Intro to Quantum Programming

Matt Norby
Senior Consultant, Manifest Solutions
norbymatt@gmail.com

Agenda

- Why quantum computing?
- Quantum physics background and terminology
- A useful model for quantum computing
- Quantum algorithms
- Demo

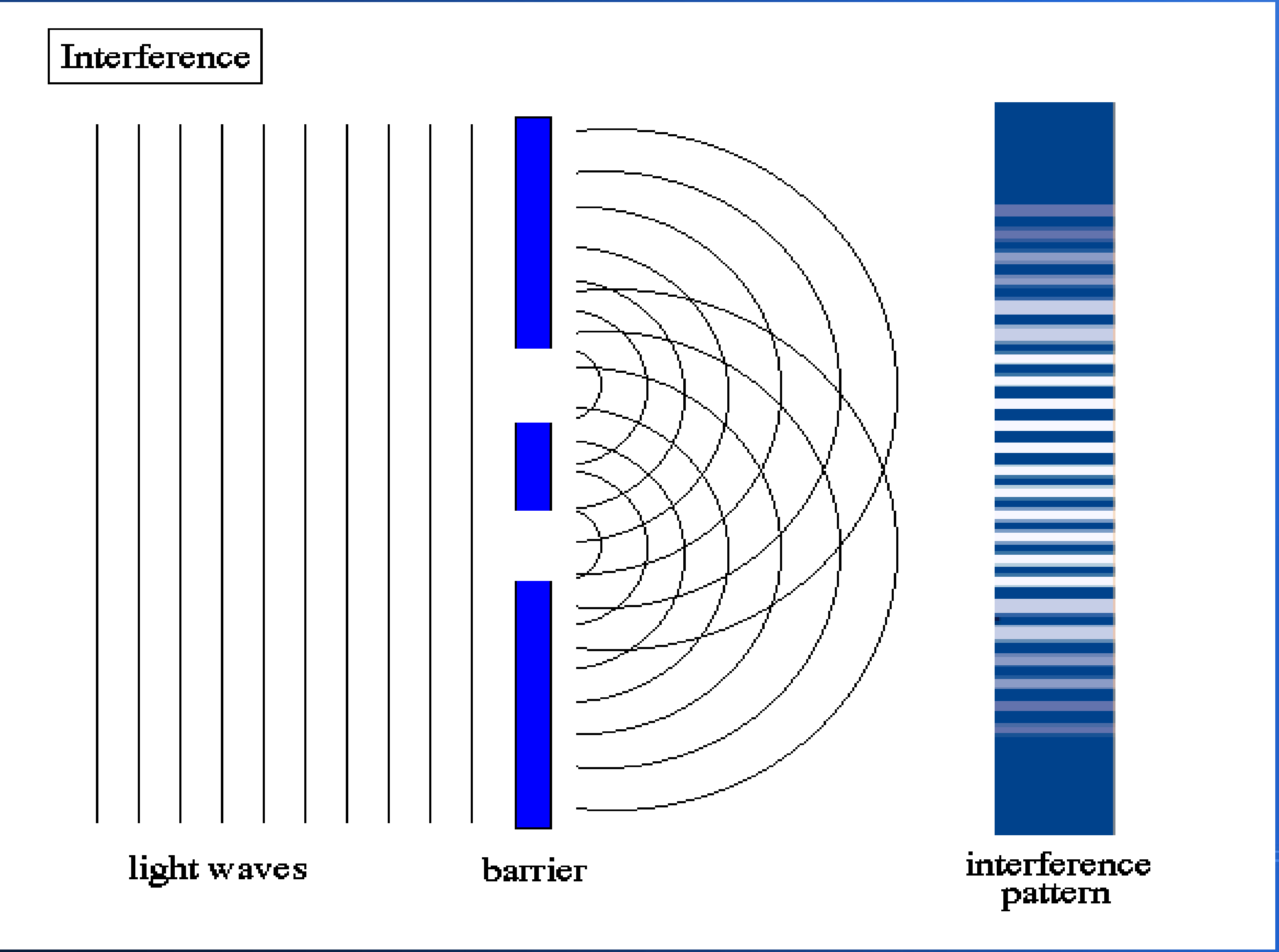
Why Quantum Computing?

- Much faster algorithms (sometimes)
- Quantum computers exist today
- Computer industry investment

What do we mean by quantum?

- The smallest possible things
- Physical effects below atomic scale
- Very different from macro-scale physics
- Wave-particle duality
- Is it matter or is it energy?

Thomas Young experiment (1801)



Thomas Young experiment (1801)

