# Introduction to Quantum Computing

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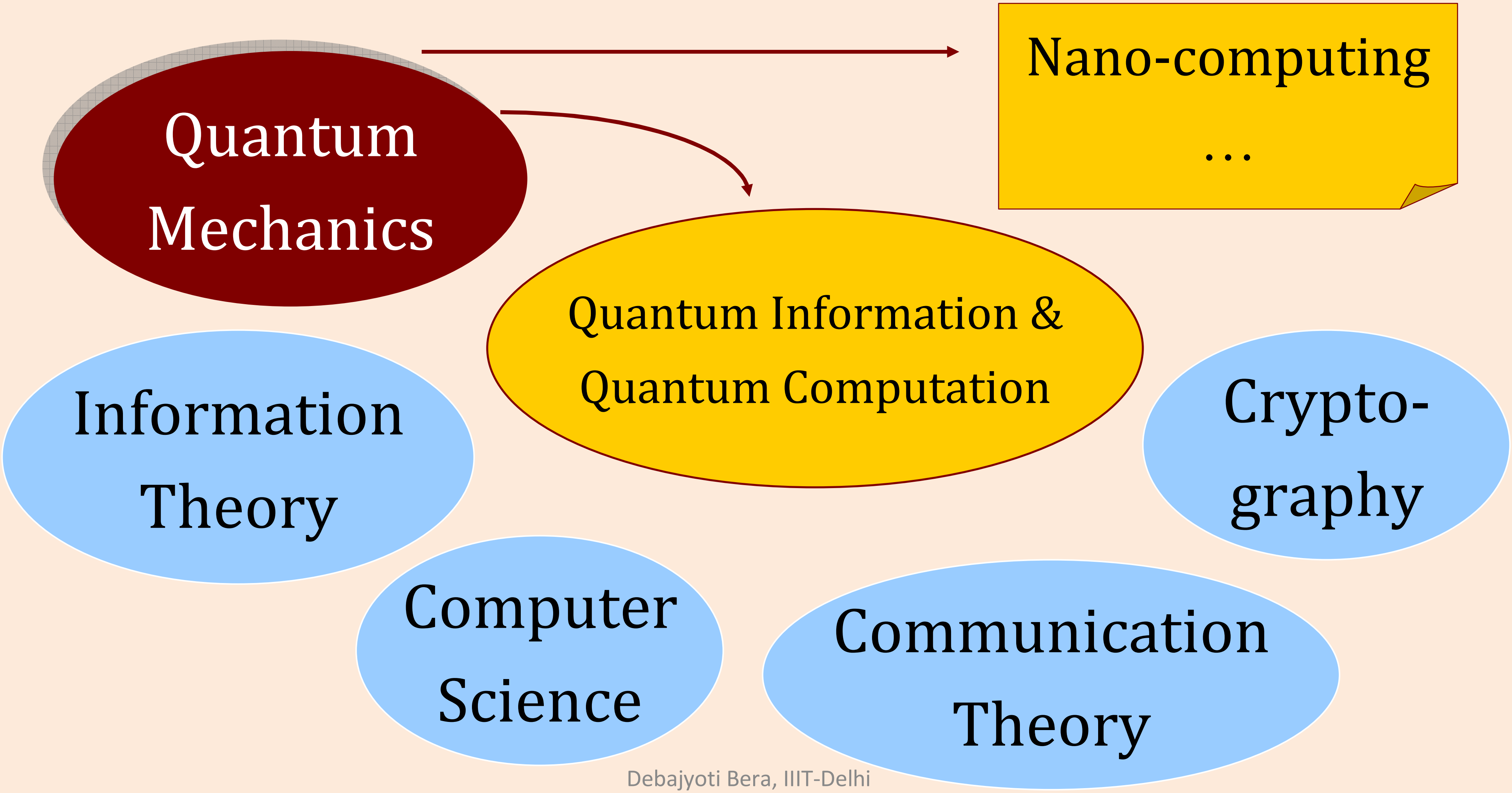
# Quantum Computing Community



Quantum Mechanics

Nano-computing

…

Quantum Information & Quantum Computation

Information Theory

Crypto-graphy

Computer Science

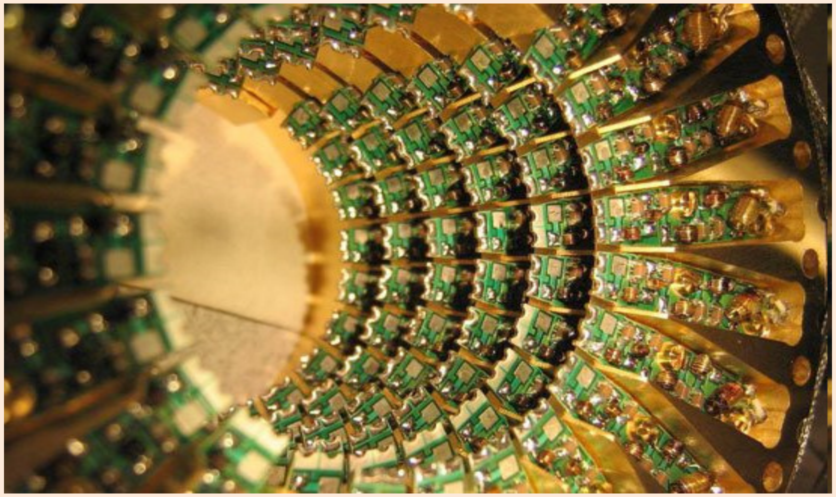
Communication Theory

# Quantum Computing for Computer Science

1. Studying different models of quantum computing
2. Design and analyse algorithms to efficiently solve problems using these models

# What is Quantum Computation

<u>Computation</u> in which the <u>operands</u> and <u>operators</u> follow the laws of <u>quantum mechanics</u>

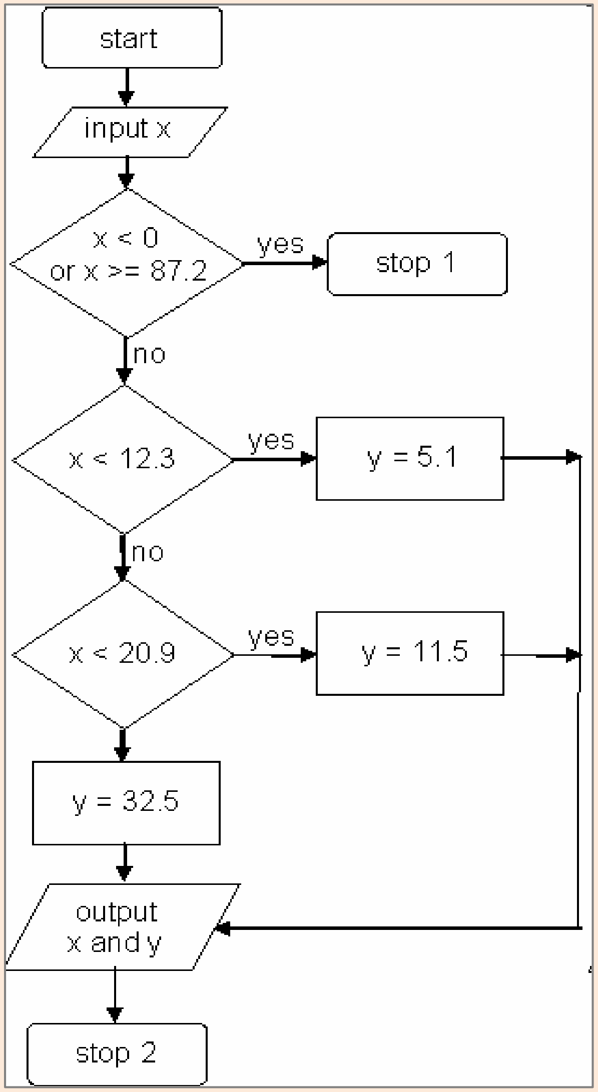


Images – (left) ©IBM, (right) © D-Wave Systems, Inc.

# Overview

1. Computation
2. Quantum Mechanics
3. Quantum Computing
4. Progress & Challenge

# What is Computation?



A <u>sequence</u> of steps,

Performed by a system

Which, given an <u>input,</u>

Produces <u>output</u>

Where, each step involves

<u>Operation</u> on values

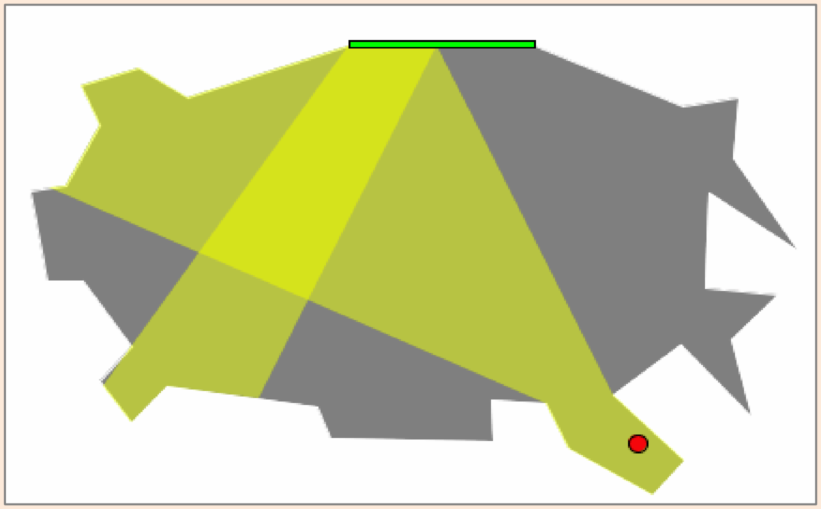
# Classical Computation

Calculation of compound interest on Rs 877/- for 4 years at the rate of 7% p.a.

