QUANTUM MECHANICS

How to introduce quantum ideas into an introductory class

OPTYCs 2YC Tandem meeting, August 2, 2025

My goal: Find ways to connect classical ideas to quantum ideas as much as possible and carefully show where they differ.

This is the best way to introduce quantum ideas earlier in the curriculum

It is powerful ideas, not advanced math that is important

Part 1: The Photoelectric Effect

Quanta are too small to see by the eye, so how do we interrogate them?

Consider a weak electric field. If it drives on resonance, then after some time the oscillation should have a high enough amplitude, that the electron will become unbound and be emitted.

Questions to ponder?

- How do we know what the resonance frequencies of the electrons are?
- Do we expect that it takes more time for electrons to be emitted for low amplitude than high amplitude fields?
- How do we detect the emitted electrons?
- What happens when we change the color of the light?

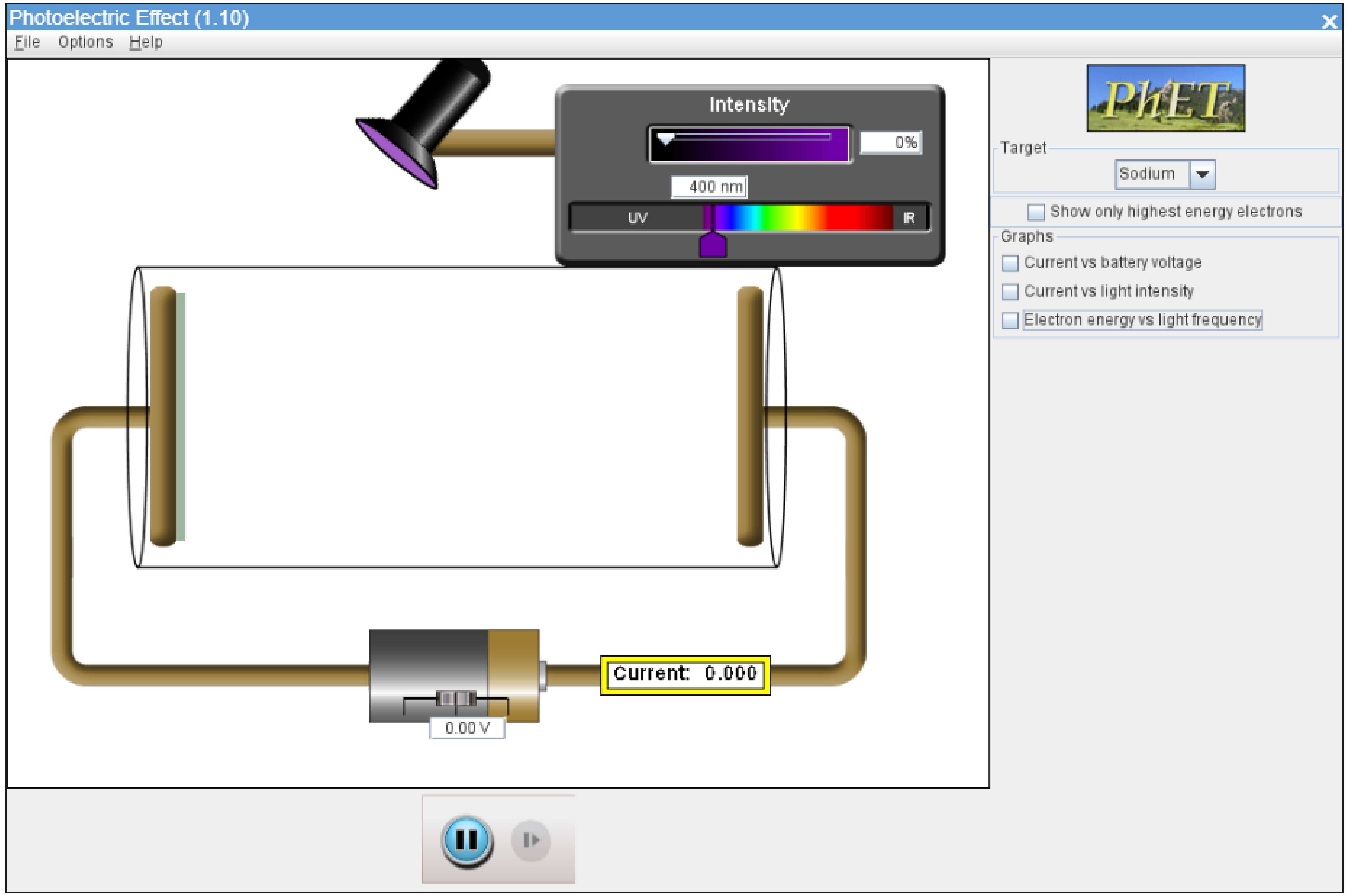
Classical predictions for resonant excitation

