REGINNA 4.0

Introduction to Quantum Computing

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University of Nova Gorica

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EIT HEI Initiative
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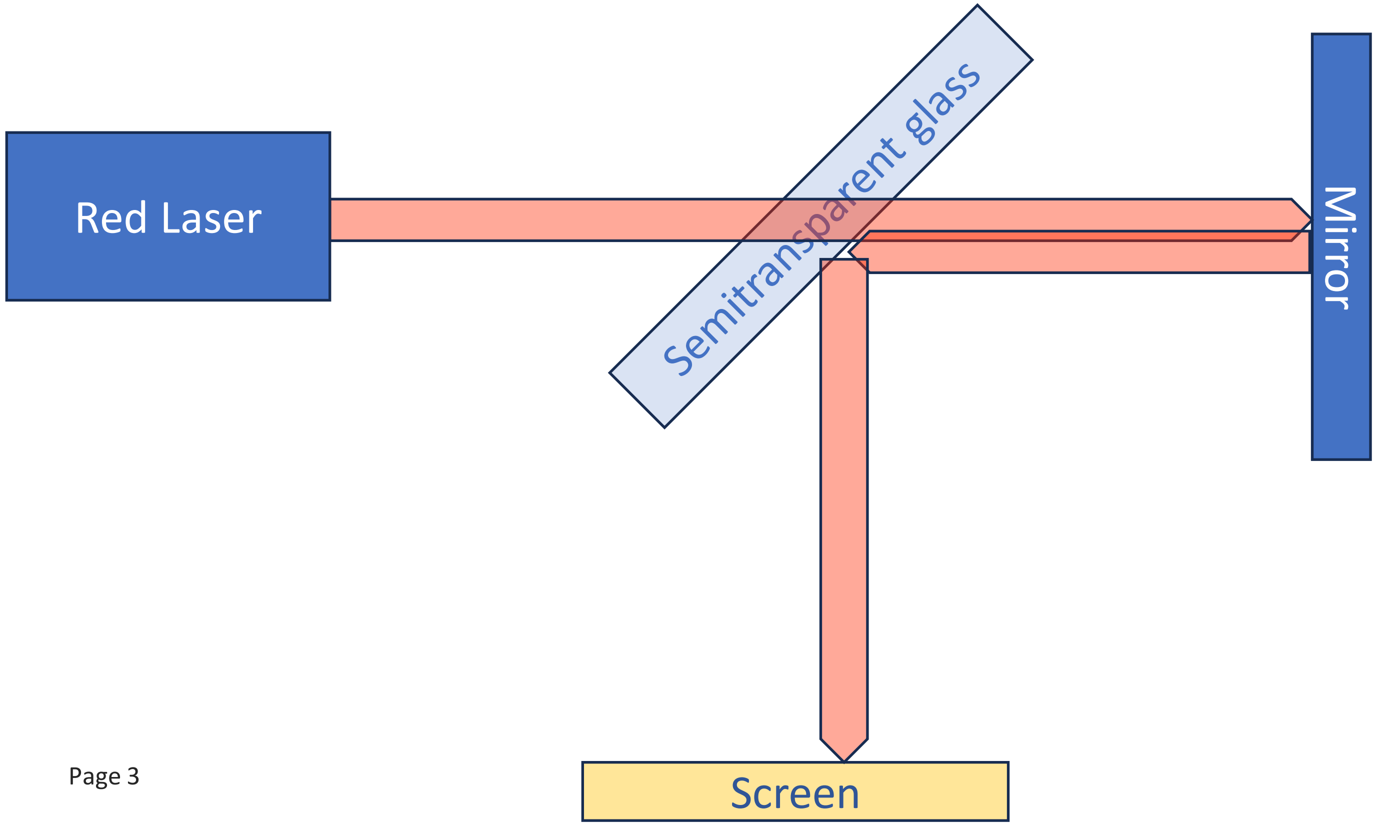
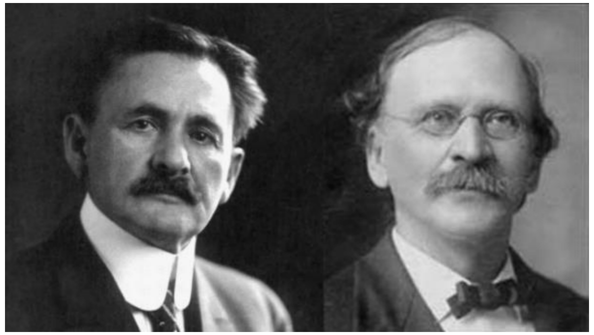
Outline

- Michelson-Morley experiment
- Two-slits experiement
- Classical computer
- Introduction to qubit
- Two beam—splitters‘ experiment
- Mathematical description of two beam-splitters‘ experiment
- Tutorial on quantum computer (Qiskit)

