INTERACTIONS of LIGHT and MATTER

Light has been described both as a particle and as a wave. The electron has wave-like properties too. This has led to different ways of thinking, not only about light, but also about matter. These ideas are explored using experimental evidence and conceptual models so that the development of the ideas can be followed alongside developments in technology.

- explain the results of Young’s double slit experiment in terms of
  - evidence for the wave-like nature of light
  - constructive and destructive interference of coherent waves in terms of path differences, \( pd = n \lambda \), \( pd = (n - \frac{1}{2}) \lambda \) respectively
  - qualitative effect of wavelength, distance of screen and slit separation on interference patterns;

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Wave model

In 1690 Huygens proposed the wave theory of light. This model suggests that light is transmitted as a wave between source and observer. The wave does not require a medium for transmission.

- Linear Propagation: The direction of energy transmission is perpendicular to the wave front. Two sets of waves pass through each other, apparently unaffected, as do two beams of light.
- Reflection: Can be explained in terms of waves.
- Refraction: Can be explained in terms of waves. The wave model predicts velocity changes on refraction of light that are, in fact, verified by experiment.
- Inverse Square Law: A spherical wave starting from a point obeys the inverse square law.
- Diffraction; Interference and Polarisation: These effects can all be explained with the wave model.

Young’s Double Slit Experiment:

This experiment showed that light would produce an interference pattern, because it diffracted when passing through very small slits if the sources were close enough together. Young explained this result, using Huygens’ Principle and assuming that each narrow slit acted as a source of secondary waves which spread out behind the slits and interfered with each other to form the bright and dark bands.

The pattern produced has a pattern of nodes and antinodes just like sound or water. A series of light and dark lines were observed on the screen. Dark lines correspond to cancellation, or nodes, bright lines to antinodes.

Antinodes were where crests met crests and troughs met troughs and constructively interfered with each other to form the bright lines. Nodes were formed where crests met troughs and troughs met crests and the displacements cancelled each other out by deconstructive interference, producing lines of minimum intensity.
The pattern can be described algebraically as $x = \frac{n\lambda L}{d}$. Where $x$ is the distance between the central maximum and the local maximum, $n$ is the nodal line, $\lambda$ is the wavelength, $L$ is the perpendicular distance from the slits to the screen, and ‘$d$’ is the distance between the two slits. The study design is specific, you only need to have a qualitative understanding of this relationship.

**Example 305: 1971 Question 58  (1 mark)**
With reference to the simple particle model of light propagation, which of the following statements are true?

A. It accounts satisfactorily for reflection at a surface,
B. It yields an inverse-square law for the decrease in light intensity with distance from a point source,
C. It predicts that light which is incident on a surface will exert pressure on that surface.
D. It predicts that light will travel more slowly in a refracting material than in a vacuum.

*(One or more answers)*

**Example 306: 1971 Question 59  (1 mark)**
With reference to the wave model of light propagation, which of the following statements are true?

A. It accounts satisfactorily for both interference and diffraction effects.
B. It predicts that light will travel more quickly in a refracting material than in a vacuum.
C. It accounts satisfactorily for the photoelectric effect
D. It accounts satisfactorily for partial reflection and partial transmission at a surface.

*(One or more answers)*

**Example 307: 1973 Question 48  (1 mark)**
Which of the following phenomena cannot readily be accounted for by the particle model of light?

A. When light is reflected by a mirror the angle of reflection is equal to the angle of incidence.
B. When light passes through a slit it is diffracted
C. When light passes from air to water it is refracted
D. The intensity of light from a point source decreases with increasing distance from the source.
E. Light exerts a pressure when falling on a surface
Example 308: 1976 Question 58  (1 mark)

Sound exhibits wave behaviour. Which of the following statements provides the best evidence for the truth of this statement?

A. Sound can be produced by vibrating objects
B. Sound can be reflected
C. Sound can be refracted
D. Diffraction effects can be readily observed with sound
E. Windows can be shattered by sounds of high intensity
F. Sound travels at 300 m s⁻¹ in air

Example 309: 1976 Question 59  (1 mark)

Sound is not a form of electromagnetic radiation. Which of the above statements is the best evidence for the truth of this statement?

When light of single wavelength passes through two close, narrow slits a pattern of light and dark bands is observed on a screen that is about 2 metres from the slits. The experimental arrangement is illustrated below.

Example 310: 1997 Question 4  (1 mark)

Explain, giving reasons, whether the particle model or the wave model for light best explains the observations of this experiment.
Jac and Jules are observing a demonstration of Young’s double slit experiment. Their teacher, Mel, has set up a He-Ne laser of wavelength 632 nm and directed the beam onto a set of two parallel slits. A pattern from these slits has been projected onto a distant wall.

The teacher asks each student to estimate the difference between the length of the lines P1 and P2, which are the lines between the centre of each slit and the 6th bright spot.

Example 311: 2004 Pilot Question 10   (3 marks)

Estimate the difference in length between P1 and P2.
A group of students is studying Young’s double slit experiment using microwaves ($\lambda = 3.0$ cm) instead of light. A microwave detector is moved along the line PQ, and the maxima and minima in microwave intensity are recorded. The experimental apparatus is shown below.

Example 312: 2008 Question 3 (2 marks)
What is the path difference $S_1Z - S_2Z$ in cm?

Example 313: 2008 Question 4 (2 marks)
Explain why there is a maximum in microwave intensity detected at point Y.

The students reduce the separation of the slits $S_1$ and $S_2$.

Example 314: 2008 Question 5 (2 marks)
Explain the effect of this change on the pattern of maxima and minima along the line PQ.
Louise and Thelma set up the apparatus shown below. It consists of a laser providing light of a single wavelength, which passes through two narrow slits and produces a pattern of bright and dark bands on a screen some distance away.

