Physics Notes

A level Physics

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Contents

1 Circular Motion, Gravitation and Oscillation

1.1 Circular Motion

1.1.1 Measurement

Angles or angular displacement is usually measured in radians. $360° = 2\pi rad$

> One Radian is the angle subtended at the center of a circle by an arc of length equal to the radius of the circle

The time period of rotation is T and frequency is f

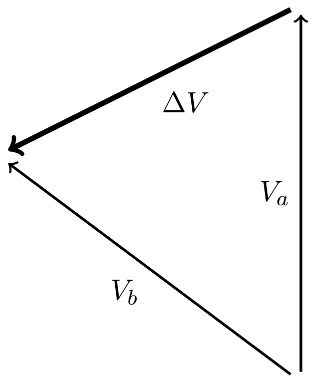
$$\omega = \frac{2\pi}{T} = 2\pi f$$

1.1.2 Angular Velocity and Centripetal Force

The speed at which a object rotates is called it's angular velocity. It is measured in $rad\ s^{-1}$ and is represented by ω. This is different from it's linear velocity.

$$\omega = \frac{\Delta\theta}{\Delta t} \qquad\qquad v = \omega r$$

Even if a rotating object has constant angular velocity, it's linear velocity is not constant. This is because velocity is a vector and an object in circular motion is constantly changing direction. Since there is a change in velocity, there is acceleration. This acceleration is called centripetal acceleration. It can be calculated using a vector diagram.



$$a = \frac{\Delta V}{\Delta t}$$

$$\Delta V = V_b - V_a$$

The Centripetal acceleration is due to centripetal forces, which can be gravity or tension in a string. This can be calculated by $F = ma$. Centripetal acceleration can also be calculated by the following formulas: $a = v\omega$, $a = \frac{v^2}{r}$, and $a = \omega^2 r$. Multiplying by mass gives $F = mv\omega$, $F = \frac{mv^2}{r}$, and $F = m\omega^2 r$

1.2 Gravitation

1.2.1 Newton's Law of Gravitation

> Any two point masses attract each other with a force that is directly proportional to the product of their masses and inversely proportional to the square of the separation.

Newtons law can be summarised in the following equations.

$$\text{force} \propto \text{product of masses}$$
$$\text{force} \propto \frac{1}{\text{distance}^2}$$
$$F = \frac{GMm}{r^2} \qquad \text{Introducing the constant G, where } G = 6.67 \times 10^{-11} Nm^2kg^{-2}$$

1.2.2 Gravitational Field Strength

> The gravitational field strength at a point is the gravitational force exerted per unit mass on a object at a point.

This is represented by g

$$g = \frac{F}{m} \qquad g = \frac{GM}{r^2}$$

1.2.3 Gravitational Potential

> The gravitational potential at a point is the work done per unit mass to bring a abject from infinity to a point

It is zero at infinity and negative at any point in the universe. It is represented by the Greek letter ϕ (phi) and is calculated using the following formula

$$\phi = \frac{-GM}{r}$$

1.2.4 Orbiting Under Gravity

The equations of circular motion and gravitation can be combined to give the equation for orbits under gravity

$$F = \frac{mv^2}{r} = \frac{GMm}{r^2}$$
$$\text{so } v^2 = \frac{GM}{r}$$

For an object in a geostationary orbit, the time period can be calculated by using the following formula

$$T^2 = \left(\frac{4\pi^2}{GM}\right) r^3$$

1.3 Oscillations

Oscillations or vibrations are to and fro motions. They have three key properties: Frequency, amplitude and period

1.3.1 Phase

Phase describes the point that an oscillating mass has reached within the complete cycle of an oscillation. It is often measured in degrees or radians.

1.3.2 Simple Harmonic Motion (s.h.m.)

There are three requirements for a mechanical system to be in s.h.m:

- A mass that oscillates
- A position where the mass is in equilibrium
- A restoring force that acts to return the mass to it's equilibrium position.

The force is directly proportional to the displacement from the equilibrium position. The following equations describe s.h.m for a oscillator which is at the equilibrium position at $t = 0$

$$x = x_0 \sin \omega t$$
$$v = v_0 \cos \omega t$$
$$a = -\omega^2 x$$
$$v = \pm\omega\sqrt{x_0^2 - x^2}$$
$$v_{max} = \omega x_0$$

1.3.3 Resonance and Damping

Resonance is a phenomenon observed in systems with forced oscillations. The following statements apply to systems in resonance

- It's natural frequency is equal to the frequency of the driver.
- It's amplitude is maximum
- It absorbs the greatest possible energy from the driver.

