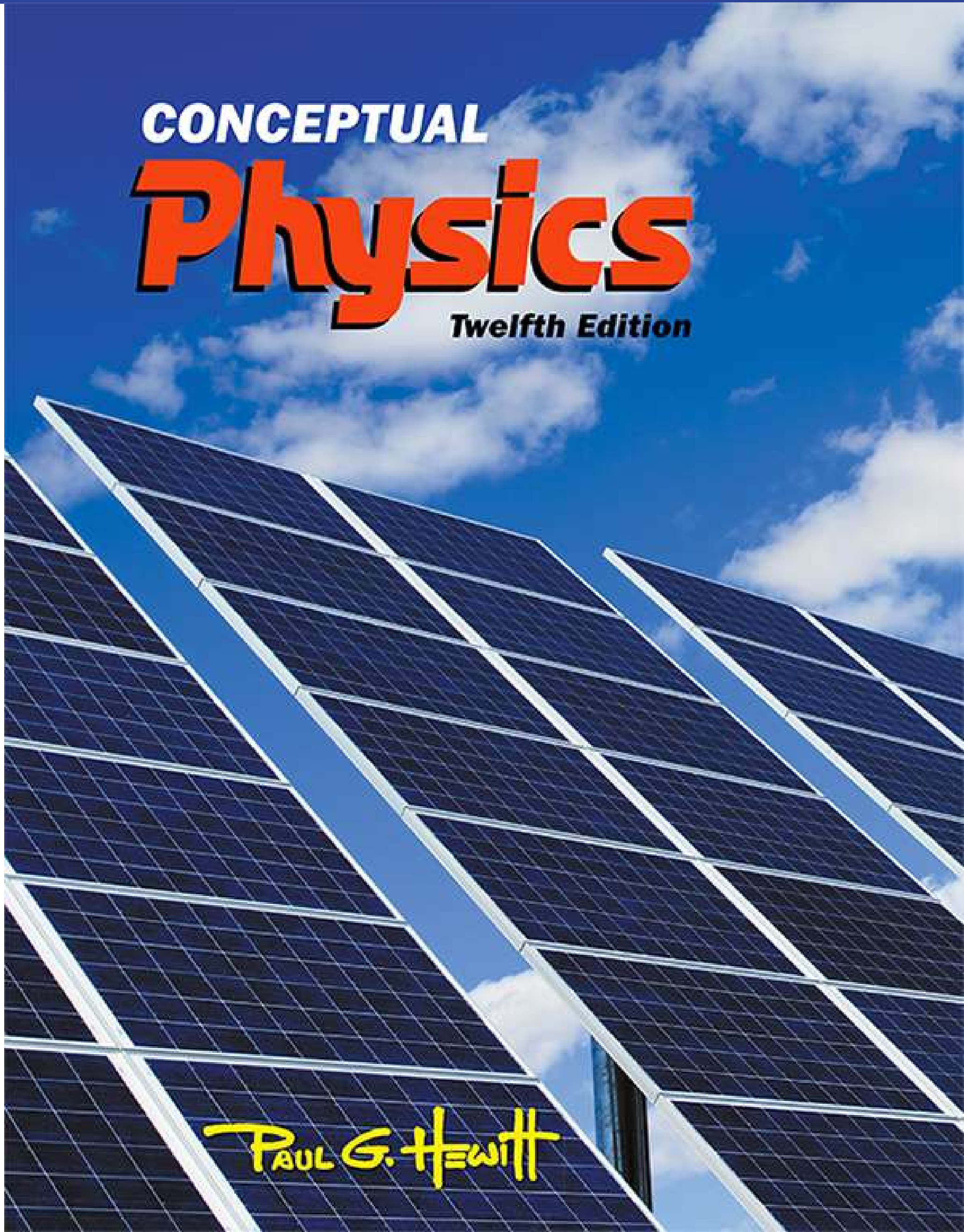
Lecture Outline

Chapter 31:
Light Quanta



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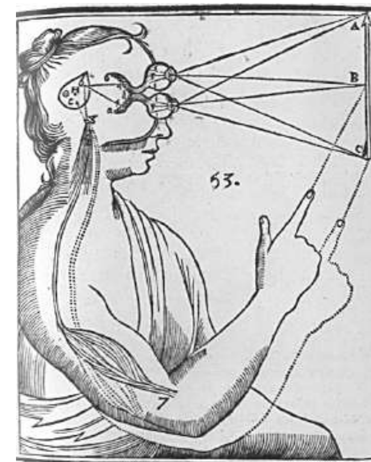
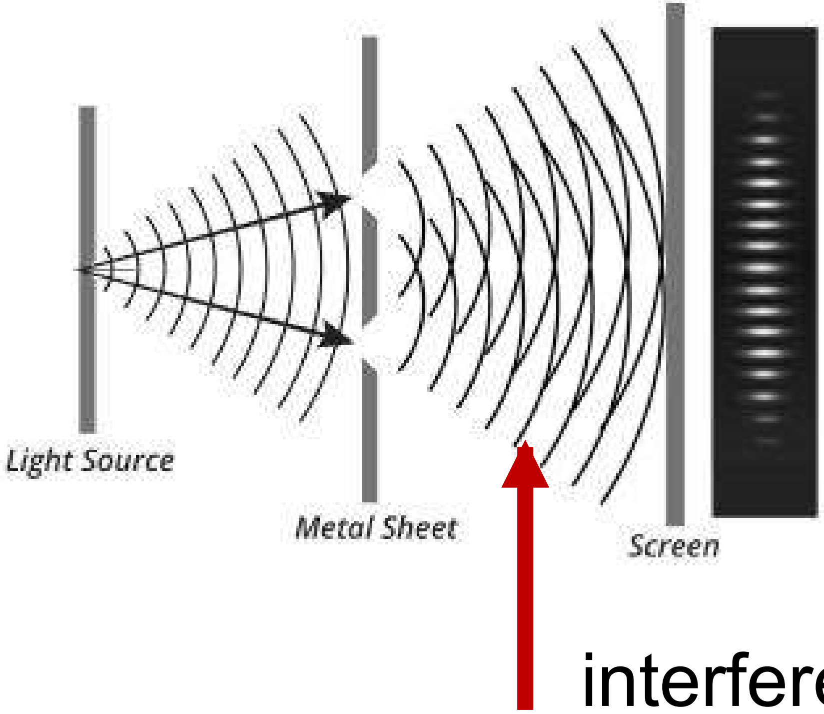
Birth of Quantum Theory

- There has been a long historical debate about the nature of light:
- -Euclid, Ptolemy and Plato thought light was emitted from the eye.
- Aristotle and Ibn al-Haytham believed light entered the eye.
