to sense rotor angle.
- The output is a digital 1 or 0 for each sensor, depending on the magnetic field nearby.
- Each is mounted 120-degrees apart on the back of the motor.
- As the rotor turns, the Hall sensors output logic bits which indicate the angle.





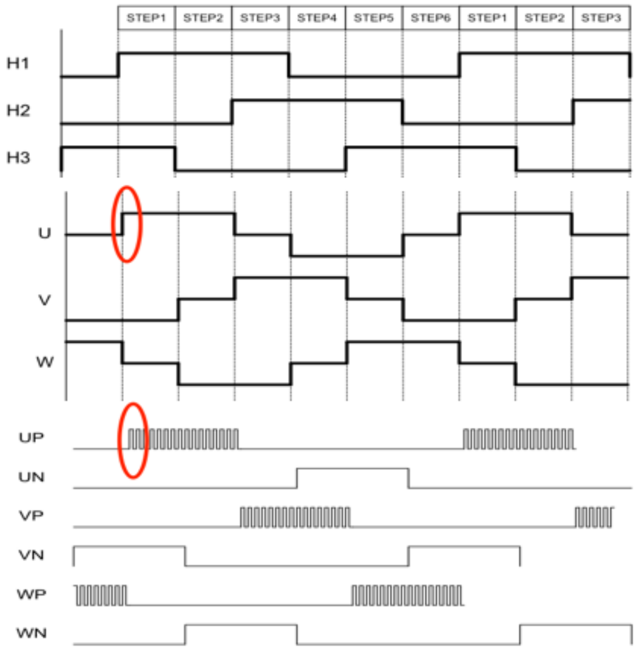
Since we can performing commutation electronically, we need to synchronise the driving signal to the rotor position. In other words, we need to SENSE the position of the permanent magnets on the rotor. This is achieved by the Hall Effect Sensors.

The Hall sensor, named after the man who discovered the effect, create very low level changes in voltage in proportion to a local magnetic field. Most sensors on the market include the amplification and comparator needed to make them a digital device.

They add cost and length to the motor, and they are subject the harsh environment of the motor, so they limit the heat capability and power of the motor. The rest of the motor made with copper, iron and magnets can normally handle much more heat than silicon can.

Hall Sensor Commutation and PWM

- The combination of all three sensors produce six unique logic combinations or steps.
- These three bits are decoded into the motor phase combinations.
- We can divide up the phase data into individual transistor gate signals.
- We can see in this diagram how we can modulate one transistor at a time to regulate the motor voltage, and also the speed.



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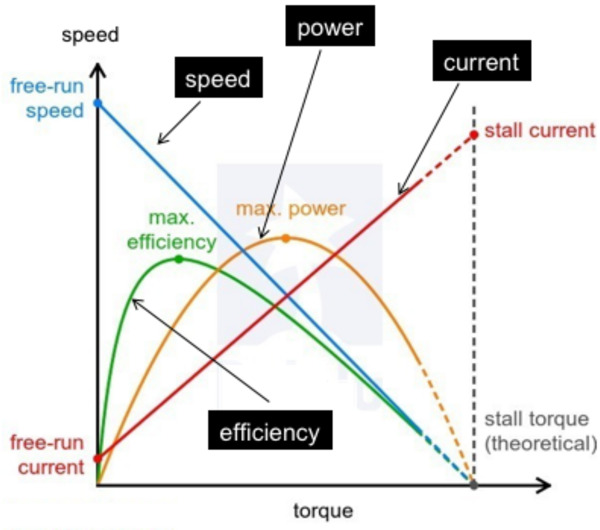
You can take the three Hall signals as digit bits, and assign them a number, based on their binary states. You could say that step 1 is binary 101, step 2 is 001, etc. Filling in a table of 6 combinations, plus the two other invalid states of 000 and 111 gives all the combinations. Then, let the U-phase upper transistor be ON when the Halls are equal to 001 (decimal 1) or 101 (decimal 5).

Of course, this table is only valid when the motor is going in one direction. For reverse operation, you could build a new table where the opposite transistor (swap upper and lower) is on for each state.

Remember, we describe these as being fully on or off for clarity, but they can be pulse width modulated at some duty cycle. We can easily GATE the control signal with a PWM signal to control the speed as in brushed DC motors.

Torque, Speed, Power, Efficiency

- Speed of a DC motor as torque increases.
- Here is the relationships of various parameters: speed, current, power and efficiency, as a function of torque.



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In consider which motor to use, you need to examine the way speed changes with torque. In DC motors, the torque drops with increasing speed. Hence you get the power and efficiency curves as shown. There is a maximum power (transferred) and maximum efficiency point at some torque level. The datasheet of the motor will always specify this.