(without using formula)

1. Compute interest after 1 year
2. Add interest to principle
3. This is the new principle
4. Compute interest after 2 years ...

# Classical Computing: Examples

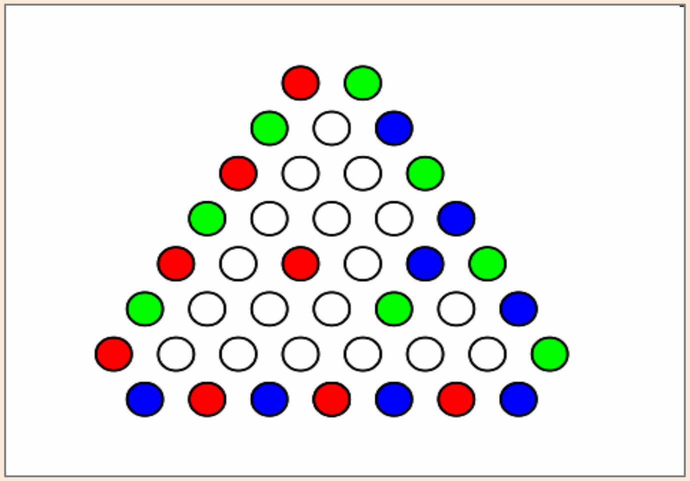


Winning a game of chess

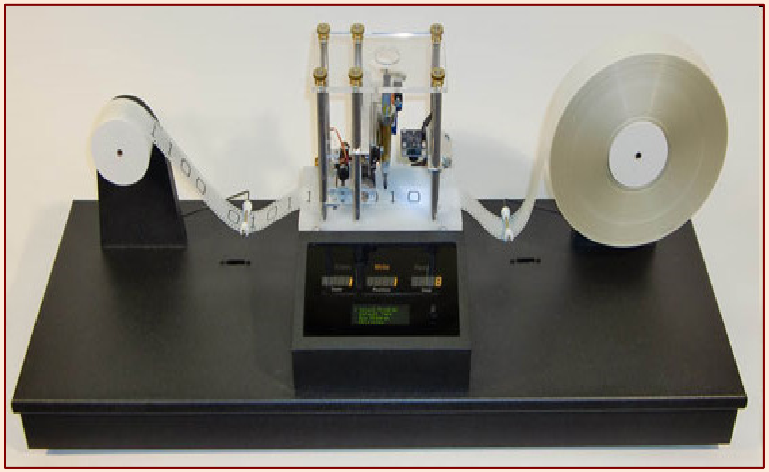
Cheapest flight to Delhi

Finding way to home

Placement of cameras



# Analysis of Computation



Models of Computation

- Boolean Circuit
- Turing Machine
- Cellular Automata
- Genetic Algorithm, Neural Network, …

Metrics for Analysis

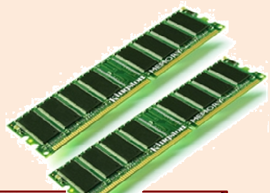
- Time to perform operations
- Space to store operands, …

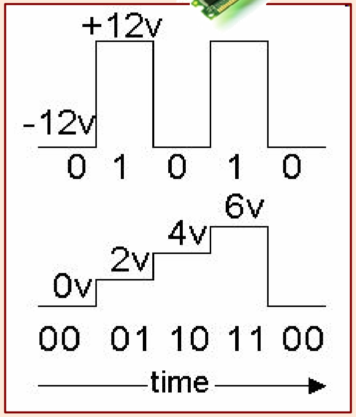
# Operations & Operands

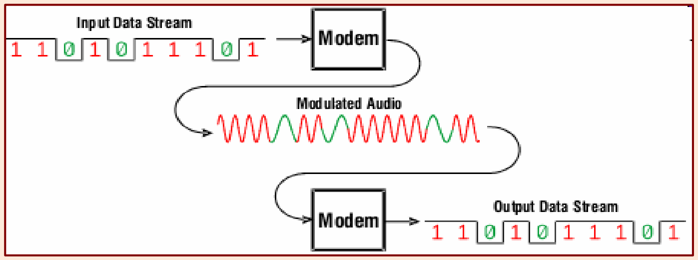
Operations
on
Operands

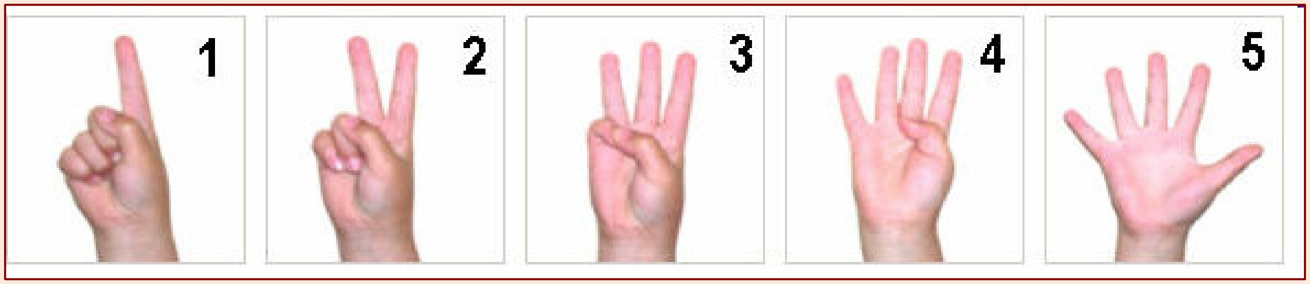
=

Change of state
of
“Some Thing”









# Operations & Operands

Operations

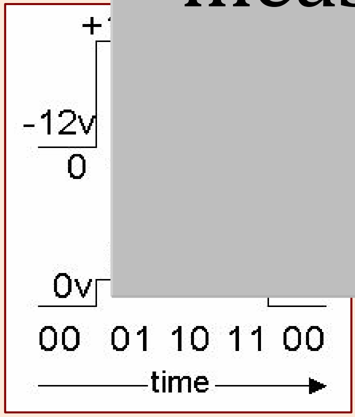
C

Change of state

f

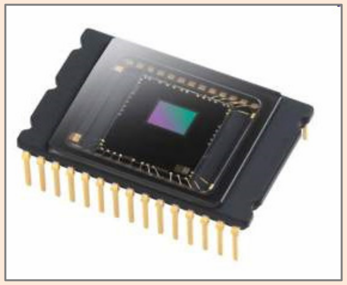
Data/Value

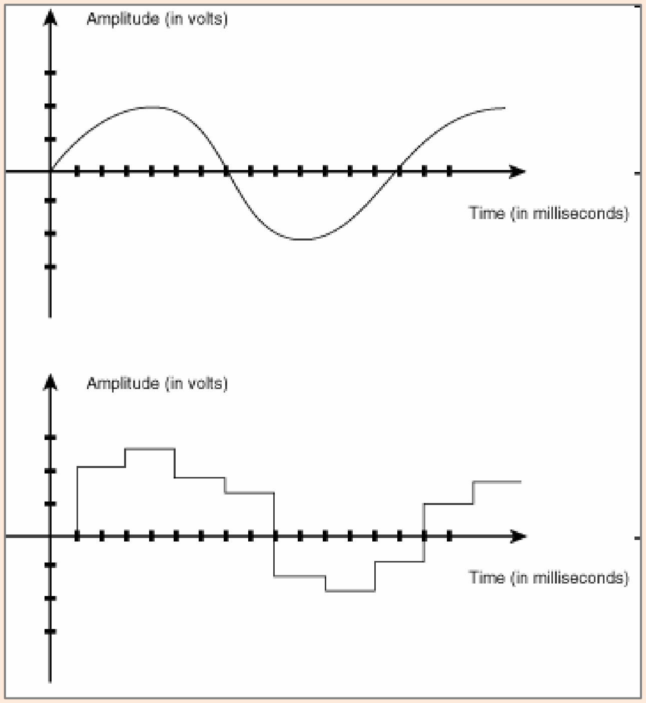
measurable property observable using <u>macroscopic</u> methods

