Quantum Computing I

CSCI 2050U - Computer Architecture

Randy J. Fortier
@randy_fortier

OntarioTech UNIVERSITY

Outline

- Experiments with light
- Basic principles of quantum mechanics
  - Observer effect
  - Indeterminacy
  - No cloning theorem
  - Superposition
  - Entanglement
- Myths about quantum mechanics and quantum computing

Experiments with Light

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Polarizing Filter

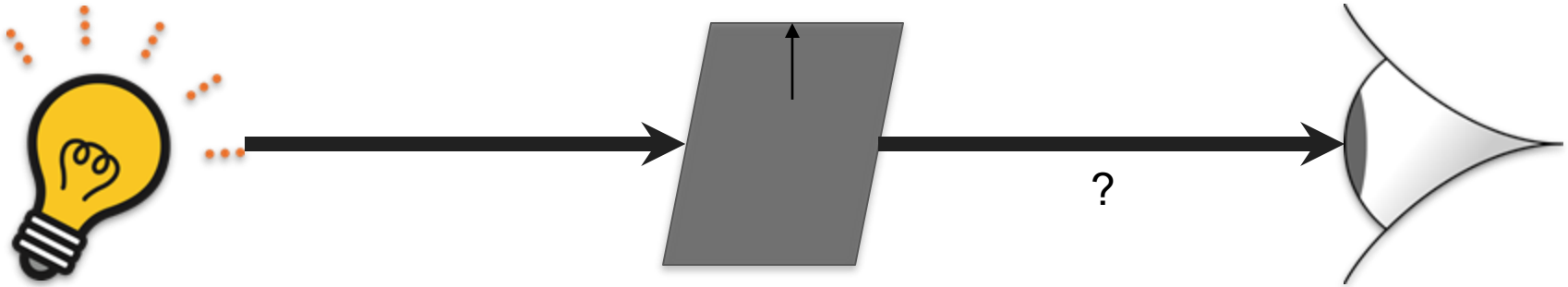
- A polarizing filter is a filter that blocks some light that is improperly aligned, and allows other light that is aligned
- Alignment of light?
  - Light is a combination of electric field and magnetic field waves (electromagnetic)
  - These two waves are perpendicular to each other, but the specific alignment differs for light produced in the sun (for example)
  - Some (artificial) light is already polarized (i.e. aligned in the same direction)
- You could try this experiment at home
  - You can buy polarization filters for a few dollars
  - Many of you may have polarized sunglasses, which work the same way

Polarizing Filter

- A polarizing filter can be treated as a measurement device
  - It is a little bit different from a typical measuring device, as we'll later see
  - Any given polarizing filter has an orientation (which direction is up)
  - Unpolarized light has a 50% chance of being measured as horizontal and 50% chance of being measured as vertical (i.e. not horizontal)

Experiment #1: One Filter

- Unpolarized light is directed through a single polarization filter to a detector
  - What do you think should happen? How much light will be observed?



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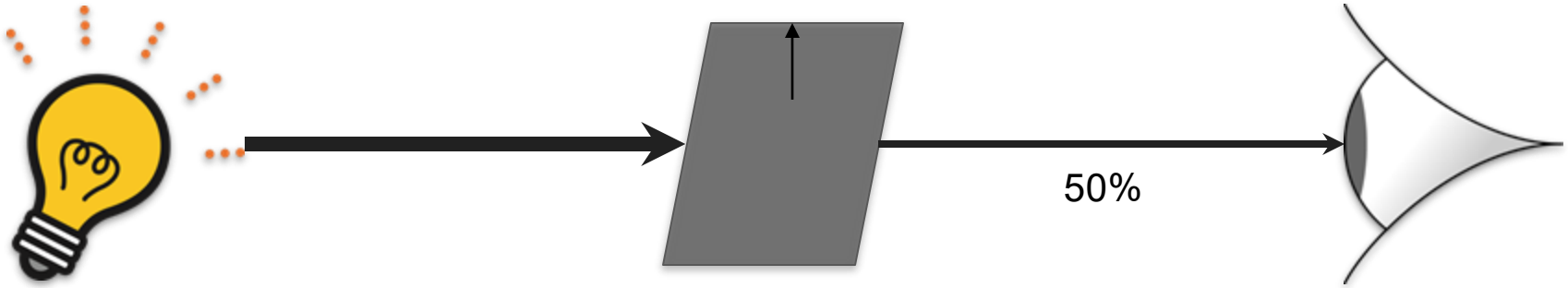