- Some believed light to be particle-like:
  → the Pythagoreans and Newton
- Others believed it to be wavelike:

→ Empedocles and Huygens

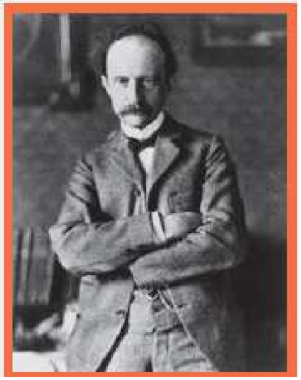


- Young's double-slit experiment in 1801 proved that light was a wave.

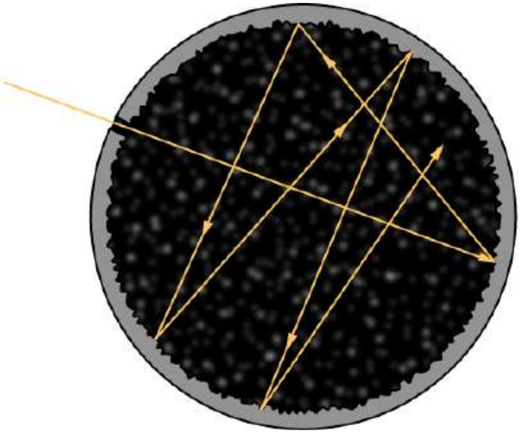


interference means waves

- Young was supported by the theorist James Clerk Maxwell and the experimentalist Heinrich Hertz.



