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LECTURE 6A

Transistors & MOSFET

Electromechanical Devices
MMME2051

Module Convenor – Surojit Sen

Learning Outcomes

- Analogue Electronics
- **Transistor**
  - **PN** Junction - **Diode**
  - **NPN** v **PNP**
- **MOSFET**
  - **N-channel**
  - **P-channel**
- **Push-Pull Pair**

Topics covered so far (past 5 weeks)

Electrical Engineering

- Charge, current, voltage, power, energy
- Kirchhoff's and Ohm's Laws
- DC Circuits and how to solve them
- Energy Storing Elements – Inductors & Capacitors
- What is AC
- Impedance, Complex numbers, & Phasors
- AC Circuits and how to solve them
- CIVIL
- Active v Reactive v Apparent Power in AC
- Power Factor
- Resonance
- 3-phase AC – Star/Delta configuration
- Induction Motors & Electromagnetism

Digital Electronics

- Information – any system requires exchange of information
- Digital v Analog information
- Number System – Binary v Decimal v Hexadecimal
- Digital Logic Circuits – what makes a computer "decisive"
- AND v OR v NOT gates
- Combinational Logic – multiple gates combined to produce the desired outcome – e.g., reactor shutdown
- Shaft Encoder
- JK Flip Flop (SR v D v T configurations)
- Bit Shifter
- R-2R Ladder
- Flash Converter

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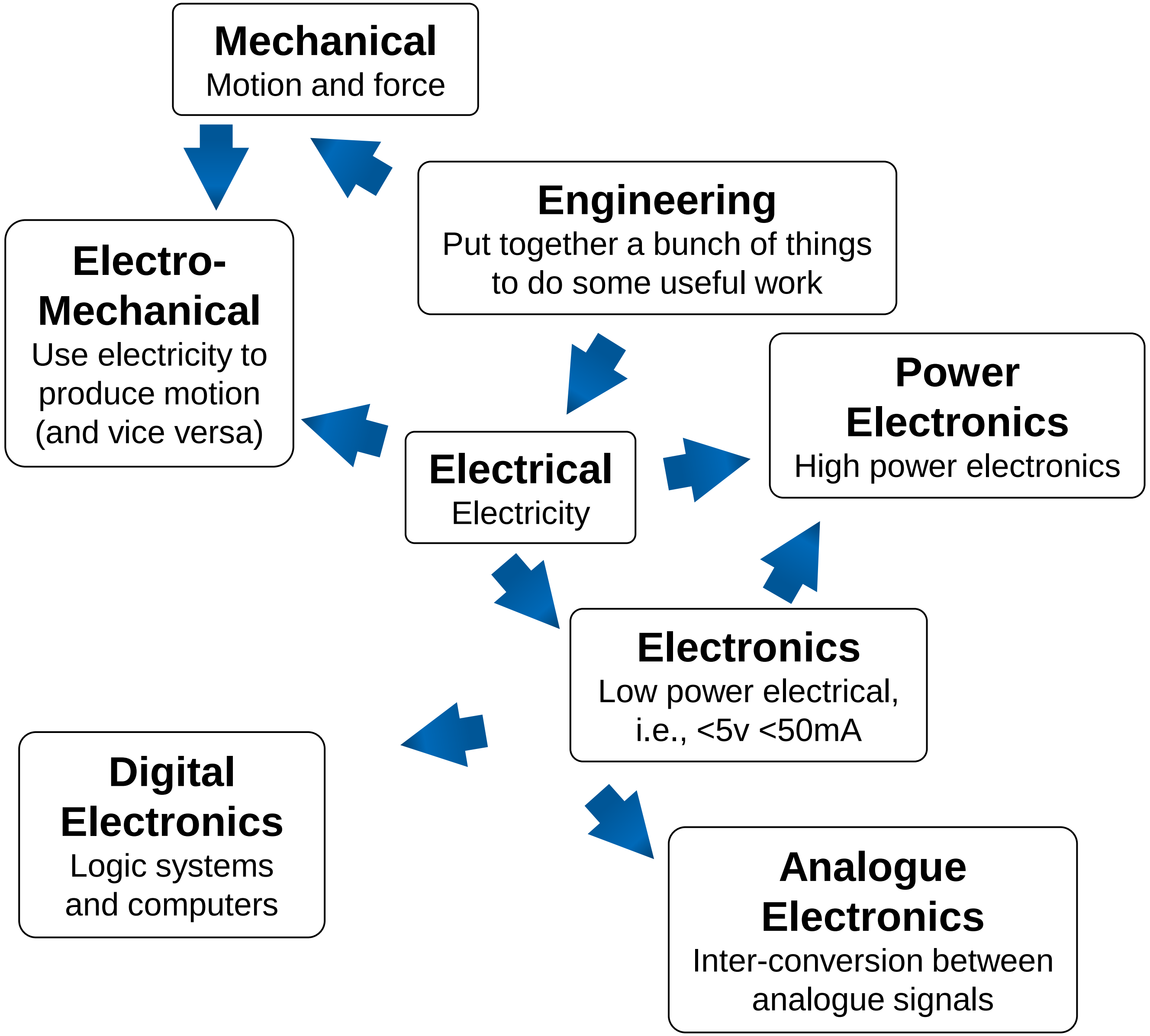
Analogue Electronics



Analogue Electronics

Inter-conversion between analogue signals (amplification & processing) using an electrical analogue variable (like voltage or current – usually voltage)

Greek word "*analogos*" means proportional, i.e., a signal/information is proportional to a physical variable like voltage

Information (e.g., sound of guitar) is conveyed through a pair of copper wires as a voltage signal, voltage across the two wires being proportional to the sound level

As analogue signals are continuous (unlike digital signals that are discrete), they are susceptible to corruption due to noise very easily

Transistors
Electronic switch used to open/close the "gate" in an electrical circuit

MOSFETs
Like the transistor (it is also an electronic switch) but used for higher power applications

Op-Amps
Amplifier used in circuits for analogue signal amplification, attenuation, integration and differentiation

Strain Gauge
Used to convert force into electrical signal – for measurement of mechanical force or displacement

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Electrical Switch

A switch is exactly what you are thinking of – something that physically breaks (opens) or makes (closes) an electrical path – stopping/resuming flow of electrons, or current

We have seen usage of electrical switches in digital circuits so far (e.g., in the bit-shifter)

How do they actually work?

Operate manually

Or you can use an Solenoid (Mechanical Relay)

OR, use a SOLID STATE RELAY

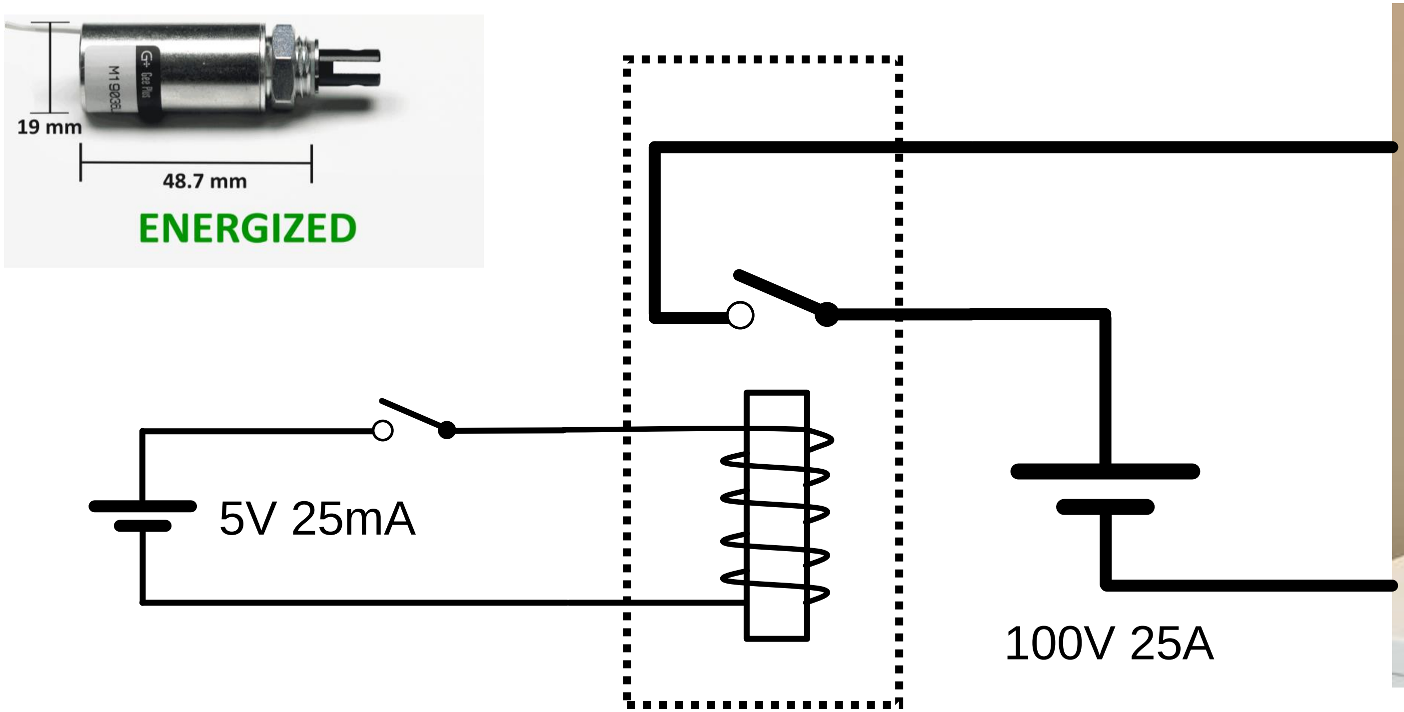
- Much less power
- Silent
- Faster
- Increased lifetime (no mechanical movement)
- Bounce-less
- No sparking

Bipolar Junction Transistor (or **BJT**, or simply **Transistor**) **is the most common form of electronic switch** – switch state ON/OFF controlled by a digital signal

- Open is not “really” Open, closed is not “really” closed
- Polarity sensitive
- More power loss as heat in the switched path

Electrical Switch

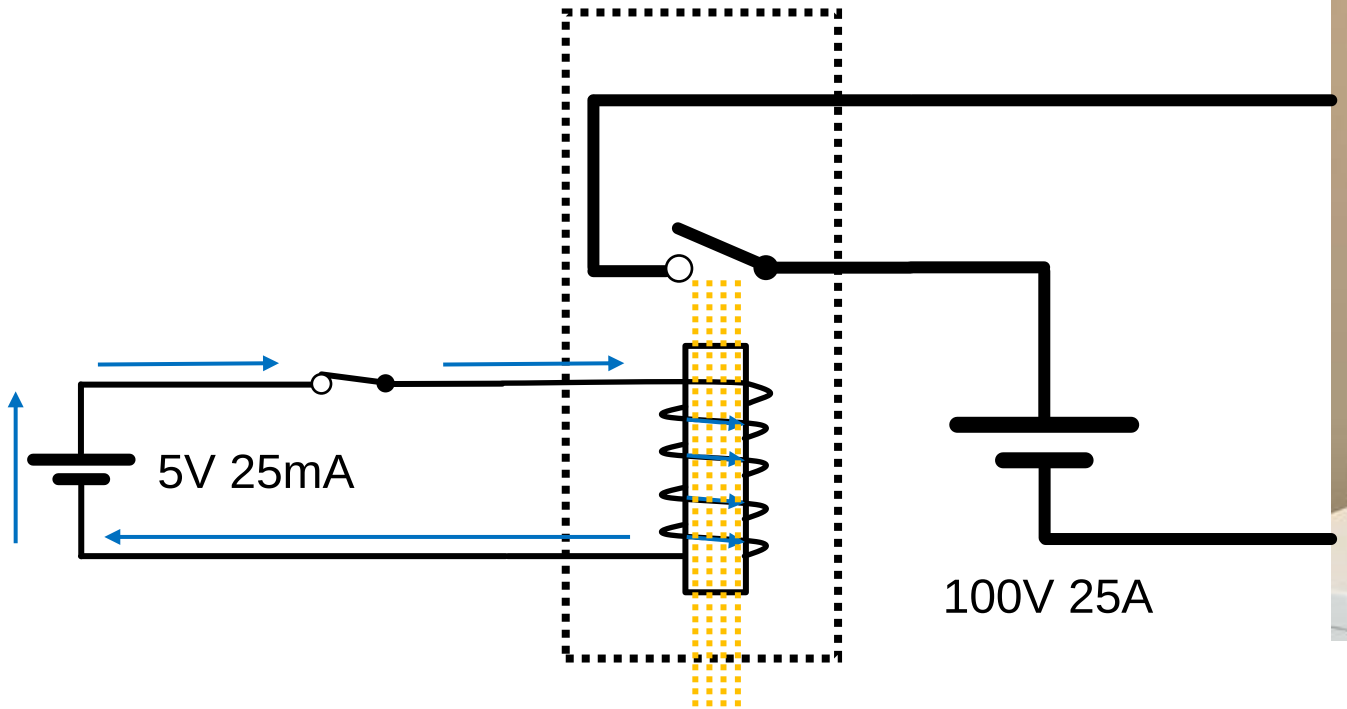
Let us visualise a scenario where you want to turn on/off a powerful induction motor