Experiment #2: Two Filters, Aligned

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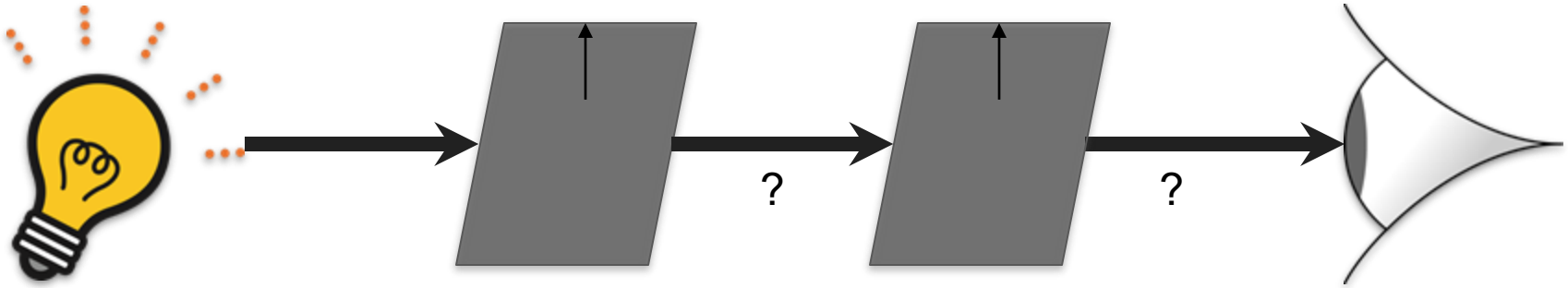

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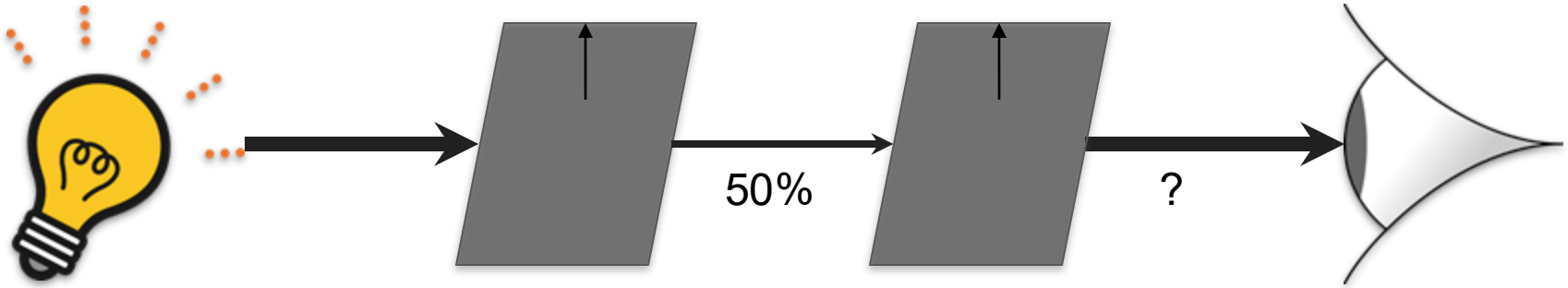