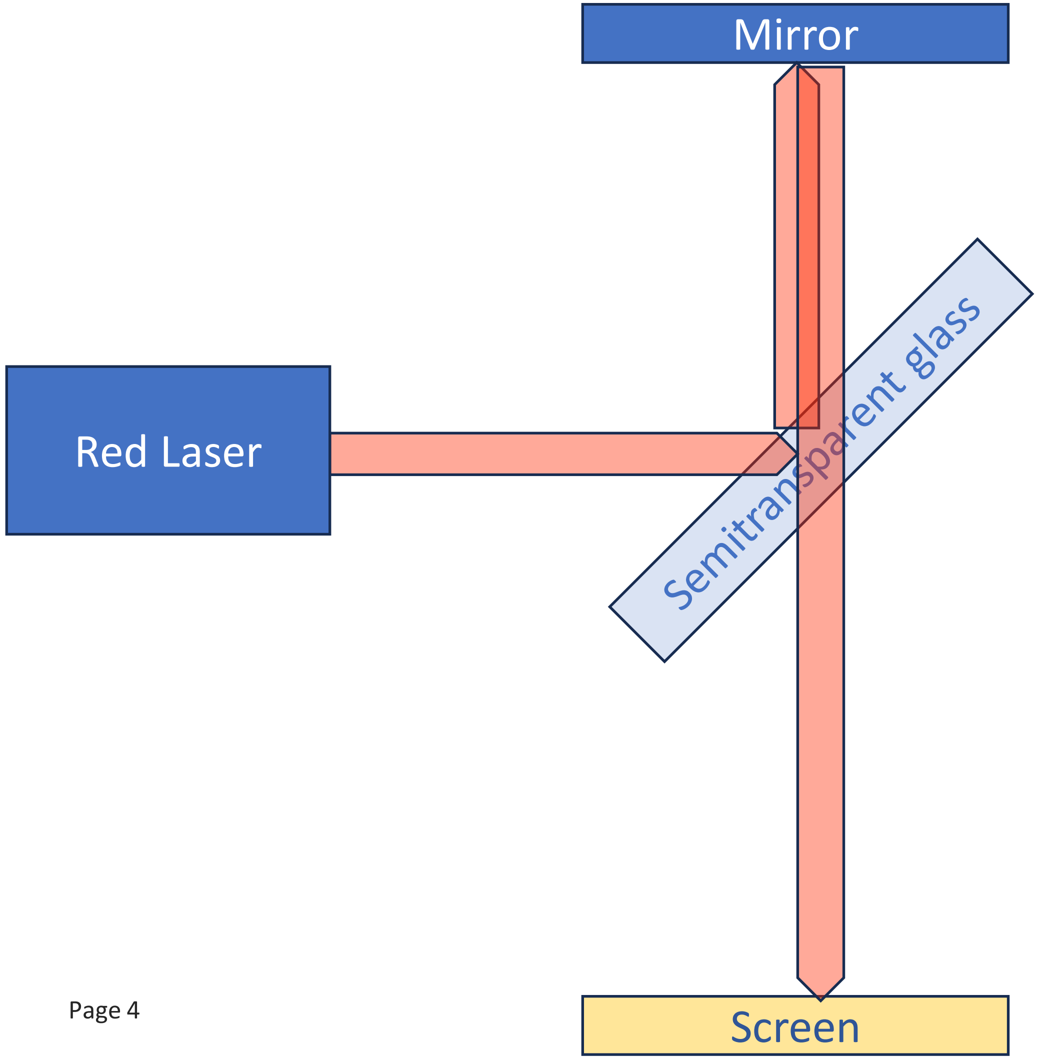
Michelson – Morley experiment





between April and July 1887

Michelson – Morley experiment



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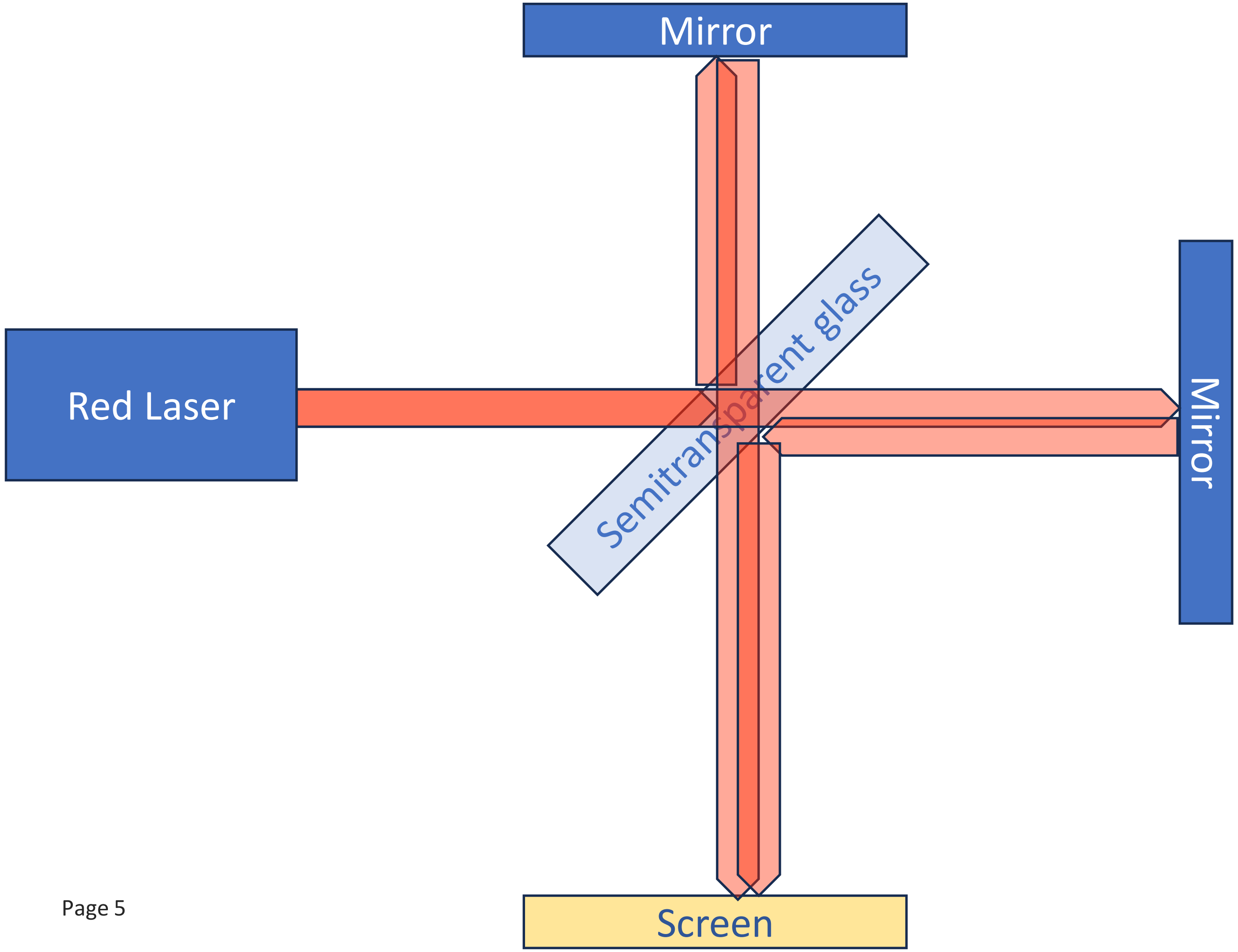
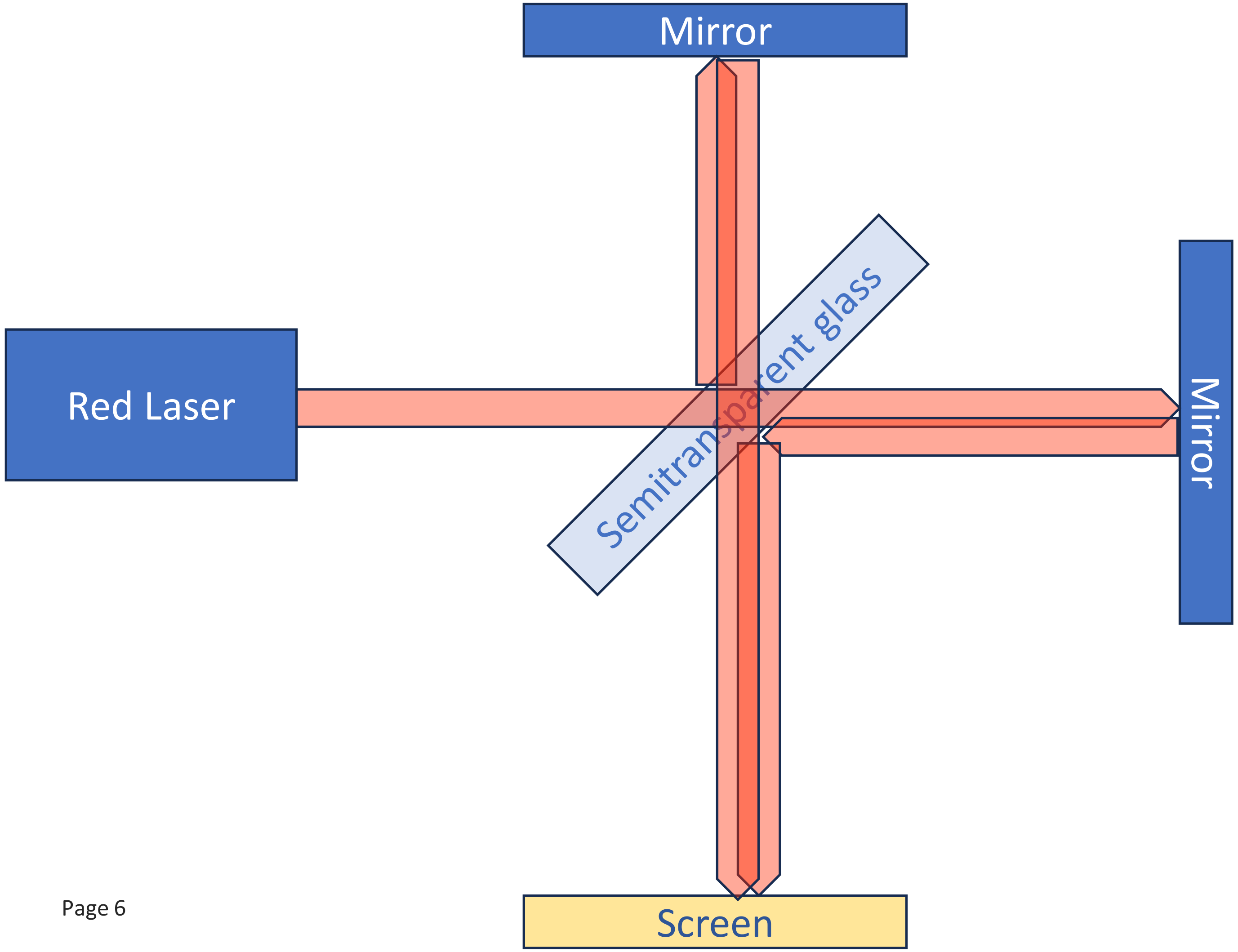
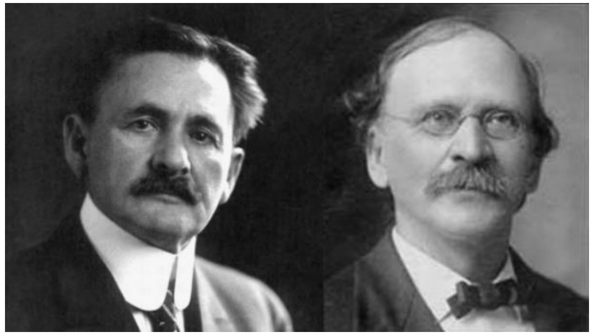