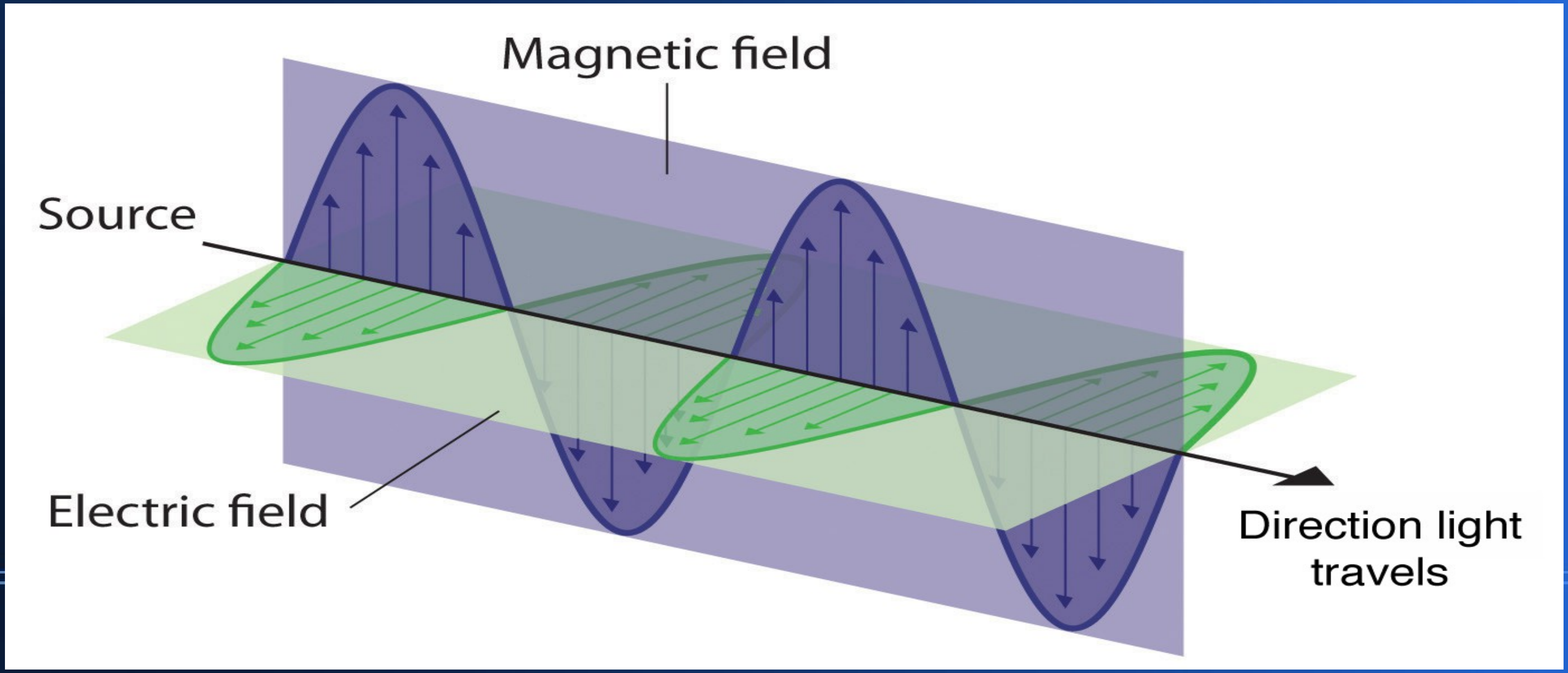
The first “double-slit” experiment

- If light is a particle, we see 2 lighted areas
- If light is a wave, we see an interference pattern

Result: interference pattern → light is a wave

James Clerk Maxwell (1860s)

- Light, magnetism, and electricity are related
- Light is an electromagnetic wave
- Frequency x Wavelength = speed of light



Max Planck (1900)

Electromagnetic radiation come in quanta

- E = hv
- h = Planck's constant
- v = Frequency

→ Not possible to have energy lower than h.

→ Light exists as discrete “photons” of energy.

What is quantum?

- OED: “A discrete quantity of energy proportional in magnitude to the frequency of the radiation it represents” (plural = quanta)
- Discrete = indivisible, countable