Damping is when a oscillating system loses energy (due to friction or air resistance). Critical Damping is minimum amount of energy required to return a damped system to equilibrium without oscillating

2 Communication Systems

2.1 Modulation

2.1.1 F.M. and A.M.

When sending information over radio waves, the information must be modulated in some way. A common way of modulating is Amplitude Modulation or AM. We can see in Fig 2.1 that the amplitude of the modulated wave changes to match the value of the signal. In Frequency Modulation or F.M. the frequency of the modulated wave varies with time. Example can be seen in Fig 2.1

2.1.2 Side-bands and Bandwidth

The frequency of the carrier wave is known as the carrier frequency (f_c). When the carrier wave is modulated, it is known to carry two more frequencies called Side-band frequencies ($f_c - f_m$ and $f_c + f_m$). The bandwidth is $2f_m$

2.1.3 Comparison

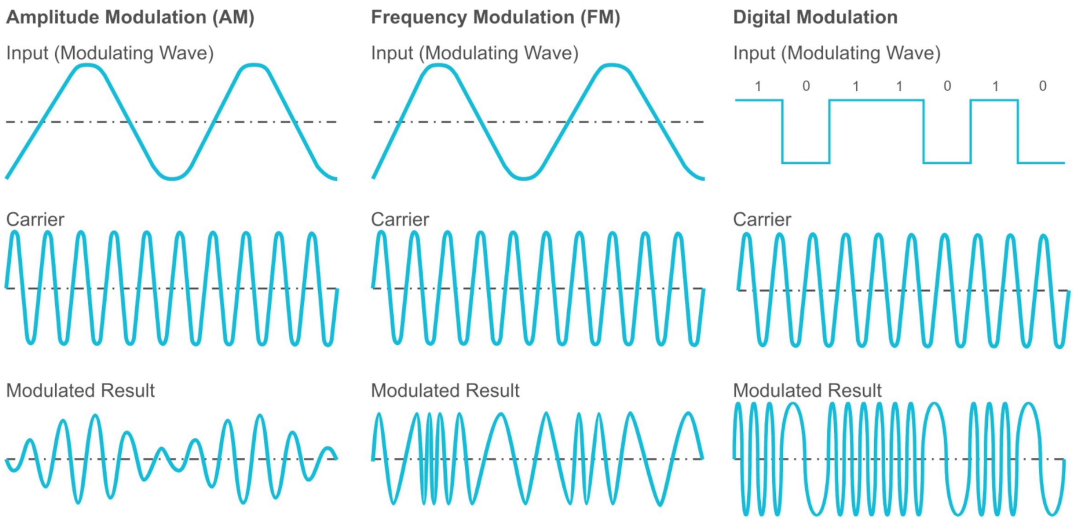
FM	AM
Less Electrical Interference and Noise Greater bandwidth produces better sound	Greater area covered by one transmitter Smaller bandwidth allows for more stations Cheap Radio Sets

2.2 Digital Signals

2.2.1 Advantages of Digital signals

- Noise can be fixed through regeneration.
- Digital Signals are more compatible with modern technologies
- Digital electronic systems are more reliable, robust and easier to build.
- Digital signals build in safe-guards so that if there is an error in reception, the required parts of the signal can be sent again.

Figure 2.1: Comparison of FM and AM [3]



2.2.2 ADC, DAC and Sampling

When converting between analogue and digital signals, signals must be sampled at regular intervals. The rate at which it is sampled is called the Sample Rate. The resolution at which the signal is sampled is called the bit-depth