Michelson – Morley experiment





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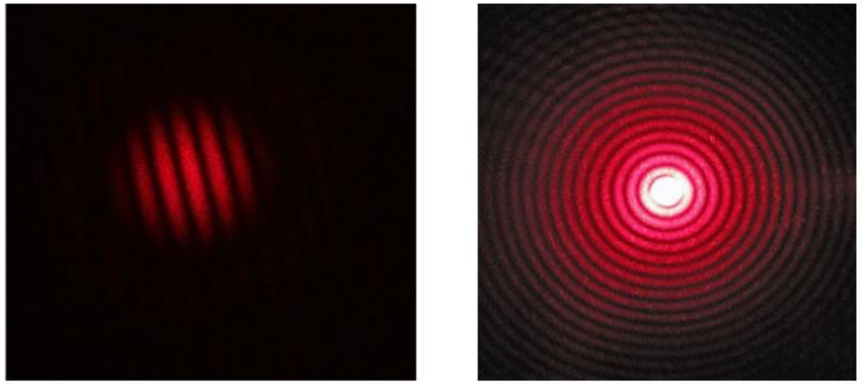
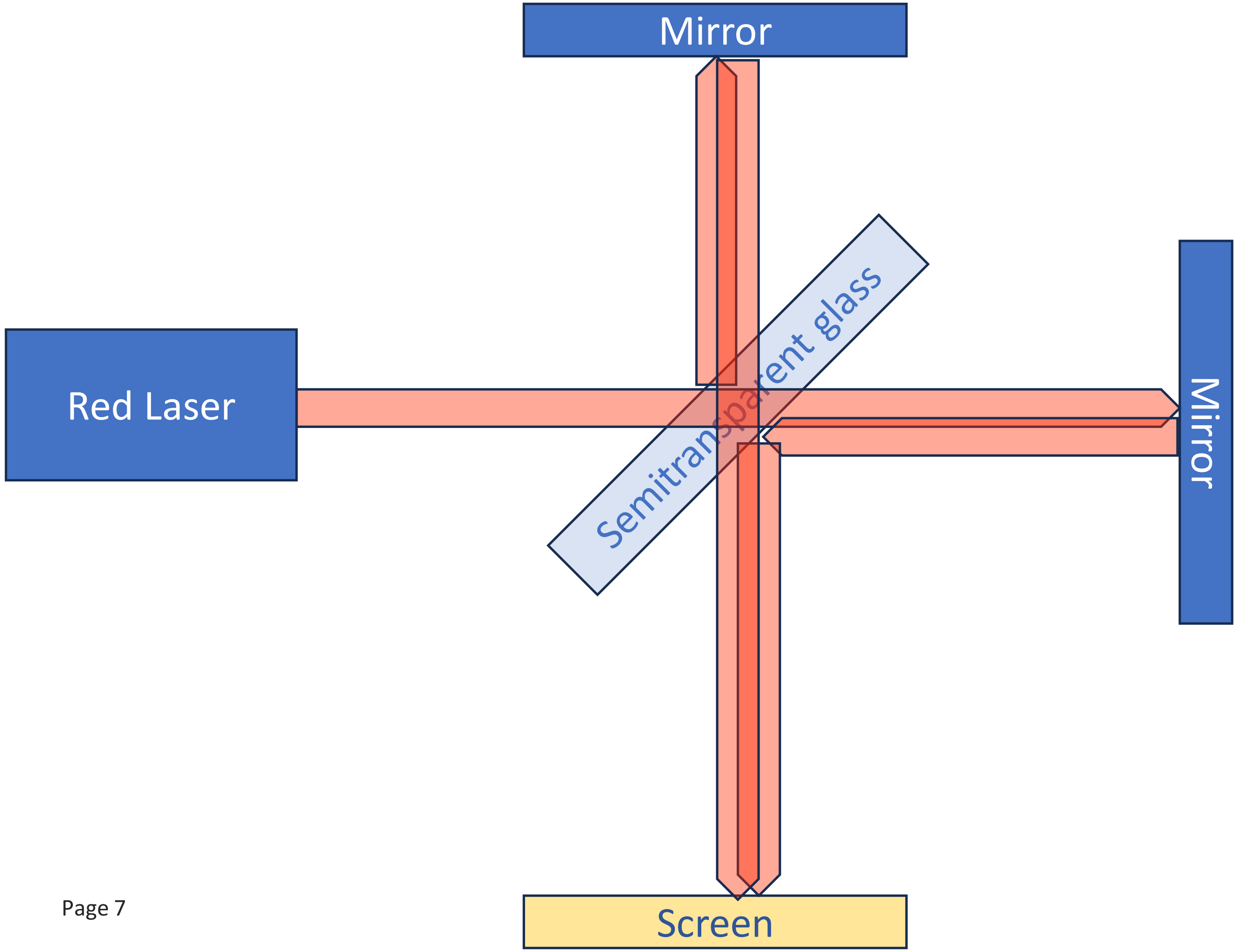
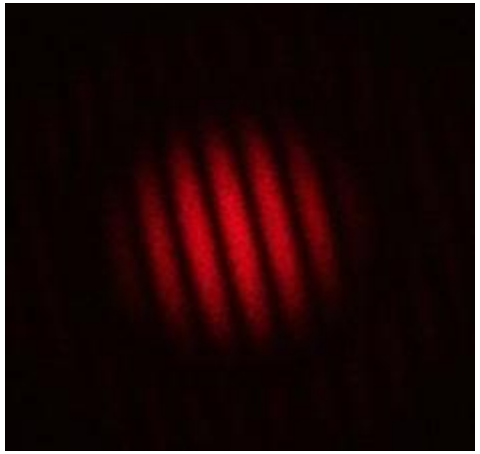
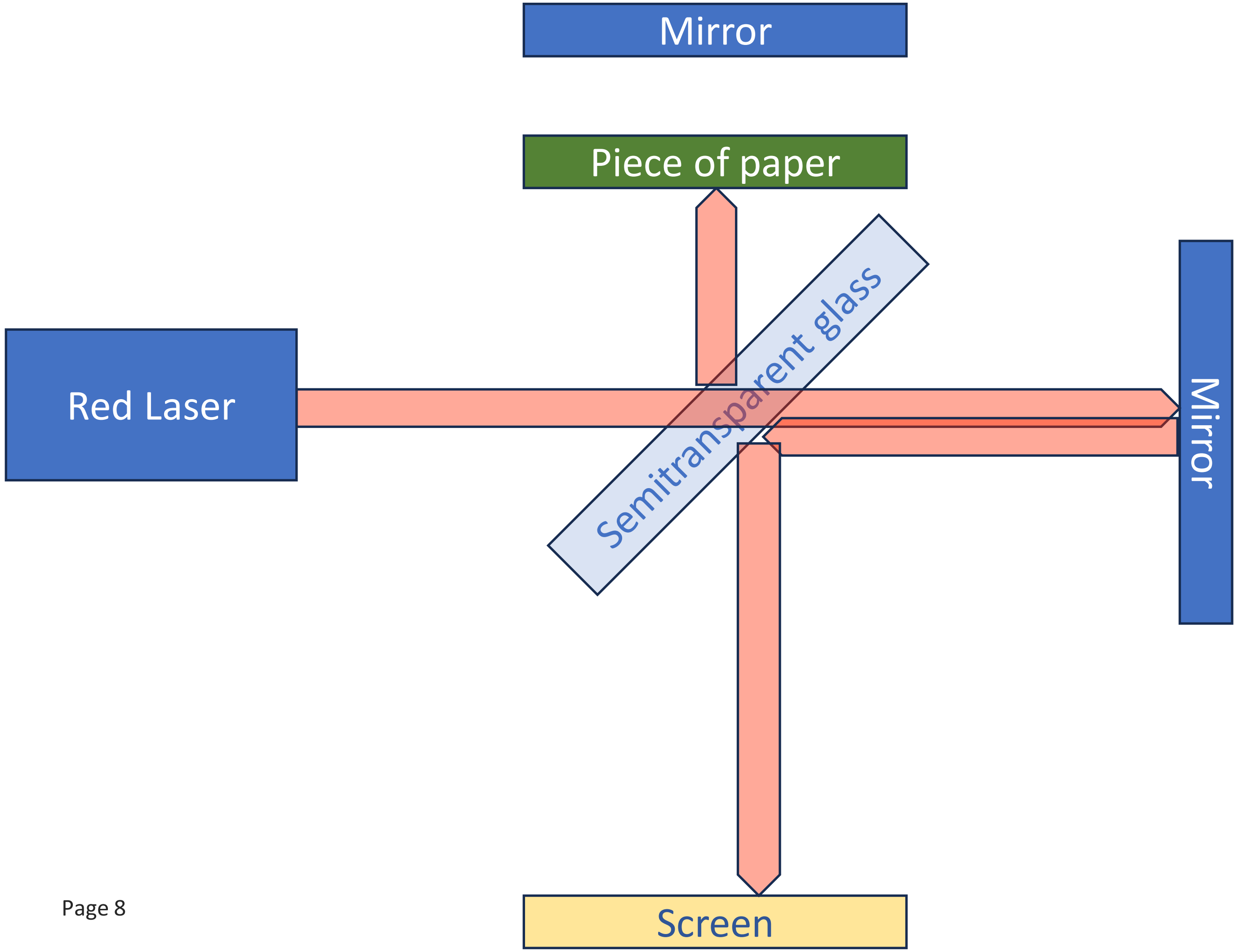