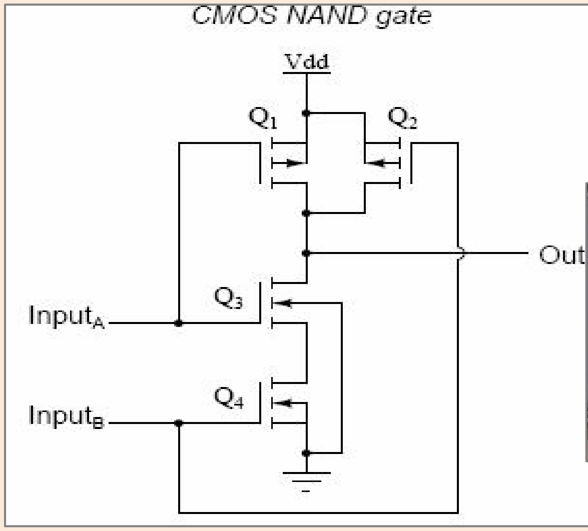


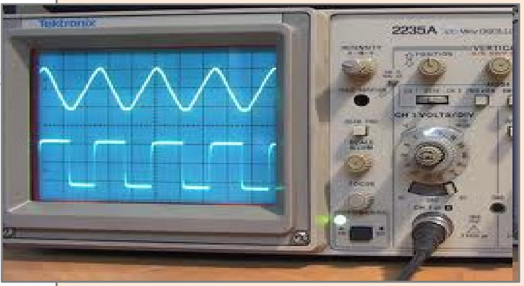
# Classical “bits” and operations

- Bit – digital signal – 0 or 1
- Operations – Boolean functions







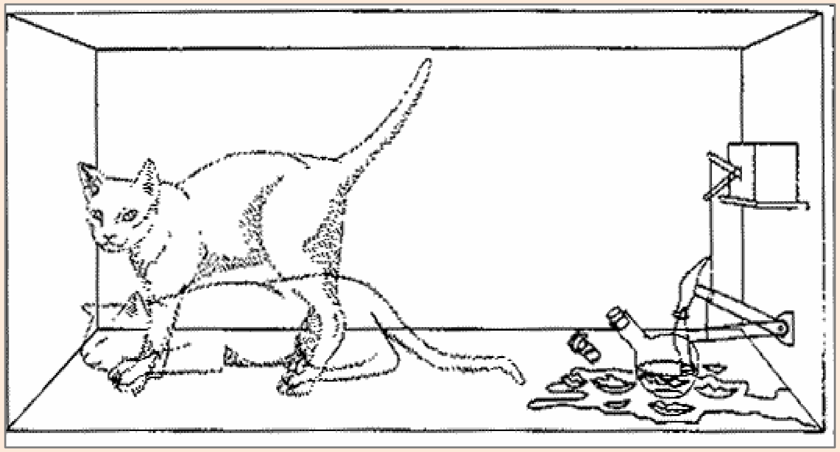


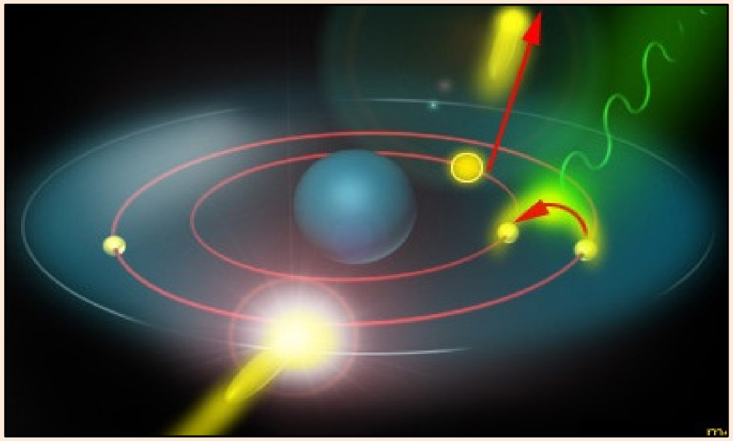
Digital circuits & logic gates

Macroscopic CMOS transistors

# Quantum Mechanics

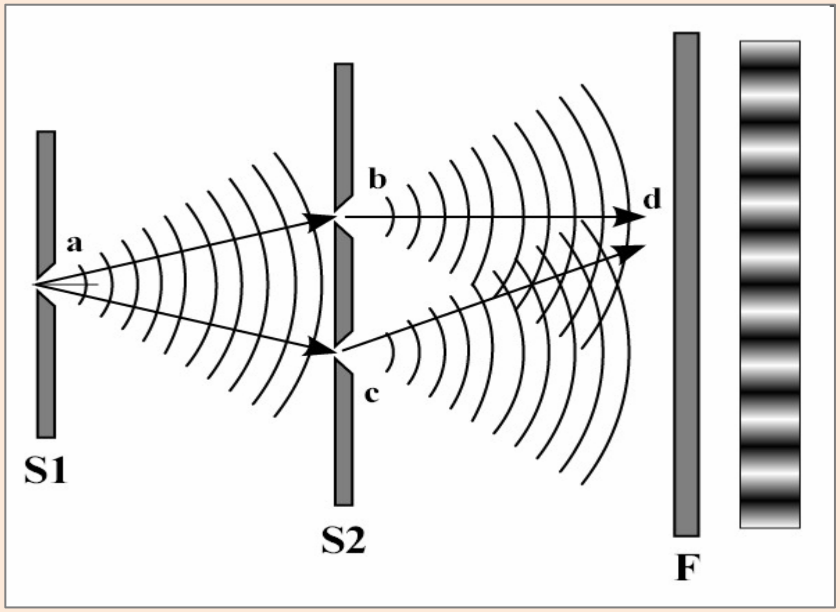
A proposed theory of nature (reality) that seems to be able to explain many facts about <u>small particles</u> which couldn't be (easily) explained using other theories.



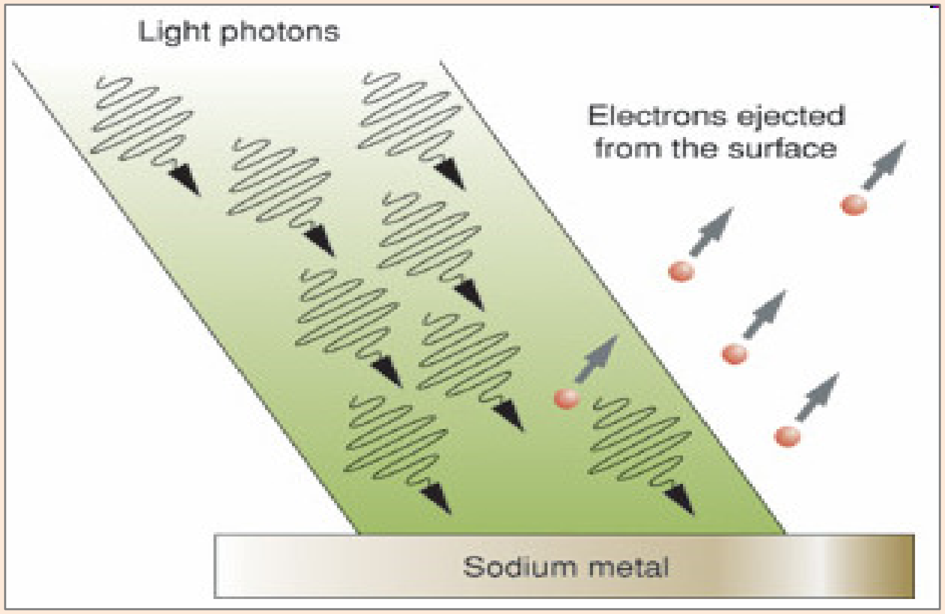


# Reality of LIGHT?

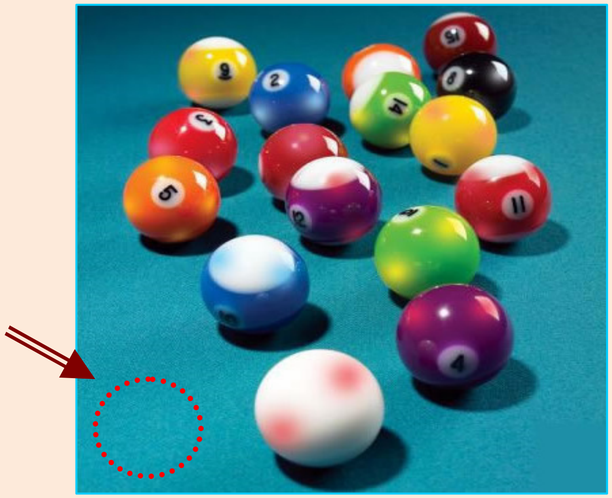
1803 – light behaves like a wave
(Double slit expt.)