Example 315: 2009 Question 3 (3 marks)
Before doing the experiment, Louise believes that the central band (the one exactly opposite the centre point between the two slits) is a dark band. Thelma believes that this is a bright band. Who is correct? Outline your reasoning clearly.

Example 316: 2009 Question 4 (2 marks)
The pattern of bright and dark bands is shown below.

Precision measurement shows that the path difference to the middle of dark band A (that is, the distance AS₂ – AS₁) is greater than the path difference to the middle of dark band B by 496 nm. From this information, determine the wavelength of the laser. You may include a diagram.
Two students set up a two-slit interference experiment with a source of laser light, as shown below.

The wavelength of the light from the laser is 612 nm. The figure below shows a sketch of the central section of the interference pattern that they obtain. The central band \( C \), which is a bright band, is labelled.

Example 317: 2012 Question 2a (2 marks)
The light energy output of the laser is \( 5.0 \times 10^{-3} \) J s\(^{-1}\). Calculate the number of photons leaving the laser every second.

Another laser that produces light of a different wavelength is now used. The pattern is now spaced more closely. The first figure below shows the new pattern and the second figure shows the original pattern. The second bright band to the left of \( C \) in the new pattern is at the position labelled \( Y \). In the original pattern this was the position of the second dark band to the left of \( C \).

Example 318: 2012 Question 4 (2 marks)
Calculate the wavelength of the light produced by this new laser.
The apparatus for a Young's double-slit experiment is shown below.

A beam of green light ($\lambda = 550$ nm) is incident on the slits.

**Example 319: 2013 Question 22c**  (3 marks)

The path difference from the slits to the second bright band from the centre of the interference pattern is $1.4 \times 10^3$ nm.
Calculate the path difference (in metres) from the slits to the first dark band from the centre of the pattern.
A group of students carries out a two-slit interference experiment using light with a wavelength of 420 nm. The arrangement of the students’ apparatus and the resulting interference pattern are shown below.
The point M on the screen is at the centre of the interference pattern. There is a bright band at point P on the screen. It is the second bright band to the right of M, as shown.

Example 320: 2014 Question 19b  (3 marks)
The students repeat the experiment using light of a different wavelength. They find that, at the point P on the screen, there is now a dark band. It is the second dark band to the right of M.
Calculate the wavelength of this light. Show your working.
• analyse the photoelectric effect in terms of
  – evidence for the particle-like nature of light
  – experimental data in the form of graphs of photocurrent versus electrode potential, and of kinetic energy of electrons versus frequency
  – kinetic energy of emitted photoelectrons, \( E_{k\text{max}} = hf - W \), using energy units of joule and electron-volt
  – effects of intensity of incident irradiation on the emission of photoelectrons;
• describe why the wave model of light cannot account for the experimental photoelectric effect results;

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<td>1a, b, c, d</td>
<td>21a, b, c, d</td>
<td>20a, b</td>
<td>18a, b, c, d</td>
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In 1909 Millikan determined that

\[
\text{Mass of electron} = 9.1 \times 10^{-31} \text{ kg}
\]

\[
\text{Charge of electron } e = -1.6 \times 10^{-19} \text{ C}
\]

This charge is known as the ELEMENTARY CHARGE. Any charged material must have a whole number multiple of this amount of charge. We say that charge is quantised.

**Electric fields**

An electric field \( E \) is the region around a charged body where another charged body would experience electric forces of attraction or repulsion. The direction of the electric field is defined as the direction of the force on a positive charge placed in the field.

**Electric forces**

Electric forces are given by the product of the electric field and the quantity of charge.

\[
F_E = qE
\]

Where \( F_E \) = electric force (N)  
\( q \) = charge (C)  
\( E \) = electric field (N/C)

**Electric fields between charged plates**

In the region between parallel charged plates, the electric field \( E \) is uniform. The strength of the field depends on the potential difference between the plates and the distance between the plates.

\[
E = \frac{\Delta V}{d}
\]

Where \( E \) = electric field strength (V/m)  
\( \Delta V \) = potential difference (V)  
\( d \) = distance between plates (m)

**Electrons moving between charged plates**

In the region between charged plates, the electric field \( E \) is constant, and so a constant electric force \( F_E \) acts on any electrons between the plates.

The electric force does work on these electrons and they gain kinetic energy as they move towards the positive plate. Unit of work and energy = joules (J)

A convenient unit of energy when dealing with electrons is the electron volt (eV). An electron gains 1eV of energy when it is accelerated across a potential difference of 1 volt.

\[
\text{Work} = \Delta KE = q \times \Delta V
\]

\[
1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}
\]

To convert from J to eV, divide the energy (in Joules) by \( 1.6 \times 10^{-19} \).
A pair of charged parallel plates have a potential difference of 10 000 volt between them, and are 3.0 mm apart, as shown below.

Example 321: 2000 Question 1  (2 marks)
Calculate the magnitude of the electric field between the plates.
(Give your answer in the unit V m⁻¹)

Example 322: 2000 Question 2  (2 marks)
Calculate the work done on an electron crossing from the negative plate to the positive plate. Give your answer in joule. (e = 1.6 × 10⁻¹⁹ C)

Example 323: 2001 Question 1  (2 marks)
In an electron microscope, electrons are accelerated from rest across a potential difference of 10 kV. Calculate the kinetic energy of an electron, in joule, after being accelerated from rest across a potential difference of 10 kV.
Photoelectric effect
The discovery of the photoelectric effect dramatically changed the way scientists were thinking about light. The particle model had lost support since Young’s double slit interference experiments. The wave model could not explain the photoelectric effect. It sometimes happens that when light falls on certain metals, electrons are ejected from the metal. These electrons are known as photoelectrons.