Let us use a **mechanical relay** – we could have directly operated the motor switch manually but that would be dangerous as we are handling a high power circuit

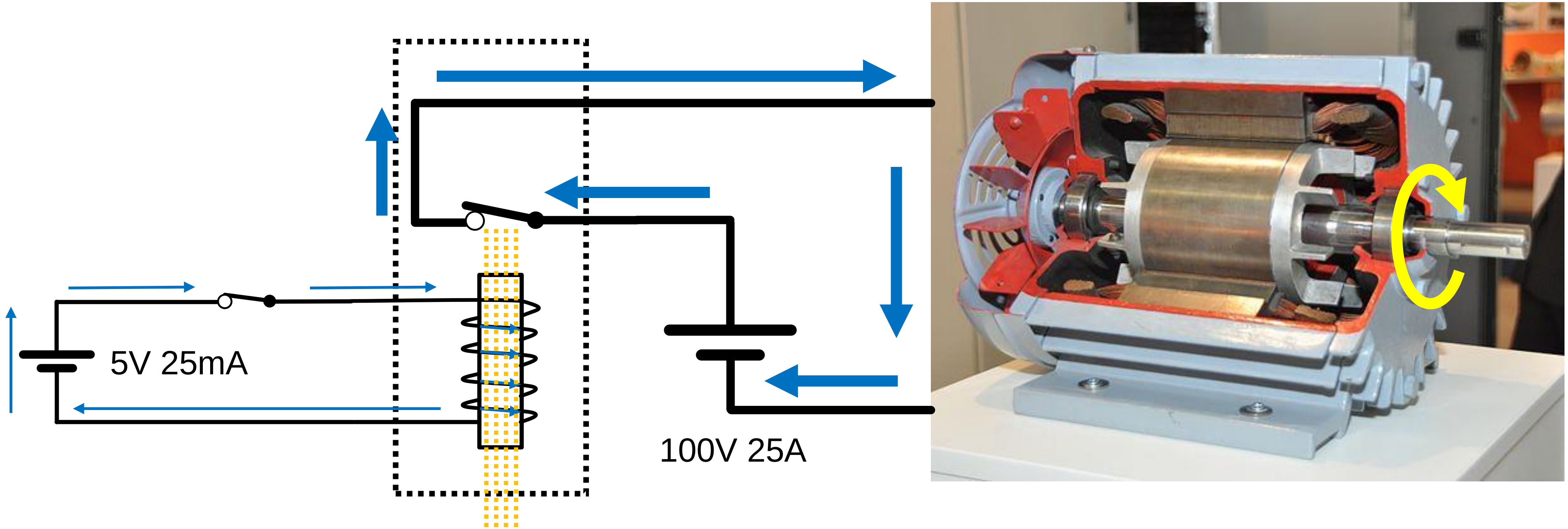
Electrical Switch

Low current flows through the coil circuit thus creating a magnet



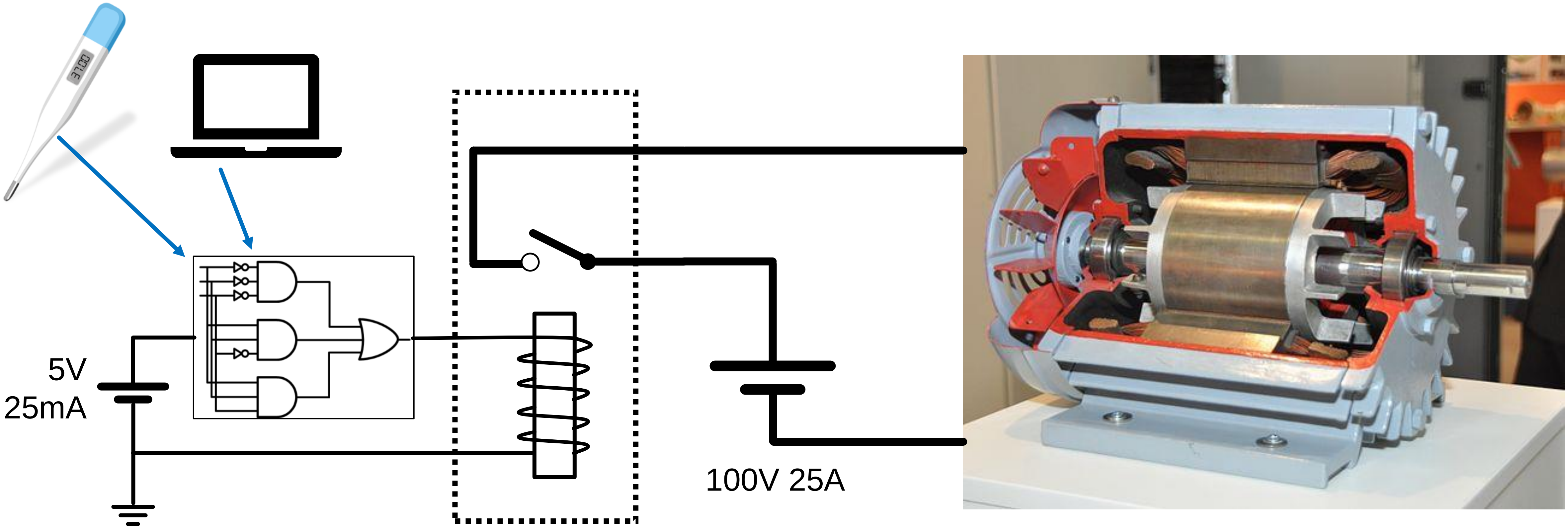
Electrical Switch

Electromagnet will pull the switch to close the circuit and causing current to flow in the high power side



Electrical Switch

The advantage of using the relay is that we can use a digital logic circuit to turn on/off the motor



But the **mechanical relay** has certain **drawbacks** (see previous slides) that we may want to avoid if possible – Let us see how the **transistor** is made!

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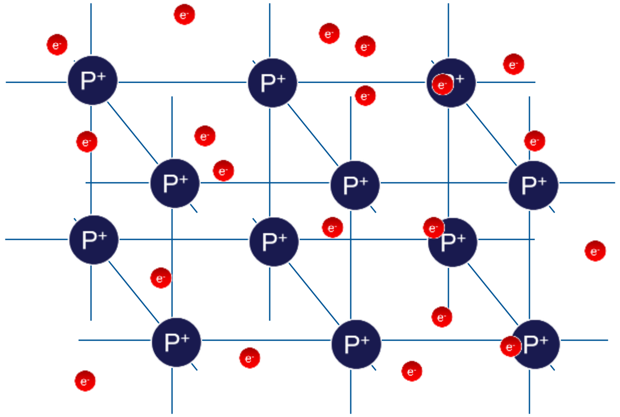
Semiconductor

Conductor

Easily allows current to flow through it

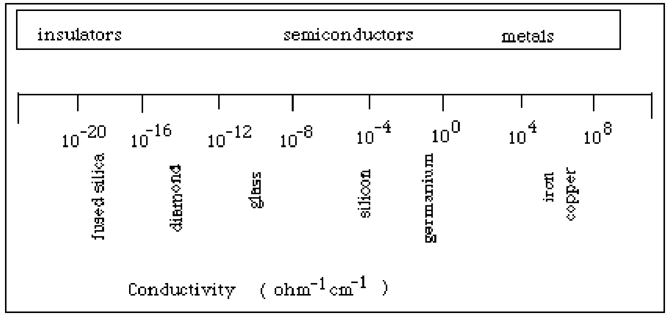
$$R \rightarrow 0\Omega$$

All metals are conductors

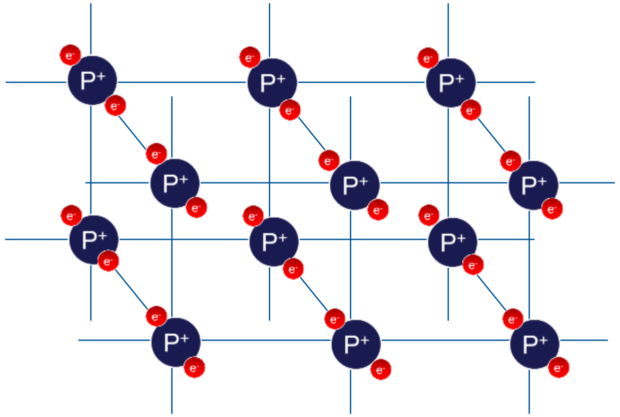


Semiconductor

Electrical resistance is midway between the two



Silicon

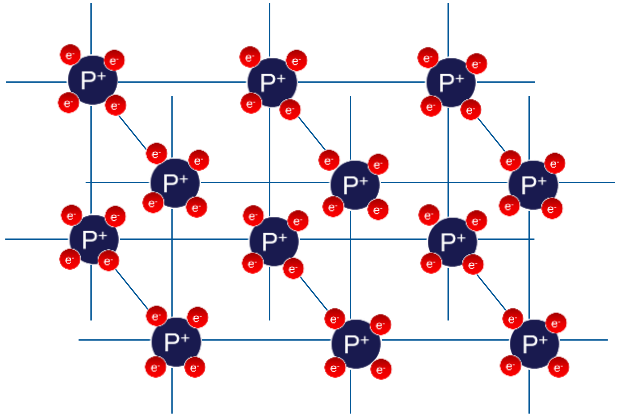


Insulator

Strongly impedes flow of current through it

$$R \rightarrow \infty\Omega$$

Plastic, rubber, wood etc.



Semiconductor

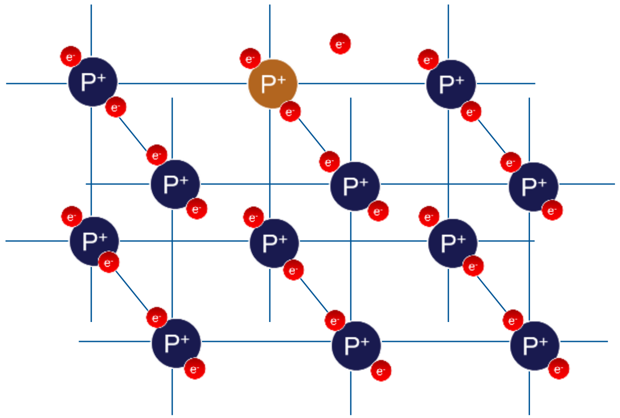
https://www.youtube.com/watch?v=k12GMjtN8aA

Doping – control how much "semi" conduction happens!

Pure semiconductors (called "intrinsic") are often intentionally doped by a specific impurity (order of few parts per million) to alter its electrical properties (called "extrinsic")

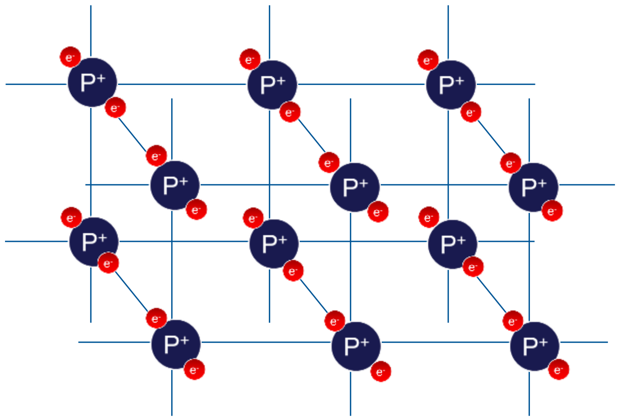
N-type Doping

Group V elements of periodic table (electron donor) are infused into the lattice structure of silicon that donate an electron