1905 – light is made of photons
(Photoelectric effect)



# Particle -vs- Wave

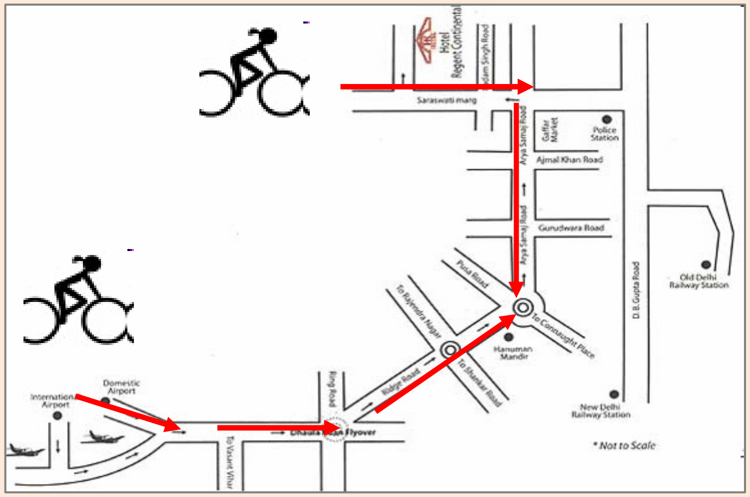


P
A
R
T
I
C
L
E

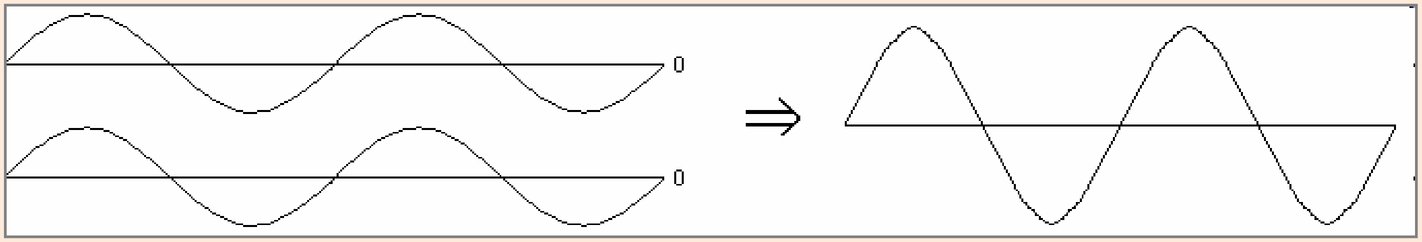
W
A
V
E

# Particle -vs- Wave

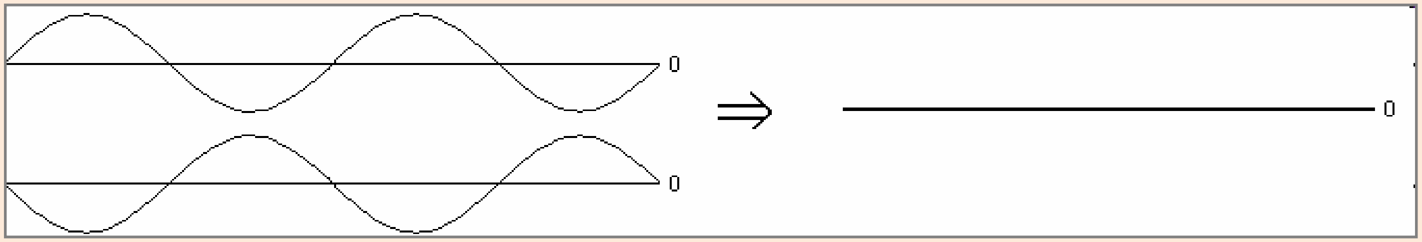
PARTICLE



W
A
V
E

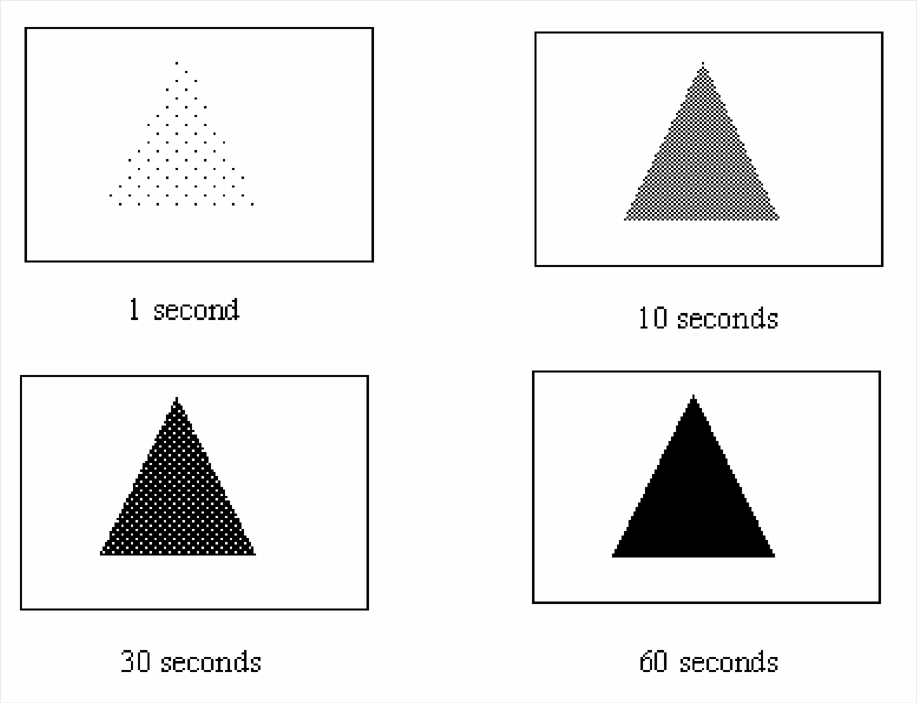


constructive interference

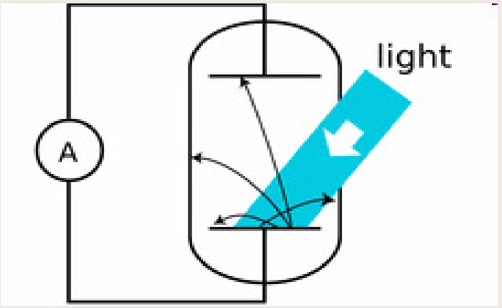


destructive interference

# Light as Particle



Expose photographic plate to a short burst of light



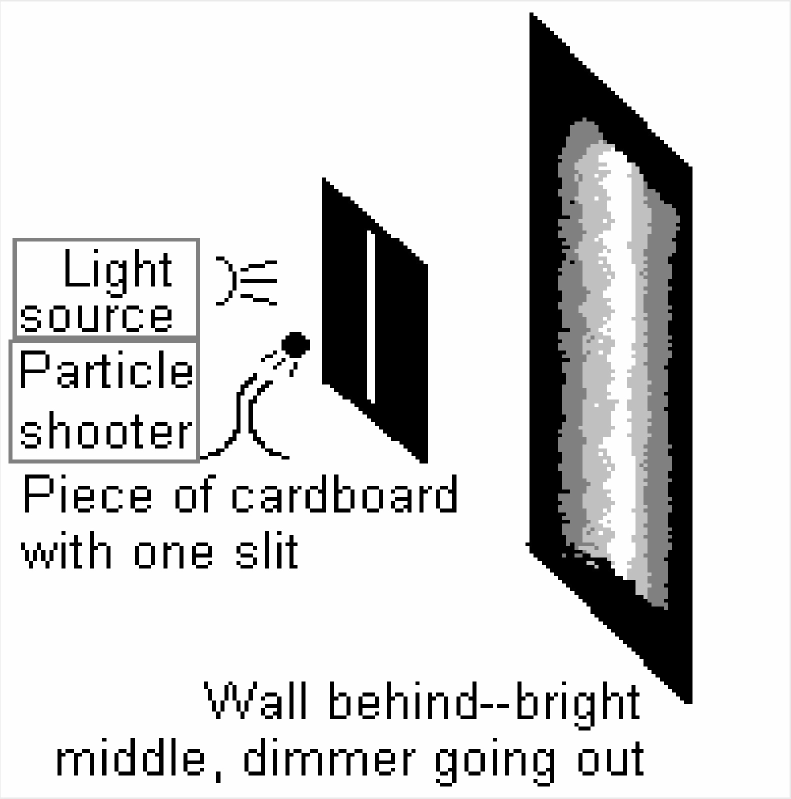
Photoelectric effect

A beam of light strikes a capacitor plate inside a vacuum tube, and electrons are ejected.

