INTRO TO QUANTUM COMPUTING

Week 11 Lab

QUANTUM MECHANICS - I

<insert name>

<insert date>

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PROGRAM FOR TODAY

- Logistics and ground rules
- Canvas attendance quiz
- Pre-lab zoom feedback
- Questions from last week
- Lab content
- Post-lab zoom feedback

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LOGISTICS

- **Homework:** The week 11 homework is due, like all homework assignments, on Sunday, at 11:59 p.m. ET on Canvas.

- **Canvas:** Contains all required course information and materials
  - TAs will not be able to respond to messages on Canvas
  - If you have a question on logistics, email **student@qubitbyqubit.org**

- **Piazza:** We will not be able to address all content-questions in lecture or lab
  - Look at answers to similar questions on Piazza or Discord
  - Post your question in the relevant folder in Piazza (see Piazza orientation video)
  - We will explore new content and will likely answer your question in future weeks ☺

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CANVAS ATTENDANCE QUIZ

- Please log into Canvas and answer your lab section's quiz (using the password posted below and in the chat).
  - This is lab number:
  - Passcode:

- If you participated in the fall semester of QxQ, do you feel more confident in your STEM skills since you started the course?

- **This quiz not graded, but counts for your lab attendance!**

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PRE-LAB ZOOM FEEDBACK

On a scale of 1 to 5, how would you rate your understanding of this week's content?

- 1 –Did not understand anything
- 2 – Understood some parts
- 3 – Understood most of the content
- 4 – Understood all of the content
- 5 – The content was easy for me/I already knew all of the content

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LEARNING OBJECTIVES FOR LAB 11

- Distinguishing between particles and waves
  - Particle and wave properties
  - Ripple on a rope
  - deBroglie wavelength of electrons
- Why do wave-like properties of particles show up at small lengths?
  - Double-slit experiment with light
  - Double-slit experiment with electrons
  - Double-slit experiment with everyday objects
- Double-slit experiment with single electrons*

*Optional content

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QUESTIONS FROM LAST WEEK

- Defining numpy arrays

```
A = np.array([[1, 3 , 4 ]])  vs A = np.array([1, 3 , 4 ])
```


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MOTIVATION

Why do we care about waves and particles in quantum computing?

- Qubits are made of objects that show wave- and particle-like behavior!
- Quantum mechanics is the mathematical description of objects that show such behavior
- Qubits and quantum gates are governed by the rules of quantum mechanics

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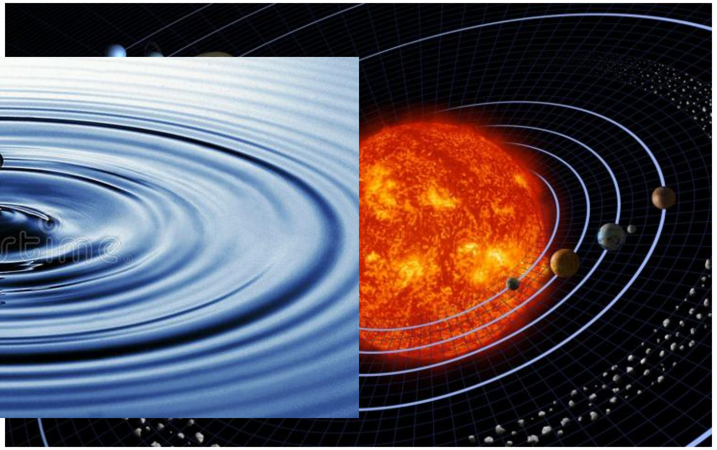
WAVE OR PARTICLE?

Wave

Particle



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WAVE AND PARTICLE PROPERTIES

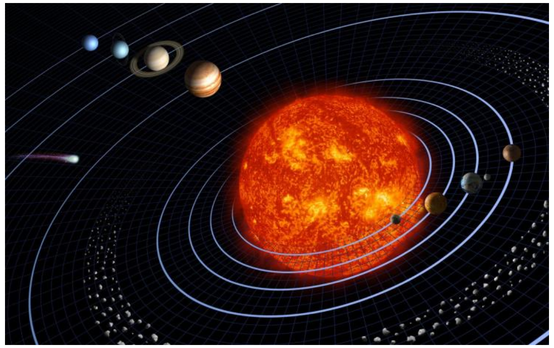
How did you know which was a wave and which was a particle?

Wave properties

- Repetition (wavelength/frequency)
- How often does the wave repeat?

- Speed
- How fast is the wave?

Particle properties



- Position
- Where is the particle?

- Mass
- How heavy is the particle?

- Speed
- How fast is the particle?

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RIPPLE ON A ROPE - WAVE OR PARTICLE?

RIPPLE ON A ROPE – A BIT OF BOTH!

“Where is the ripple” as well as “how often does the ripple repeat” are meaningful questions!

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EVERYTHING IS RIPPLES

- The distinction between ‘wave’ and ‘particle’ is fuzzy, even in objects we see around us
  - Ripples on a rope, waves on a beach

- Early 20th century physicists found that treating atoms, molecules, ions, electrons, protons, neutrons as particles alone was limited and did not explain all their properties
  - At small length scales, **everything** behaves in this fuzzy way!

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QUESTIONS?

Questions on content so far?

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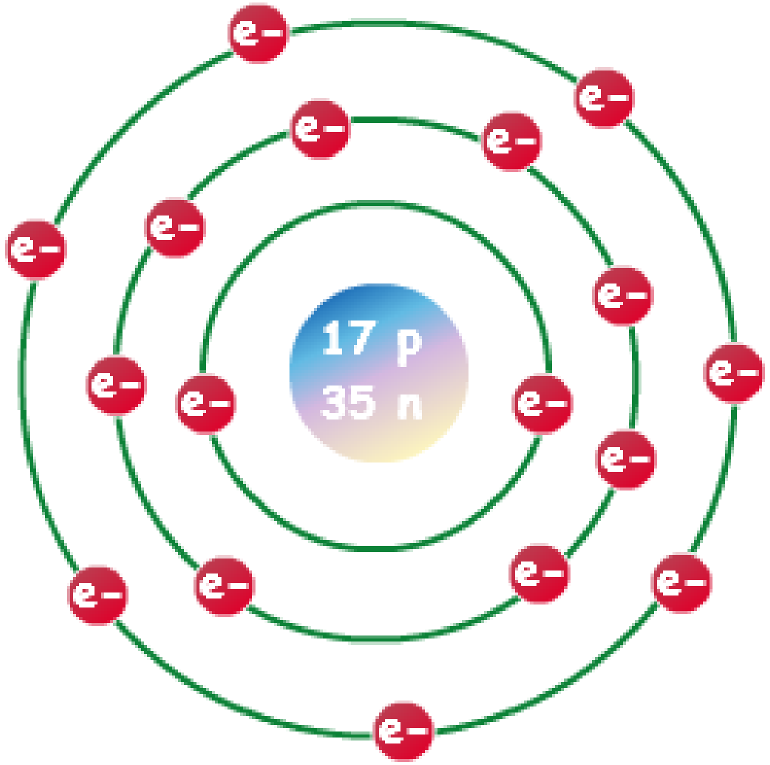
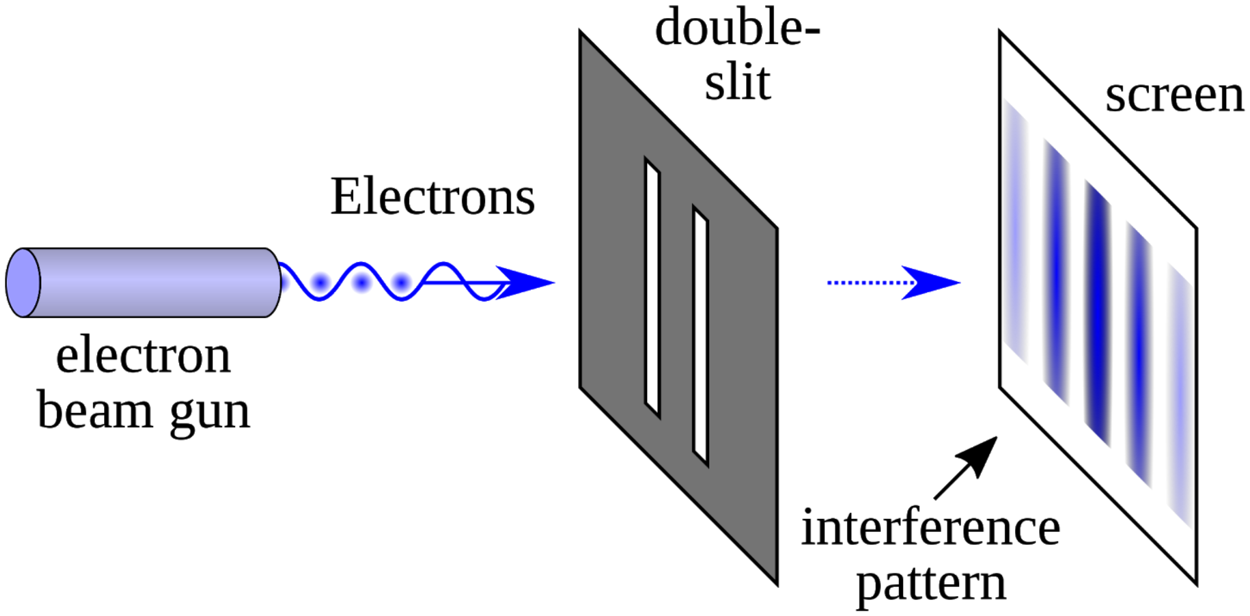
ELECTRONS – PARTICLES OR WAVES?