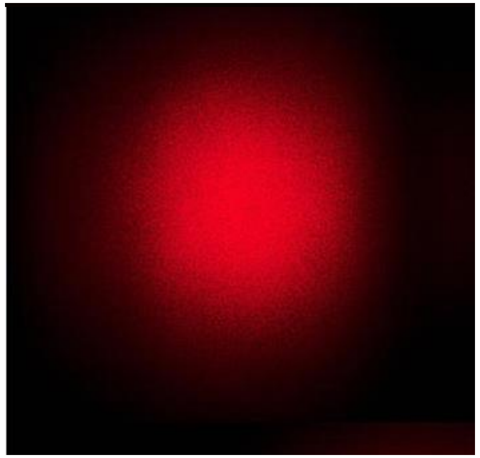
Michelson – Morley experiment



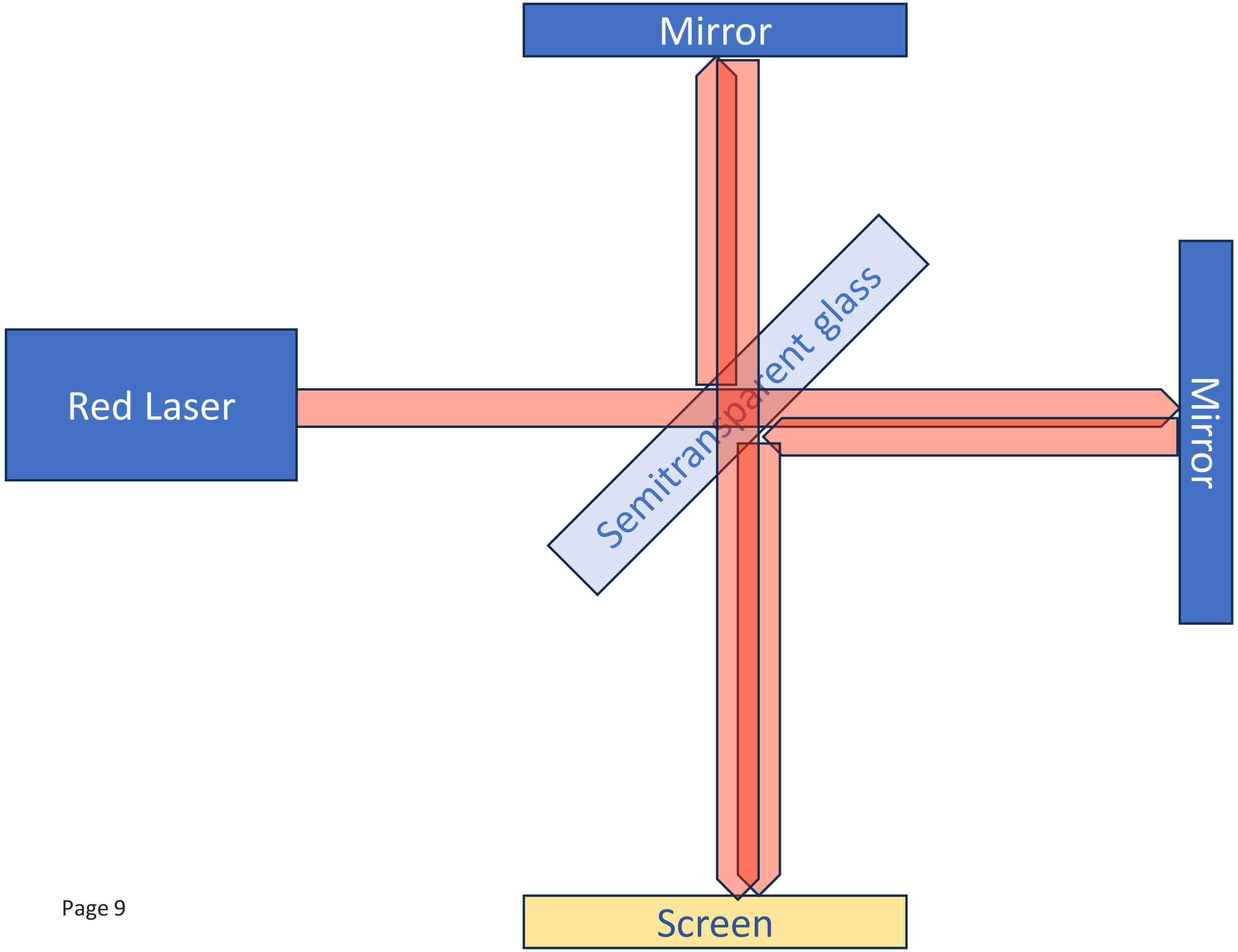


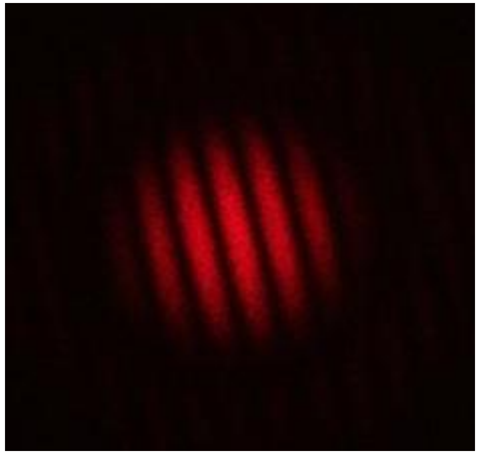
Michelson – Morley experiment



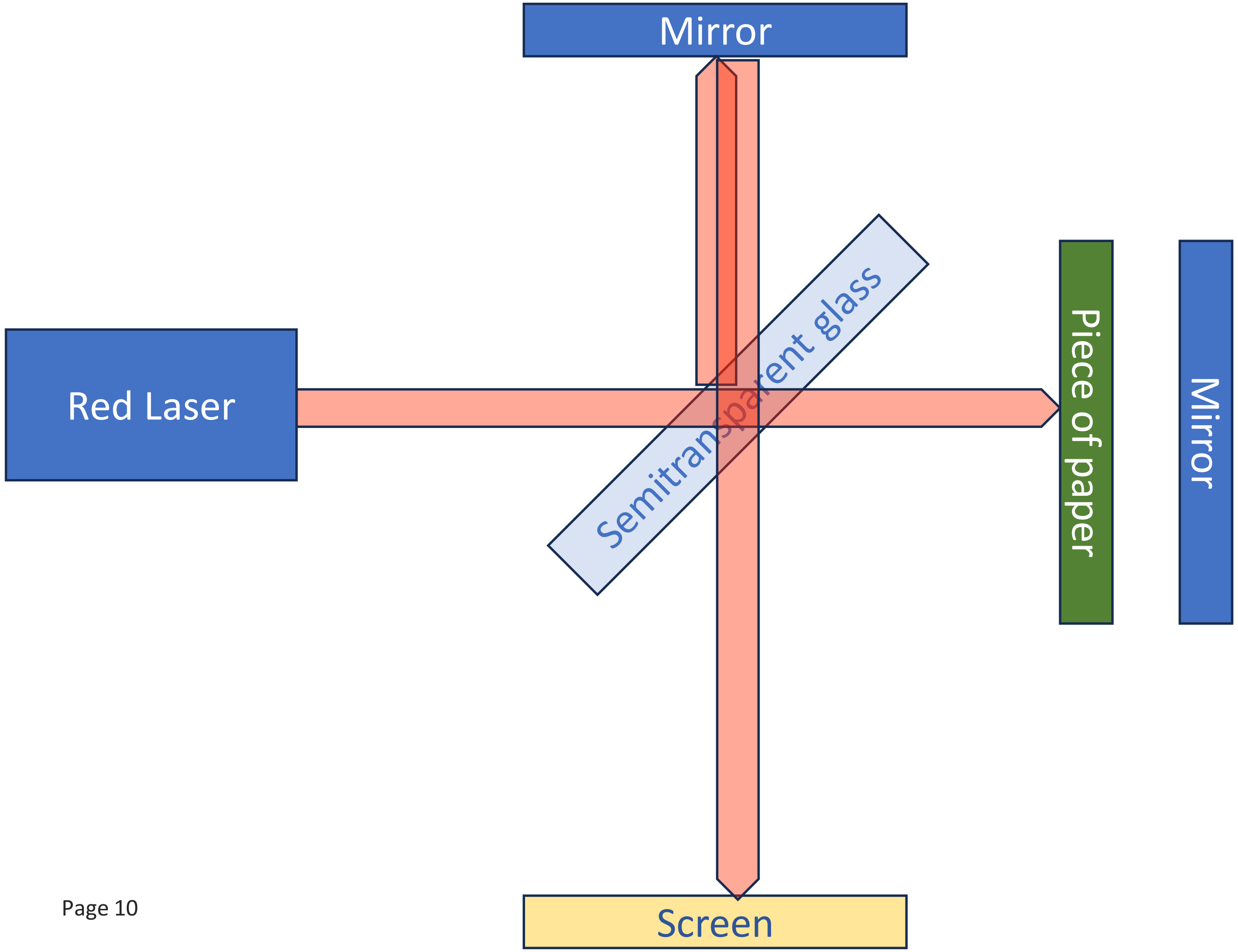


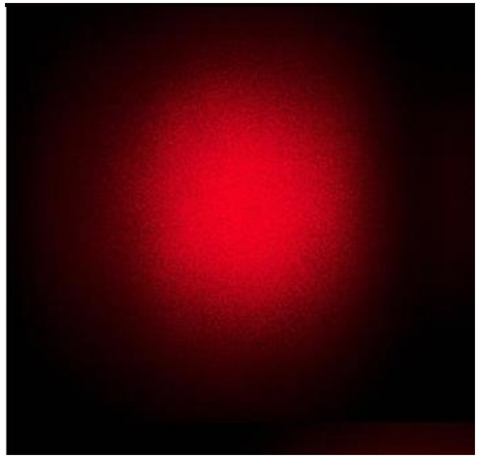