2.3 Crosstalk and Signal Attenuation

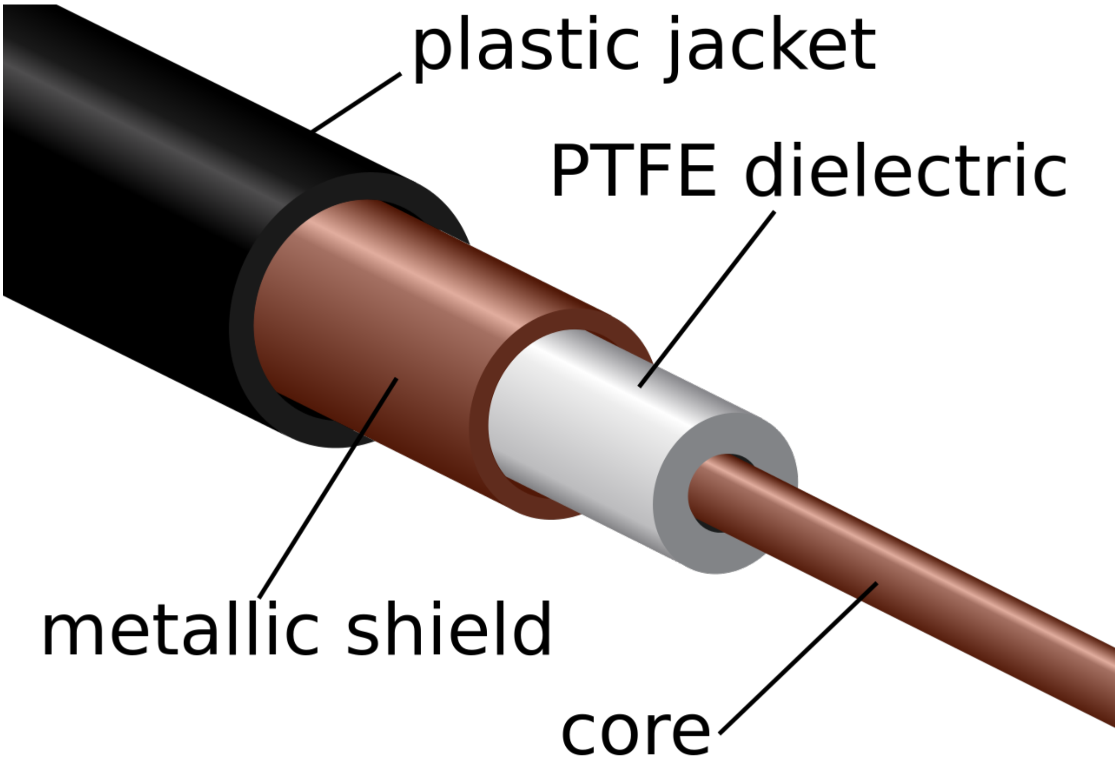
> Crosstalk or Cross-linking occurs when a signal transmitter in one circuit or channel creates an undesired effect in another circuit or channel

> Signal Attenuation is the gradual decrease in power of a signal the further it travels.

The decrease in power from P_1 to P_2 can be very high. A $\log_{10}$ is used and the ratio is represented in Bels (often multiplied by 10 and written as deciBels or dB)

$$\text{Attenuation} = 10 \log_{10} \left(\frac{P_1}{P_2} \right) \text{dB}$$

Figure 2.2: A Co-axial Cable [4]



2.4 Channels of Communications

2.4.1 Wire Pairs and Co-axial cables

Telephones used to use pairs of wires to carry signals. The difference in the Potential differences of the wires was the signal, but they easily picked up noise. The closer the wires were, the less noise was picked up, so they were twisted together.

Coaxial reduces the amount of crosstalk in the wire when the transmission occurs at high speeds. The copper core usually carries the signal and the copper braid (metallic shield) is connected to earth. see Fig 2.4.1 Since electromagnetic radiation does not travel easily through metal, interference does not occur at the core.

Wire Pairs	Coaxial
Cheap and convenient	Expensive
Strongly attenuate signal	Less attenuating
Low bandwidth	High bandwidth
Pushes up interference/noise	Less interference and noise
Crosstalk	less Crosstalk
Low security	More secure

2.4.2 Radio Waves and Microwave links

Various electromagnetic waves are used to carry informations. In waves such as sky-waves, the ionosphere is used to reflect the waves.