- Light must have a frequency whose energy is at least as large as the highest bound energy of the electron. (resonance matching)
- When we emit electrons on resonance, the kinetic energy should only weakly depend on the intensity and frequency of light. (emission immediately on reaching threshold)
- Low amplitude light takes longer to first emit electrons. (resonance takes time to build up)
- We should see materials dependence on the minimal frequency for resonance matching.

What is observed in an experiment?

- Low frequency light emits no electrons regardless of the intensity.
- Electrons are emitted immediately with no delay when the frequency is high enough.
- The critical frequency varies with the metal used.
- Higher intensity light emits more electrons; their maximal kinetic energy is independent of the intensity, but depends on the frequency of the light.

Let's explore with the Phet simulation

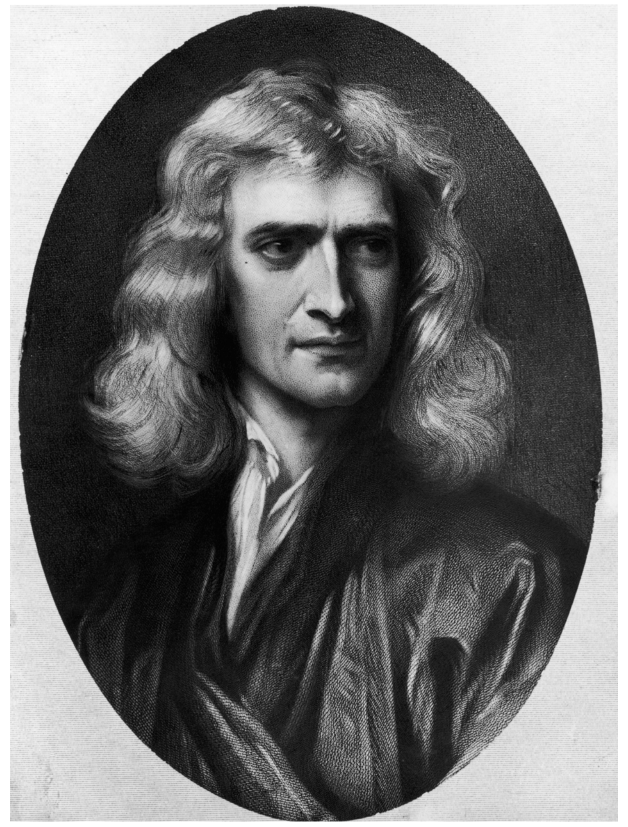
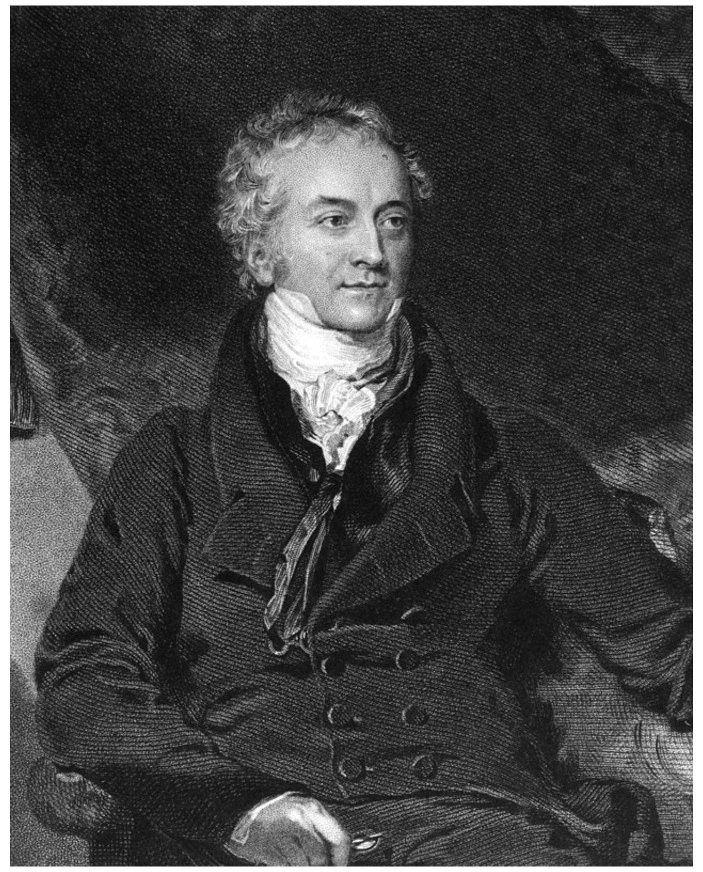


