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LECTURE 7

Force Measurement & Stepper Motor

Electromechanical Devices
MMME2051

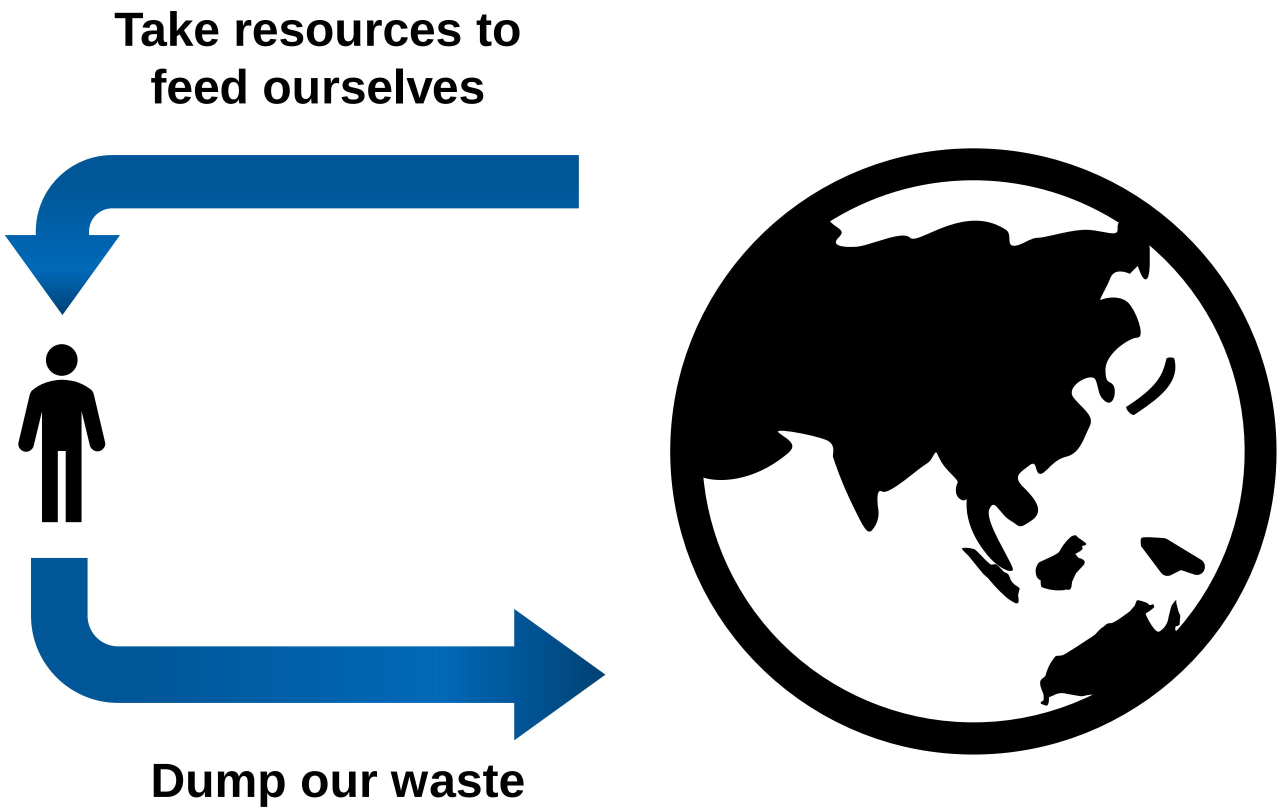
Module Convenor – Surojit Sen

Learning Outcomes

- **Sustainability Development Goals @UoN**
- **Revision of Op Amps (previous week)**
- **Piezoelectric** properties of Quartz
  - **Integrating** Amplifier
  - **Differencing** Amplifier
- **Strain Gauge**
  - **Resistivity** v Resistance
  - **Wheatstone Bridge**
- **Stepper Motor**

Why should we be sustainable?

- This is exactly what animals do
- **Assumption** is – Earth is an **bottomless source and sink**
- Worked great when we started – **not true any more**!
- **Earth's capacity is declining** – to provide resources as well as to absorb waste
- Being Sustainable means we should consider the £ associated with taking & dumping



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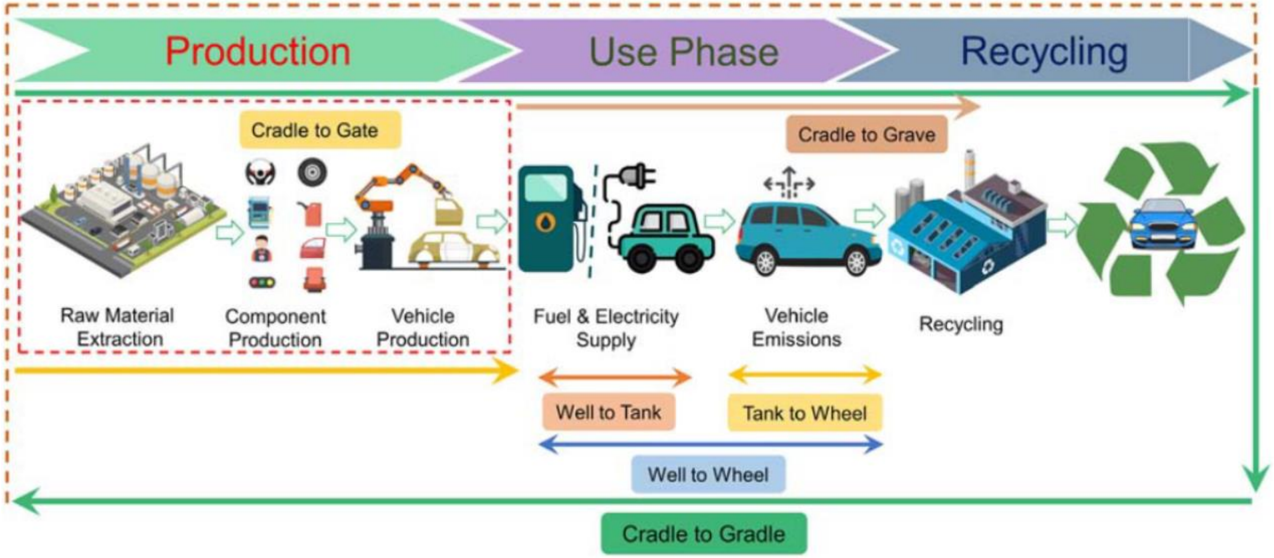
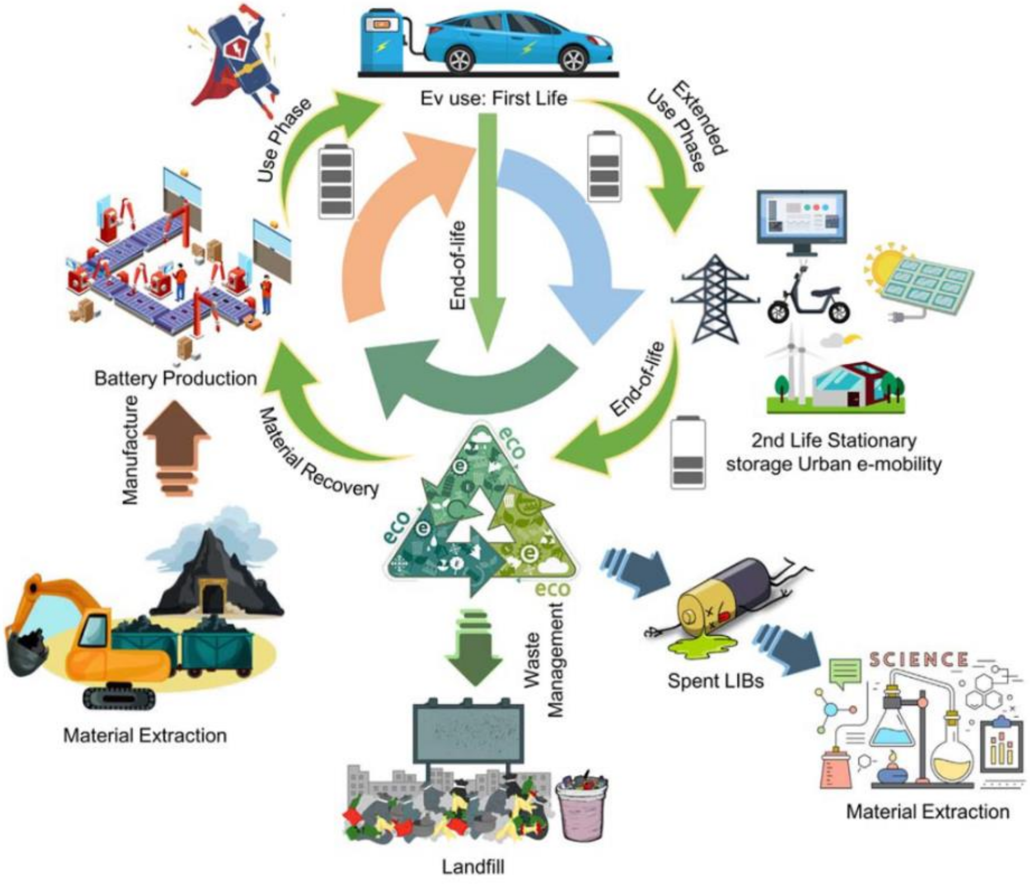
Sustainable Development Goals (SDGs)

1. No poverty
2. Zero hunger
3. Good health and wellbeing
4. Good quality education
5. Gender equality
6. Clean water and sanitation
7. Affordable and clean energy
8. Decent work and economic growth
9. Industry, innovation and infrastructure
10. Reduced inequalities
11. Sustainable cities and communities
12. Responsible consumption and production
13. Climate action
14. Life below water
15. Life on land
16. Peace, justice and strong infrastructure
17. Partnerships for good

Sustainable Development Goals (SDGs)

How am I contributing?



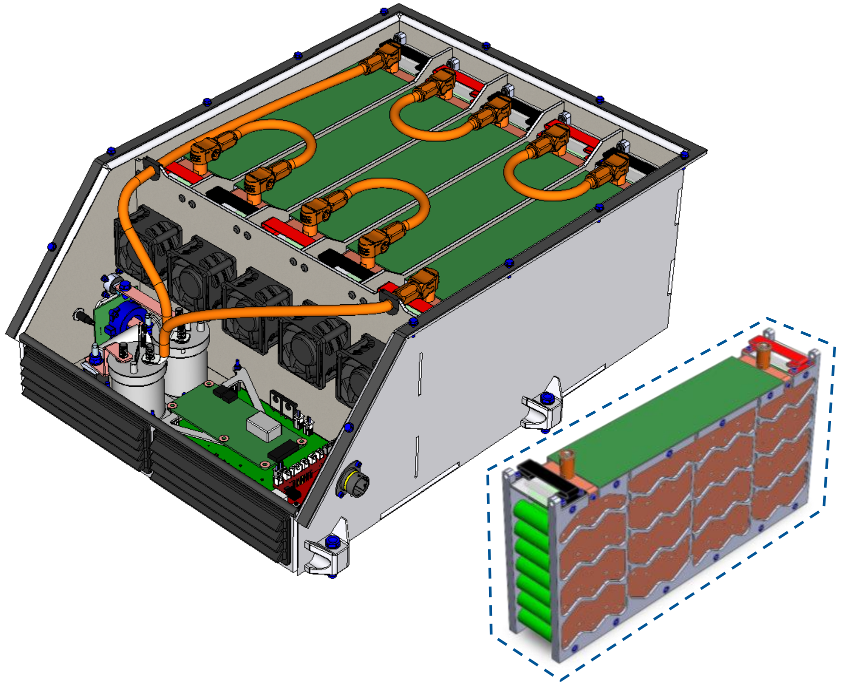


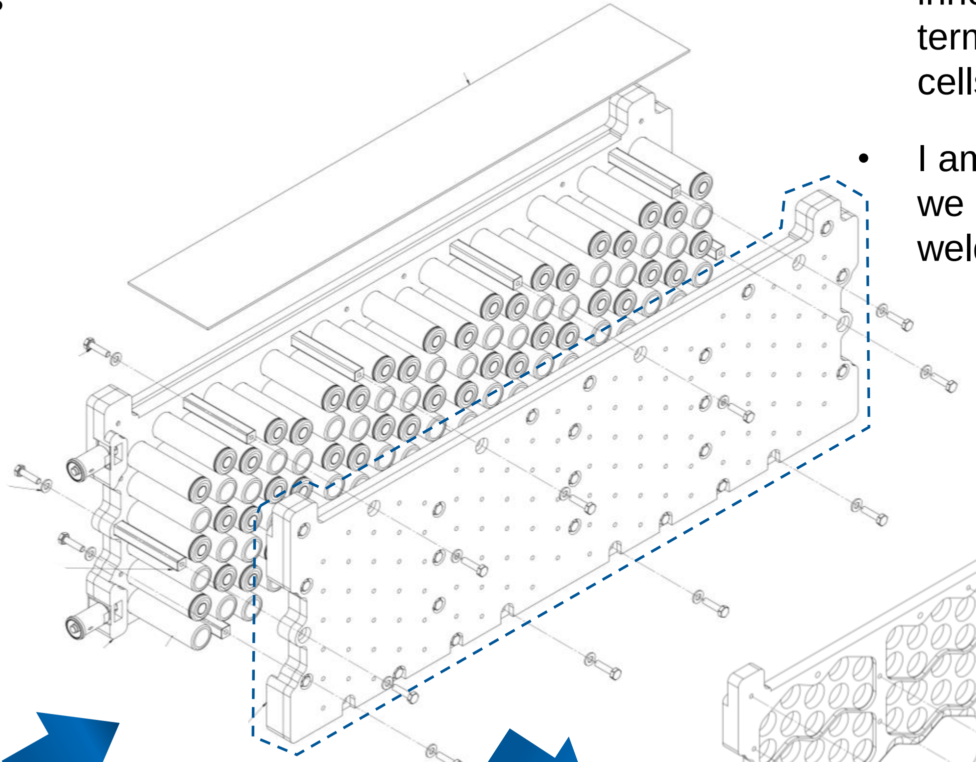
Source:
Xiaoning Xia, Pengwei Li, A review of the life cycle assessment of electric vehicles: Considering the influence of batteries, Science of The Total Environment, Volume 814, 2022, 152870, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2021.152870.
(https://www.sciencedirect.com/science/article/pii/S0048969721079493)

Sustainable Development Goals (SDGs)

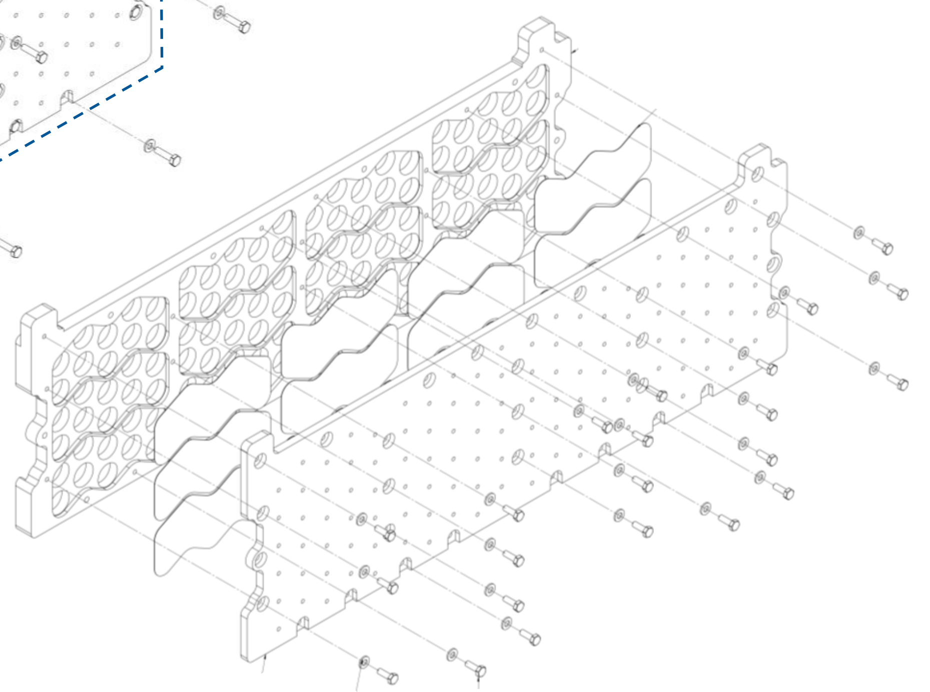
How am I contributing?

- Normal EV battery is made of multiple modules
- Cells in module tied together by copper plates welded to terminals
- Reliable – but no repairable or reusable
- Only way to recycle is to crush and chemically extract minerals





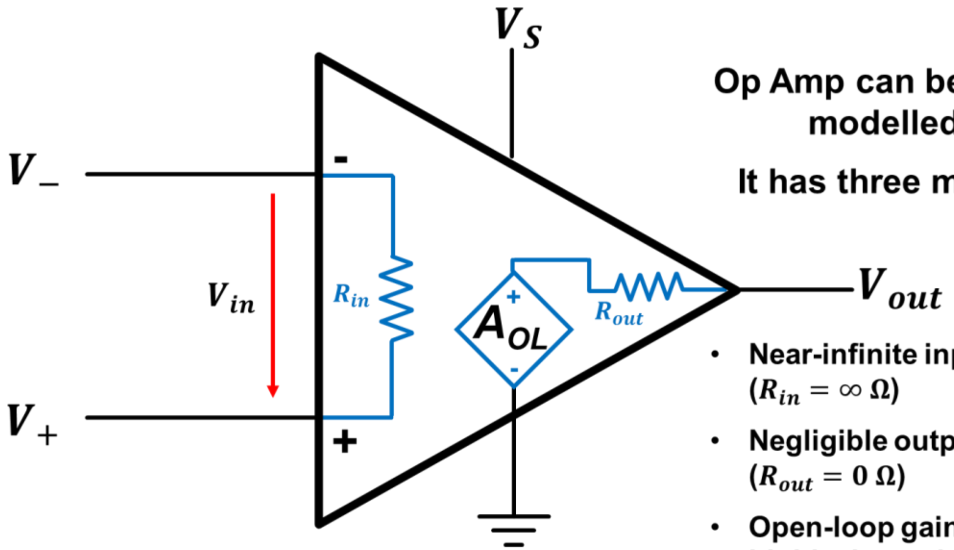
- By eliminating the “weld” feature, batteries inherently are sustainable – increase life term, swap faulty batteries, use degraded cells in domestic power applications
- I am researching on the effects of this – can we make a battery pack (without any welding) that is reliable?