Max Planck was studying the radiation (light) emitted by atoms of a “blackbody radiator” when they vibrate, then give off light.”



To explain the experimental results, he had to assume that the energy of the vibrating atoms was *quantized*…it could not take on any value, but only certain values.

Planck believed that the energy of the vibrating atoms was quantized, not that the light itself was.

Classwork

1. Which theory of light, the wave theory or the particle theory, did the findings of Young, Maxwell, and Hertz support?

3. What exactly did Max Planck consider quantized: the energy of vibrating atoms or the energy of light itself?

Quantization

- Quantum physics states that in the microworld of the atom, the amount of energy in any system is *quantized*—not all values of energy are possible.
- → Every energy is an integer multiple of the most basic amount, **the quantum**.
- Examples of *quanta* (pl. of *quantum*):
- A person is the quantum of society.
- A penny is the quantum of US money.

Example: The energy in a beam of laser light, which is a whole-number multiple of a single lowest value of energy—one quantum

Quantization and Planck's Constant

The quanta of light, and of electromagnetic radiation in general, are the photons.

→A photon is a quantum of light energy

- Energy E of a light quantum:

$$E = hf$$

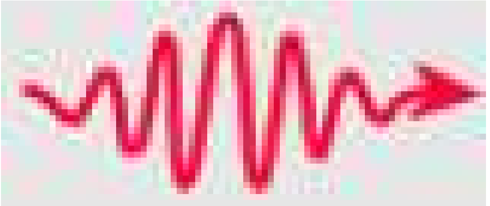
- where h is Planck's constant

$h = 6.63 \times 10^{-34}$ Js = a very small amount

f = the "frequency" of a particle

The photon is a particle:

with wave properties?



Classwork

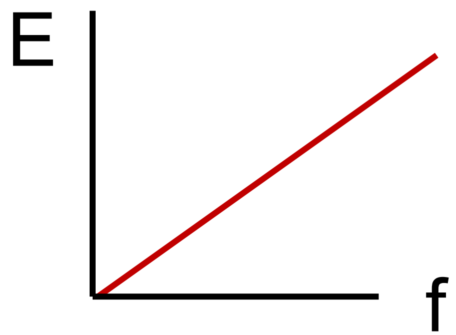
4. What is a quantum of light called?

5. In the formula $E = hf$, does f stand for wave frequency, as defined in Chapter 19?

The energy of a photon:

The energy of a single photon depends only on its frequency f:

$$E = hf$$



Higher frequency → more energy

Which has a higher f, red or blue light?

Which has more energy, red or blue light?

Which has a higher f, radio waves or x-rays?

Which has more energy, radio waves or x-rays?

