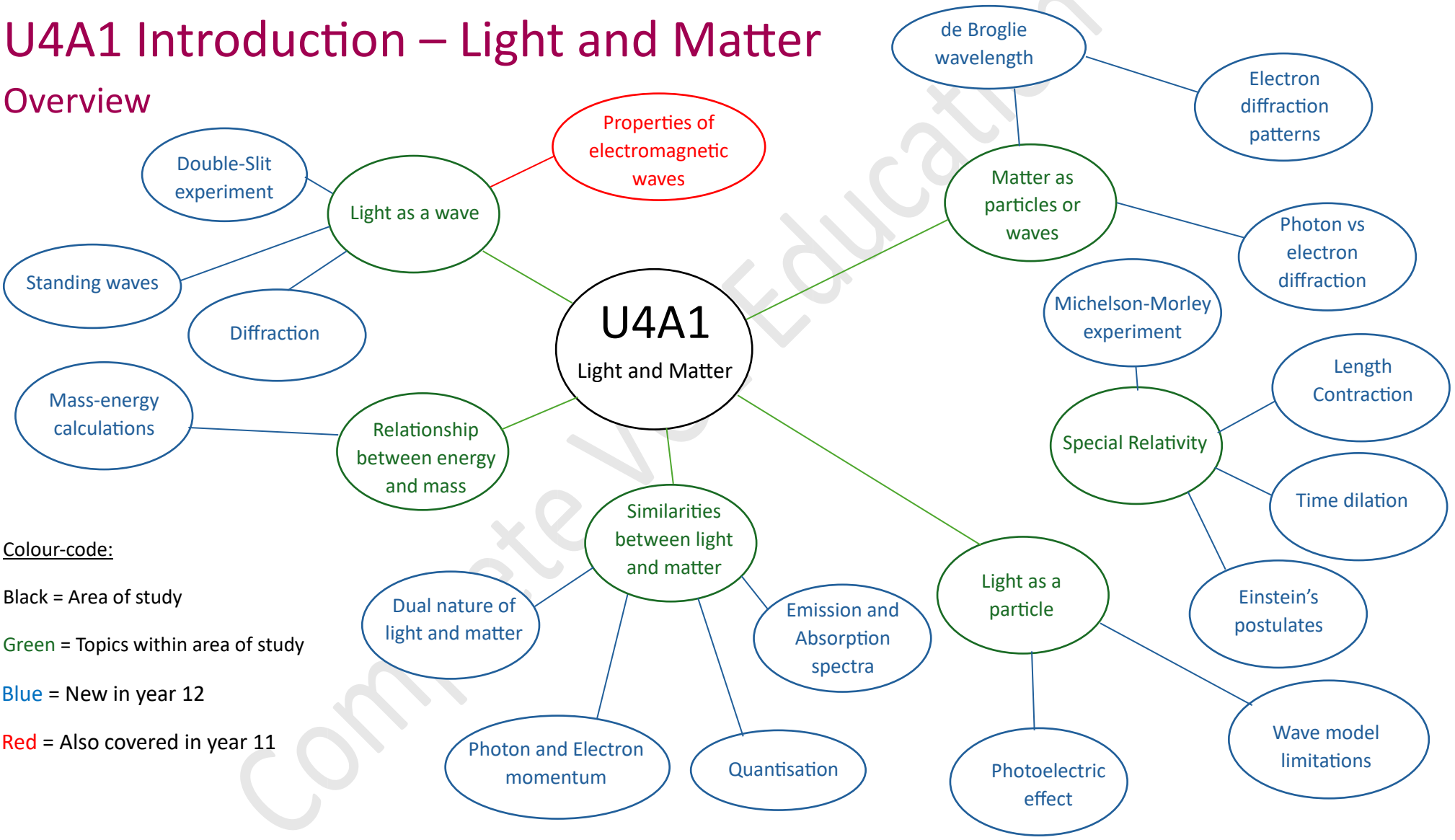
U4A1 Introduction – Light and Matter

Overview



Colour-code:

Black = Area of study

Green = Topics within area of study

Blue = New in year 12

Red = Also covered in year 11

Topic 1 – Light as a wave

Subtopic	Elaboration	Relevant Year 11 Knowledge	Formulas and Concepts	SAC/Exam Tips	Example Questions
Properties of electromagnetic waves	The basics of how the we understand electromagnetic waves to work, with concepts ranging from how they are produced, hey they propagate and whether or not they need a medium. Most relevant knowledge can be drawn back to Y11.	• Basic wave calculations using formulas such as $v = f\lambda$ • Knowing that electromagnetic waves are transverse and do not require a medium • Speed of light being constant in a vacuum $c = 3.0 \times 10^8$ m s^{-1}	• **Production of electromagnetic waves:** Whilst not fully encompassing, this delves into their production via means of accelerating charges, which produce changing electric fields and thus changing magnetic fields.	• Not much to mention since this is essentially the 'revision stage' from Y11. • Concepts will help explain previously mentioned topics, such as the production of light from a synchrotron.	• 'Compare the speed of gamma and microwave radiation in a vacuum' • 'What kind of wave is an electromagnetic wave?'
Diffraction	Details how waves (such as light) can 'bend' around small openings, and how the extent of this relates to other factors.		• **The relationships in diffraction** Waves diffract relative to the ratio of $\frac{\lambda}{w}$, where if it is less than 1, there will be little diffraction. But if the gap is smaller, or wavelength larger, then diffraction will increase in extent.	• These questions are fairly simple as demonstrated by the two-piece relationship. • They are typically used to complement an extended application question..	• 'Explain why it is harder to obtain a 5G signal compared to 4G using your knowledge of diffraction'
Standing waves	Delves into how waves can reflect onto each other and result in seemingly stationary waves known as 'standing waves'		• **How standing waves are formed** Knowledge of this is only required in situations where there are nodes at either end of the wave. Standing waves form different results depending on the wavelength and how many **full** wavelengths one can divide into the length.	• These questions have been simplified from the past, as node/antinode ended standing waves used to be assessable. • They can be tricky when dealing with figuring out the original wavelength from a given harmonic, so practice is necessary.	• 'From this third harmonic, determine the original wavelength of this standing wave'

Young's Double-Slit Experiment	Essentially the most major piece of evidence for the wave model of light, historically speaking, as light was previously thought of to be a particle.		• **Evidence for wave-like nature of light** The existence of an interference pattern implies the wave-like nature of light. • **Path difference** Calculations involving formulas such as $\left(n+\frac{1}{2}\right)\lambda$ and $n\lambda$ relating to destructive and constructive interference respectively. • **Variables of the double-slit experiment** $\Delta x = \frac{\lambda L}{d}$, where the effects of gap width, distance from screen and wavelength all affect the distance of each band apart from each other.	• Can be a wide variety of either cookie-cutter questions when it comes to explaining the double-slit experiment, or potentially more tricky when dealing with path difference calculations. • Understanding of how interference patterns are produced is absolutely key to understanding this topic.	• 'Detail the evidence for the wave-like nature of light using a well-known experiment' • Finding whether two waves will result in constructive or destructive interference at a particular point of intersection.