Sustainable Development Goals (SDGs)

https://www.youtube.com/watch?v=qfOgdj4Okdw

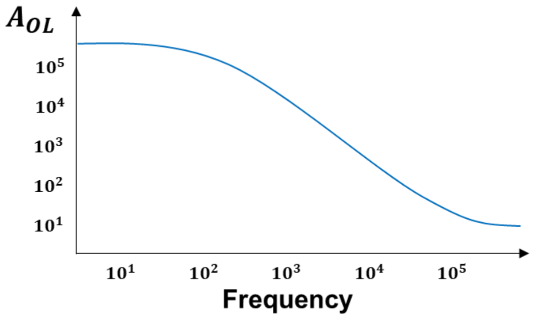
Revision of Op Amps

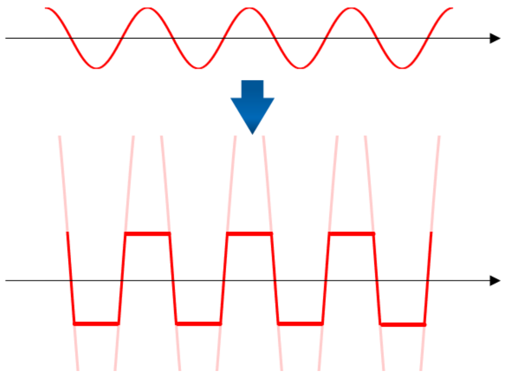


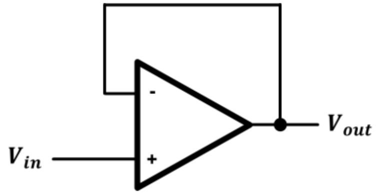
Op Amp can be simplistically modelled like this

It has three main features:

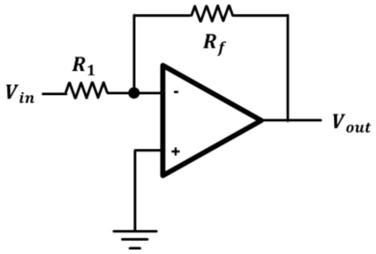
- Near-infinite input impedance ($R_{in} = \infty\ \Omega$)
- Negligible output impedance ($R_{out} = 0\ \Omega$)
- Open-loop gain is very high and highly dependent on frequency



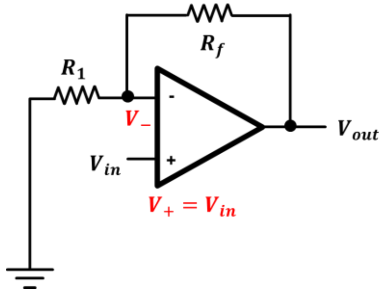




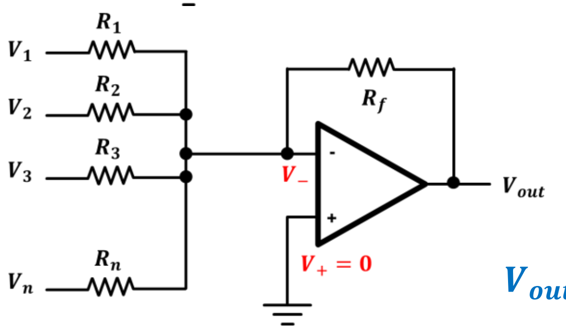
$$\frac{V_{out}}{V_{in}} = 1$$



$$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_1}$$



$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_1}$$



$$V_{out} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n}\right)$$

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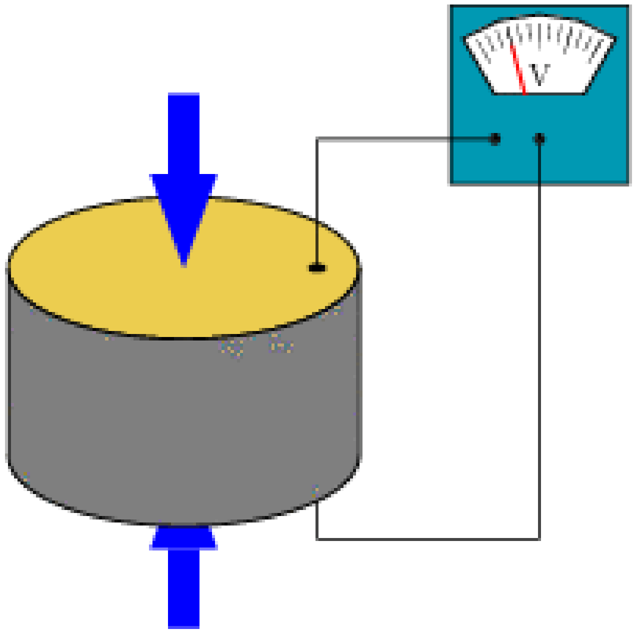
Piezoelectric effect of Quartz



Piezoelectricity is the electric charge that gets accumulated in some materials upon application of **mechanical stress**

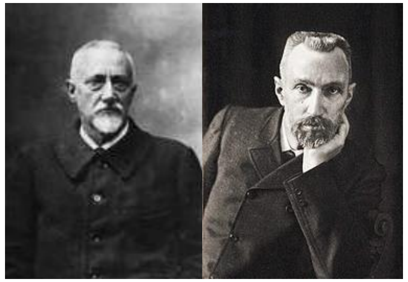
Words derived from *Piezein* (meaning 'to squeeze') and *Elektron* (electricity)

$$\boldsymbol{Q \propto F}$$

This relation is of extreme importance!

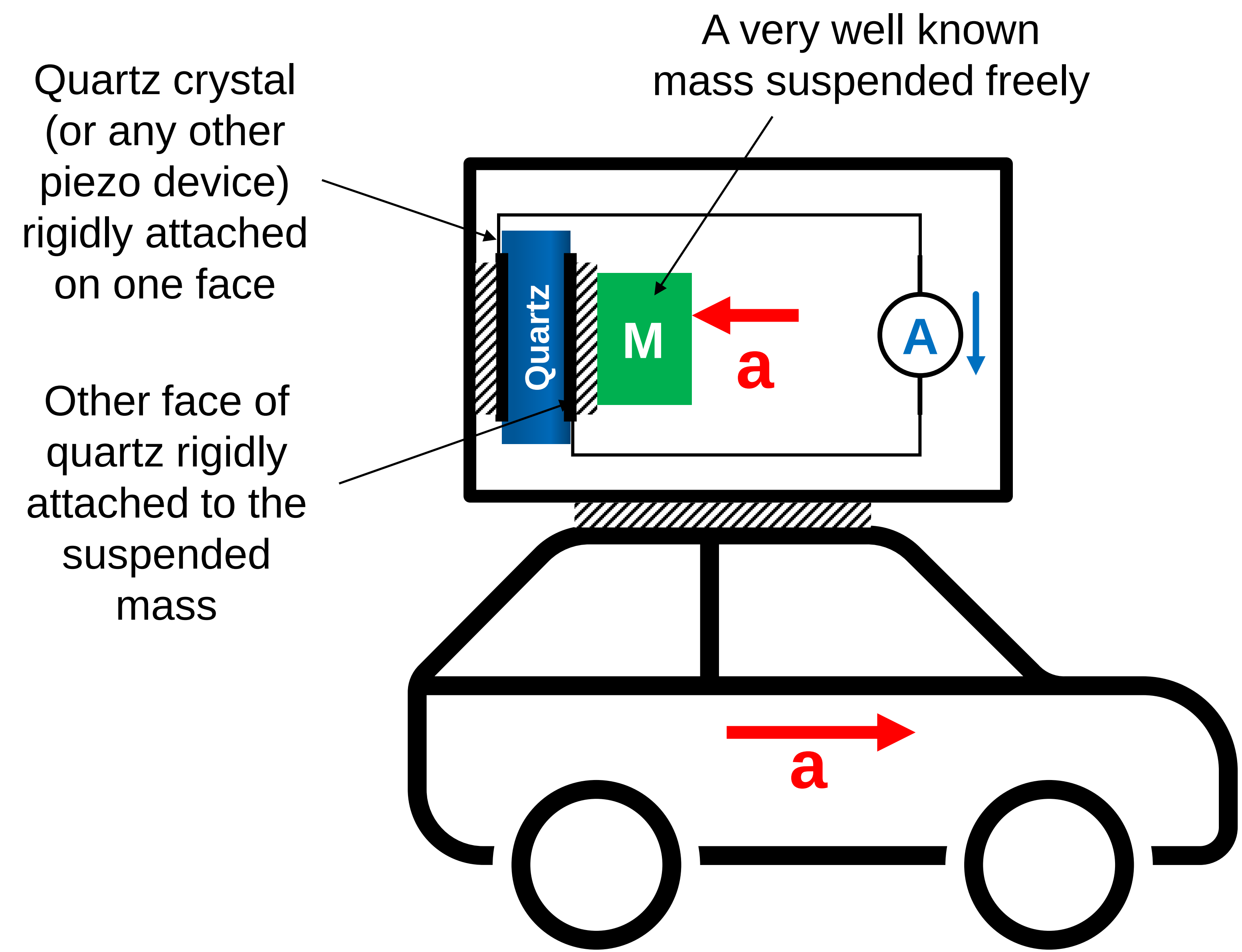
This allows us to measure force in terms of electricity

Let us see how we do this



Jacques & Pierre Curie, French physicist brothers discovered piezoelectricity in 1880. Pierre is the same guy who won the Nobel prize with wife Marie Sklodowska-Curie for radiation

Piezoelectric effect of Quartz



Let us find a relation between acceleration and current

$$Q \propto F$$

$$Q = k_1 F$$

$$Q = k_1 M a$$

Differentiating both sides with respect to time

$$\frac{dQ}{dt} = k_1 M \frac{da}{dt}$$

We know current is rate of movement of charge

$$i = k_1 M \frac{da}{dt}$$

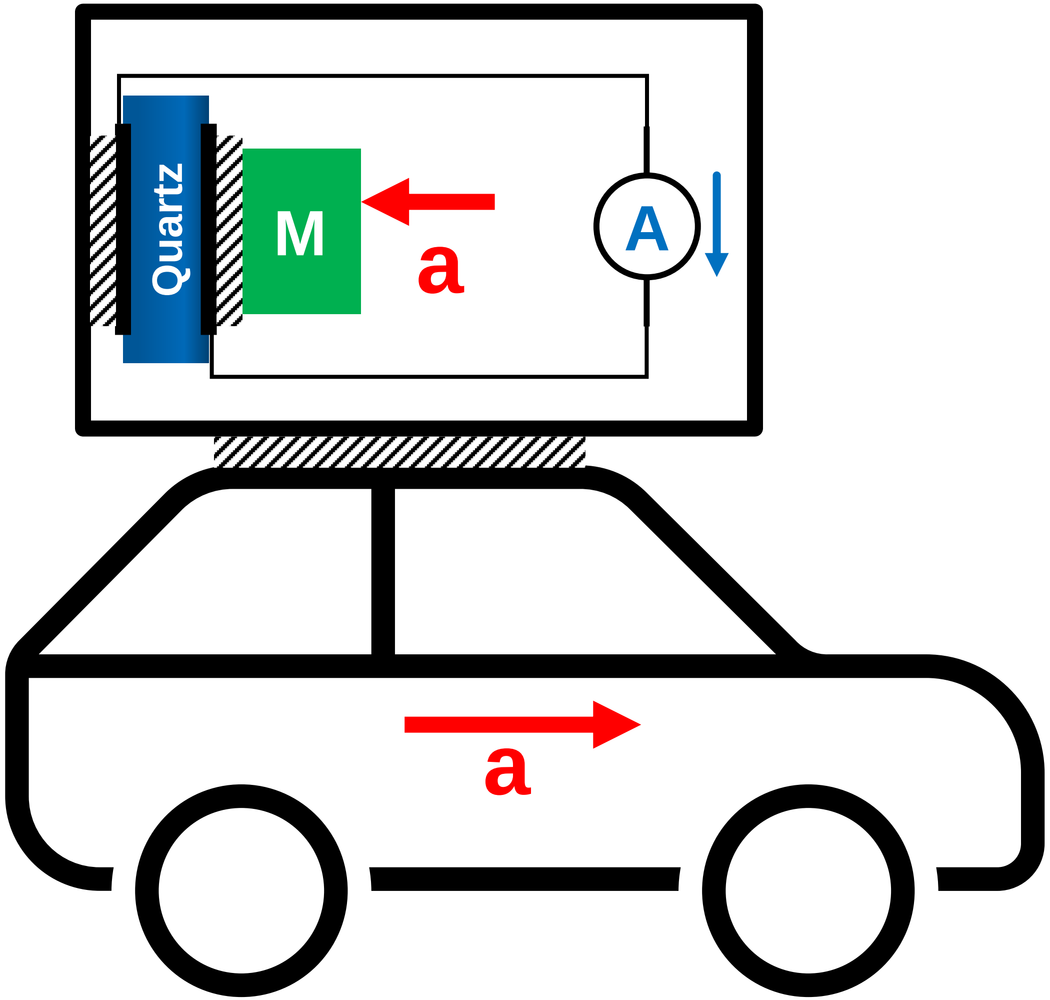
Piezoelectric effect of Quartz

How do we get acceleration signal?

We need to **integrate** the **current signal**

One way is to convert this to a **digital signal** and process it in a computer – but this is too much effort!

Let us try an analog way!



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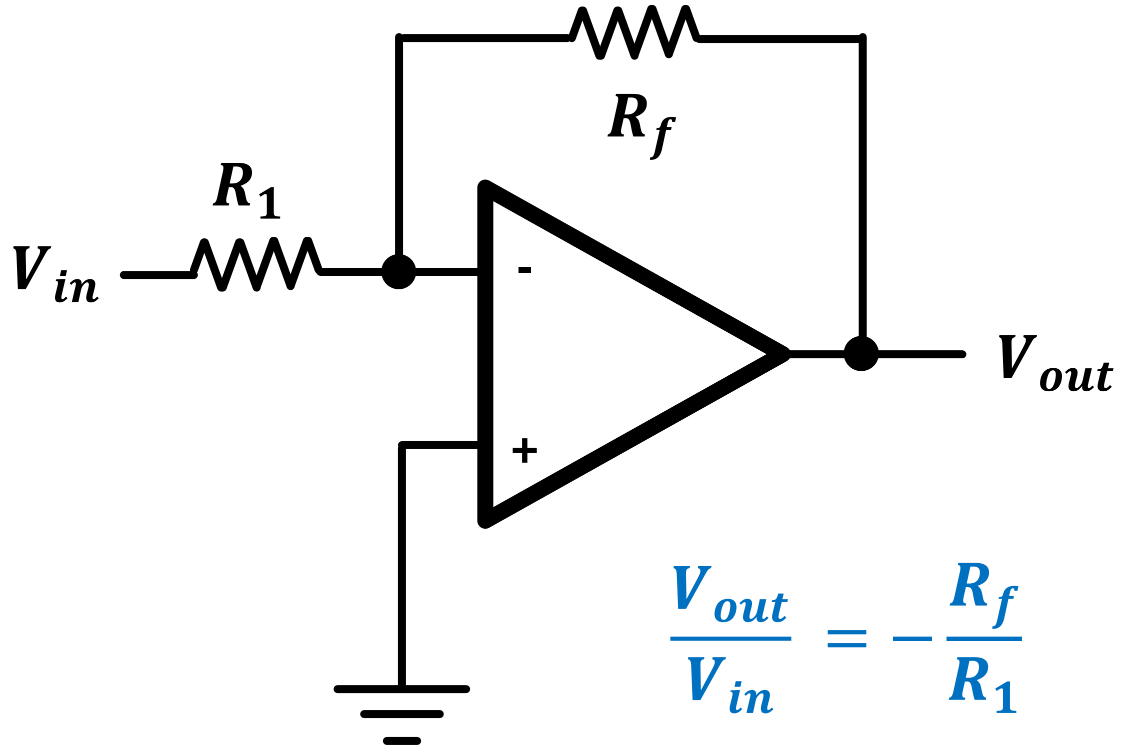
Integrating Amplifier

Recall the Inverting Amplifier



$$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_1}$$

What if we use an energy storing element (like capacitor/inductor) in place of the resistive element in feedback path?