Phet simulation website

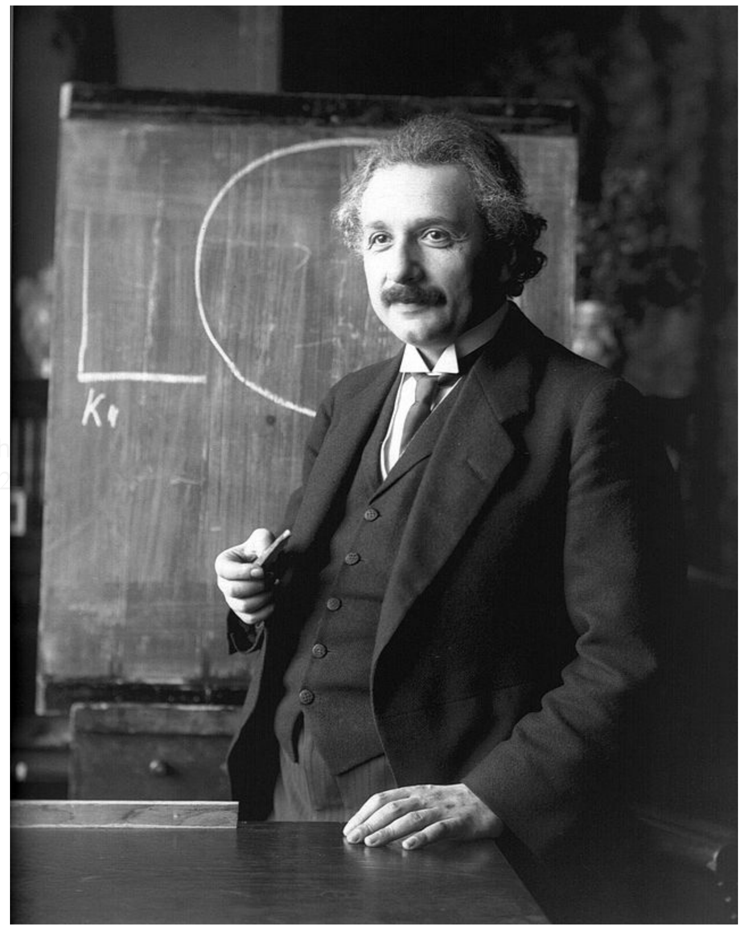
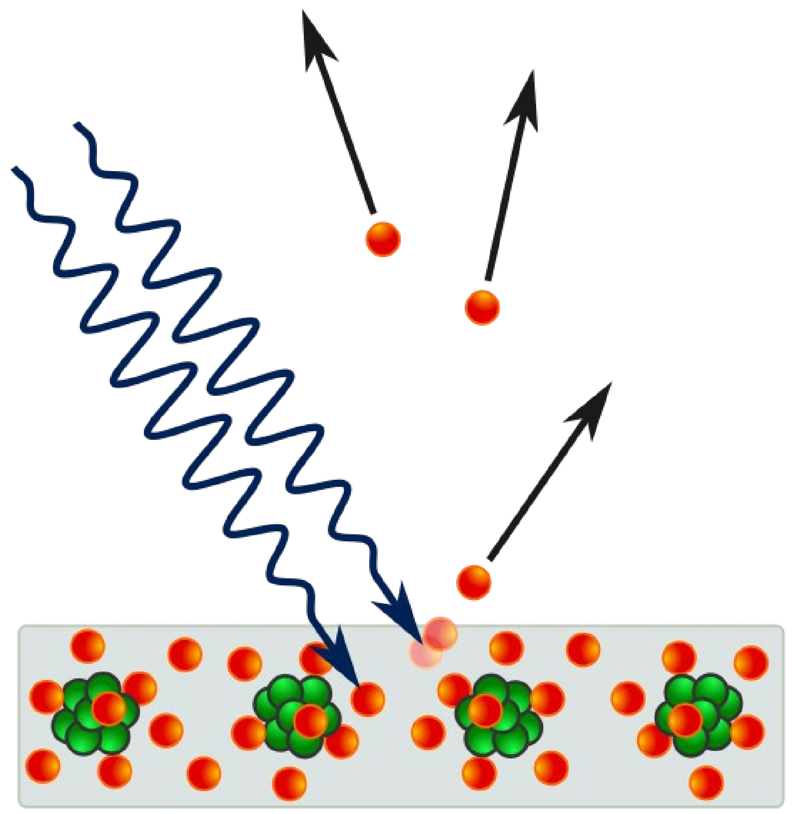
Discussion on the photoelectric effect?

