The Two-Slit Experiment, And the Quantum Circuit Model

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3/8/2025

Outline

- Basic Quantum Concepts
- The Two-Slit Experiment

My bits…

- PhD from University of Manchester, UK (2001), in Parallel Computing Group
- Cofounded the CSE department and Parallel Computing lab at Egypt-Japan University of Science and Technology
- Visited IBM Centre of Advanced Studies, Cairo and INRIA Rennes, France, Institute of Statistical Mathematics, Waseda University, and Meisei University, Tokyo
- Many grants from IBM, Amazon, ITIDA, STDF, and ASRT
- TPC at ICCD, ARCS, and Supercomputing conferences
- Member of the organising committee of the 2025 IEEE Quantum Computing and Engineering Conference
- The founding chair for the Cairo ACM Chapter
- Currently the dean of the ITCS school, Nile University

Intro to the Quantum Research Group

- The Team
  - Dr Ahmed El-Mahdy, NU
  - Dr Marwa Sorour, NU
  - Dr Norhan Elsayed, NU
  - Eng Mustafa Fathy [MSc Student]
  - Eng Ahmed Jamal [MSc Student]
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- Collaborators:
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  - Prof Kazunori Ueda, Waseda University
  - Prof Keiji Kimura, Waseda University
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  - Prof Tamer Abulfadr, NU

- Undergraduate Students
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  - Muhammed Megahed ali
  - Eyad Essam Elsanory
  - Bishoy Ashraf Halim
  - Abdullah Tarek Abdellatif
  - Islam Nasr Atwan

- Alumni
  - Yusuf Alsawah [BSc Student]
  - Mohammed Abdulsami [BSc Student]
  - Omar Abdelrasoul [BSc Student]
  - Youssef AbdElWahab [BSc Student]
  - Mostafa Ragab [BSc Student]

Major Emerging Technologies to the Field

The Generative AI

- **~$400 Billons** investment from Alphabet, Amazon, Apple, Meta, and Microsoft (Economist)
- Expected to increase the **global GDP by 7%** (Goldman Sachs)
- AI has **hacked the operating system of humans** (Yuval Harari)

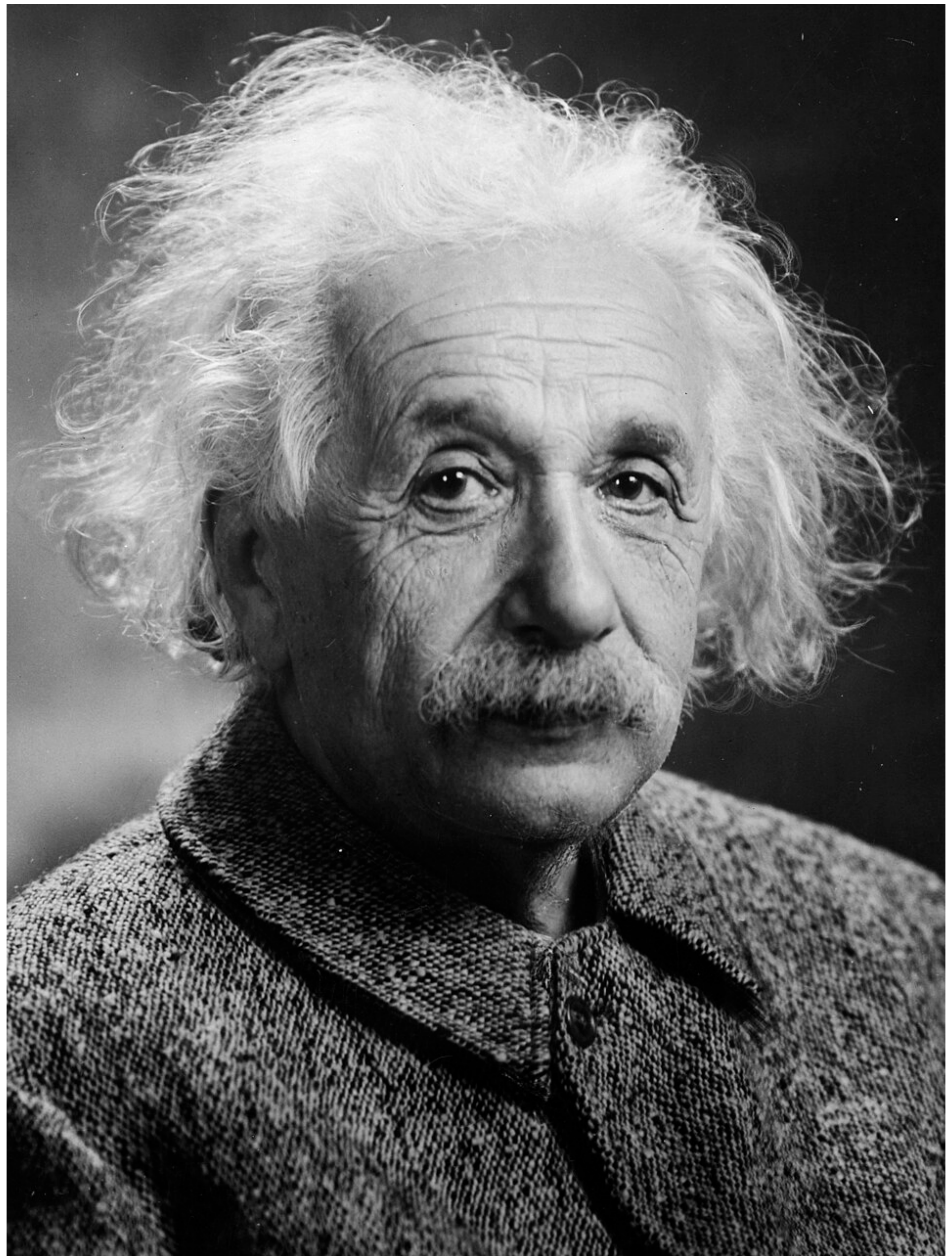
Quantum Computing

- It can make computers **exponentially faster**
- And has **exponentially less memory**
- Quadratic **better sensing** accuracy
- Provides ‘true’ **secure communication**
- They do exist!

Quantum Computing Concepts Few Minutes!

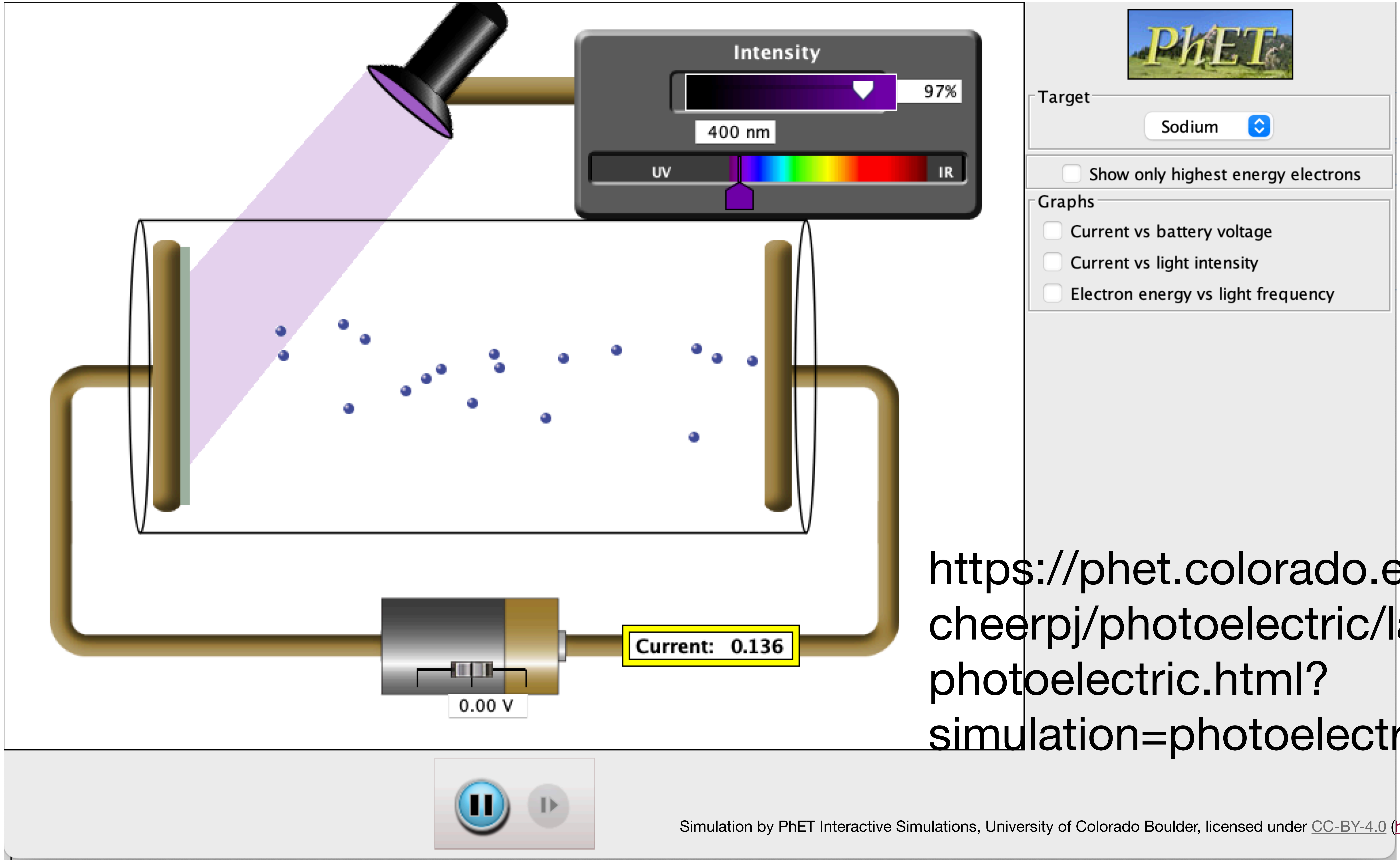
What is ‘Quantum’?

- Let’s go back to **1905**
- Puzzle: Materials emit electrons when exposed to light, but only work is ultraviolet-ish light, no matter how strong the light is!
- Albert Einstein found why and got a **Nobel Prize** in 1921!
- Now, let’s use Carl Wieman’s (another Nobel laureate) PhET Interactive Simulations



Albert Einstein

The Photoelectric Effect



https://phet.colorado.edu/sims/cheerpj/photoelectric/latest/photoelectric.html?simulation=photoelectric

Explanation

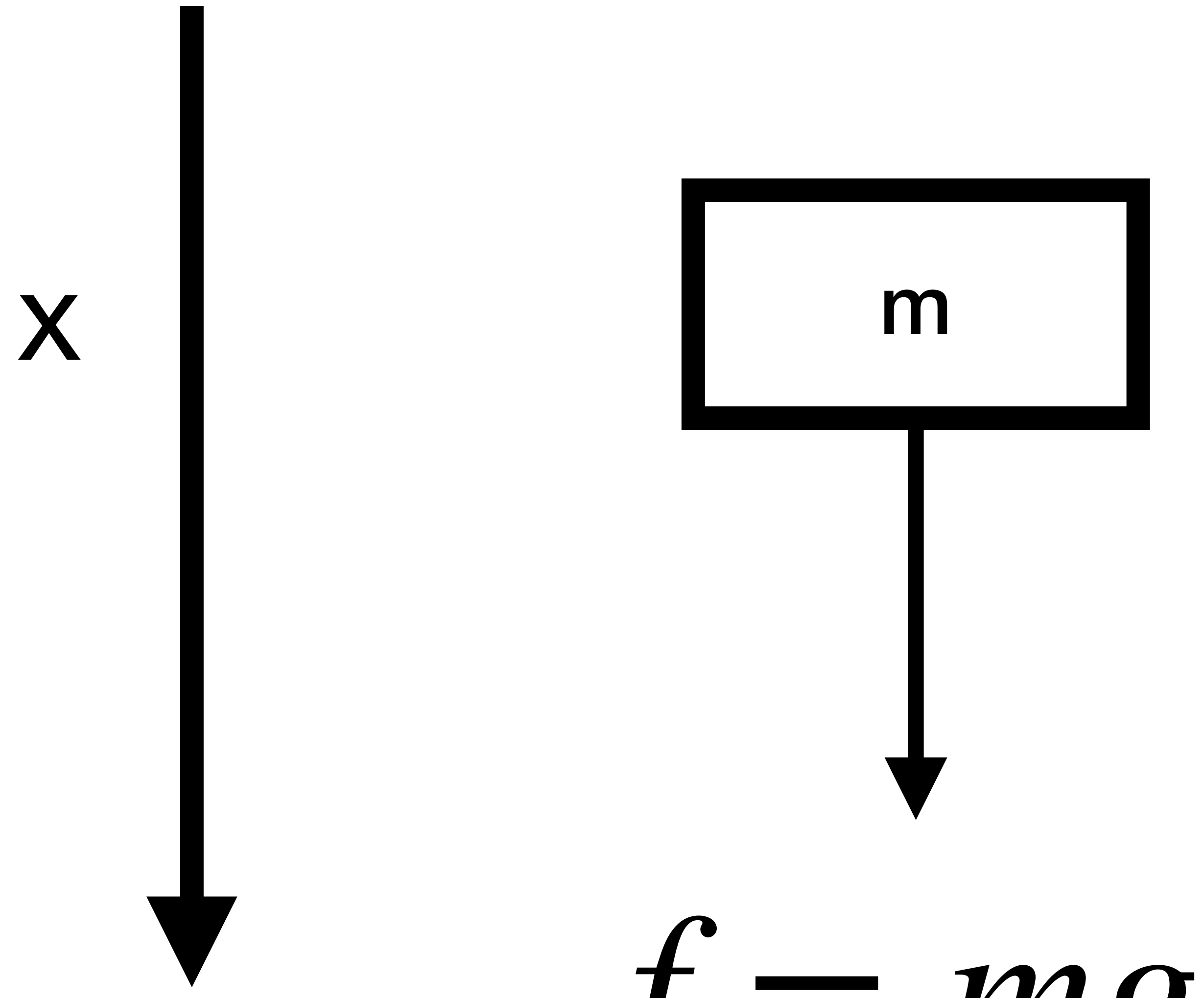
- Light consists of **packets,** or **quanta** of light
- E is energy
- h is Planck's constant
- v is light frequency

$$E = hv$$

What is ‘Classical Mechanics’?