We know that we need to integrate the current signal – this is done by a capacitor

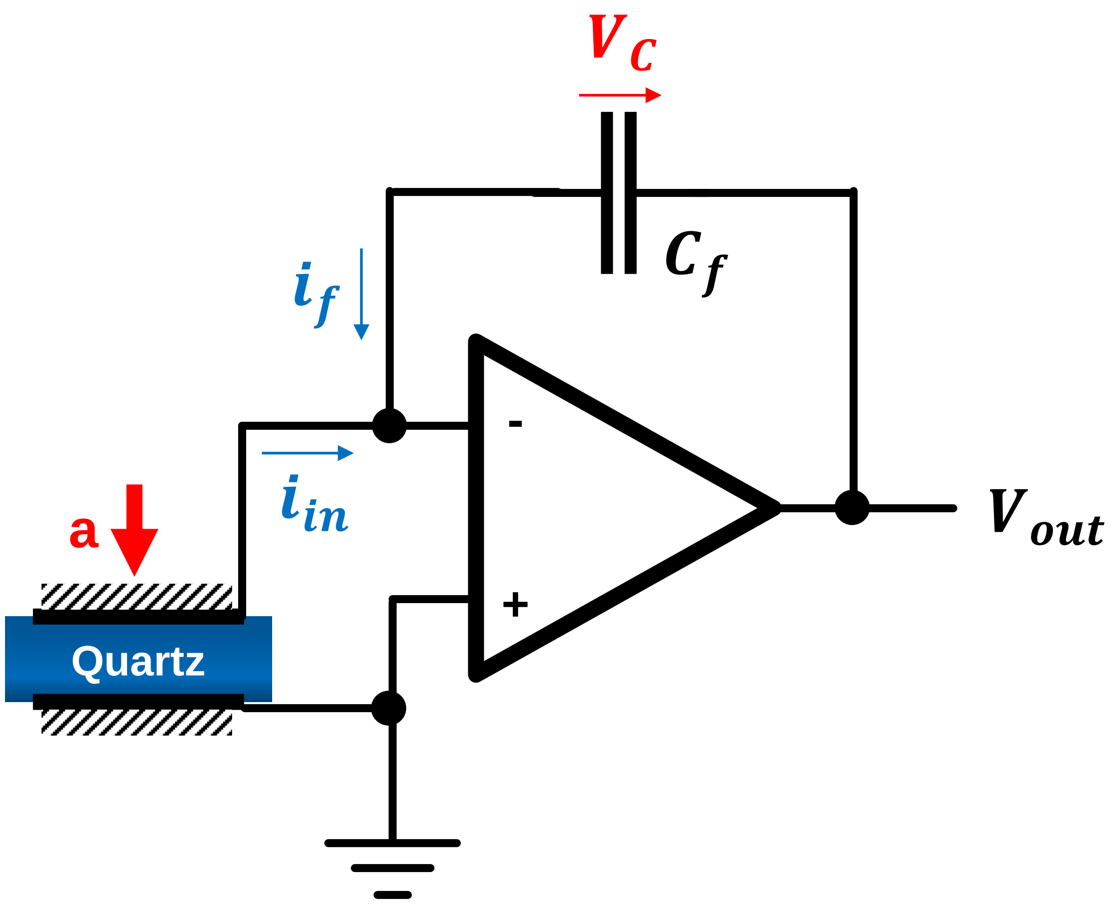
Recalling the Capacitor equation:

$$Q = CV$$

$$\frac{dQ}{dt} = i = C\frac{dV}{dt}$$

Let us replace the $\boldsymbol{V_{in}}$ and $\boldsymbol{R_1}$ at the inverting input with the piezoelectric element, and $\boldsymbol{R_f}$ with a capacitor:

Integrating Amplifier



Let us solve the circuit again like we did for inverting amplifier:

$$V_{out} = A_{OL}(V_+ - V_-)$$

$$V_{out} = A_{OL}(0 - V_-)$$

$$V_{out} = -A_{OL}V_-$$

But we can calculate V_- from the current:

$$V_- = V_{out} - V_C$$

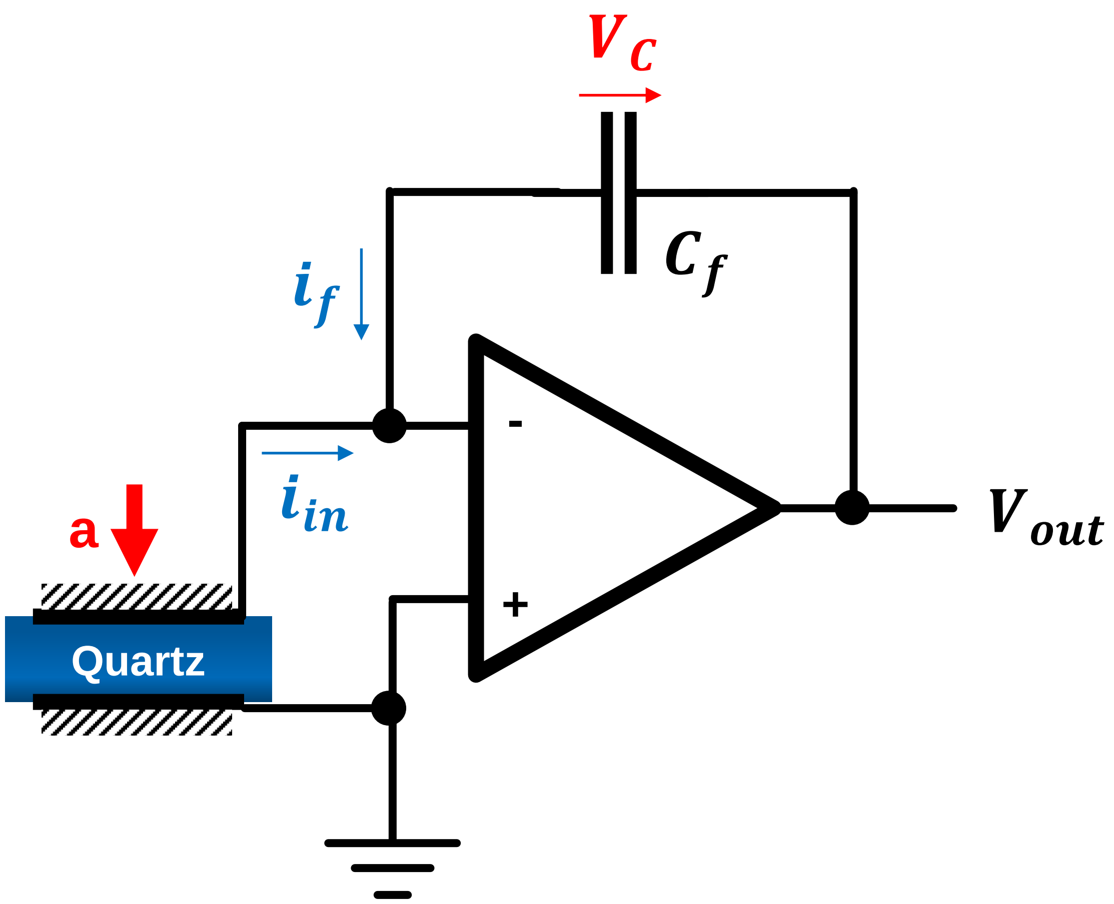
As input resistance of op amp is ∞:

$$i_f = -i_{in} = -k_1 M \frac{da}{dt}$$

From the capacitor equation:

$$\boldsymbol{i_f = C_f \frac{dV_C}{dt} = -k_1 M \frac{da}{dt}}$$

Integrating Amplifier



- $V_{out} = -A_{OL}V_{-}$
- $V_{-} = V_{out} - V_C$

$$i_f = C_f \frac{dV_C}{dt} = -k_1 M \frac{da}{dt}$$

Integrating both sides w/r/t time:

$$C_f V_C = -k_1 M a$$

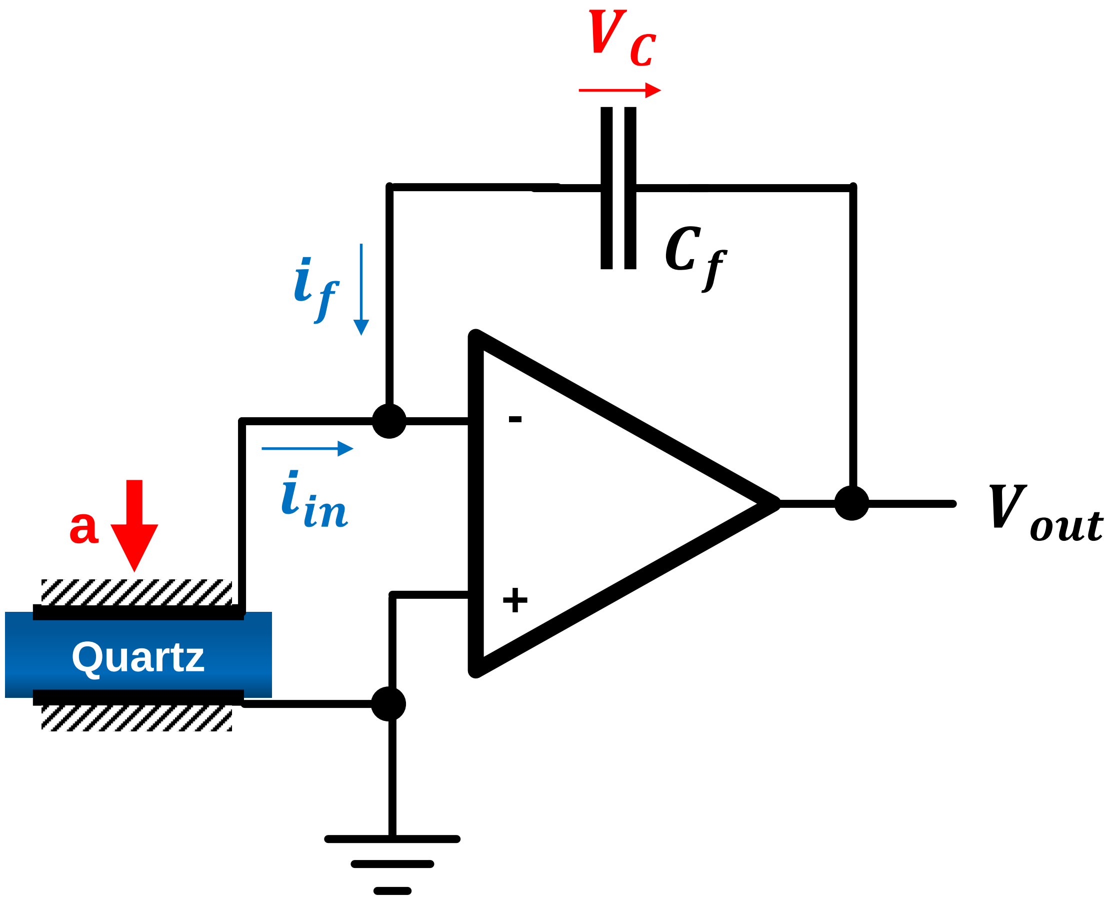
$$\boldsymbol{V_C = -\frac{k_1 M}{C_f} a}$$

Applying this relation to resolve for output

$$V_{out} = -A_{OL}(V_{out} - V_C)$$

$$\boldsymbol{V_C = -V_{out}\frac{(1 + A_{OL})}{A_{OL}}}$$

Integrating Amplifier



$$V_C = -V_{out}\frac{(1 + A_{OL})}{A_{OL}}$$

As $A_{OL} \gg 1$:

$$V_C = -V_{out}\frac{(A_{OL})}{A_{OL}}$$

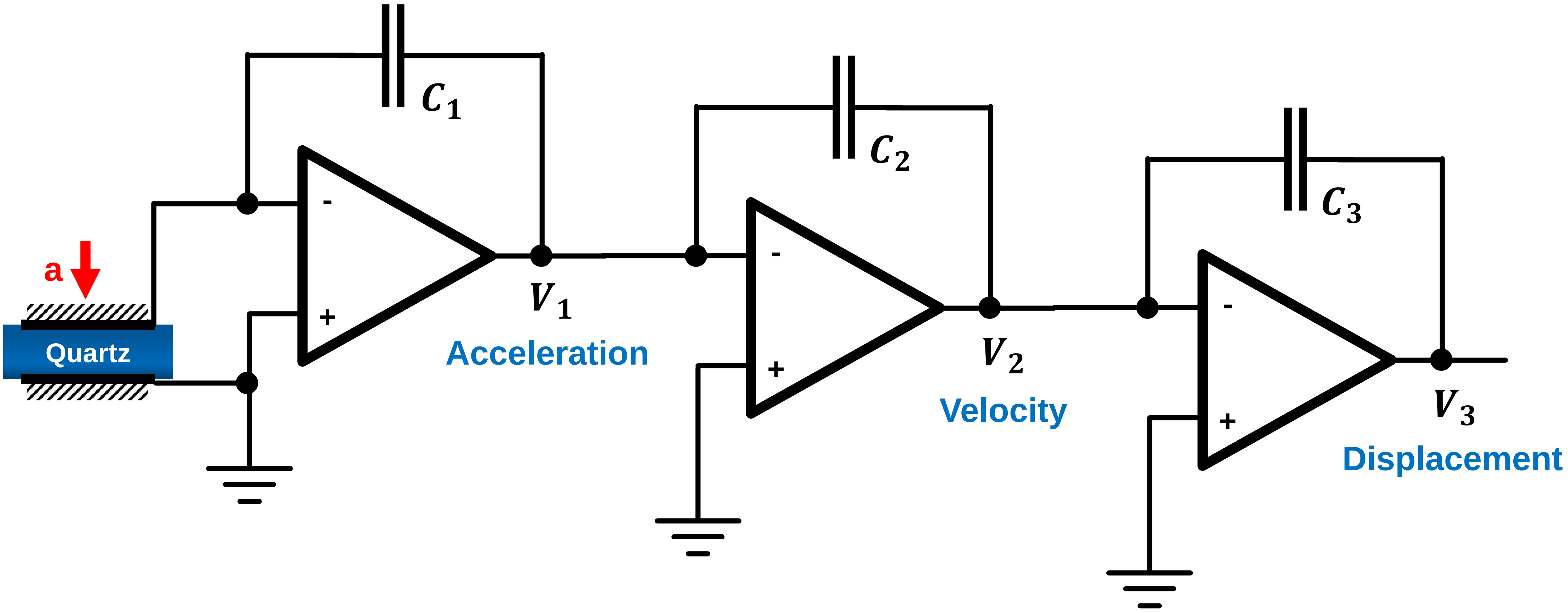
$$V_C = -V_{out}$$

$$-\frac{k_1 M}{C_f}a = -V_{out}$$

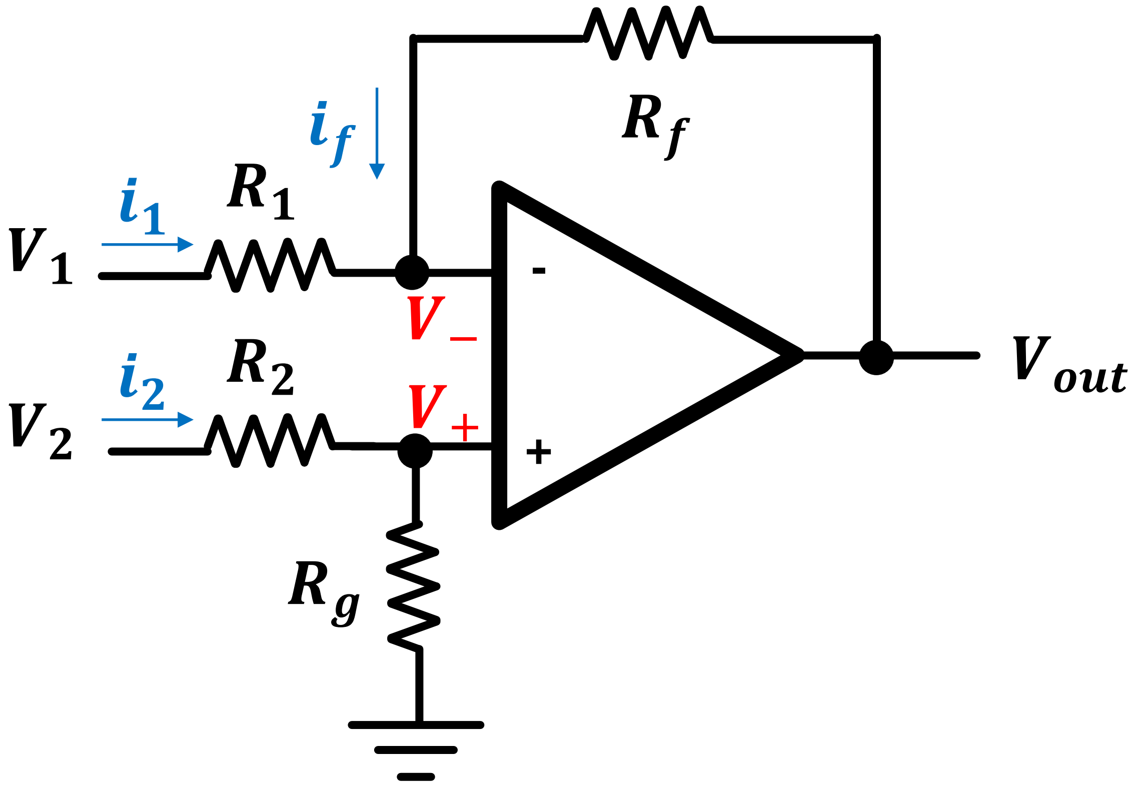
$$V_{out} = \frac{k_1 M}{C_f}a$$

Integrating Amplifier

We can stack multiple integrators to get velocity and displacement



Differencing Amplifier

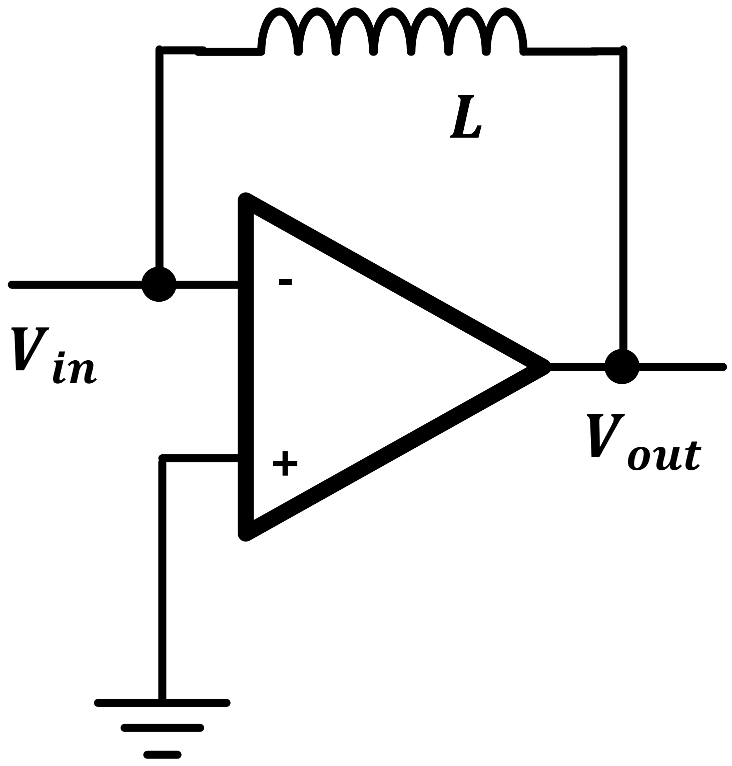


- $V_1 - V_- = i_1 R_1$
- $V_{out} - V_- = i_f R_f$
- $V_+ = \frac{R_g}{R_2+R_g} V_2$
- $A_{OL}(V_+ - V_-) = V_{out}$

- $i_1 = -i_f$
  - $\frac{V_1 - V_-}{R_1} = -\frac{V_- - V_{out}}{R_f}$
  - $V_- = \frac{V_1 R_f + V_{out} R_1}{R_f + R_1}$
- $A_{OL}(V_+ - V_-) = V_{out}$
  - $A_{OL}\left(\frac{R_g}{R_2+R_g} V_2 - \frac{V_1 R_f + V_{out} R_1}{R_f + R_1}\right) = V_{out}$

$$V_{out}\left(\frac{R_1}{R_1+R_f}\right) = V_2\left(\frac{R_g}{R_2+R_g}\right) - V_1\left(\frac{R_f}{R_1+R_f}\right)$$

Differencing Amplifier



You have learnt how to do integration operation using a capacitor in the feedback circuit

What would happen if you replace the capacitor with an inductor?