Phosphorus
Arsenic
Antimony

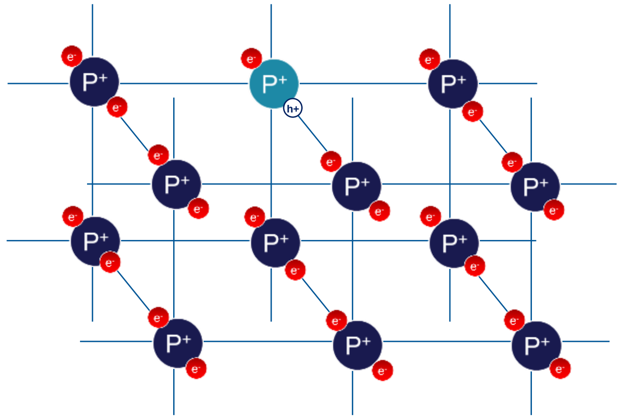
Silicon



Boron
Aluminium
Gallium

P-type Doping

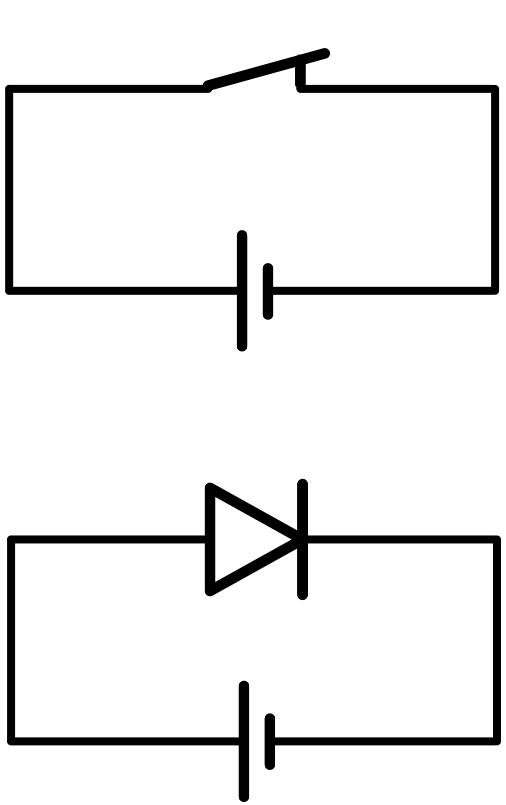
Group III elements of periodic table (electron acceptor) are infused into the lattice structure of silicon that an electron



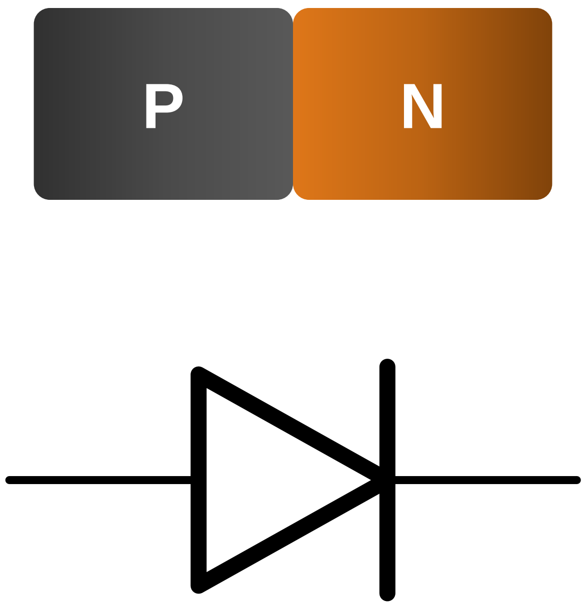
Diode

PN Junction (Diode)

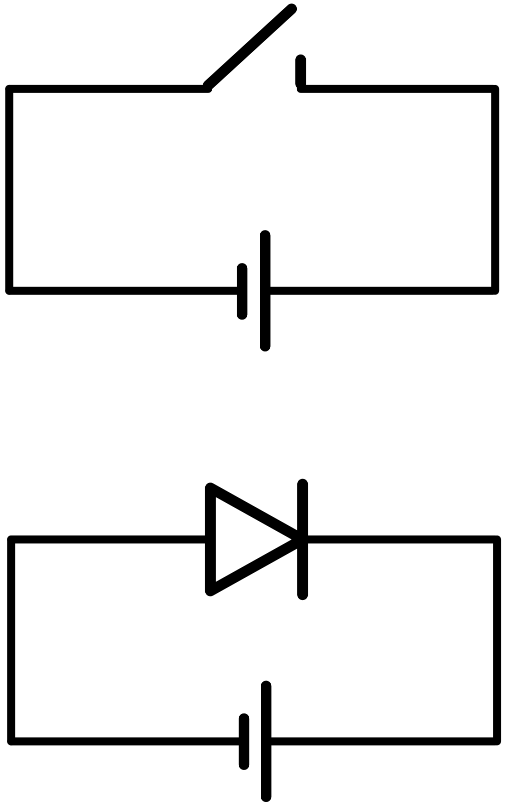
Basic building block of all electronics – one-way valve