Michelson – Morley experiment



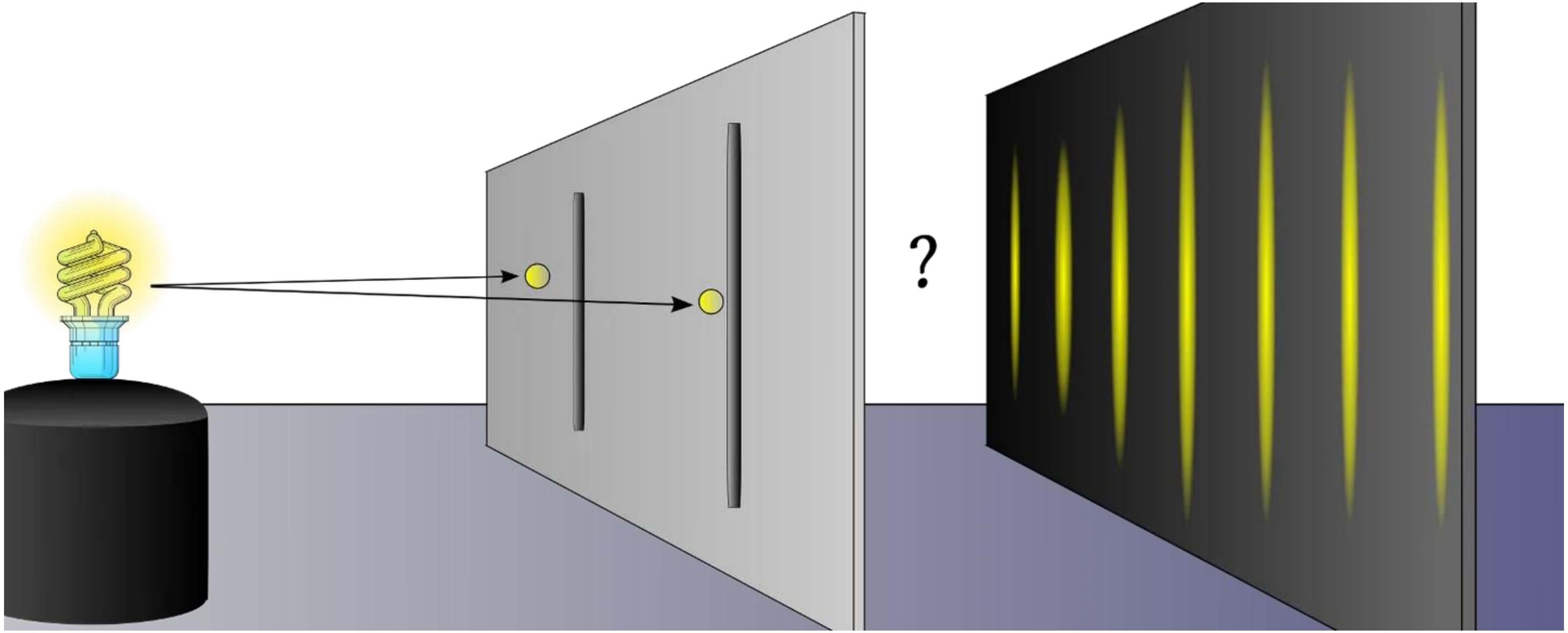


Michelson – Morley experiment

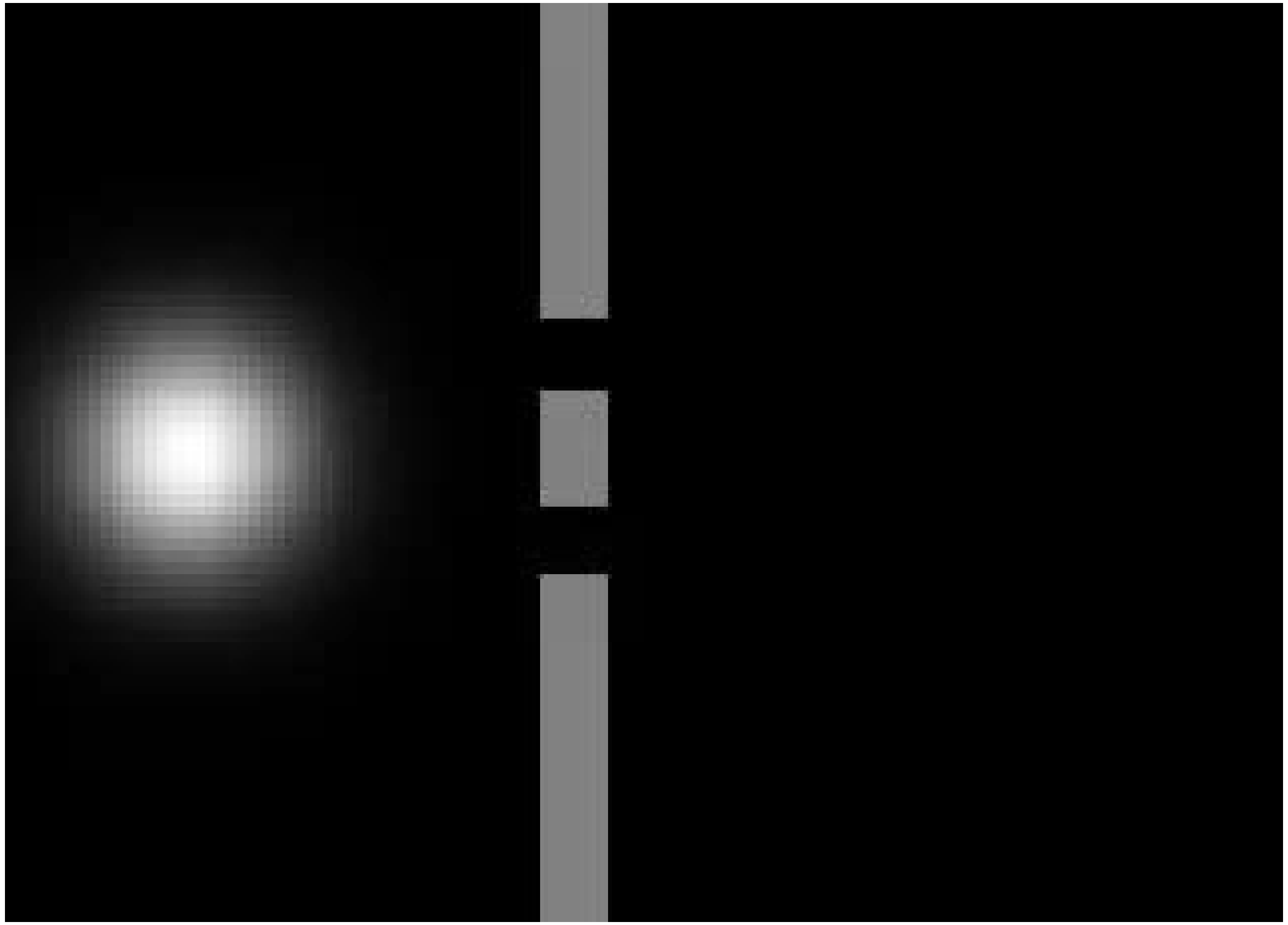




Two-slits experiment setup

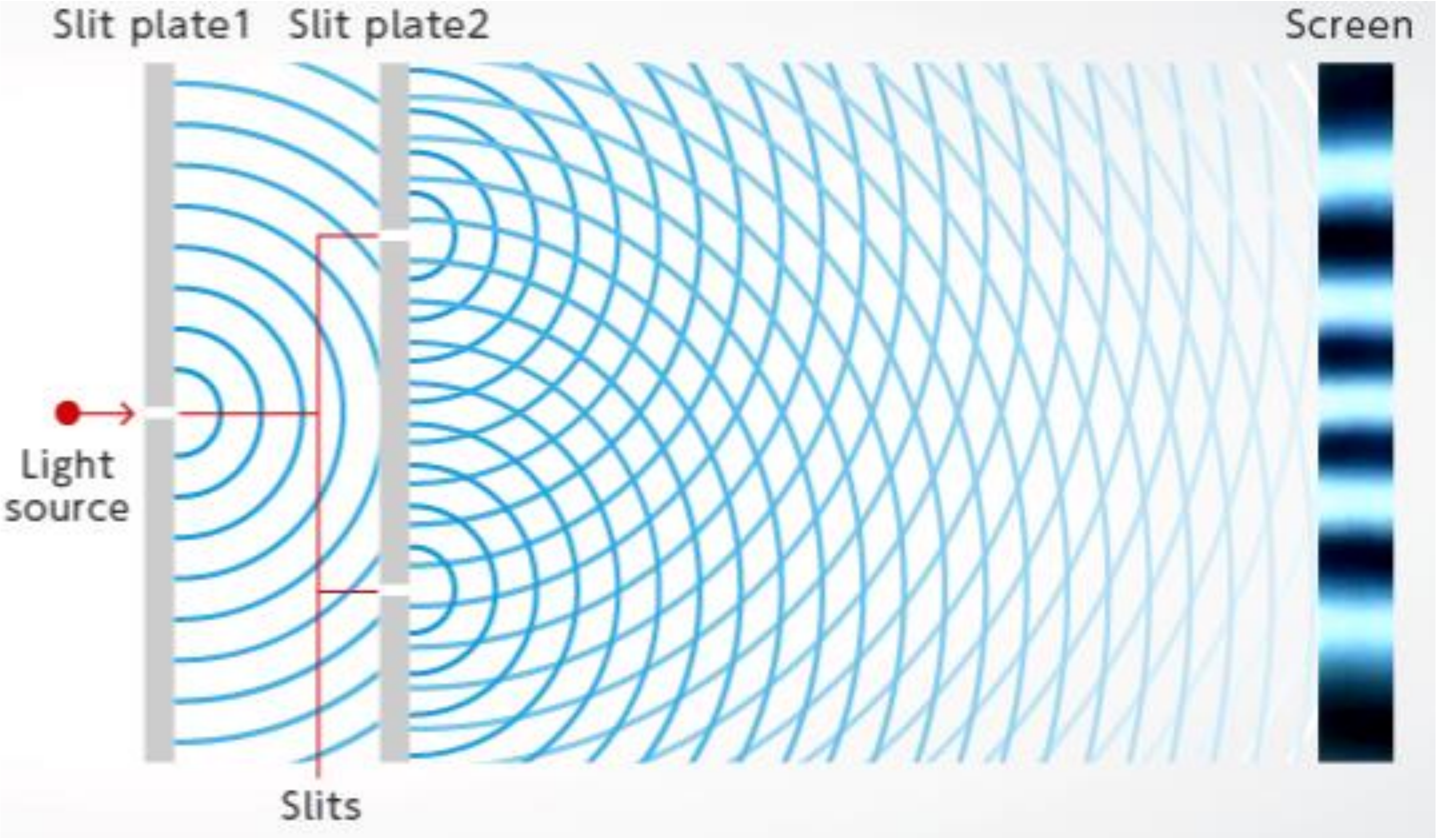


Two-slits experiment computer simulation

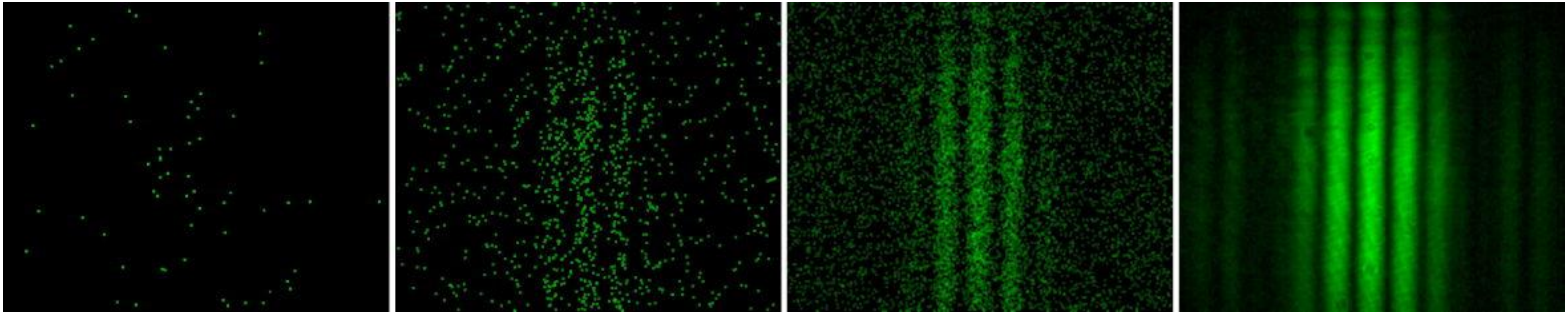


