Quantum Physics
In a Nutshell

CLASSICAL PHYSICS

- Classical physics is the physics of the motion, energies, and interactions of objects in the everyday world around us.
- In the double-slit experiment, tennis balls and all other *classical particles* move as localized particles through the slits and once they hit the screen they produce the following distribution:

- If we use water waves, sound, or any other *classical waves* they spread out behind the double-slit barrier and produce an *interference pattern*.
- Light also spreads out behind the double-slit barrier and produces an interference pattern.

QUANTUM PHYSICS

- Quantum physics is revealed in the physics of isolated processes, typically with very small subatomic objects.
- In the electron double-slit experiment, each electron hits the detection screen as a particle.
- After many electrons hit, an interference pattern forms, demonstrating wave behaviour.

- The same interference pattern forms even when we fire electrons one at a time.

- These results show that electrons exhibit both wave and particle behaviour, i.e., *wave–particle duality*.
- The de Broglie wavelength describes the wave behaviour of particles such as electrons. It is given by the equation

$$\lambda = h/p$$

- Light also exhibits wave–particle duality. In the double-slit experiment light hits the detection screen as an individual particle, but over time it forms an interference pattern like a wave.
- A particle of light is called a *photon* and its energy is given by

$$E = hf$$

- All quantum objects, including protons, neutrons, atoms, and molecules, exhibit wave–particle duality.
- When we look at the electron to see what it is doing while passing through the double-slit barrier, we are making a measurement which perturbs the electron and destroys the interference pattern. This demonstrates *measurement disturbance*.
- We can predict the overall behaviour of the electrons in the double-slit experiment, but nobody really knows what the electrons are doing between the source and the detector. To complete the picture, physicists have proposed various interpretations, including:

i) thinking of electrons as spread-out waves that collapse to point-like particles once they are measured (Collapse Interpretation),
ii) thinking of electrons as particles that are guided by an invisible wave (Pilot Wave Interpretation),
iii) thinking of parallel universes that come into being when we make measurements at the quantum level (Many Worlds Interpretation)
iv) thinking exclusively about the direct results of measurements (Copenhagen Interpretation).

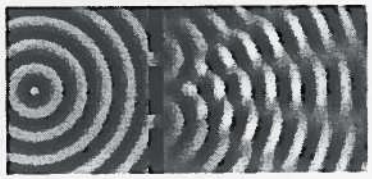
- In spite of these differing views, quantum physics plays a crucial role in a number of everyday technologies including computers, remote control devices, lasers, and cell phones.

Worksheet 01:
Video Summary

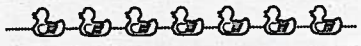
Useful equations: $\lambda = h/p$ $E = hf$

01. Baseballs are fired at a barrier with two narrow slits. Behind the barrier is a wall. Draw a distribution that shows where the baseballs hit the wall.

02. A water wave passes a two-slit barrier, as shown below, generating an interference pattern.

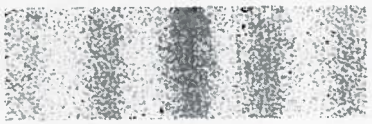


(a) Imagine a rubber duck is floating at each maxima and minima along the reference line shown. Using the diagram below, draw a vertical line for each duck that will show how its vertical position changes over time.



(b) The relative height each rubber duck moves is related to the amount of energy passing at that point. A longer vertical line represents more energy than a shorter line. Describe where the energy is greatest. How does the energy distribution between maxima mimic the energy distribution in a double-slit interference pattern for light?

03. The photograph below shows an interference pattern from the electron double-slit experiment.



(a) The distance between neighbouring interference maxima is 120 µm. Why is this distance so much smaller than the distance between maxima for water waves?
(b) What aspects of the image illustrate the particle nature of electrons?
(c) What aspects of the image illustrate the wave nature of electrons?
(d) How can an electron be a particle and a wave at the same time? Spend a few minutes formulating your explanation for what is going on and then discuss it with your neighbour.

04. The double-slit experiment is performed using light with a wavelength of 580 nm. The light's intensity is so low that only one photon passes through the slits each second. This means no two photons ever interact with each other in the experiment.

(a) What is the energy of each photon emitted?
(b) What aspects of this experiment demonstrate the particle nature of light?
(c) What aspects of this experiment demonstrate the wave nature of light?

05. One of the largest objects that physicists have used to produce an interference pattern is a molecule called PFD (perfluoroalkyl-functionalized diazobenzene, $C_{36}H_{12}F_{36}N_2O_4$). It has a mass of 1.7×10^{-24} kg. In the experiment, the molecule had a de Broglie wavelength of 2.8×10^{-12} m. Calculate the molecule's velocity.

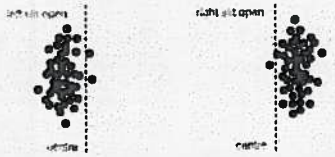
06. What happens to the interference pattern created in the electron double-slit experiment when detectors are used to determine which slit an electron is passing through? How do the researchers explain this result?