Part 2: Single Photon Sources and Detection

Photon: Wave or particle?

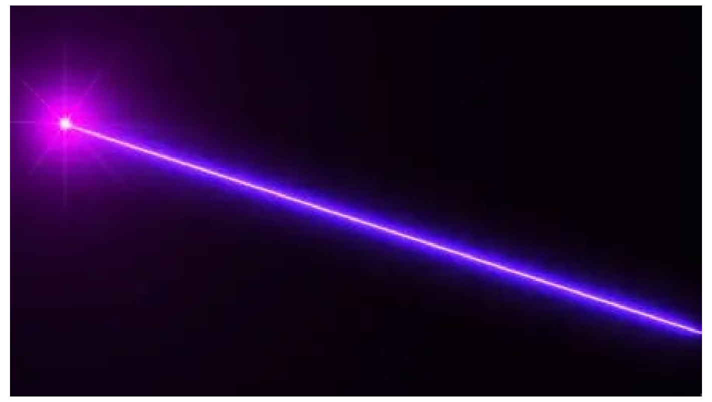
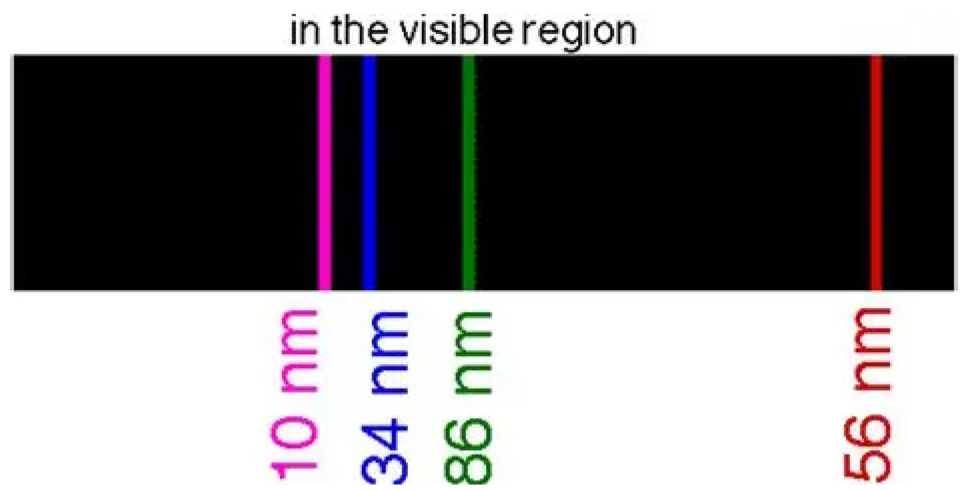

- Newton first proposed light was a particle because it cast sharp shadows
- Thomas Young showed it had wave properties from the two-slit experiment, but this was not widely accepted until Francois Arago illustrated Poincare's spot
- Einstein later showed that the photoelectric effect suggests particles of light.