Recall that capacitor and inductor do exactly opposite things

Does this mean you can do derivative operation using op amp in this configuration?

Try solving this circuit on your own

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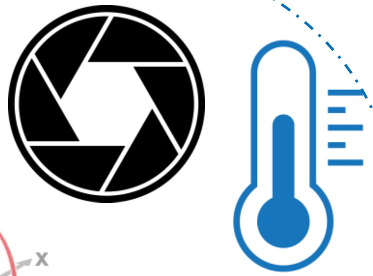
Mechanical ↔ Electrical in Real World

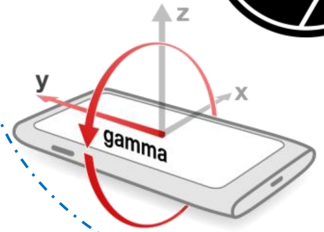
Why do we need to inter-convert between mechanical (force, motion) and electrical (analog, digital) signals?

Physical World

Computer “actuates” by producing movement via force and torque

Digital World





Computer senses physical signals like light, sound, temperature, pressure, movement etc.

Mechanical ↔ Electrical in Real World

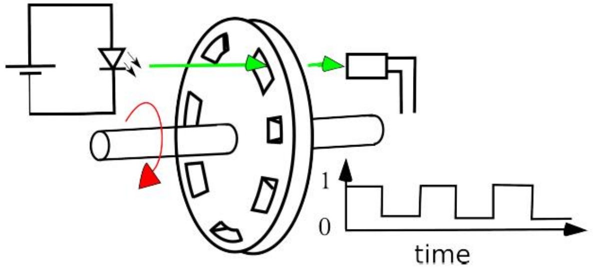
Why do we need to inter-convert between mechanical (force, motion) and electrical (analog, digital) signals?

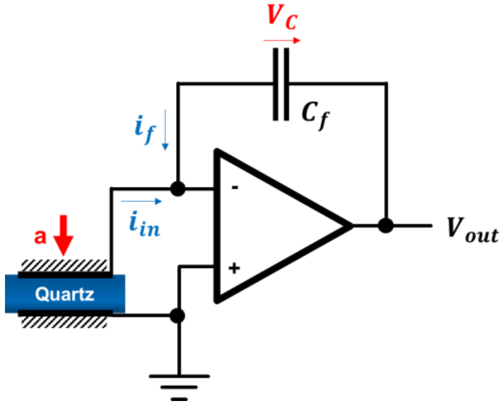
Actuation

- Induction Motor
- Electric relay
- Stepper Motor (we will study later today)

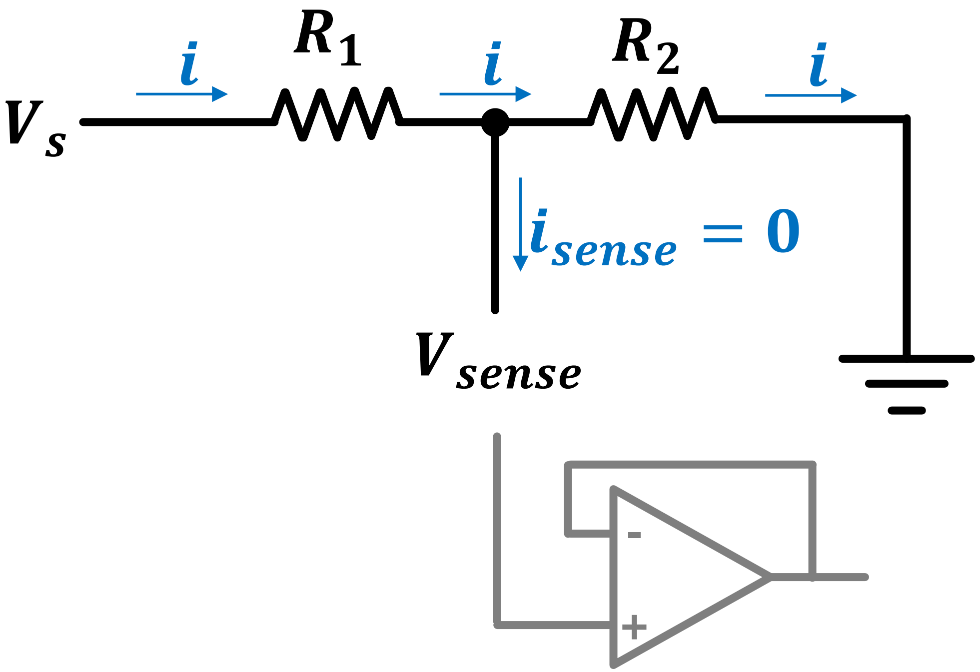
Sensing

- Shaft Encoder
- Piezoelectric acceleration sensor
- Accurately measuring the effect of motion/force on resistance of a material!
  - Potentiometer
  - Strain Gauge





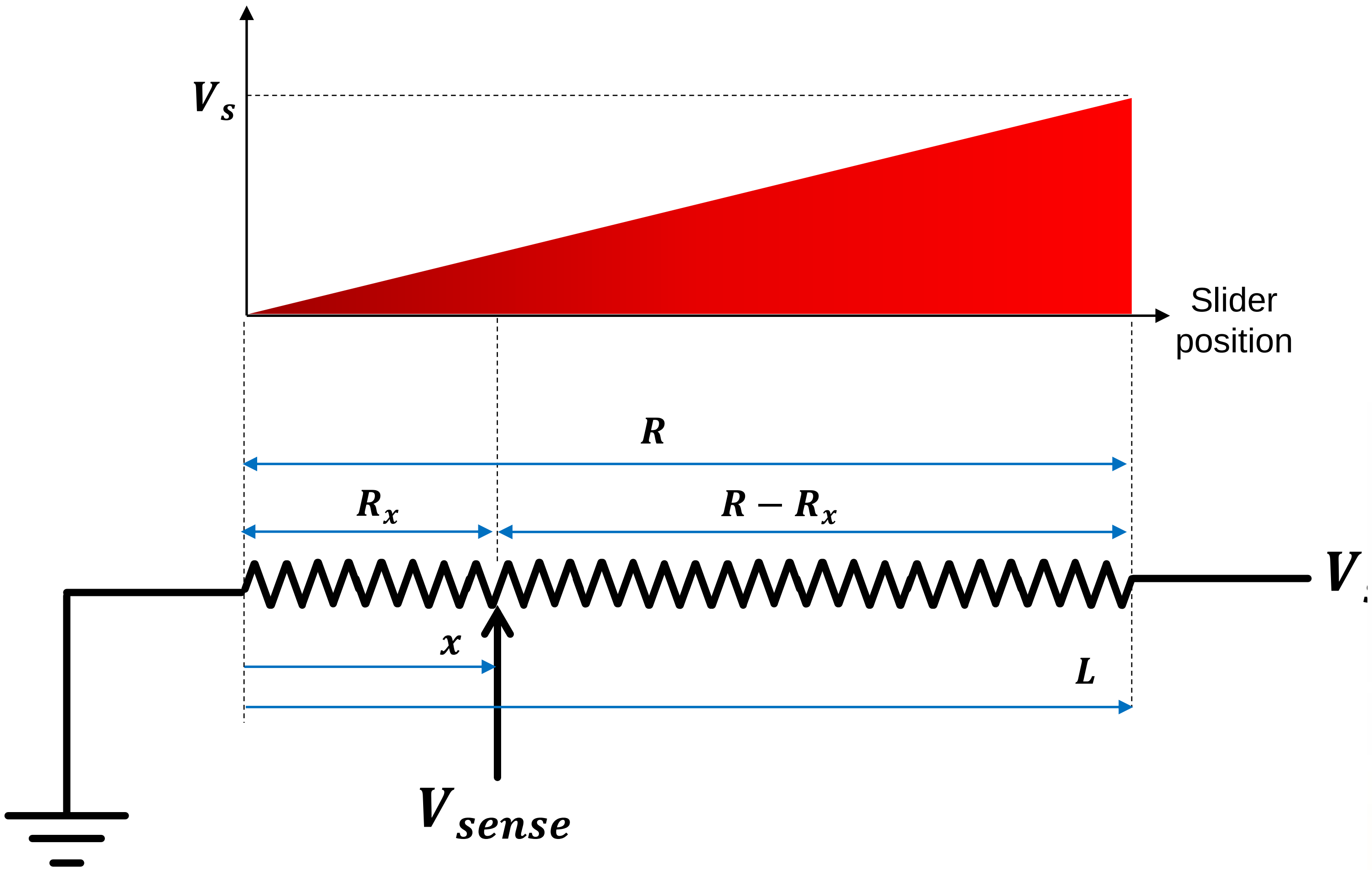
Potentiometer

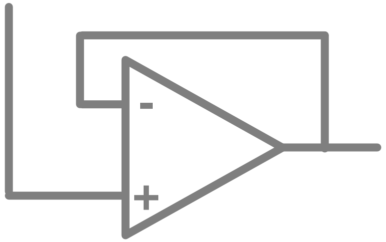


- $i = i$
- $\frac{V_s - V_{sense}}{R_1} = \frac{V_{sense} - 0}{R_2}$
- $R_2 V_s - R_2 V_{sense} = R_1 V_{sense}$
- $R_2 V_s = R_1 V_{sense} + R_2 V_{sense}$
- $R_2 V_s = (R_1 + R_2) V_{sense}$

$$V_{sense} = \frac{R_2}{R_1 + R_2} V_s$$

Potentiometer





$$V_{sense} = \frac{x}{L} V_s$$

Potentiometer is a variable resistance device (also called a Rheostat) is a three-terminal device, two terminals are the top and bottom voltage, and third terminal is the slider contact

Potentiometer

Potentiometer is a variable resistance device (also called a Rheostat) is a three-terminal device, two terminals are the top and bottom voltage, and third terminal is the slider contact

Advantages

- Simple and inexpensive
- Variable DC voltage output directly

Disadvantages

- Relies on mechanical slider, friction causes wear
- Contact resistance at slider is variable, difficult to compensate

Strain Gauge

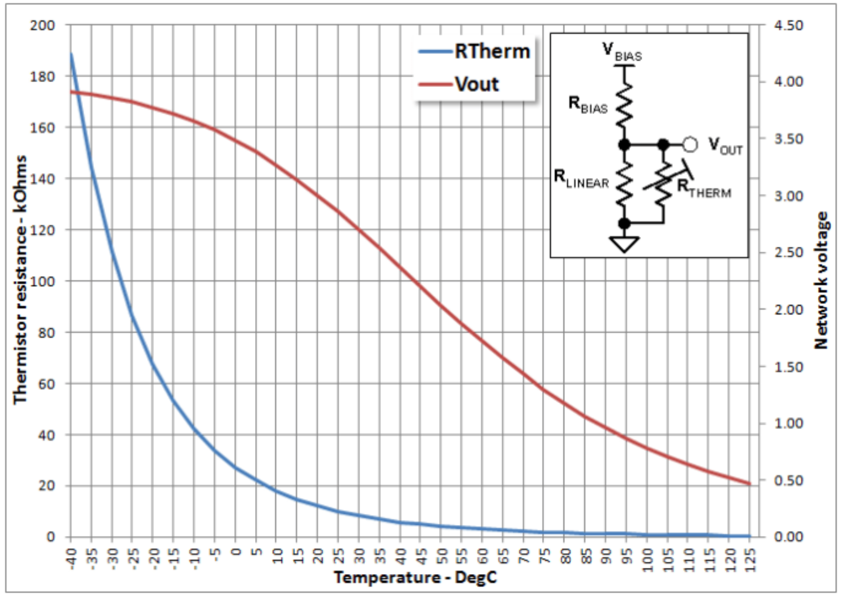
ρ – Resistivity
Varies with the material, it is a function of temperature as well

$$R = \rho \frac{l}{A}$$

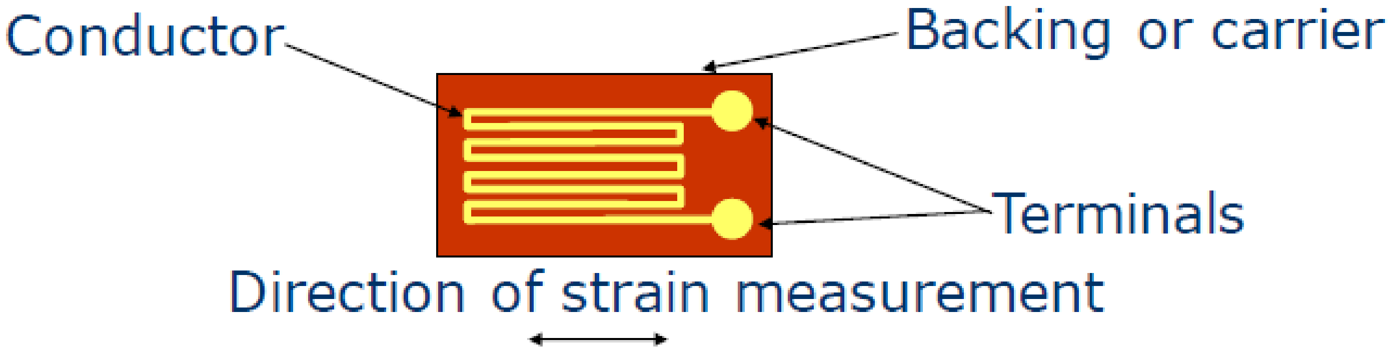
l – Length of conductor
If you double the length, you double the resistance

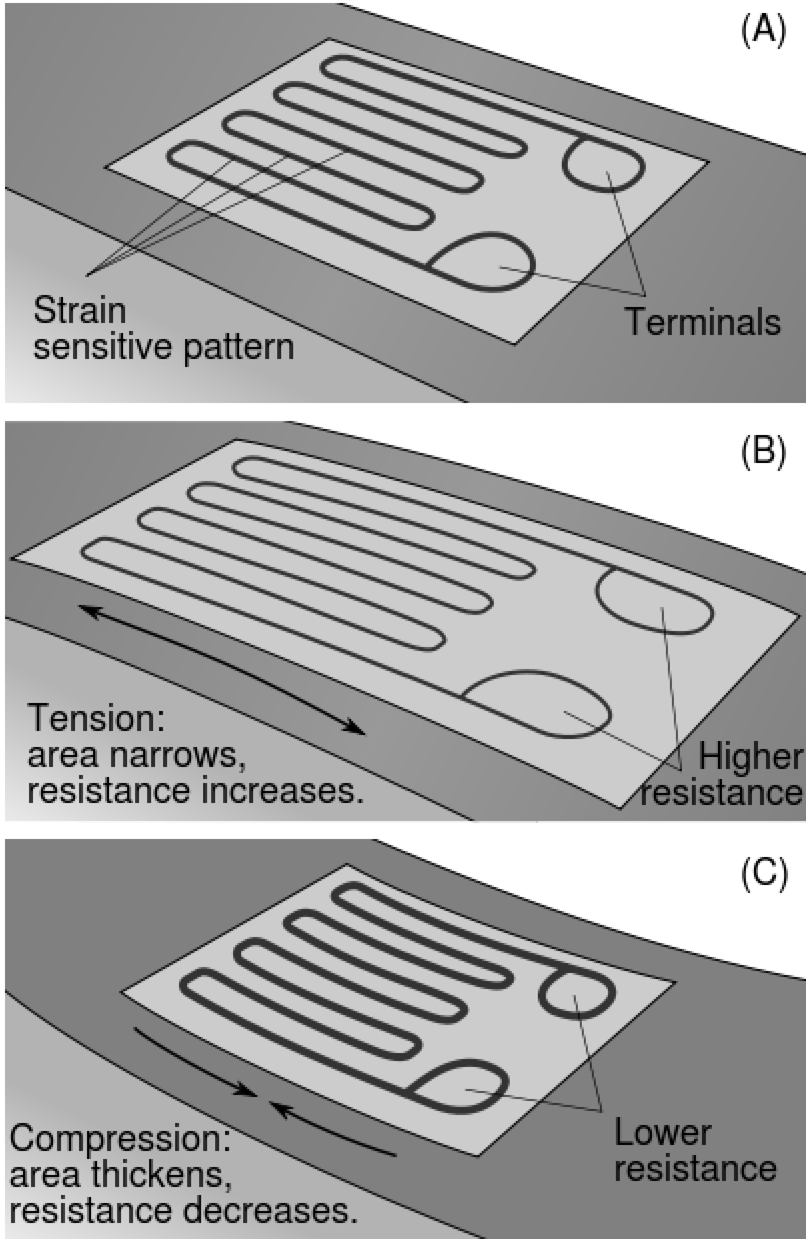
A – Cross-Sectional Area of conductor
If you double the Area, you halve the resistance

Resistivities	
Material	Resistivity ρ (Ω·m)
Insulators	
Teflon	1.0×10^{23}
Quartz	7.5×10^{17}
Rubber	7.5×10^{17}
Glass	7.5×10^{17}
Conductors	
Nichrome alloy	1.6×10^{-6}
Lead	2.2×10^{-7}
Iron	9.7×10^{-8}
Tungsten	9.7×10^{-8}
Aluminium	2.7×10^{-8}
Gold	2.2×10^{-8}
Copper	1.7×10^{-8}
Silver	1.6×10^{-8}
Graphene	1.0×10^{-8}