Do not just look at the maximum torque figure or the maximum speed figure. They do not tell the full story – they only give you're the free-running speed and the torque when the motor is stalled (not turning).

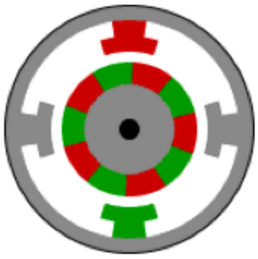
A video on How a Brushless DC Motor works

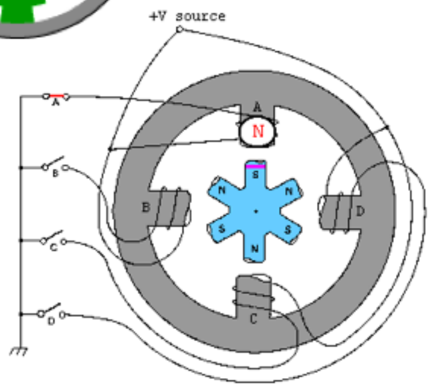
This video can be found on:

https://www.youtube.com/watch?v=bCEiOnuODac

Principle of a stepper motor – full steps

- The rotor of a permanent magnet stepper motor consists of permanent magnets and the stator has two pairs of windings.
- Just as the rotor aligns with one of the stator poles, the second phase is energized.
- The two phases alternate on and off and also reverse polarity.
- There are four FULL steps. One phase lags the other phase by one step. This is equivalent to one forth of an electrical cycle or 90° .
- Electronic circuits are used to switch supply voltages to the appropriate windings in the stator to advance each step. (See animation.)





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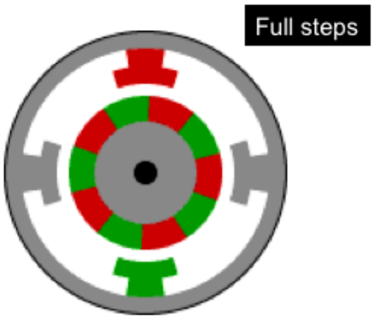
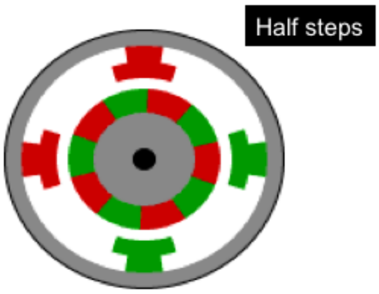
A stepper motor is a type of DC motor which has a full rotation divided in an equal number of steps. It is a type of actuator highly compatible with microprocessor control, as it is essentially an electromechanical converter of digital impulses into proportional movement of its shaft, providing precise speed, position and direction control in an open-loop fashion, without requiring encoders, end-of-line switches or other types of sensors as conventional electric motors require. Unlike brushless DC motor, you just send digital pulses to each of the windings and the motor turns. You cannot control the speed by PWM, but you control the speech the rate at which you rotate the pulses between the switches.

The steps of a stepper motor represent discrete angular movements, that take place in a successive fashion and are equal in displacement, when functioning correctly the number of steps performed must be equal to the control impulses applied to the phases of the motor. The final position of the rotor is given by the total angular displacement resulting from the number of steps performed. This position is kept until a new impulse, or sequence of impulses, is applied. These properties make the stepper motor an excellent execution element of open-loop control systems. A stepper motor does not lose steps, i.e. no slippage occurs, it remains synchronous to control impulses even from standstill or when braked, thanks to this characteristic a stepper motor can be started, stopped or reversed in a sudden fashion without losing steps throughout its operation.