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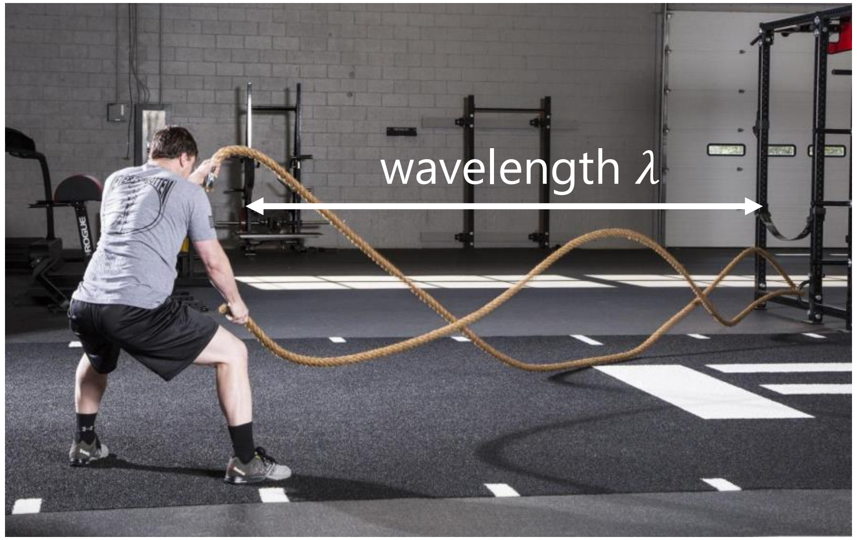
ELECTRONS – A BIT OF BOTH

Planck's constant is *tiny*! It sets the scale of the relationship between particle and wave properties.

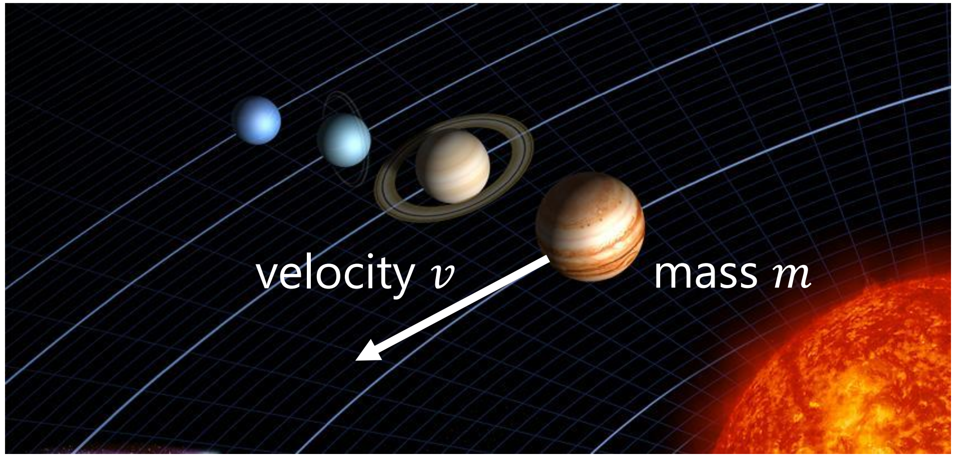


Planck's constant
$h = 6.626 \times 10^{-34}\, Js$

wavelength

$$\lambda = \frac{h}{p}$$

momentum
$p = m \cdot v$



Practice: what is λ for electrons, with $m = 9.1 \times 10^{-31}$ kg and $v = 2 \times 10^{8}$ m/s ?