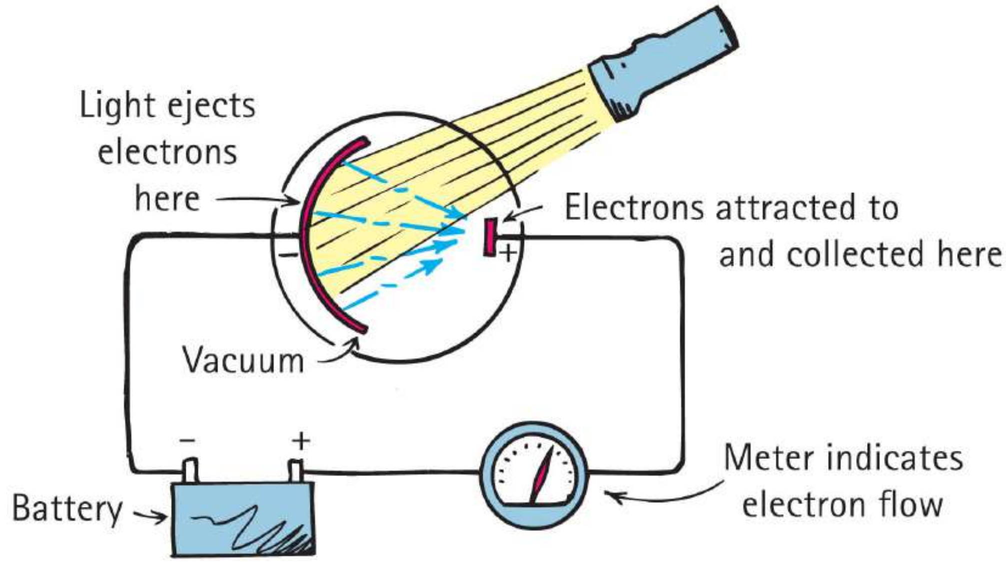
Classwork

6. Which has the lower energy quanta: red light or blue light? Radio waves or X-rays?

- Quantization
  - The idea that the natural world is granular rather than smoothly continuous

- Quantum
  - Any elemental particle that makes up matter or carries energy
  - → Electrons are elementary particles

The Photoelectric Effect

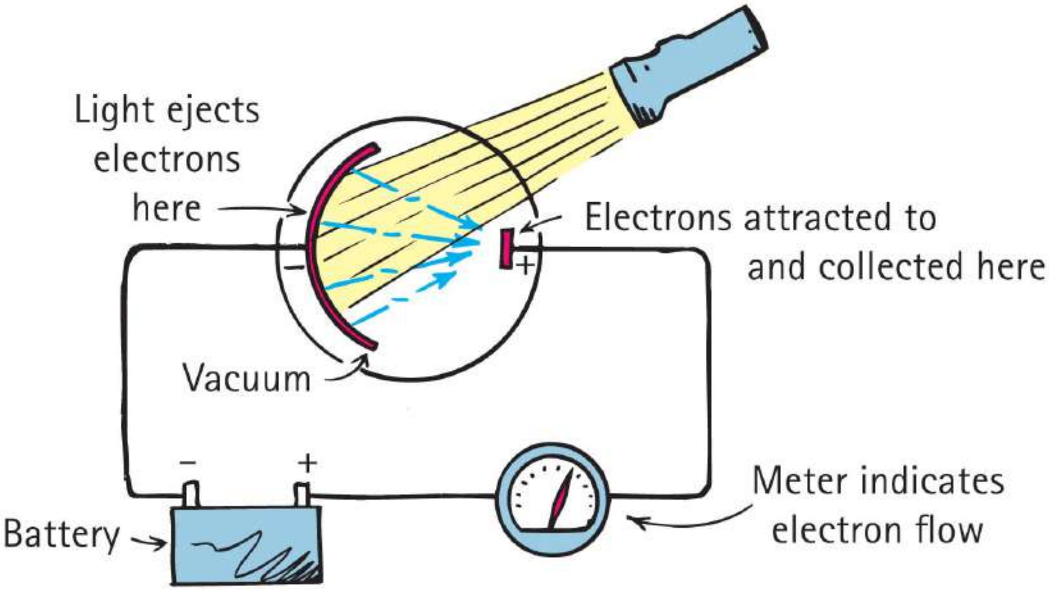


- Shine light on a negatively charged metal plate.
- Electrons are ejected from the metal and are attracted to the positive plate.
- This produces a current.