Topic 2 – Light as a particle

Subtopic	Elaboration	Relevant Year 11 Knowledge	Formulas and Concepts	SAC/Exam Tips	Example Questions
Photoelectric effect	Flips the previous topic on its head and delves into how another experiment seemed to support the particle nature of light.		• **Quantised energy of photons:** Formulas that describe the energy of photons in joules. 'h' is Planck's constant = 6.63 x 10^{-34} J s. • **Photoelectric effect experiment:** An experiment involving the emission of electrons from a metal cathode using only light. Critical to understanding the dual-nature of light. $E_{k\,max} = hf - \phi$ gives the maximum kinetic energy of electrons expelled, and can be used to calculate a variety of variables.	• Questions are often heavy on short calculations alongside knowledge on how to explain the theory to answer many 'why' questions. • Highly recommended to have some rearranged formulas and ones that aren't present on the VCAA sheet. Also be cautious of which units Planck's Constant has.	• Finding the stopping voltage of a certain photoelectric effect experiment • Explain how the photoelectric effect experiment's results supported the particle-like nature of li
Wave model limitations	Highly similar to the last subtopic, except detailed through the lens of explaining why the wave model is not supported by the photoelectric effect experiment.		• **The photoelectric effect rejects the wave model** Many of the key findings of the experiment are simply not possible if the wave model were exclusively true, but potentially possible if the particle model were true…	• Using knowledge from the last subtopic to explain the contrast. Imperative to fully appreciate both models to properly answer these explanation questions.	• Explain how the wave model of light is rejected by the results of the photoelectric effect.

Topic 3 – Matter as particles or waves

Subtopic	Elaboration	Relevant Year 11 Knowledge	Formulas and Concepts	SAC/Exam Tips	Example Questions
de Broglie Wavelength	Explores how matter can also have a wave-like nature, if observed under the right conditions. Rather than photons, electrons are typically analysed in this field and contrasted against light's nature.		• **Electron diffraction** Historic experiments were done to examine whether electrons would behave as a wave or particle when accelerated through a slit. While many suggested they would simply go through like a particle, it in fact produced a diffraction pattern, implying a wave-like nature! • **Calculating de Broglie wavelength** $\lambda = \frac{h}{p}$ Using the above formula, the wavelength of matter can be found, where 'p' in this context refers to momentum. Every mass has a de Broglie wavelength, though it is not observable in everyday life. • **Comparing photon and electron diffraction patterns** In reality, one can produce an identical diffraction pattern from a photon and electron as long as they have the **same wavelength.**	• Question difficulty is typically increased by linking back to previous subtopics, in particular with asking why large masses such as humans, do not diffract while passing through a door. • This subtopic is rather theory-focused with most concepts relying on understanding rather than rote-learning to do well in SACs or exams.	• 'Under what conditions could a photon and electron produce the same diffraction pattern?' • 'Calculate the de Broglie wavelength of a 1.0 kg apple falling at 10 m s^{-1}'

Topic 4 – Similarities between light and matter

Subtopic	Elaboration	Relevant Year 11 Knowledge	Formulas and Concepts	SAC/Exam Tips	Example Questions
Photon and electron momentum	An extension of the previous subtopic from Topic 3, which mostly goes into how to actually calculate the momentum of photons and electrons in relation to finding their energies. (Such as for if they have identical diffraction/interference patterns)		• **Photon momentum:** $p = \frac{h}{\lambda}$ Since light can be modelled as a particle, it should theoretically be able to have momentum. A key thing to note is that photons and electrons of the same wavelength often do not have the same momentum.	• Most of the questions will involve comparing diffraction patterns between electrons and photons, then finding the momentum of each. • Fairly straightforward given enough practice with questions. Highly recommended to add extra formulas relating energy and momentum that aren't found on the VCAA formula sheet to your own.	• 'Compare and contrast between the momentum of an electron and photon producing the same diffraction pattern. Use calculations to support your answer'
Quantisation	Links back to the idea of standing waves to explain the distinct energy levels of the electrons around an atom. Quantised essentially just means discrete.		• **Quantised energy states of electrons** Understanding that electrons have a de Broglie wavelength and are travelling in orbits, thus meaning that their wavelengths must be a whole integer multiple of their circumference to destructively interfere and cancel out itself.	• There are really only two types of questions that can be asked for this subtopic, being either: - Explain the quantised energy states of electrons around atoms. - Drawing standing wave energy level diagram	• 'Draw a diagram of the n = 2 orbit around an atom'
Emission and absorption spectra	Adds onto the previous subtopic as another way to demonstrate the quantised energy levels of an atom's electrons. Emission is now framed as the expulsion of a photon, rather than just 'light' generically speaking.		• **Emission spectra** The spectrum of light that is captured when a the electrons around an atom are 'excited' and release a photon equivalent to the change in energy level when returning to ground state. As per the formulas $E = hf$ and $E = hf = \frac{hc}{\lambda}$ • **Absorption spectra** Quite similar to an emission spectra, just reversed. The method is reversed and the spectrum itself is quite literally inverse of the emission spectra. Drawing of energy level diagrams for both will be required.	• Many emission/absorption spectra questions are multi-step compounds questions that involve energy calculations and energy level diagram drawing. • Are quite simple with practice. However particular care should be taken with diagram drawing as it is quite common for students to draw their arrows either beginning or ending in the wrong level or direction!	• 'Explain how the existence of emission spectra supports the model of electrons and quantised energy levels' • 'Draw an arrow corresponding with the emission of a 4.5 eV photon.'