We can determine the location:

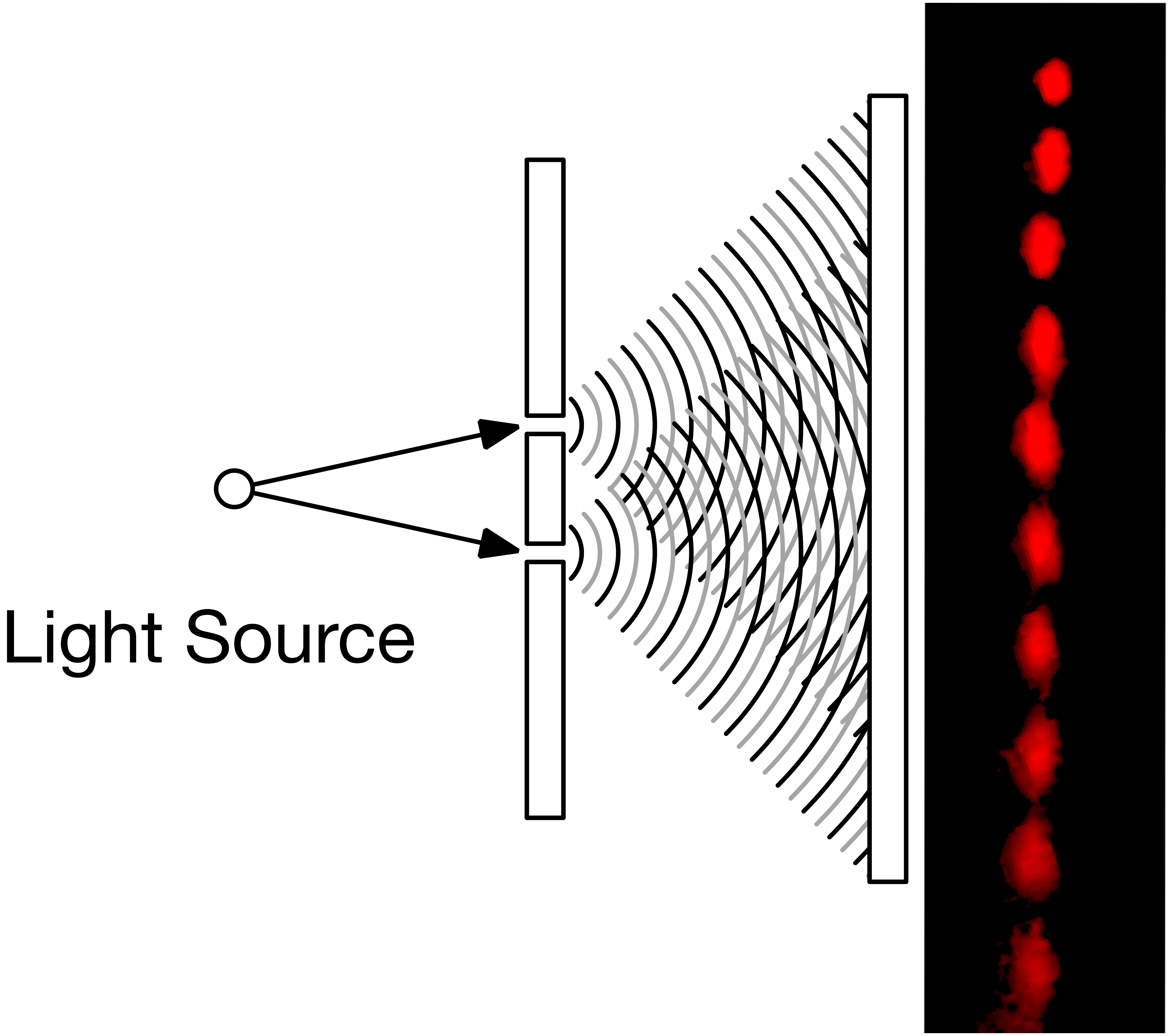
$$x(t) = \frac{1}{2}gt^2$$



$$f = mg$$

Now What is ‘Quantum Mechanics’?

- Let’s go back to **1804!**
- Thomas Young’s **double-slit** experiment
- He showed a strange interference pattern with light
- Let’s see, again, another PhET simulation



Waves and Interference

https://phet.colorado.edu/sims/html/waves-intro/latest/waves-intro_all.html

The State and How It Changes

- Let's go back to 1925
- **Erwin Schrödinger** finds how to compute the wave values at all locations
- And he got the **Nobel Prize** in 1933
- It is the wave values at all locations at a given time

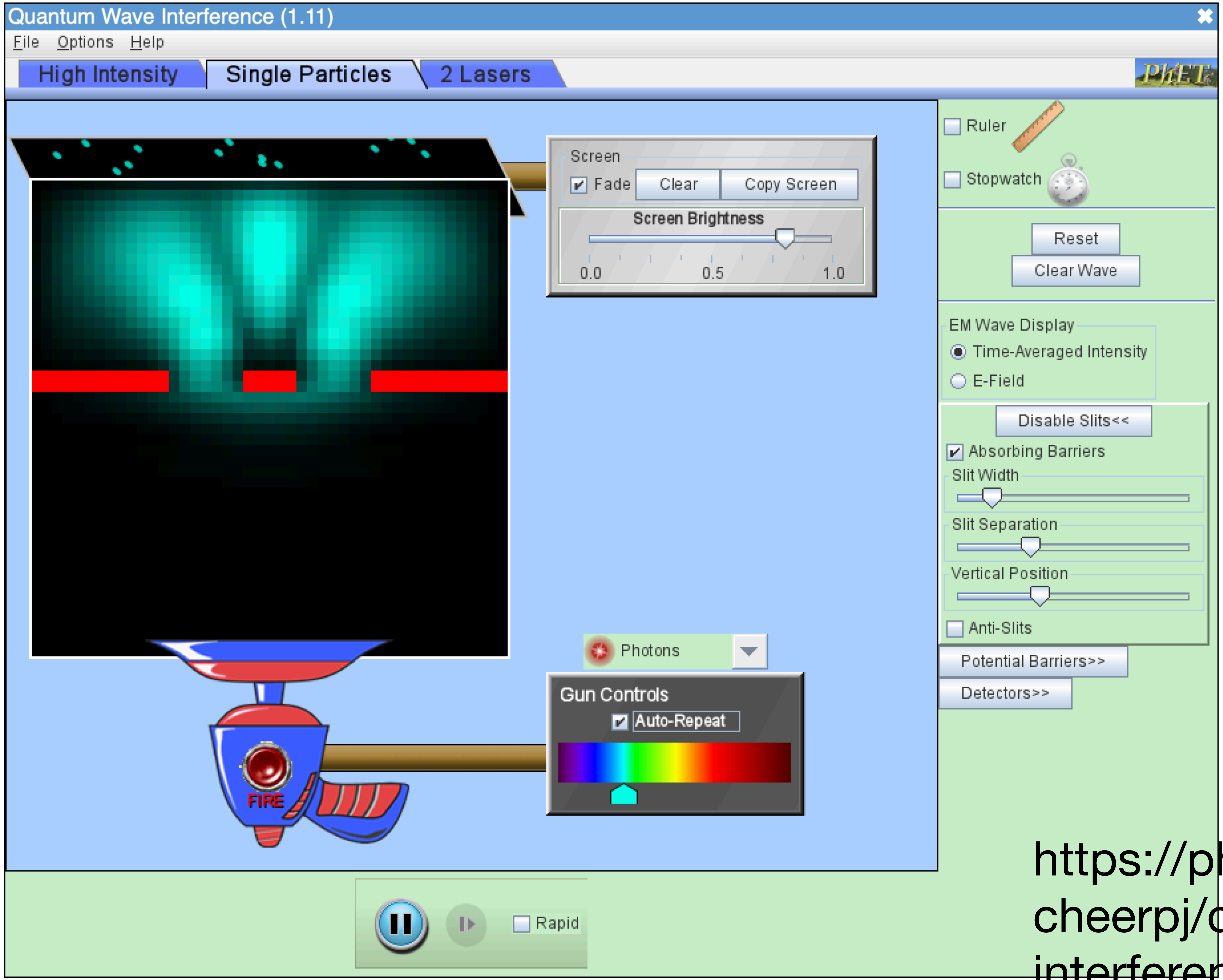
$$i\hbar \frac{d}{dt} |\Psi\rangle = \hat{H} |\Psi\rangle$$

Erwin Schrödinger

But Where is the Particle?

- Let's go back again to 1926
- **Max Born** found that when we look, the wave function **collapses**
- We see the photon at one location only
- The location is determined by the strength of the amplitude

Max Born



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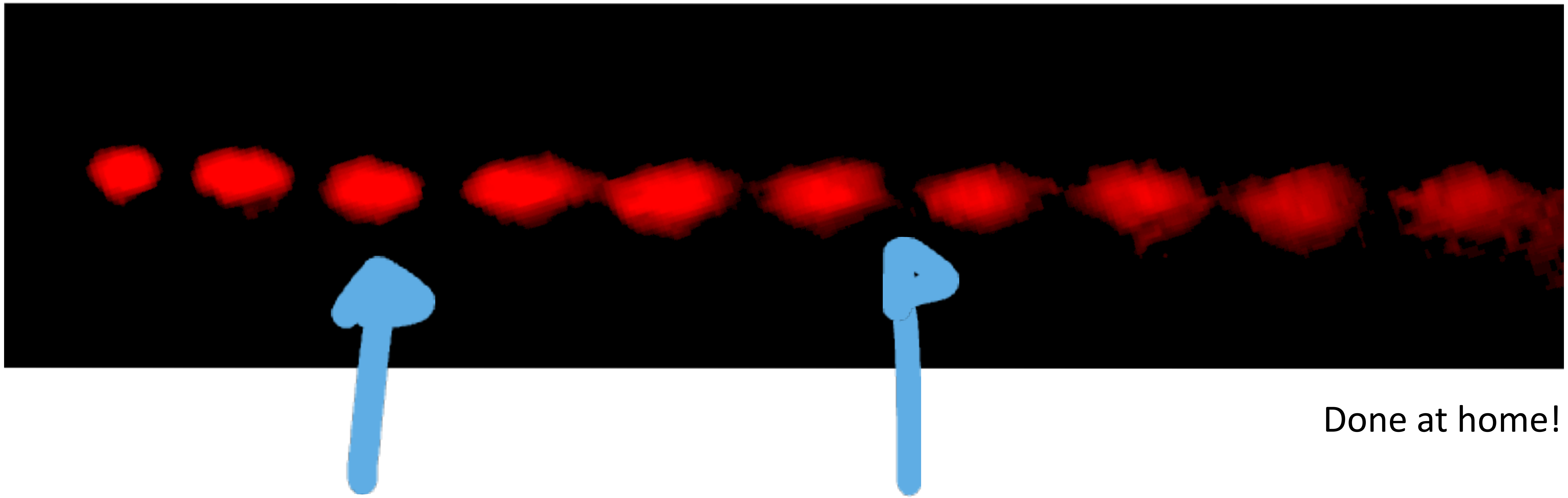
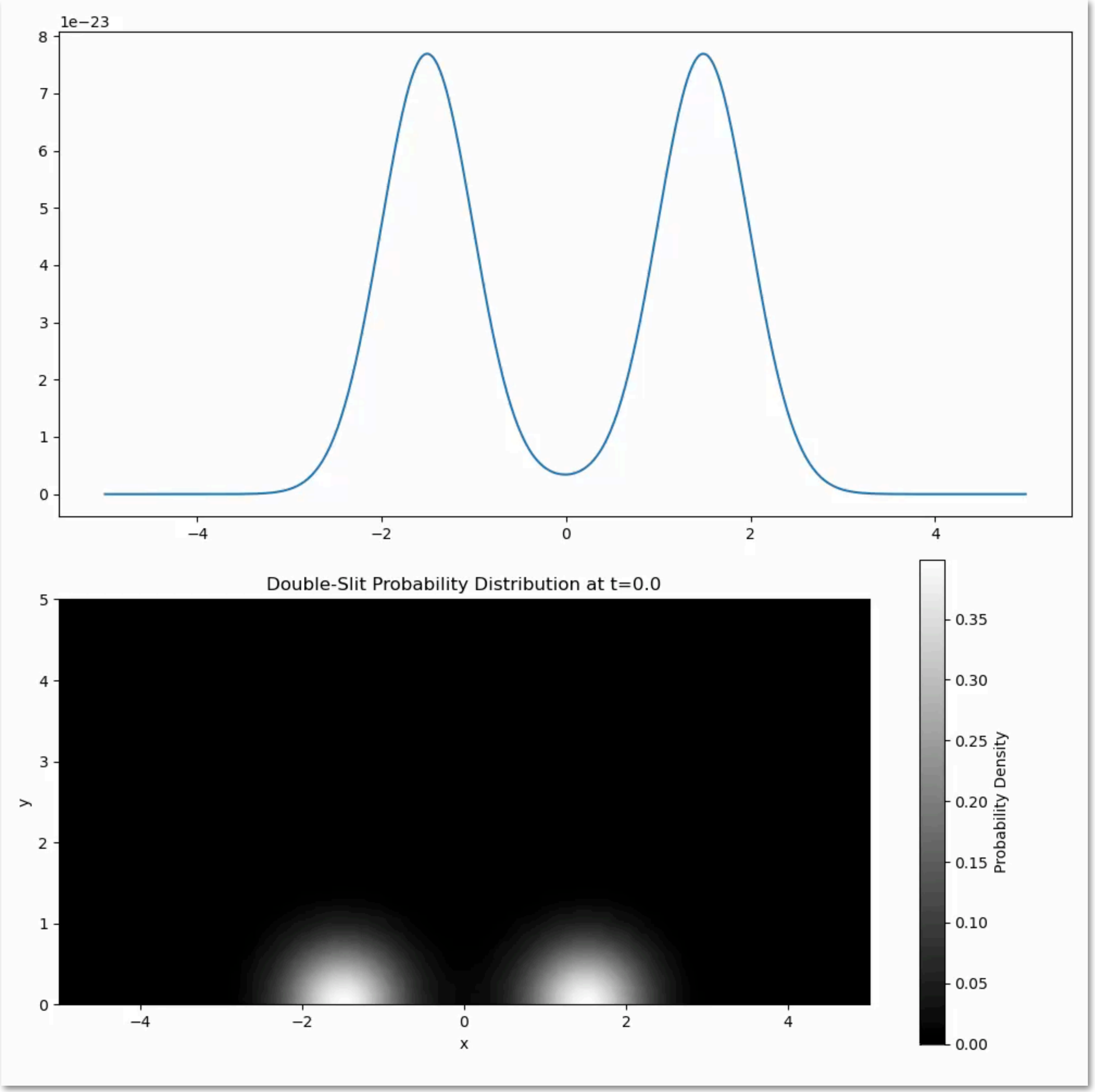
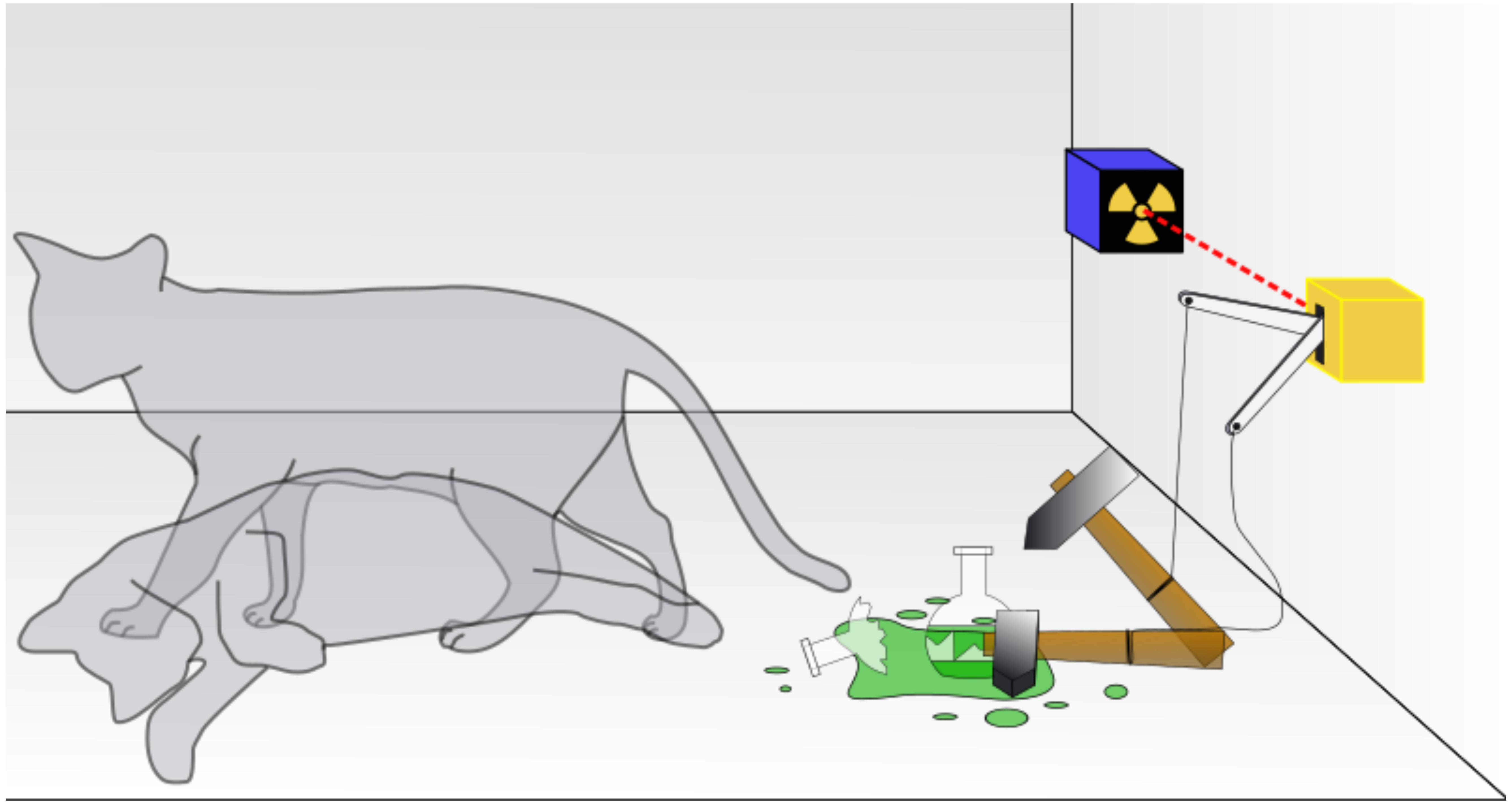
https://phet.colorado.edu/sims/cheerpj/quantum-wave-interference/latest/quantum-wave-interference.html