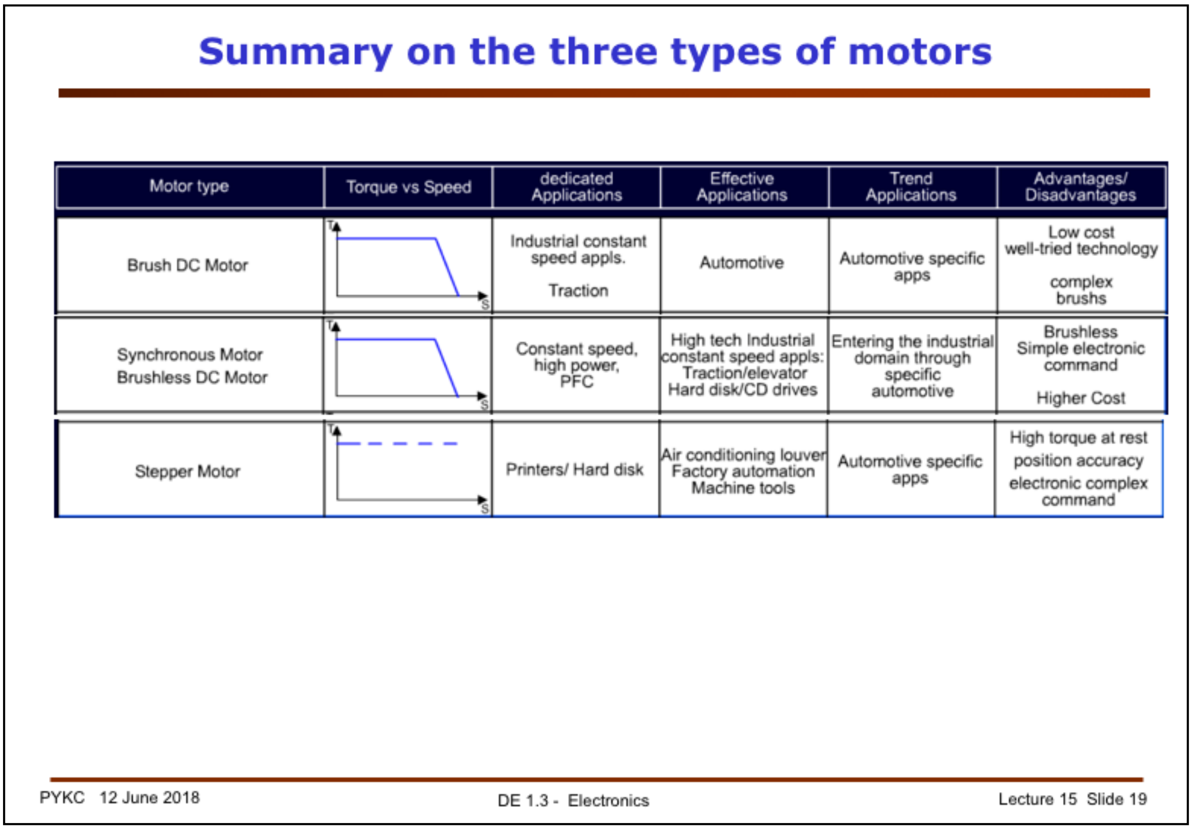
Principle of a stepper motor – half steps

- By energizing two windings some of the time, we get a half-step stepper motor.
- The commutation sequence for a half-step stepper motor has eight steps instead of four.
- The main difference is that the second phase is turned on before the first phase is turned off. Thus, sometimes both phases are energized at the same time.
- During the half-steps the rotor is held in between the two full-step positions.
- A half-step motor has twice the resolution of a full step motor. It is very popular for this reason.
- Step resolution can also be increased with more poles in the stator, resulting in more steps.
- Stepper motors is normally run open loop without sensors or feedback.
- Good for applications such as printers.





Stepper motors can be controlled in full steps. However, by pulsing the neighbour earlier (i.e. between phases), we can move the rotor to the half way point as shown in the animation here. This is called the half-stepper.



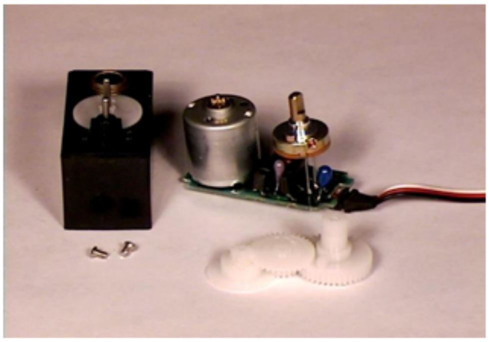
Motor type	Torque vs Speed	dedicated Applications	Effective Applications	Trend Applications	Advantages/ Disadvantages
Brush DC Motor		Industrial constant speed appls. Traction	Automotive	Automotive specific apps	Low cost well-tried technology complex brushs
Synchronous Motor Brushless DC Motor		Constant speed, high power, PFC	High tech Industrial constant speed appls: Traction/elevator Hard disk/CD drives	Entering the industrial domain through specific automotive	Brushless Simple electronic command Higher Cost
Stepper Motor		Printers/ Hard disk	Air conditioning louver Factory automation Machine tools	Automotive specific apps	High torque at rest position accuracy electronic complex command

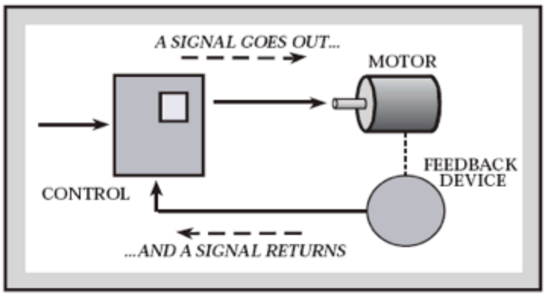
This is a summary of the characteristics of the three types of motors we have looked at so far.