Forward Bias



Diode

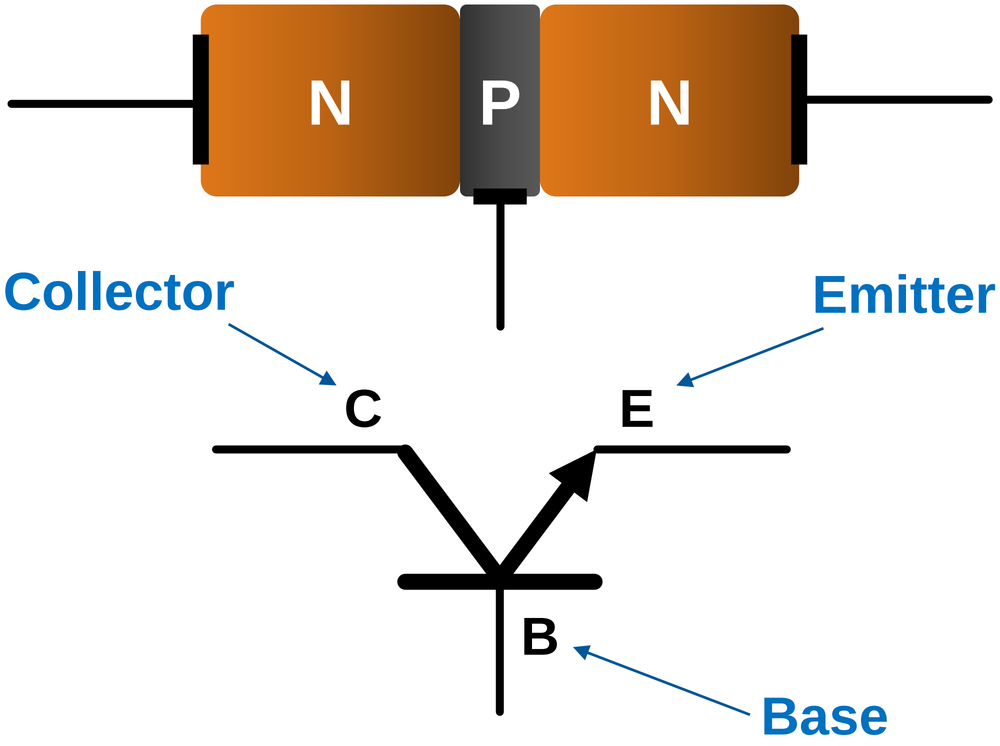


Reverse Bias

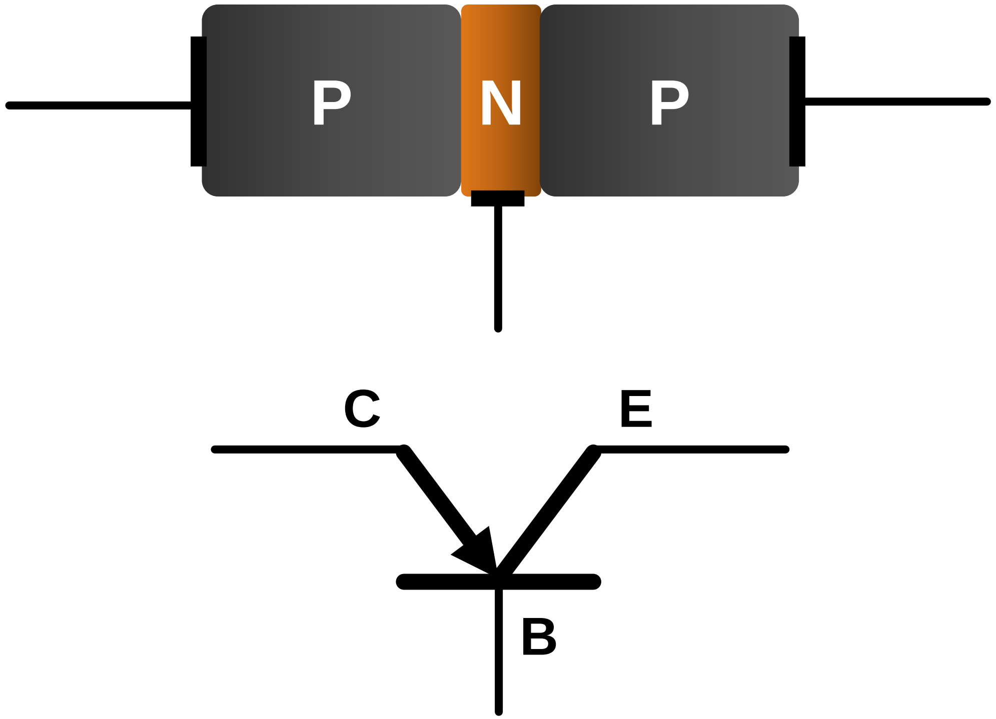
Transistor

BJT – Bipolar Junction Transistor

The first electronic switch



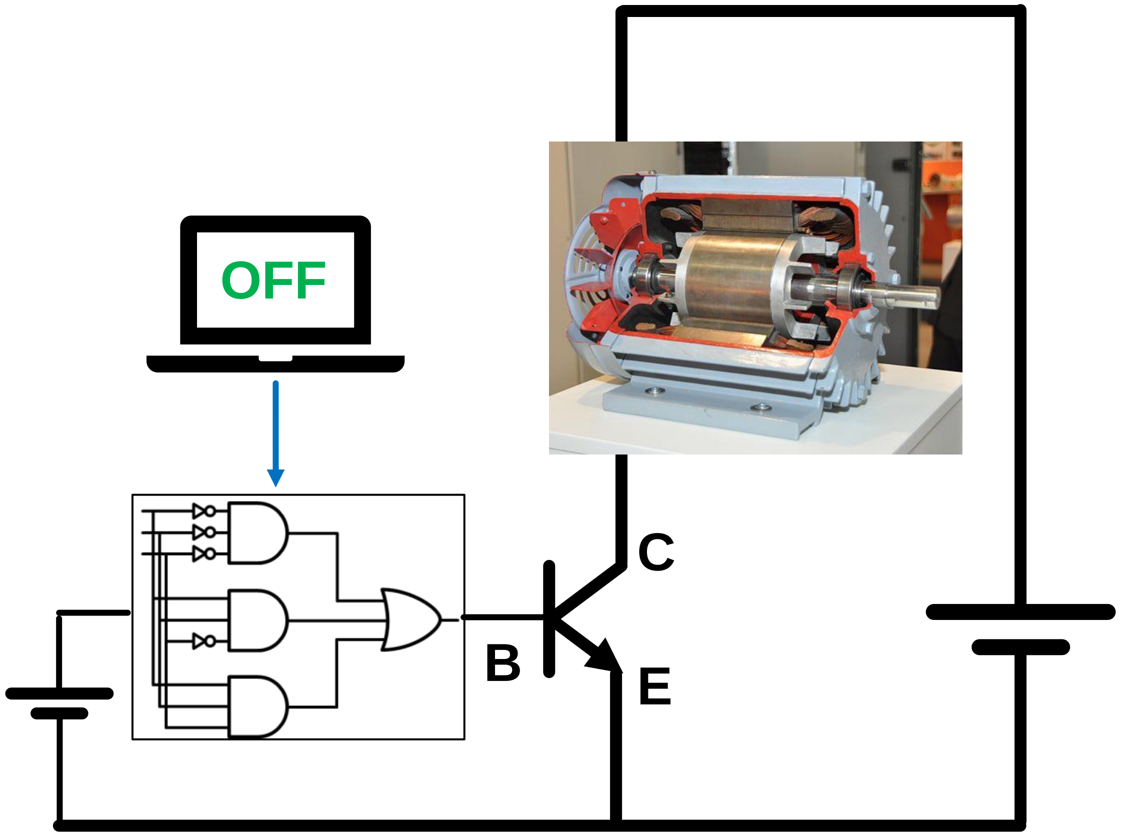
NPN Transistor



PNP Transistor

Transistor

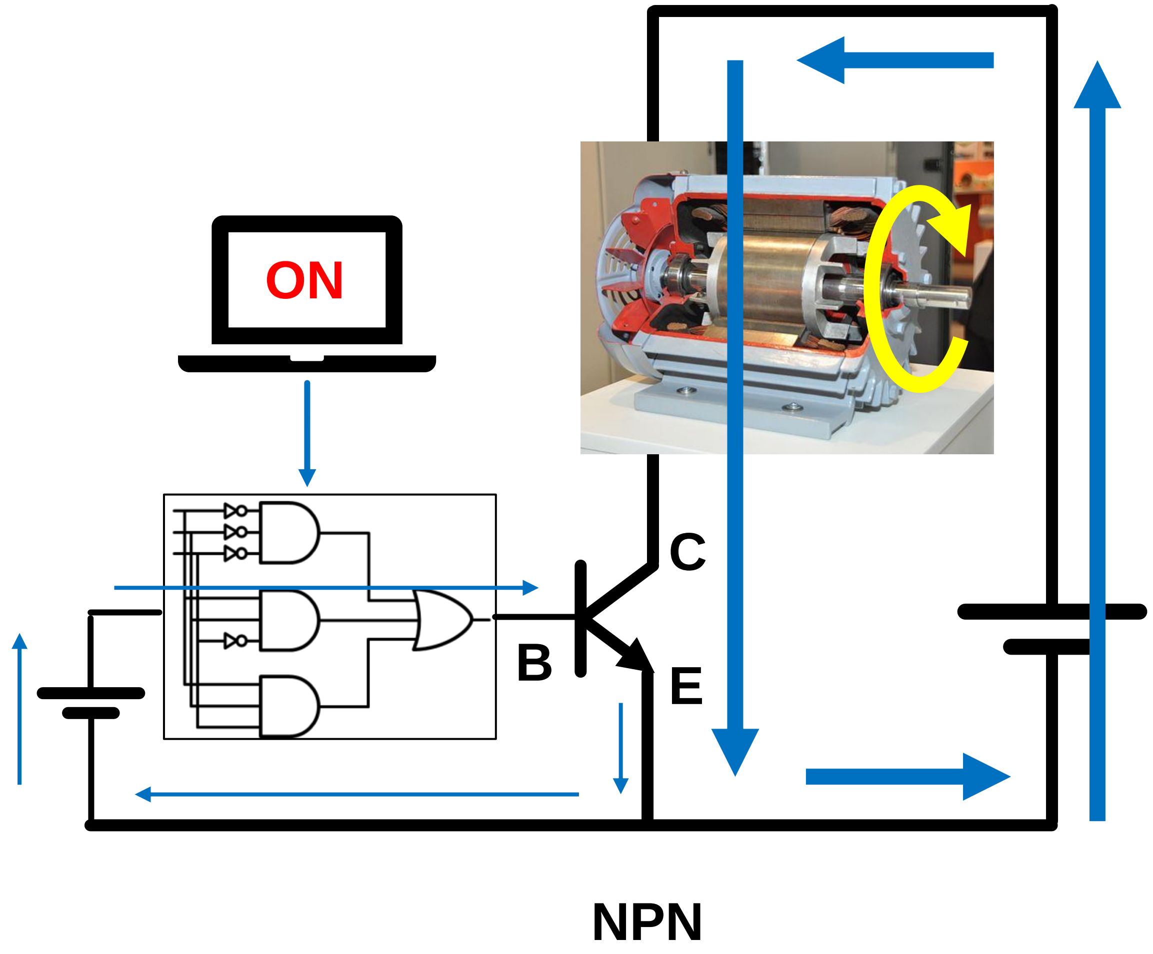
Let us see how we use the NPN transistor to turn on/off the motor



NPN

Transistor

Let us see how we use the NPN transistor to turn on/off the motor



We are effectively using a low power digital signal to actuate a high power load

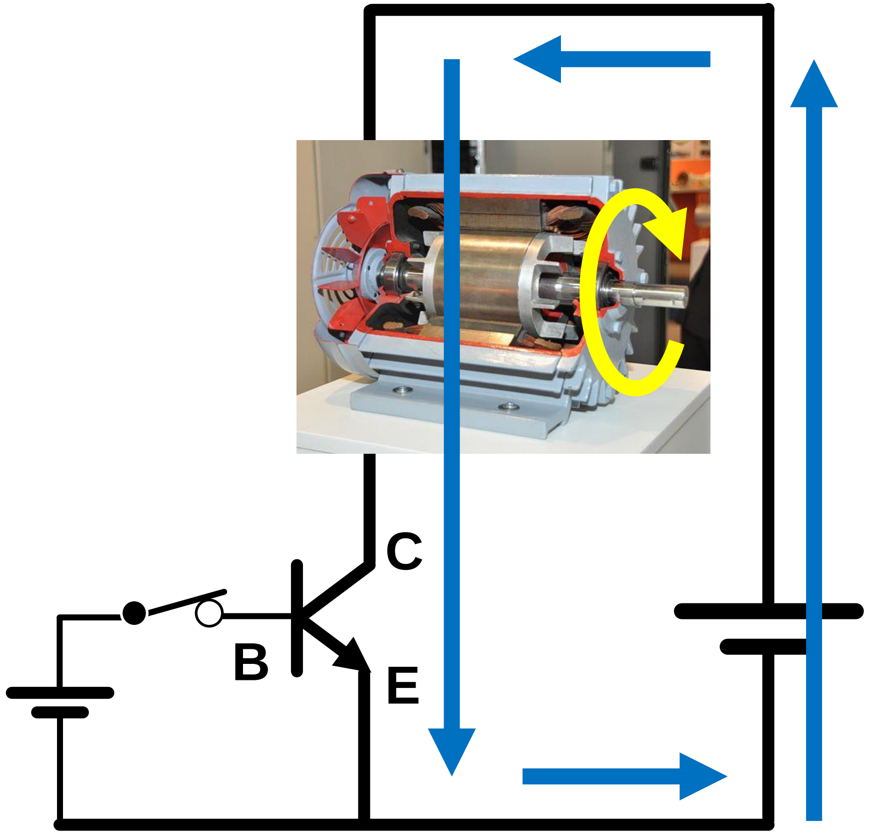
A transistor has two modes of operation:

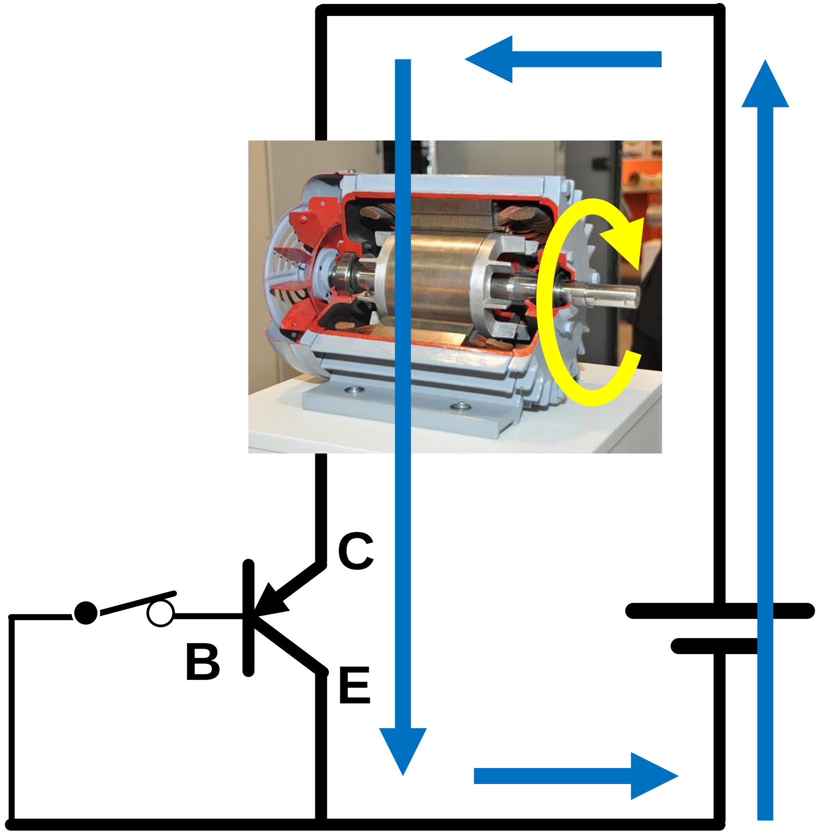
- **Active** – use as amplifier, i.e., output current (C to E) is proportional to input base current
- **Saturation/Cut-off** – use as on/off switch

We shall only study about using the transistor in its saturation/cut-off region, i.e., ON/OFF only

There are other ways of signal amplification – we shall study op-amps in the next part today

Transistor





ON

NPN
Give a HI signal to base

PNP
Give a LO signal to base

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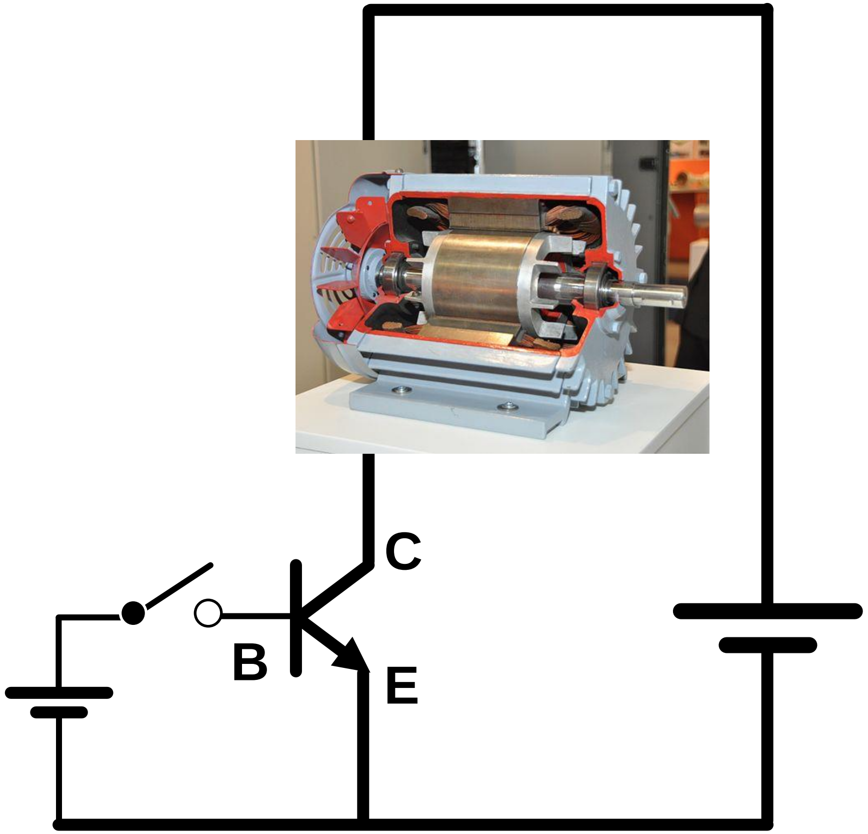
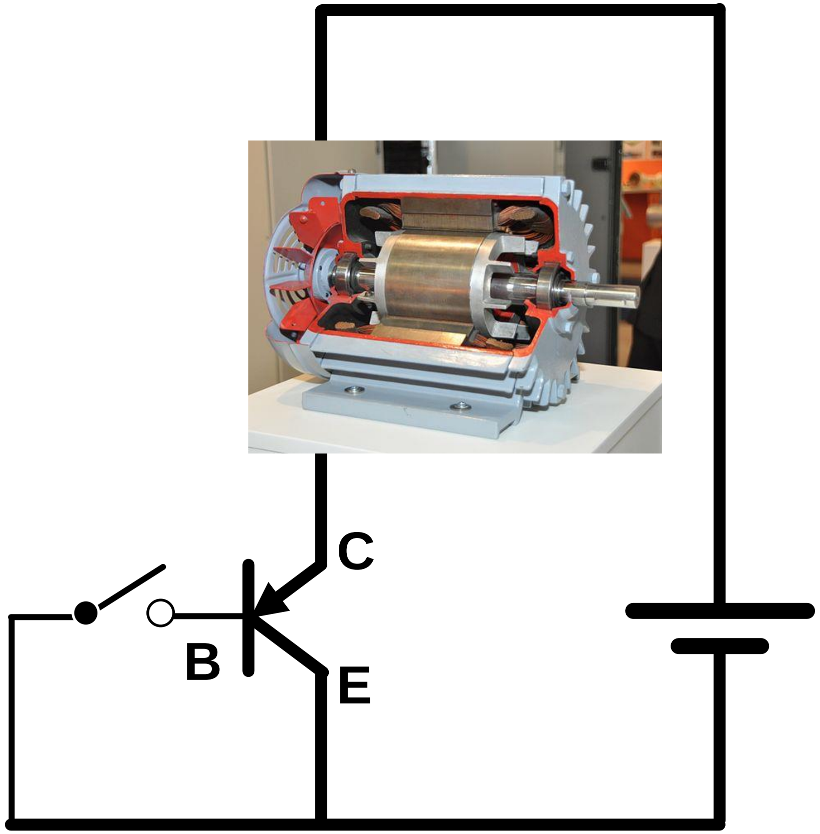
Transistor