computer simulation

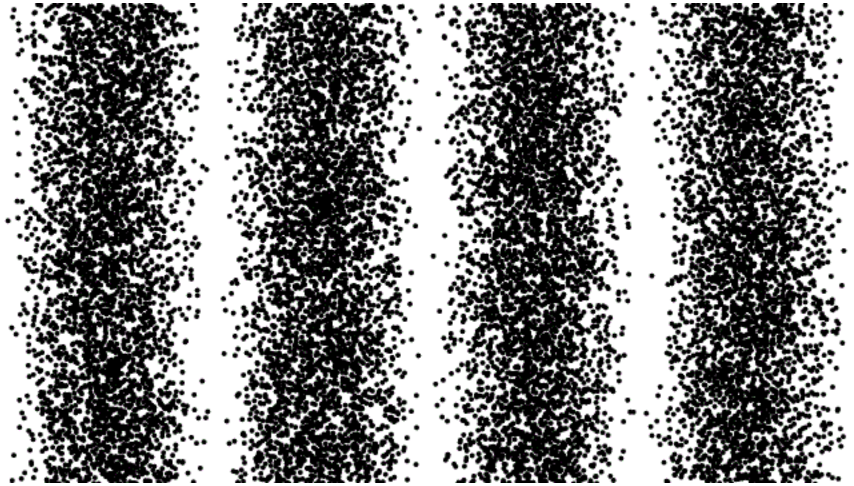
Two-slits experiment



Two-slits experiment with low light intensity

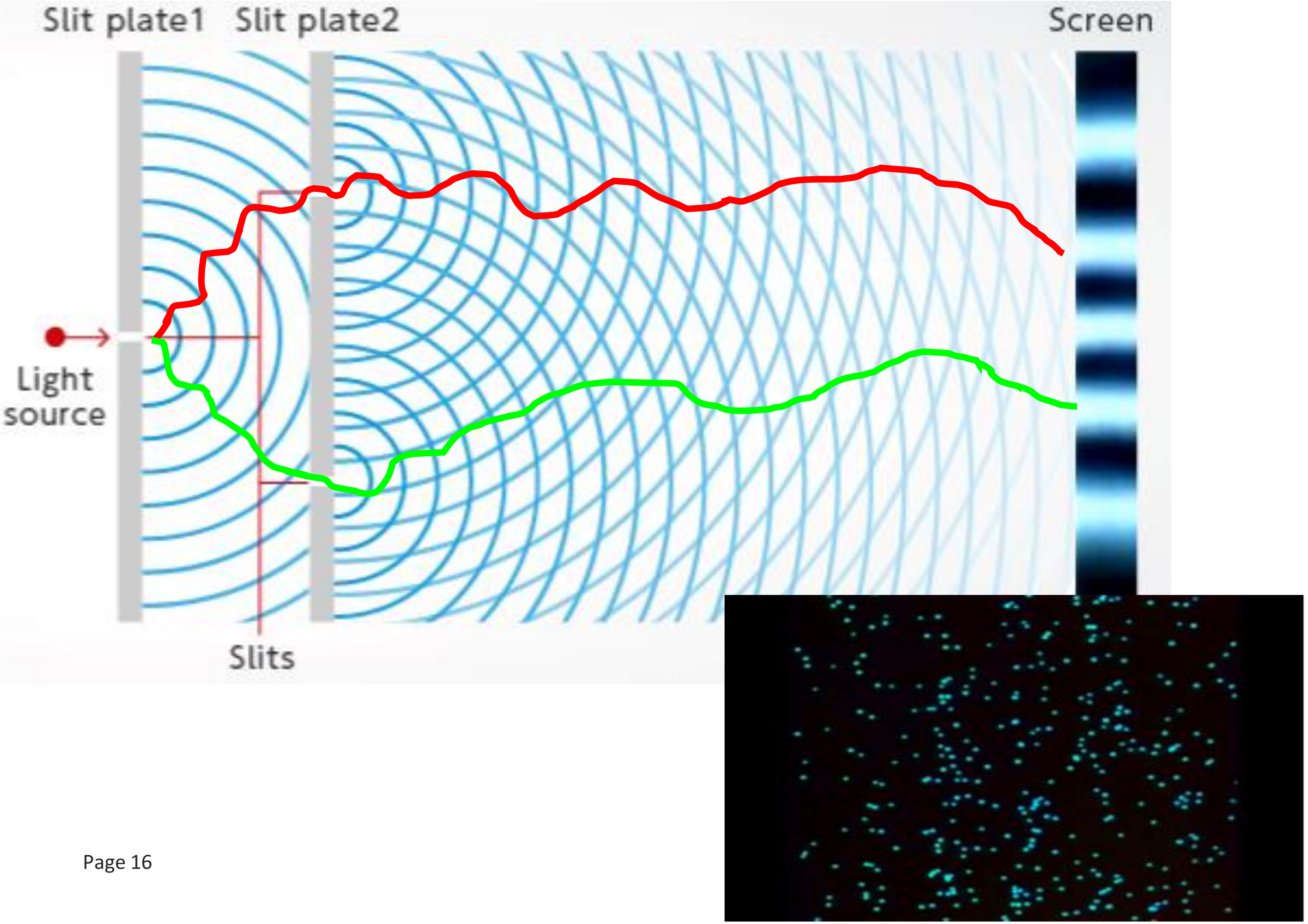


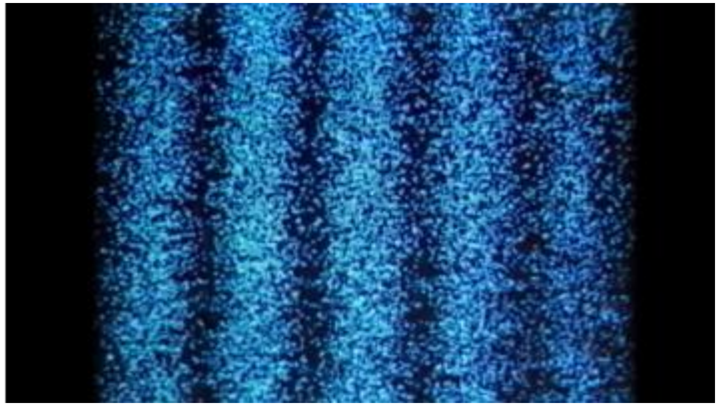
number of photons



computer simulation