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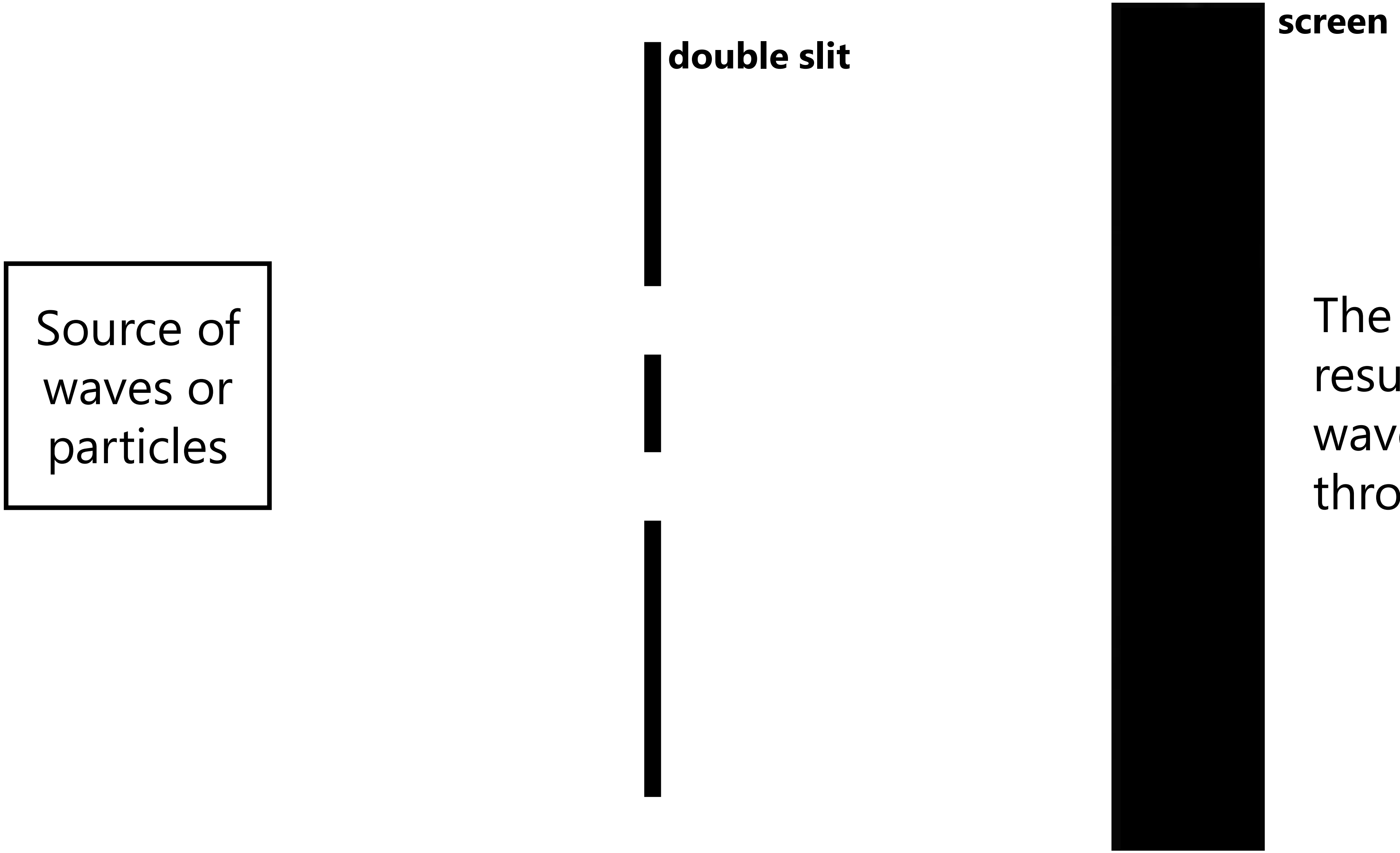
THE DOUBLE SLIT EXPERIMENT



The screen captures the result of the waves/particles passing through the slits

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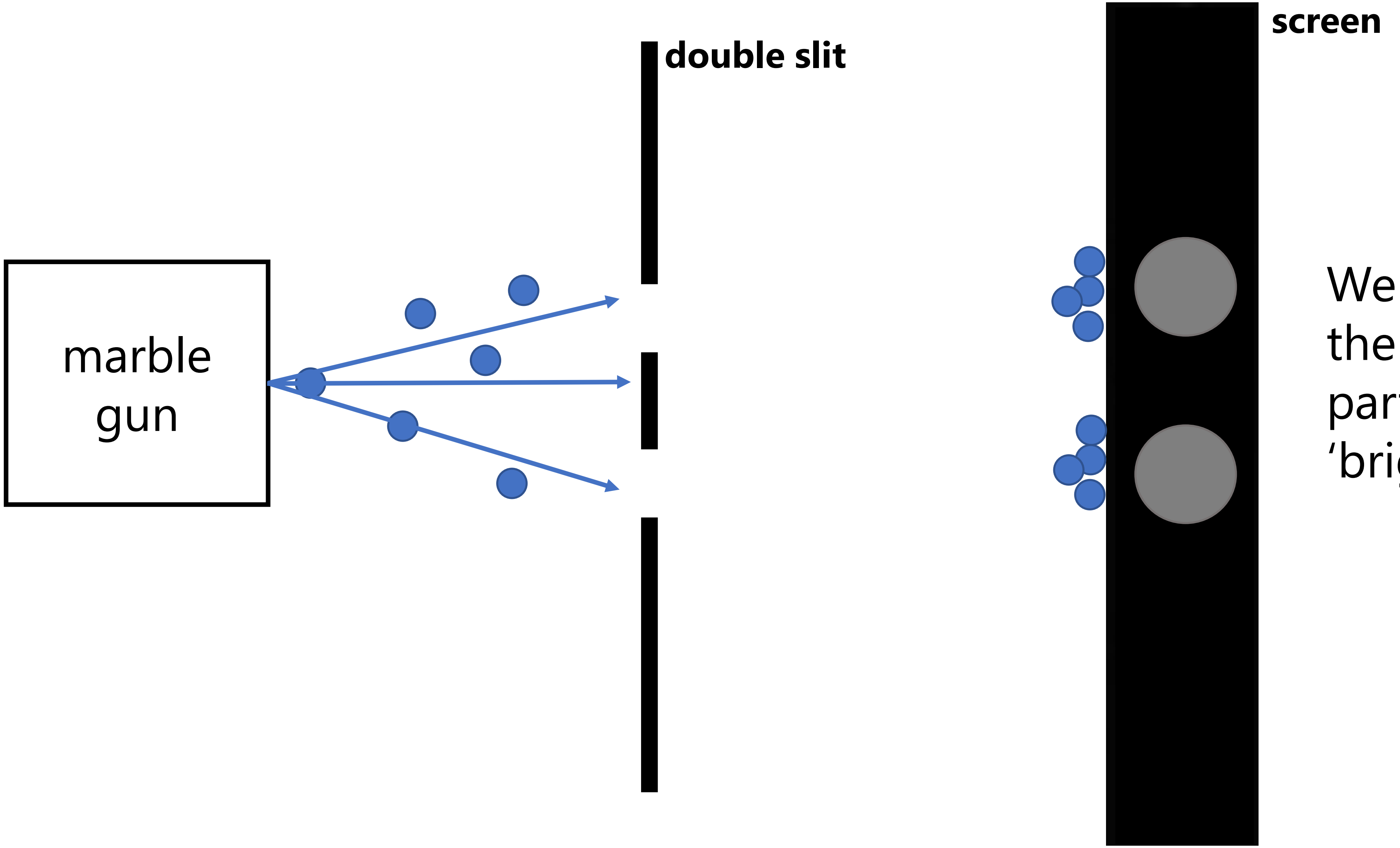
THE DOUBLE SLIT EXPERIMENT - PARTICLES