The experiment can be used to show that the number of electrons ejected depends upon the light intensity. As the light intensity increased, so too did the size of the current. More electrons were escaping from the metal when the light was brighter.

When the battery is reversed, some important results are obtained.
• As the anode is made more negative fewer electrons get across the tube- this means that the ejected electrons must have a range of kinetic energies. Electrons with little or no KE are stopped as soon as the anode becomes negative - those with the most KE being stopped by \( V_c \) volts. Energetic electrons come from the surface, less energetic electrons from below the metal surface.
• The value of \( V_c \), the cut off voltage, depends upon the colour, not the intensity of the light. With most metals, low frequency light will not generate electrons.
• More intense light generates more electrons, but does not increase their energy.

When the frequency (i.e. colour) of the light shining on the metal changes, there is a frequency at which the electrons begun to be emitted from the metal. This is called the THRESHOLD or CUT-OFF FREQUENCY (\( f_c \)). Below this frequency, no emission occurs, even for very intense light.

![Diagram showing the photocurrent versus anode potential for different colors of light.](image)

These results cannot be explained using wave mechanical ideas. These would suggest that the energy carried by the wave would be distributed among all the atoms of the metal, building up until sufficient energy was available to ionise the atoms.

Thus intense light should produce a current more quickly than dim light. This is not so, electron emission is a factor of frequency not intensity. The results can be explained if it is assumed that light comes in random packets and not waves. The energy of one of these photons is transferred to one atom only, not spread to many, and hence the photoelectrons are observed immediately.
The figure above represents a photo-electric tube, in which light of a particular frequency and constant intensity strikes the plate; electrons of charge e are emitted and travel to the collector. As the potential difference between the collector and plate is varied, the current measured by the milli-ammeter varies as shown below.

Example 324: 1981 Question 47  (1 mark)

Why is the photo-electric current constant at positive values of $V$?

A. The electric field between the collector and the plate remains constant as $V$ is increased; thus increases in $V$ do not increase the kinetic energy of the emitted electrons.

B. For a particular light intensity, there is a corresponding number of electrons emitted per second; when all of these have been collected, further increases in $V$ do not increase the current.

C. All the photo-electrons have the same mass, charge, and kinetic energy, and none of these quantities is affected by changes in $V$.

D. Ohm's Law applies to the photo-electric tube; as $V$ is increased, its resistance increases, and so the current remains constant.
Example 325: 1981 Question 48  (1 mark)
If the frequency of the light striking the plate were now varied systematically, which of the graphs (A - F) would best represent the relationship between the magnitude of $V_o$ and $f$?

Example 326: 1981 Question 49  (1 mark)
In 1905, Einstein proposed the following equation to account for the photo-electric effect:

\[ E = hf - w. \]

The quantity $w$ is

A  a constant, whose value is characteristic of the particular metal used in the plate

B  a constant which depends on the frequency of the light

C  the gradient of the $i$ - $V$ graph in the negative region

D  equal to $V_o$
An experiment is carried out to investigate the photoelectric effect. Light of a single frequency shines onto a clean metal plate M inside an evacuated glass tube as shown below.

When the voltage V between the plates is varied, the current measured by the ammeter varies as shown below. V is the voltage of the right-hand plate relative to the plate receiving light.

Example 327: 1997 Question 2 (1 mark)
What is the maximum kinetic energy of electrons ejected from the plate M? Give your answer in joule.

The light source is replaced by one of much higher intensity.

Example 328: 1997 Question 3 (1 mark)
How does this affect the voltage at which the current is zero? Explain your answer using a photon model for light.
Einstein’s explanation of the photoelectric effect was that each photon of light gave up its energy completely when it collided with an electron in a metal.

The energised electron used up some of this energy in overcoming the binding force of the atoms in the metal and escaped with the remaining energy.

The energy that the electron uses up to escape from the metal is called the BINDING ENERGY or WORK FUNCTION (W) of the metal. Hence the work function (binding energy) is the difference between the energy of the incident photon and the maximum KE of the electrons that are ejected.

This quantity is a property of the metal and varies from metal to metal.

Thus the maximum Kinetic energy of the escaped electron is given by

\[
E_k = qV_c = hf - W
\]

**Kinetic Energy vs Frequency graph.**

If a graph of the KE of the ejected electrons is plotted against the frequency of the incoming light the following can be deduced:

- There is a threshold frequency below which the electrons are not emitted.
- Different metals have different threshold frequencies
- The gradient of the graph is the same for all metals, it is Planks constant
- The equation of the graph, an energy equation, is \( E_k = hf - W \) where \( E_k \) is the Kinetic Energy of the ejected electrons, \( h \) a universal constant and \( W \) a constant for the material. This can be written as \( hf = E_k + W \)
- The constant \( h \) is Planck’s constant and has the value of \( 6.626 \times 10^{-34} \) J s. or \( 4.136 \times 10^{-15} \) eV s.
- \( W \) is either called the work function or the binding energy of the metal.
Monochromatic ultraviolet light is incident on a magnesium surface, from which electrons are ejected. The graph shows the maximum kinetic energy of individual electrons for light of various frequencies.

**Example 329: 1979 Question 66 (1 mark)**

The gradient, $k$, of this graph can be used to estimate

A. the charge on the electron  
B. the charge/mass ratio of the electron  
C. Planck's constant  
D. the ionization energy of magnesium

**Example 330: 1979 Question 67 (1 mark)**

What is the minimum amount of energy, $E_{\text{min}}$, required to remove a single electron from a magnesium surface?