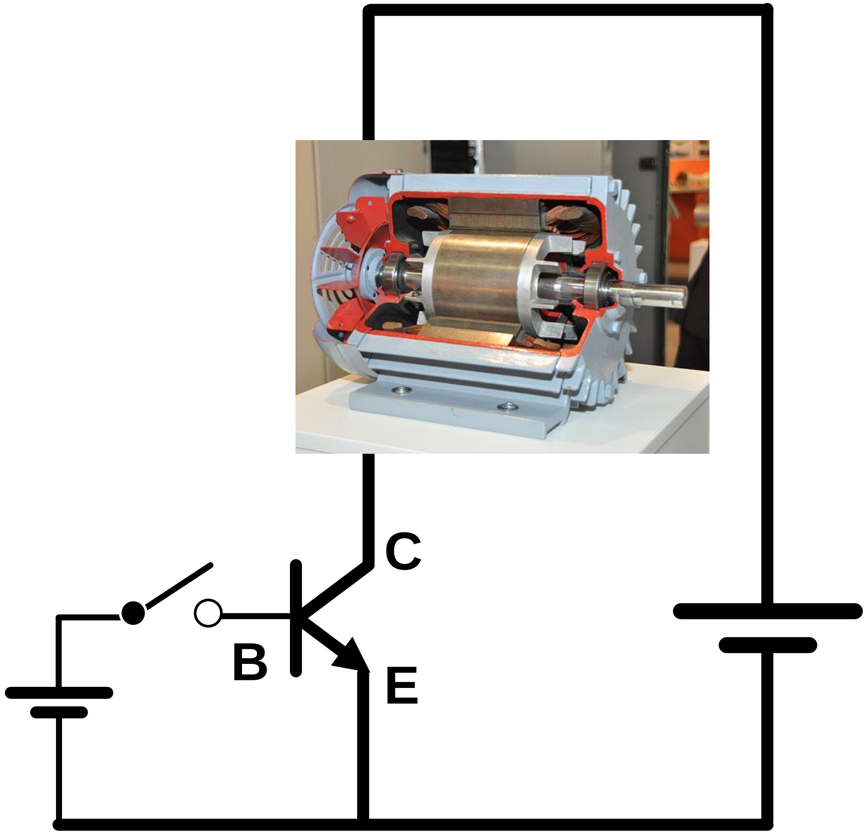
OFF



NPN
Give a LO signal to base
Base automatically pulls to ground when no voltage applied

PNP
Give a HI signal to base
Base automatically pulls up when no voltage applied

Transistor



NPN

Give a LO signal to base

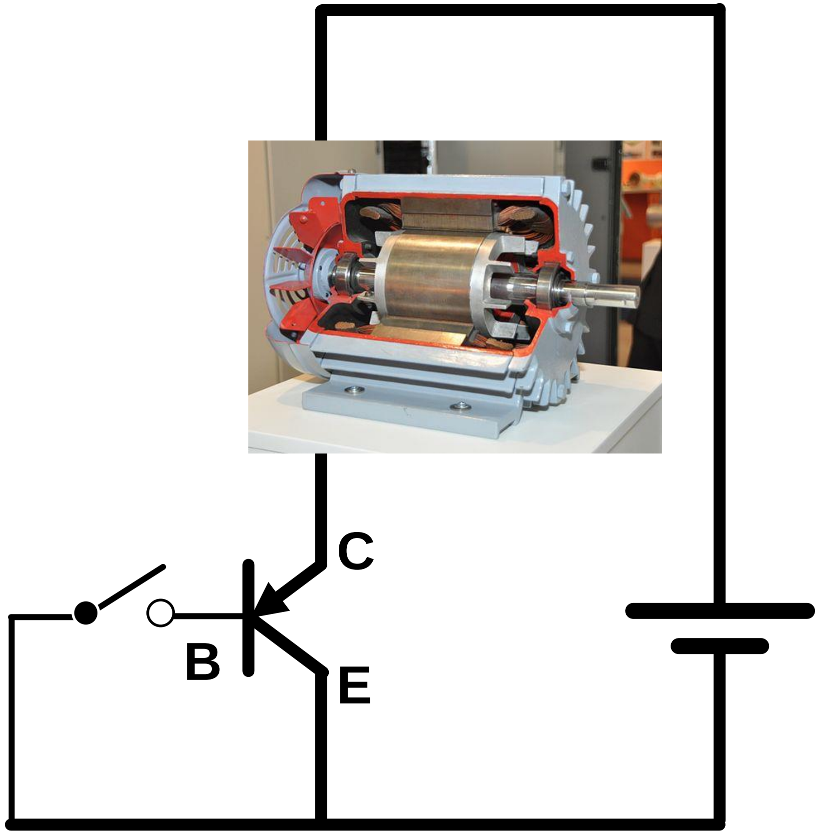
Base automatically pulls to ground when no voltage applied

Does the behaviour of PNP appear odd?

Why would you want to apply a LO signal to turn something ON?

Recall Active HI and Active LO from previous lecture!

If the logic circuit had an Active LO output signal, the information "Activate the motor" would be represented as a LO voltage!



PNP

Give a HI signal to base

Base automatically pulls up when no voltage applied

Transistor

Transistors, just like anything else in the world, are not a one-size-fits-all!

Advantages

- **Turn on and turn off very quickly**
- **Inexpensive**

Disadvantages

- **Continually need a base current to stay on**
- **Output current (collector to emitter) capability is fairly limited, not enough to drive high power motors**

MOSFET

Metal Oxide Semiconductor

Field Effect Transistor

They use a different method of turning ON/OFF an electrical path that allows it to switch high currents as well

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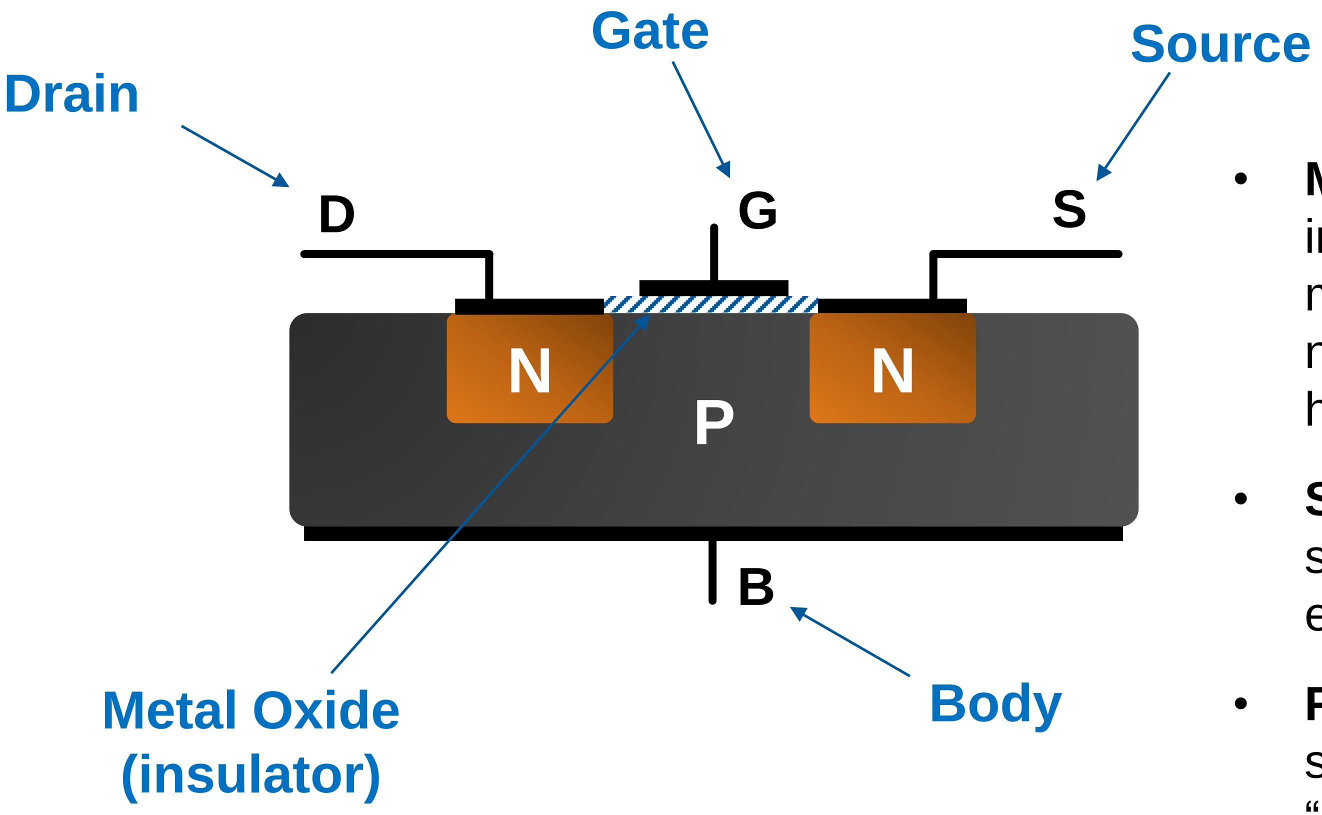
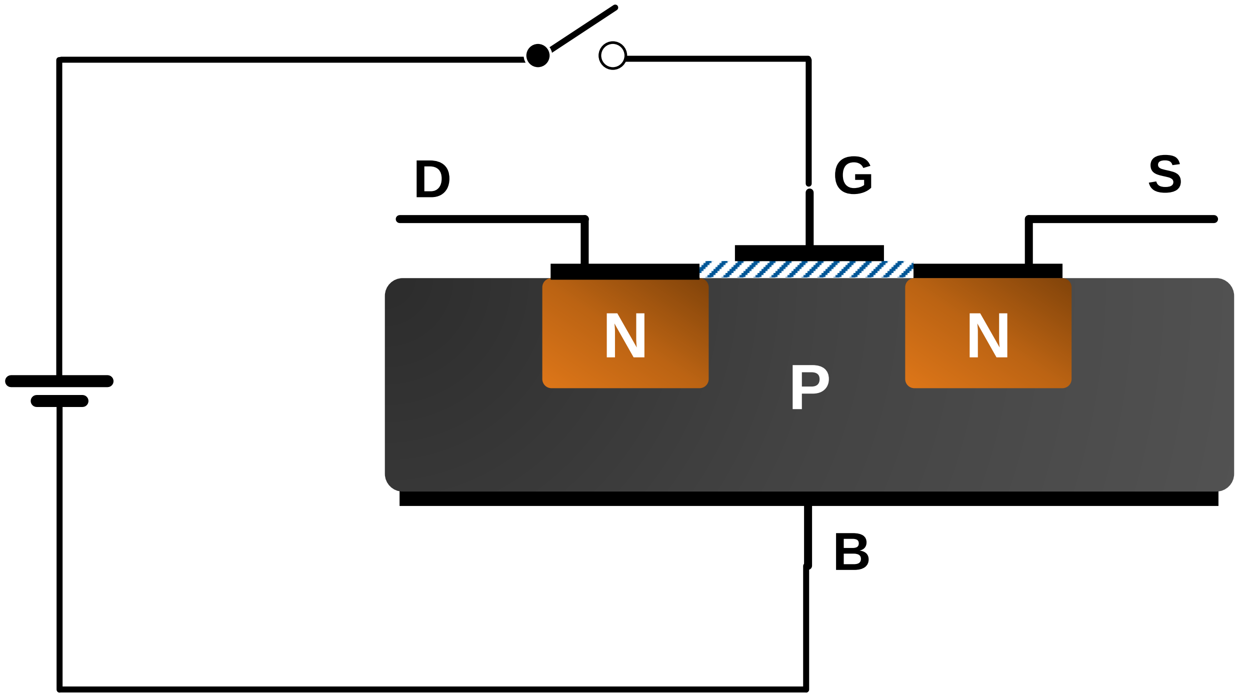
MOSFET

Metal Oxide Semiconductor Field Effect Transistor



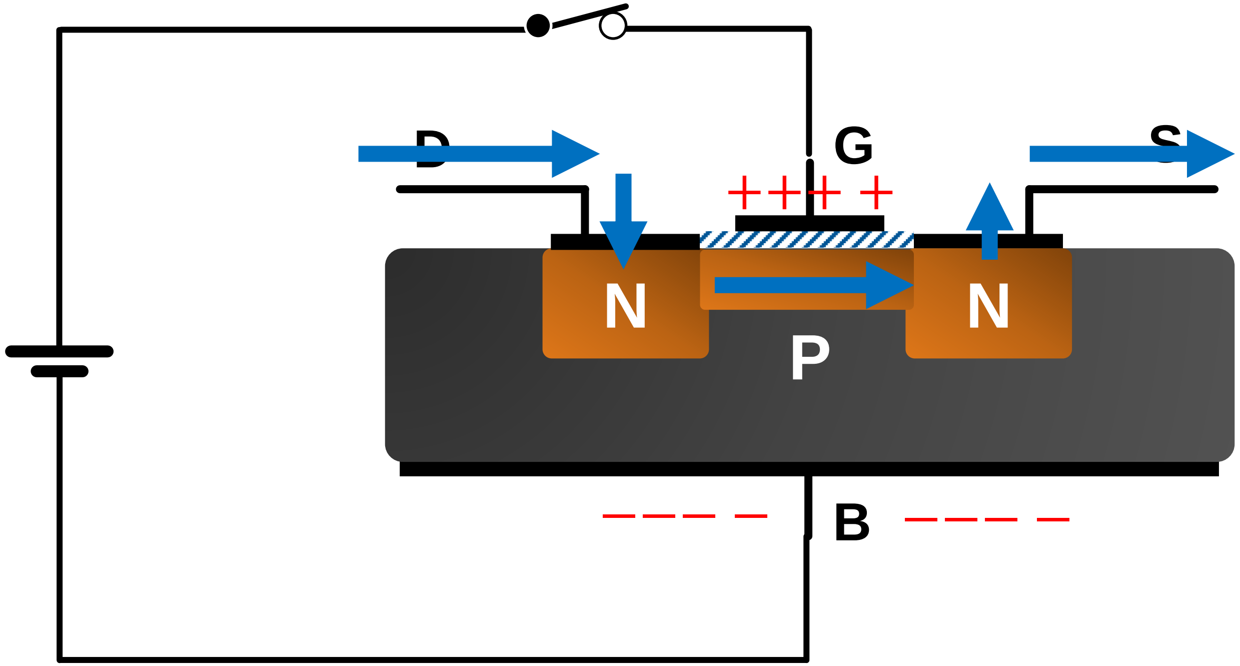
- **M**etal **O**xide – the insulator in the first MOSFETs were made of a metal oxide – nowadays better materials have superseded
- **S**emiconductor – the main substrate body is an extrinsic semiconductor
- **F**ield **E**ffect **T**ransistor – switching on happens due to “Field Effect”, i.e., like in a capacitor

How does a MOSFET work?