We see two spots on the screen with lots of particles, i.e., two 'bright' spots

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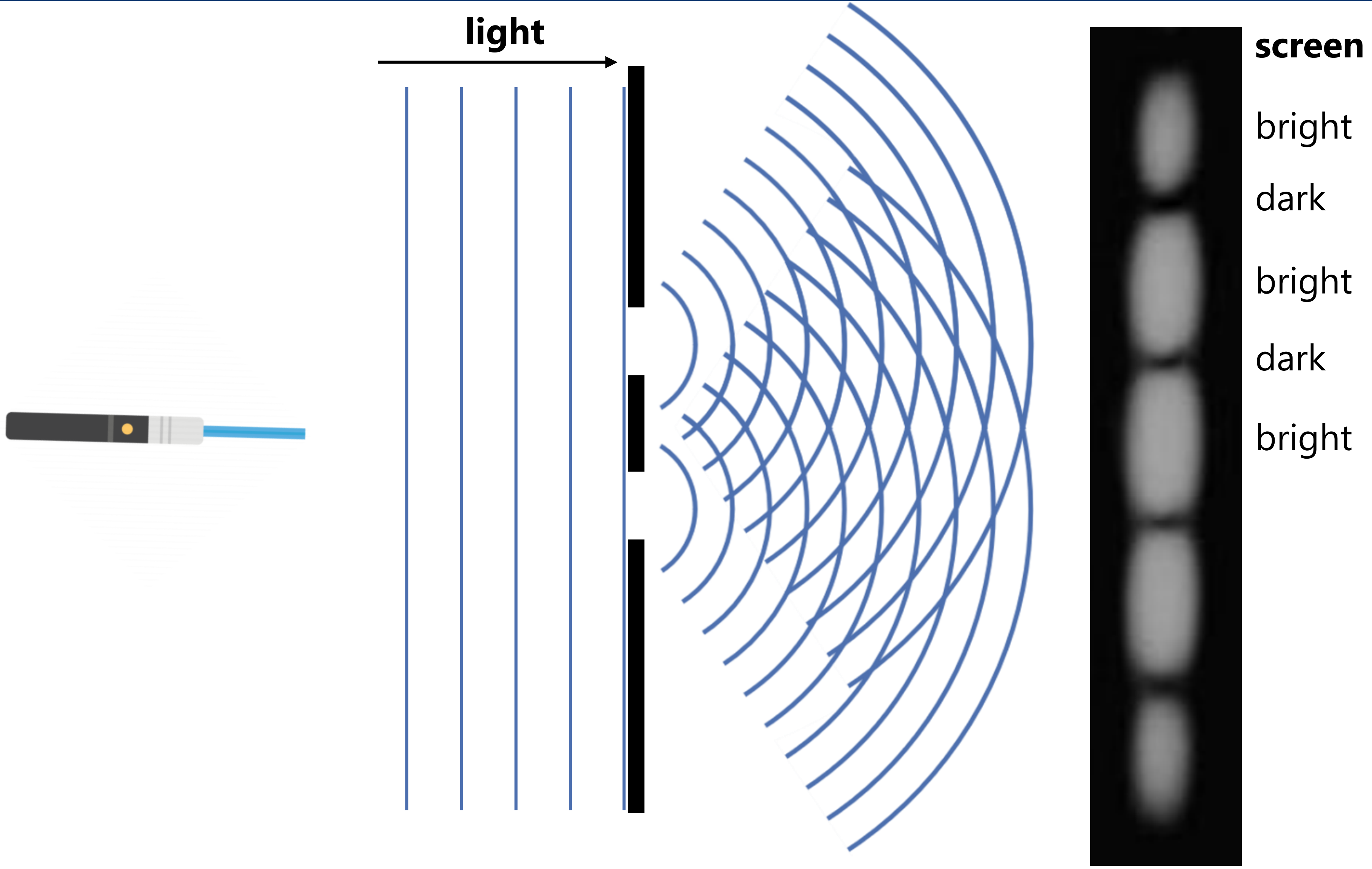
THE DOUBLE SLIT EXPERIMENT - WAVES



- With waves, we see multiple bright and dark spots due to wave interference
- This experiment tells us that light behaves like a wave!

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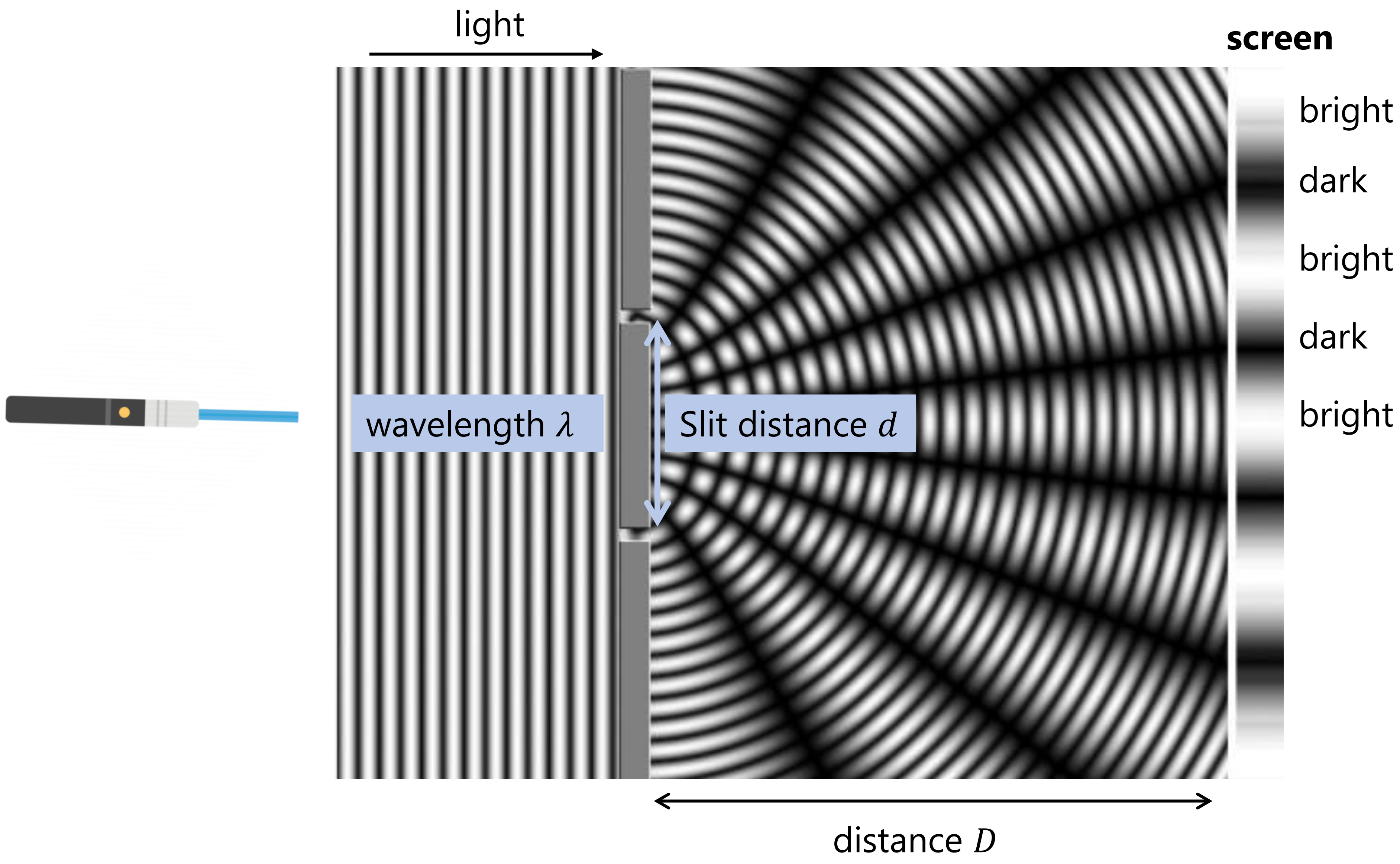
THE DOUBLE SLIT EXPERIMENT



spacing $s = \frac{D\lambda}{d}$

spacing depends on d! As d increases, the spacing gets smaller and smaller and harder to see

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VARYING THE SLIT SPACING

spacing $s = \frac{D\lambda}{d}$

$1\ \text{mm} = 1 \times 10^{-3}\ \text{m}$
$1\ \mu\text{m} = 1 \times 10^{-6}\ \text{m}$
$1\ \text{nm} = 1 \times 10^{-9}\ \text{m}$

Problem 1: What is the spacing s with distance $D = 1$ m, slit distance $d = 1$ mm and using red light $\lambda = 800$ nm ?

Problem 2: What is the spacing s with distance $D = 1$ m, slit distance $d = 10$ mm and using red light $\lambda = 800$ nm ?