**Example 331: 1979 Question 68 (1 mark)**

If another metal had been used instead of magnesium, one would expect that

A. $k$ and $E_{\text{min}}$ would both have different values  
B. $k$ would be different, but $E_{\text{min}}$ would be the same  
C. $k$ would be the same, but $E_{\text{min}}$ would be different  
D. $k$ and $E_{\text{min}}$ would still be the same.
Example 332: 1979 Question 69 (1 mark)
Monochromatic light, of fixed frequency $12 \times 10^{14}$ Hz but variable intensity, is shone onto the magnesium surface. Which of the following graphs best shows the relationship between $E_{\text{max}}$ (the maximum kinetic energy of individual electrons) and intensity?

Example 333: 1982 Question 48 (1 mark)
Which of the following figures best represent the relationship between $V_s$ and the frequency of the light, $f$, for four different metals?

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Example 334: 1982 Question 49  (1 mark)
Blue light of a particular intensity is found to cause photoelectric emission from a sodium surface, but not from a platinum surface. In order to produce photoelectric emission from platinum, which one or more of the following changes would be necessary?

A. Replace the blue light by light of much longer wavelength.
B. Replace the blue light by light of much shorter wavelength.
C. Increase the intensity of the light.
D. Reduce the temperature of the platinum.

(One or more answers)

Example 335: 1982 Question 50  (1 mark)
Which of the following best accounts for the difference in behaviour between platinum and sodium?

A. Electrons in platinum are less able to capture photons.
B. Platinum has fewer electrons than sodium.
C. More energy is needed to remove an electron from a platinum surface.
D. Photons are able to penetrate a sodium surface more easily.
An apparatus to investigate the photoelectric effect is set up as shown in the figure below. The ammeter measures the current $I$ in the circuit, and the voltmeter measures the potential $V_{EC}$ of the collector relative to the emitter. $V_{EC}$ may be made positive or negative as shown.

For an emitter made of a particular material and illuminated with light of a fixed intensity and frequency the following graph of $I$ as a function of $V_{EC}$ is obtained. $I_0$ is the current obtained for a very large value of $V_{EC}$.

Example 336: 1985 Question 46 (1 mark)

Which graph (A - F) below best represents the results expected if the intensity of the light were doubled, using the same emitter and the same frequency of light?

The experiment is repeated using the same emitter but light of a higher frequency. The intensity of light is such that the same number of photons per second falls on the emitter as originally, when obtaining the results.

Example 337: 1985 Question 47 (1 mark)

Which of the graphs (A - F) best represents the results expected?
When ultraviolet light falls on a potassium surface, electrons are emitted from the surface of the metal.

The Kinetic energy $T_{\text{MAX}}$ of the most energetic electrons is found to be dependent upon the frequency, $f$, of the radiation used, as shown in the graph above.

**Example 338: 1986 Question 47**  (1 mark)
Which of the graphs (A - E) below, represents the result if the intensity of the light were doubled?

**Example 339: 1986 Question 48**  (1 mark)
Which one or more of the graphs (A - E) below, could represent the result if the potassium were replaced by another metal?

*(one or more answers)*
The light meter of a particular camera consists of a circuit using a photoelectric cell as shown. The material of the photocathode has a cut off potential versus frequency relationship as given below.

\[ h = 4.1 \times 10^{-15} \text{ eV s.} \]

**Example 340: 1988 Question 29  (1 mark)**

What is the work function (in eV) of the cathode material?

**Example 341: 1988 Question 30  (1 mark)**

What is the maximum kinetic energy (in eV) of an ejected electron when light of frequency $7.0 \times 10^{14}$ Hz falls on the photocathode?
A photoelectric effect experiment was performed with a plate of unknown metal. The following graph was formed from the results taken during the experiment.

The cut-off frequency for this metal was found to be $5.5 \times 10^{14}$ Hz.

**Example 342: 2001 Question 4 (2 marks)**

Determine the work function for this metal from the graph. ($h = 6.63 \times 10^{-34}$ J s)

The table below shows the corresponding wavelength for the cut-off frequency for different metal surfaces.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Wavelength (nm)</th>
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<tr>
<td>Caesium</td>
<td>682</td>
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<tr>
<td>Sodium</td>
<td>545</td>
</tr>
<tr>
<td>Zinc</td>
<td>405</td>
</tr>
<tr>
<td>Magnesium</td>
<td>345</td>
</tr>
<tr>
<td>Aluminium</td>
<td>303</td>
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</table>

**Example 343: 2001 Question 5 (2 marks)**

What is the metal that was used in the original data?
Example 344: 2006 Question 2    (4 marks)
The table below contains some predictions for the behaviour of light incident on a shiny metal sheet. Complete the table by placing a “Y” (Yes) or “N” (No) in the appropriate boxes if the prediction is supported by the wave and/or particle model of light. Some answers have already been provided. It is possible for predictions to be supported by both models.

<table>
<thead>
<tr>
<th>Prediction</th>
<th>Wave model</th>
<th>Particle model</th>
</tr>
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<tbody>
<tr>
<td>The number of photoelectrons produced is proportional to the intensity of the incident beam.</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Light of low intensity will give rise to the emission of photoelectrons later than light of high intensity.</td>
<td></td>
<td>N</td>
</tr>
<tr>
<td>Light of high intensity will produce photoelectrons with a greater maximum kinetic energy than light of low intensity.</td>
<td></td>
<td>Y</td>
</tr>
<tr>
<td>Light of sufficient intensity of any frequency should produce the photoelectric effect.</td>
<td></td>
<td>Y</td>
</tr>
</tbody>
</table>

To study the photoelectric effect, students use the apparatus shown below. The apparatus consists of
• a light source
• a filter that allows only certain frequencies to pass
• a metal plate and collector electrode in a vacuum
• a variable DC source, voltmeter and ammeter.
The students shine light of different frequencies onto the metal plate. They measure the stopping (repelling) voltage (Vs) that just stops the emitted electrons reaching the collector.