Type	Frequency Range	Distance Travelled
Surface wave	up-to 3MHz	up-to 1000Km
Sky wave	3 - 30MHz	Worldwide by reflection
Space wave	30 - 300MHz	line of sight
Microwave	1-300GHz	line of sight, except when retransmitted by satellite

2.4.3 Satellites and Optic fibre

Satellites offer some extra advantages over sky-waves

- The concentration of ions in the ionosphere is constantly changing and the reflection of sky-waves is not always possible
- The satellite boosts the signal for its return to earth.
- Satellite communications use higher frequencies and hence have height bandwidth
- More channels are available for communicating on higher frequencies

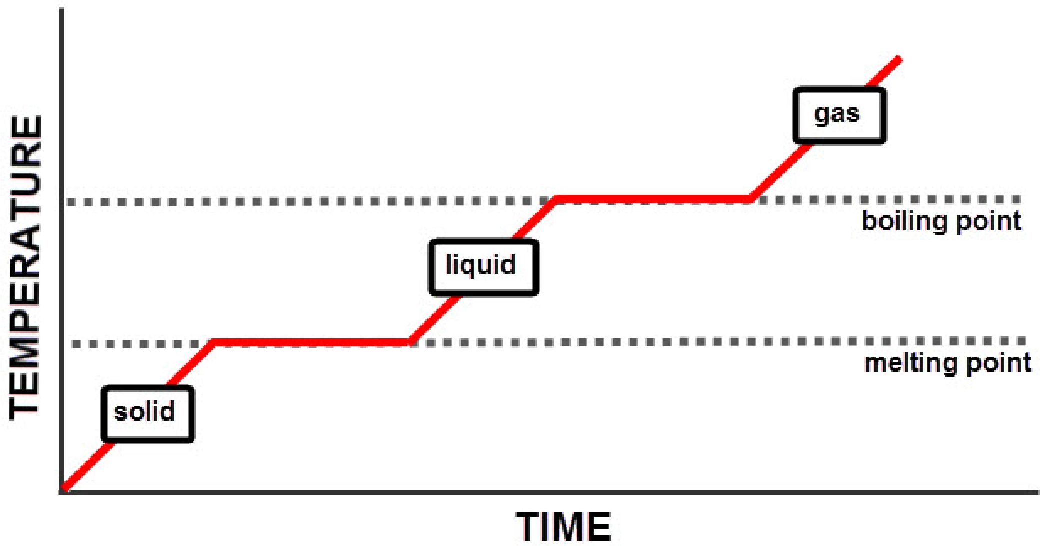
3 Thermal Physics

3.1 Changes of state

3.1.1 Energy Changes

When a solid is heated, it's temperature starts rising and it's molecules gain kinetic energy. When the solid reaches it's melting point, the heat energy is used to break the intermolecular bonds. The temperature remains constant but the separation between the particles significantly increases and hence the potential energy of the molecules increases. The solid starts melting. After the solid has completely melted, the temperature starts rising again and the Kinetic energy increases until the liquid reaches it's boiling point. Again, the heat energy is used up in breaking up intermolecular bonds, and the temperature stops rising until all of the liquid has turned into gas. After that the temperature continues to increase velocity. A summary can be seen in Fig. 3.1

Figure 3.1: Energy Changes [2]



The energy supplied to a substance when it is changing state (at a constant temperature) is called the latent heat of change in state for that material.

3.1.2 Evaporation

Liquids can change into gasses without reaching boiling point. In a liquid some molecules move faster than the others. These molecules break free and form a vapor above the liquid. This is called evaporation. Since higher energy particles leave the liquid, the temperature of the liquid decreases.

3.2 Internal Energy

3.2.1 Energy of the particles

> The internal energy of a system is the sum of the random distribution of kinetic and potential energies of it's atoms or molecules

There are two ways in which the internal energy of a system can be increased.

- **By heating the system** : When a material is heated, the kinetic energy of the particles increases.
- **By doing work on the system** : When a gas is compressed, the molecules strike the walls and move faster.

3.2.2 What is Temperature

Temperature is a measure of the average kinetic energy of the particles in the system. A common scale is the Celsius scale, where 0 °C is the freezing point of water and 100 °C is the boiling point of water. The Thermodynamic or Kelvin scale uses the absolute zero as 0 K. For matter at absolute zero, it is impossible to remove any more energy out of it. The other fixed point is at 273.15 K, the triple point of water.

$$\theta(°\mathrm{C}) = T(\mathrm{K}) - 273.15$$

3.2.3 The First Law of Thermodynamics

> The first law of thermodynamics states that the total energy of an isolated system remains constant.