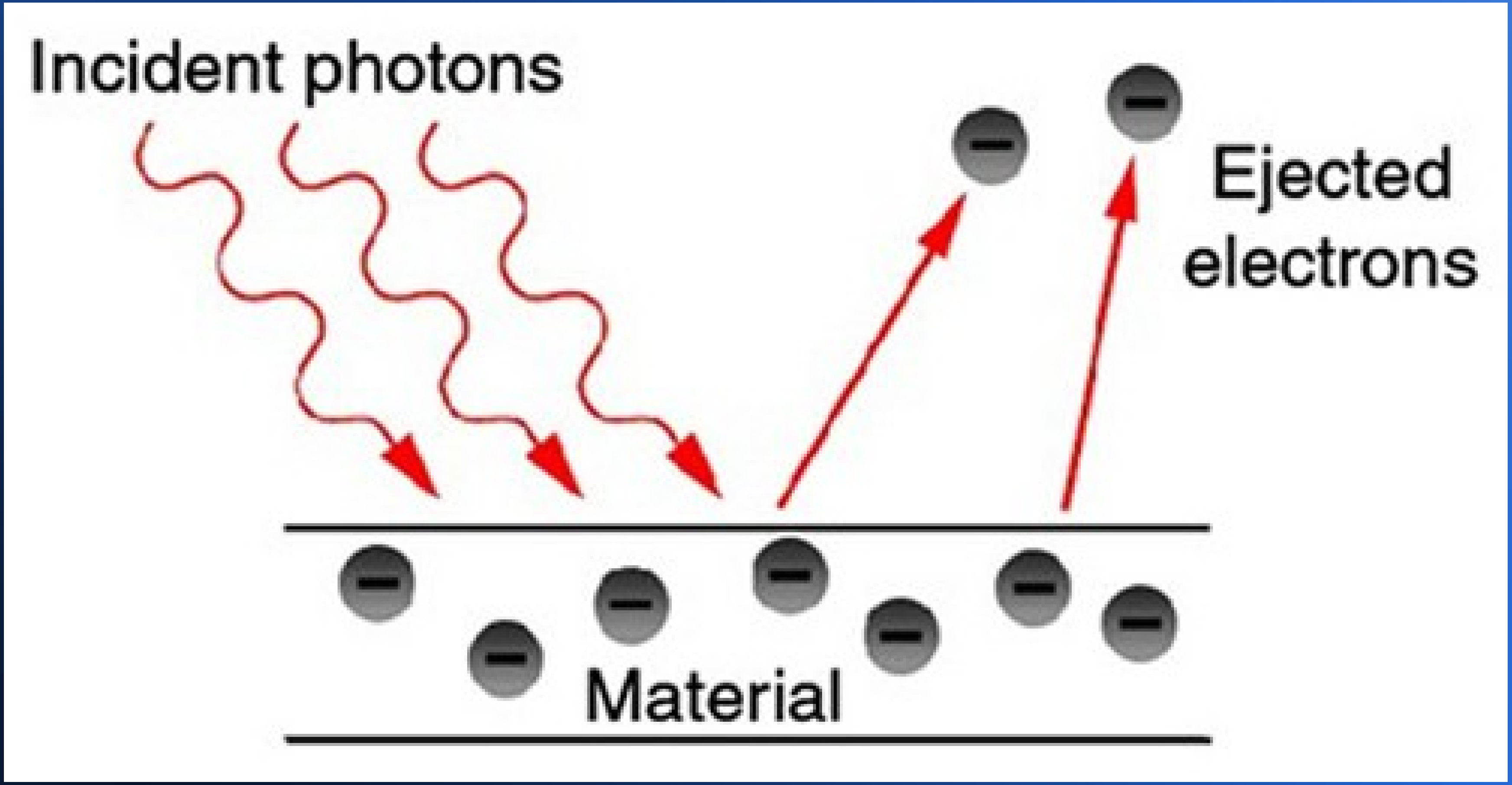
Albert Einstein (1905)

Photoelectric effect

- Above a threshold frequency, light causes electrons to be released from metal
- More light releases more electrons
- Higher frequency light imparts more energy

→ Light comes in quanta

Albert Einstein (1905)



Born / Heisenberg (1925)

Matrix model of quantum mechanics

- Probability of being in a given state
- Imaginary numbers were needed
- Corollary: uncertainty principle
  - Cannot know both position and momentum

Born / Heisenberg (1925)

Paul Dirac followed up with Dirac notation

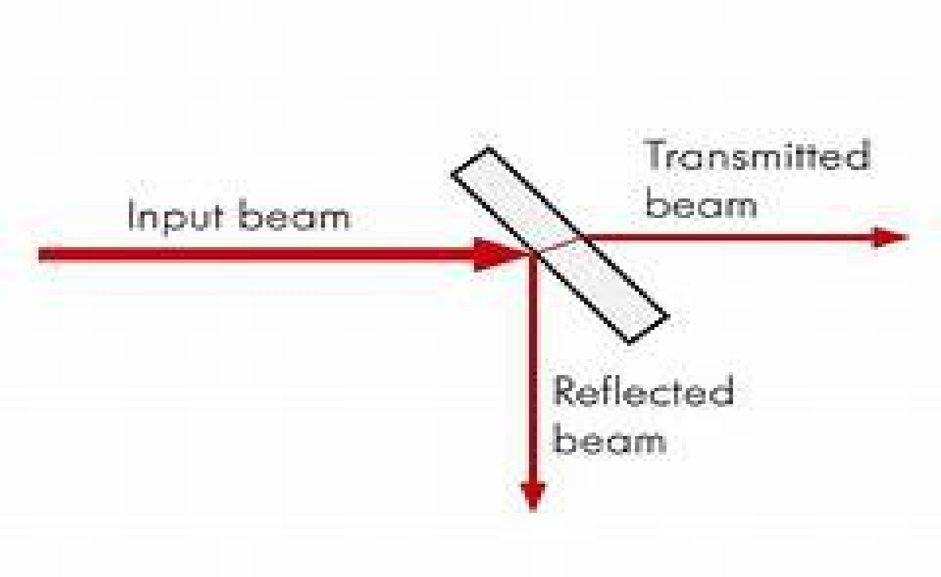
$$|0\rangle = \boxed{\begin{pmatrix} 0 \\ 1 \end{pmatrix}} \qquad |1\rangle = \boxed{\begin{pmatrix} 1 \\ 0 \end{pmatrix}}$$

→ More compact than matrix representation

Alain Aspect (1972)

