G491: Physics in Action
Revision Notes
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Curvature of Wavefronts

Light can be viewed as beams travelling between points. However, from most light sources, the light radiates outwards as a series of wavefronts. Light from a light source is bent - wavefronts of light have a property known as curvature.

As light travels further away from its source, its curvature decreases. Consider a sphere expanding gradually from a point, which represents a given wavefront of light. As the sphere expands, the curvature of its surface decreases when we look at any part of the surface with a constant area. It should be noted at this point that light from a source infinitely far away has 0 curvature - it is straight. This is useful, as ambient light (light from a source that is far away) can be assumed to have a curvature of 0, as the difference between this and its actual curvature is negligible.

The curvature of a wavefront is given as:

\[ C = \frac{1}{v}, \]

where \( v \) is the distance from the wavefront to the in-focus image depicted by the light. Curvature is measured in dioptres (D).

Power of lenses

The function of a lens is to increase or decrease the curvature of a wavefront. Lenses have a 'power'. This is the curvature which the lens adds to the wavefront. Power is measured in dioptres, and is given by the formula:

\[ P = \frac{1}{f}, \]

where \( f \) equals the focal length of the lens. This is the distance between the lens and the point where an image will be in focus, if the wavefronts entering the other side of the lens are parallel.
The Lens Equation

Overall, then, the formula relating the curvature of the wavefronts leaving a lens to the curvature of the wavefronts entering it is:

\[
\frac{1}{v} = \frac{1}{u} + \frac{1}{f}
\]

where \(v\) is the distance between the lens and the in-focus image formed, \(u\) is the distance between the lens and the object which the in-focus image is of, and \(f\) is the focal length of the lens. The power of the lens can be substituted in for the reciprocal of \(f\), as they are the same thing.

The Cartesian Convention

If we were to place a diagram of the lens on a grid, labelled with cartesian co-ordinates, we would discover that measuring the distance of the object distance is negative, in comparison to the image distance. As a result, the value for \(u\) must always be negative. This is known as the Cartesian convention.

This means that, if light enters the lens with a positive curvature, it will leave with a negative curvature unless the lens is powerful enough to make the light leave with a positive curvature.

Types of Lens

There are two types of lens:

Converging lenses add curvature to the wavefronts, causing them to converge more. These have a positive power, and have a curved surface which is wider in the middle than at the rim.

Diverging lenses remove curvature from the wavefronts, causing them to diverge more. These have a negative power, and have a curved surface with a dip in the middle.
Magnification

Magnification is a measure of how much an image has been enlarged by a lens. It is given by the formula:
\[ M = \frac{h_2}{h_1} \]

where \( h_1 \) and \( h_2 \) are the heights of the image (or object) before and after being magnified, respectively. If an image is shrunk by a lens, the magnification is between 0 and 1.

Magnification can also be given as:
\[ M = \frac{v}{u} \]

where \( v \) and \( u \) are the image and object distances. Therefore:
\[ M = \frac{h_2}{h_1} = \frac{v}{u} \]

An easy way to remember this in the middle of an exam is the formula:
\[ I = AM \]

where \( I \) is image size, \( A \) is actual size of the object \( M \) is the magnification factor.

Questions

1. A lens has a focal length of 10cm. What is its power, in dioptres?
2. Light reflected off a cactus 1.5m from a 20D lens forms an image. How many metres is it from the other side of the lens?
3. A lens in an RGB projector causes an image to focus on a large screen. What sort of lens is it? Is its power positive or negative?
4. What is the focal length of a 100D lens?
5. The film in a camera is 5mm from a lens when automatically focussed on someone's face, 10m from the camera. What is the power of the lens?
6. The light from a candle is enlarged by a factor of 0.5 by a lens, and produces an image of a candle, 0.05m high, on a wall. What is the height of the candle?
Reflection

Reflection is when light 'bounces' off a material which is different to the one in which it is travelling. You may remember from GCSE (or equivalent) level that we can calculate the direction the light will take if we consider a line known as the 'normal'. The normal is perpendicular to the boundary between the two materials, at the point at which the light is reflected. The angle between the normal and the ray of light is known as the angle of reflection (r). The ray of light will be reflected back at the same angle as it arrived at the normal, on the other side of the normal.

Refraction

Refraction is when light changes velocity when it travels across the boundary between two materials. This causes it to change direction. The angle between the normal and the refracted ray of light is known as the angle of incidence (i).

The Refractive Index

The refractive index is a measure of how much light will be refracted on the boundary between a material and a 'reference material'. This reference material is usually either air or a vacuum. It is given by the following formula:

\[ n = \frac{c_0}{c_1} \]

where \( c_0 \) is the speed of light in a vacuum (3 \( \times \) 10^8 m/s) and \( c_1 \) is the speed of light in the material.

Snell's Law

We can relate the refractive index to the angles of incidence and reflection using the following formula, known as Snell's Law:

\[ n = \frac{\sin i}{\sin r} = \frac{c_0}{c_1} \]

Total Internal Reflection

Normally, when light passes through a non-opaque material, it is both reflected and refracted. However, sometimes, rays of light are totally internally reflected; in other words, they are not refracted, so no light goes outside the material. This is useful in optic fibres, which allow a signal to be transmitted long distances at the speed of light because the light is totally internally reflected.
**Critical Angle**

The critical angle is the minimum angle of reflection, for a given material, at which rays of light are totally internally reflected. At the critical angle (C), the angle of incidence must be 90°, as any smaller angle of incidence will result in refraction. Therefore:

\[
\sin r = \frac{\sin 90°}{n}
\]

Since \(\sin 90° = 1\):

\[
n = \frac{\sin r}{\sin 90°} = \frac{1}{n}
\]

\[
\sin r = \frac{1}{n} = \sin C
\]

In word form, in a material with refractive index \(n\), light will be totally internally reflected at angles greater than the inverse sine of the reciprocal of the refractive index.