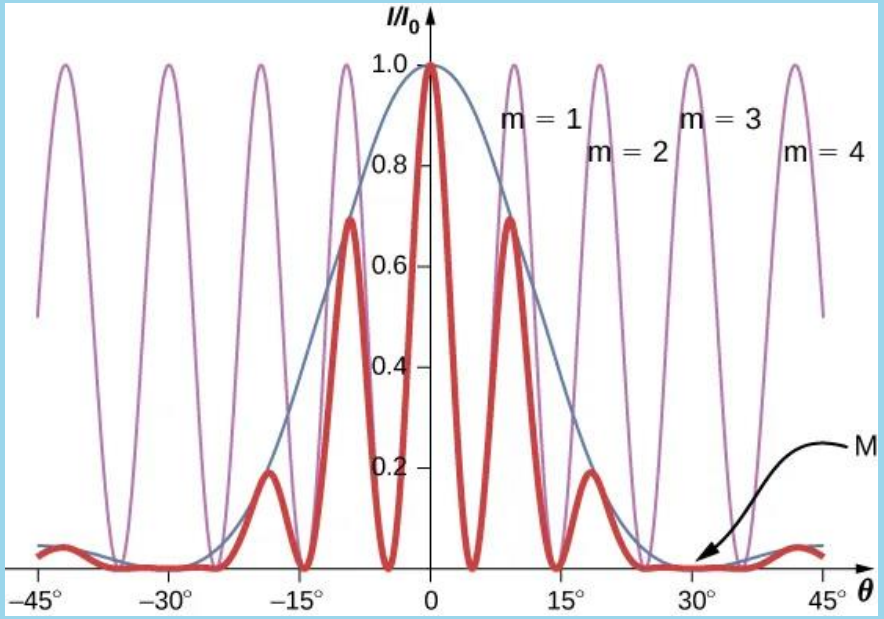
We don’t know where a single photon will travel!!!





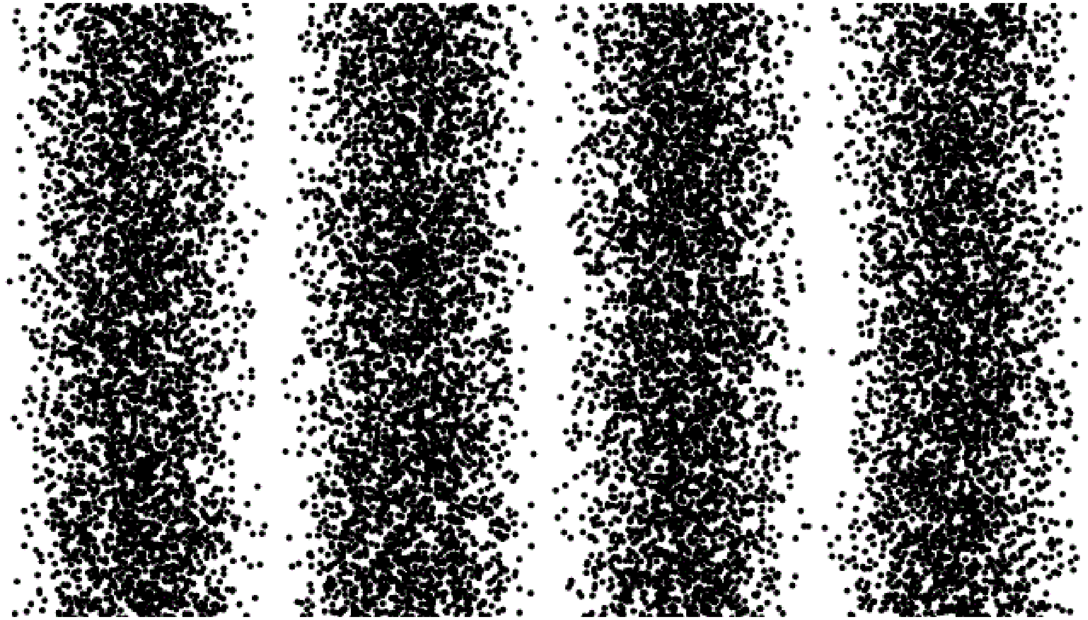
Mathematics

- We don‘t know where a single photon will travel -> we know **the probability**
- We know where bunch of photons will travel – interference pattern