Strain Gauge





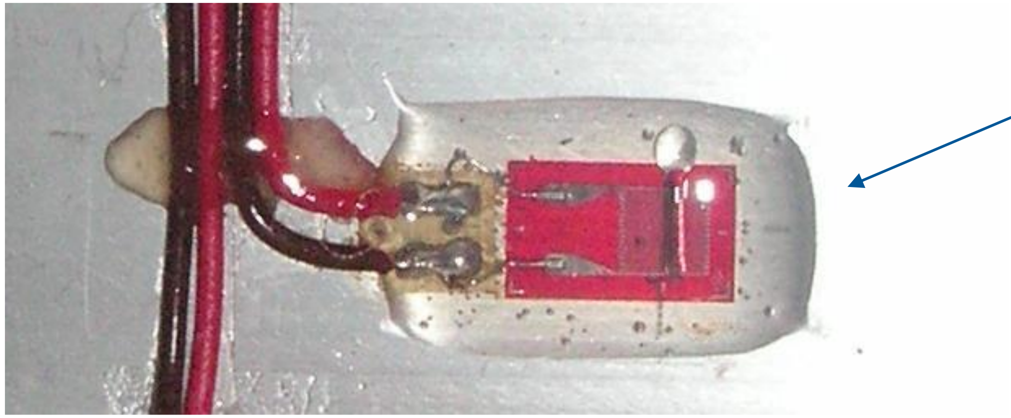
Essentially, when you **stretch** a conductor, you make it thinner and longer, i.e., **increasing** the resistance

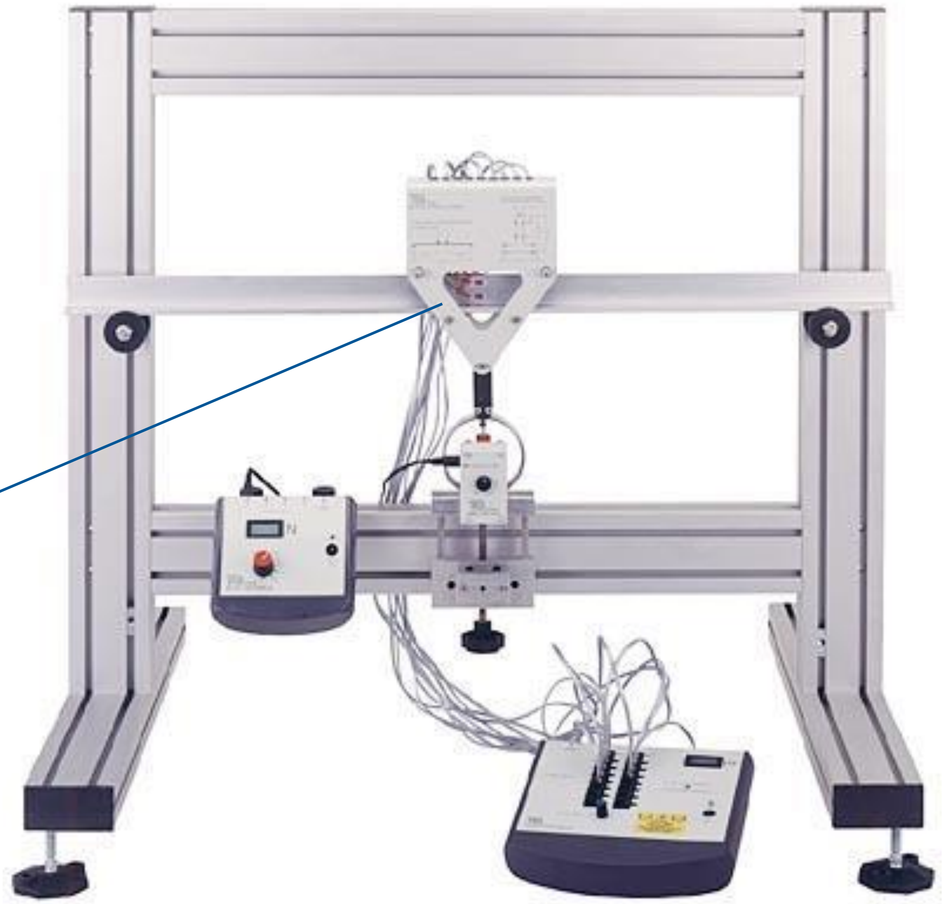
When you **compress**, you make it thicker and shorter, i.e., **reducing** the resistance

All you need to do now, is to measure the CHANGE in resistance!

Strain Gauge

You used this a year ago in your beam bending lab!

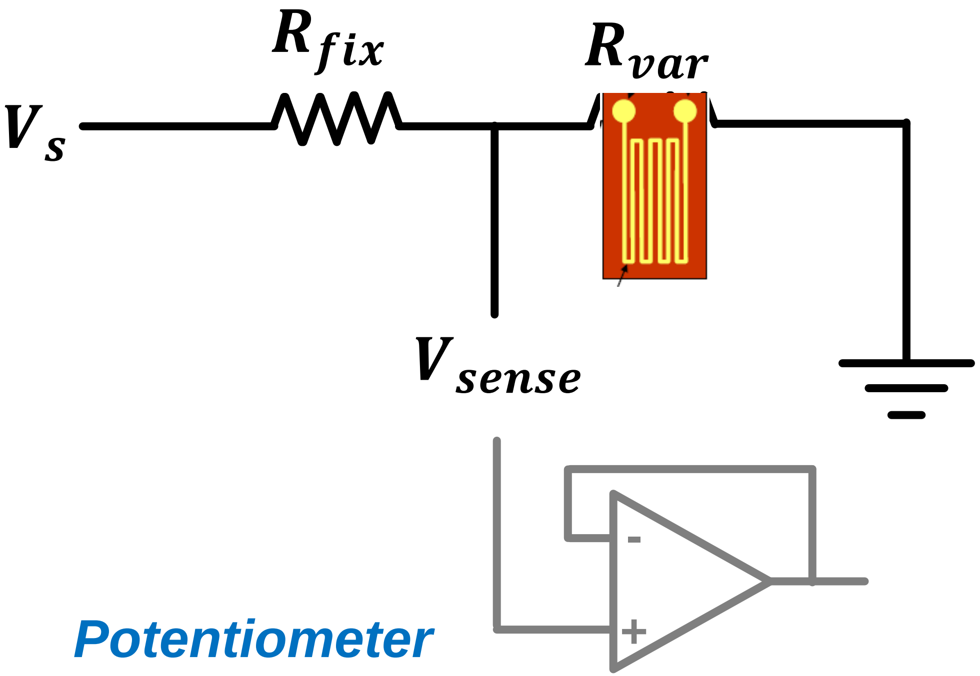




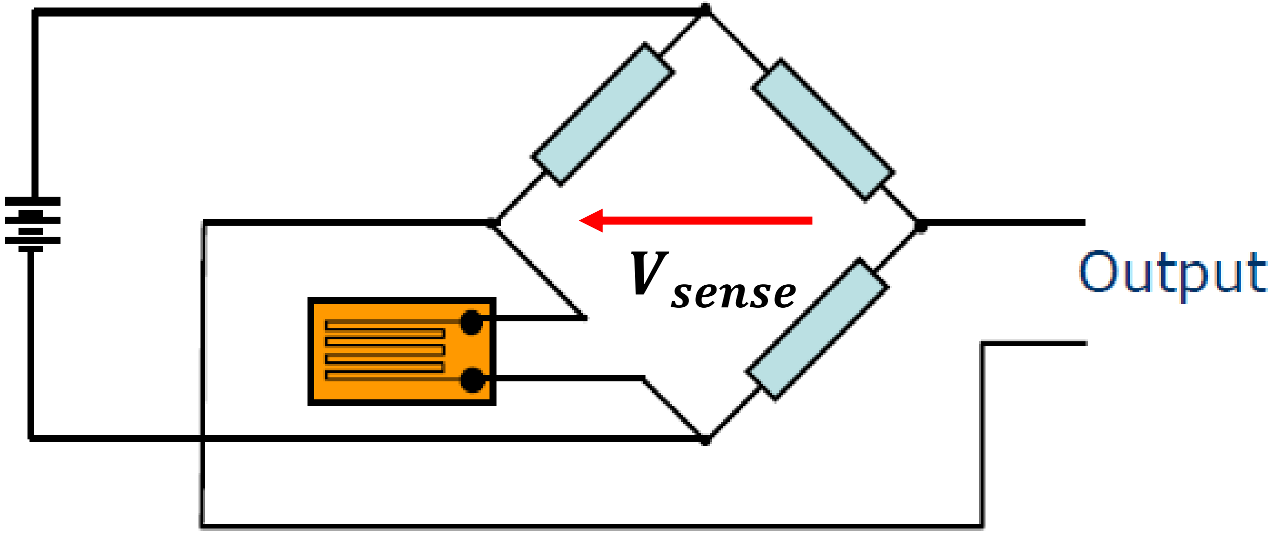
But how do we measure resistance?

We can simply apply a fixed-known voltage and measure the current!

But, measuring current is difficult and expense, measuring voltage isn't!