This means that the energy supplied to a system by heating it or doing work on it increases the internal energy of the system.

$$\text{Increase in internal energy} = \text{Energy supplied by heating} + \text{Energy supplied by doing work}$$
$$\Delta u = q + w$$

3.3 Thermometers

3.3.1 Types of thermometers

Thermometers are devices that are used to measure temperature. They use some property of the material which changes with temperatures. This could be:

- The resistance of a electrical resistor
- The voltage produced by a thermocouple
- The color of an electrically heated wire
- The volume of a fixed mass of gas at constant pressure

3.3.2 Thermocouple thermometer vs. Resistance thermometer

Feature	Resistance thermometer	Thermocouple thermometer
robustness	very robust	robust
range	Thermistor: narrow range, resistance wire: wide range	can be wide
size	larger than thermocouple, has greater thermal capacity therefore slower acting	smaller than resistance thermometers, has smaller thermal capacity, so quicker acting and can measure temperature at a point
sensitivity	Thermistor: high sensitivity over narrow range, resistance wires: less sensitive	can be sensitive if appropriate metal are chosen
linearity	Thermistor : fairly linear over narrow range, resistance wire: good linearity	non-linear so requires calibration
remote operation	long conducting wires allow the operator to be at a distance from the thermometer	long conducting wires allow the operator to be at a distance from the thermometer

3.4 Calculating energy changes

3.4.1 Specific heat capacity

> The specific heat capacity of a substance is the energy required per unit mass of the substance to raise the temperature by 1 K

This can be represented with the following formula

$$\text{Specific heat capacity} = \frac{\text{energy supplied}}{\text{mass} \times \text{temperature change}}$$
$$C = \frac{E}{m\Delta\theta}$$

3.4.2 Specific latent heat

> The specific latent heat of a substance is the energy per kilogram of the substance to change it's state without any change in temperature

When a substance melts, the quantity is called the specific latent heat if fusion; for boiling, it's the specific latent heat of vaporisation.

$$\text{latent heat} = \frac{\text{Energy to change state}}{\text{mass}}$$

4 Electromagnetism

4.1 Electric Fields

4.1.1 Coulomb's Law

An electrically charged object produces an electric field on the space around it. This field exerts a force on the other charged objects in the field. Coulomb's law describes this force.

> Any two point charges exert an electrical force on each other that is proportional to the product of the charges and inversely proportional to the square of the distance between them.

This law can be mathematically represented as,

$$F \propto \frac{1}{r^2} \qquad\qquad F \propto Q_1 Q_2$$

Combining and resolving the proportionality results in,

$$F = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2} \tag{4.1}$$

Here $\frac{1}{4\pi\epsilon_0}$ is the constant of proportionality, and ϵ_0 is called the permittivity of free space. It equals approximately $8.85\,\mathrm{F\,m^{-1}}$

4.1.2 Electric field strength

> The electric field strength at a point is the force per unit charge exerted on a stationary positive charge at that point

Mathematically,

$$F = \frac{E}{Q} \tag{4.2}$$

For a uniform electric field between charged parallel plates, it is also,

$$E = \frac{V}{d}$$

Where, V is the potential difference between the plates, and d is the distance between them.

To calculate the electric field strength for a radial field we can combine the formulas 4.1 and 4.2,

$$E = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2 Q_2}$$
$$\implies E = \frac{Q}{4\pi\epsilon_0 r^2}$$

4.2 Electric potential

4.2.1 Energy changes in a uniform field

Electrical potential energy is the potential energy of a charge due to it's position in a electric field. The electric potential at a point is the potential energy per unit charge at that point.

In a uniform field, this can be represented as,

$$V = \frac{W}{Q} \tag{4.3}$$

Where, V is the electric potential, Q is the charge, and W is the work done in having the charge from the negative plate to the positive plate. The potential of zero is defined as "earth" or "ground".

4.2.2 Energy changes in a radial field

The electric field strength increases as we move closer to a charged object. To calculate the electric potential we can integrate the equation for coulomb's law, equation 4.1, and combine it with equation 4.3 to get.

$$V = \frac{Q}{4\pi\epsilon_0 r}$$

Here the zero potential is defined as the potential at a infinite distance away from the charge.