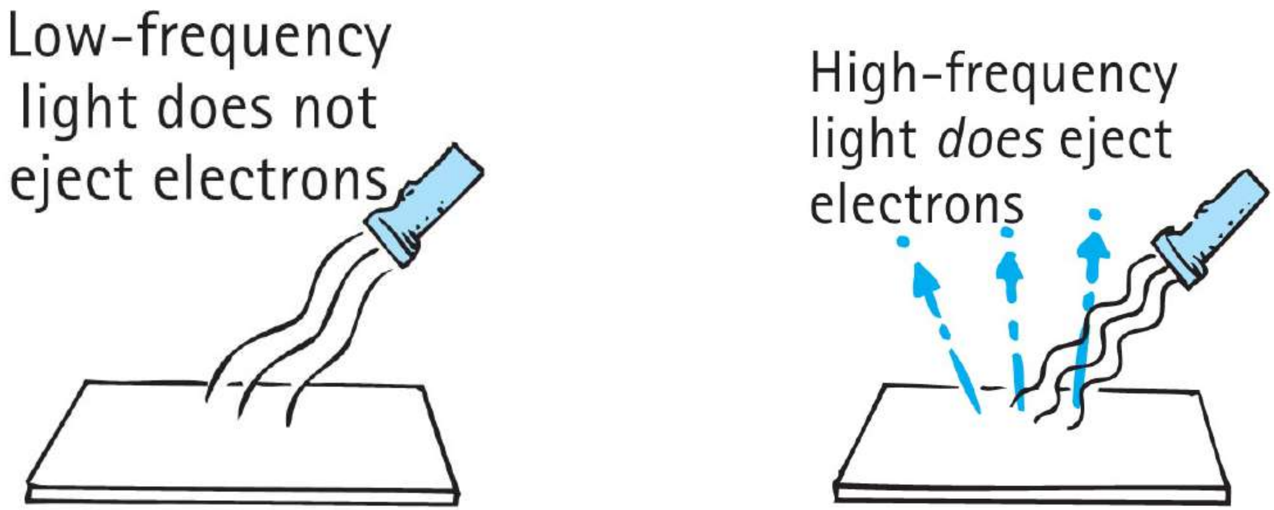
Why the name? Photo- = light

-electric = electron current

The Photoelectric Effect



- If we instead charge this plate with enough negative charge to repel the electrons, the current is stopped.
- We can then calculate the kinetic energy of the ejected electrons from the easily measured potential difference between the plates.



Odd results:

Bright red light ejected no electrons.

Dim UV light did eject electrons.

Why *odd*?

Because bright light **wave** means a high-energy.

A dim light wave means low-energy.

Why did dim UV work, but bright red didn't???

The Photon View:

Einstein:

1. Light is a stream of **particles** (photons).
2. Photons interact with the metal *one at a time.*
3. Only high-energy photons dislodge electrons.
4. Energy of photon E = hf
5. What's a high-energy photon? UV

   What's a low-energy photon? red
6. What is a **bright** light? Many photons.

   What is a **dim** light? A few photons.

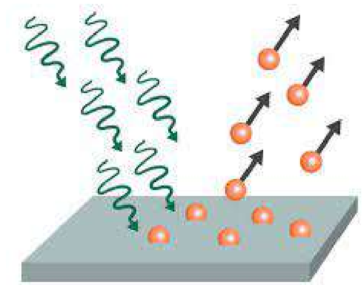
→ So bright red light was many weak photons.

→ And dim UV light was a few strong photons.