07. You are discussing the electron double-slit experiment with a friend. She says: "Physicists understand the experiment completely. Each electron leaves the source as a classical particle and hits the screen as a classical particle. All researchers agree that an electron is a classical particle in the experiment." Write a three to four line reply to your friend that explains why she is mistaken.

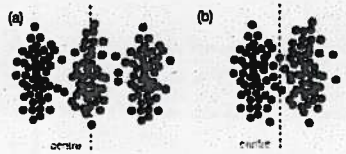
08. Quantum physics is part of your everyday life. List at least five of the technological applications discussed in the video.

Worksheet 02:
Concept Questions

01. Tennis balls are sent toward two slits. The distributions of the marks they make on a wall on the other side of the barrier when one slit is open are shown below.



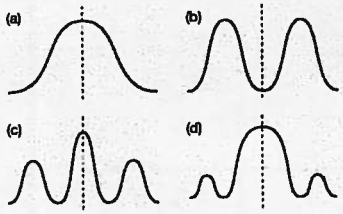
Which distribution would you expect to see if both slits are open at the same time?



02. Which statement correctly describes how waves behave when they occupy the same location at the same time?

(a) A crest overlapping with a crest will constructively interfere to produce a minima.
(b) A crest overlapping with a trough will constructively interfere to produce a minima.
(c) A trough overlapping with a trough will constructively interfere to produce a maxima.
(d) A trough overlapping with a trough will destructively interfere to produce a maxima.

03. A water wave passes through two slits. Which pattern best matches the amplitude of the resulting wave?



04. Classical particles are different from classical waves because classical particles

(a) are spread out and generate an interference pattern in the double-slit experiment.
(b) are localized and generate an interference pattern in the double-slit experiment.
(c) are localized and generate a distribution that is the sum of each single-slit distribution.
(d) are spread out and generate a distribution that is the sum of each single-slit distribution.

05. The video shows the interference of light of a single colour. What would you expect if white light were used?

(a) bands of white light and darkness
(b) bands of different colours of light and darkness
(c) a white central maxima and alternating bands of different colours of light and darkness on either side
(d) no interference pattern

06. To better understand the double-slit experiment, it was important to send electrons through one at a time because

(a) the detector needed time to reset in order to detect the next electron.
(b) the slits were too narrow to allow two electrons to pass at the same time.
(c) this prevented the electrons from interacting with each other.
(d) time is needed to generate more electrons.

07. In the double-slit experiment, electrons

(a) behave like waves and behave like particles.
(b) split in half and go through both slits simultaneously.
(c) behave like particles, but are waves.
(d) are both waves and particles at the same time.

Actual image from the electron double-slit experiment

Worksheet 02:
Continued

08. You get sunburn from ultraviolet light but not from visible light. This is because UV photons have a greater

(a) mass.
(b) frequency.
(c) speed.
(d) wavelength.

09. Why have interference effects with tennis balls not been observed?

(a) The de Broglie wavelength equation, $\lambda = h/p$, is only for sub-microscopic objects.
(b) The experiment has not been done yet
(c) The de Broglie wavelength for a tennis ball will be much smaller than for an atom.
(d) The de Broglie wavelength for a tennis ball will be larger than for an atom.

10. All quantum objects exhibit wave–particle duality. In the double-slit experiment this is shown by the fact that individual objects hit the screen

(a) at specific locations and build up an interference pattern after a large number have hit.
(b) in a spread-out way and build up an interference pattern after a large number have hit.
(c) at specific locations and build up a particle distribution after a large number have hit.
(d) in a spread-out way and build up a particle distribution after a large number have hit.

11. If we do measurements to determine which slit an electron went through, we find that

(a) half of the electron goes through each slit.
(b) the whole electron goes through both slits.
(c) the whole electron goes through one or the other slit.
(d) it is impossible to detect an electron.

12. With electrons in the double-slit experiment, physicists know

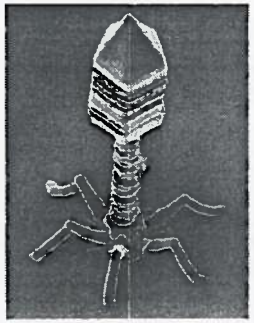
(a) where an electron will hit the screen.
(b) which slit the electron went through, without the aid of a detector.
(c) that the electron went through both slits.
(d) that all of the interpretations give the same predictions for the overall results.

13. There are competing ideas about what is actually happening between the source and the detector in the double-slit experiment. In which of the interpretations does a single electron go through one and only one slit?

(a) Pilot Wave and Collapse
(b) Pilot Wave and Many Worlds
(c) Collapse and Many Worlds
(d) Pilot Wave, Collapse, and Many Worlds

14. An electron microscope can produce clearer images of significantly smaller objects than a light microscope can because the electrons have a

(a) larger frequency.
(b) smaller size.
(c) slower speed.
(d) shorter wavelength.



Electron microscope image of a virus

15. Which quantum application has had the greatest effect on your life?

(a) solar panels
(b) transistors
(c) lasers
(d) other