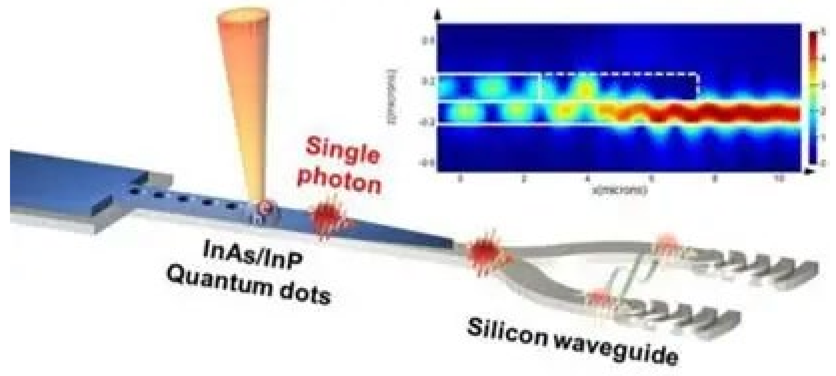



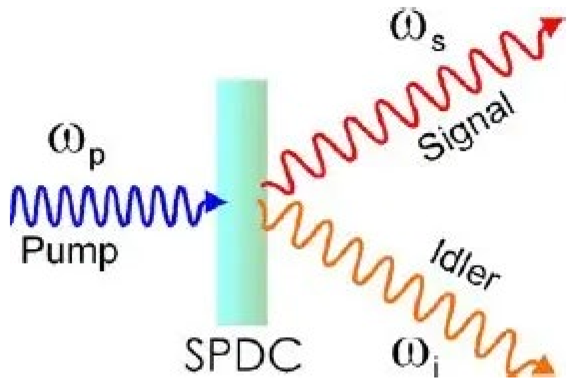
Different types of light sources

- Classical light
  - Thermal sources (blackbody radiation)
    - Incandescent lightbulb
    - The sun
  - Stimulated emission sources
    - Light-emitting diode
    - Laser
- Quantum light
  - Atomic
    - Spontaneous emission from atoms
  - Solid state
    - Quantum dots
  - Nonlinear crystal
    - Parametric down conversion