Capacitor-like Field is created – shorting Drain and Source

Apply a high enough **positive voltage** at Gate with respect to the Body (which is usually grounded)



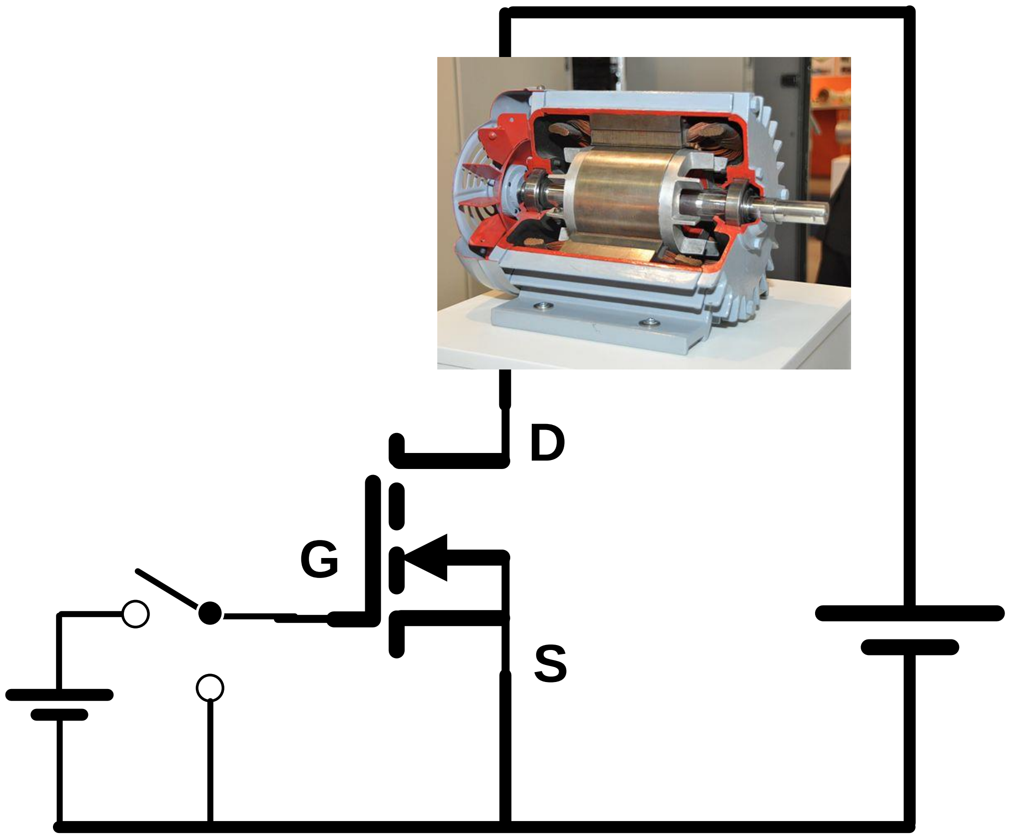
Note that:

- Only required to charge the capacitor maintain it (only apply voltage, no continuous current needed)
- On the flipside, the charged capacitor requires intentional discharging when you want to turn it off
- Load current can be very high

Positive voltage on the Gate terminal attracts all the electrons in the P-substrate

This electric field creates an N-type channel allowing current flow between Drain and Source, hence "closing the switch"

MOSFET



N-Channel Enhancement-type

This is the symbol of

N-MOSFET Enhancement type

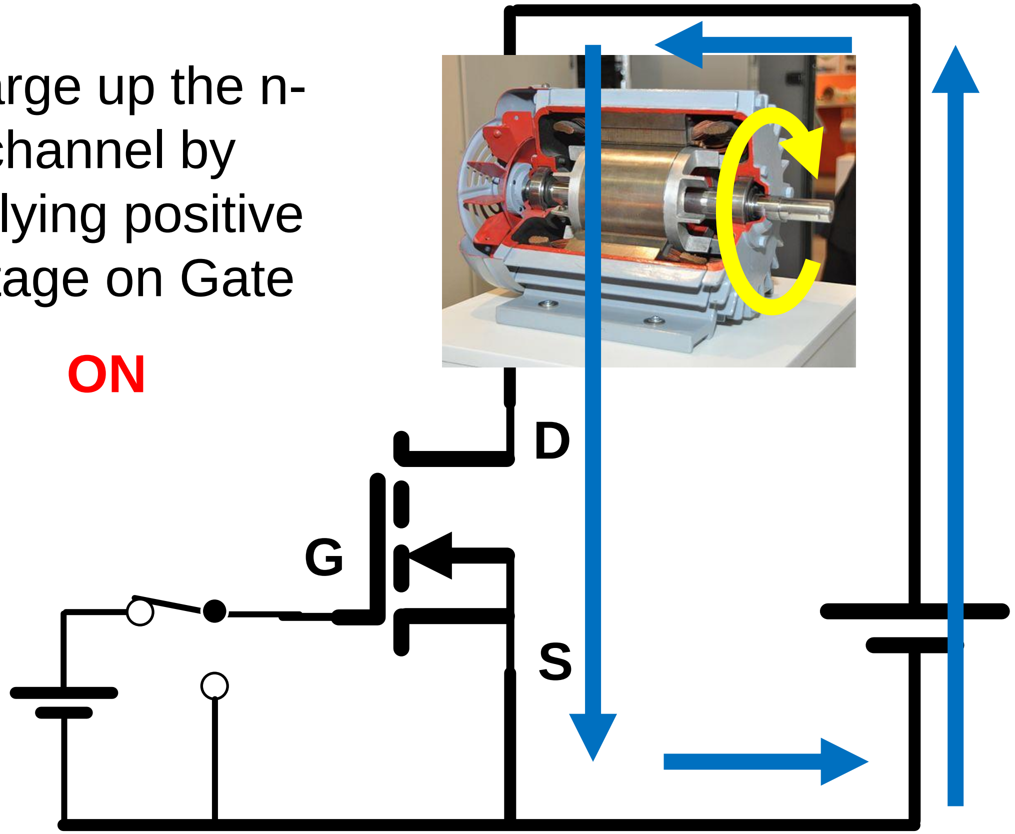
Remember for MOSFET, as it is a capacitor, **it needs to be charged and discharged** (both) to turn on or off – simply removing voltage from Gate does not work like the BJT

Also note that when using the symbol, the Body terminal is not shown. It is usually assumed that the Source is connected to the Body, and both are grounded

MOSFET

Charge up the n-channel by applying positive voltage on Gate

ON



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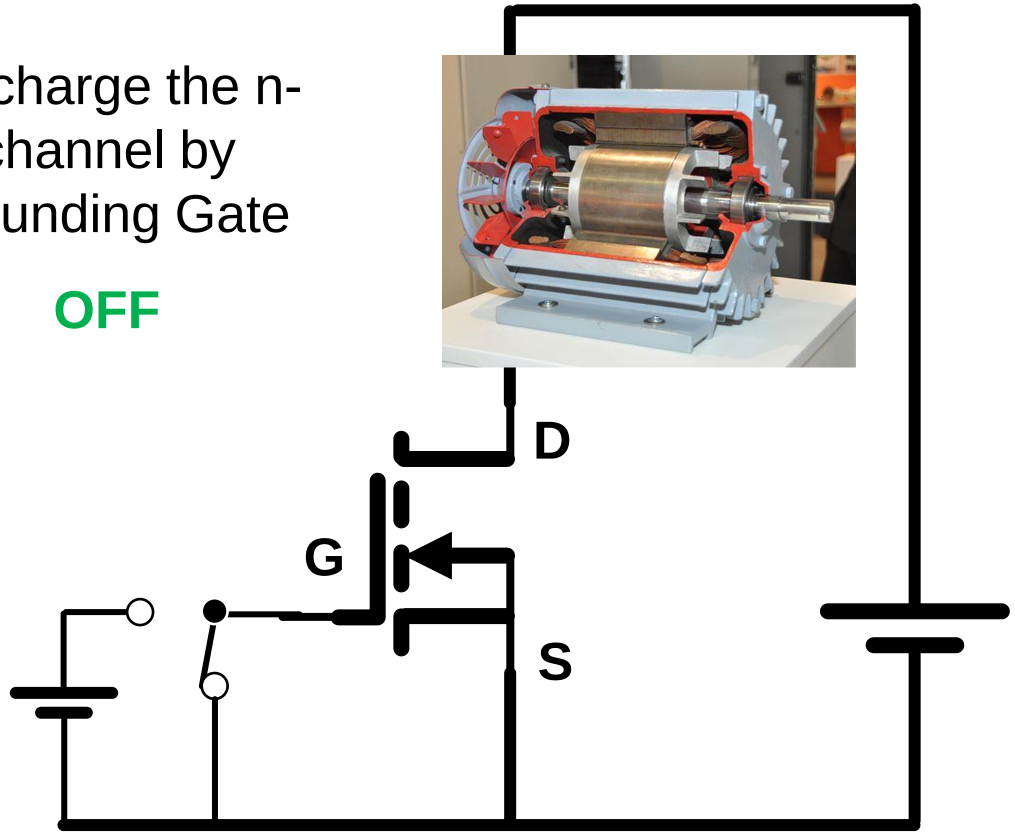
MOSFET