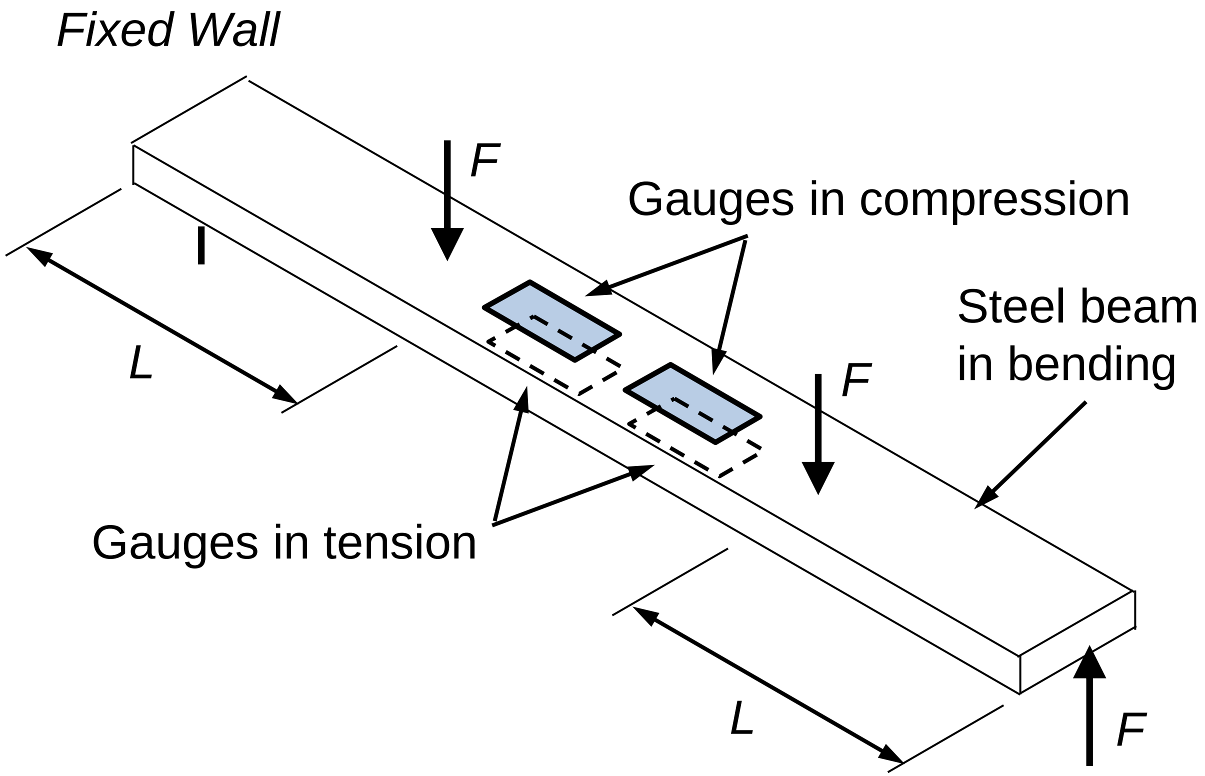


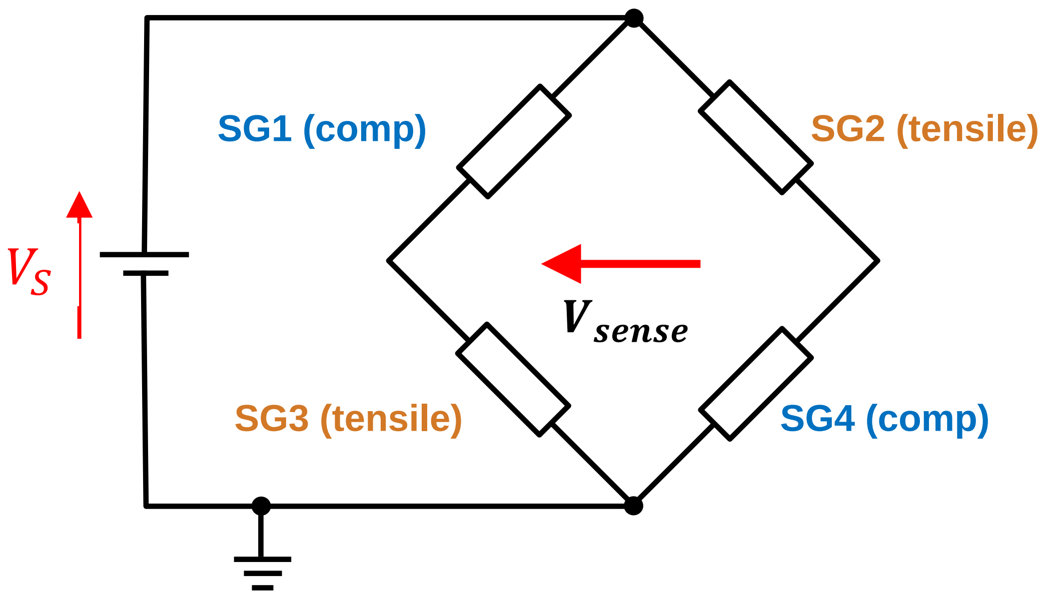
Potentiometer



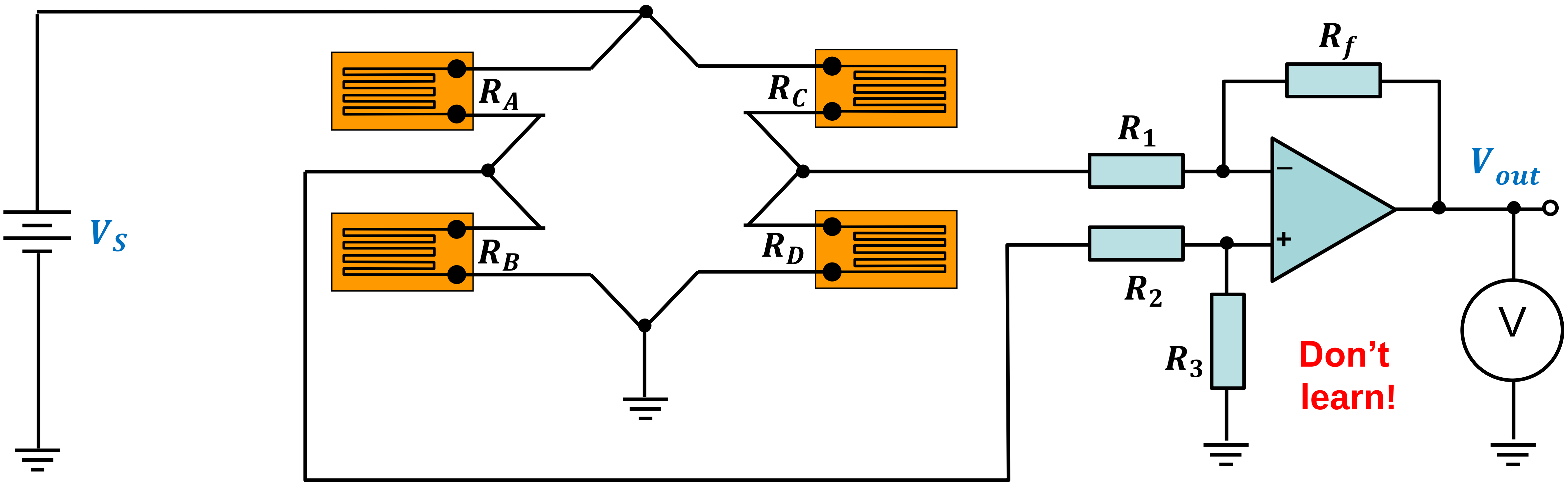
Wheatstone Bridge

A way to increase Sensitivity



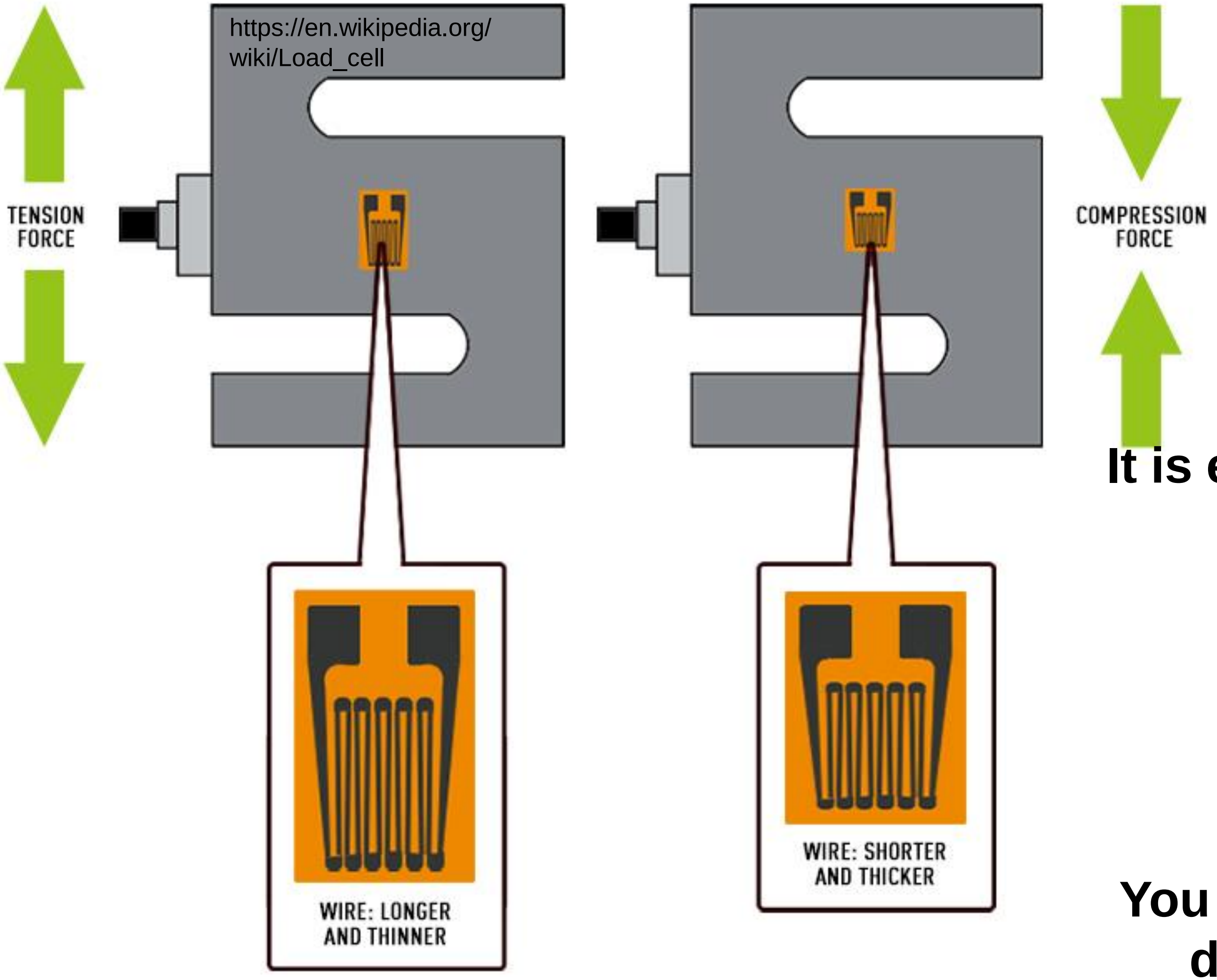


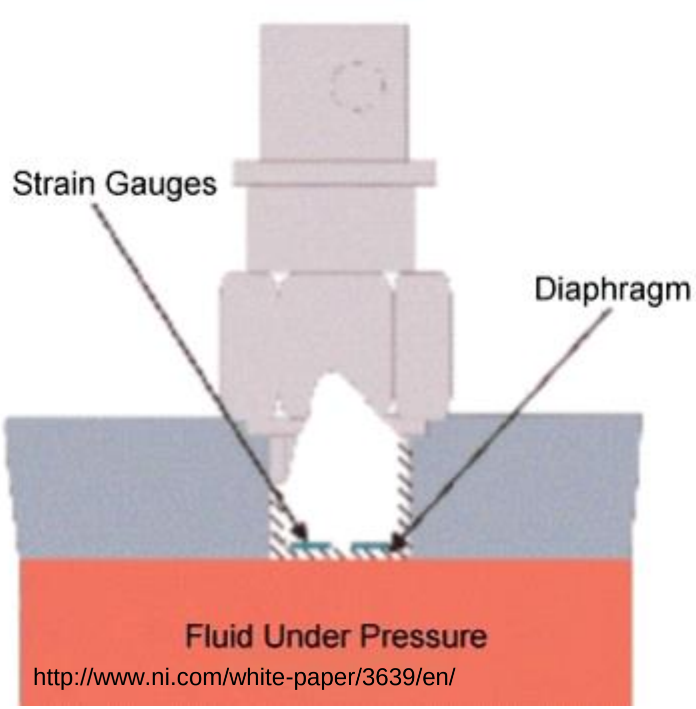
A way to increase Sensitivity



Can you find out the relationship between the strain and voltage output? Homework!

Strain Gauge





It is essentially a Spring!

$$\boldsymbol{F = kx}$$

$$\boldsymbol{R = \rho \frac{l}{A}}$$

You measure R, deduce x, deduce F

http://www.firstsensor.com.cn/Product/`

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- **Stepper Motor**

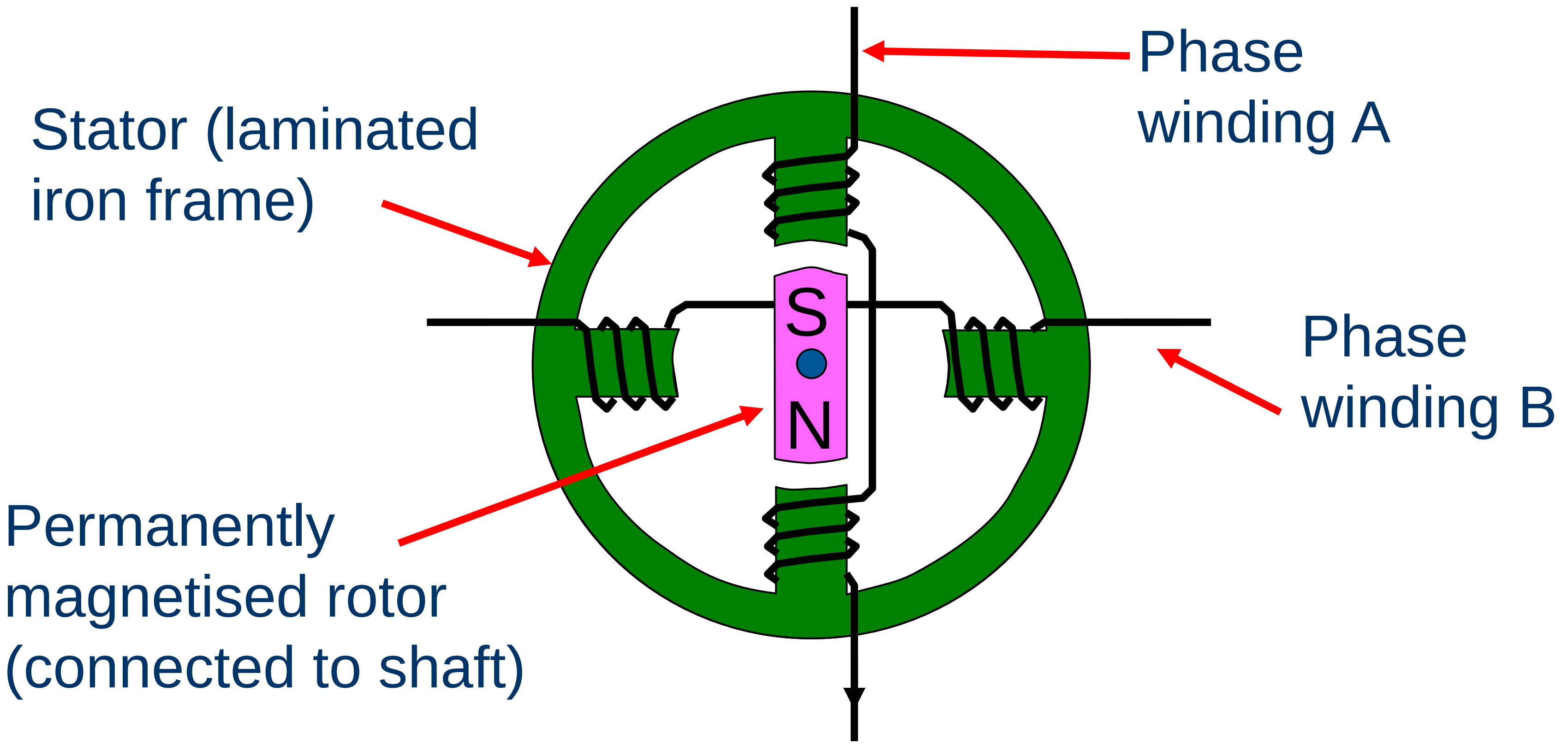
Another kind of motor with similar concept

- Student projects sometimes use **stepper motors** for positioning
- We'll look at them briefly now as they also use something like the **rotating magnetic field**
- Will see these also in **electronics lab**

Stepper motors: basic introduction

- Simple and convenient way of providing precise movement
- They are used in a wide variety of applications including:
  - Computer peripherals
  - Laboratory equipment
  - Student projects

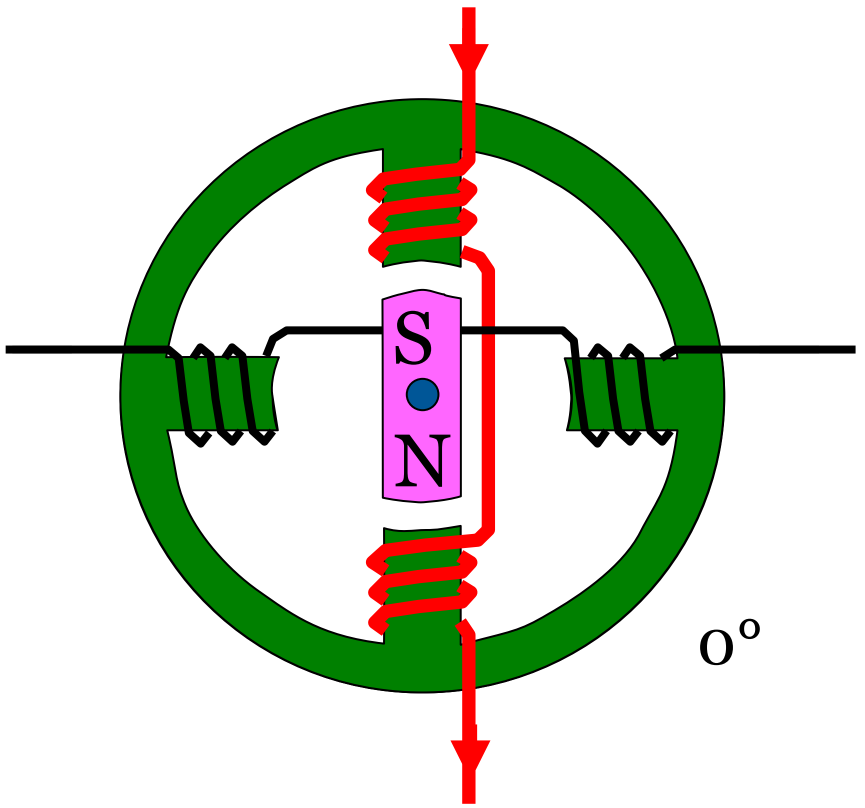
Simplified diagram of a permanent-magnet stepper motor



How a stepper motor works

- Rotor is (usually) permanently magnetised
- Attracted to a different pair of poles at each step
- Moves from pole to pole as each pair of poles is energised
- So it moves in a series of steps

How a stepper motor works



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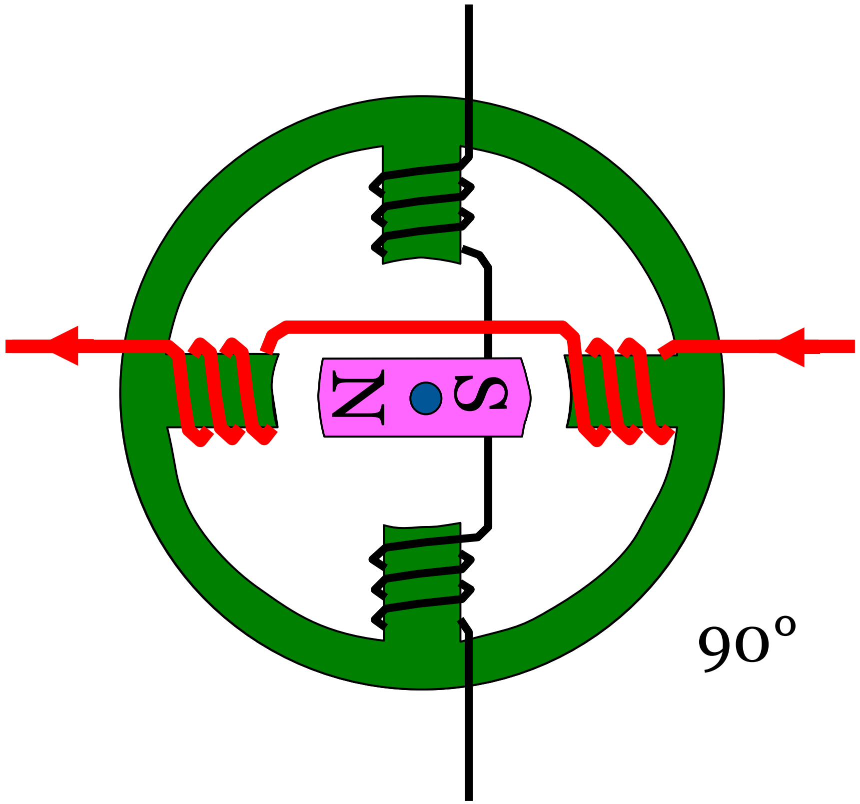

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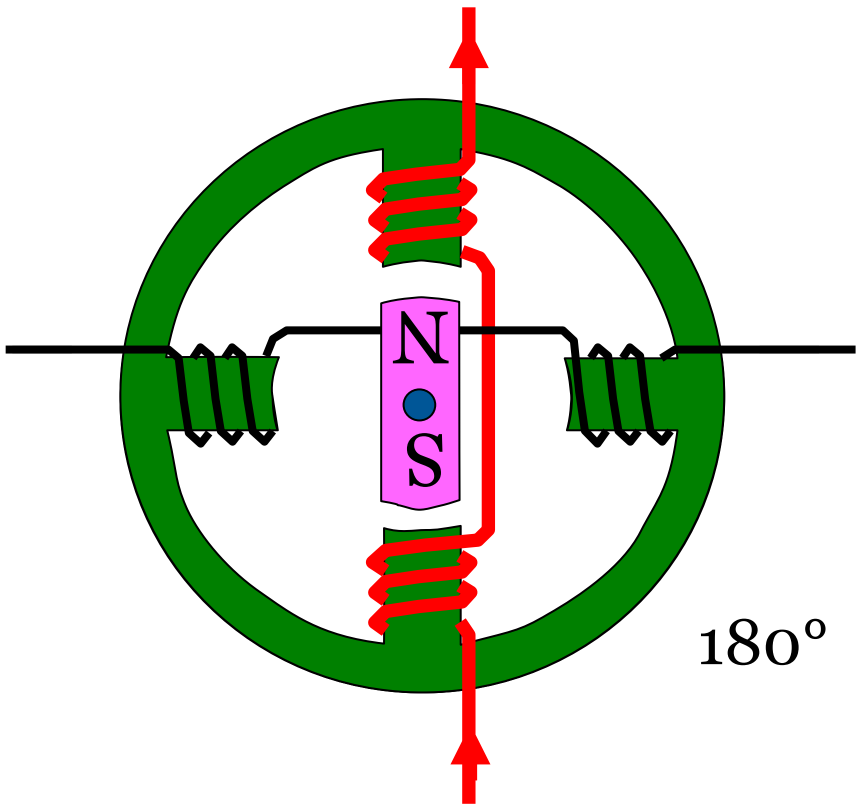

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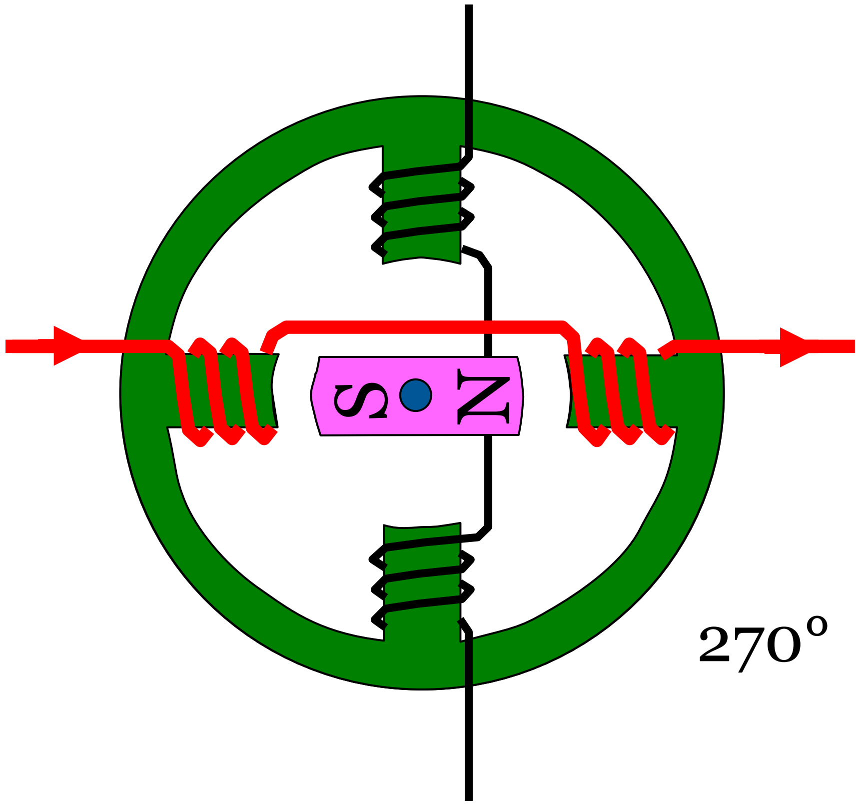