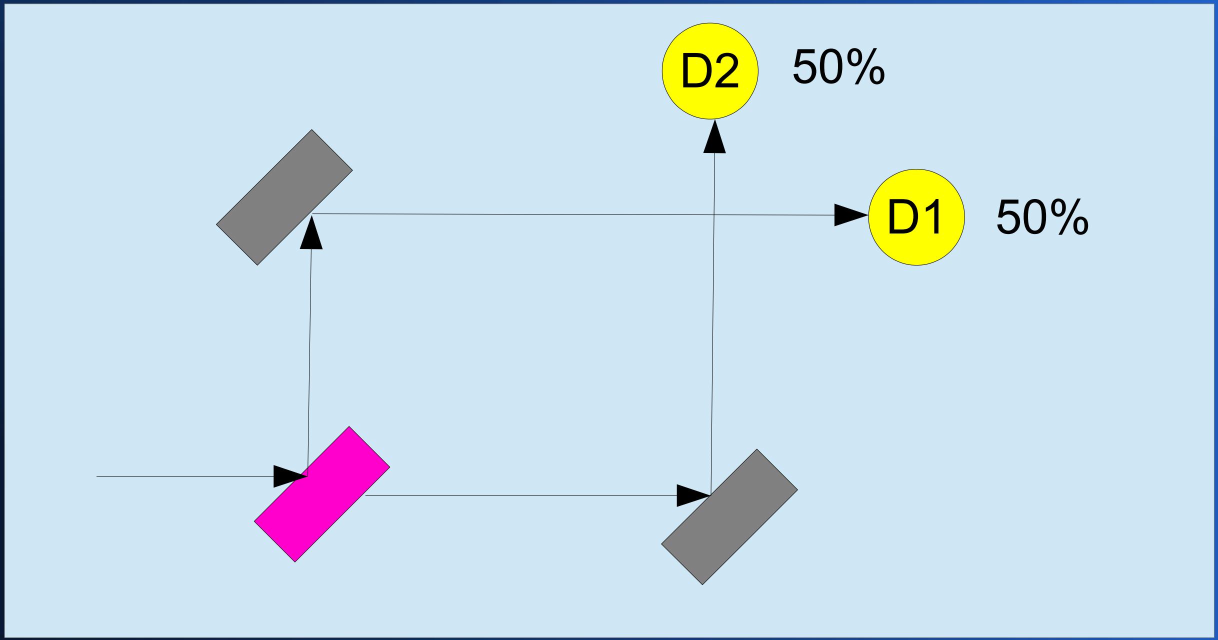
- If you fire one photon at a beamsplitter, it goes one way or the other (not both)
- Equal probability for each path

→ Particle behavior with one beamsplitter



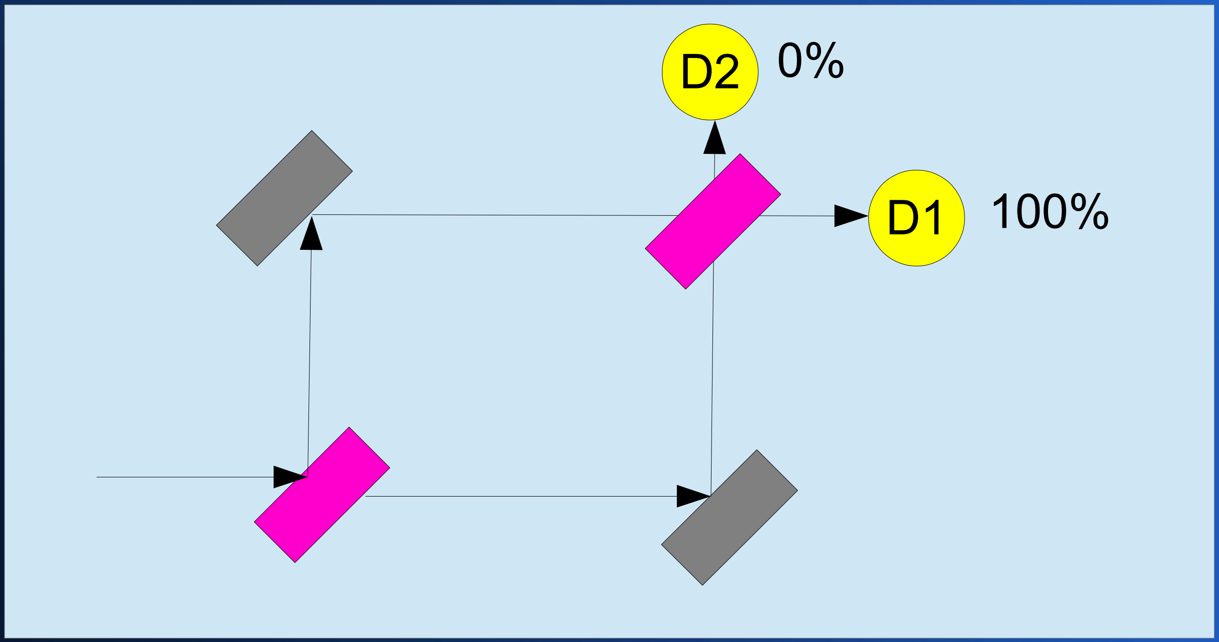
Alain Aspect (1972)

- If you fire one photon at a beamsplitter, and reflect the paths so that they cross, the photon still goes only one way or the other (not both)