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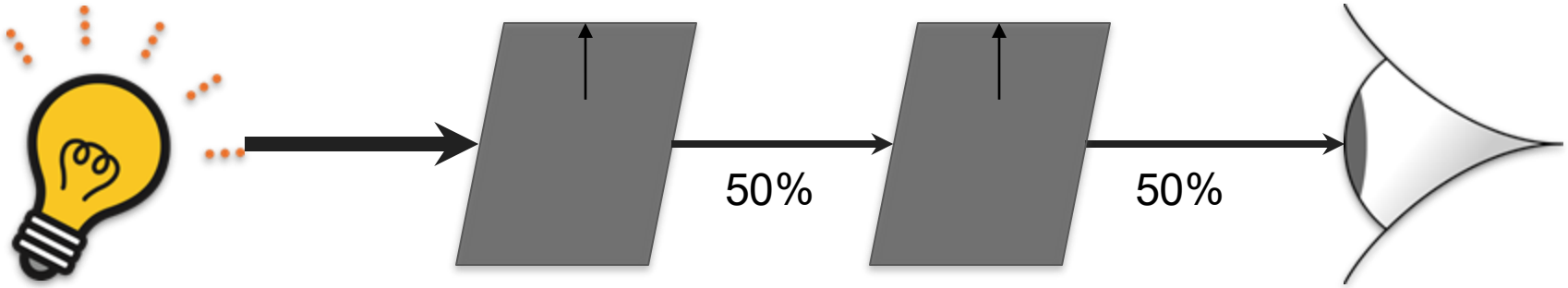

Experiment #3: Two Filters, Orthogonal

- Unpolarized light is directed through two polarization filters, each aligned in perpendicular directions
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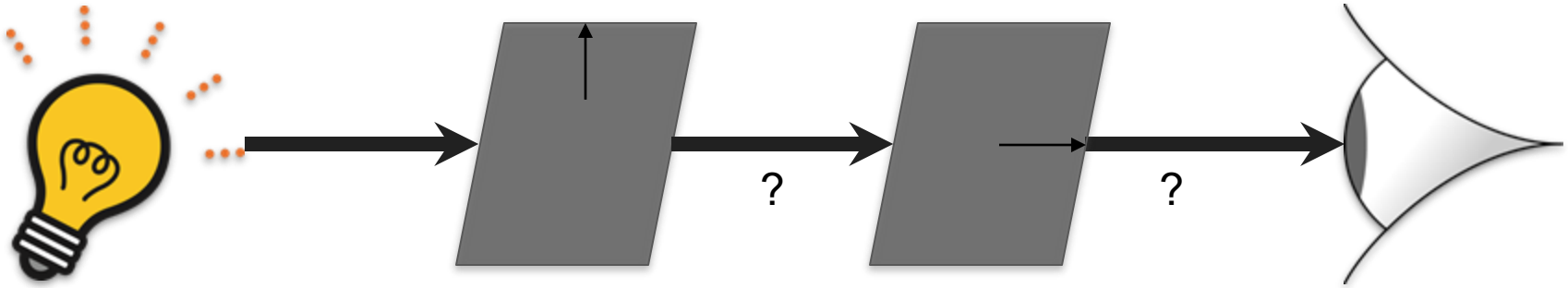

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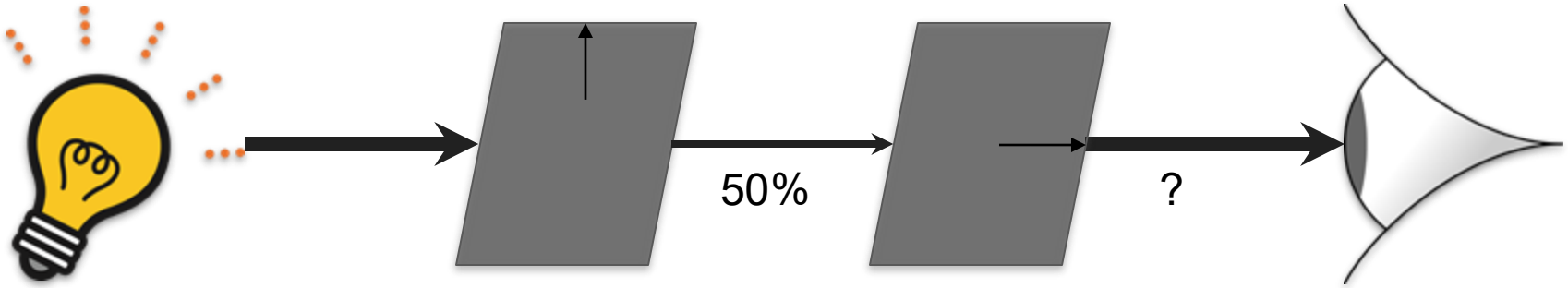