**Questions**

1. A ray of light is reflected from a mirror. Its angle to the normal when it reaches the mirror is 70°. What is its angle of reflection?

2. The speed of light in diamond is \(1.24 \times 10^8\) m/s. What is its refractive index?

3. The refractive index of ice is 1.31. What is the speed of light in ice?

4. A ray of light passes the boundary between air and a transparent material. The angle of refraction is 20°, and the angle of incidence is 10°. What is the speed of light in this material? Why is it impossible for this material to exist?

5. What is the critical angle of a beam of light leaving a transparent material with a refractive index of 2?

/Worked Solutions/

**See also**

- Optics/Refraction
Communication

A-level Physics (Advancing Physics)/Digital Storage

Digital Data

There are two different types of data: analogue and digital. Analogue data can, potentially, take on any value. Examples include a page of handwritten text, a cassette, or a painting. Digital data can only take on a set range of values. This enables it to be processed by a computer. Examples include all files stored on computers, CDs, DVDs, etc.

Pixels

Digital images are made up of pixels. A pixel represents the value of an individual square of the image, and it has a value assigned to it. The total number of pixels in an image is just like the formula for the area of a rectangle: number of pixels across multiplied by number of pixels down. When representing text, each pixel is one character (for example, a letter, a number, a space, or a new line).

Bits

Each pixel's value is digital: it takes on a definite value. In a higher quality image, each pixel can take on a greater variety of values. Each pixel's value is encoded as a number of bits. A bit is a datum with a value of either 0 or 1. The more values a pixel can take on, the more bits must be used to represent its value. The number of values (N) that a pixel represented by I bits can take on is given by the formula:

\[ N = 2^I \]

Hence:

\[ I = \frac{\log N}{\log 2} \approx \frac{\log N}{0.3} \]

A pixel may be represented by values for red, green and blue, in which case each colour channel will have to be encoded separately. When dealing with text, the number of values is equal to the number of possible characters.

Overall, for an image:

Amount of information in an image (bits) = number of pixels x bits per pixel.
Bytes

A byte is equal to 8 bits. The major difference between bytes and SI units is that when prefixes (such as kilo-, mega-, etc.) are attached, we do not multiply by $10^3$ as the prefix increases. Instead, we multiply by 1024. So, 1 kilobyte = 1024 bytes, 1 megabyte = $1024^2$ bytes, 1 gigabyte = $1024^3$ bytes, and 1 terabyte = $1024^4$ bytes.

Questions

1. An image transmitted down a SVGA video cable is 800 pixels wide, and 600 pixels high. How many pixels are there in the image?

2. A grayscale image is encoded using 3 bits. How many possible values can each pixel have?

3. The characters in a text document are numbered from 0 - 255. How many bits should each character be encoded with?

4. A page contains 30 lines of text, with an average of 15 characters on each line. Each character is represented by 4 bits. How many megabytes of uncompressed storage will a book consisting of 650 pages like this fill on a computer's hard disk?

5. A 10cm wide square image is scanned into a computer. Each pixel is encoded using 3 channels (red, green and blue), and each channel can take on 256 possible values. One pixel is 0.01 mm wide. How much information does the scanned image contain? Express your answer using an appropriate unit.

A-level Physics (Advancing Physics)/Digital Processing

As we have already seen, a digital image consists of pixels, with each pixel having a value which represents its colour. For the purposes of understanding how digital images are manipulated, we are going to consider an 8-bit grayscale image, with pixel values ranging from 0 to 255, giving us $2^8$ levels of grey. 0 represents white, and 255 represents black. This is the image we are going to consider:

```
000 000 000 000 150 150 150 050 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 205 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 095
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
```

The image consists of an edge, and some random noise. There are two methods of smoothing this image (ie. removing noise) that you need to know about:
**Mean Smoothing**

In order to attempt to remove noise, we can take the mean average of all the pixels surrounding each pixel (and the pixel itself) as the value of the pixel in the smoothed image, as follows:

```
000 000 000 000 050 100 150 133 133 133
000 026 026 026 050 100 150 139 139 139
000 026 026 026 050 106 173 173 150 150
000 026 026 026 050 106 173 173 150 150
000 000 000 000 050 106 173 173 150 150
043 028 000 000 050 100 150 150 150 150
043 028 000 000 050 100 150 150 150 150
043 028 000 000 050 100 150 144 144 144
000 000 000 000 050 100 150 144 144 144
000 000 021 021 071 100 150 144 144 144
000 000 000 000 150 150 150 150 150 150
```

This does remove the noise, but it blurs the image.

**Median Smoothing**

A far better method is, instead of taking the mean, to take the median, as follows:

```
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
000 000 000 000 150 150 150 150 150
```

For this image, this gives a perfect result. In more complicated images, however, data will still be lost, although, in general, less data will be lost by taking the median than by taking the mean.
**Edge Detection**

We can detect the positioning of edges in an image using the 'Laplace rule', or 'Laplace kernel'. For each pixel in the image, we multiply its value by 4, and then subtract the values of the pixels above and below it, and on either side of it. If the result is negative, we treat it as 0. So, taking the median-smoothed image above, edge detection gives the following result:

```
000 000 000 000 150 000 000 000
000 000 000 000 150 000 000 000
000 000 000 000 150 000 000 000
000 000 000 000 150 000 000 000
000 000 000 000 150 000 000 000
000 000 000 000 150 000 000 000
000 000 000 000 150 000 000 000
000 000 000 000 150 000 000 000
000 000 000 000 150 000 000 000
```

**Questions**

1. How could the above methods be applied to a digital sound sample?

2. Which of the above methods would be suitable for smoothing sharp edges? Why?

3. Use median smoothing to remove noise from the following image of a white cat in a snowstorm (the black pixels have a value of 255):

```
000 000 000 000
000 000 000 000
000 000 000 000
000 000 000 000
```

4. Why would mean sampling not be appropriate for smoothing the image given in question 3?

5. Use mean smoothing to remove noise from the following image of a black cat in a coal cellar:

```
000
000
000
000
```

/Worked Solutions/
Digitisation of a signal is the process by which an analogue signal is converted to a digital signal.