Motor type	Torque vs Speed	dedicated Applications	Effective Applications	Trend Applications	Advantages/ Disadvantages
Brush DC Motor		Industrial constant speed appls. Traction	Automotive	Automotive specific apps	Low cost well-tried technology complex brushs
Synchronous Motor Brushless DC Motor		Constant speed, high power, PFC	High tech Industrial constant speed appls: Traction/elevator Hard disk/CD drives	Entering the industrial domain through specific automotive	Brushless Simple electronic command Higher Cost
Stepper Motor		Printers/ Hard disk	Air conditioning louver Factory automation Machine tools	Automotive specific apps	High torque at rest position accuracy electronic complex command

Principle of Servo Motor

- Servo motors and are constructed out of basic DC motors, running in a close loop, by adding:
  - some gear reduction
  - a position sensor for the motor shaft
  - an electronic circuit that controls the motor's operation
- The basic hobby servo has a 180:1 gear ratio. The motor is typically small.
- Typically, a potentiometer (variable resistor) measures the position of the output shaft at all times so the controller can accurately place and maintain it's setting.





Finally, we will consider a type of motor which is really a DC motor put into a control feedback loop. This is the servo motor.

Servo Motor Control

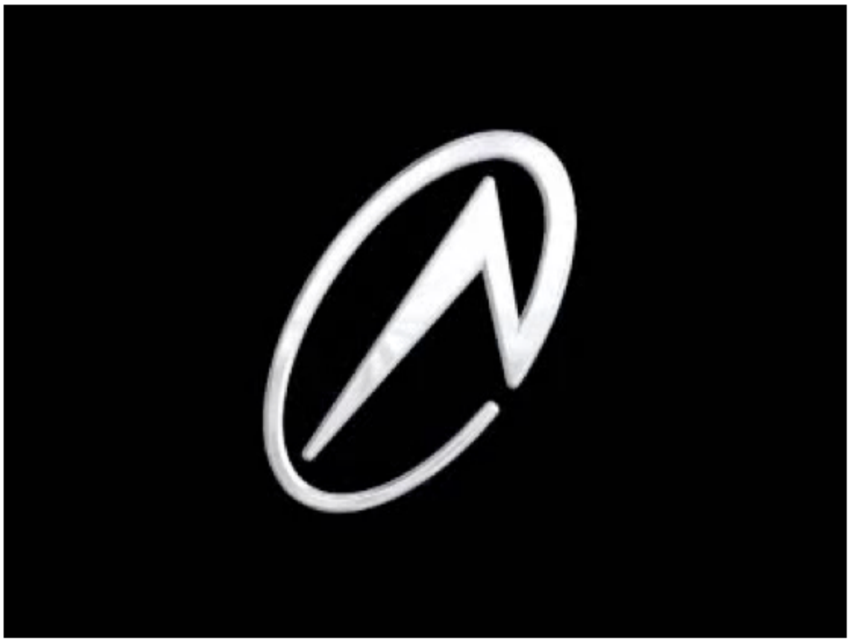
- An external controller (such as the Pyboard) tells the servo where to go with a signal know as pulse proportional modulation (PPM) or pulse code modulation (which is often confused with pulse width modulation, PWM).
- PPM uses 1 to 2ms out of a 20ms time period to encode its information.
- A control wire communicates the desired angular movement. The angle is determined by the duration of the pulse applied to the control wire.
- The servo expects to see a pulse every 20 milliseconds (.02 seconds). The length of the pulse will determine how far the motor turns. A 1.5 millisecond pulse will make the motor turn to the 90 degree position (often called the neutral position).
- If the pulse is shorter than 1.5 ms, then the motor will turn the shaft to closer to 0 degrees. If the pulse is longer than 1.5ms, the shaft turns closer to 180 degrees.
- The Pyboard has library functions to control Servo motors directly.

A servo motor accepts position commands using pulses – known as pulse proportional modulation (or pulse code modulation), which is different from pulse width modulation. PWM is really an analogue signal disguised as a digital signal. The analogue voltage is the average (or DC) voltage of the signal, which is the same as the duty cycle x maximum amplitude. You can use any periodicity with a PWM signal

The PPM signal on the other hand has fixed fixed period (20 msec) and the information about the angel go to is encoded in the DURATION of the pulse. So a 1.5 msec pulse will turn the motor to 90 degree position (or neutral). Width of 1ms to 2ms will turn the motor shaft from 0 to 180 degrees.

So, a PWM signal on a DC motor controls its speed; a PPM signal on a servo motor controls its shaft position.

A video on comparing stepper and servo motors



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You can find this video on:

https://www.youtube.com/watch?v=mAObZa_PE_8