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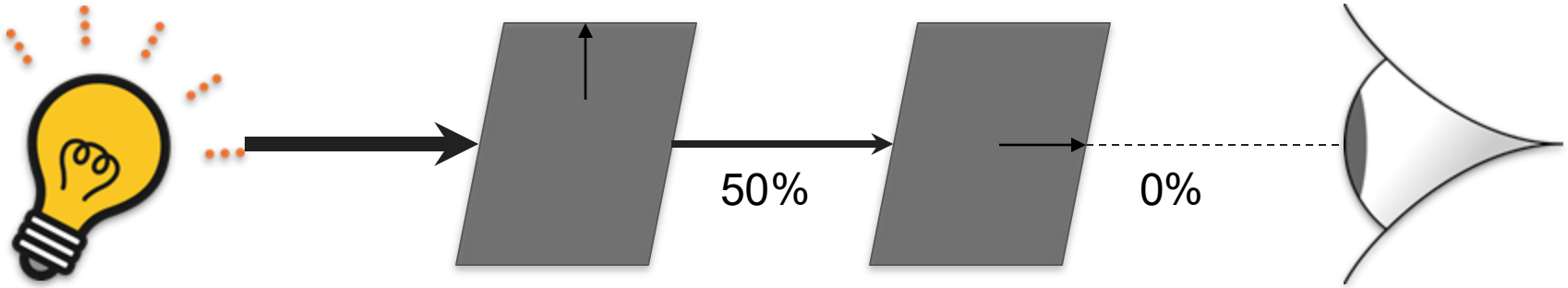

Experiment #4: Dirac's 3-Filter Experiment

- Unpolarized light is directed through three polarization filters, aligned vertically, at 45º, and finally horizontally
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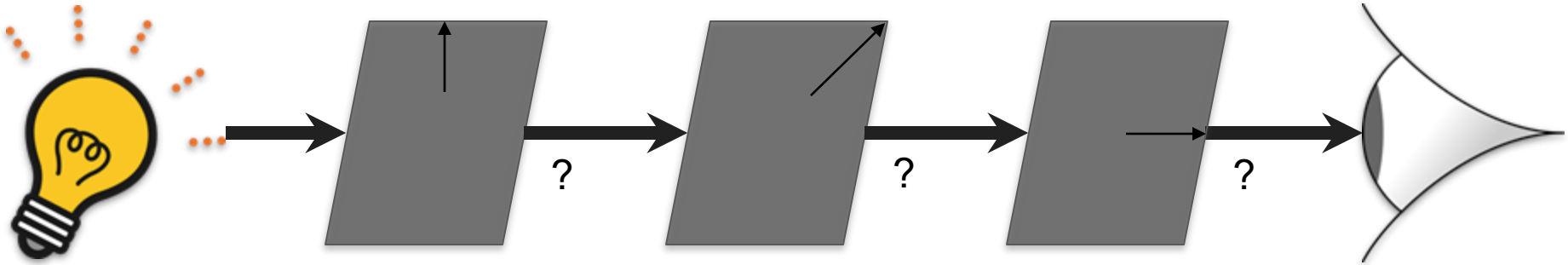

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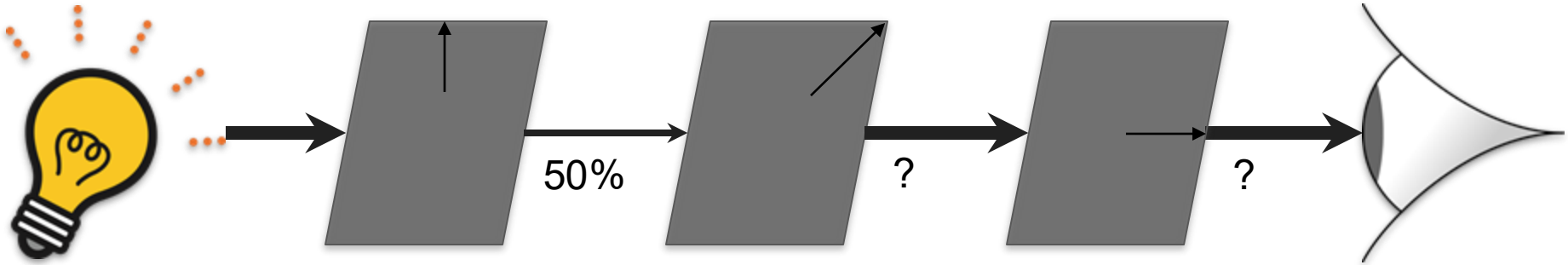