Done at home!
Photon is here!
No Photon is here!


1e−23
8
7
6
5
4
3
2
1
0
−4
−2
0
2
4
Double-Slit Probability Distribution at t=0.0
5
4
3
2
1
0
y
−4
−2
0
2
4
x
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Probability Density

Schrödinger's Cat i.e. *Superposition and Collapse!*

- The cat is both **dead** and **alive**!
- Erwin Schrödinger's idea to show issues in quantum mechanics!



Entanglement

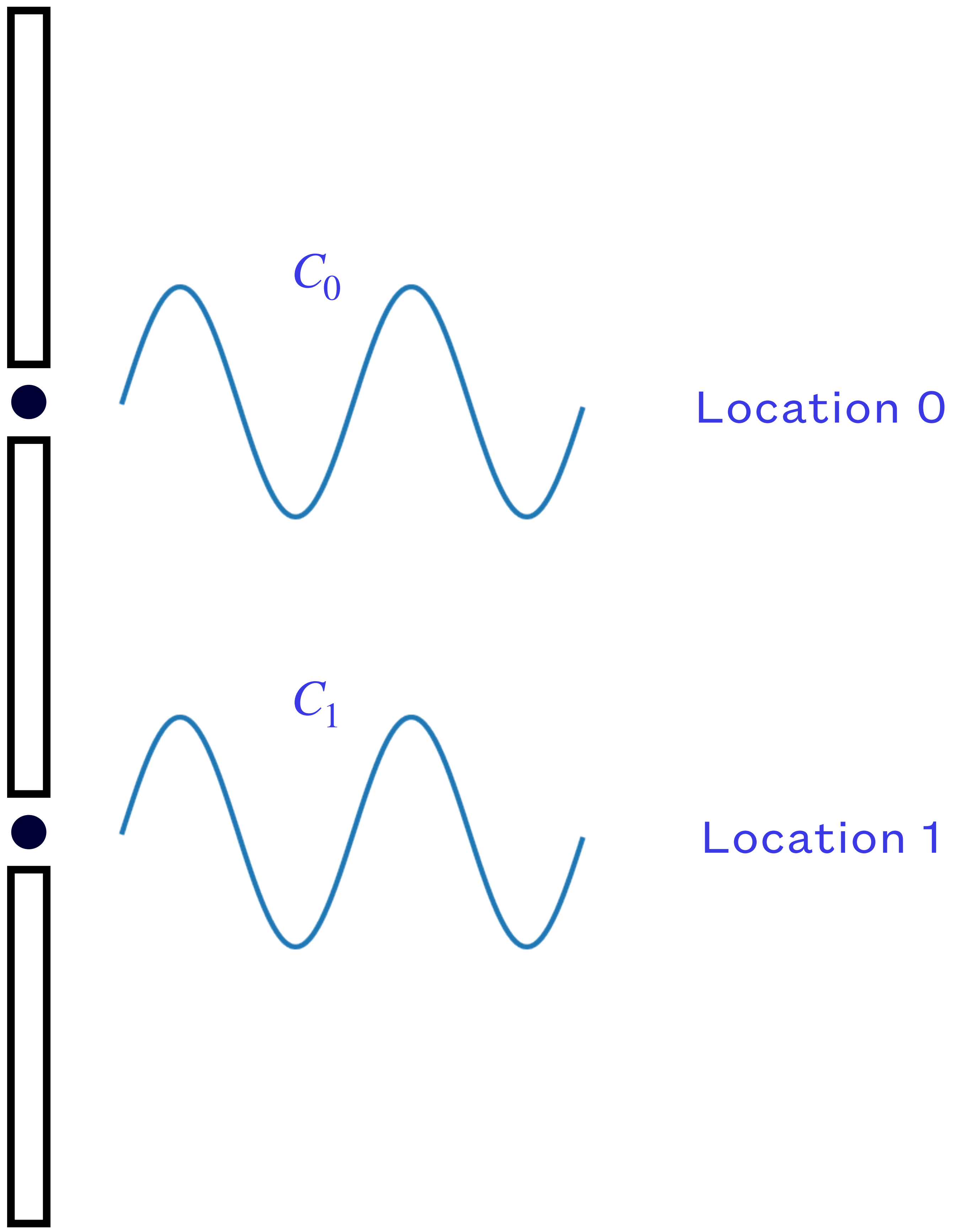
😸/🙀 😸/🙀

Both are the same
when we look

😸/🙀 ⟷ 😸/🙀

Half a universe away!

Both are the same
when we look!



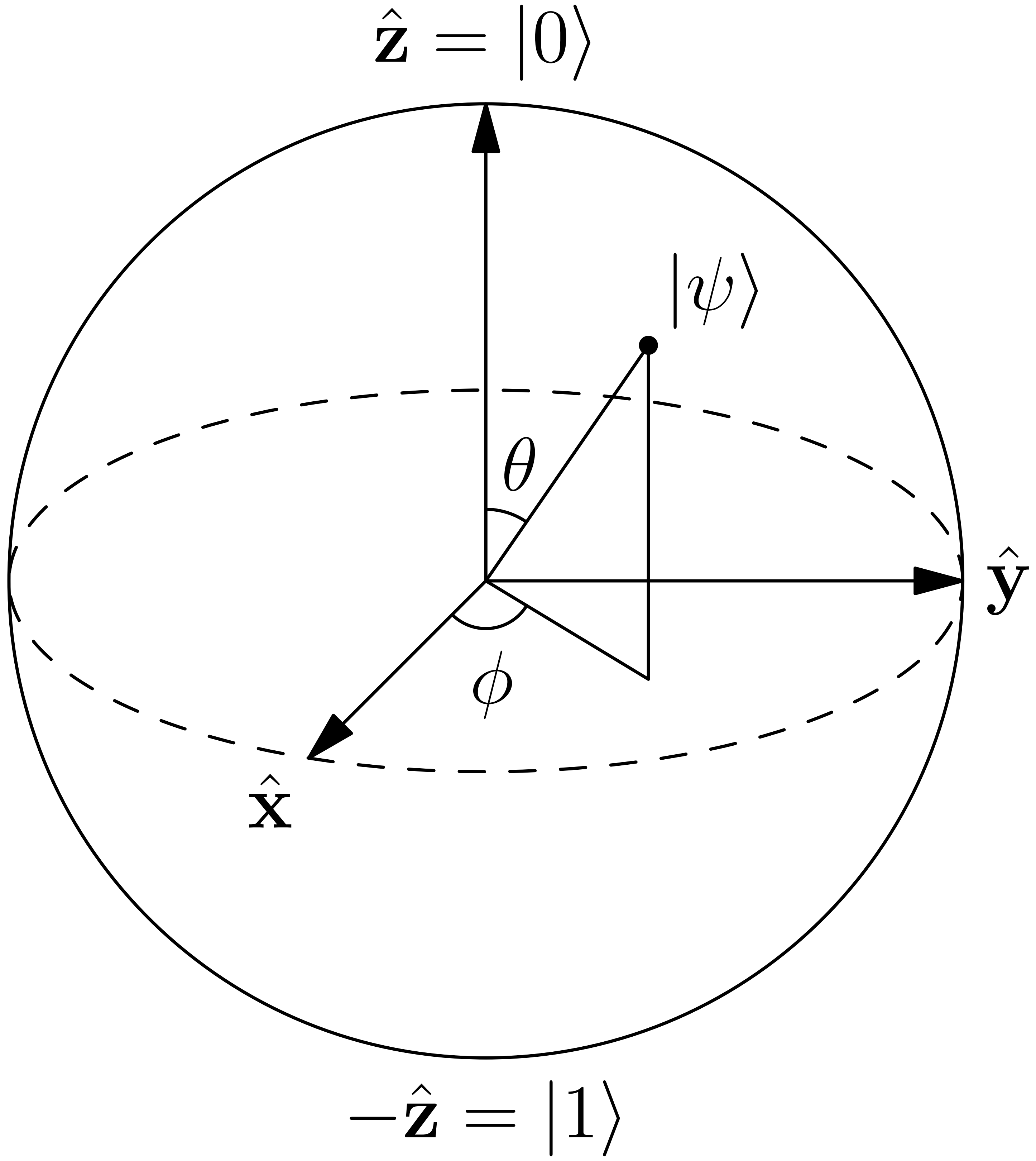
The State
The Wave Function!