Corpuscular Model of Light – Isaac Newton

Taken from http://www.lightandmatter.com/html_books/lm/ch34/ch34.html
http://www.antonine-education.co.uk/physics_as/module_1/topic_3/topic_3_particle_model_of_light.htm

# Young's Double Slit Expt.

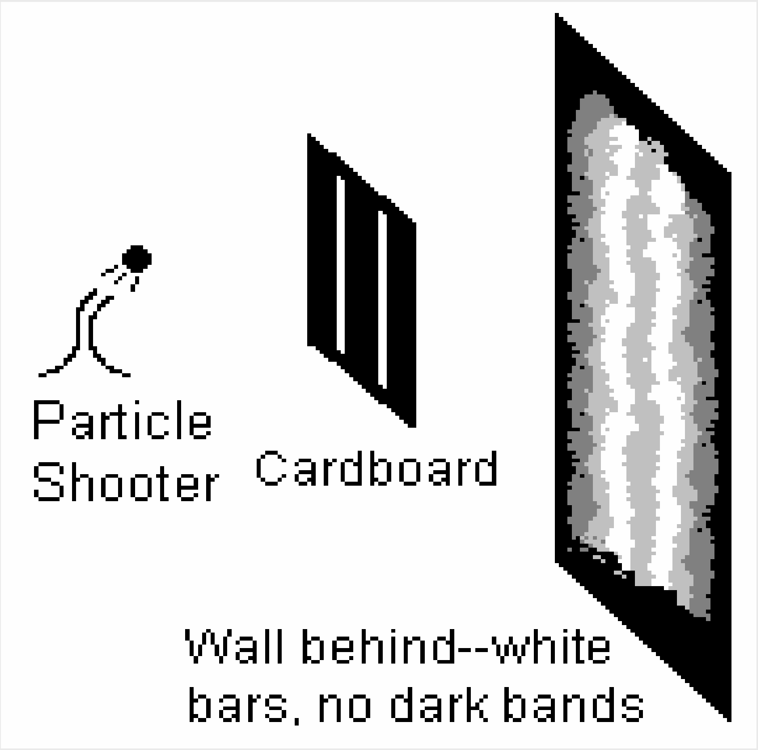


Single slit with light

Single slit with particles

- Bright band behind the slit
- Band fades towards outside

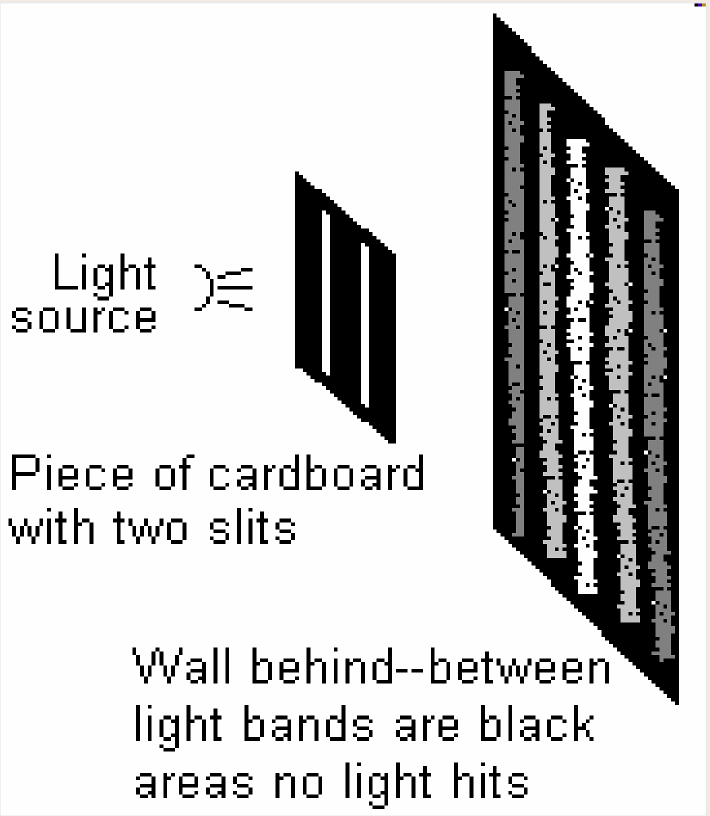
# Young's Double Slit Expt.



Double slit with particles

- Two bright bands behind the slits …
- Bands fade towards outside

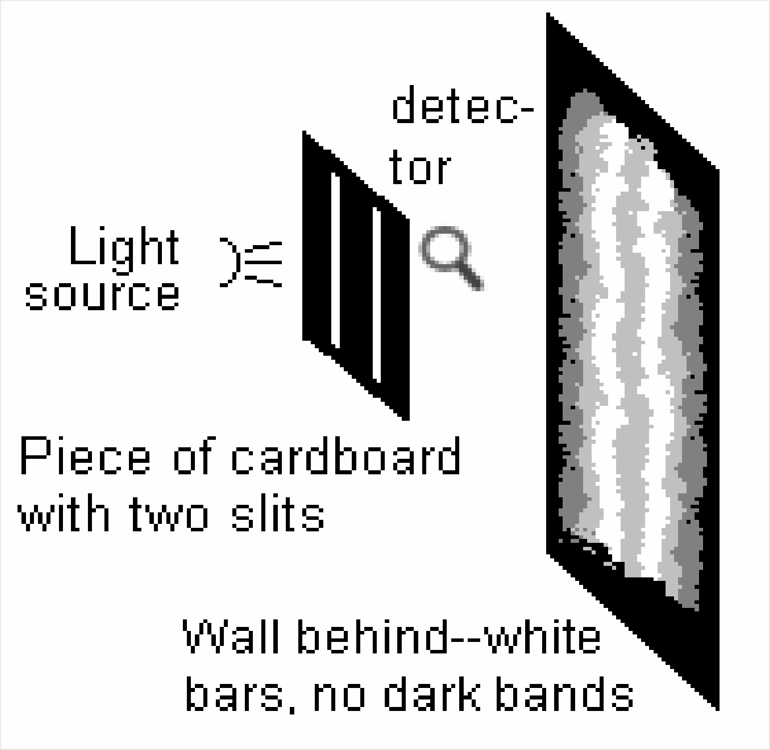
# Young's Double Slit Expt.



Double slit with light

- Two bright bands behind the slits …
- Alternate bright and dark bands towards outside

# Young's Double Slit Expt.



Double slit with light +

Photon-detector at one slit

- Two bright bands behind the slits …
- Alternate bright and dark bands towards outside

<u>Just like particle!</u>

# Quantum Mechanical properties of Light, Electron, …

- Both <u>Particle</u> & <u>Wave</u>
- Behaves like a particle whose "presence" follows a wave pattern (wavefunction)
  - Simultaneously present at all places
  - … unless observed …
  - During observation, found at <u>any one place</u> with "some possibility" decided by the wavefunction

$$\boxed{|\Psi\rangle}$$

- Interference & other properties of waves…

# Quantum Computing Basics

Many properties follow <u>wavefunction</u>:

- simultaneously all possible values
- “collapses” to one value during observation

# Quantum Computing

Assuming ...

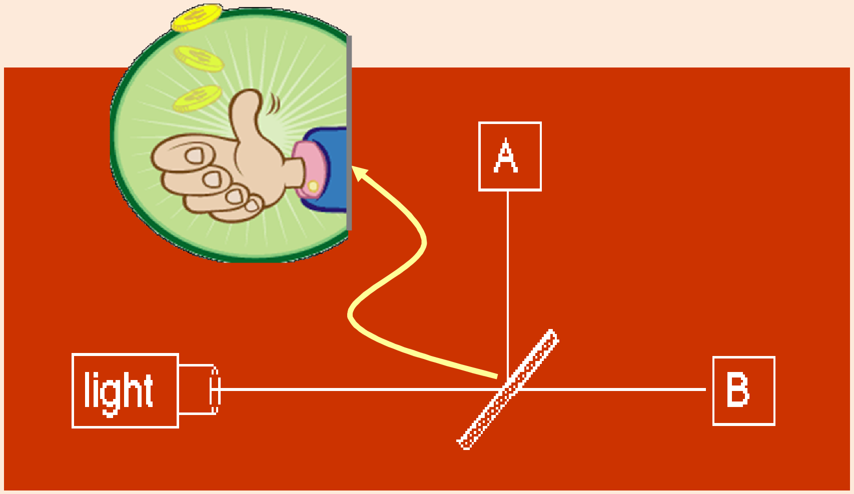
Machines which follow principles of quantum mechanics…

... Can we compute more effectively?