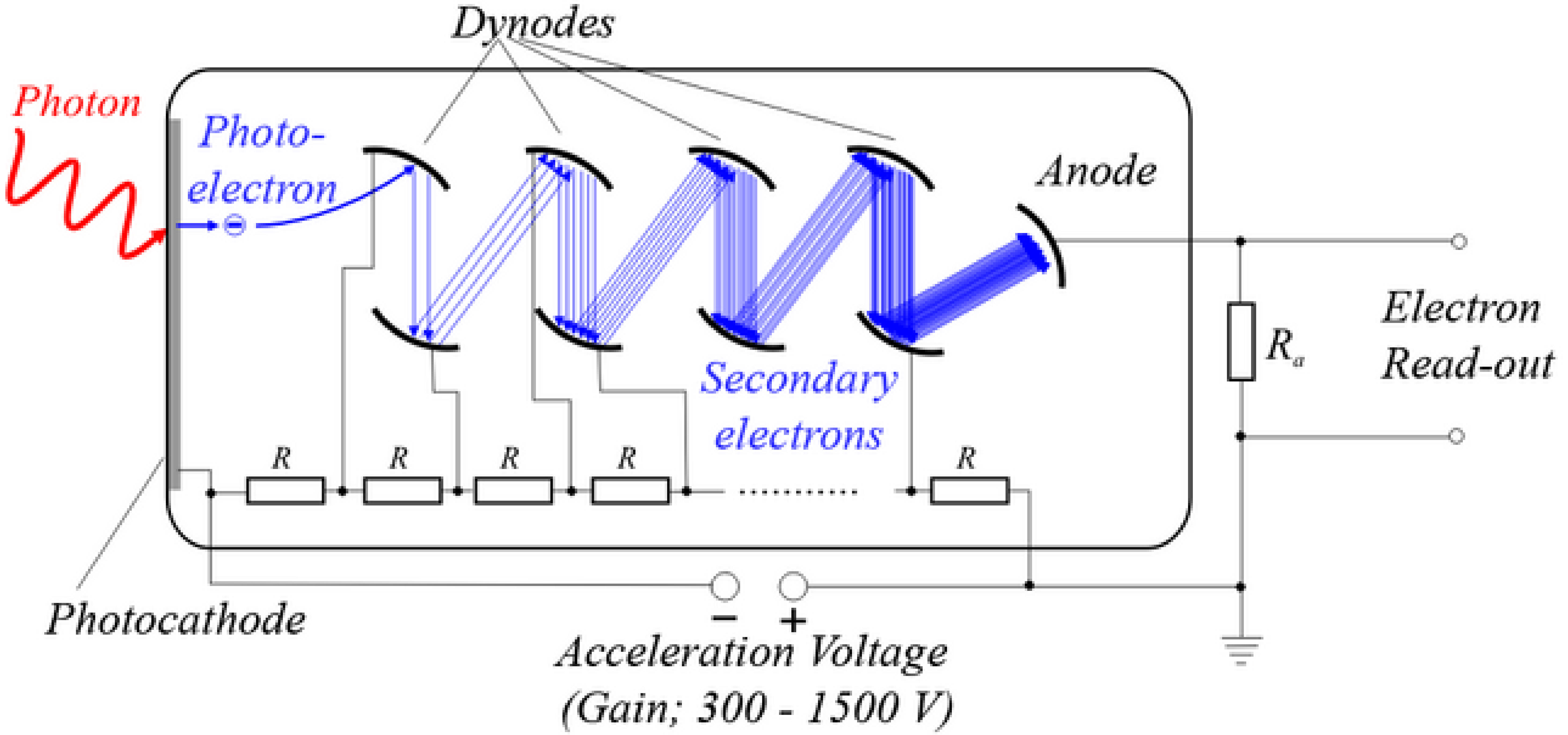




Dim classical light is not a single photon source

Even a dim laser!

How to detect single photons



Use the photoelectric effect for single-photon sensitivity

Amplify the single emitted electron many-fold to make a large enough current pulse it can be measured with classical equipment