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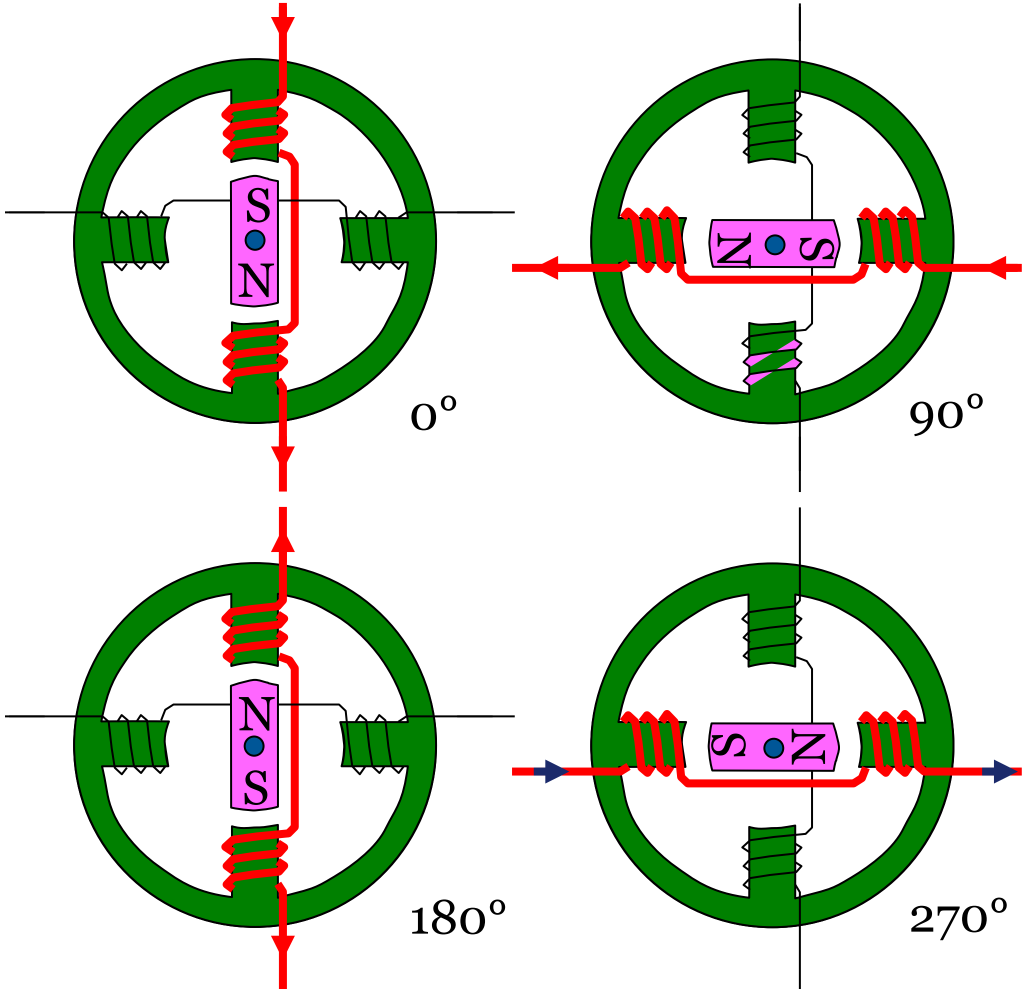
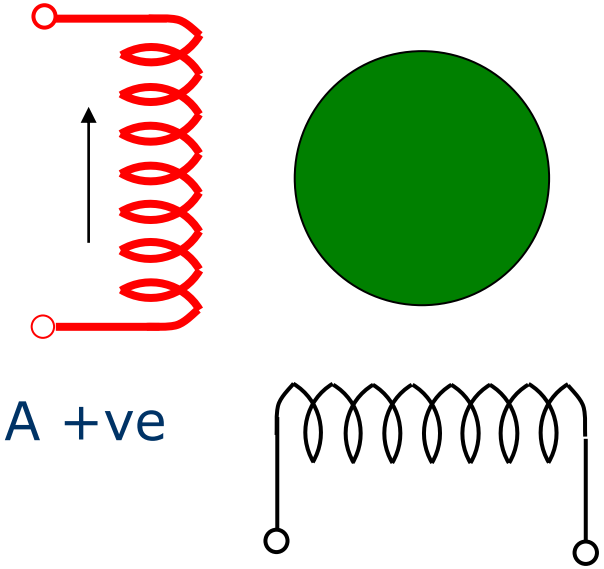
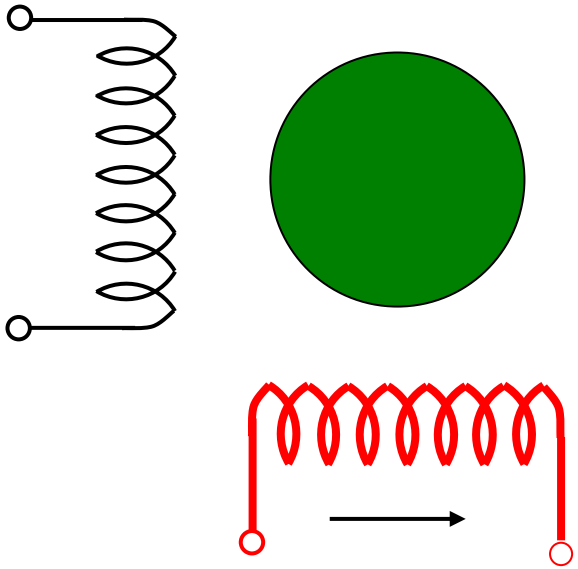


Need a method of switching windings in either direction



Phase A +ve

Need a method of switching windings in either direction



Phase B +ve

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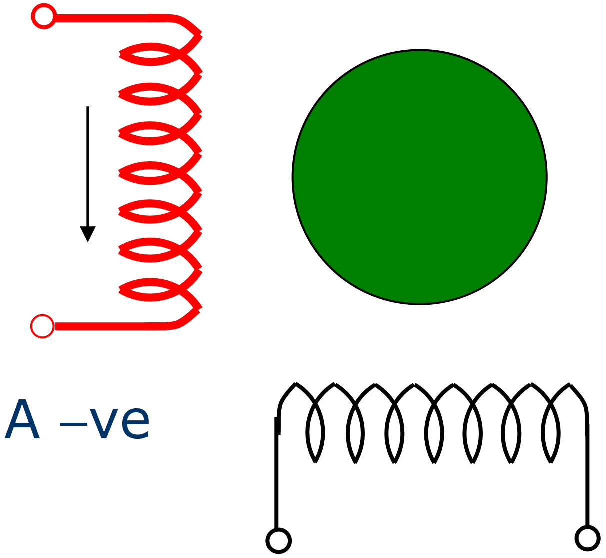

Phase A –ve

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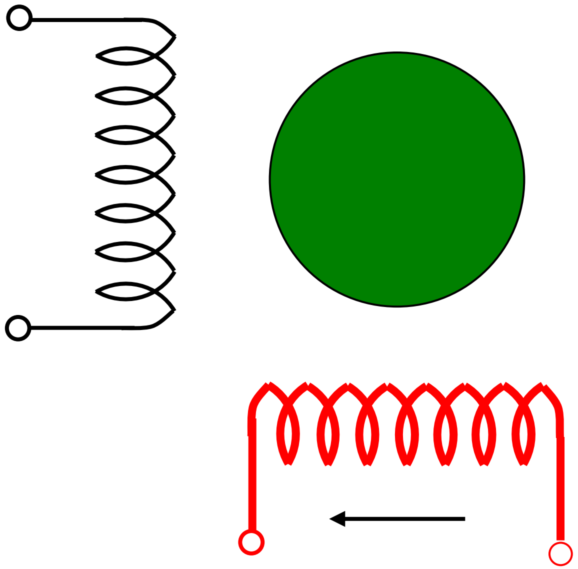
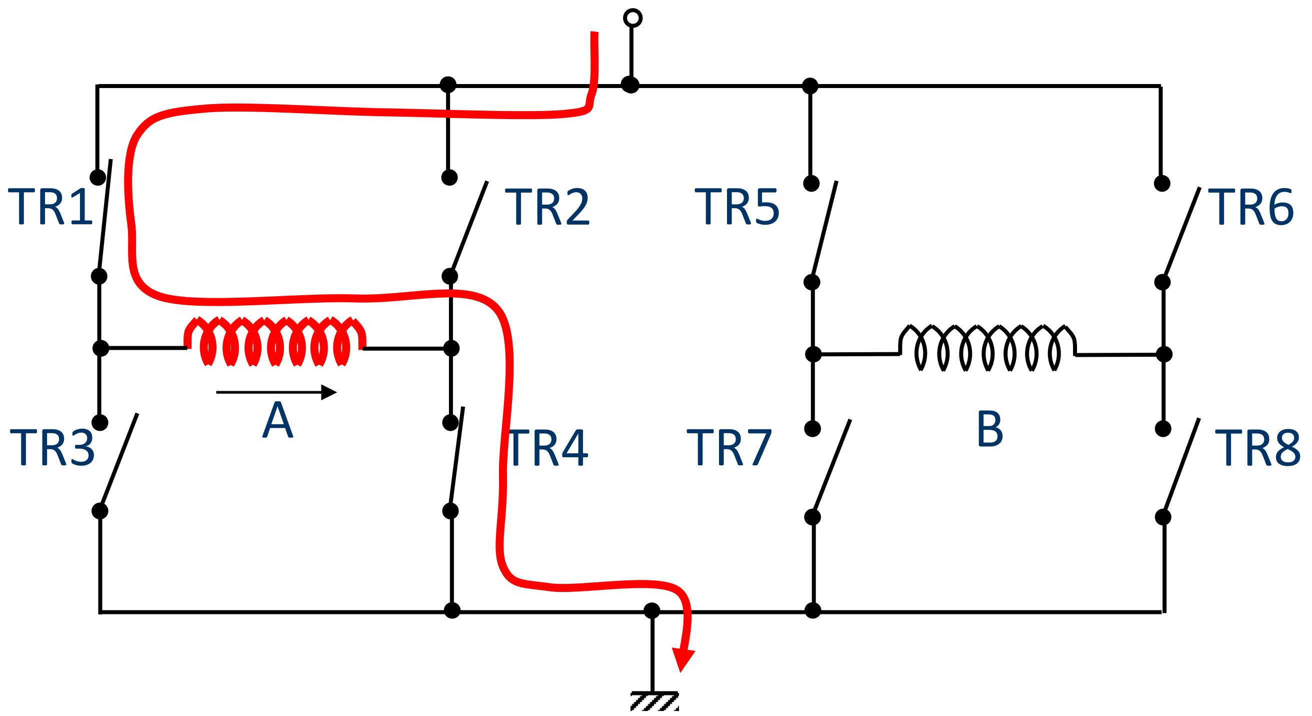


Phase B –ve

What provides the sequenced supply to the windings?

- To make this work we need a circuit with switches we can operate on command of signals
- Note: “switches” are actually **power transistors** or something similar
- Will learn about transistors and their use as switches with Dr MacKenzie

Circuit to switch on windings in either direction



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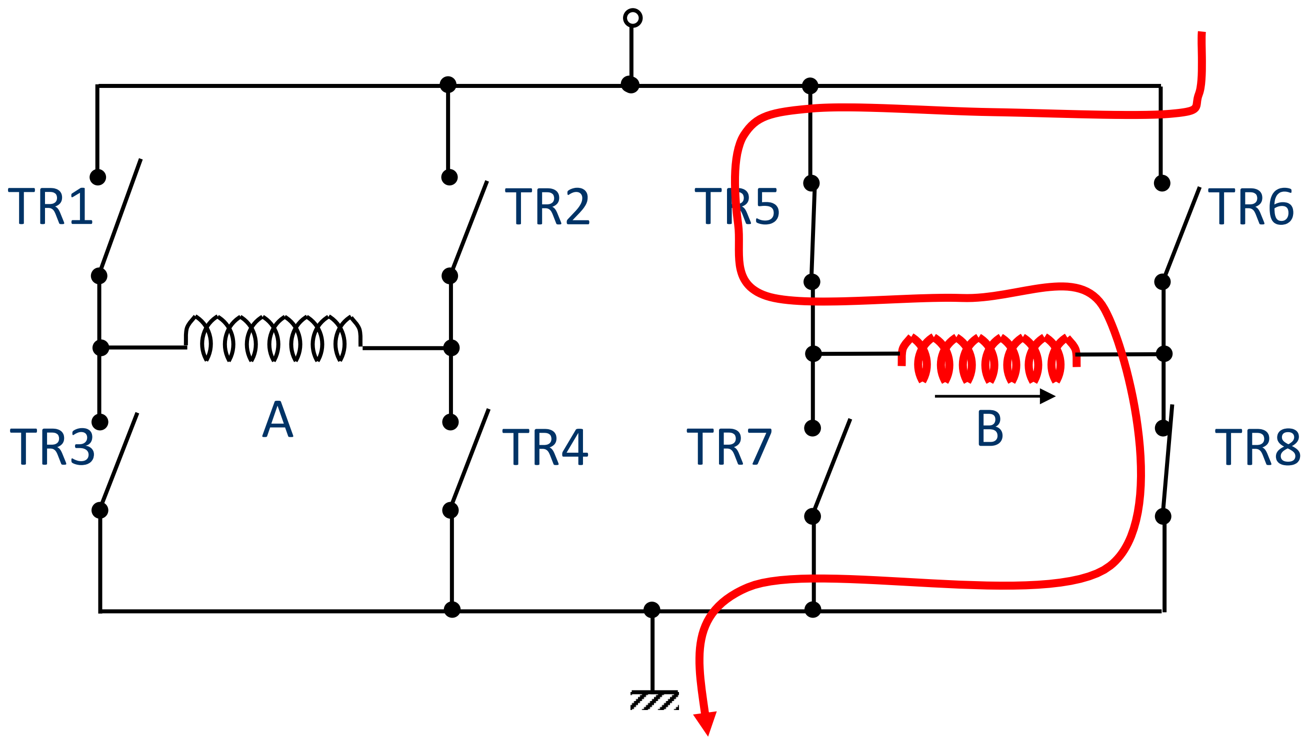

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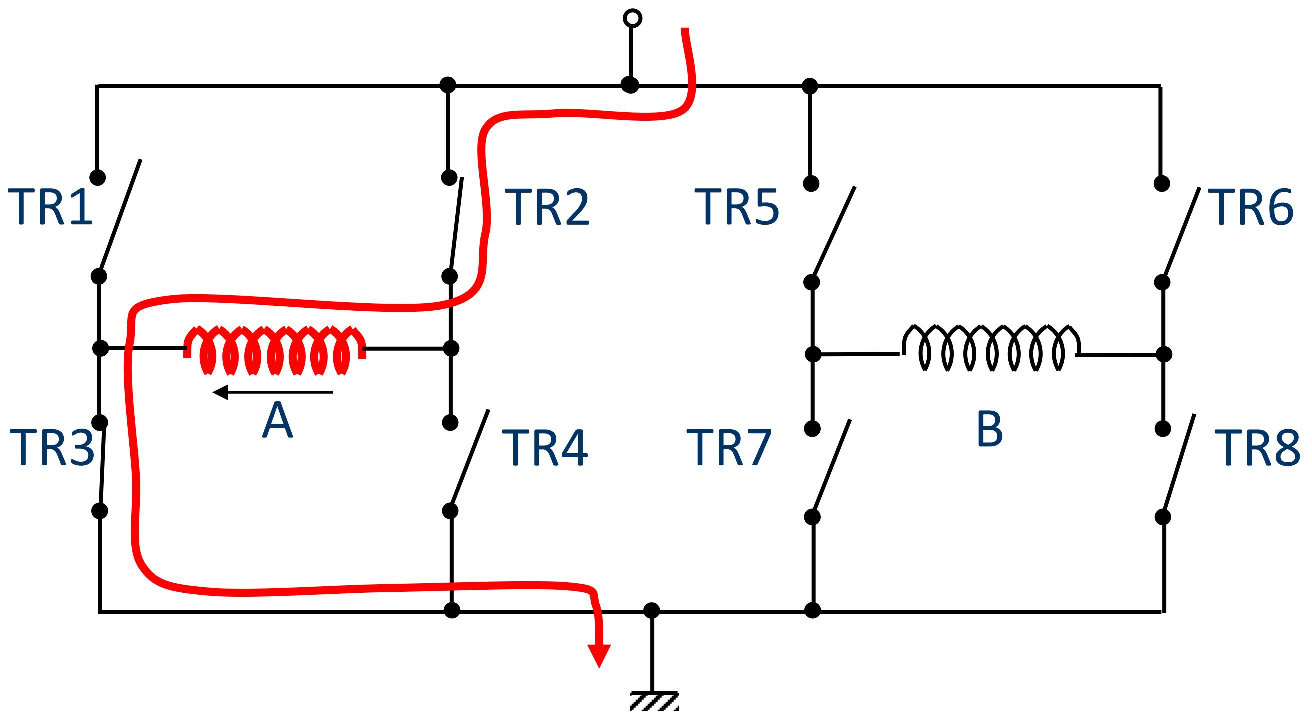