- Less time
- More space
- Fewer error

Quantum is <u>better than</u> Classical

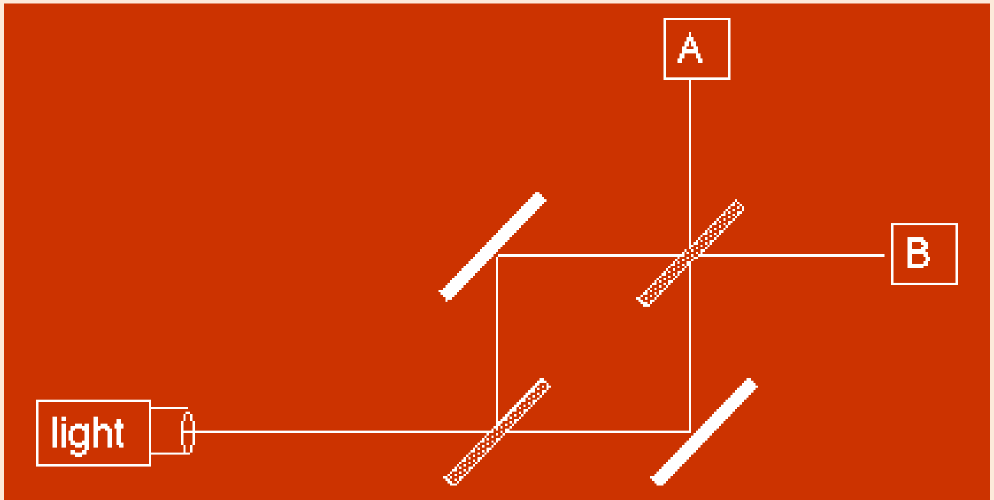
# Using Photons for Data



1. 50% photons leaving the light source arrive at detector A
2. Rest 50% arrive at B

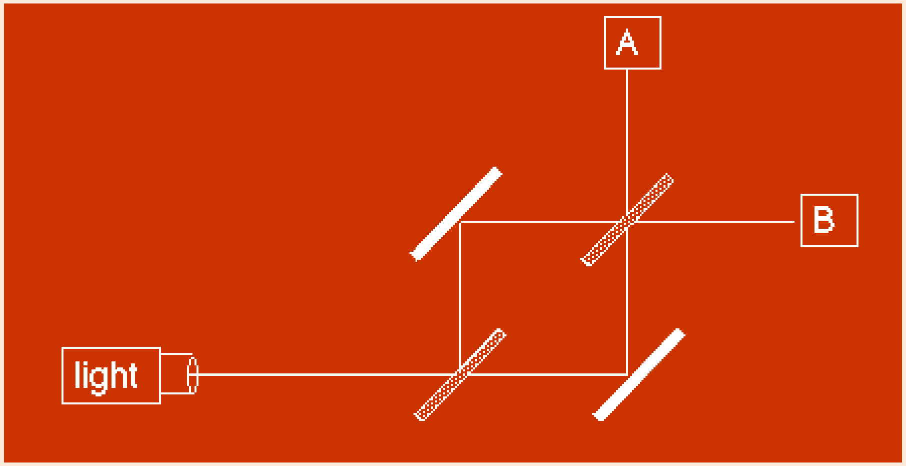
<ins>All photons</ins> leaving the source arrive at A !!!

Expt. setup: Equal path lengths, rigid mirrors, only one photon in the apparatus at a time.



Pictures taken from "Quantum Logic" presentation by Marek Perkowski

# Quantum Bits – "qubits"



Combined State/
Wavefunction

Individual
States / Possibilities

$$|\Psi\rangle = \alpha_1|S_1\rangle + \alpha_2|S_2\rangle + \alpha_3|S_3\rangle + \cdots$$

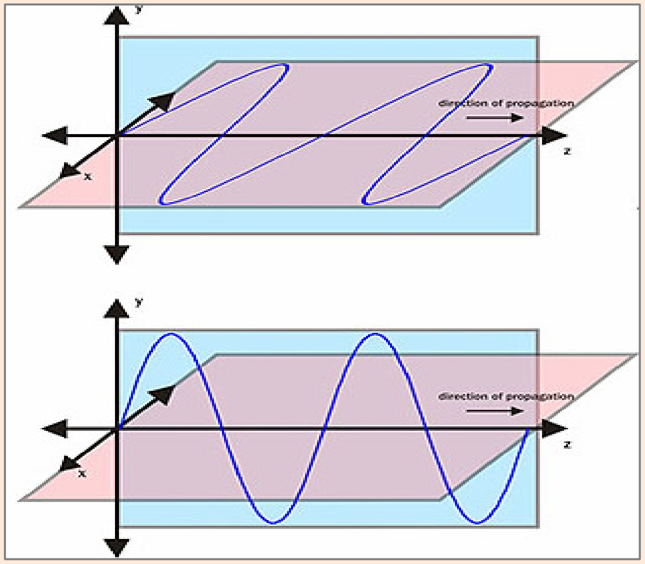
Amplitude (value of possibility)
— can be –ve (interference)

# Qubits

- Infrared Photon – polarisation (.1msec)
- Trapped Ion – energy levels (15sec)
- Trapped Atom – energy levels (3sec)
- Nuclear Spins – spin orientation (2-25sec)

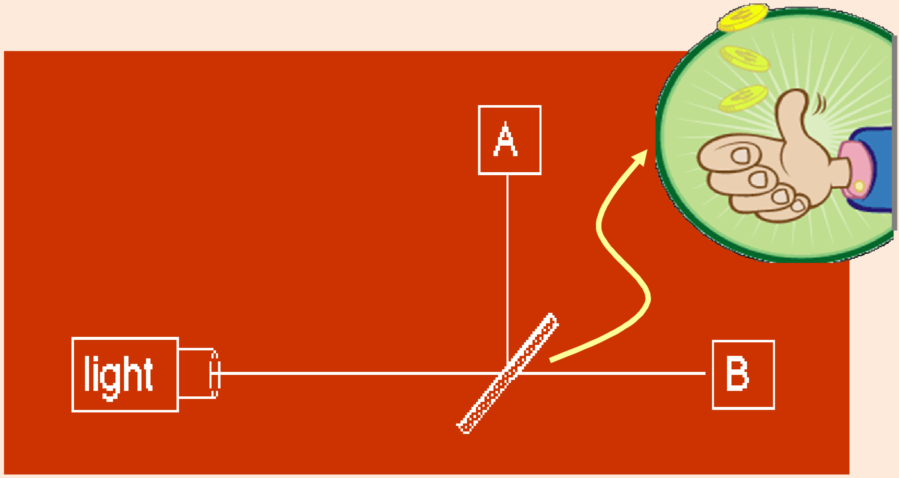
Mathematically…

A state with k possibilities is a unit-vector in $\mathbb{C}^k$



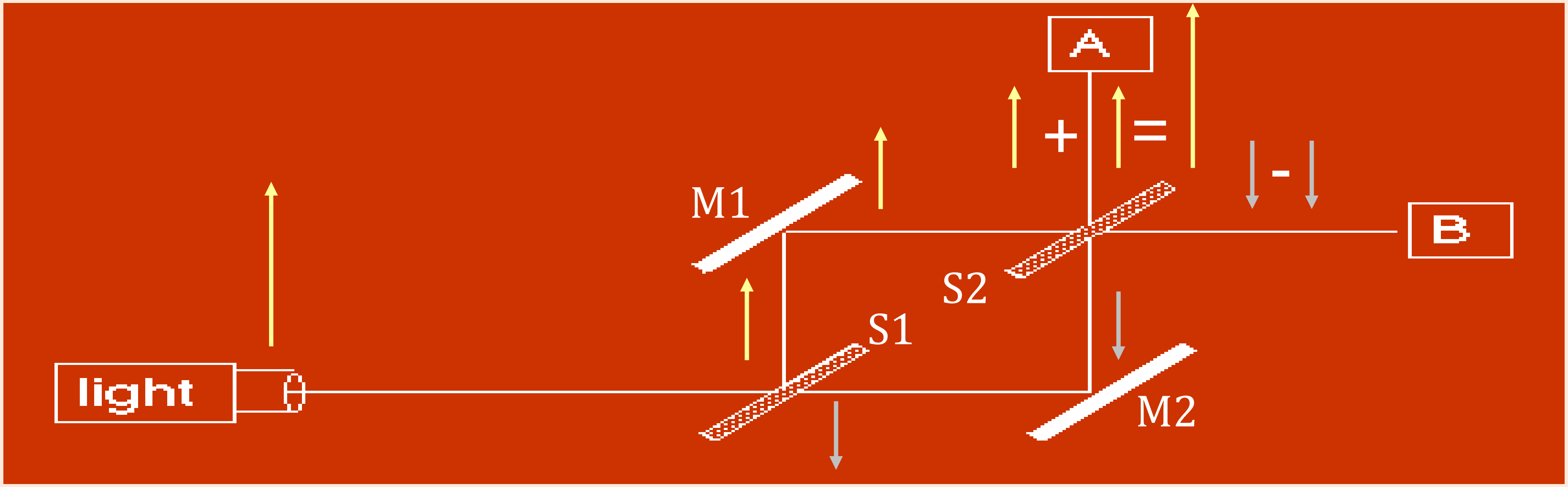
Taken from http://universe-review.ca/R13-11-QuantumComputing.htm

# Operations on Photons



$$
|\uparrow\rangle \rightarrow \frac{1}{\sqrt{2}}|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle
$$

$$
|\downarrow\rangle \rightarrow \frac{1}{\sqrt{2}}|\uparrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\rangle
$$