Dual nature of light and matter	Goes into detail about certain scenarios tested which suggest that light and matter can behave in both manners given the correct conditions. Of note are the single-photon double slit experiment, and the electron double slit experiment..		• **Single-photon double slit experiment** One would expect that a single photon could not produce an interference pattern, however experiments have shown that they are still able to, supporting the notion of a dual nature. • **Electron double slit experiment** A perplexing discovery was that if electrons were observed during the double-slit experiment, they would actually produce two distinct bands rather than an interference pattern. The observation in this case would be detecting which slit the singular electron passed through. If this detection did not take place, then an interference pattern would manifest.. Disregarding the implications of the wave equation, this also supports the dual-nature theory of matter…	• On the note of 'observing the electron', do not worry about the implications regarding the wave equation, as it is not examinable in VCE physics! • Both concepts are simply applications of the previous subtopics • As expected, most of these questions are explanation questions, usually around 3 marks, so quite a bit of rote-learned detail is required…	• Using a famous experiment, explain the wave-particle duality of light.

Topic 5 – Einstein's special theory of relativity

Subtopic	Elaboration	Relevant Year 11 Knowledge	Formulas and Concepts	SAC/Exam Tips	Example Questions
Einstein's Postulates of Special Relativity	A bit of a sidetrack from wave-particle duality. This subtopic focuses on the contrast of Einstein's postulates regarding his theory of relativity versus classical Newtonian physics.		• **The postulates:** - "The laws of physics are the same in all inertial frames of reference" - "The speed of light has a constant value for all observers regardless of their motion, or the motion of the source" • **Contrast with Newtonian relativity** Classical physics suggests that if one moves toward a light source at a certain speed, they should measure the speed of the light to be 'c' + their speed, which we know isn't true for example.	• These questions on SACs and exams will always involve compare/contrast and explain type questions. Thus a solid theoretical understanding is imperative.	• 'Compare and contrast between Einstein's theory of special relativity and classical Newtonian relativity'