- The state is:
  - C_0 and C_1
  - => $\begin{bmatrix} C_0 \\ C_1 \end{bmatrix}$
  - $\begin{bmatrix} C_0 \\ C_1 \end{bmatrix} = C_0 \begin{bmatrix} 1 \\ 0 \end{bmatrix} + C_1 \begin{bmatrix} 0 \\ 1 \end{bmatrix}$
  - $|\psi\rangle = C_0 |0\rangle + C_1 |1\rangle$

For a Digital Quantum Computer

- The state for a **single qubit** is given by:
  - $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where $|\alpha|^2 + |\beta|^2 = 1$, and α, β are complex numbers
- When measuring the state, the output is:
  - State $|0\rangle$ with probability $|\alpha|^2$
  - State $|1\rangle$ with probability $|\beta|^2$

Bloch Sphere
Visualising the State



- $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$
- $|\psi\rangle = |\alpha|e^{i\phi_1}|0\rangle + |\beta|e^{i\phi_2}|1\rangle$
- $|\psi\rangle = e^{i\phi_1}\left(|\alpha||0\rangle + |\beta|e^{i(\phi_2-\phi_1)}|1\rangle\right)$
- $|\psi\rangle = |\alpha||0\rangle + |\beta|e^{i\phi}|1\rangle$
- $|\psi\rangle = \cos(\theta/2)|0\rangle + \sin(\theta/2)e^{i\phi}|1\rangle$
- $0 \leq \phi < 2\pi$
- $0 \leq \theta \leq \pi$

Quantum Mechanics Postulates

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- Quantum state as a **complex vector**
- Evolution of quantum state:
  - Schrödinger equation
  - $|\psi'\rangle = U|\psi\rangle$, **matrix-vector multiplication** (linear algebra)
- Measurement
  - The state **becomes classical** upon measurement
- Composition
  - The system state is the **tensor product** of subsystem states.

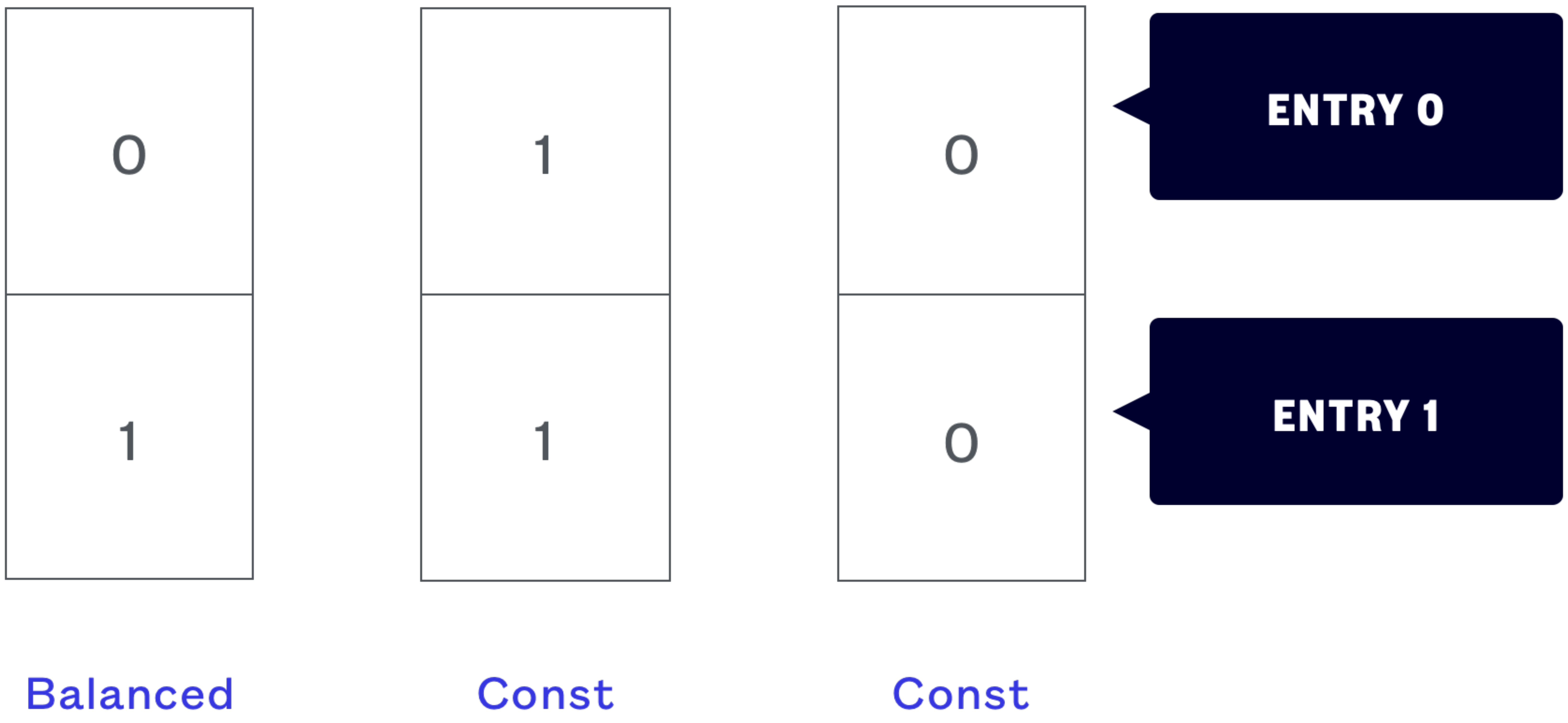
Let's Do a Quantum Computation Using Classical Waves!

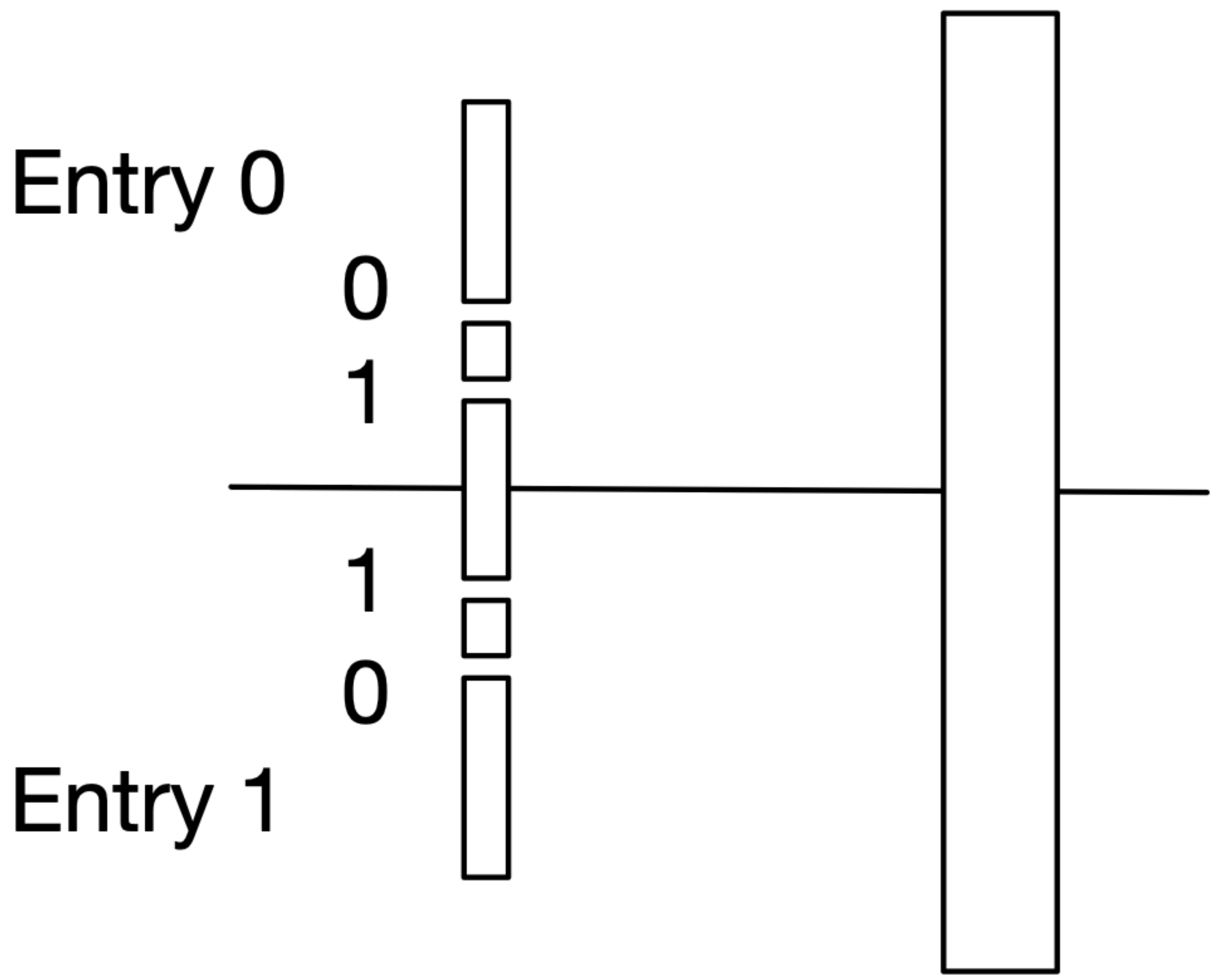
Let’s Do a Quantum Computation!

0	1	0
1	1	0
1	1	1
1	1	0
0	1	1
0	1	0
1	1	1
0	1	1
Balanced	Const	Balanced

- You will be given a list of numbers, where:
  - The numbers are all the same; i.e. all 0’s or 1’s (Constant)
  - Or the same number of 0’s and 1’s are equal (Balanced)
- Your task is to find out which type it is, quickly!

Let's make it simple!