Reset to measure again after the event is recorded

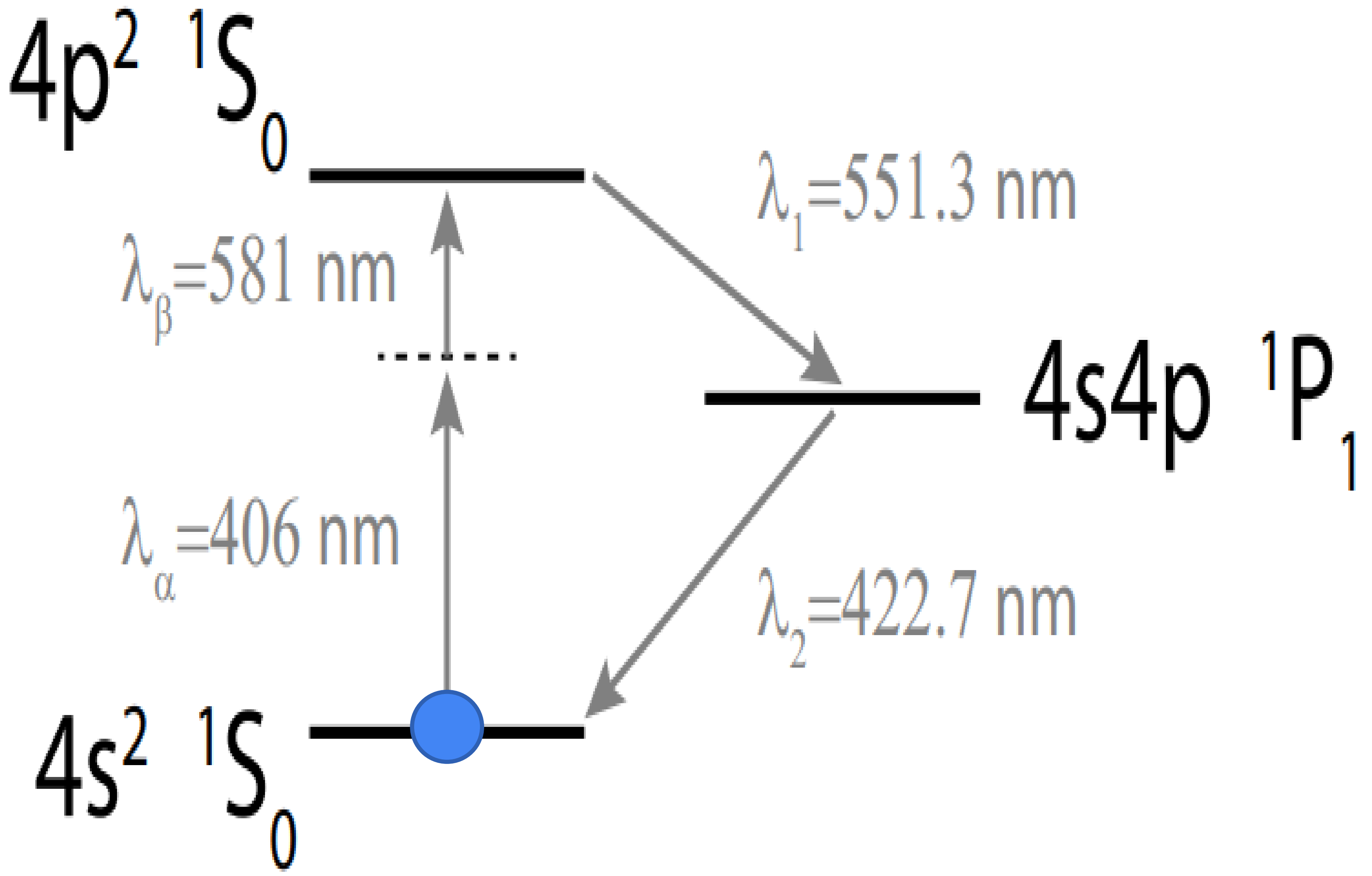
A single photon can be imaged with a PMT once and only once!!

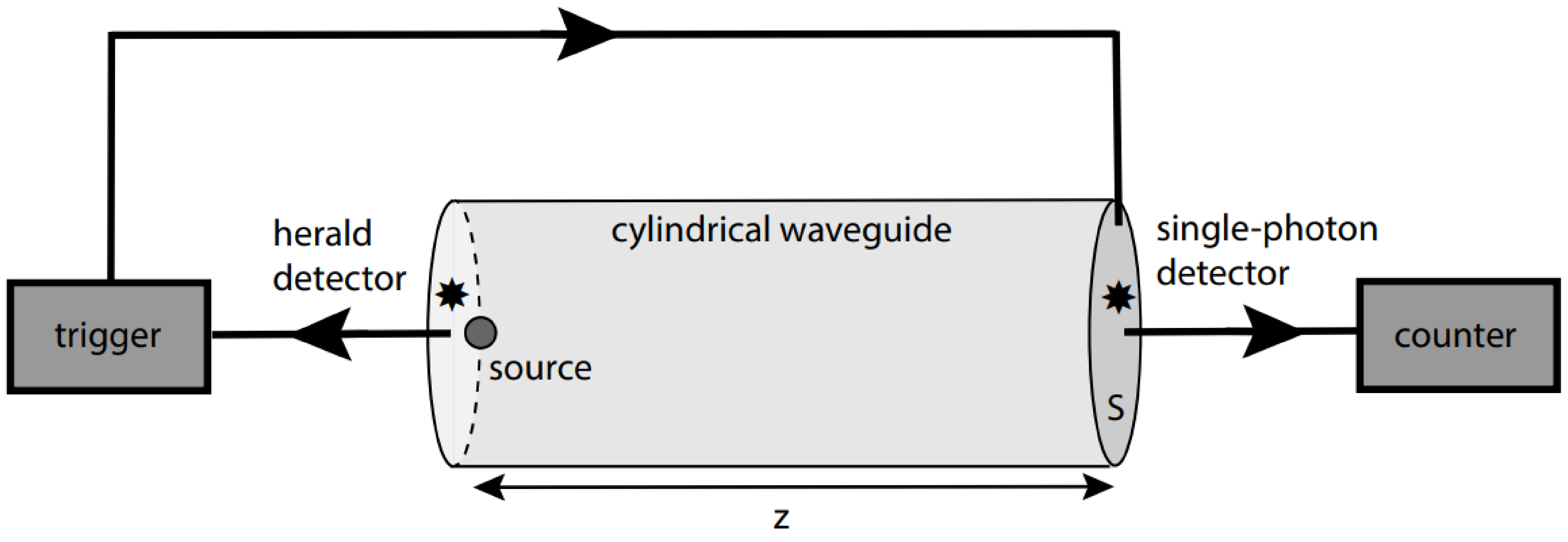
Because it is destroyed upon detection.