Digitisation & Reconstruction

Let us consider the voltage output from a microphone. The signal which enters the microphone (sound) is an analogue signal - it can be any of a potentially infinite range of values, and may look something like this waveform (from an artificial (MIDI) piano):

When the microphone converts this signal to an electrical signal, it samples the signal a number of times, and transmits the level of the signal at that point. The following diagram shows sample times (vertical black lines) and the transmitted signal (the red line):

When we wish to listen to the sound, the digital signal has to be reconstructed. The gaps between the samples are filled in, but, as you can see, the reconstructed signal is not the same as the original sound:

Sampling Rate

The sampling rate when digitising an analogue signal is defined as the number of samples per second, and is measured in Hertz (Hz), as it is a frequency. You can calculate the sampling rate using the formula:

\[
\text{Sampling Rate (Hz)} = \frac{\text{No. of samples}}{\text{No. of seconds}}
\]

The higher the sampling rate, the closer the reconstructed signal is to the original signal, but, unfortunately, we are limited by the bandwidth available. Theoretically, a sampling rate of twice the highest frequency of the original signal will result in a perfect reconstructed signal. In the example given above, the sampling rate is far too low, hence the loss of information.

Number of Levels

Another factor which may limit the quality of the reconstructed signal is the number of bits with which the signal is encoded. For example, if we use 3 bits per sample, we only have 8 \((2^3)\) levels, so, when sampling, we must take the nearest value represented by one of these levels. This leads to quantization errors - when a sample does not equal the value of the original signal at a given sample point.

Questions

1. Take samples for the signal below every 0.1ms, and then produce a reconstructed signal. How does it differ from the original?
2. A signal is sampled for 5 seconds at a sampling rate of 20 kHz. How many samples were taken?

3. Most sounds created by human speech except for ‘ss’ and ‘ff’ have a maximum frequency of 4 kHz. What is a suitable sampling rate for a low-quality telephone?

4. Using a sampling rate of 20 kHz and 3 bits, sample the following signal, and then produce a reconstructed signal. What is the maximum frequency that can be perfectly reconstructed using this sampling rate?
The frequency of a wave describes how many waves go past a certain point in one second. Frequency is measured in Hertz (usually abbreviated Hz), and can be calculated using the formula:

\[ V = f \lambda \]

where \( V \) is the velocity of the wave (in \( \text{m s}^{-1} \)), \( f \) is the frequency of the wave (in Hz), and \( \lambda \) (the Greek letter lambda) is the wavelength of the wave (distance from one peak / trough to the next, in m).

**Multiple Frequencies**

Let us consider the following signal (time is in ms, and the y-axis represents volts):

This signal is constructed from a number of different sine waves, with different frequencies, added together. These sine waves are as follows:
Frequency Spectra

Each of these sine waves has a different frequency. You can see this, as they have different distances between their peaks and troughs. These frequencies can be plotted against the amplitude of the wave, as in the table, and chart drawn from it, below:

<table>
<thead>
<tr>
<th>Wave (y=)</th>
<th>Period (ms)</th>
<th>Amplitude (V)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3sin x</td>
<td>6.284</td>
<td>3</td>
<td>159</td>
</tr>
<tr>
<td>sin(0.5x + 40)</td>
<td>12.566</td>
<td>1</td>
<td>80</td>
</tr>
<tr>
<td>2sin(3x - 60)</td>
<td>2.093</td>
<td>2</td>
<td>478</td>
</tr>
</tbody>
</table>
This chart is known as the frequency spectrum of a signal.

**Fundamental Frequency**

The fundamental frequency is the lowest frequency that makes up a signal. In the above example, the fundamental frequency is 80 Hz. It is always the frequency farthest to the left of a frequency spectrum, ignoring noise. Other frequencies are known as overtones, or harmonics.

**Questions**

1. What is the frequency of an X-ray (wavelength 0.5nm)?
2. A sound wave, with a frequency of 44 kHz, has a wavelength of 7.7mm. What is the speed of sound?
3. What is the fundamental frequency of the following signal?
4. Approximately how many harmonics does it contain?

5. The three sine waves \( \sin x^\circ \), \( 4\sin(2x-50)^\circ \) and \( 0.5\sin(3x+120)^\circ \) are added together to form a signal. What are the frequencies of each of the waves? What is the signal's fundamental frequency? Assume that the waves are travelling at the speed of light, and that \( 60^\circ = 1 \text{mm} \).

/Worked Solutions/
**A-level Physics (Advancing Physics)/Bandwidth**

Bandwidth is the frequency of a signal. Although original signals have varying frequencies, when these are transmitted, for example, as FM radio waves, they are modulated so that they only use frequencies within a certain range. FM radio modulates the frequency of a wave, so it needs some variation in the frequencies to allow for transmission of multiple frequencies. Since bandwidth is a frequency, it is the number of bits per second. The bandwidth required to transmit a signal accurately can be calculated by using 1 as the number of bits, giving the formula:

\[ B = \frac{1}{t} \]

where \( B \) is bandwidth (in Hz), and \( t \) is the time taken to transmit 1 bit of data (in s).

The bandwidth of a signal regulates the bit rate of the signal, as, with a higher frequency, more information can be transmitted. This gives us the formula (similar to the formula for lossless digital sampling):

\[ b = 2B \]

where \( b \) is the bit rate (in bits per second), and \( B \) is the bandwidth (in Hz).

**Questions**

1. A broadband internet connection has a bit rate of 8Mbit s\(^{-1}\) when downloading information. What is the minimum bandwidth required to carry this bit rate?