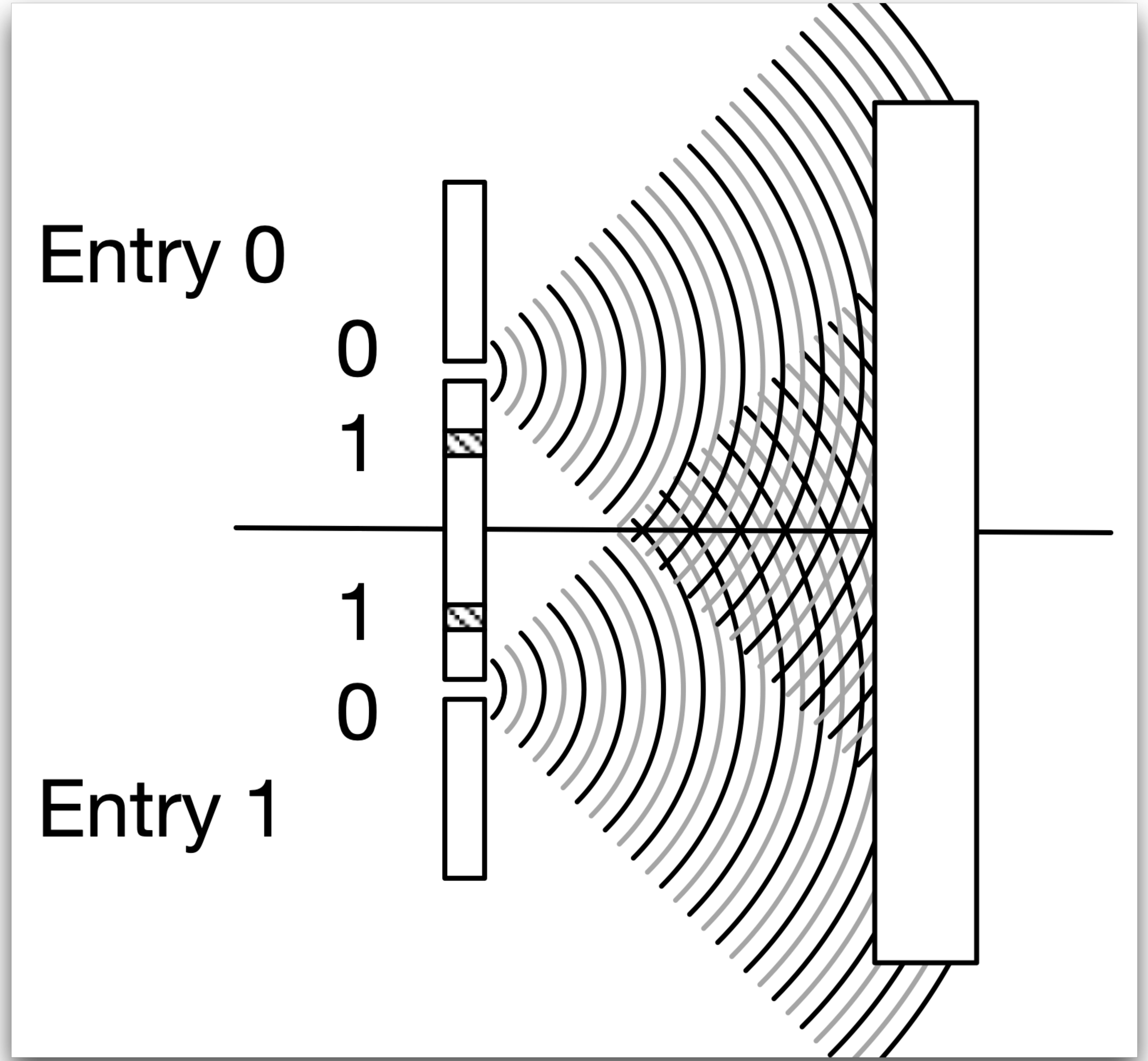


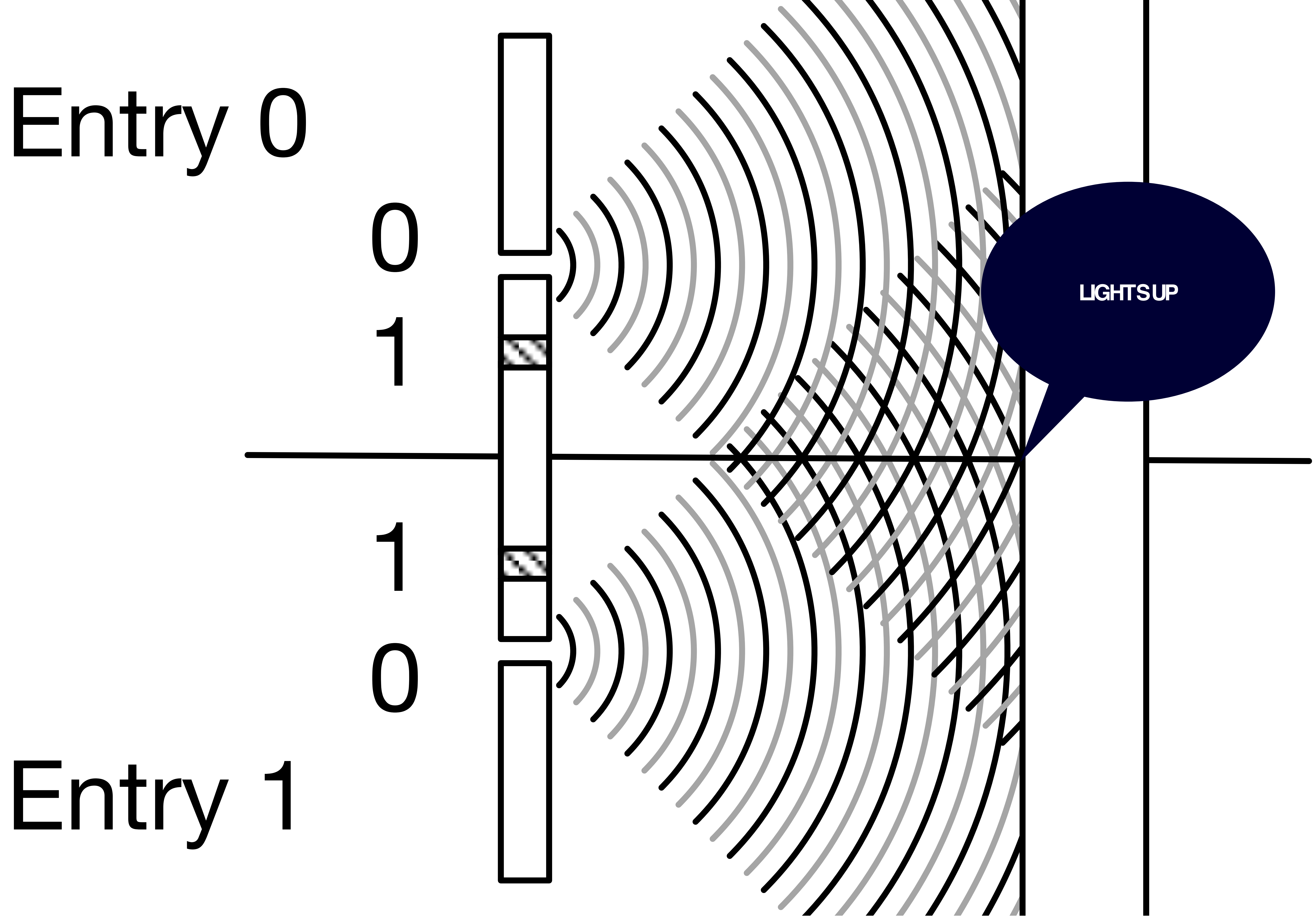


Entry 0
0
1
1
0
Entry 1

0
0

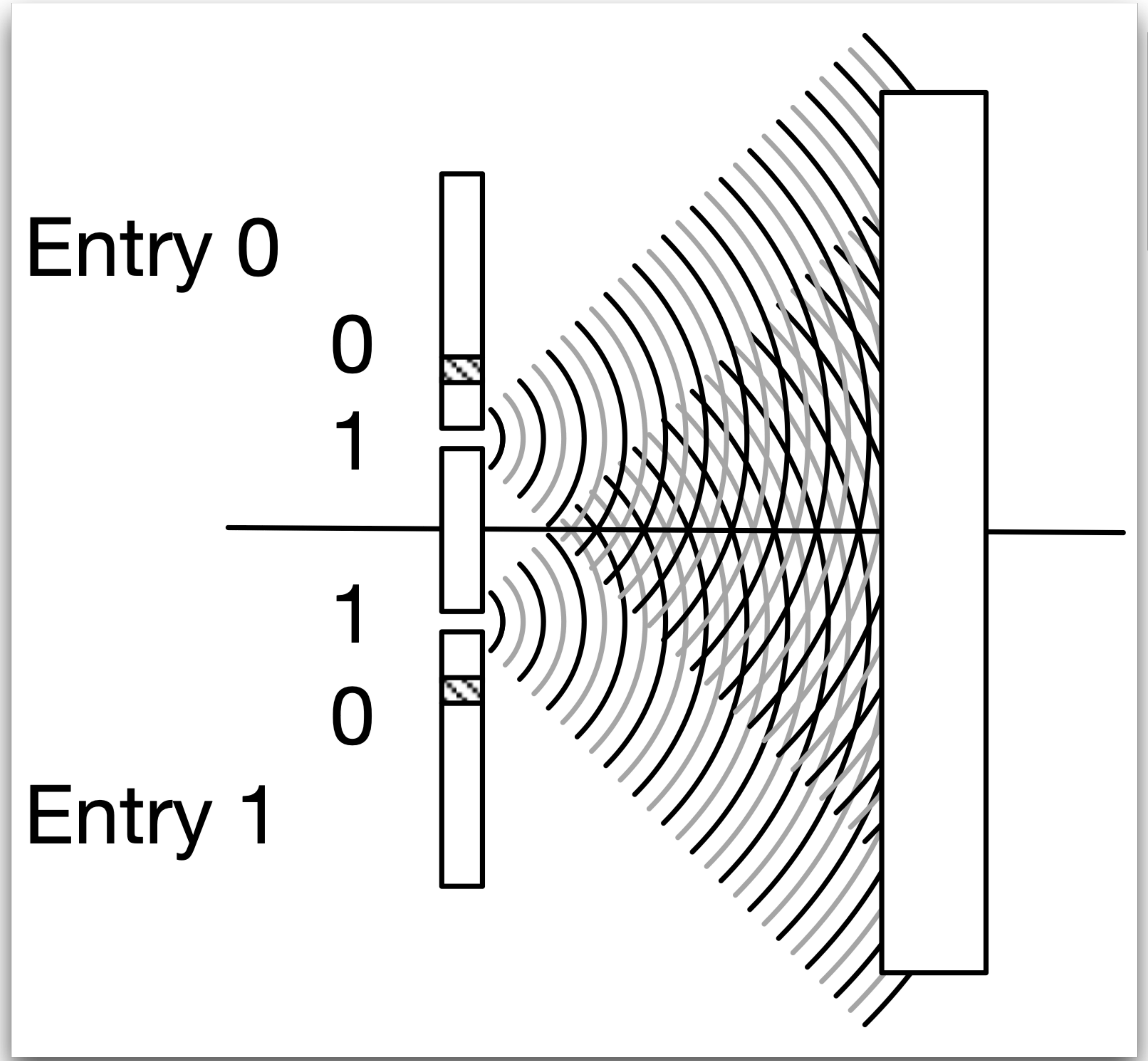
Const

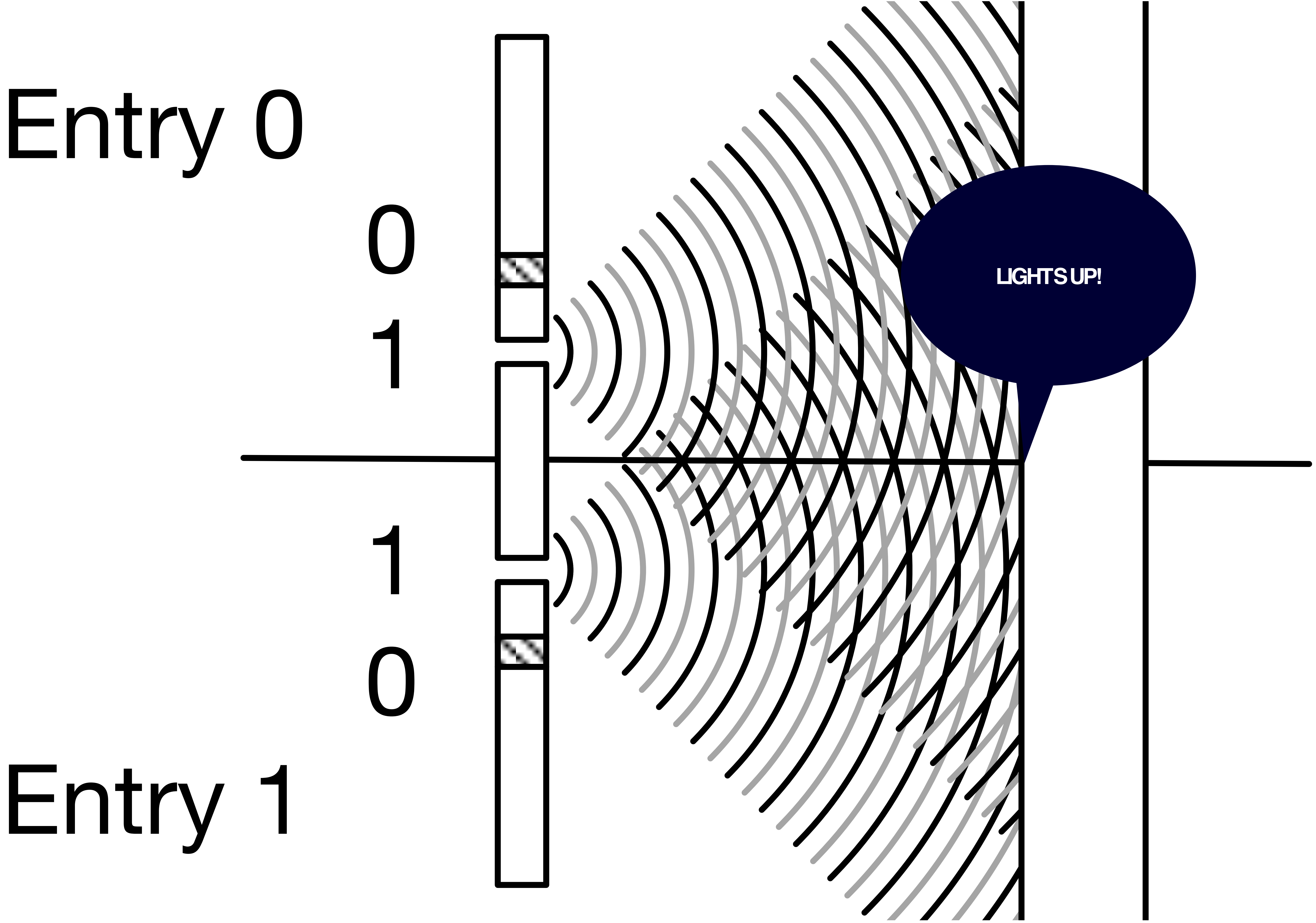



Entry 0
0
1
1
0
Entry 1
LIGHTS UP

1
1

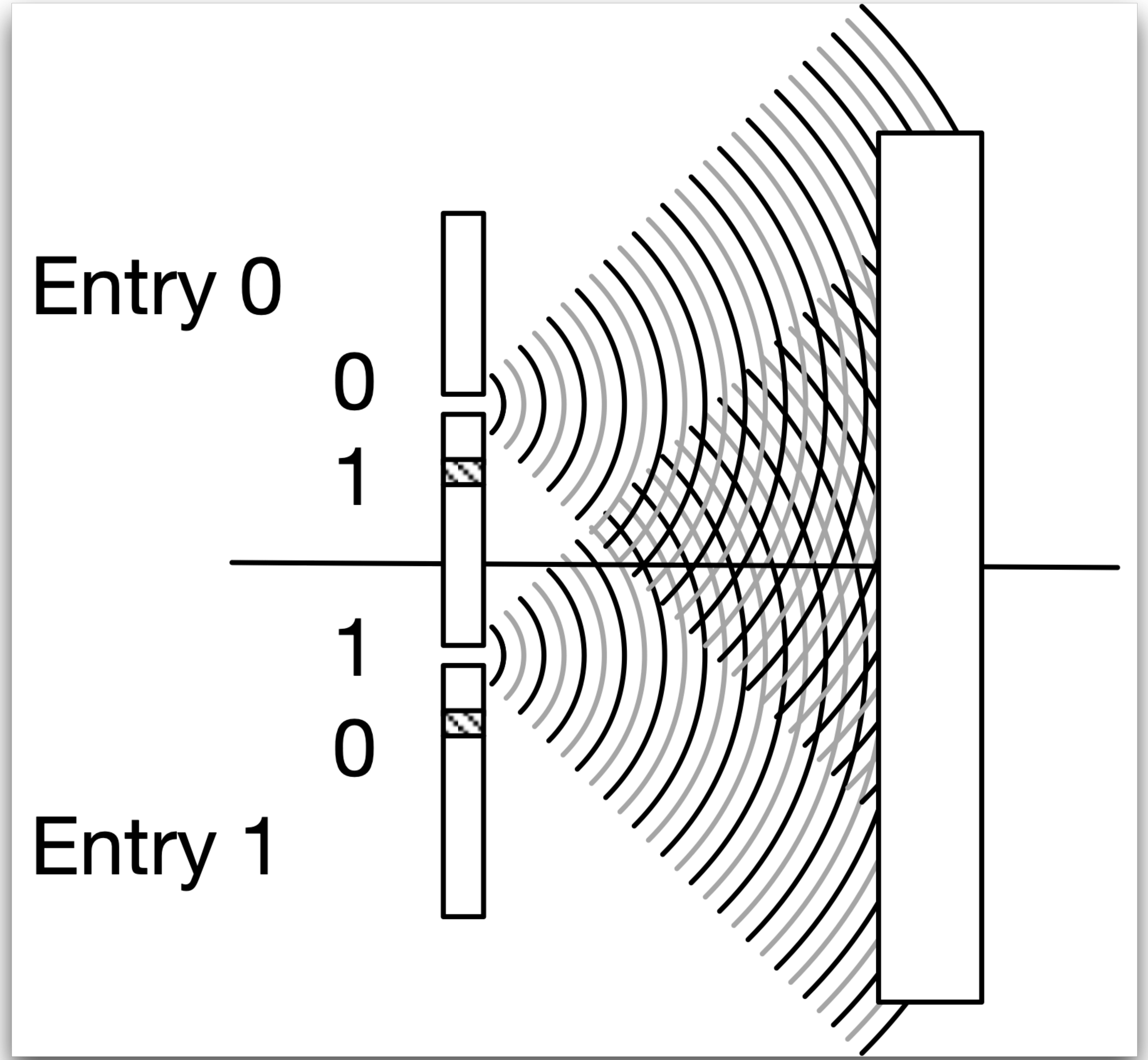
Const

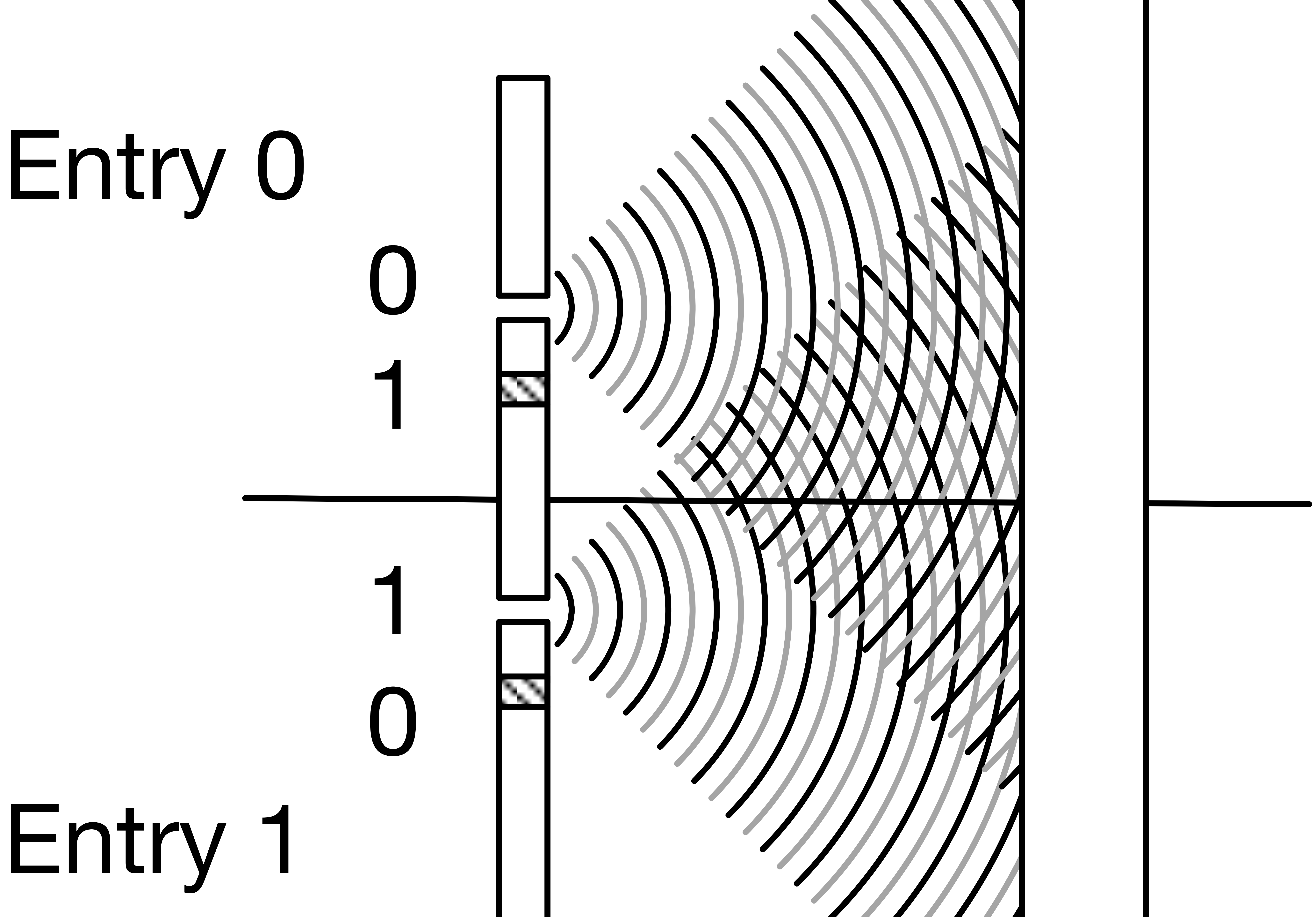



Entry 0
0
1
1
0
Entry 1
LIGHTS UP!

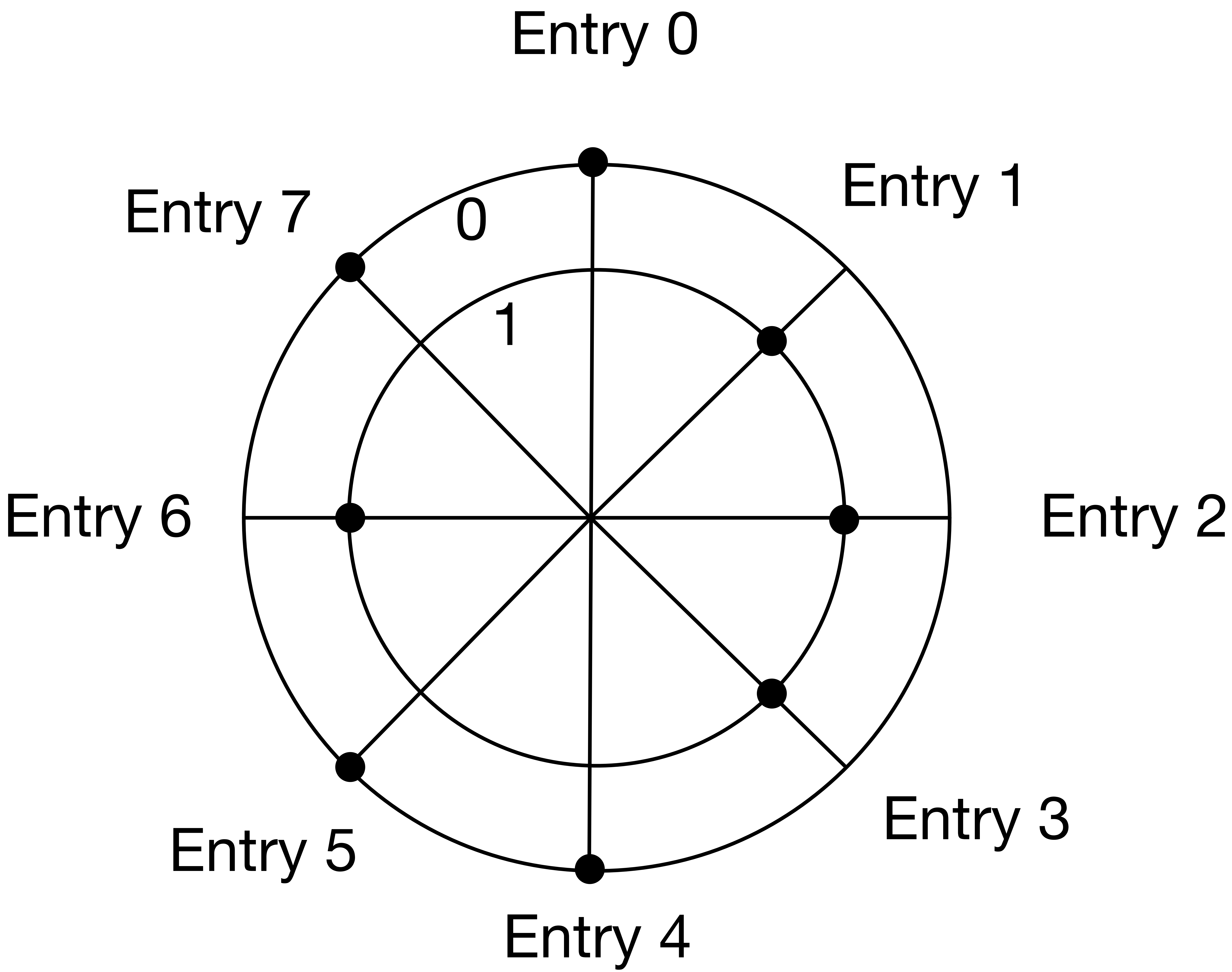
0
1

Balanced

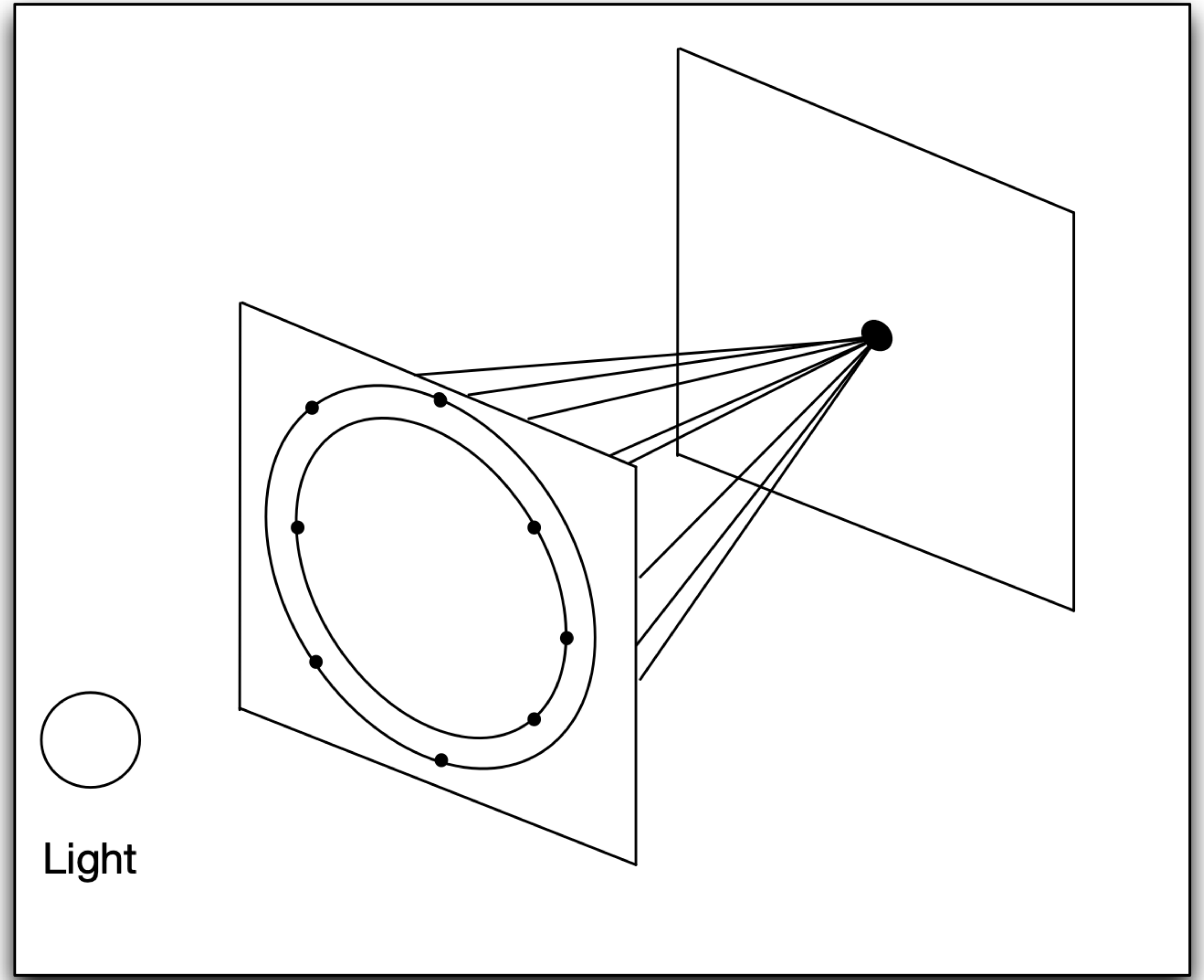



Entry 0
0
1