The data that the students gathered is shown in the table following.
<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Stopping voltage (Vs)</th>
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<tbody>
<tr>
<td>$6.0 \times 10^{14}$</td>
<td>0.50</td>
</tr>
<tr>
<td>$6.6 \times 10^{14}$</td>
<td>0.80</td>
</tr>
<tr>
<td>$7.2 \times 10^{14}$</td>
<td>1.10</td>
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<tr>
<td>$8.0 \times 10^{14}$</td>
<td>1.50</td>
</tr>
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</table>

**Example 345: 2008 Question 6  (3 marks)**

Draw a suitable graph from the data above. Label axes and provide units.

**Example 346: 2008 Question 7  (3 marks)**

What value did the students determine from the graph for Planck’s constant? Include a unit.

**Example 347: 2008 Question 8  (2 marks)**

The work function is the minimum energy (eV) required to remove a photoelectron from a metal. What value did the students determine from the graph for the work function of the metal of the plate?
Students set up the apparatus shown below to study the photoelectric effect.

The apparatus consists of
- a source of white light
- a set of filters that only allow light of selected wavelengths to pass through
- a metal plate and a collector electrode enclosed in an evacuated (no air) glass case
- a voltmeter (V), ammeter (A), and variable DC voltage source in a circuit, as shown.

With a particular filter in place, the students gradually increase the voltage as measured by the voltmeter, V, from zero. They plot the current measured through the ammeter, A, as a function of the voltage measured by the voltmeter, V. This is shown below.

Example 348: 2011 Question 5  (2 marks)
Explain why the current drops to zero at X.
Vishvi is carrying out photoelectric effect experiments. Her apparatus is shown below.

Vishvi uses two metal plates in the photoelectric cell. One plate is made of zinc and the other is made of aluminium. Vishvi uses light of a particular frequency to illuminate the zinc plate and then the aluminium plate, but finds that photoelectrons are emitted only by the zinc plate.

**Example 349: 2012 Question 1b  (3 marks)**

In an effort to eject photoelectrons from the aluminium plate, Vishvi increases the intensity of the light beam, but still finds that no photoelectrons are emitted.

Explain how this observation supports the particle model of light, but not the wave model of light.

In another photoelectric experiment, Vishvi uses light with a frequency of $7.50 \times 10^{14}$ Hz to eject photoelectrons from a sodium surface. The work function of sodium is 2.28 eV.

**Example 350: 2012 Question 1c  (3 marks)**

Calculate the maximum kinetic energy (in eV) of these photoelectrons.

**Example 351: 2012 Question 1d  (1 mark)**

Calculate the stopping voltage that would be required to just prevent the most energetic electrons from reaching the collector electrode.
Students are investigating the photoelectric effect by shining monochromatic light with a frequency of $1.00 \times 10^{15}$ Hz onto a sodium plate. Their apparatus is shown below.

The graph shows the relationship between the photocurrent and the reading on the voltmeter.

Example 352: 2013 Question 21a (1 mark)
Use the information in the graph to calculate the maximum kinetic energy (in joules) of the photoelectrons.

Example 353: 2013 Question 21b (2 marks)
Calculate the work function (in eV) of sodium.
Example 354: 2013 Question 21d (2 marks)

The students change the light source to one with a different frequency. They observe that the photocurrent is zero and remains at zero regardless of the size or sign of the voltage. Explain this observation.
A group of students carry out an experiment where light of various frequencies is shone onto a metal plate. The maximum kinetic energy of the emitted electrons for each frequency is recorded and the results are plotted to produce the graph shown. Take Planck’s constant as $6.63 \times 10^{-34}$ J s.

**Example 355: 2014 Question 20b (3 marks)**

The intensity of the light is increased and the experiment is repeated with the same frequencies. The students find that the graph of frequency against maximum kinetic energy for this second experiment is exactly the same as for the first experiment. Explain why this result provides evidence for the particle-like nature of light.
• compare the momentum of photons and of matter of the same wavelength including calculations using \( p = h/\lambda \);
The momentum of photons

In 1923, Compton showed that X-ray photons could collide with electrons and scatter, leaving with a longer wavelength (less energy) than before. This is only possible if the photons were able to transfer momentum and hence energy to the electrons.

Maxwell suggested that photons do have momentum given by

\[ p = \frac{E}{c} \]

where \( c \) is the speed of light and \( E \) is the energy of the photon.

As the energy of the photon is related to its frequency by Planck’s equation, and, since \( v = f \lambda \) for waves, the momentum equation can be written as

\[ p = \frac{hf}{c} = \frac{h}{\lambda} \]

A 10^{-18} J photon has a wavelength of about 2.0 × 10^{-7} m. Electrons can exhibit wave-like properties very similar to such photons, if they have the appropriate momentum. (\( h = 6.63 \times 10^{-34} \) J s).

**Example 358: 1997 Question 6**  \( (2 \) marks)  
Calculate the value of the momentum of one of these electrons. Give your answer to two significant figures.

**Example 359: 2009 Question 9**  \( (2 \) marks)  
A source is designed to produce X-rays with a wavelength of 1.4 × 10^{-10} m. What is the momentum of one of these X-ray photons?
• explain the effects of varying the width of gap or diameter of an obstacle on the diffraction pattern produced by light of appropriate wavelength in terms of the ratio $\lambda/w$ (qualitative);

• interpret electron diffraction patterns as evidence for the wave-like nature of matter;

• compare the diffraction patterns produced by photons and electrons;

• calculate the de Broglie wavelength of matter, $\lambda = h/p$;

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Diffraction

When light passes through a narrow aperture, a hole or a slit, it spreads out. This effect is known as diffraction. Amount of diffraction $\propto \frac{\lambda}{d}$. To observe diffraction effects with the small wavelength of visible light, a very narrow slit must be used.