2. The same connection has a bandwidth of 100 kHz reserved for uploading information. What is the maximum bit rate that can be attained when uploading information using this connection?

3. A lighthouse uses a flashing light and Morse Code to communicate with a nearby shore. A 'dash' consists of the light being on for 2s. The light is left off for 1s between dots and dashes. What is the bandwidth of the connection?

4. The broadband connection in question two is used to upload a 1Mbyte image to a website. How long does it take to do this?

/Worked Solutions/
Electricity

A-level Physics (Advancing Physics)/Charge

Electrons, like many other particles, have a charge. While some particles have a positive charge, electrons have a negative charge. The charge on an electron is equal to approximately \(-1.6 \times 10^{-19}\) coulombs. Coulombs (commonly abbreviated C) are the unit of charge. One coulomb is defined as the electric charge carried by 1 ampere (amp) of current in 1 second. It is normal to ignore the negative nature of this charge when considering electricity.

If we have \(n\) particles with the same charge \(Q_{\text{particle}}\), then the total charge \(Q_{\text{total}}\) is given by:

\[
Q_{\text{total}} = n Q_{\text{particle}}
\]

By a simple rearrangement:

\[
n = \frac{Q_{\text{total}}}{Q_{\text{particle}}}\]

Questions

1. How much charge do 1234 electrons carry?
2. How many electrons does it take to carry 5 C of charge?
3. The total charge on 1 mole of electrons (\(6 \times 10^{23}\) particles) is equal to 1 faraday of charge. How many coulombs of charge are equal to 1 faraday?

/Worked Solutions/
A-level Physics (Advancing Physics)/Current

Current is the amount of charge (on particles such as electrons) flowing through part of an electric circuit per second. Current is measured in amperes (usually abbreviated A), where 1 ampere is 1 coulomb of charge per second. The formula for current is:

\[ I = \frac{\Delta Q}{\Delta t} \]  

([The triangle (greek letter /delta/) means change in the quantity])

where \( I \) is current (in A), \( Q \) is charge (in C) and \( t \) is the time it took for the charge to flow (in seconds).

In a series circuit, the current is the same everywhere in the circuit, as the rate of flow of charged particles is constant throughout the circuit. In a parallel circuit, however, the current is split between the branches of the circuit, as the number of charged particles flowing cannot change. This is Kirchoff’s First Law, stating that:

\[ i_1 + i_4 = i_2 + i_3 \]

“Any point in an electrical circuit where charge density is not changing in time [ie. there is no buildup of charge, as in a capacitor], the sum of currents flowing towards that point is equal to the sum of currents flowing away from that point.”

In mathematical form:

\[ \sum I_{in} = \sum I_{out} \]  

(The character that resembles a sideways M is the Greek letter /sigma/, meaning 'sum of'.)

Questions

1. 10 coulombs flow past a point in a wire in 1 minute. How much current is flowing through the point?
2. How long does it take for a 2A current to carry 5C?
3. In the diagram on the left, \( I = 9A \), and \( I_1 = 4.5A \). What is the current at \( I_2 \)?
4. What would \( I \) equal if \( I_1 = 10A \) and \( I_2 = 15A \)?
5. In the diagram on the left, in 5 seconds, 5C of charged particles flow past \( I_1 \), and 6.7C flow past \( I_2 \). How long does it take for 10C to flow past \( I_1 \)?
A-level Physics (Advancing Physics)/Voltage

Charge moves through a circuit, losing potential energy as it goes. This means that the charge travels as an electric current. Voltage is defined as the difference in potential energy per unit charge, i.e.

\[ V = \frac{E}{Q} \]

where \( V \) is voltage (in V), \( E \) is the difference in potential energy (in joules) and \( Q \) is charge (in coulombs).

There are two electrical properties which are both measured in volts (commonly abbreviated V), and so both are known under the somewhat vague title of 'voltage'. Both are so called because they change the potential energy of the charge.

**Electromotive Force (EMF)**

Electrical power sources (such as batteries) 'push' an electric current around a circuit. To do this, they have to exert a force on the electrons. This force is known as electromotive force, or EMF. The current travels around a circuit (from the negative pole of the power source to the positive) because of the difference in EMF between either end of the source. For example, the negative end of a battery may exert 9V of EMF, whereas the positive end exerts no EMF. As a result, the current flows from negative to positive.

**Potential Difference**

As charge travels around a circuit, each coulomb of charge has less potential energy, so the voltage (relative to the power source) decreases. The difference between the voltage at two points in a circuit is known as potential difference, and can be measured with a voltmeter.

**Series Circuits**

In a series circuit, the total voltage (EMF) is divided across the components, as each component causes the voltage to decrease, so each one has a potential difference. The sum of the potential differences across all the components is equal to the potential difference (but batteries have their own 'internal resistances', which complicates things slightly, as we will see).

**Parallel Circuits**

In a parallel circuit, the potential difference across each branch of the circuit is equal to the EMF, as the same 'force' is pushing along each path of the circuit. The number of charge carriers (current) differs, but the 'force' pushing them (voltage) does not.

**Questions**

1. A battery has an EMF of 5V. What is the total potential difference across all the components in the circuit?
2. The voltages (relative to the voltage of the battery) on either side of a resistor are -6V and -5V. What is the potential difference across the resistor?
3. At a given point in a circuit, 5C of charge have 10 kJ of potential energy. What is the voltage at this point?
4. Why do the electrons move to a point 1cm further along the wire?