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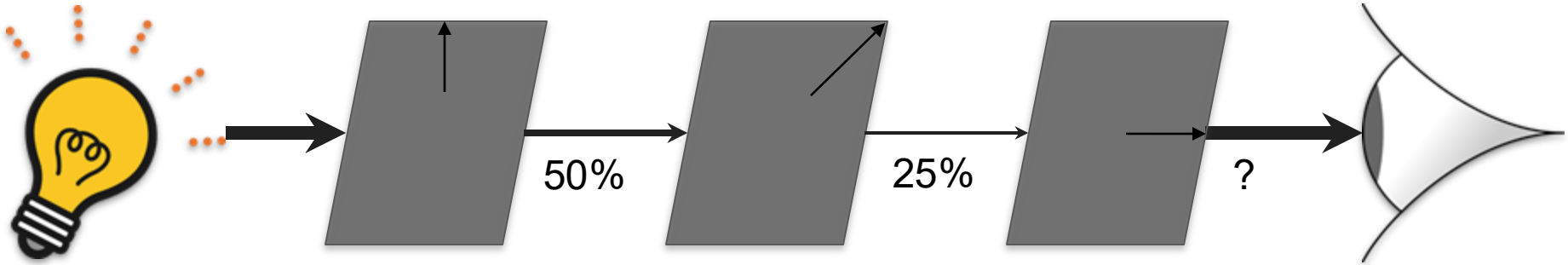

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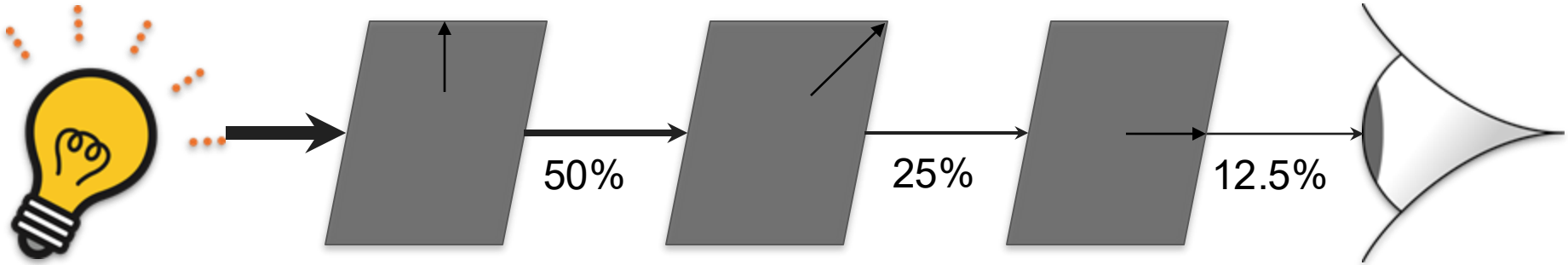
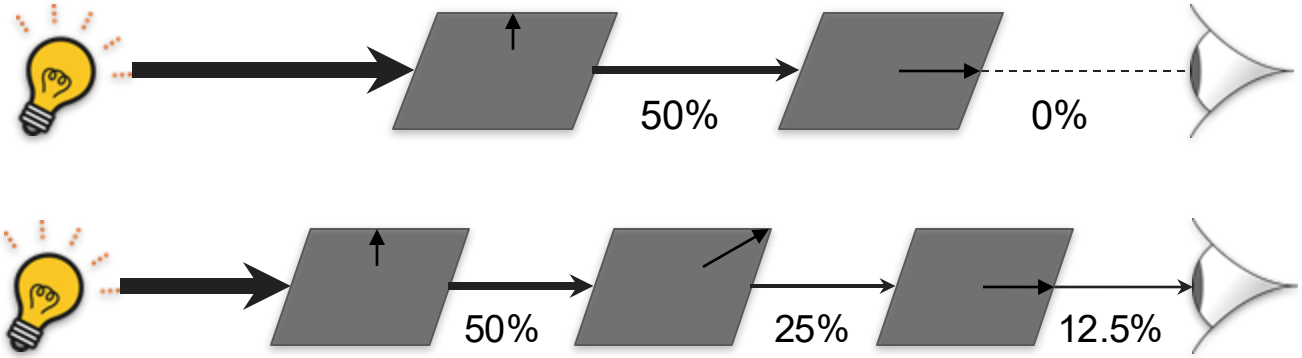