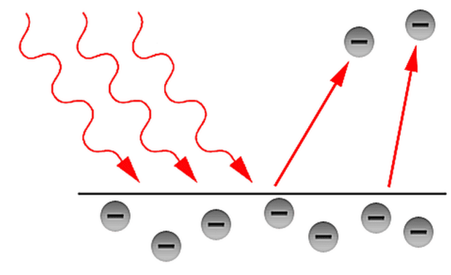
Classwork

2. Does the photoelectric effect support the wave theory or the particle theory of light?

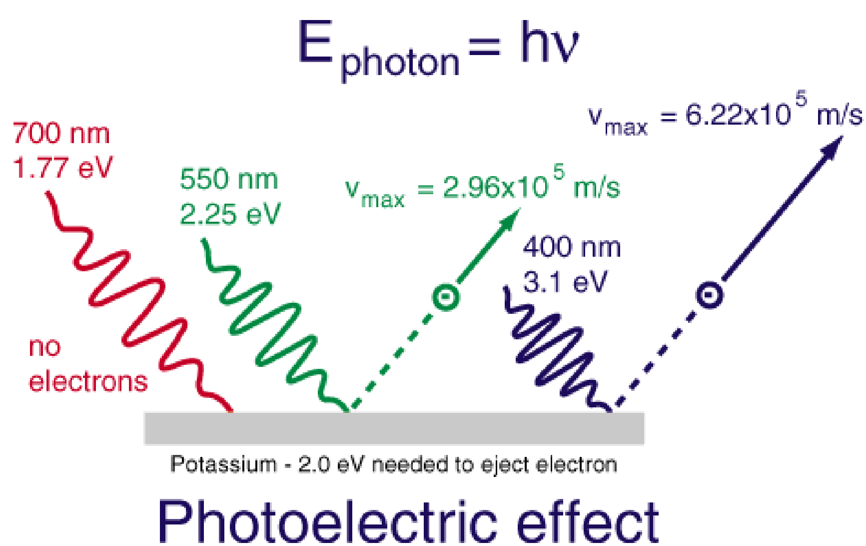
If photon is “strong” enough (if its frequency is high enough), then one photon ejects one electron:



The photon must have a certain minimum energy (the work function) to break the electron free.



Any extra photon energy goes into the electron’s kinetic energy (it is ejected with more speed.)



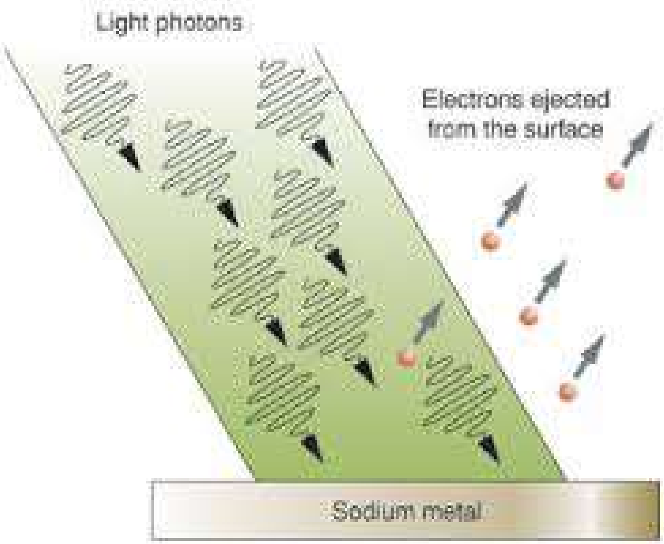
Classwork

7. Which are more successful in dislodging electrons from a metal surface: photons of violet light or photons of red light? Why?

8. Why won't a very bright beam of red light impart more energy to an ejected electron than a feeble beam of violet light?

The Photoelectric Effect
CHECK YOUR NEIGHBOR

In the photoelectric effect, the brighter the illuminating light on a photosensitive surface, the greater the



A. velocity of ejected electrons.
B. number of ejected electrons.
C. Both A and B.
D. None of the above.

The Photoelectric Effect
CHECK YOUR ANSWER

In the photoelectric effect, the brighter the illuminating light on a photosensitive surface, the greater the

B. number of ejected electrons.

The Photoelectric Effect
CHECK YOUR NEIGHBOR, Continued

In the photoelectric effect, the higher the frequency of the illuminating light on a photosensitive surface, the greater the

A. velocity of ejected electrons.
B. number of ejected electrons.
C. Both A and B.
D. None of the above.

The Photoelectric Effect
CHECK YOUR ANSWER, Continued

In the photoelectric effect, the higher the frequency of the illuminating light on a photosensitive surface, the greater the

A. **velocity of ejected electrons.**

Wave–Particle Duality

- Wave–particle duality
  – A photon behaves as a **particle** when emitted by an atom or absorbed by photographic film or by the chip in your camera or phone.