Human eye can resolve features $\sim 300\ \mu\text{m}$ or larger at a distance $D = 1$ m

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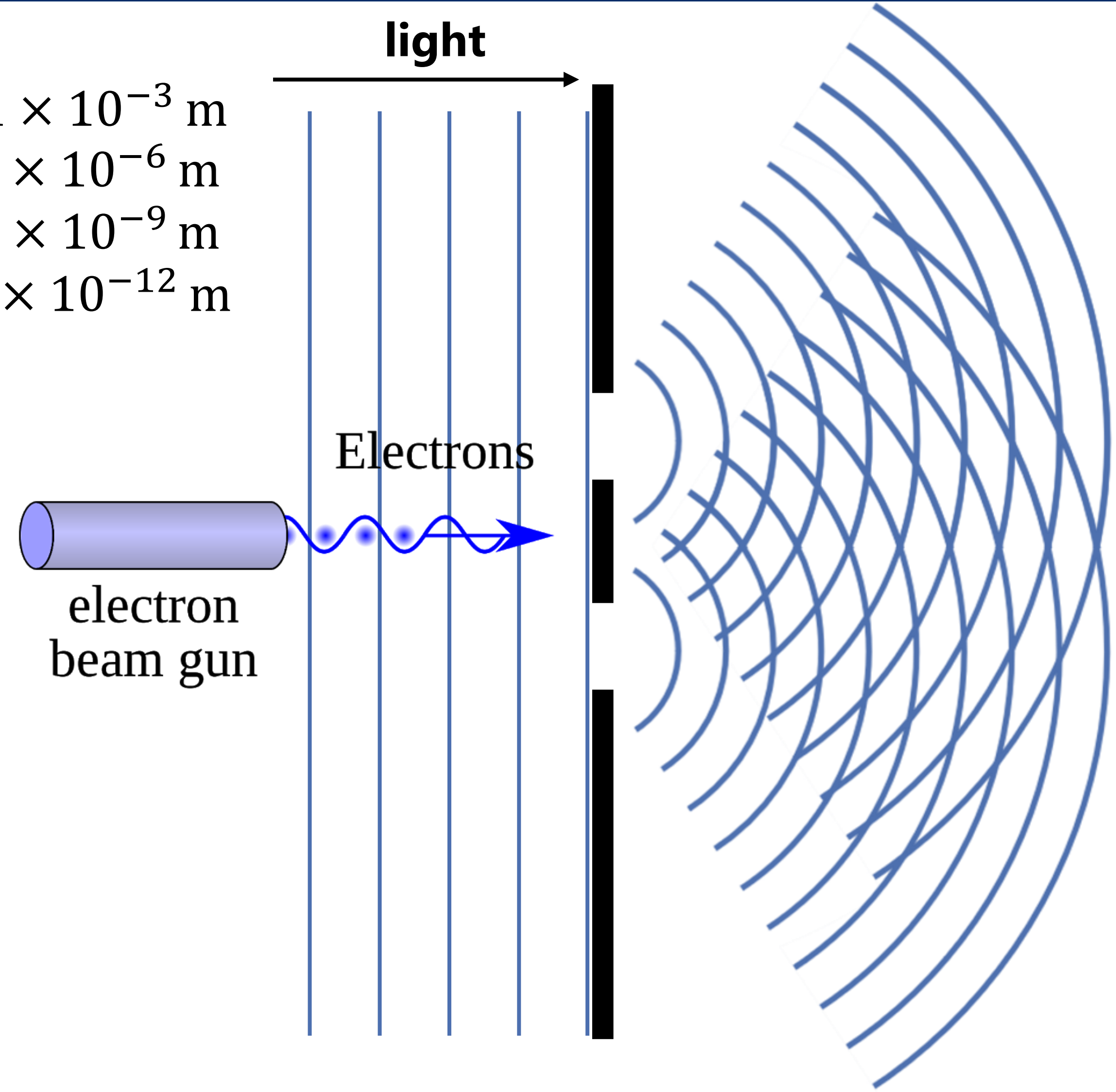
ELECTRON DOUBLE SLIT EXPERIMENT

$1\ \text{mm} = 1 \times 10^{-3}\ \text{m}$
$1\ \mu\text{m} = 1 \times 10^{-6}\ \text{m}$
$1\ \text{nm} = 1 \times 10^{-9}\ \text{m}$
$1\ \text{pm} = 1 \times 10^{-12}\ \text{m}$



spacing $s = \frac{D\lambda}{d}$

Problem: What is the spacing s with distance $D = 1$ m, slit distance $d = 1$ mm and using electrons with $\lambda = 3.6$ pm ?

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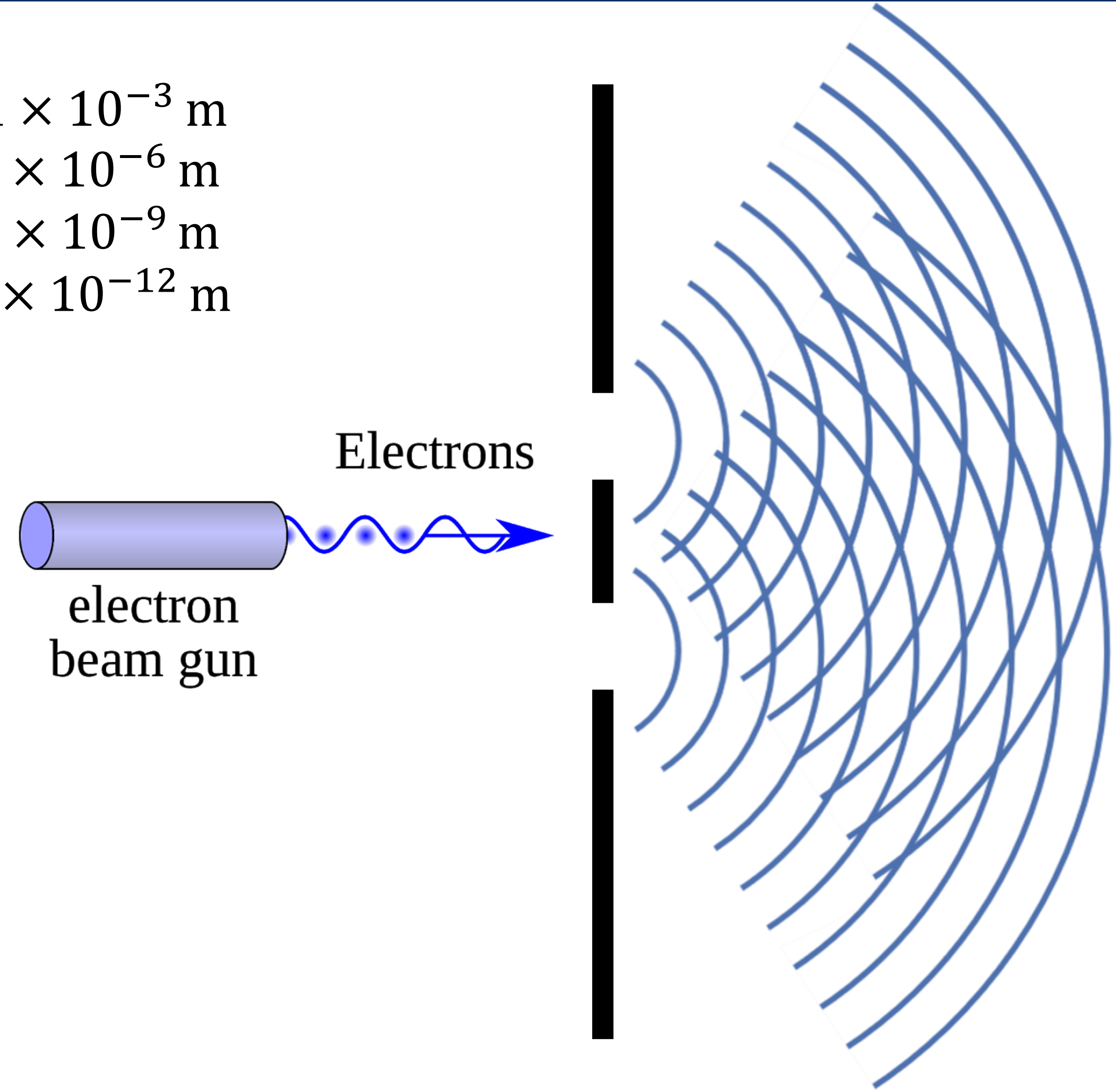
ELECTRON DOUBLE SLIT EXPERIMENT