The wave nature of electrons

If electrons can behave as waves inside an atom, they might be able to exhibit other wave properties like interference. This was shown in electron scattering experiments - definite patterns of reinforcement (antinodes) and reduction (nodes) were found in scattering. The gaps that the electrons were passing through in scattering were very small, in the order of the radius of an atom; hence the electrons wavelengths must be much smaller than that of light.

The wave-like nature of matter

In 1923 de Bröglie speculated that if light waves could behave like particles, then particles of matter should behave like waves. He argued that the universe should be symmetrical and that the equation $p = \frac{h}{\lambda}$ should apply to particles as well as waves. Experiments with electrons clearly show that they can diffract and interfere with each other. Protons and neutrons also have been shown to exhibit wave-like behaviour.

de Bröglie suggested that the wavelength of a particle of matter could be found by using the same relationship that applies to photons, i.e. $p = \frac{h}{\lambda}$ de Bröglie wavelength $\lambda = \frac{h}{p} = \frac{h}{mv}$

The wavelength is inversely proportional to the momentum. With any mass that is not sub-atomic, the product of ‘mv’ is so large that $\lambda$ is always of the order 10^{-33} m, too small for us to see.

When sound and light waves pass through narrow slits, they show diffraction effects only when the slit is about 1 – 50 $\lambda$. Thus, a particle could be expected to show diffraction only if it is passing through a gap 1 - 50 times its de Bröglie wavelength.

For most large particles this is impractical as the physical size of the particle is far too large. Only in the case of small particles such as electrons, is the de Bröglie wavelength enough for diffraction and interference effects to occur.
Example 360: 2007 Question 6  (2 marks)
In an experiment, monochromatic laser light of wavelength 600 nm shines through a narrow slit, and the intensity of the transmitted light is recorded on the screen some distance away as shown below. The intensity pattern seen on the screen is also shown below.

Which one of the intensity patterns (A - D) below best indicates the pattern that would be seen if a wider slit was used?

A.  
B.  
C.  
D.  

Example 361: 1998 Question 8  (3 marks)
Calculate the de Bröglie wavelength of electrons with a speed of $1.0 \times 10^7$ m s$^{-1}$. 
Example 362: 2001 Question 2  (3 marks)
Calculate the de Bröglie wavelength of an electron after being accelerated across 10 kV.

Example 363: 2003 Question 4  (3 marks)
Katie and Jane are discussing wave-particle duality. Jane wonders whether wave-particle duality might explain why she missed hitting the softball in a recent match – maybe the wave nature of the softball allowed it to diffract around the bat! Katie said that this was not a reasonable explanation and that we cannot see the wave nature of a softball. A softball has a mass of 0.20 kg and the pitcher throws it at about 30 m s⁻¹.

Explain to Jane, using an appropriate calculation, why she would be unable to see the wave nature of a moving softball.

Electron Diffraction Patterns
One experiment that is used to show the wave nature of electrons is the electron diffraction pattern. Electrons are sent through a piece of metal as they pass through they leave a pattern on a screen. Only half of the pattern is projected onto the screen, then x-rays are sent through the metal and the pattern from the x-rays is projected onto the other half of the screen. If the two patterns align then the x-rays must have the same wavelength as the electrons.
The pattern is formed from diffraction as the wave fronts travel between the atoms. Then the wavefronts interfere with each other to form bright and dark rings.
The two images below show a radiolarian, a unicellular organism, taken with an electron microscope and an optical microscope. The electron microscope gives a clearer image than the optical microscope.

Example 364: 2001 Question 3 (3 marks)

Explain why the electron microscope gives a clearer image than the optical microscope.

The wave-like nature of individual photons

Water waves and sound waves demonstrate interference by interacting with each other. With photons it is not quite so straightforward. When the double slit experiment is performed using light, it is possible to lower the intensity so that only one photon of light passed through the slits at a time. (this was done by Taylor) i.e., there was no chance of the photons interacting, but interference was still observed.

A series of bright and dark bands were eventually formed on the photographic plate that was being used. The pattern of interference was an interference pattern as predicted by the wave model. The photons behave like particles in that they go through either one slit or the other, but they don't form a pattern consisting of two narrow lines that you would expect from particles. The photons don't interact with each other, yet after passing through the slit each photon has a high probability of heading towards one of the bright bands.
Example 365: 1998 Question 6  (2 marks)
When a beam of light passes through a very narrow single slit a pattern is produced on a screen. Explain what this pattern tells us about the nature of the individual photons that make up the beam of light.

Wave-particle duality of light
The argument about whether light was a wave or a particle was settled in the 1920's. The wave model explained refraction, diffraction and interference of light. The particle model explained the photoelectric effect. Light is neither a wave nor a particle. Photons exhibit both wave and particle properties. This is called WAVE-PARTICLE DUALITY.

Example 366: 2005 Question 6  (3 marks)
Calculate the de Broglie wavelength of the electrons. You must show your working.
A beam of X-rays, wavelength $\lambda = 250$ pm ($250 \times 10^{-12}$ m), is directed onto a thin aluminium foil. The X-rays scatter from the foil onto the photographic plate. After the X-rays pass through the foil, a diffraction pattern is formed as shown in the figure on the left.

In a later experiment, the X-rays are replaced with a beam of energetic electrons. Again, a diffraction pattern is observed which is very similar to the X-ray diffraction pattern. This is shown in the figure on the right.