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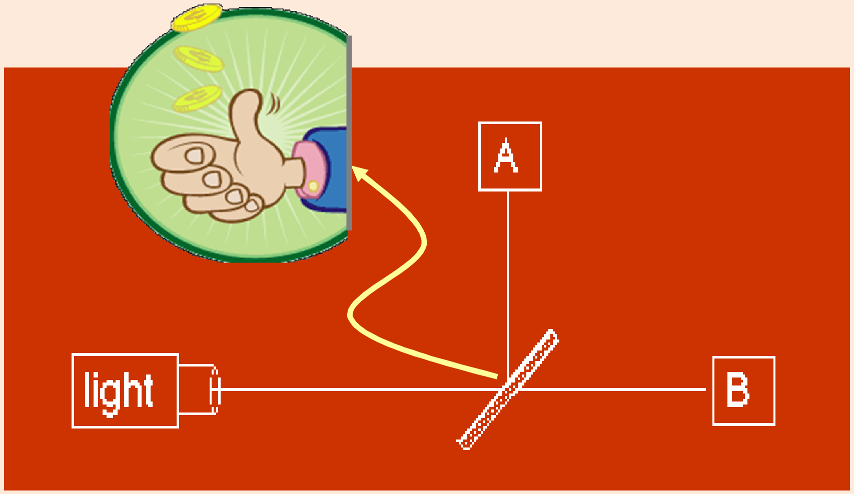
Pictures taken from “Quantum Logic” presentation by Marek Perkowski

# Quantum Operators



$$|\uparrow\rangle \rightarrow \frac{1}{\sqrt{2}}|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle$$

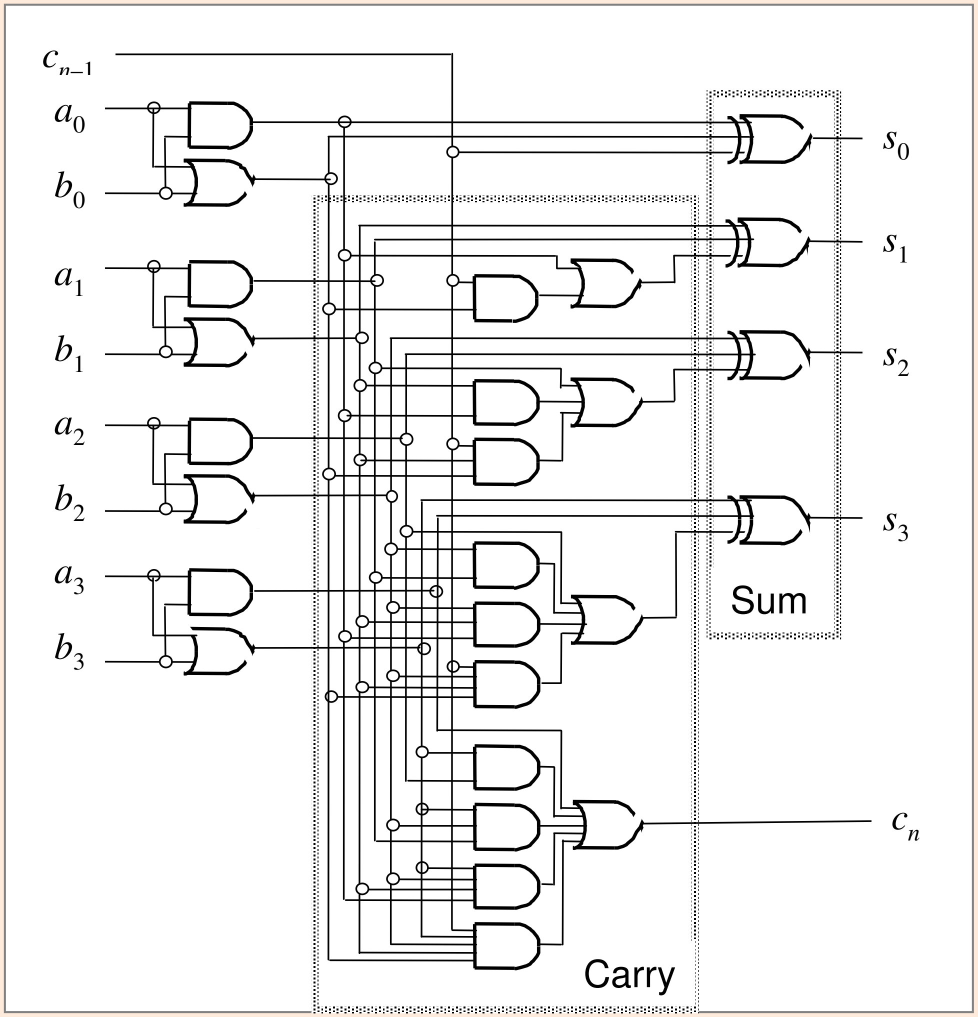
$$|\downarrow\rangle \rightarrow \frac{1}{\sqrt{2}}|\uparrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\rangle$$

Hadamard Operator

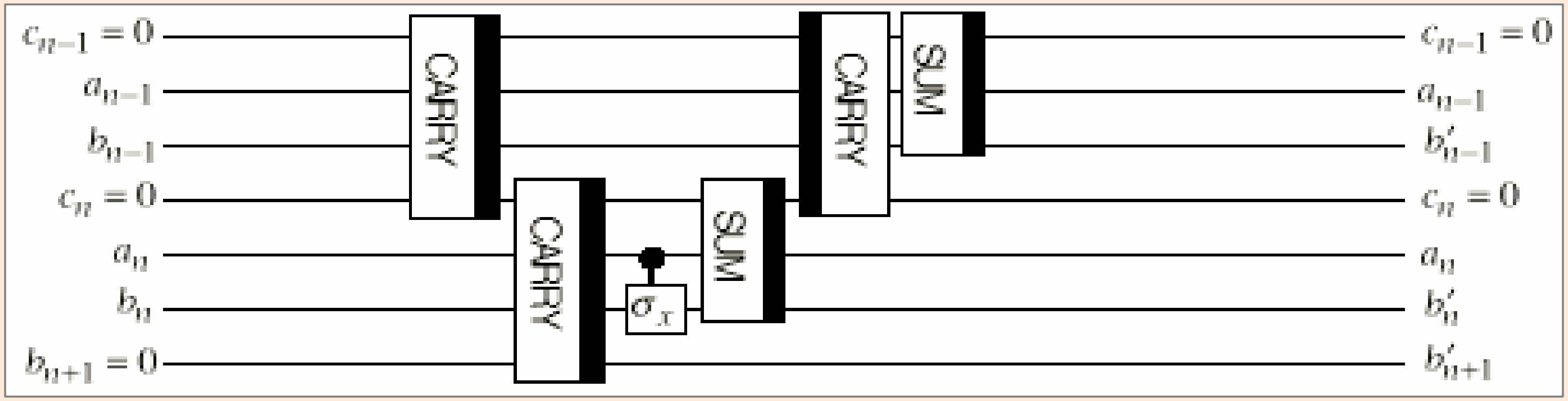
Unitary operators (length-preserving, over complex numbers)

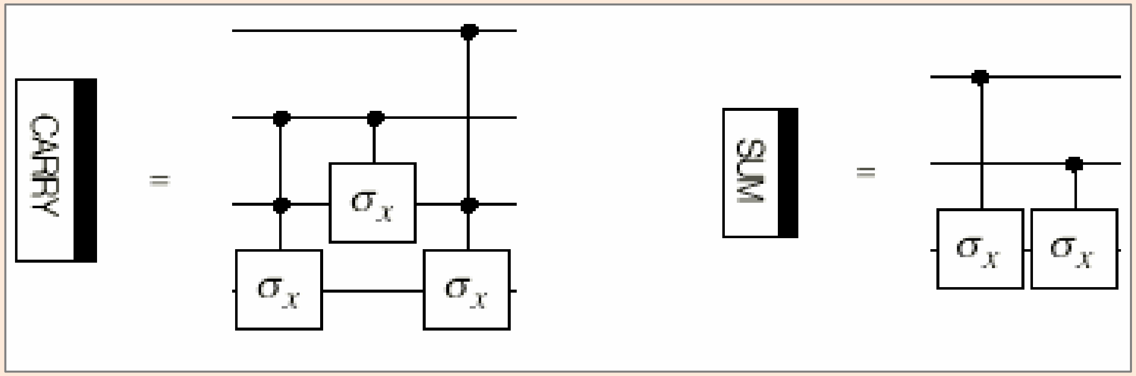
- NMR
- Optical Lattice
- Trapped Ion QC
- Cavity QED

# Classical Adder



# Quantum Adder





$\sigma_x$ :Pauli rotation

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

# Unlike Classical …

- ✓Superposition
- ✓Measurement
- ✓Interference
- ✓No copying
- ✓Entanglement (multi qubit)

<u>At the same time, both 0 & 1</u>

vs.

At the same time, either 0 OR 1

# Unlike Classical …

- ✓Superposition
- ✓Measurement
- ✓Interference
- ✓No copying
- ✓Entanglement (multi qubit)

Reality is independent of observation

VS

<u>Reality changes after observation</u>

# Unlike Classical …

- ✓Superposition
- ✓Measurement
- ✓Interference
- ✓No copying
- ✓Entanglement (multi qubit)

Multiple occurrence increases probability

vs.

Multiple occurrence may decrease probability

# Unlike Classical …

✓Superposition

✓Measurement

✓Interference

✓No copying

✓Entanglement (multi qubit)

<u>Cannot duplicate a state (qubit)</u>

vs.

Can create arbitrary copies of data

# Unlike Classical …

✓Superposition

✓Measurement

✓Interference

✓No copying

✓Entanglement (multi qubit)

Value affected by far-off operations

vs.