A. Aspect / R. Grangier (1986)

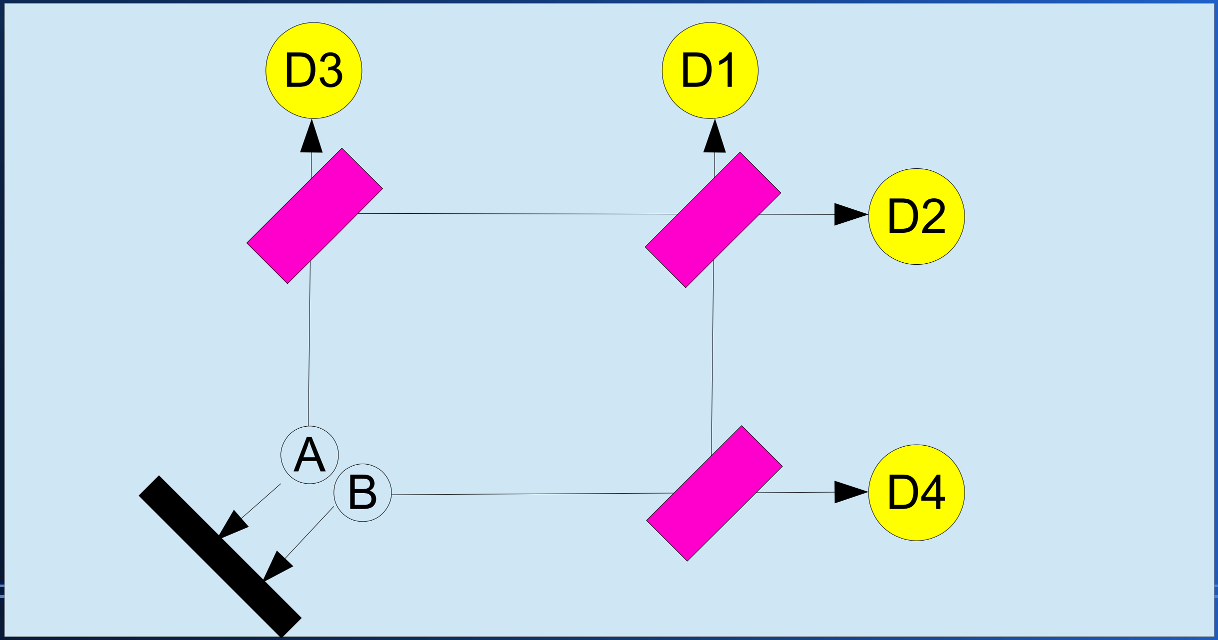
- If you reflect equal-length paths so that they cross at a second beamsplitter, the photon follows one path after the second beamsplitter



A. Zeilinger (1995)

"Quantum eraser" experiment

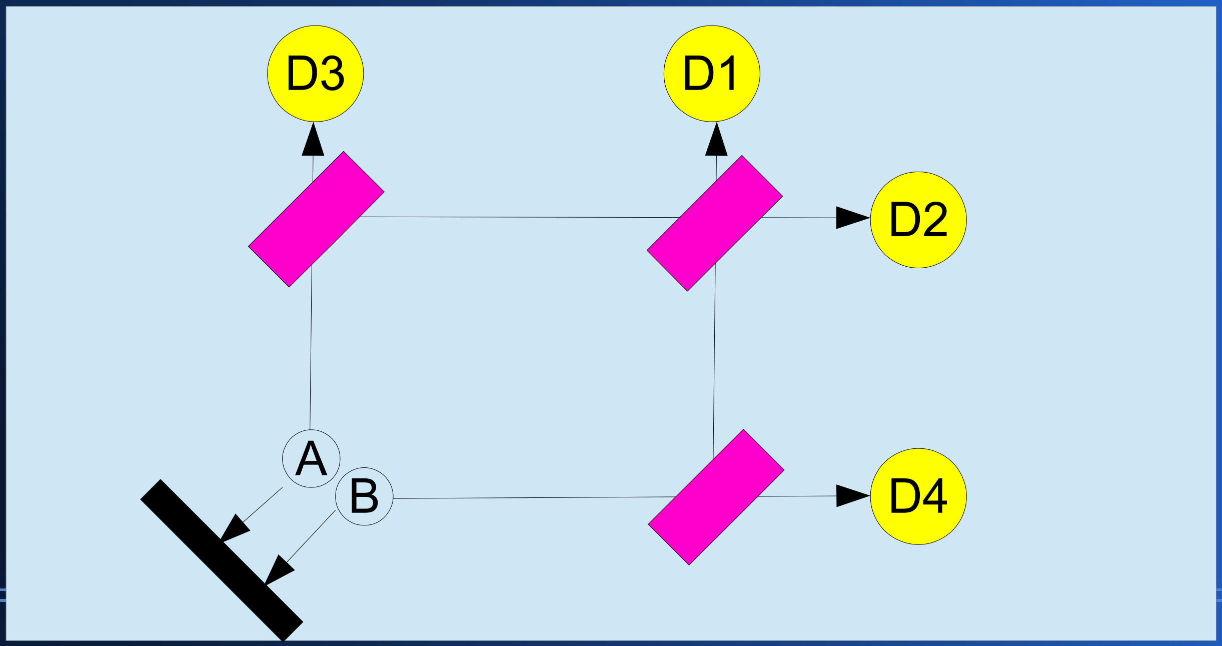
- Entangled "system" and "environment" photons
- Collect or discard "which way" information



A. Zeilinger (1995)

→ When “which way” info is known (D3/D4), there is no interference pattern on the screen

When not known, there is interference (D1/D2)