1
0
Entry 1

For the longer list

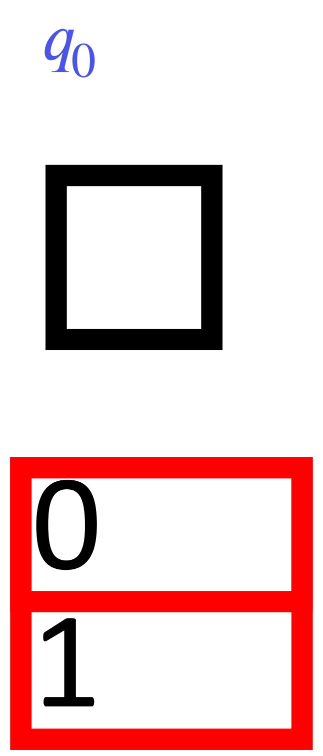


Entry 0	0
Entry 1	1
Entry 2	1
Entry 3	1
Entry 4	0
Entry 5	0
Entry 6	1
Entry 7	0

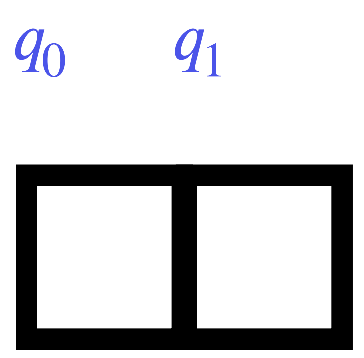

Light

The Quantum Bits (or QuBits!)

Qubits



- For two qubits!



- 00
- 01
- 10
- 11
- 00,01
- 00,10
- 00,11
- 01,10
- 01,11
- 10,11
- 00,01,10
- 00,01,11
- 00,10,11
- 01,10,11
- 00,01,10,11

For 7 qubits we can represent possibilities larger than the number of atoms in the universe!