Value affected by only local operations

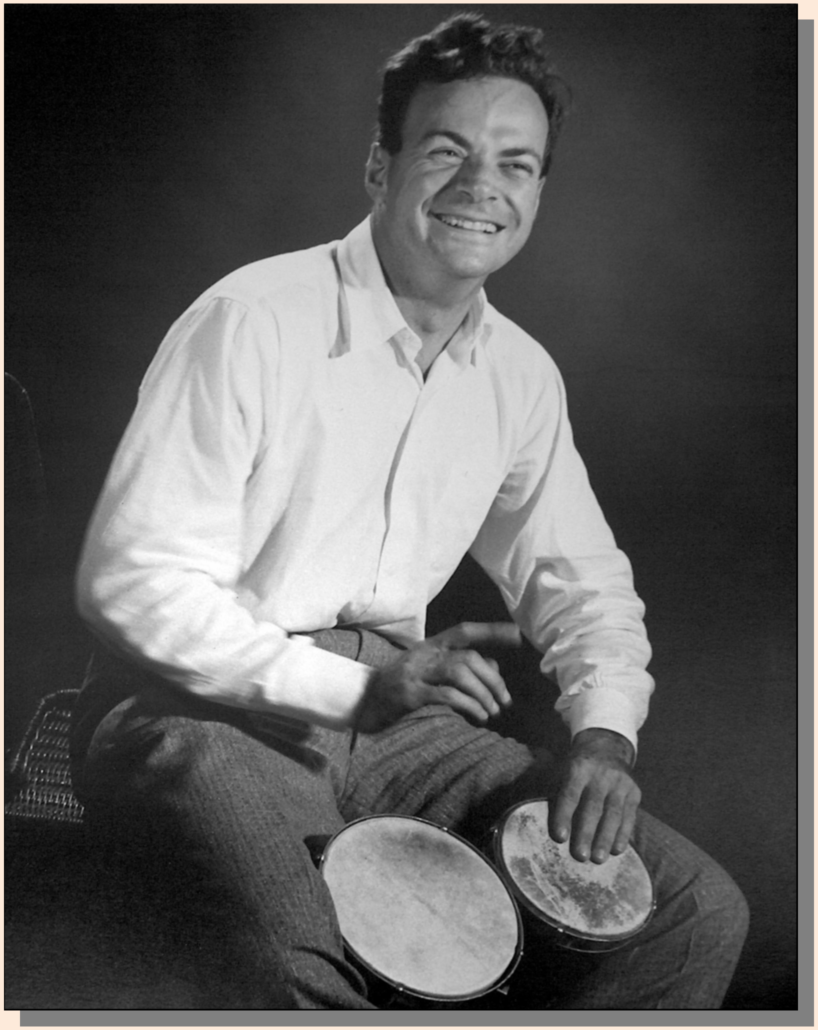
# Secret Recipe

- In quantum systems possibilities count, even if they never happen!
- Each of exponentially many possibilities can be used to perform a part of a computation at the same time.
- It may be possible to cancel out “bad” possibilities during computation.

# Pitfalls!

- Gates and circuits must be reversible (<u>lossless computation</u>)
- During measurement, all possible computations <u>except only one</u> are destroyed
- <u>Temporary copies</u> of intermediate results cannot be made
- <u>Interference with environment</u> completely changes computation (decoherence)

# Quantum Computing: 1982 …



## 1982

Simulating Physics with Computers

- *Richard Feynman*

“Nature isn't classical, dammit, and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.”

# **... 1985 ...**

<u>Church-Turing thesis</u> (1930-1950): Anything that can be computed (by a mechanical process) can be computed by a Turing machine.

<u>1985</u>

<u>Church-Turing-Deutsch thesis</u>: Anything that can be computed by a physical process can be computed by a universal computing device (Universal Quantum Turing Machine).

# … 1993 …

1985: Deutsch – (inefficient) universal quantum Turing machine

## 1993

- Bernstein-Vazirani / Yao – efficient universal quantum Turing machine
- Equivalence of quantum computing models: quantum Turing machine & quantum circuit

# … 1994 – 1996 …

1994 - Peter Shor came up with a quantum algorithm to factor very large numbers incredibly fast.

1997 - Lov Grover developed a quantum search algorithm which takes significantly lesser time to search unstructured database.

Both better than known classical algorithm!

# … 1998 – 2001 …

## Experimental demonstrations

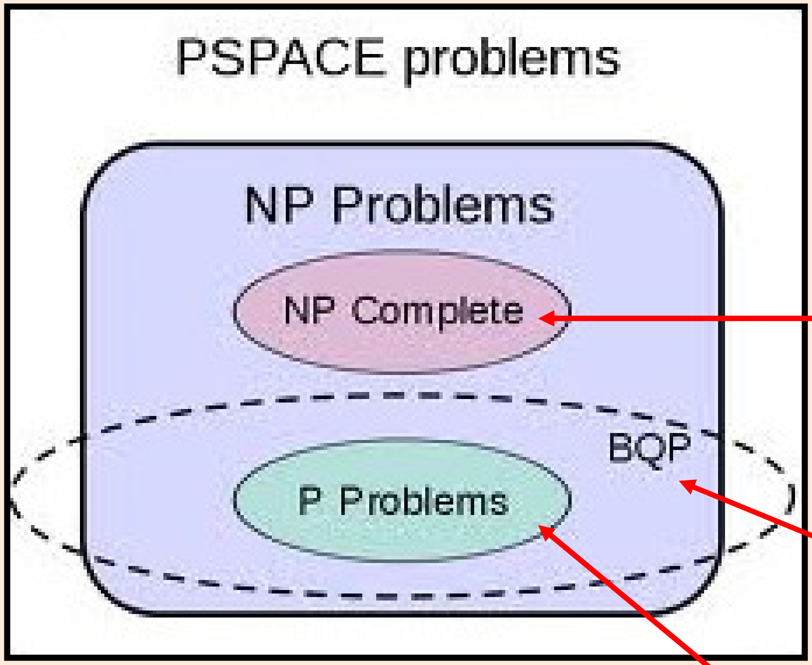
- 2-qubit NMR quantum computer to solve Deutsch's problem (Oxford University, IBM-Stanford-MIT)
- 3-qubit, 5-qubit, 7-qubit NMR computer
- Execution of Grover’s algorithm on an NMR computer
- Execution of Shor’s algorithm to factor 15

# **… 2001 – 2011 …**

## Theory of Quantum Computing

- ✓ Efficient quantum circuits
  - Smaller size, lesser time, fewer faults
- ✓ Efficient quantum algorithms
  - Lesser storage, lesser time, fewer error
- ✓ Efficient quantum communication protocols
  - Lesser communication
- ✓ Also! Problems for which quantum algorithm <u>provably</u> cannot do <u>significantly</u> better than classical algorithms

# Challenges (for Comp. Sc.)



Possibly hard for classical computers

Timetable scheduling for large school

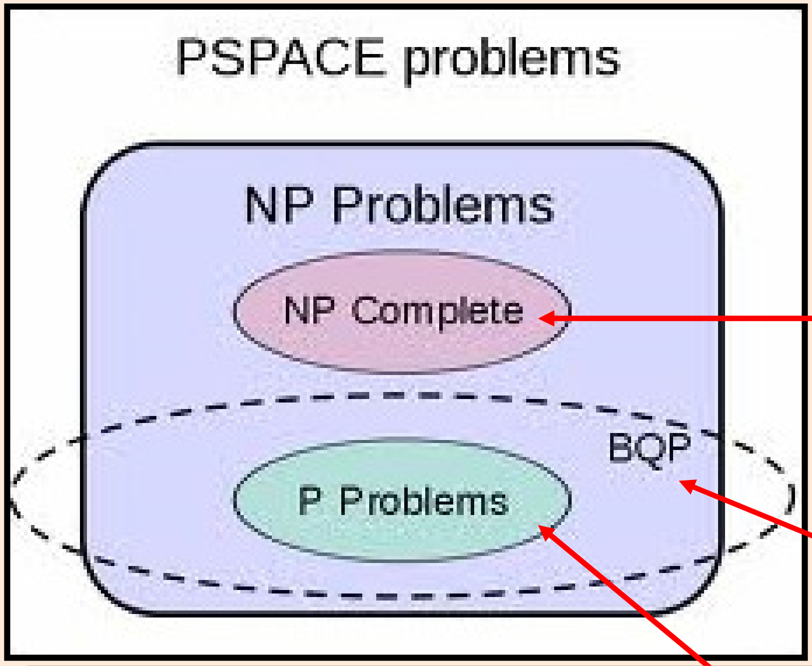
Easily solved by quantum computers

Factoring a very large number

Easily solved by classical computers

Testing if a number is prime

# Challenges (for Comp. Sc.)



Possibly hard for classical computers

Timetable scheduling for large school

Easily solved by quantum computers

Factoring a very large number

- Find efficient solutions for hard problems
- Understand which problems are still hard
- Make solutions robust to errors and failures