4.2.3 Defining electric potential

> The electric potential at a point is equal to the work done in bringing unit positive charge from infinity to a point

4.3 Comparing gravitational and electric forces

Gravitational Field	Electric fields
Origin: Arises from masses	**Origin:** Arise from electric charges
Vector forces: Only gravitational attraction, no repulsion	**Vector forces:** Both electrical attraction and repulsion are possible (because of positive and negative charges)
All gravitational fields: field strength $g = \frac{F}{m}$. i.e. field strength is force per unit mass	**All electric fields:** field strength $E = \frac{F}{Q}$. i.e. field strength is force per unit positive charge
Units: F is in N, g is in $\mathrm{N\,kg^{-1}}$ or $\mathrm{m\,s^{-1}}$	**Units:** F is in N, E is in $\mathrm{N\,C^{-1}}$ or $\mathrm{V\,m^{-1}}$
Uniform gravitational fields: parallel gravitational field lines $g =$ constant	**Uniform electric fields:** parallel electric field lines $E = \frac{V}{d} =$ constant
Spherical gravitational fields: radial field lines force given by Newton's laws: $F = \frac{GMm}{r^2}$ field strength is therefore: $g = \frac{GM}{r^2}$ (force and field strength obey an inverse square law with distance)	**Spherical electric fields:** radial field lines force given by coulomb's law: $F = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2}$ field strength is therefore: $E = \frac{Q}{4\pi\epsilon_0 r^2}$ force and field strength obey an inverse square law with distance
Gravitational potential: given by $\phi = -\frac{GM}{r}$ potential obeys an inverse relationship with distance and is zero at infinity potential is a scalar quantity and is always negative	**Electric potential:** given by: $V = \frac{Q}{4\pi\epsilon_0 r}$ potential obeys an inverse relationship with distance and is zero at infinity potential is scalar quantity

4.4 Capacitors

4.4.1 What are Capacitors

Capacitors are electronic devices that store energy, and gradually release it. They have two leads connected to two plates separated by an insulating material called the **dielectric** When a potential difference is applied across the terminals of a capacitor, equal and opposite charges are stored on the plates. When the potential difference is removed, the stored charge produces it's own voltage. If the capacitor is connected to a complete circuit, then the charge flows out releasing the energy. Figure 4.1 shows the construction of a capacitor.

4.4.2 Capacitance

Different Capacitors have different capacities to store charge. Capacitance is a measure of how much charge a capacitor can store. The greater the capacitance, the greater charge a capacitor stores for a given potential difference across it.

> The capacitance of a capacitor is the charge stored on one plate per unit potential difference between the plates.

Mathematically,

$$\text{Capacitance} = \frac{\text{Charge}}{\text{Potential difference}}$$
$$C = \frac{Q}{V} \tag{4.4}$$

The unit of capacitance is the **farad**, F

$$1\,\text{F} = 1\,\text{C}\,\text{V}^{-1}$$

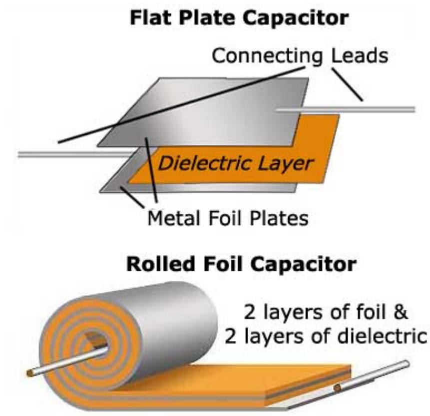


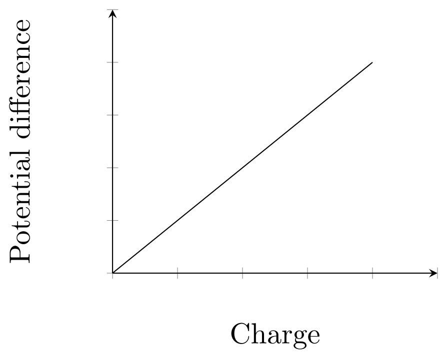
Figure 4.1: Construction of a Capacitor. [1]

4.4.3 Energy stored in a capacitor

As the charge stored in a capacitor increases, the repulsion makes it harder to store more charge in the capacitor, and more energy us required. Fig 4.2 shows a graph of Voltage against charge on a capacitor. The work done in moving charge Q across a potential difference of V is the product QV. Here, the work done is the area under the graph of figure 4.2,

$$W = \frac{1}{2}QV \tag{4.5}$$

Figure 4.2: Potential Difference against charge



by substituting equation 4.4 into equation 4.5 we get two new equations,

$$W = \frac{CV^2}{2} \tag{4.6}$$
$$W = \frac{Q^2}{2C} \tag{4.7}$$

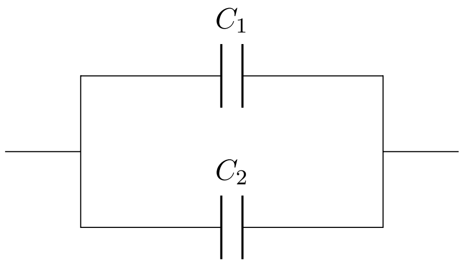
4.5 Capacitors in a circuit

4.5.1 Capacitors in parallel

When two capacitors are connected in parallel, they are equivalent to a single capacitor with larger plates. Hence their combined capacitance is the sub of their individual capacitances.