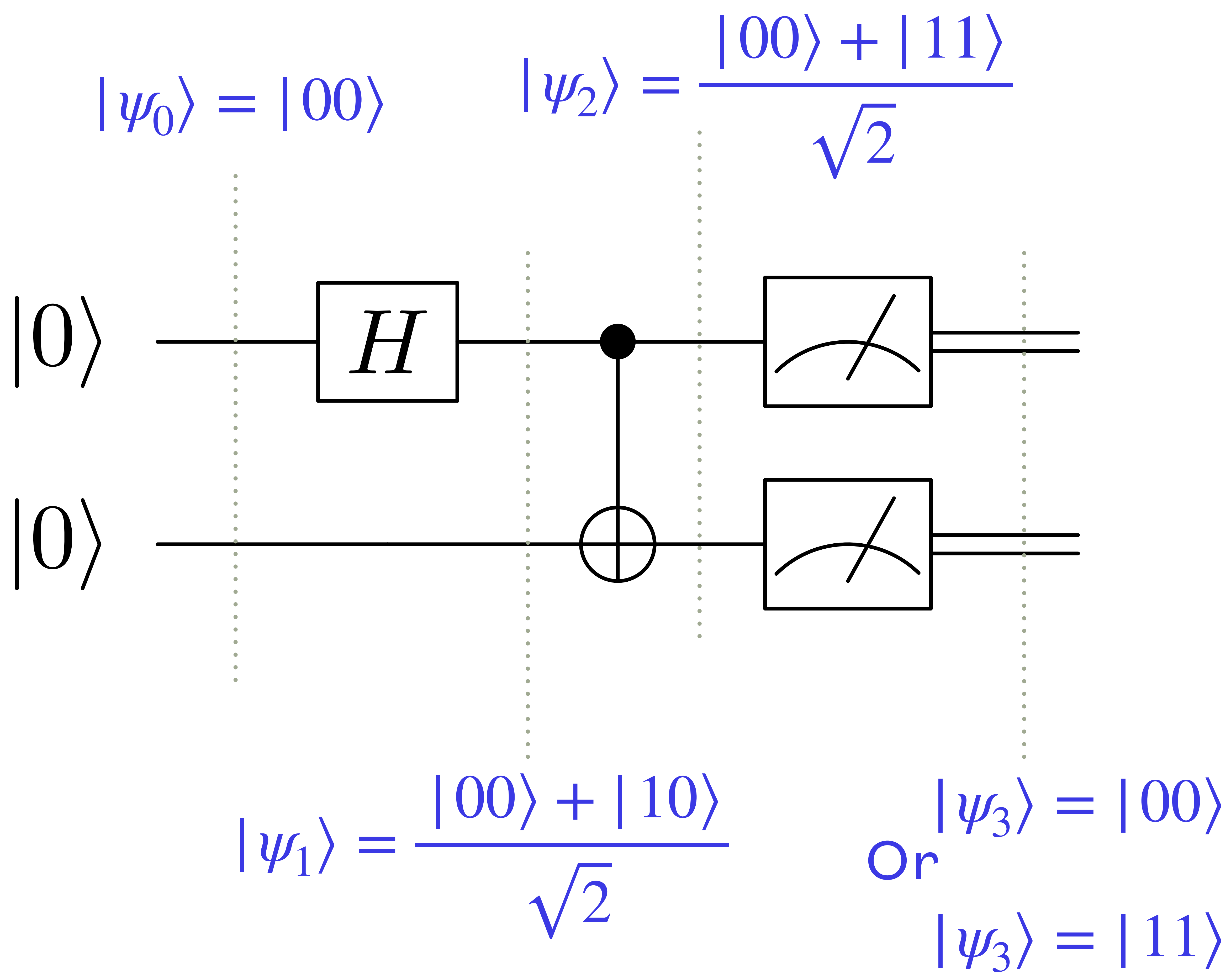
The Quantum Register
Concise Physical Space

$q_1 q_0$

$$00 \rightarrow C_{00}$$
$$01 \rightarrow C_{01}$$
$$10 \rightarrow C_{10}$$
$$11 \rightarrow C_{11}$$

- A two-qubit register holds four waves!
- An n-qubit register holds 2^n waves!
- If all waves are the same:
    - We will have 2^{2^n} possibilities!

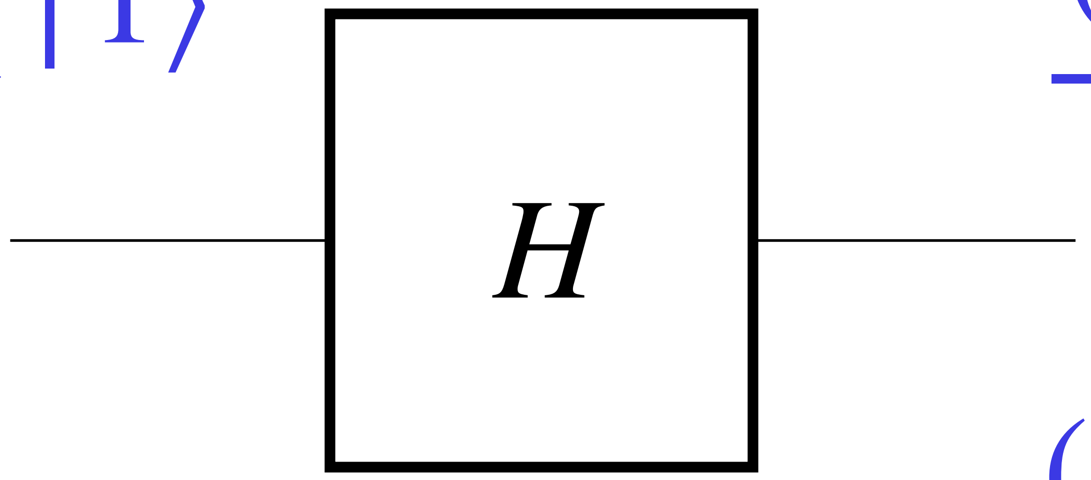
Quantum Computing
The Circuit Model



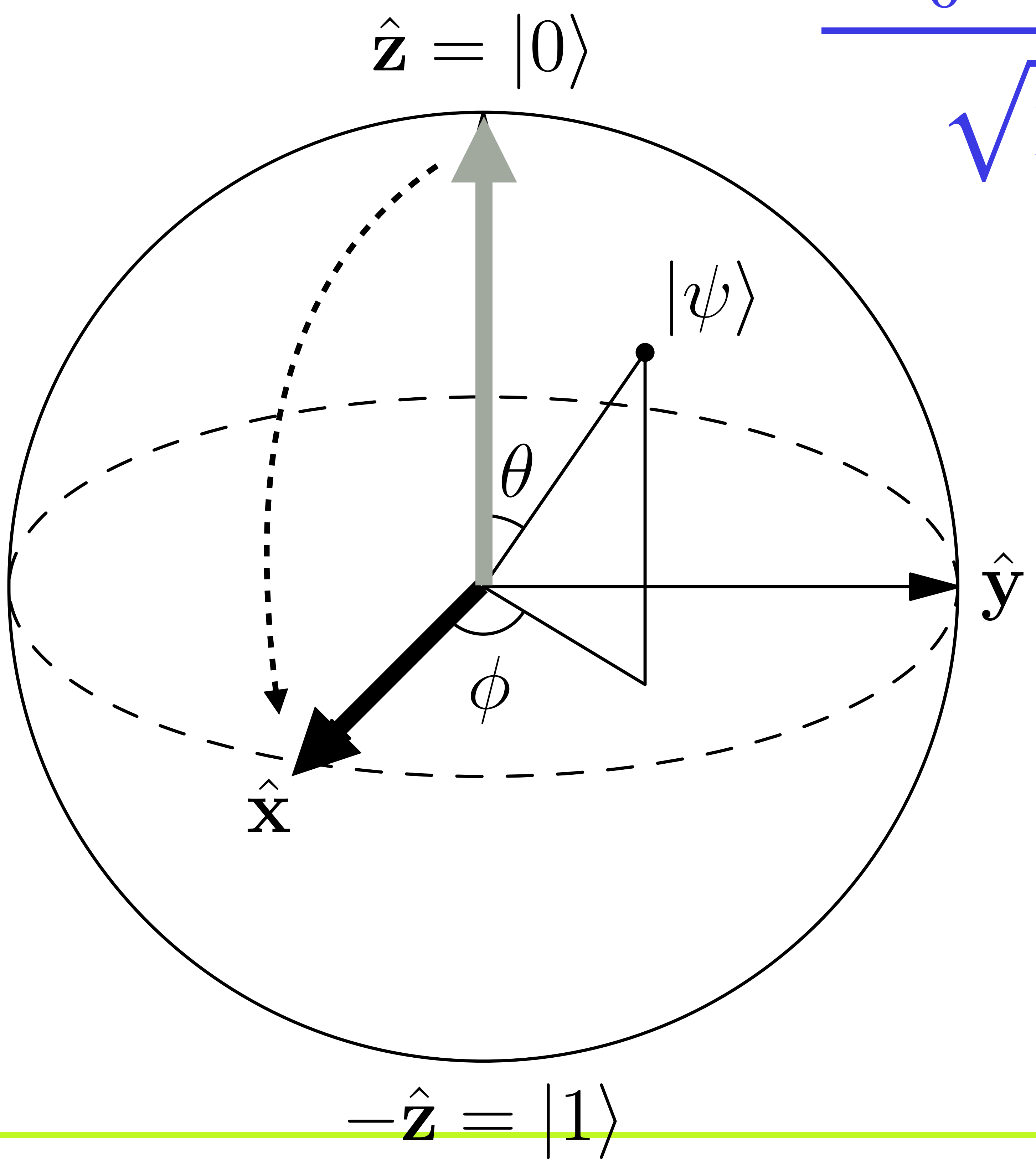
- A set of computation stages
- Each stage has single qubit and two-qubit **gates**
- A gate performs transformation on an input quantum states
- Computation evolves from left to right
- No cloning!
- All computations are reversible

Gates
Hadamard

$$C_0|0\rangle + C_1|1\rangle$$



$$\frac{(C_0 + C_1)}{\sqrt{2}}|0\rangle + \frac{(C_0 - C_1)}{\sqrt{2}}|1\rangle$$

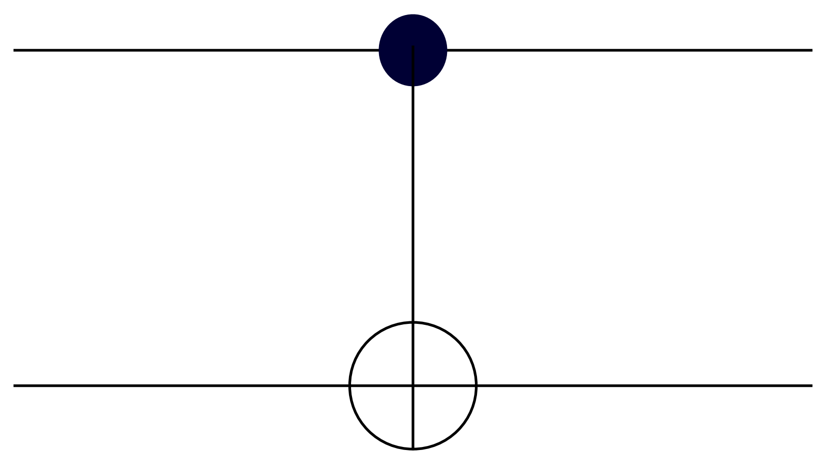


- Interferes the two waves at all locations
  - Location 0: no shifts
  - Location 1: π degrees shift
- The key gate for generating the super-position of all classical states

Gates

CNOT

$$C_{00}|00\rangle + C_{01}|01\rangle + C_{10}|10\rangle + C_{11}|11\rangle$$



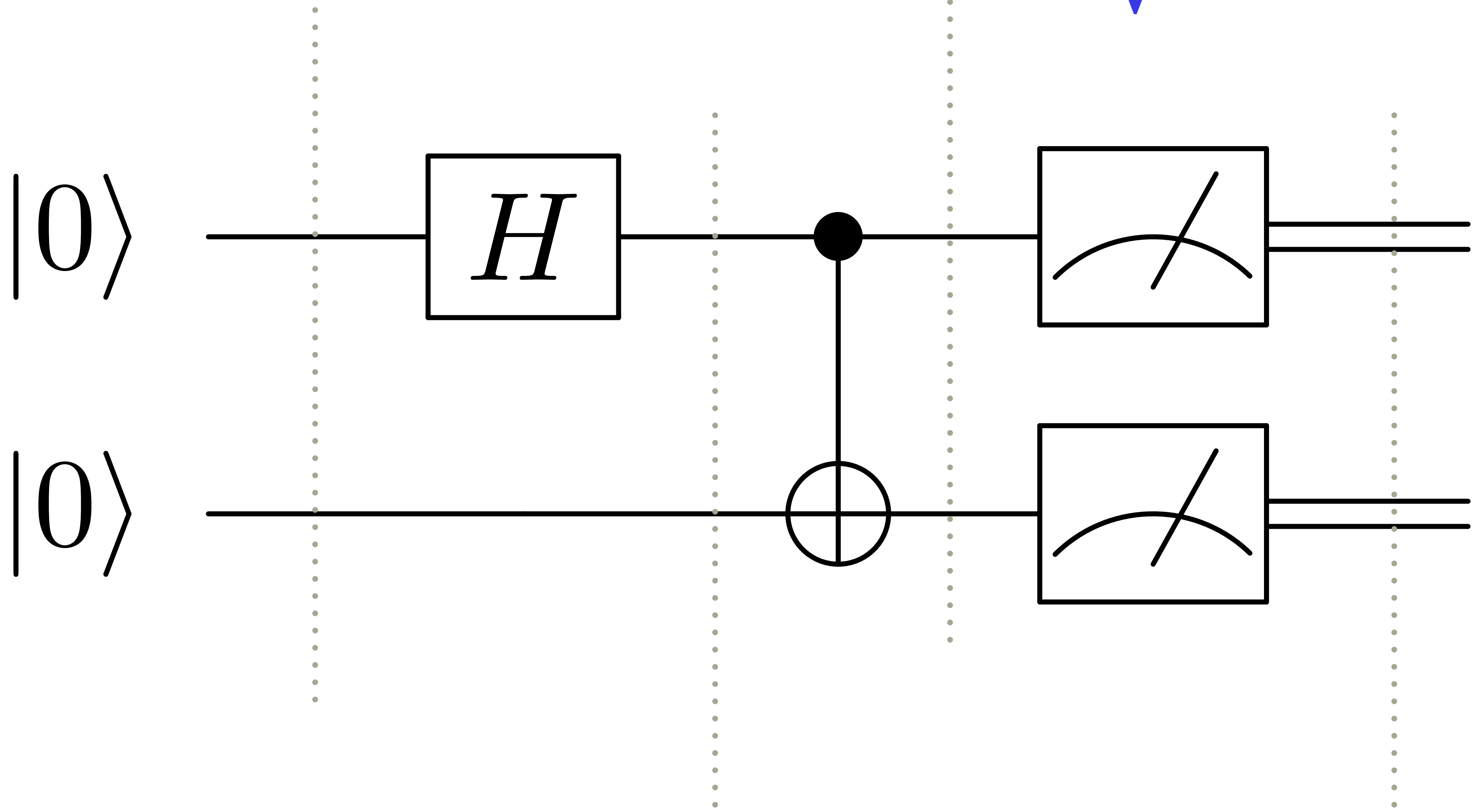
$$C_{00}|00\rangle + C_{01}|01\rangle + C_{10}|11\rangle + C_{11}|10\rangle$$