**Example 367: 2006 Question 11 (3 marks)**

Assuming the two diffraction patterns are identical, estimate the momentum of the electrons. Include the unit.

Neutrons are subatomic particles and, like electrons, can exhibit both particle-like and wave-like behaviour.

A nuclear reactor can be used to produce a beam of neutrons, which can then be used in experiments.

The neutron has a mass of $1.67 \times 10^{-27}$ kg.

The neutrons have a de Broglie wavelength of $2.0 \times 10^{-10}$ m.

The neutron beam is projected onto a metal crystal with interatomic spacing of $3.0 \times 10^{-10}$ m.

**Example 368: 2007 Question 5 (2 marks)**

Would you expect to observe a diffraction pattern? Explain your answer.
X-rays of wavelength 0.20 nm are directed at a crystal and a diffraction pattern is observed. The X-ray beam is replaced by a beam of electrons. A similar diffraction pattern is observed with the same spacing.

**Example 369: 2011 Question 11  (2 marks)**
What must be the energy, in eV, of each electron to produce this pattern?

A beam of electrons is travelling at a constant speed of $1.5 \times 10^5$ m s$^{-1}$. The beam shines on a crystal and produces a diffraction pattern. The pattern is shown below. Take the mass of one electron to be $9.1 \times 10^{-31}$ kg.

The beam of electrons is now removed and replaced by a beam of X-rays. The resulting pattern has the **same spacing** as that produced by the electron beam.

**Example 370: 2012 Question 3b  (3 marks)**
Calculate the energy (in eV) of one X-ray photon.
Students aim X-rays with a photon energy of 80 keV at a thin metal foil. The resulting diffraction pattern is shown below.

Example 371: 2013 Question 23a (2 marks)
Calculate the magnitude of the momentum of a single X-ray photon.

Example 372: 2013 Question 23b (3 marks)
The students are aware that electrons can also be used to form diffraction patterns. They wish to use a beam of electrons to form a diffraction pattern with fringe spacings identical to those previously.
Student A says that the fringe spacing will be identical if the electrons have the same momentum as the X-rays. Student B says that the fringe spacing will be identical if the electrons have the same energy as the X-rays.
Which student is correct? Explain your answer.
Thuy is doing some experiments on the diffraction of photons. She is using a beam of photons with an energy of 4.1 eV. The beam is incident on a small circular aperture and the resulting diffraction pattern is produced on a photon-sensitive screen behind the aperture. This pattern is shown below.

A second experiment is then performed with the same light beam incident on a circular aperture with a larger diameter.

**Example 373: 2014 Question 21b**  (1 mark)
Complete the following sentence by circling the correct words that are shown in **bold** font.
Corresponding rings in the second diffraction pattern would have diameters that are **larger than** / **the same size as** / **smaller than** the rings in the original pattern.

**Example 374: 2014 Question 21c**  (2 marks)
Give your reasoning for your answer to **part b**.
Thuy now carries out another experiment, comparing the diffraction of X-ray photons and electrons. A beam of X-ray photons is incident on a small circular aperture. The experiment is then performed with a beam of electrons incident on the same aperture. The X-ray photons and electrons have the same energy. The diffraction patterns have the same general shape, but very different spacings.

Example 375: 2014 Question 21d (3 marks)

Explain why the electron diffraction pattern has a different spacing from the X-ray diffraction pattern, even though the electrons and the photons have the same energy.
Physicists use the expression ‘wave-particle duality’ because light sometimes behaves like a particle and electrons sometimes behave like waves.

**Example 376: 2015 Question 20b  (2 marks)**

What evidence do we have that electrons can behave like waves? Explain how this evidence supports a wave model of electrons.

- **describe the quantised states of the atom in terms of electrons forming standing waves, recognising this as evidence of the dual nature of matter;**

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**Quantum physics**

Max Planck proposed that energy travels in discrete packets called quanta. Prior to Planck’s work, energy was thought to be continuous, but this theory left many phenomena unexplained. In 1900 Max Planck began to study the range of electromagnetic radiation that emanates from a very hot body (black body radiation). When a body is heated, it first glows red; with further heating it turns to white and eventually blue (i.e. the wavelength of light emitted becomes shorter and it frequency becomes higher with increasing temperature).

He found that \[ E = \frac{hc}{\lambda} \]  
\( c \) = speed of light  
\( \text{or } E = hf \)  
\( f \) is the frequency of the light.

**Quantised energy levels in atoms - the Bohr model**

The model for the atom that Rutherford proposed in 1911, that the atom consisted of a small dense, positively charged nucleus surrounded by a cloud of electrons, has a weakness because the accelerating electrons should radiate energy and spiral into the nucleus.

In 1913, Bohr, said that the electrons should not be considered to be orbiting like planets. He said that they simply existed outside the nucleus with certain amounts of energy. According to Bohr, the electrons in the atom existed in certain discrete ENERGY LEVELS.
• Each element has certain allowed energy levels that are unique to that element.
• Electrons can only exist in one of these allowable energy levels, not in between. Ie. energy levels are quantised.
• If an electron is given extra energy it can move up to a higher energy level by absorbing an amount of energy equal to the difference between the energy levels.
• When an electron in a higher energy level returns to its normal (ground state) energy level, it emits the energy in the form of a photon. The energy of the photon \( (E = h \nu) \) is equal to the difference in energy levels the electron moves between.

**Example 377: 2004 Sample Question 11**  (2 marks)
The pattern below is meant to represent the ‘standing wave-state’ of an electron in a hydrogen atom. Which value of ‘n’ would best describe this pattern?