$$C_{\text{total}} = C_1 + C_2 + C_3 + ...$$

Figure 4.3: Capacitors in parallel



4.5.2 Capacitors in series

For a system where capacitors are connected in series, like in fig 4.4, the reciprocal of the total capacitance is the sub of the reciprocal of the individual capacitances.

$$C_{\text{total}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_2} + ...$$

Figure 4.4: Capacitors in series

4.5.3 Sharing charge between capacitors

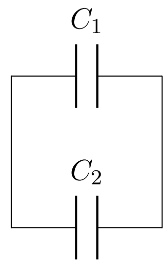
If a capacitor, with a capacitance of C_1 is charged with a power supply to a voltage of V_{init}, and then connected to a second capacitor with capacitance C_2, the charge is shared between the capacitors. As shown in Figure 4.5, the capacitors are in parallel, so the capacitance is calculated by,

$$C_{\text{total}} = C_1 + C_2$$
$$Q = C_1 V_{\text{init}}$$

Since charge is conserved, we can calculate the potential difference across the capacitors as,

$$V_{\text{new}} = \frac{Q}{C_{\text{total}}}$$

Figure 4.5: Capacitors sharing charges



4.6 Capacitance of isolated bodies

All bodies have capacitance. For a conducting sphere of radius r insulated from its surroundings, carrying a charge of Q, will have a potential on the surface of V, and a capacitance of C, where,

$$V = \frac{Q}{4\pi\epsilon_0 r} \qquad C = 4\pi\epsilon_0 r$$

4.7 Components of an electronic sensing system

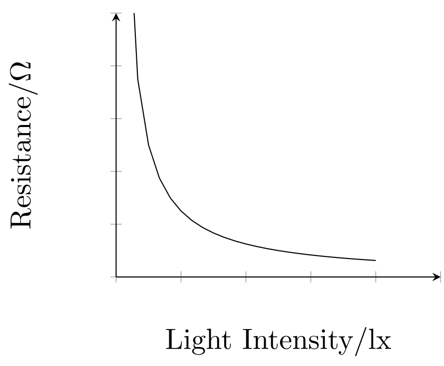
4.7.1 Piezoelectric speakers

Some crystals such as quartz produce an electric field when a force is applied and the shape of the crystal changes. This is called the piezoelectric effect. Such crystals are used in microphones as piezoelectric transducers.

4.7.2 The Light-Dependent Resistor (LDR)

A LDR is made of a high-resistance semiconductor. If light falling on the LDR is of high enough frequency, photons are absorbed by the semiconductor. As some photons are absorbed, electrons are released from the atoms in the semiconductor. The resulting free electrons conduct electricity and reduce the resistance of the semiconductor. Fig. 4.6 Shows the relationship of Resistance and light intensity, and Fig. 4.7 Shows an LDR used in a circuit.

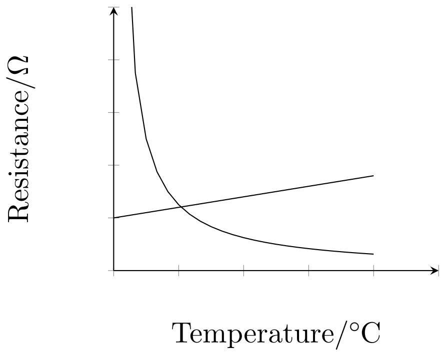
Figure 4.6: Resistance/Light Intensity Graph for an LDR



4.7.3 Thermistor

Thermistors are often made of a semiconductor material. When the temperature of the thermistor rises, the number of free electrons increases, reducing it's resistance. A thermistor with such a property is called a negative temperature coefficient thermistor. Fig. 4.8 shows how the resistance of a thermistor changes with temperature.