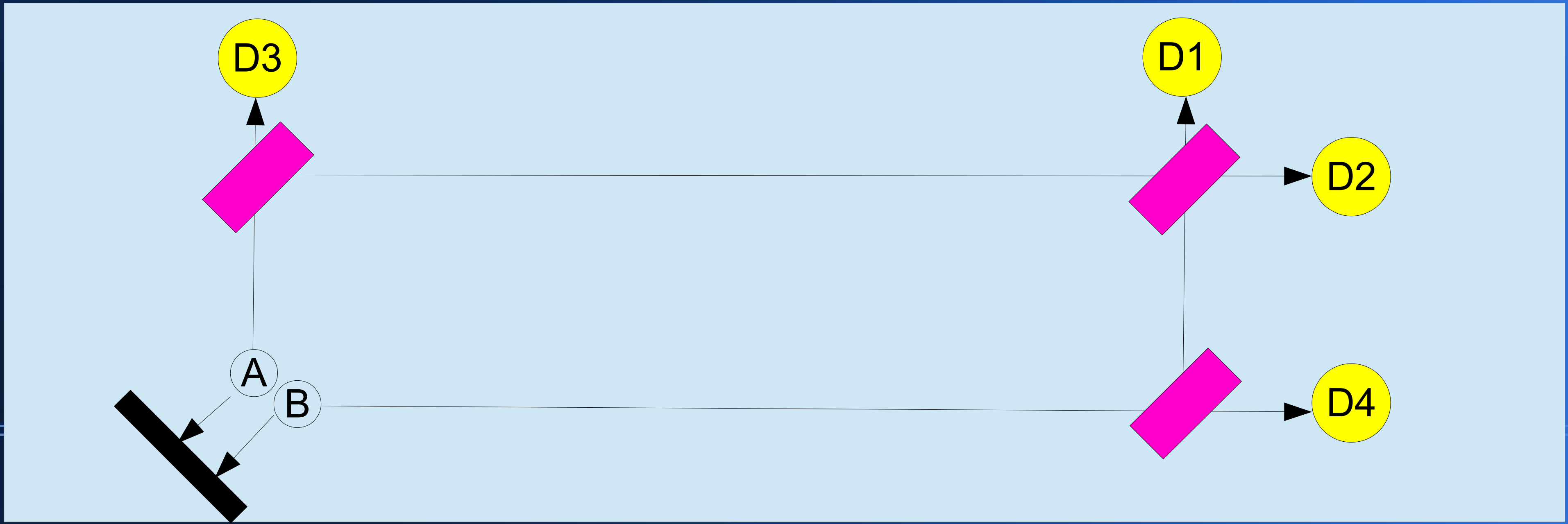


Yoon-Ho Kim et al. (1999)

"Delayed choice quantum eraser" experiment

- Hit the screen *before* the "which way" decision

→ When "which way" info is known, there is no interference pattern; when not known, there is (!)



Quantum Programming

How do we harness this behavior in a computer?

- Qubits
- Quantum gates
- Superposition
- Entanglement

Qubits

- Represent a value of zero or one, or a “superposition” of both zero and one
- Manipulated via quantum gates
- Today's best commercially available quantum computers contain a few dozen qubits
  - D-Wave box at USC has 1098 qubits

Key features of qubits

- Orientation that can be measured
- Capable of being in multiple states at once (superposition)
- Behaves like a particle (predictable path)
- Behaves like a wave (interference)
- One quantum can be “entangled” with another

Examples of qubits

- Photon of light
  - Measure: polarization of light
- Electron (trapped in a “quantum dot”)
  - Measure: electron spin
- Positron
  - Measure: positron spin
- Ion
  - Measure: energy levels

Superposition

- In superposition, a qubit represents both zero and one at the same time
- Probability of measuring zero or one
- Hadamard gate
- Measuring the qubit's value destroys superposition

Use superposition to try 0 and 1 at the same time.

Entanglement

- Entangled qubits measure either the **same** value or **opposite** values, depending on how they are entangled
- Hadamard gate + Controlled NOT (CNOT) gate
- Measuring one qubit guarantees the outcome of the other qubit

Use entanglement to relate values across qubits.

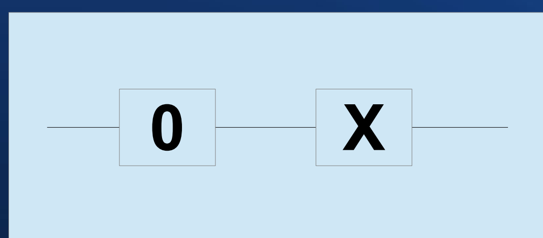
Quantum Gates

- X (like a NOT)
- Swap
- Hadamard (superposition, one qubit)
- CNOT (controlled NOT)
- Toffoli

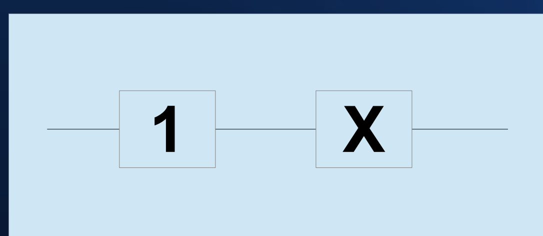
All quantum gates are their own inverses.