$1\ \text{mm} = 1 \times 10^{-3}\ \text{m}$
$1\ \mu\text{m} = 1 \times 10^{-6}\ \text{m}$
$1\ \text{nm} = 1 \times 10^{-9}\ \text{m}$
$1\ \text{pm} = 1 \times 10^{-12}\ \text{m}$



spacing $s = \frac{D\lambda}{d}$

Can we change the slit distance d to make the spacing visible? $D = 1$ m, $\lambda = 3.6$ pm, and we want $s = 300\ \mu\text{m}$?

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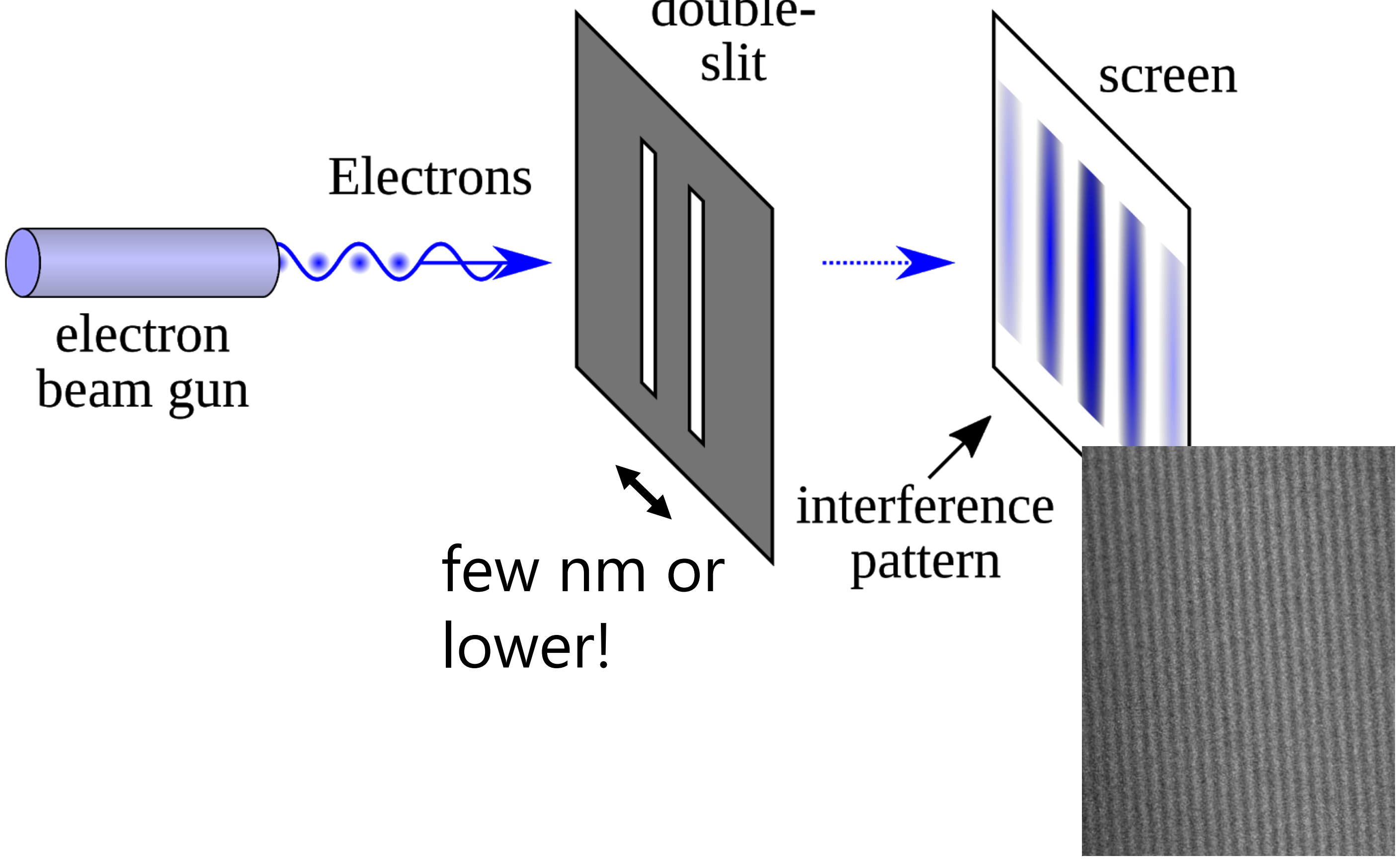
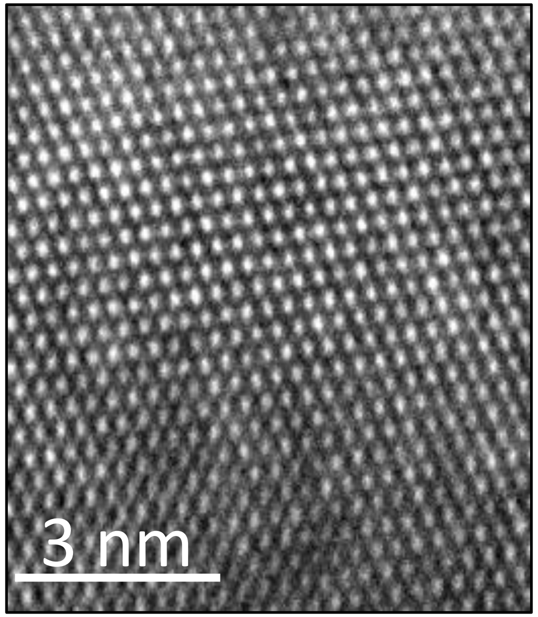
ELECTRON DOUBLE SLIT EXPERIMENT



- How can we make such small slits?
  - Gaps between atoms in crystals!