- Controlled NOT
- Inverts the second qubit if the first qubit is 1

Quantum Computing
The Circuit Model

$|\psi_0\rangle = |00\rangle$

$$|\psi_2\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$



$$|\psi_1\rangle = \frac{|00\rangle + |10\rangle}{\sqrt{2}}$$

$|\psi_3\rangle = |00\rangle$

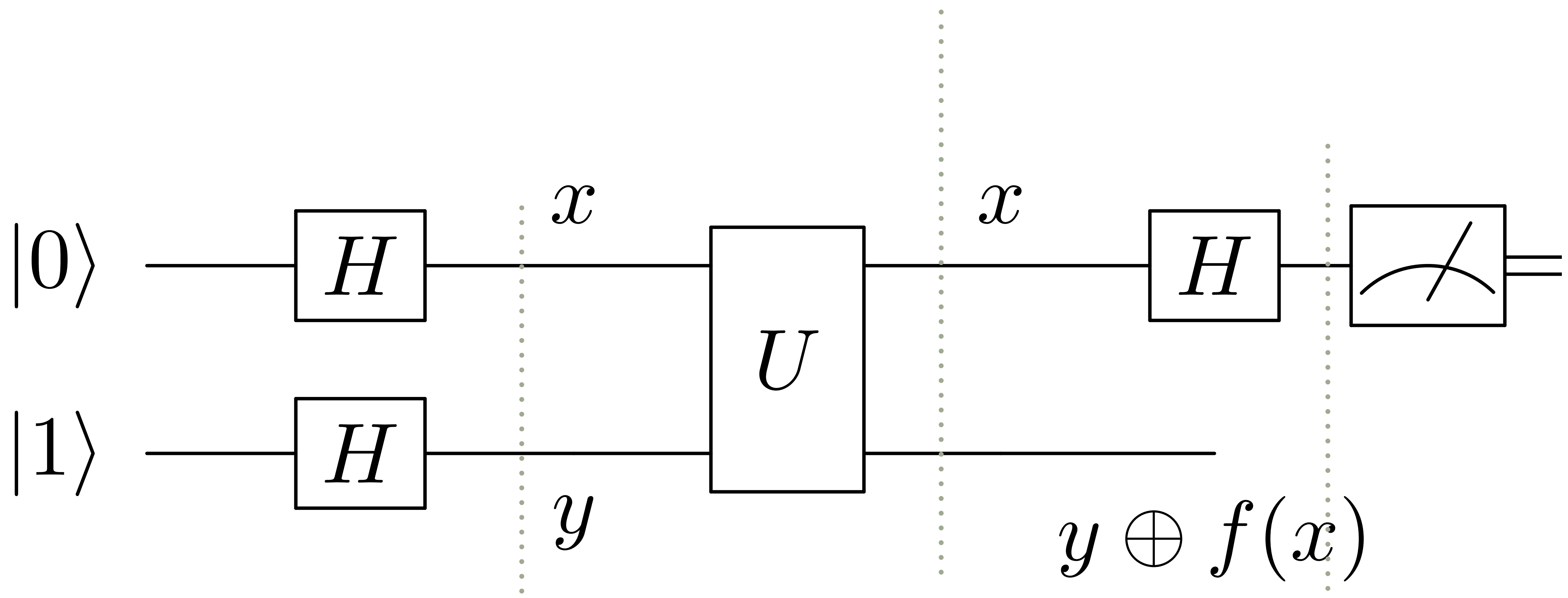
Or

$|\psi_3\rangle = |11\rangle$

- A set of computation stages
- Each stage has single qubit and two-qubit **gates**
- A gate performs transformation on an input quantum states
- Computation evolves from left to right
- No cloning!
- All computations are reversible

Let's Build a Circuit for Deutsch's Algorithm

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}\left((-1)^{f(0)}|0\rangle + (-1)^{f(1)}|1\rangle\right)\left(|0\rangle - |1\rangle\right)$$



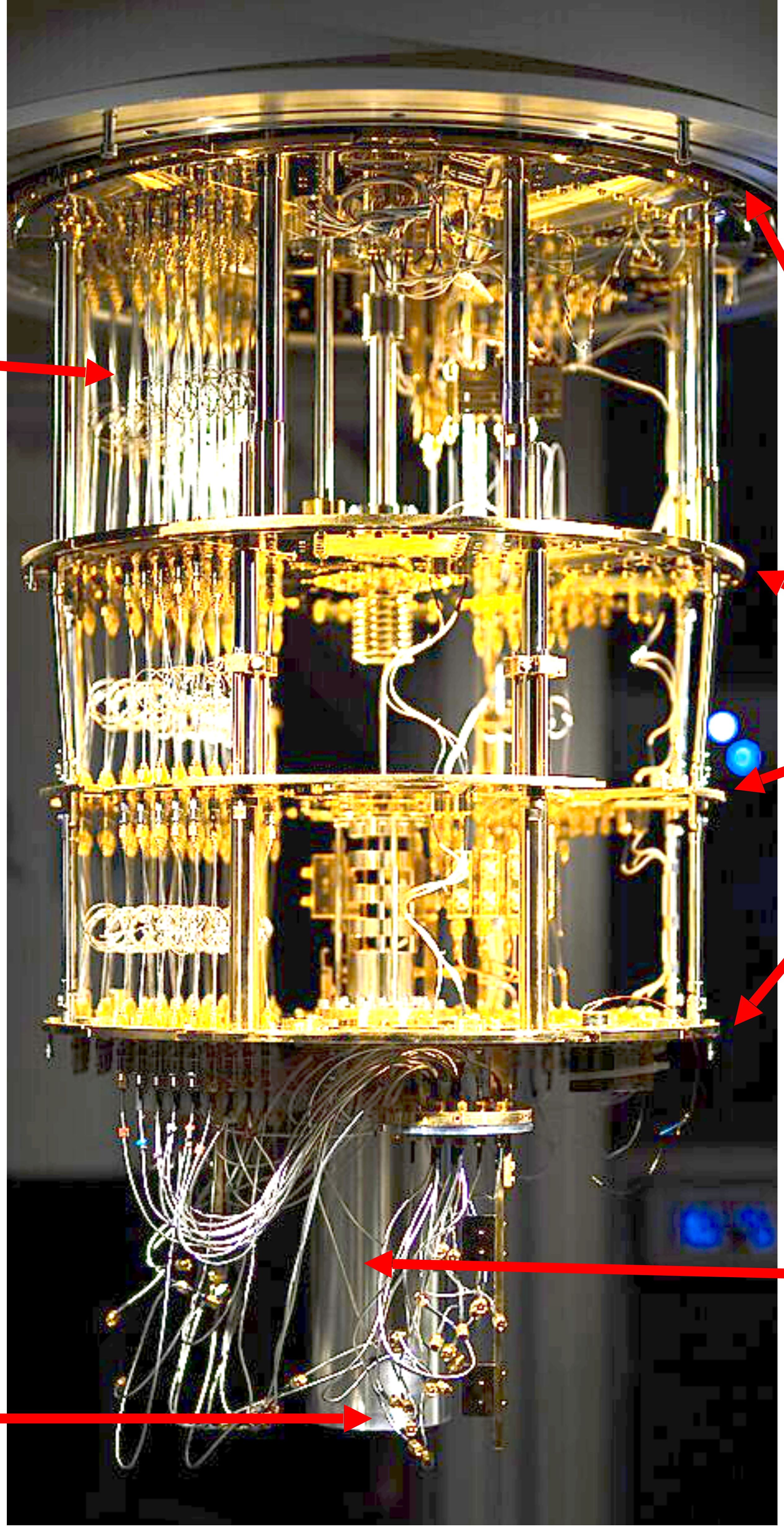
$$|\psi_1\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)\left(|0\rangle - |1\rangle\right)$$

- If **constant**, then $f(0) = f(1)$, the state is $|0\rangle$
- Otherwise, **balanced** where $f(0) = \overline{f(1)}$ the state is $|1\rangle$

$$|\psi_3\rangle = \frac{1}{2}\Big(\left((-1)^{f(0)} + (-1)^{f(1)}\right)|0\rangle + \left((-1)^{f(0)} - (-1)^{f(1)}\right)|1\rangle\Big)\left(|0\rangle - |1\rangle\right)$$

The Quantum Processor

Microwave Cables (Control and Data)

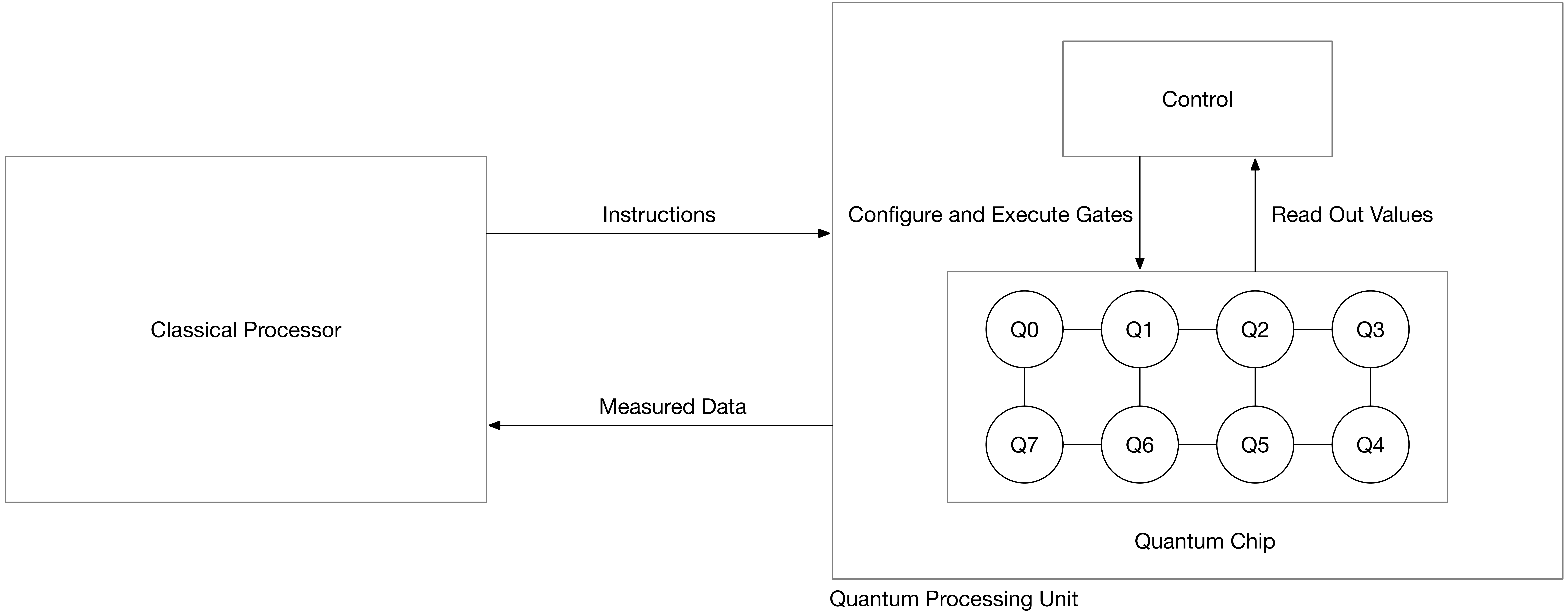


Cooling Levels

Magnetic Shield

Quantum Chip (~10mk)

Quantum Processor Architecture



Quantum Implementation Technologies

- Trapped Ions
  - The state is represented through being at a special energy level
  - Operation is done through the laser of microwave pulse interactions
- Superconductors
  - Relies on current IC technologies
  - Microwave and magnetic fields-based operations
- Photonics
  - Currently not typical, but it has started to gain interest
  - Some relies on linear optics and can operate at room temperature; concerns of noise

Quantum Implementation Technologies, cont

- Neutral Atoms
  - Relies on moving atoms with laser twizzers!
  - No cooling with low noise
- Nitrogen Vacancy Centres
  - Relies on artifacts in crystals
  - Low cost, but not scalable
- Quantum Dots
  - Relies on confining electrons in space
  - Low noise by, not scalable

System Stacks

Classical Systems	
Classical Algorithms	
high-level languages	
Compilers	OS
Assembly Language	
Classical Processor with Transistors	

Quantum Systems
Quantum Algorithms
Quantum high-level languages: e.g. Python
Quantum Compliers: error correction, noise mitigation, transpilation, circuit optimisation
Low-Level language: e.g. OpenQASM
Quantum Device with Qubits

Classical Systems

Quantum Systems

“We have entered the Noisy Intermediate-Scale Quantum (NISQ) era,”

John Preskill, Caltech

Characteristics of Existing Quantum Systems

- 50-1000 qubits
- Error rate $10^{-3}, 10^{-4}$
- Short lived qubits, fraction of a second
- Players include:
  - IBM (now 1121 qubits!), Google, 50 qubits superconducting machines with cloud access
  - Intel, building quantum systems
  - IonQ 79-qubit, trapped-ion technology
  - University of Science and Technology of China in Hefei, 43 qubits, photonics technology

Reading List

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- Schuld, Maria, and Francesco Petruccione. Machine learning with quantum computers. Vol. 676. Berlin: Springer, 2021.

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Thank You

شكرا جزيلا