Reflections

- It is odd that adding another filter between two filters add more light
  - This isn't like filters that we know (e.g. consider a blue and red filter)
  - Objects at the quantum scale behave fundamentally differently from those at the macroscopic scale



Principles of Quantum Mechanics

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Observer Effect

- Measuring a property of a quantum scale object irreversibly changes that property
  - e.g. A polarization filter changes the polarization of all of the light that passes through it
- If a photon is measured to be vertical, that means it is actually changed to be vertically polarized
  - Subsequent measurements of the polarization will be vertical with 100% probability

https://en.wikipedia.org/wiki/Observer_effect_(physics)

Indeterminacy

- In the first experiment, the light was unpolarized and had a 50% chance of passing through the vertically-aligned filter
  - You may be tempted to think that 50% of the light was already vertical before reaching the filter (and 50% was not)
  - This explains the results of this experiment, but this intuition is incorrect
  - The light was neither vertical nor horizontal until it was measured
  - The light's polarization was changed probabilistically
    - This sort of behaviour is unusual, as most macroscopic objects behave deterministically

https://en.wikipedia.org/wiki/Quantum_indeterminacy

No Cloning Theorem

- We cannot make a copy of a qubit
  - If we want a copy of a qubit, the closest thing we can do is perform the exact same transformations on the same starting state
  - Another useful option is to undo the transformations that we've done

https://en.wikipedia.org/wiki/No-cloning_theorem

Superposition

- In the 3-filter experiment, the light was polarized to 45º after the second filter
  - From the perspective of the third polarization filter, is this horizontal or vertical?
  - The simple answer is, it is both (diagonal is a combination of horizontal and vertical)
- In quantum mechanics, many objects have properties than can be in a superposition in this way
  - e.g. the spin of an electron
  - The probabilities do not have to be 50%/50%, however
- An object in superposition is a mixture of two different states
  - This is a key difference that makes quantum computers different from classical computers, where bits can only have one of two states (0 or 1)

https://en.wikipedia.org/wiki/Quantum_superposition

Entanglement

- It is also possible to entangle two (or more) particles such that measuring one of them also affects the state of the other particle
  - We can't easily demonstrate this concept with our simple apparatus, unfortunately

https://en.wikipedia.org/wiki/Quantum_entanglement

Quantum Myths

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Myths about Quantum Mechanics

- Schrödinger's cat
  - This is a macroscopic phenomenon, of course, not quantum
  - The thought experiment was actually introduced in order to point out how ridiculous the idea of superposition was
    - Weirdly, superposition is one of the most intuitive of the "weird" quantum phenomena
  - The valid part of this thought experiment is that the qubit is not a $|0\rangle$ or a $|1\rangle$ until we measure it

Myths about Quantum Computers

- Quantum computers will replace classical computers
  - Many problems cannot be solved any faster on a quantum computer than they can on a classical computer
  - There are some problems, however, which are ideal for quantum computers
    - e.g. Factoring a huge number into its constituent primes (Shor's Algorithm)

- Related video about post-quantum cryptography: https://www.youtube.com/watch?v=-UrdExQW0cs

Myths about Quantum Computers

- Quantum supremacy
  - This is a somewhat arbitrary milestone defined by the companies working on quantum computers that says you have to compute something that a classical computer cannot solve efficiently
  - Google claims to have achieved this in 2019
    - I have my doubts
  - Uncertainty upon measuring a quantum bit (called a qubit) is the major limitation for quantum computers today
    - It is often required to run the same program 1000 times, to be sure of the answer

Wrap-up

- Experiments with light
- Basic principles of quantum mechanics
  - Observer effect
  - Indeterminacy
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What is next?

- Qubits vs. bits
- Qubit implementations
  - Photons
  - Electrons
- Quantum circuits
  - Initialization
  - Transformations
  - Measurement