X Gate

Inverts the state of a qubit



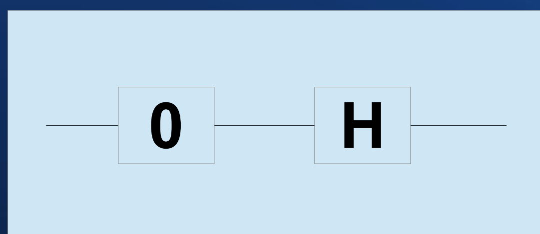
Result is 1



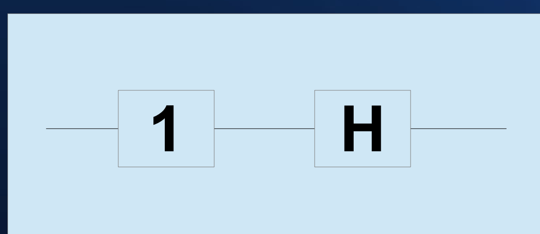
Result is 0

Hadamard (H) Gate

Places a qubit in superposition



50% chance to return 1 or 0



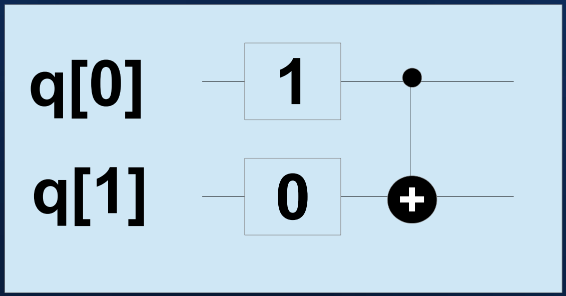
50% chance to return 1 or 0

These are the quantum equivalent of “Hello World”.

CNOT Gate

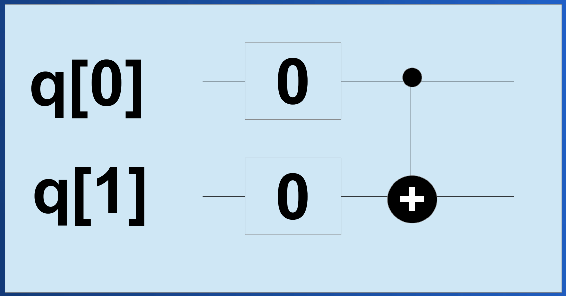
Given 2 qubits, flip the state of the 2^{nd} if the first is 1 (no change otherwise)

Use together with H to entangle qubits



Result is 1

Result is 1

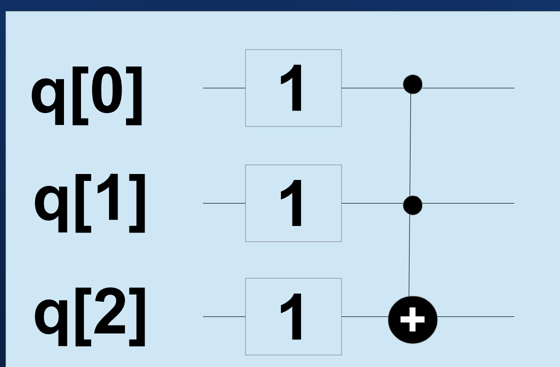


Result is 0

Result is 0

Toffoli Gate

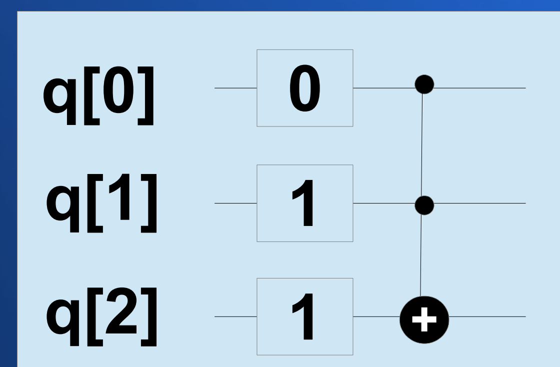
Given 3 qubits, flip the state of the 3rd if the first 2 are 1 (no change otherwise)



Result is 1

Result is 1

Result is 0



Result is 0

Result is 1

Result is 1

Grover's Algorithm

Given an unindexed collection of data, find one specific item among N elements

Assume the data is not indexed or sorted

- Conventional computer: O(N)
- Quantum computer: O(sqrt(N))