PMT's can have dark counts

- Any stray photon can set off the photomultiplier tube
- As can any stray electron (tickling the dragon's tail)
- Dark counts are reduced when the detector is made colder
- But, they cannot be prevented

Calcium cascade single photon source





Let us now explore how we can verify we have a single photon source

Questions about single photons?

Please don't just call them particles of light

Curriculum for a more detailed treatment

- Week one: The story of photons and electrons
- Week two: The Stern-Gerlach experiment
- Week three: Formalism for two-state quantum systems
- Week four: Single and two-slit diffraction of light and advanced ideas (delayed choice, interaction-free measurements)
- Week five: Using quantum computers to simulate single-quantum experiments (Stern-Gerlach, two-slit experiment (and delayed choice variant), Mach-Zehnder interferometer
- Week six: The canonical commutation relation
- Week seven: The simple harmonic oscillator
- Week eight: Angular momentum
- Week nine: hydrogen

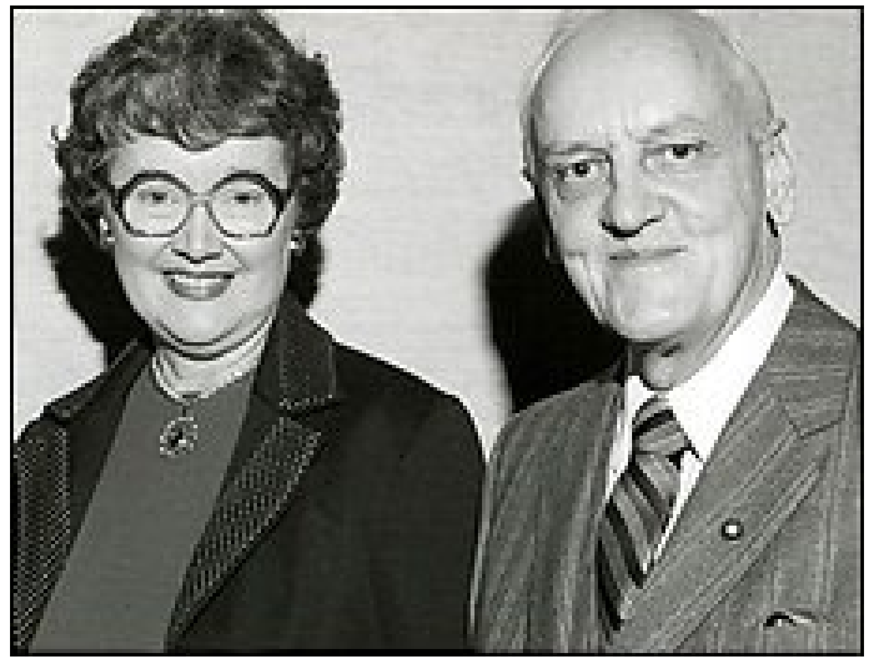
Additional resources

- For the photoelectric effect, the UW tutorials have a nice one on the photoelectric effect.
- My courses on edX, the github repository quantum mechanics for everyone, and the website quantum.georgetown.domains
- My Youtube channel has many different levels of discussions
- We have a number of recent Am. J. Phys. articles that discuss these ideas.
- Ask me for advice at anytime.
- We will be developing more materials this Fall.

Thanks to

Leanne Doughty

Jason Tran



Georgetown quantum resources

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