  Evidence: photoelectric effect

  – But it behaves as a **wave** in traveling from a source to the place where it is detected.

  Evidence: Young's experiment

  – In this sense, light can be both a wave and a particle!

Wave–Particle Duality, Continued

This film was exposed to light for longer and longer:

(a)

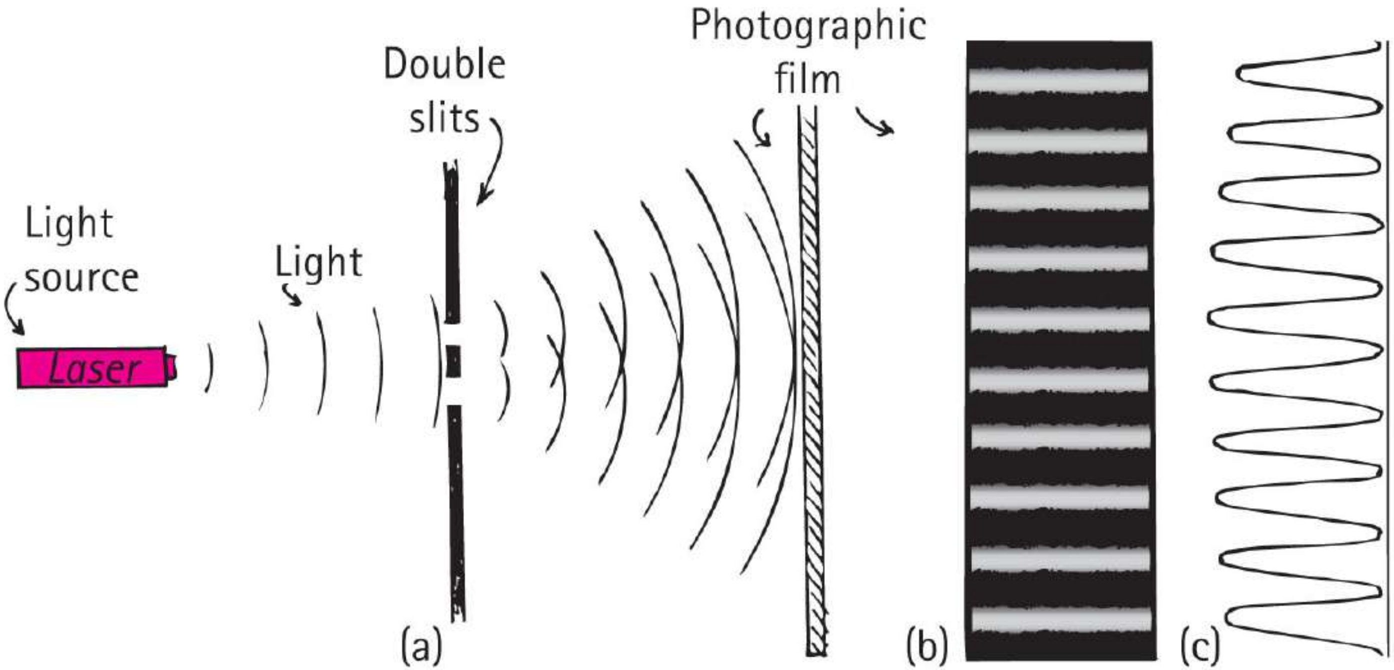

– This image is built up photon by photon.
– This is why images appear grainy up close.
– Light acts like a particle hitting the film.

Classwork

9. Why do photographs in a book or magazine look grainy when magnified?

10. Does light behave primarily as a wave or as a particle when it interacts with the crystals of matter in photographic film?