Discharge the n-channel by grounding Gate

OFF



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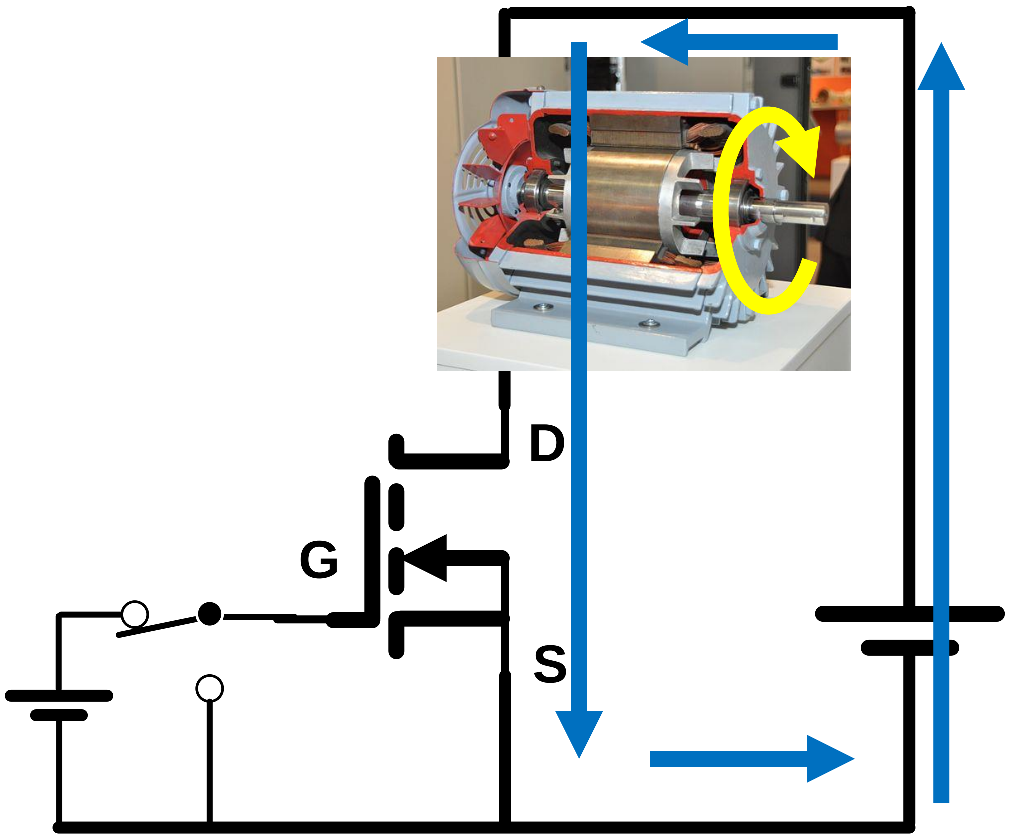
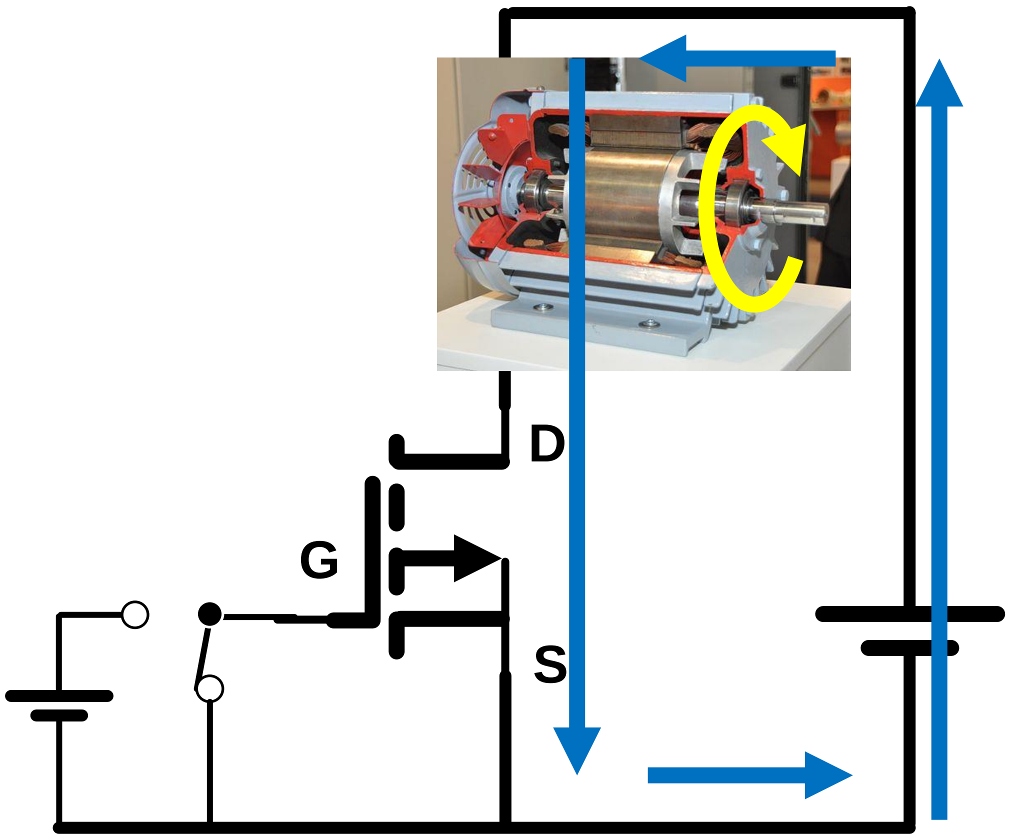
MOSFET

As with BJT, there is a P-type as well



N-Channel Enhancement-type

ON



P-Channel Enhancement-type

MOSFET

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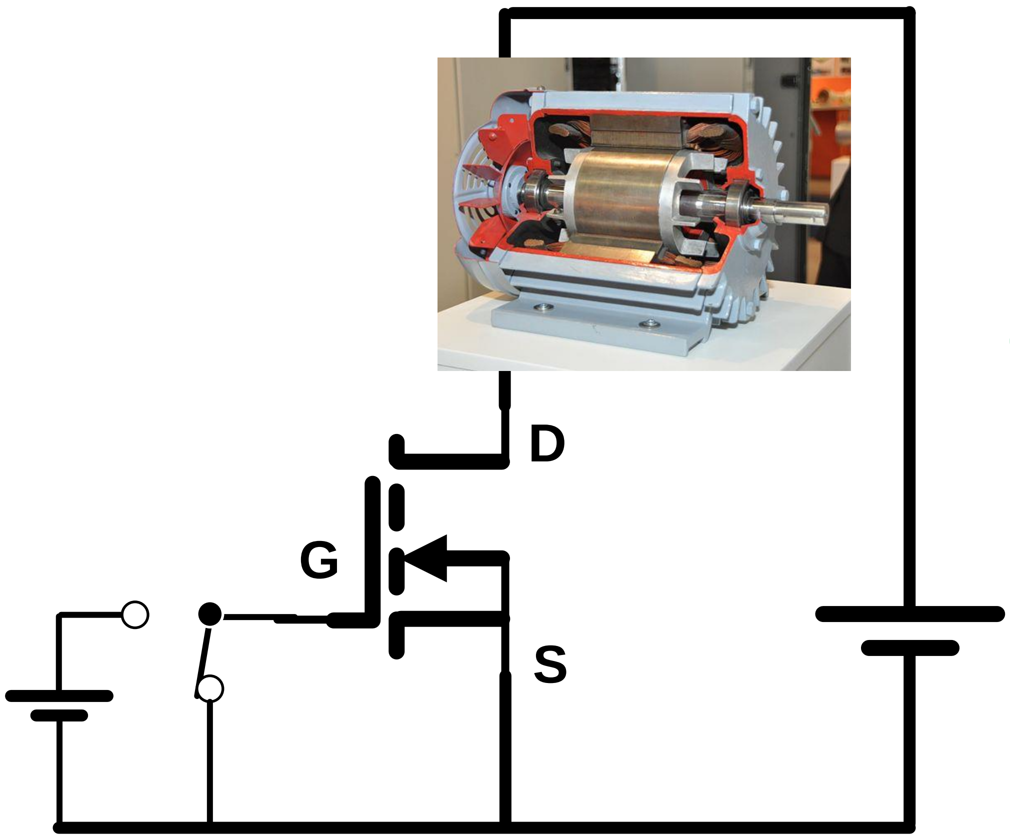
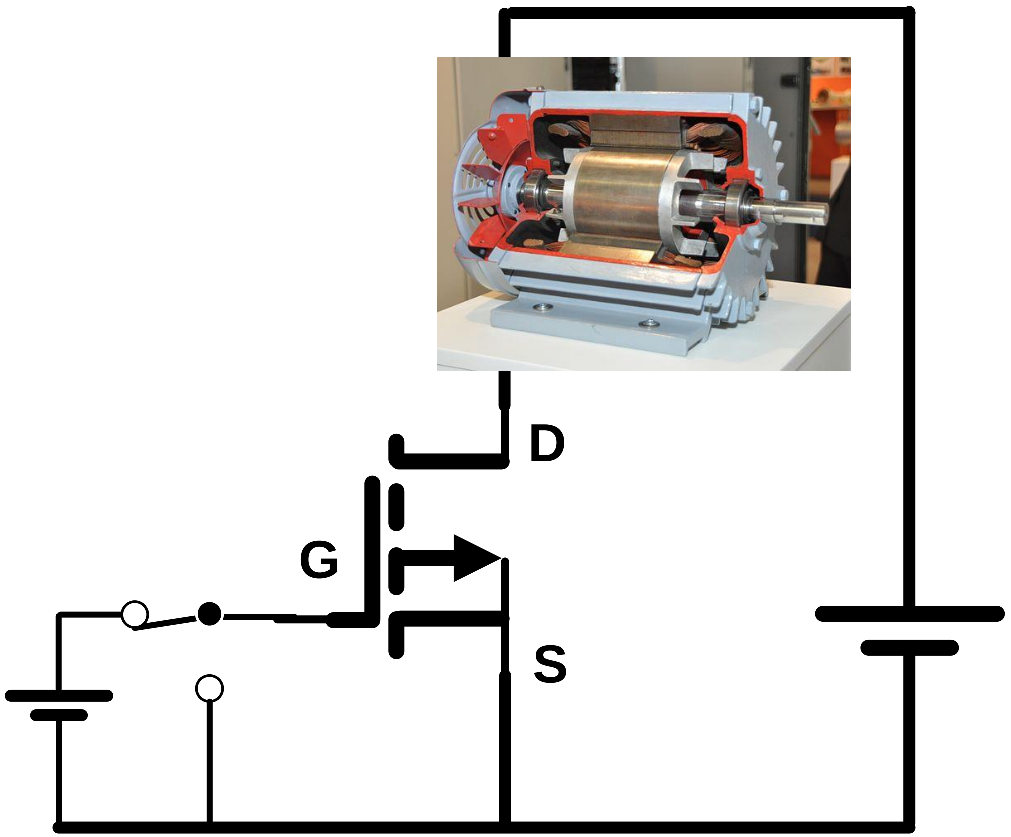


N-Channel Enhancement-type

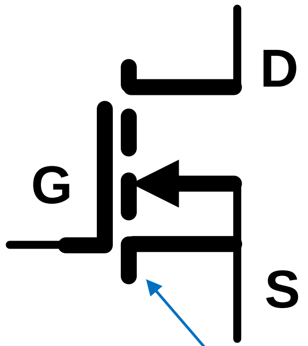
OFF



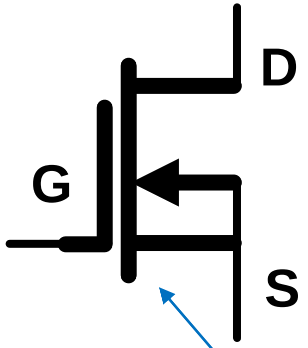
P-Channel Enhancement-type

MOSFET

There is another kind called “Depletion Type”



N-Channel Enhancement-type



N-Channel Depletion-type

Depletion-type MOSFET works just like the Enhancement-type, but you apply a voltage to make the FET **insulating** (instead of conducting)

Essentially, the switch behaves like a **normally-closed switch**, and you need to apply a voltage to open it

Notice that this line is dashed – indicates insulating normally

Notice that this line is solid – indicates conducting normally

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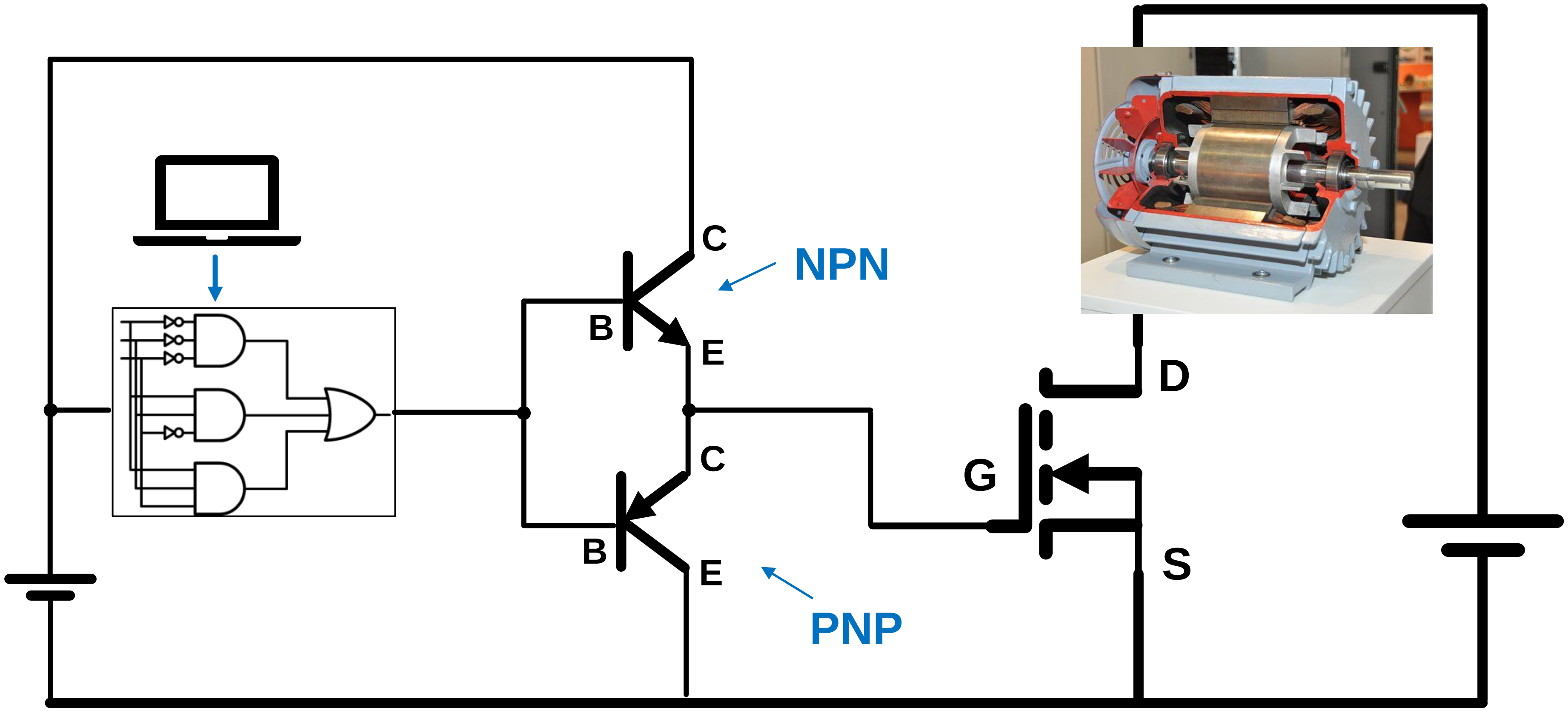
Push-Pull Pair Circuit

We have certain advantages and disadvantages of both BJT and MOSFET – we can combine them to get best of both worlds!