/Worked Solutions/
A-level Physics (Advancing Physics)/Power

Power is a measure of how much potential energy is dissipated (i.e., converted into heat, light, and other forms of energy) by a component or circuit in one second. This is due to a drop in the potential energy, and so the voltage, of charge. Power is measured in Watts (commonly abbreviated W), where 1 W is 1 J s\(^{-1}\). It can be calculated by finding the product of the current flowing through a component/circuit and the potential difference across the component/circuit. This gives us the equation:

\[
P = \frac{E}{t} = IV
\]

where \(P\) is the power dissipated (in W), \(E\) is the drop in potential energy (in Joules, J), \(t\) is the time taken (in s), \(I\) is the current (in A) and \(V\) is either potential difference or electromotive force (in V), depending on the component being measured.

Since power is the amount of energy changing form per second, the amount of energy being given out each second will equal the power of the component giving out energy.

You should be able to substitute in values for \(I\) and \(V\) from other formulae (\(V=IR, Q=It\)) in order to relate power to resistance, conductance, charge and time, giving formulae like these:

\[
P = I^2R \\
P = \frac{V^2}{R} \\
P = \frac{QV}{t}
\]

Questions

1. The potential difference across a 9W light bulb is 240V. How much current is flowing through the light bulb?
2. How much energy is dissipated by a 10W component in 1 hour?
3. The potential difference across a top-notch kettle, which can hold up to 1 litre of water, is 240V, and the current is 12.5 A. 4.2 kJ of energy is required to heat a litre of water to 100°C. Assuming 100% efficiency, how long does it take to boil 1 litre of water?
4. How much energy is dissipated by a 100Ω resistor in 10 seconds if 2A of current are flowing?
5. The charge on an electron is \(-1.6 \times 10^{-19}\) C. How long does it take for a mole (6 x 10\(^{23}\) particles) of electrons to flow through a 40W light bulb on a 240V ring main?

/Worked Solutions/
A-level Physics (Advancing Physics)/Resistance and Conductance

Conductance is a measure of how well an artefact (such as an electrical component, not a material, such as iron) carries an electric current. Resistance is a measure of how well an artefact resists an electric current.

Resistance is measured in Ohms (usually abbreviated using the Greek letter Omega, Ω) and, in formulae, is represented by the letter R. Conductance is measured in Siemens (usually abbreviated S) and, in formulae, is represented by the letter G.

Resistance and conductance are each other’s reciprocals, so:

\[ R = \frac{1}{G} \quad \text{and} \quad G = \frac{1}{R} \]

**Ohm's Law**

Ohm's Law states that the potential difference across an artefact constructed from Ohmic conductors (i.e., conductors that obey Ohm's Law) is equal to the product of the current running through the component and the resistance of the component. As a formula:

\[ V = IR \]

where \( V \) is potential difference (in V), \( I \) is current (in A) and \( R \) is resistance (in Ω).

**In terms of Resistance**

This formula can be rearranged to give a formula which can be used to calculate the resistance of an artefact:

\[ R = \frac{V}{I} \]

**In terms of Conductance**

Since conductance is the reciprocal of resistance, we can deduce a formula for conductance (G):

\[ \frac{1}{G} = \frac{V}{I} \]

\[ G = \frac{I}{V} \]

**The Relationship between Potential Difference and Current**

From Ohm's Law, we can see that potential difference is directly proportional to current, provided resistance is constant. This is because two variables (let us call them \( x \) and \( y \)) are considered directly proportional to one another if:

\[ x = ky \]

where \( k \) is any positive constant. Since we are assuming that resistance is constant, \( R \) can equal \( k \), so \( V=RI \) states that potential difference is directly proportional to current. As a result, if potential difference is plotted against current on a graph, it will give a straight line with a positive gradient which passes through the origin. The gradient will equal the resistance.
In Series Circuits

In a series circuit (for example, a row of resistors connected to each other), the resistances of the resistors add up to give the total resistance. Since conductance is the reciprocal of resistance, the reciprocals of the conductances add up to give the reciprocal of the total conductance. So:

$$\Sigma R = R_1 + R_2 + ... + R_n$$

$$\frac{1}{\Sigma G} = \frac{1}{G_1} + \frac{1}{G_2} + ... + \frac{1}{G_n}$$

In Parallel Circuits

In a parallel circuit, the conductances of the components on each branch add up to give the total conductance. Similar to series circuits, the reciprocals of the total resistances of each branch add up to give the reciprocal of the total resistance of the circuit. So:

$$\Sigma G = G_1 + G_2 + ... + G_n$$

$$\frac{1}{\Sigma R} = \frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n}$$

When considering circuits which are a combination of series and parallel circuits, consider each branch as a separate component, and work out its total resistance or conductance before finishing the process as normal.

Questions

1. The potential difference across a resistor is 4V, and the current is 10A. What is the resistance of the resistor?
2. What is the conductance of this resistor?
3. A conductor has a conductance of 2S, and the potential difference across it is 0.5V. How much current is flowing through it?
4. A graph is drawn of potential difference across an Ohmic conductor, and current. For every 3cm across, the graph rises by 2cm. What is the conductance of the conductor?
5. On another graph of potential difference and current, the graph curves so that the gradient increases as current increases. What can you say about the resistor?
6. 3 resistors, wired in series, have resistances of 1kΩ, 5kΩ and 500Ω each. What is the total resistance across all three resistors?
7. 2 conductors, wired in parallel, have conductances of 10S and 5S. What is the total resistance of both branches of the parallel circuit?
8. The circuit above is attached in series to 1 10Ω resistor. What is the total conductance of the circuit now?

/Worked Solutions/
A-level Physics (Advancing Physics)/Internal Resistance

Batteries, just like other components in an electric circuit, have a resistance. This resistance is known as internal resistance. This means that applying Ohm's law ($V = IR$) to circuits is more complex than simply feeding the correct values for $V$, $I$ or $R$ into the formula.