Electron microscope image of silicon crystal, showing atoms

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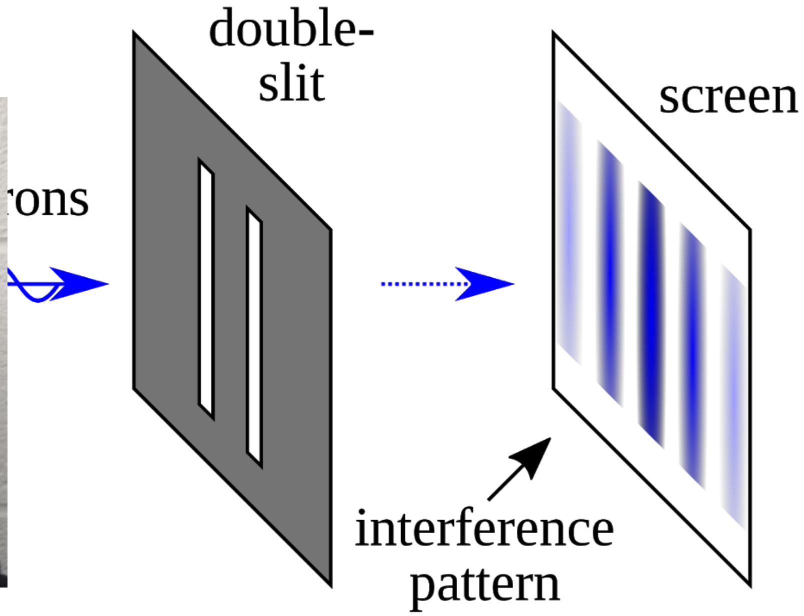
HUMAN DOUBLE SLIT EXPERIMENT(?)



Let's find Rahul's wavelength if he runs towards the slits at a speed of $v = 8$ m/s, assuming he weighs $m = 70$ kg.

Planck's constant

$h = 6.626 \times 10^{-34}\ Js$

wavelength

$$\boxed{\lambda = \frac{h}{p}}$$

momentum

$p = m \cdot v$

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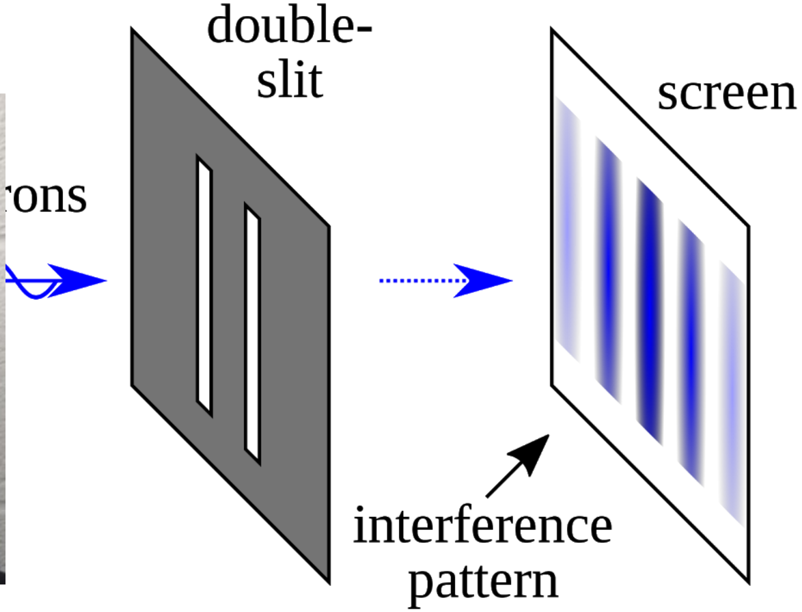
HUMAN DOUBLE SLIT EXPERIMENT(?)



Now let's find the slit distance required to see the interference pattern

$$\text{spacing } s = \frac{D\lambda}{d}$$

Radius of a proton $\sim 1 \times 10^{-15}$ m

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KEY TAKEAWAYS

- Particles and waves are human-made buckets to sort phenomena we see around us
  - Particles have mass, position, speed, etc.
  - Waves have wavelength, frequency, speed, etc.

- Pulses and ripples can possess both particle and wave-like properties
  - At the nanoscale, everything behaves like pulses and ripples!

- The wave-like nature of particles is expressed by their deBroglie wavelength
  - For the wave-like nature of particles to become observable, we have to manipulate them on the scale close to their deBroglie wavelength

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QUESTIONS?

Questions on content so far?

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POST-LAB ZOOM FEEDBACK

After this lab, on a scale of 1 to 5, how would you rate your understanding of this week's content?

- 1 –Did not understand anything
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FURTHER READING AND RESOURCES

- Dr. Quantum's guide to the double-slit experiment
- https://www.hitachi.com/rd/research/materials/quantum/doubleslit/index.html – A description of a double-slit experiment with electrons from Hitachi, a major manufacturer of electron microscopes
- https://physicsworld.com/a/the-double-slit-experiment/ - History of the double slit experiment with electrons, with links to important papers and relevant articles

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OPTIONAL CONTENT

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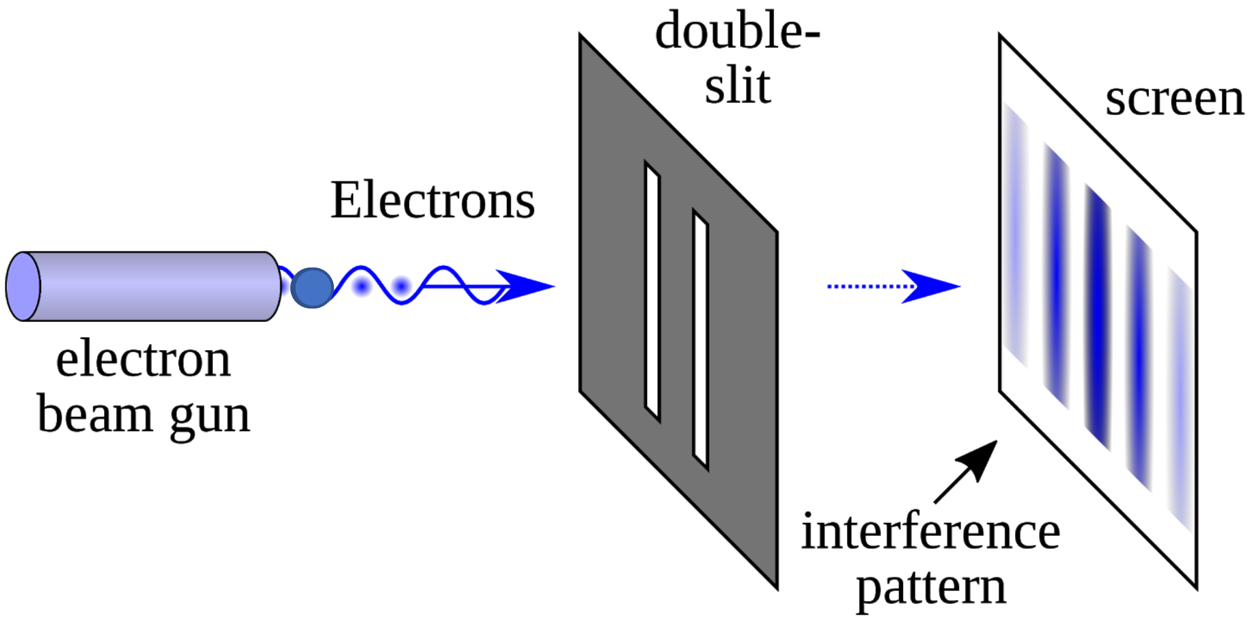
MORE ON THE DOUBLE SLIT EXPERIMENT



Could we shoot the electrons one-by-one? What do you expect to happen?