Grover's algorithm has been proven optimal

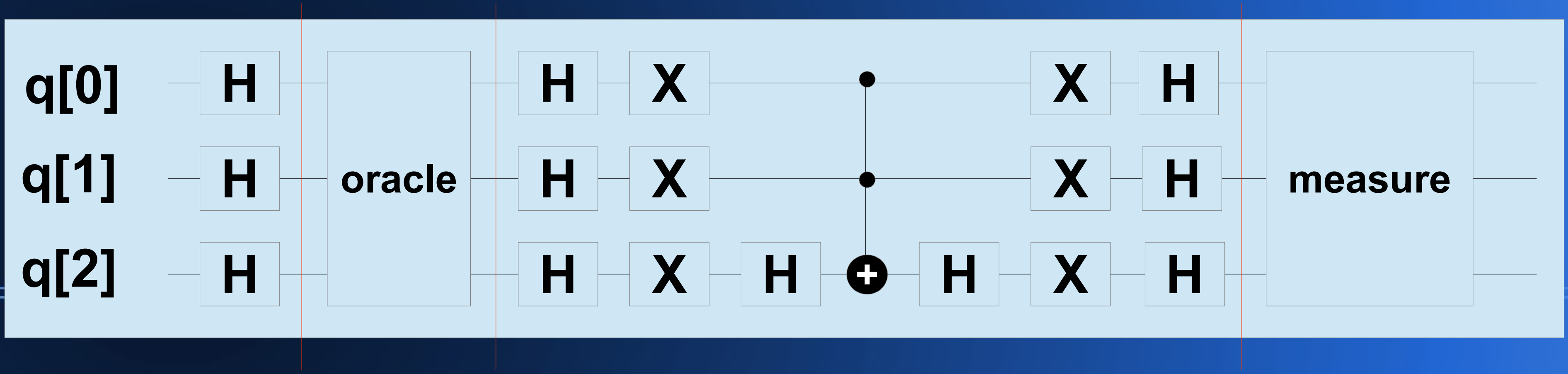
Grover's Algorithm

Requirements

- $\log_2 N$ qubits (e.g. $N = 1{,}000{,}000 \rightarrow k = 20$)
- An “oracle” function
  - Returns 1 for the element we want
  - Returns 0 for everything else
  - “Black box” - no need to know how it works

Grover's Algorithm

1. Place all qubits in superposition (H gates)
2. Run the oracle function on all qubits
3. Use a diffusion operator to increase amplitude of the correct input, decrease the others
4. Measure all qubits



Grover's Algorithm

Result is likely to be correct, but not guaranteed

- Repeat oracle + diffusion
  - Pi * sqrt(N) / 4 = optimal number of iterations
- Or call the oracle function again to verify the result

Shor's Algorithm

- Given a number N, find a nontrivial factor (not 1 or N)
- Uses patterns in modulo arithmetic to make pretty good guesses at the factors

Shor's Algorithm

Consider the sequence:

$x \bmod N$, $x^2 \bmod N$, $x^3 \bmod N$, etc.

Powers of 2	2	4	8	16	32	64	128	256	512
Mod 15	2	4	8	1	2	4	8	1	2

Powers of 2	2	4	8	16	32	64	128	256	512
Mod 21	2	4	8	16	11	1	2	4	8

Euler showed that the period evenly divides $(p - 1)(q - 1)$, as long as x is not divisible by p or q.

Shor's Algorithm

Inverse Quantum Fourier Transform (QFT)

- Transforms a periodic sequence into its period
- Uses interference to amplify the correct answer
- After transformation, measurement indicates the period

Shor's Algorithm

- Does it break encryption?
  - Requires 4 (log N) + 2 qubits to factor N
  - e.g. 44,743 < 65,536 = 2^{16} requires 66 qubits
  - Commercially available: approx. 55 qubits
  - Most powerful: 1098 qubits, or N up to 2^{274}

Common Problems

Algorithms are probabilistic

- They reach the correct solution... usually
- Run the program multiple times, or confirm the result another way if possible

Common Problems

Decoherence

- On real quantum hardware, qubit states can degrade during program execution
- Use redundant entangled qubits
- Run the program multiple times, or confirm the result another way if possible

Simulator

- Like a conventional debugger
- Can run backwards
  - Quantum operations are reversible
- Decoherence is never an issue
- Cannot check the state of entangled qubits

IBM Quantum Computer

- Quantum computer in the cloud
- Free access with IBM account
- Limited qubits per day (15) per user
- Simulator use is unlimited
- Program will run 1024 times

Comparison

Conventional Computer	Quantum Computer
GB of memory	< 1100 qubits
Bit represents 0 or 1	Qubit represents 0, 1, or superposition
Deterministic output	Chance of an incorrect result
Programs run in one direction	Programs can run forward or backward
“Normal” speed	Faster for some classes of problems
Designed for office conditions	May require extreme cold, shielding, etc.
Usual learning curve for new languages	Steep learning curve

Other Quantum Computing Terms

Quantum Teleportation

- Uses two entangled qubits and two bits to transfer an input qubit state to another location
- Teleports quantum states, not matter
- Requires a way to send the two bits to the target
- Record distance: 89 miles
- Largest to date: Quantum state of an atom

Other Quantum Computing Terms

Quantum Supremacy

- Ability of a quantum computer to do something a conventional computer cannot
- Google article in Nature (Oct 2019): 200 sec vs. 100 million years to check numbers for randomness

Questions?

?

Further Reading

- The Quantum Zoo by Marcus Chown (2006)
- The Amazing Story of Quantum Mechanics by James Kakalios (2010)
- Natural Computing by Dennis Shasha and Cathy Lazere (2010)
- Through Two Doors at Once by Anil Ananthaswamy (2018)
- Quantum Computing for Babies by Chris Ferrie (2018)

On The Web

- http://www.quantum-inspire.com
- http://www.quantumplayground.net/#/home
- https://quantum-computing.ibm.com/login
- YouTube: PBS Quantum Mechanics
- https://ai.googleblog.com/2019/10/quantum-supremacy-using-programmable.html
- https://www.nature.com/articles/nature11472

On The Web

- http://www.alienryderflex.com/polarizer/

Thank You!