The existence of internal resistance is indicated by measuring the potential difference across a battery. This is always less than the EMF of the battery. This is because of the internal resistance of the battery. This idea gives us the following formula:

\[ PD \text{ across battery} = \text{EMF of battery} - \text{voltage to be accounted for} \]

Let us replace these values with letters to give the simpler formula:

\[ V_{\text{external}} = E - V_{\text{internal}} \]

Since $V = IR$:

\[ V_{\text{external}} = E - IR_{\text{internal}} \]

You may also need to use the following formula to work out the external potential difference, if you are not given it:

\[ V_{\text{external}} = I\Sigma R_{\text{external}} \]

You should also remember the effects of using resistors in both series and parallel circuits.
Questions

1. A 9V battery is short-circuited. The potential difference across the battery is found to be 8V, and the current is 5A. What is the internal resistance of the battery?

2. What is the EMF of the battery in the following circuit?

3. What is the internal resistance of the battery in the following circuit?
A potential divider, or potentiometer, consists of a number of resistors, and a voltmeter. The voltage read by the voltmeter is determined by the ratio of the resistances on either side of the point at which one end of the voltmeter is connected.

To understand how a potential divider works, let us consider resistors in series. The resistances add up, so, in a circuit with two resistors:

\[ \Sigma R = R_1 + R_2 \]

If we apply Ohm's law, remembering that the current is constant throughout a series circuit:

\[ \frac{\Sigma V}{I} = \frac{V_1}{I} + \frac{V_2}{I} \]

Multiply by current (I):

\[ \Sigma V = V_1 + V_2 \]

So, just as the resistances in series add up to the total resistance, the potential differences add up to the total potential difference. The ratios between the resistances are equal to the ratios between the potential differences. In other words, we can calculate the potential difference across a resistor using the formula:
\[ V_{\text{resistor}} = \sum V \times \frac{R_{\text{resistor}}}{\sum R_{\text{external}}} \]

In many cases, you will be told to assume that the internal resistance of the power source is negligible, meaning that you can take the total potential difference as the EMF of the power source.

A potential divider may work by combining a variable resistor such as an LDR or thermistor with a constant resistor, as in the diagram below. As the resistance of the variable resistor changes, the ratio between the resistances changes, so the potential difference across any given resistor changes.

Alternatively, a potential divider may be made of many resistors. A 'wiper' may move across them, varying the number of resistors on either side of the wiper as it moves, as in the following diagram:

Questions

1. A 12 kΩ resistor and a 20 kΩ resistor are connected to a 9V battery. A voltmeter is connected across the 12kΩ resistor. What is the reading on the voltmeter? (Assume negligible internal resistance.)

2. A potential divider consists of 100 5Ω resistors, with a wiper which moves on one resistor for every 3.6° a handle connected to it turns. The wiper is connected to a voltmeter, and the circuit is powered by a 120V power source with negligible internal resistance. What is the reading on the voltmeter when the handle turns 120°?

3. A 9V battery with internal resistance 0.8Ω is connected to 3 resistors with conductances of 3, 2 and 1 Siemens. A voltmeter is connected across the 3 and 2 Siemens resistors. An ammeter is placed in the circuit, between the battery and the first terminal of the voltmeter, and reads 2A. What is the reading on the voltmeter?

/Worked Solutions/
A-level Physics (Advancing Physics)/Sensors

A sensor is a device which converts a physical property into an electrical property (such as resistance). A sensing system is a system (usually a circuit) which allows this electrical property, and so the physical property, to be measured.

Temperature Sensor

A common example of a sensing system is a temperature sensor in a thermostat, which uses a thermistor. In the most common type of thermistor (an NTC), the resistance decreases as the temperature increases. This effect is achieved by making the thermistor out of a semiconductor. The thermistor is then used in a potential divider, as in the diagram on the right. In this diagram, the potential difference is divided between the resistor and the thermistor. As the temperature rises, the resistance of the thermistor decreases, so the potential difference across it decreases. This means that potential difference across the resistor increases as temperature increases. This is why the voltmeter is across the resistor, not the thermistor.

Properties

There are three main properties of sensing systems you need to know about:

Sensitivity

This is the amount of change in voltage output per unit change in input (the physical property). For example, in the above sensing system, if the voltage on the voltmeter increased by 10V as the temperature increased by 6.3°C:

\[ S = \frac{10}{6.3} \approx 1.59 \text{V/°C} \]

Resolution

This is the smallest change in the physical property detectable by the sensing system. Sometimes, the limiting factor is the number of decimal places the voltmeter can display. So if, for example, the voltmeter can display the voltage to 2 decimal places, the smallest visible change in voltage is 0.01V. We can then use the sensitivity of the sensor to calculate the resolution.

\[ S = 1.59 = \frac{0.01}{R} \]

\[ R = \frac{0.01}{1.59} \approx 0.006 \text{°C} \]
**Response Time**
This is the time the sensing system takes to display a change in the physical property it is measuring. It is often difficult to measure.

**Signal Amplification**
Sometimes, a sensing system gives a difference in output voltage, but the sensitivity is far too low to be of any use. There are two solutions to this problem, which can be used together:

**Amplification**
An amplifier can be placed in the system, increasing the signal. The main problem with this is that the signal cannot exceed the maximum voltage of the system, so values will be chopped off of the top and bottom of the signal because it is so high.

**Wheatstone Bridge**
This solution is far better, especially when used prior to amplification. Instead of using just one pair of resistors, a second pair is used, and the potential difference between the two pairs (which are connected in parallel) is measured. This means that, if, at the sensing resistor (eg. thermistor / LDR) the resistance is at its maximum, a signal of 0V is produced. This means that the extremes of the signal are not chopped off, making for a much better sensor.

**Questions**
An LDR’s resistance decreases from a maximum resistance of 2kΩ to a minimum resistance of 0Ω as light intensity increases. It is used in a distance sensing system which consists of a 9V power supply, a 1.6 kΩ resistor, the LDR and a multimeter which displays voltage to 2 decimal places measuring the potential difference across one of the two resistors.