![Pattern Diagram]

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**Example 378: 2005 Question 11**  (3 marks)
Describe how the wave-particle duality of electrons can be used to explain the quantised energy levels of the atom.
Example 379: 2009 Question 12  (2 marks)
De Broglie suggested that the quantised energy states of the atom could be explained in terms of electrons forming standing waves. Describe how the concept of standing waves can help explain the quantised energy states of an atom. You may include a diagram.

Example 380: 2014 Question 23b  (3 marks)
According to one model of atoms, electrons in atoms move in stable circular orbits around the nucleus. In an atom modelled in this way, an electron is moving at $2.0 \times 10^6$ m s$^{-1}$. Take the mass of an electron as $9.1 \times 10^{-31}$ kg. Describe how the wave nature of electrons can be used to explain the quantised energy levels in atoms.
Example 381: 2015 Question 21a  (3 marks)
Use the model of quantised states of the atom to explain why only certain energy levels are allowed.

Example 382: 2015 Question 21b  (2 marks)
Illustrate your answer with an appropriate diagram.
• Interpret atomic absorption and emission spectra including those from metal vapour lamps in terms of a quantised energy level model of the atom, including calculations of the energy of photons absorbed or emitted, $\Delta E = hf$;
• interpret spectra and calculate the energy of photons absorbed or emitted, $\Delta E = hf$;
• analyse the absorption of photons by atoms in terms of:
  – the particle-like nature of matter
  – the change in energy levels of the atom due to electrons changing state
  – the frequency and wavelength of emitted photons, $E = hf = hc/\lambda$
    (not including the bombardment of atoms by electrons);
• identify and apply safe and responsible practices when working with light sources, lasers and related equipment.

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Energy levels in hydrogen
The ionisation energy for hydrogen is 13.6 eV. The ground state energy, level = 0 eV,

Bohr found that $E_n = E_I - \frac{E_I}{n^2}$ (not on course)

Where $E_n$ = the energy associated with a particular energy level of hydrogen
$E_I$ = ionisation energy, which is 13.6 eV for hydrogen
$n$ = any whole number, ie, 1, 2, 3 …

Photons can be emitted or absorbed.
Below are the absorption and emission lines for hydrogen (in the visible region).
The energy levels of atomic mercury are shown in the following diagram.

Example 383: 1973 Question 103  (1 mark)
A photon strikes a mercury atom in its ground state and a photoelectron is ejected with kinetic energy 30.4 eV. What was the energy of the incident photon?

The energy level diagram for the hydrogen atom is drawn below:

Example 384: 1978 Question 77  (1 mark)
What is the value of n for the ground state energy level of the hydrogen atom?

Example 385: 1978 Question 78  (1 mark)
What is the energy required to ionize a hydrogen atom originally in its ground state?
The figure below is the energy level diagram for a hydrogen atom.

![Energy Level Diagram for Hydrogen Atom]

In an experiment, hydrogen atoms are excited to the 3rd excited state and then decay. Ultimately, all atoms return to the ground state. As a result of these decays, photons of various energies are emitted.

**Example 386: 1989 Question 65 (1 mark)**

How many different photon energies could be observed in this process?

A. 1  
B. 2  
C. 3  
D. 4  
E. 5  
F. 6

**Example 387: 1989 Question 66 (1 mark)**

What is the highest frequency of radiation (in Hz) emitted in this process?  
(Planck's constant, \( h = 4.135 \times 10^{-15} \) eV s.)
The figure below is part of the emission spectrum for hydrogen taken from sunlight. Each emission line is displayed with the wavelength in units of nanometres (nm).

Example 388: 2001 Question 6 (2 marks)
Calculate the energy of the photon, in eV, that is indicated by the spectral line marked $\beta$ in the figure.

Example 389: 2001 Question 7 (2 marks)
On the energy level diagram for hydrogen below, indicate with an arrow (↓) the energy level transition for the spectral line marked $\beta$ above.
The spectrum of photons emitted by excited atoms is being investigated. Shown below is the atomic energy level diagram of the particular atom being studied. Although most of the atoms are in the ground state, some atoms are known to be in $n = 2$ and $n = 3$ excited states.

Example 390: 2005 Question 10  (2 marks)
Calculate the wavelength of the photon emitted when the atom changes from the $n = 2$ state to the ground state ($n = 1$).
The figure below shows part of the emission spectrum of hydrogen in more detail.

With a spectroscope, Val examines the spectrum of light from the sun. The spectrum is continuous, with colours ranging from red to violet. However there were black lines in the spectrum, as shown below.

Example 391: 2007 Question 9 (3 marks)
Explain why these dark lines are present in the spectrum from the sun.
The figure below shows the quantised energy levels in the hydrogen atom, relative to the ground state.

- Ionisation: 13.6 eV
- n = 6: 13.2 eV
- n = 5: 13.1 eV
- n = 4: 12.8 eV
- n = 3: 12.1 eV
- n = 2: 10.2 eV
- Ground state: 0 ground state

Example 392: 2008 Question 12 (2 marks)

What is the shortest wavelength photon that can be emitted when an atom decays from the n = 4 level?
The energy levels of the hydrogen atom are discrete (quantised) and there are no stable levels between them.

**Example 393: 2012 Question 4b  (3 marks)**

In terms of the properties of the electron, explain why only certain energy levels are stable.
An energy-level diagram for a sodium atom is shown below.

Example 394: 2013 Question 20a  (2 marks)

An atom is in the 3.19 eV state. It returns to the ground state, emitting one or more photons. Calculate the longest wavelength of light that could be emitted by the atom.

Example 395: 2013 Question 20a  (3 marks)

Explain, with a calculation, why the emission spectrum of sodium shows a spectral line at 588.63 nm.