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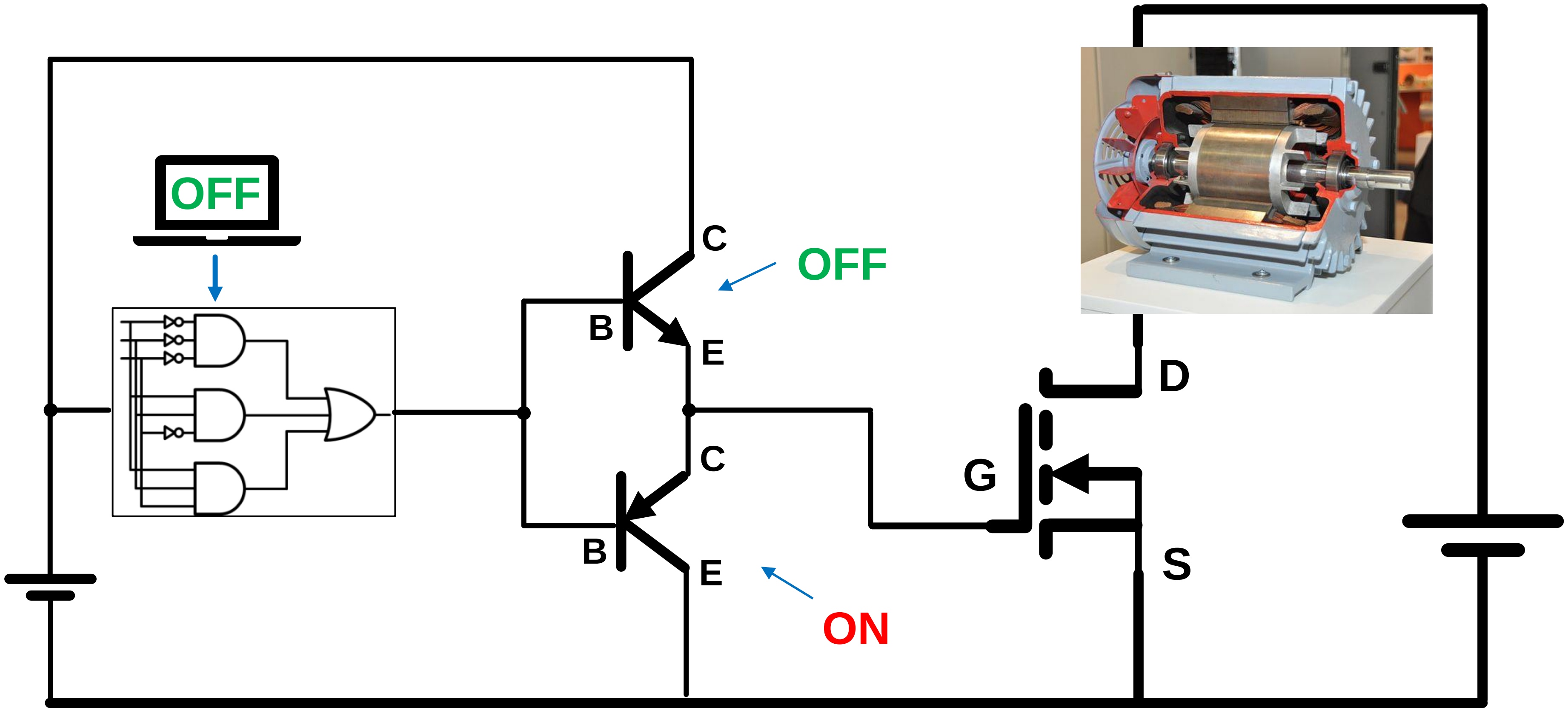

Push-Pull Pair Circuit

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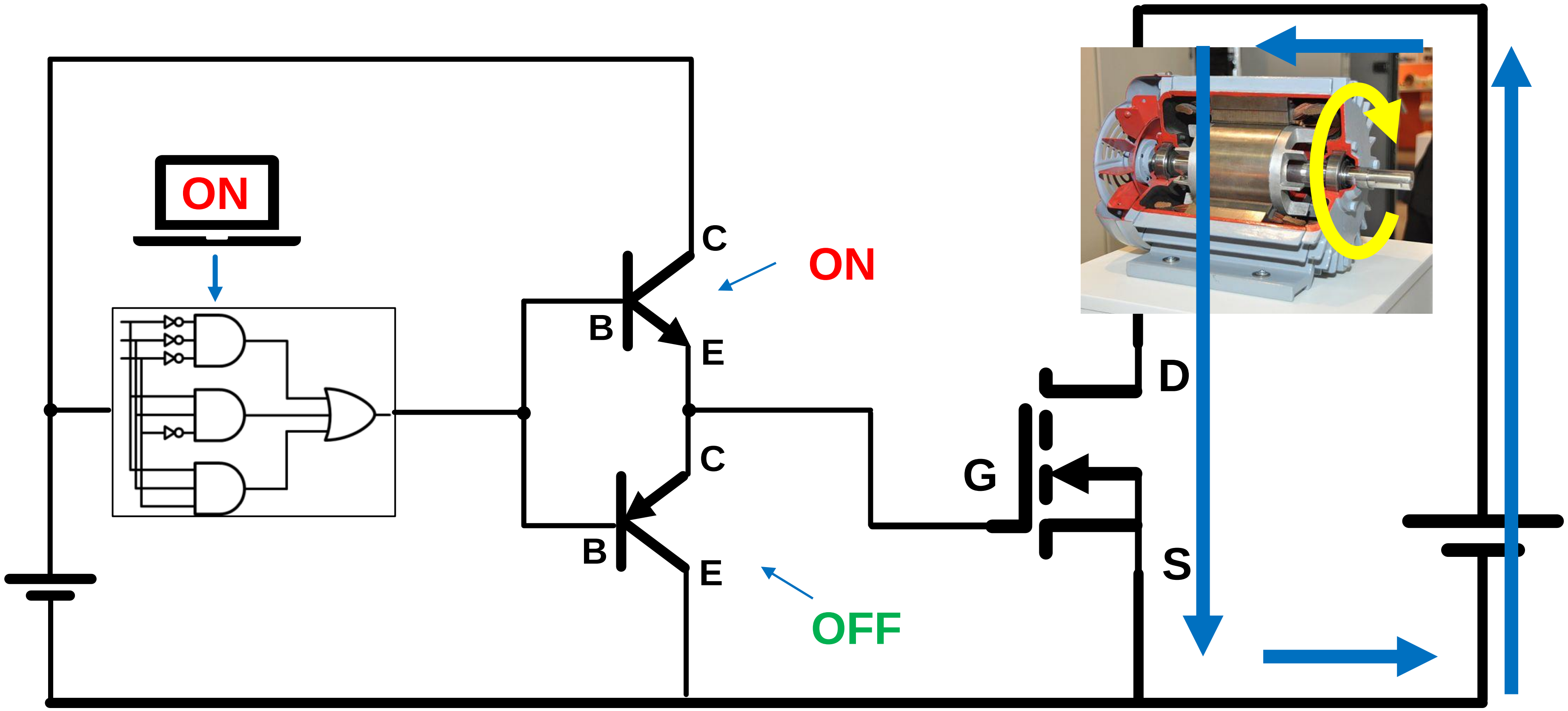

Push-Pull Pair Circuit

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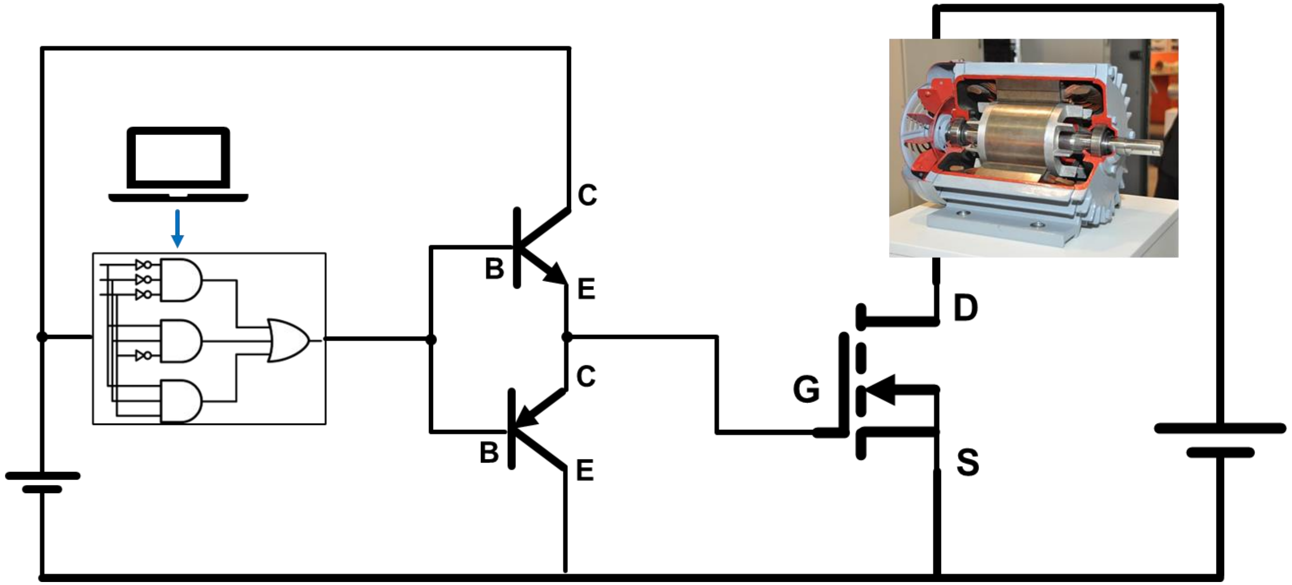

Salient features of the Push-Pull pair:

- Digital circuit is only supplying the base current (order of few mA) of the BJTs
- Turn off – PNP BJT is acting quickly to discharge the "capacitor-like" N-channel in the nMOSFET to turn it off
- Turn on – NPN BJT is acting quickly to charge the "capacitor-like" N-channel to turn on the MOSFET

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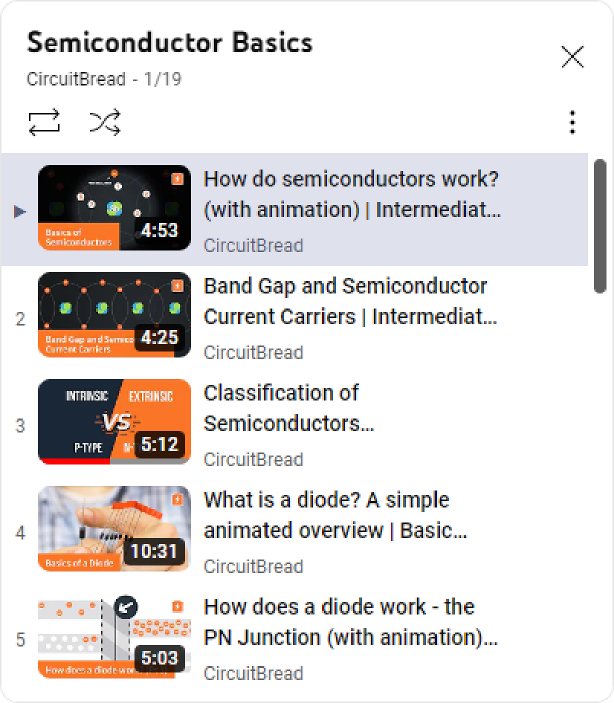

I strongly suggest you to have a quick scan of the semiconductors playlist put together by **CircuitBread** – very insightful and nice animation!

https://www.youtube.com/watch?v=n2S7kN12RDQ&list=PLfYdTiQCV_p7sDswtLZKK43BWOd2mTmHC