1. Across which resistor should the multimeter be connected in order to ensure that, as the distance from the light source to the sensor increases, the potential difference recorded increases?
2. In complete darkness, what voltage is recorded on the multimeter?
3. When a light source moves 0.5m away from the sensor, the voltage on the multimeter increases by 2V. What is the sensitivity of the sensing system when using this light source, in V m⁻¹?
4. When the same light source is placed 0m from the sensor, the potential difference is 0V. When the light source is 1m away, what voltage is displayed on the multimeter?
5. What is the resolution of the sensing system?
6. Draw a circuit diagram showing a similar sensing system to this, using a Wheatstone bridge and amplifier to improve the sensitivity of the system.
7. What is the maximum potential difference that can reach the amplifier using this new system (ignore the amplification)?
8. If this signal were to be amplified 3 times, would it exceed the maximum voltage of the system? What would the limits on the signal be?

/Worked Solutions/
A-level Physics (Advancing Physics)/Resistivity and Conductivity

Resistivity and conductivity are material properties: they apply to all examples of a certain material anywhere. They are not the same as resistance and conductance, which are properties of individual artefacts. This means that they only apply to a given object. They describe how well a material resists or conducts an electric current.

Symbols and Units

Resistivity is usually represented by the Greek letter rho (ρ), and is measured in Ω m. Conductivity is usually represented by the Greek letter sigma (σ), and is measured in S m⁻¹.

Formulae

The formula relating resistivity (ρ) to resistance (R), cross-sectional area (A) and length (L) is:

\[ ρ = \frac{RA}{L} \]

Conductivity is the reciprocal of resistivity, just as conductance (G) is the reciprocal of resistance. Hence:

\[ \frac{1}{\sigma} = \frac{1}{G} \times \frac{A}{L} = \frac{A}{GL} \]

\[ σ = \frac{GL}{A} \]

You should be able to rearrange these two formulae to be able to work out resistance, conductance, cross-sectional area and length. For example, it all makes a lot more sense if we write the first formula in terms of ρ, A and L:

\[ R = \frac{ρL}{A} \]

From this, we can see that the resistance of a lump of material is higher if it has a higher resistivity, or if it is longer. Also, if it has a larger cross-sectional area, its resistance is smaller.

Questions

1. A material has a conductivity of $10^6$ S m⁻¹. What is its resistivity?
2. A pure copper wire has a radius of 0.5mm, a resistance of 1 MΩ, and is 4680 km long. What is the resistivity of copper?
3. Gold has a conductivity of 45 MS m⁻¹. What is the resistance of a 0.01m across gold connector, 0.05m long?
4. A strand of metal is stretched to twice its original length. What is its new resistance? State your assumptions.
5. Which has the greater resistivity: a plank or a piece of sawdust, made from the same wood?

/Worked Solutions/
A semiconductor has a conductivity between that of a conductor and an insulator. They are less conductive than metals, but differ from metals in that, as a semiconductor heats up, its conductivity rises. In metals, the opposite effect occurs. The reason for this is that, in a semiconductor, very few atoms are ionised, and so very few electrons can move, creating an electric current. However, as the semiconductor heats up, the covalent bonds (atoms sharing electrons, causing the electrons to be relatively immobile) break down, freeing the electrons. As a result, a semiconductor’s conductivity rises at an increasing rate as temperature rises.

Examples of semiconductors include silicon and germanium. A full list of semiconductor materials is available at Wikipedia. At room temperature, silicon has a conductivity of about 435 μS m⁻¹.

Semiconductors are usually ‘doped’. This means that ions are added in small quantities, giving the semiconductor a greater or lesser number of free electrons as required. This is controlled by the charge on the ions.

Questions
1. What is the resistivity of silicon, at room temperature?
2. What sort of variable resistor would a semiconductor be useful in?
3. If positive ions are added to silicon (doping it), how does its conductivity change?

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See Also
- The book on Semiconductors.
Material Structure

A-level Physics (Advancing Physics)/Stress, Strain & the Young Modulus

Stress
Stress is a measure of how strong a material is. This is defined as how much pressure the material can stand without undergoing some sort of physical change. Hence, the formula for calculating stress is the same as the formula for calculating pressure:

\[ \sigma = \frac{F}{A} \]

where \( \sigma \) is stress (in Newtons per square metre but usually Pascals, commonly abbreviated Pa), \( F \) is force (in Newtons, commonly abbreviated N) and \( A \) is the cross sectional area of the sample.

Tensile Strength
The tensile strength is the level of stress at which a material will fracture. Tensile strength is also known as fracture stress. If a material fractures by 'crack propagation' (i.e., it shatters), the material is brittle.

Yield Stress
The yield stress is the level of stress at which a material will deform permanently. This is also known as yield strength.

Strain
Stress causes strain. Putting pressure on an object causes it to stretch. Strain is a measure of how much an object is being stretched. The formula for strain is:

\[ \epsilon = \frac{L - l}{l} = \frac{\Delta l}{l} = \frac{L}{l} - 1, \]

where \( l \) is the original length of some bar being stretched, and \( L \) is its length after it has been stretched. \( \Delta l \) is the extension of the bar, the difference between these two lengths.

Young's Modulus
Young's Modulus is a measure of the stiffness of a material. It states how much a material will stretch (i.e., how much strain it will undergo) as a result of a given amount of stress. The formula for calculating it is:

\[ E = \frac{\sigma}{\epsilon} \]

The values for stress and strain must be taken at as low a stress level as possible, provided a difference in the length of the sample can be measured. Strain is unitless so Young's Modulus has the same units as stress, i.e. N/m² or Pa.
Stress-Strain Graphs

Stress (\(\sigma\)) can be graphed against strain (\(\varepsilon\)). The toughness of a material (i.e., how much it resists stress, in J m\(^{-3}\)) is equal to the area under the curve, between the y-axis and the fracture point. Graphs such as the one on the right show how stress affects a material. This image shows the stress-strain graph for low-carbon steel. It has three main features:

**Elastic Region**

In this region (between the origin and point 2), the ratio between stress and strain (Young's modulus) is constant, meaning that the material is obeying Hooke's law, which states that a material is elastic (it will return to its original shape) if force is directly proportional to extension.