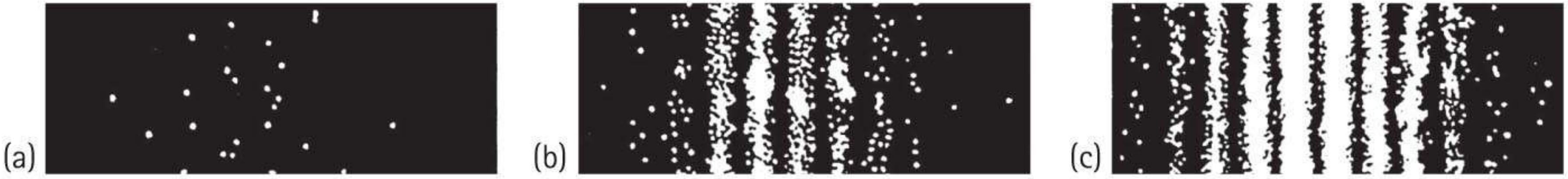
Young's Double-Slit Experiment



Monochromatic (one color) light passing through two slits, *a*, forms an interference pattern, *b*, shown graphically in *c*.

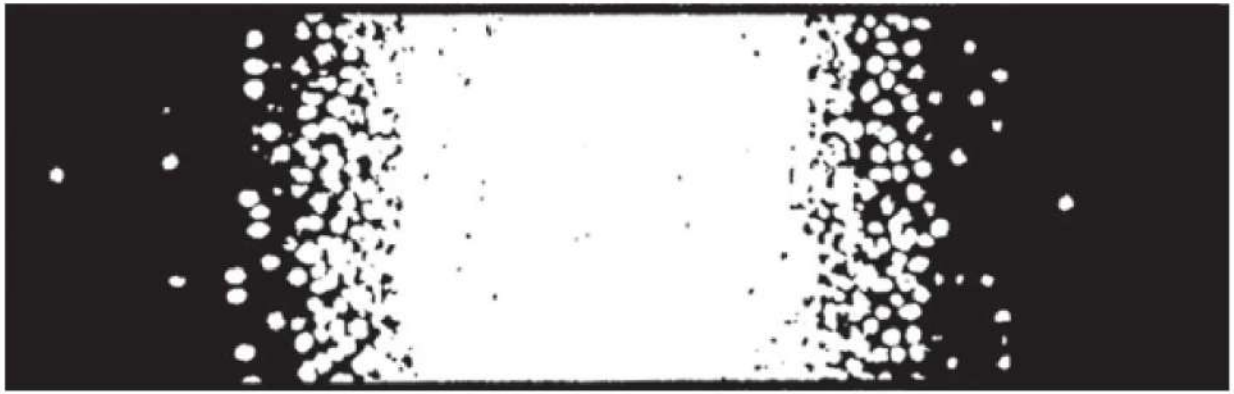
→ Pattern is explained by **wave interference**.

- Suppose we dim our light source so that only one photon at a time reaches the thin slits.
- If film behind the barrier is exposed to the light for a very short time, the film gets exposed as shown below.
  – Each spot represents the place where the film has been exposed by a photon.
  – If the light is allowed to expose the film for a longer time, a pattern of fringes begins to emerge



Double-Slit Experiment, Continued-1

- If we cover one slit so that photons striking the photographic film can pass only through a single slit, the tiny spots on the film accumulate to form a single-slit diffraction pattern.
- We find that photons hit the film at places they would not hit if both slits were open.



- How do photons traveling through one slit "know" that the other slit is open and avoid certain regions, proceeding only to areas that will ultimately fill to form an interference pattern?
  - Each single photon has wave properties as well as particle properties. The photon displays different aspects at different times.

- A photon behaves
- A) as a particle when it is being emitted by an atom or absorbed by photographic film or other detectors, and
- B) as a wave in traveling from a source to the place where it is detected.

- So the photon strikes the film as a particle but travels to its position as a wave that interferes constructively.

Classwork

11. Does light travel from one place to another in a wavelike or a particle-like way?

12. Does light interact with a detector in a wavelike or a particle-like way?

13. When does light behave as a wave? When does it behave as a particle?