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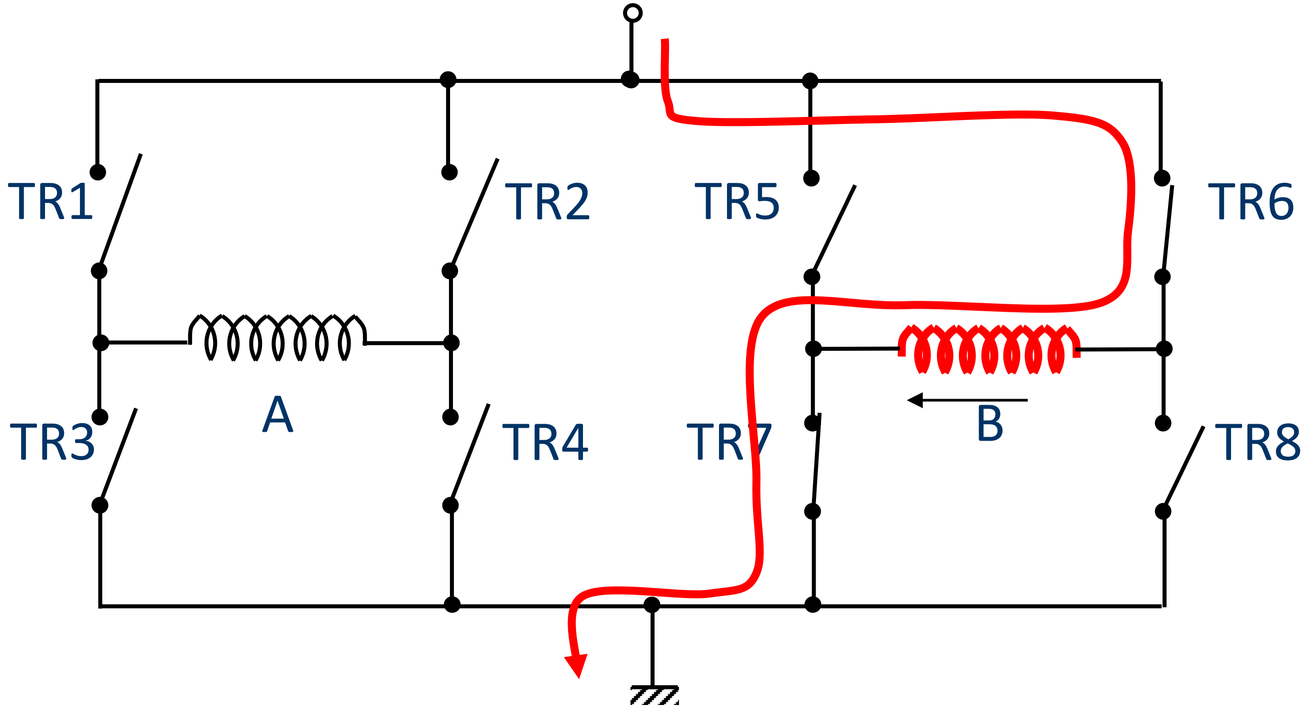
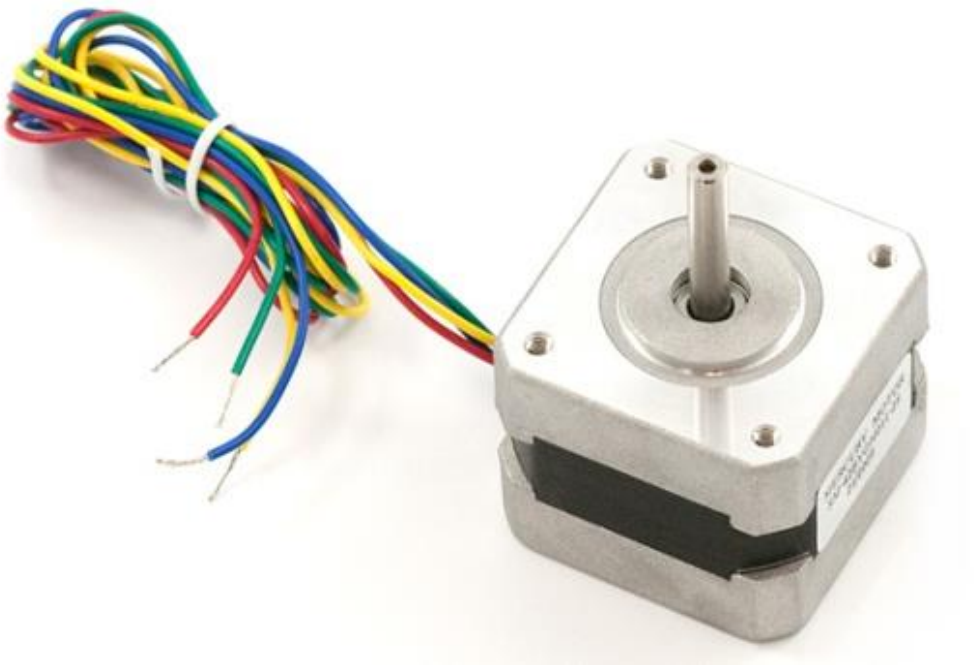


Some real stepper motors



proto-pic.com

Stepper motors within systems

- Stepper motors are usually used in computer-controlled or microprocessor controlled systems
- Usually controlled by computer giving signals for:
    - Step (move say 1.8 degrees)
    - Direction (whether step is CW or CCW)

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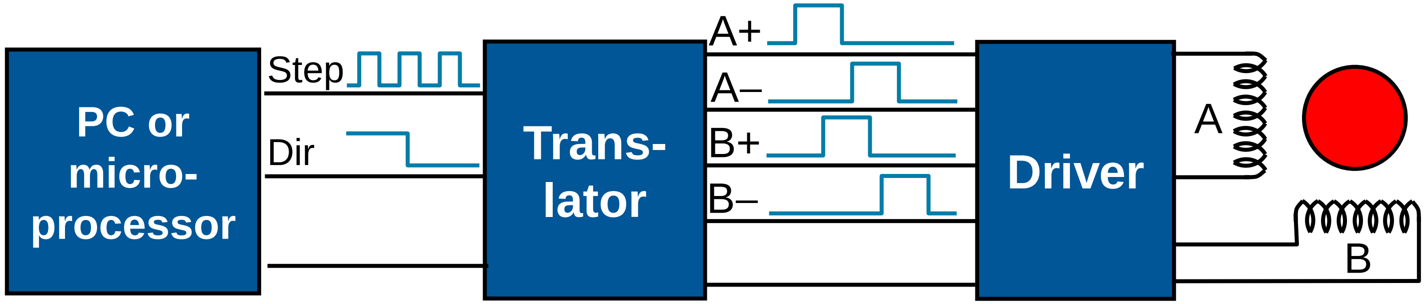
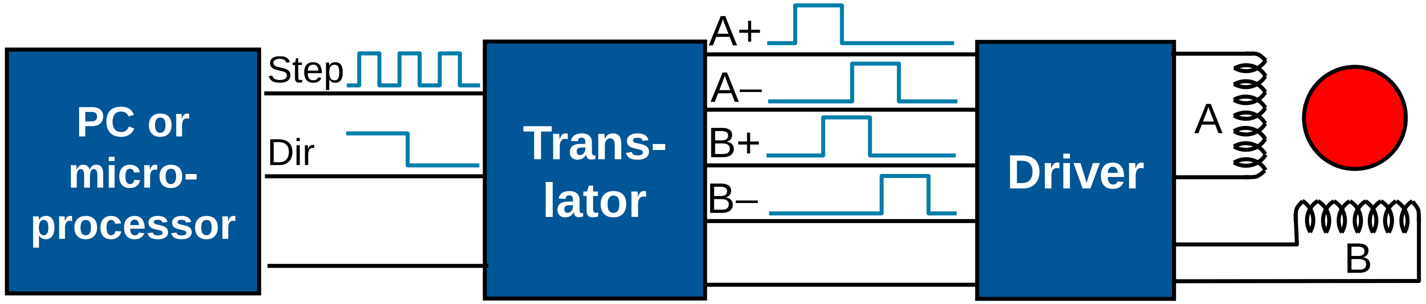


Stepper motors: a story told in electronics lectures and Lab 2

- Sequential logic (interprets “step” signals)
- Combinational logic (interprets “direction”)
- Transistors (these are the switches which connect and disconnect the windings)



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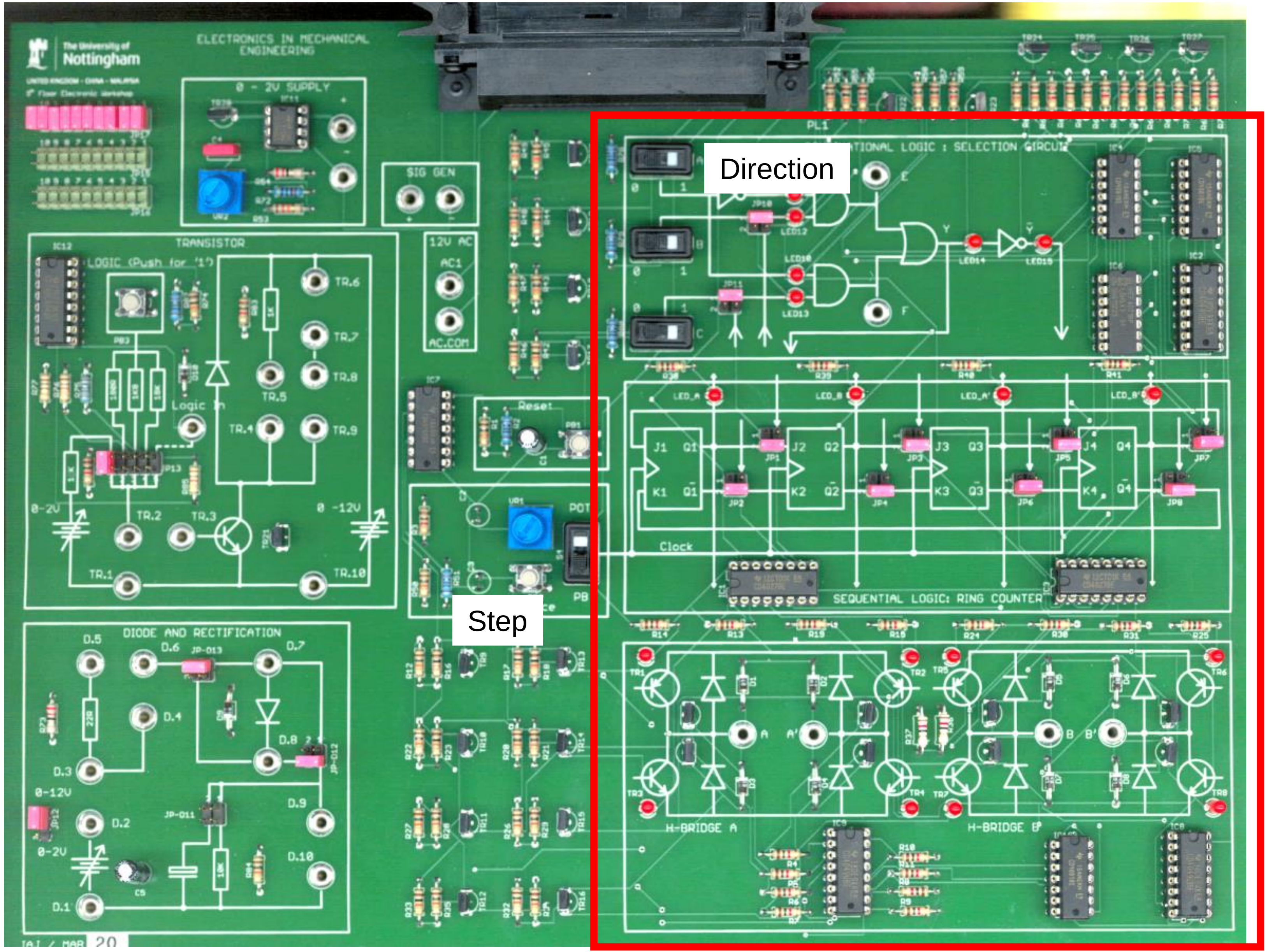

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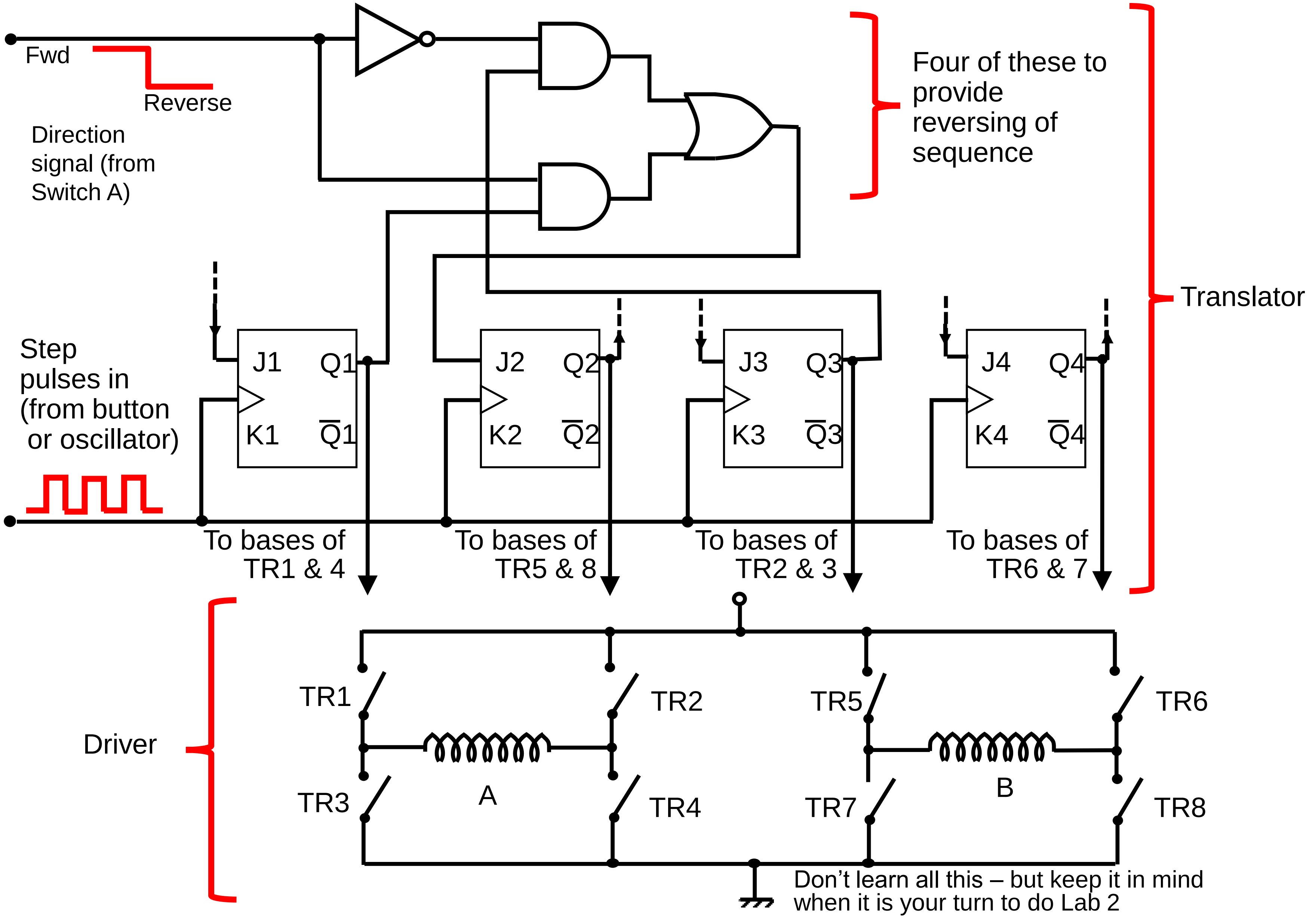
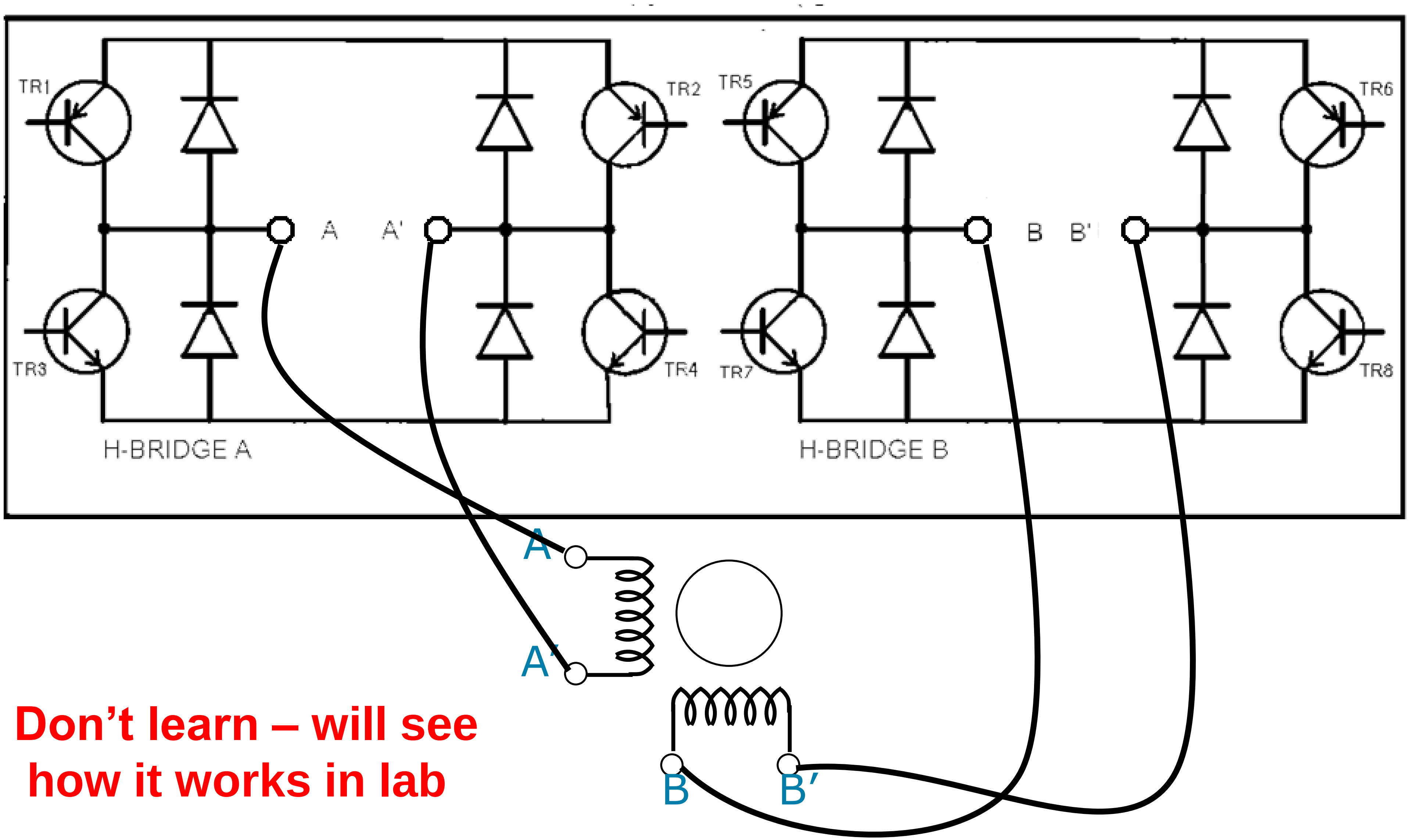


Don’t learn all this – but keep it in mind when it is your turn to do Lab 2

Stepper motors: a story told in electronics lectures and Lab 2



Don't learn – will see how it works in lab

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Summary

- **Sustainability Development Goals @UoN**
- **Revision of Op Amps (previous week)**
- **Piezoelectric** properties of Quartz
  - **Integrating** Amplifier
  - **Differencing** Amplifier
- **Strain Gauge**
  - **Resistivity** v Resistance
  - **Wheatstone Bridge**
- **Stepper Motor**

Attendance

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