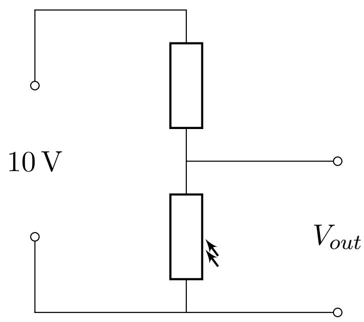
Figure 4.8: Temperature/Resistance of thermistors and wires



4.7.4 The metal wire strain gauge

A strain gauge takes advantage of the change in resistance of a metal wire as it's length and cross-sectional area changes. When a strain gauge is pressed, it's resistance increases.

Figure 4.7: LDR is a circuit



4.8 The operational Amplifier.

An amplifier produces an output with more power and usually more voltage than the input. Operational amplifier or op-amps have a very large gain and uses an external circuit to reduce the gain. The open-loop voltage G_0 is given by:

$$G_0 = \frac{\text{output voltage}}{\text{input voltage}}$$

$$G_0 = \frac{V_{\text{out}}}{V^{+}r - V^{-}}$$

4.8.1 The properties of an ideal op-amp

The ideal op-amp has the following properties:

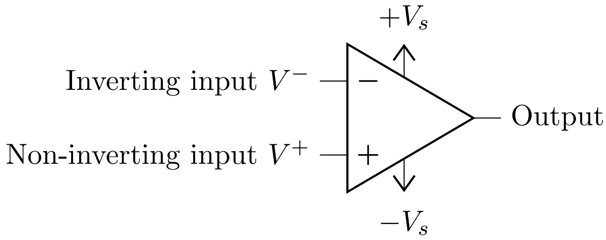
- Infinite open loop voltage
- Infinite input resistance (or impedance)
- Zero input resistance (or impedance)
- Infinite bandwidth

- Infinite slew rate (or zero time delay)
- Zero noise contribution.

4.8.2 The op-amp as a comparator

Consider the op-amp in Fig. 4.9. The output voltage is given by $V_{out} = G_0 \times (V^+ - V^-)$. When $V^+ > V^-$ and G_0 is a very large number, V_{out} is saturated to $+V_s$ and when $V^+ < V^-$, V_{out} is saturated tp $-V_s$

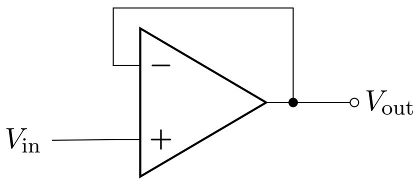
Figure 4.9: an Op-amp



4.8.3 Negative feedback

Negative feedback is when a high output causes a series of reactions resulting in the output to decrease and vice versa. We can use this to create a special op-amp circuit. Consider the op-amp in Fig 4.8.3. In this system $V_{\text{in}} = V_{\text{out}}$ and hence the $G = \frac{G_0}{1+G_0} = 1$. This op-amp draws very little current from the input, yet it can supply resonable current from it's output, thereby working as a buffer.

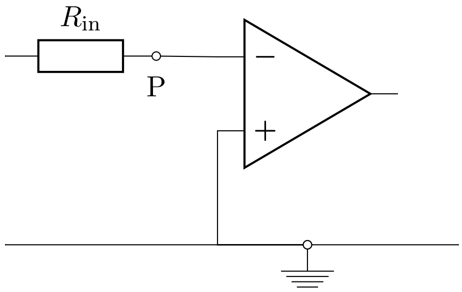
Figure 4.10: Op-amp in a feedback loop



4.8.4 The inverting amplifier

Fig 4.8.4 shows an op-amp set up as an inverting amplifier. Point P is knows as an virtual ground.

Figure 4.11: Op-amp as a inverting amplifier



Bibliography

[1] Eric Coates. *Capacitors*. http://www.learnabout-electronics.org/ac_theory/capacitors01.php. Accessed on 2018-02-03.

[2] edplace. *Energy Changes 1*. https://www.edplace.com/worksheet_info/science/keystage4/year11/topic/521/3078/energy-changes-1. Accesed on 2018-01-31.

[3] taitradioacademy. *Modulation and Radio Building Blocks*. https://www.taitradioacademy.com/topic/how-does-modulation-work-1-1/. Accessed on 2018-01-23.

[4] Tkgd2007. *Coaxial cable cutaway PTFE*. https://commons.wikimedia.org/wiki/File:Coaxial_cable_cutaway_PTFE.svg. Accesed on 2018-01-23.