Michelson-Morley experiment	A groundbreaking experiment that supports Einstein's notion of the speed of light being constant (in the same medium) regardless of motion.		• **The Michelson-Morley experiment:** The experimental design sought to find out whether light required a medium, known as 'luminiferous aether' to travel through. The setup involved splitting a beam of light to travel perpendicular to each other, then reflected back to form an interference pattern. This pattern would be compared to another produced with the entire experiment rotated 90 degrees, as any changes would indicate a change in the speed of light in different directions relative to this 'aether'. The results however proved inconclusive as all interference patterns yielded the same result.	• This is a relatively new addition to the VCE study design, so it will be difficult to find official examples of questions to answer. • That being said, almost all MM questions are almost identical, being a simple explanation and/or a drawing a diagram of the experimental setup.	• 'Draw the experimental setup of the Michelson-Morley experiment in the box below'
Time dilation	Introducing the concept of proper and dilated time in the context of thought experiments such as the light clock on a train, to real-world applications such as GPS satellites.		• **Lorentz factor** A proportion that describes the extent a length/time is affected by the effects of special relativity. The sole variable is speed as depicted: $\gamma = \frac{1}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$ • **Proper time** The time measured stationary relative to the observer • **Dilated time** The opposite of proper time, thus being time measured that is *not stationary* relative to the observer. $t = \gamma t_0$	• Like with length contraction, time dilation questions can be quite confusing at the beginning, with the main hurdle to overcome being identification of proper time and dilated time. • It may help to imagine the time being observed as a literal clock that is either moving or stationary relative to the observer.	• 'Explain why Muons are able to reach Earth's surface despite having a half-life which suggests they shouldn't be able to?' • Calculated the extent of time dilation for a spaceship moving at relativistic speeds (eg: 0.9c)
Length contraction	Introduces the concept of proper and contracted length, as a sort of 'simultaneous effect' of travelling at relativistic speeds alongside time dilation. Can usually be used as an alternative explanation for certain special relativity scenarios such as Muons reaching Earth's surface.		• **Proper length** Length that is measured stationary relative to the observer, much like proper time. • **Contracted length** Once again similar to dilated time, but with length shrinking instead. Length that is measured to be moving relative to the observer. Note that the length contracts in the direction of travel. It's important to remember that length measurement **cannot dilate** and time measured **cannot contract.** $L = \frac{L_0}{\gamma}$	• Similar predicament to time dilation, with the only real advice being practice more and more questions to get familiar with identifying proper length. • It cannot be overstated enough that **length does not dilate and time does not contract!** It's also a simple way to remember the formulas so you're not constantly checking the formula sheet.	• (again) 'Explain why Muons are able to reach Earth's surface despite having a half-life which suggests they shouldn't be able to?' • 'Calculate the length contraction of a passing 50 m spaceship if it travels at 0.987c'

Topic 6 – Relationship between energy and mass

Subtopic	Elaboration	Relevant Year 11 Knowledge	Formulas and Concepts	SAC/Exam Tips	Example Questions
Mass-energy calculations	An extension of special relativity to also include the concept of mass-dilation, or better described as the mass-energy duality. Explains several concepts such as nuclear energy, matter and antimatter and more.		• **Total and kinetic energy formulas:** Unfortunately the formulas you may be used to only apply at non-relativistic speeds, such as the classic kinetic energy formula. As such, the 'true' versions are below: $E_k = (\gamma - 1)mc^2$ $E_0 = mc^2$ $E_{tot} = E_k + E_0 = \gamma mc^2$ These formulas are also another way to explain why mass cannot be accelerated to the speed of light – it would take an infinite amount of energy!	• These questions are fairly straightforward, without much algebra beyond the base formulas. • Typically a part of a greater multi-step question.	• 'How much mass-energy does a 1500 kg spaceship have travelling at 0.99c?' • 'How much energy does it take to accelerate a 1 kg apple to 0.8c?'
Application of mass-energy concepts	Application of the mass-energy relationship to practical examples, with the most notable being nuclear power generation.		• **Nuclear power generation** The products of a nuclear fission or fusion reaction have a lower total mass than the original constituents, meaning as per the mass-energy relationship, energy is released equivalent to this deficit. • **Positron-electron annihilation** The interaction of matter and its equivalent antimatter particle will result in annihilation and the release of pure energy as per $E = mc^2$. The VCAA example of this is the positron and the electron, which can actually happen in a particle accelerator such as the LHC by CERN.	• Mostly theory based questions again, though an occasional mass-energy calculation involving nuclear reaction mass-deficit could occur. • While never really been officially tested before by VCAA, the second concept of antimatter/matter *is* technically on the study design so it'd be wise to at least understand it.	• 'Calculate the amount of energy released if the mass-defect in a particular nuclear fission reaction is…'