**Hooke's Law**

Hooke's law of elasticity is an approximation that states that the Force (load) is in direct proportion with the extension of a material as long as this load does not exceed the elastic limit. Materials for which Hooke's law is a useful approximation are known as linear-elastic or "Hookean" materials.

\[
F = -kx
\]

The relation is often denoted

\[
F \propto x
\]

The work done to stretch a wire or the Elastic Potential Energy is equal to the area of the triangle on a Tension/Extension graph, but can also be expressed as

\[
\frac{1}{2}kx^2
\]

**Plastic Region**

In this region (between points 2 and 3), the rate at which extension is increasing is going up, and the material has passed the elastic limit. It will no longer return to its original shape. After point 1, the amount of stress decreases due to 'necking', so the cross-sectional area is going down. The material will 'give' and extend more under less force.

**Fracture Point**

At point 3, the material finally breaks/fractures and the curve ends.

**Other Typical Graphs**

In a brittle material, such as glass or ceramics, the stress-strain graph will have an extremely short elastic region, and then will fracture. There is no plastic region on the stress-strain graph of a brittle material.
Questions

1. 10N of force are exerted on a wire with cross-sectional area 0.5mm\(^2\). How much stress is being exerted on the wire?

2. Another wire has a tensile strength of 70MPa, and breaks under 100N of force. What is the cross-sectional area of the wire just before breaking?

3. What is the strain on a Twix bar (original length 10cm) if it is now 12cm long?

4. What is this strain, expressed as a percentage?

5. 50N are applied to a wire with a radius of 1mm. The wire was 0.7m long, but is now 0.75m long. What is the Young's Modulus for the material the wire is made of?

6. Glass, a brittle material, fractures at a strain of 0.004 and a stress of 240 MPa. Sketch the stress-strain graph for glass.

7. (Extra nasty question which you won't ever get in an exam) What is the toughness of glass?

/Worked Solutions/

A-level Physics (Advancing Physics)/Metals

There are several physical properties of metals you need to know about:

**Electrical Conductivity**

Metals consist of positive metal ions in a 'soup' or 'sea' of free (delocalized) electrons. This means that the electrons are free to move through the metal, conducting an electric current.

**Stiffness**

The charge between the negatively charged electrons and the positively charged ions holds the ions together, making metals stiff.

**Ductility**

Since there are no permanent bonds between the ions, they can move about and slide past each other. This makes metals ductile.

**Toughness**

Metals are tough for the same reason as they are ductile: the positive ions can slide past each other while still remaining together. So, instead of breaking apart, they change shape, resulting in increased toughness. This effect is called plasticity.

**Elasticity**

When a metal is stretched, it can return to its original shape because the sea of electrons which bonds the ions together can be stretched as well.
Brittle
The opposite of tough: a material is likely to crack or shatter upon impact or force. It will snap cleanly due to defects and cracks.

Transformation
Diffusive transformation: occur when the planes of atoms in the material move past each other due to the stresses on the object. This transformation is permanent and cannot be recovered from due to energy being absorbed by the structure
Diffusionless transformation: occurs where the bonds between the atoms stretch, allowing the material to deform elastically. An example would be rubber or a shape memory metal/alloy (often referred to as SMA) such as a nickel-titanium alloy. In the shape memory alloy the transformation occurs via the change of phase of the internal structure from martensitic to deformed martensitic, which allows the SMA to have a high percentage strain (up to 8% for some SMA's in comparison to approximately 0.5% for steel). If the material is then heated above a certain temperature the deformed martensite will form austenite, which returns to twinned martensite after cooling.

Questions
1. Would you expect a metal to have more or less conductivity than a semiconductor? Why?
2. How can the stress-strain graph for a metal be explained in terms of ions in a sea of electrons?
3. As a metal heats up, what happens to its conductivity? Why?

/Worked Solutions/

A-level Physics (Advancing Physics)/Polymers
A simple polymer consists of a long chain of monomers (components of molecules) joined by covalent bonds. A polymer usually consists of many of these bonds, tangled up. This is known as a bulk polymer.

Types
A bulk polymer may contain two types of regions. In crystalline regions, the chains run parallel to each other, whereas in amorphous regions, they do not. Intermolecular bonds are stronger in crystalline regions. A polycrystalline polymer consists of multiple regions, in which the chains point in a different direction in each region.
Properties

Transparency
Polymer chains may be linked together, causing the polymer to become stiffer. An example is rubber, which, when heated with sulfur, undergoes a process known as vulcanization. The chains in the rubber become joined by sulfur atoms, making the rubber suitable for use in car tyres. A stiffer polymer, however, will usually be more brittle.

Plasticity
When a polymer is stretched, the chains become parallel, and amorphous areas may become crystalline. This causes an apparent change in colour, and a process known as 'necking'. This is when the chains recede out of an area of the substance, making it thinner, with fatter areas on either side.

Conductivity
Polymers consist of covalent bonds, so the electrons are not free to move according to potential difference. This means that polymers are poor conductors.

Boiling Point
Polymers do not have boiling points. This is because, before they reach a theoretical boiling point, polymers decompose. Polymers do not have melting points for the same reason.

Questions
1. Different crystalline structures have different refractive indexes. Why does this mean that a polycrystalline polymer is translucent?
2. What sort of polymer is a pane of perspex?
3. What sort of polymer does the pane of perspex become when shattered (but still in one piece)?

4. What sort of polymer is a rubber on the end of a pencil?

5. What happens to the translucency of an amorphous polymer when it is put under stress?

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