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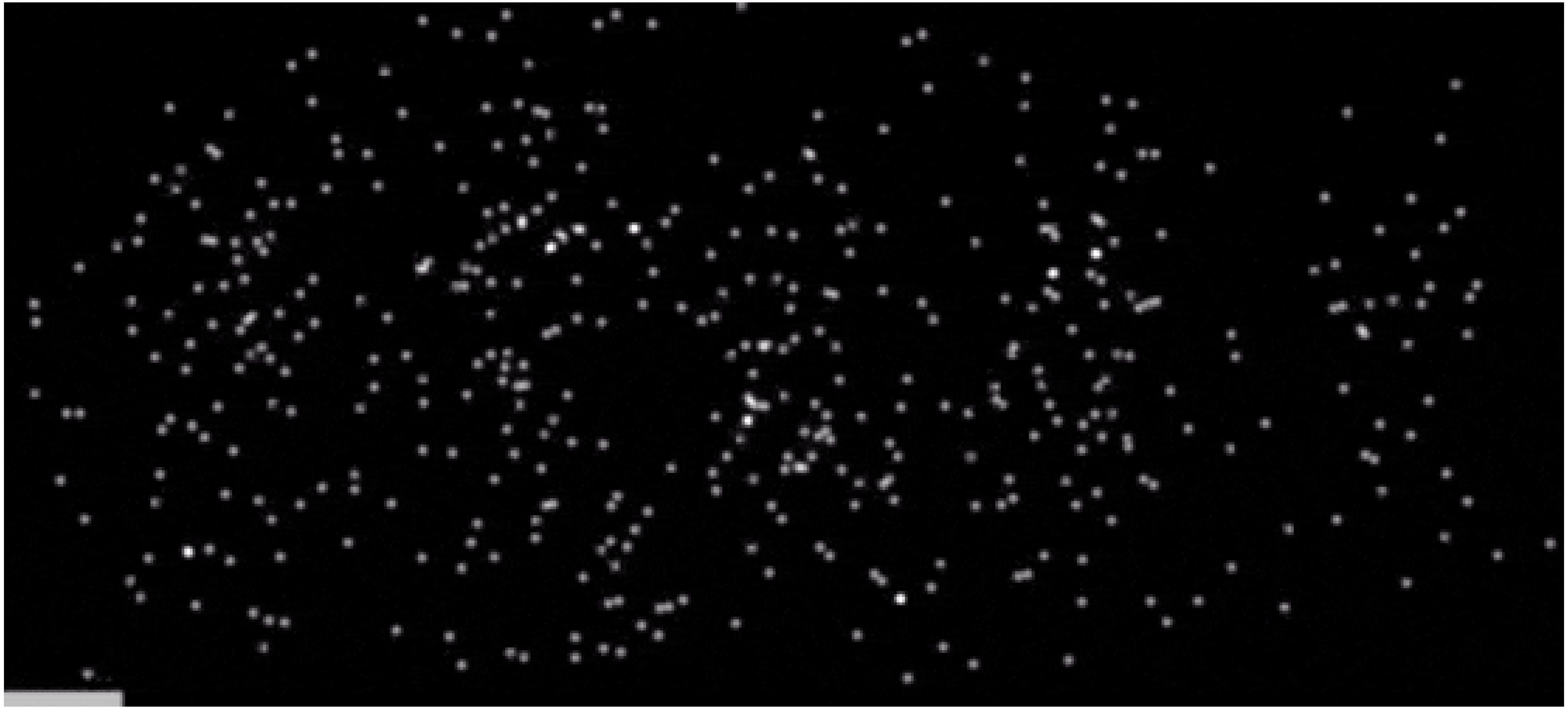
EXPERIMENT WITH SINGLE ELECTRONS

Screen



What do you notice?

Adapted from A Tonomura, J Endo, T Matsuda, T Kawasaki and H Ezawa 1989 Demonstration of single-electron build-up of an interference pattern *American Journal of Physics* **57** 117-120

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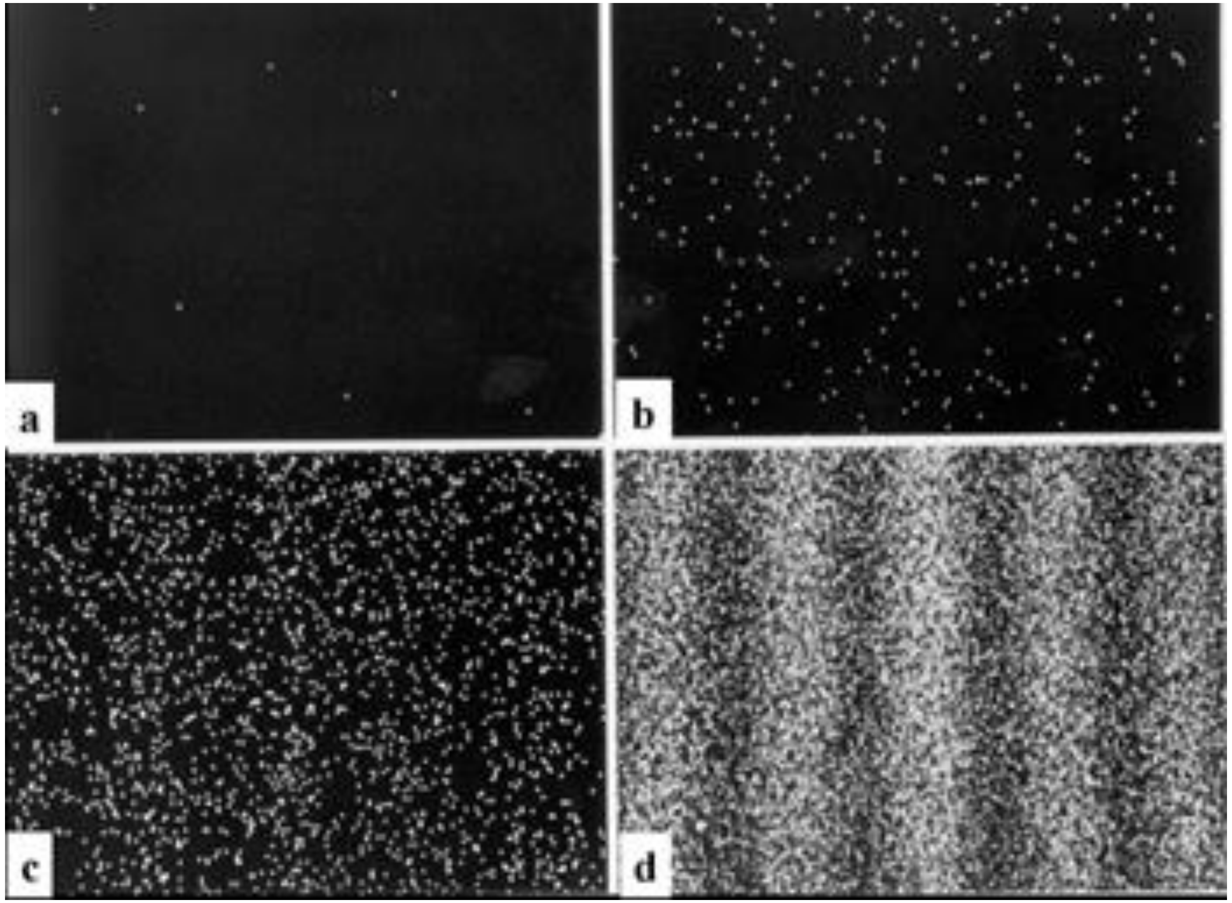
'THE MOST BEAUTIFUL EXPERIMENT IN PHYSICS'



- Each electron registers as a single spot (a 'particle')
- The double-slit interference pattern 'emerges' as more and more electrons hit the screen
- The math gives us the probability that each electron ends up at a certain point on the screen

https://www.hitachi.com/rd/research/materials/quantum/doubleslit/index.html

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