Photons

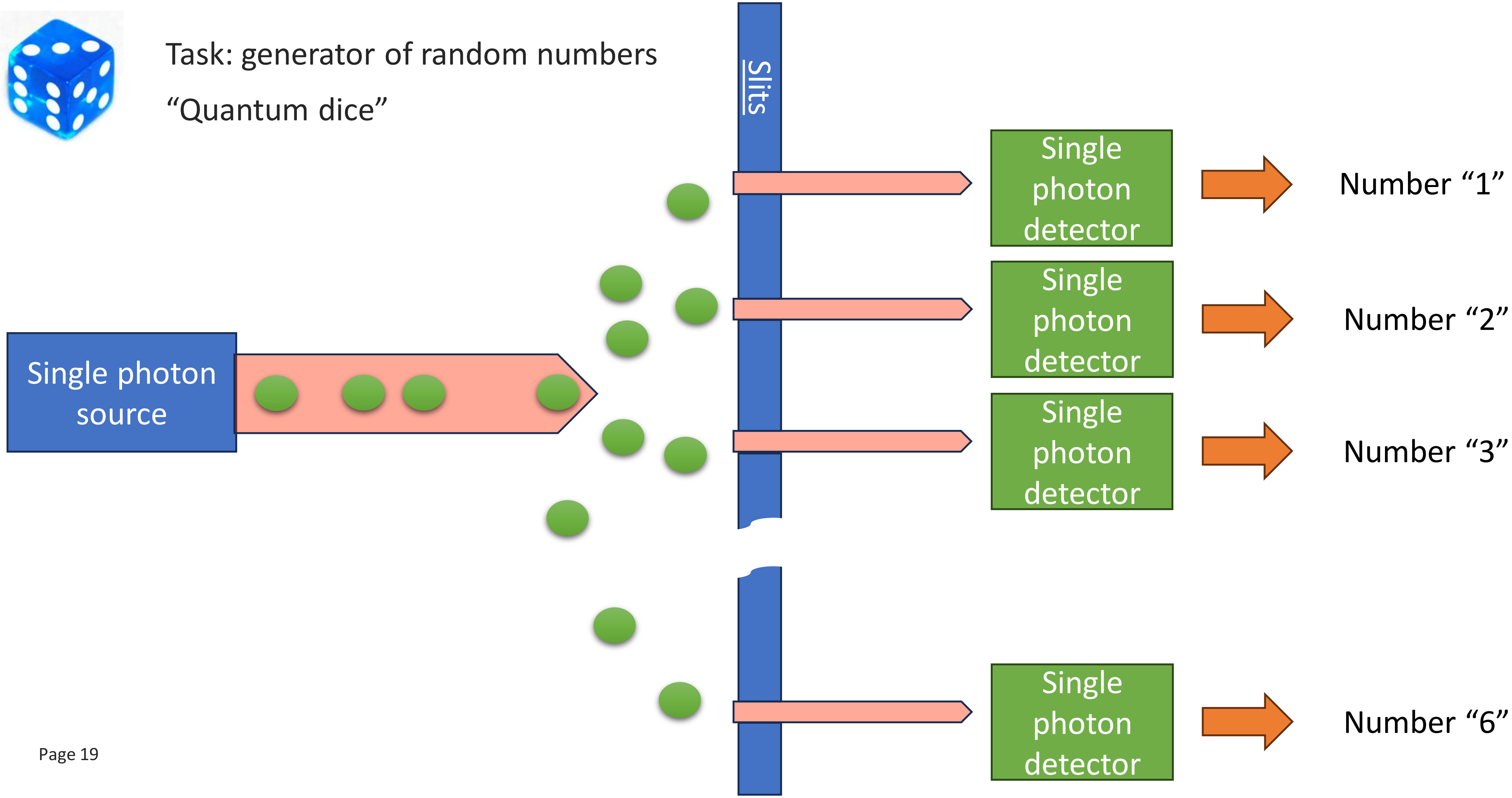
- Single photon knows where to go
- Photons interfere with each-other
- Photon obeys **quantum mechanics**



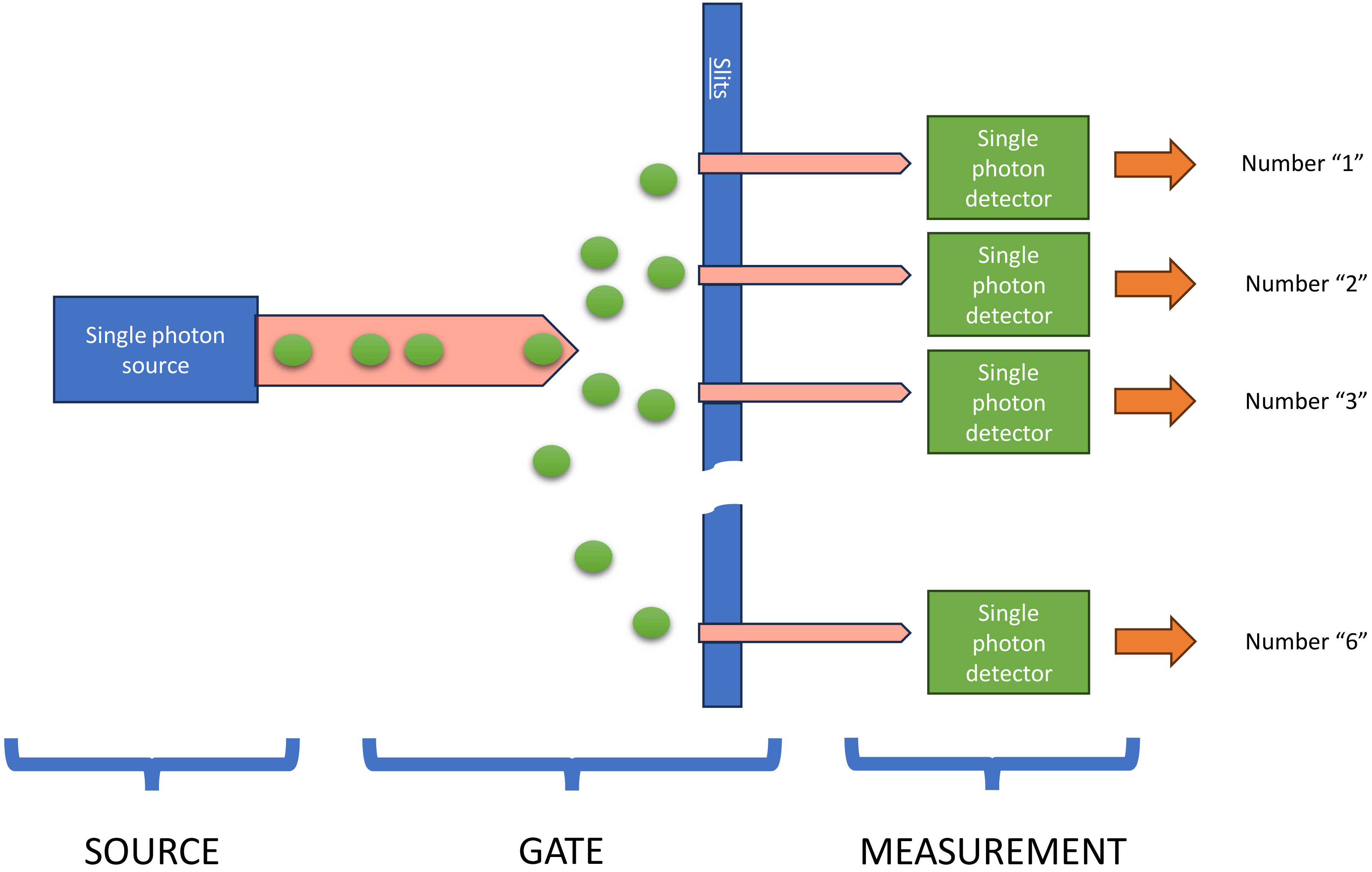
A Simple quantum computer

Task: generator of random numbers

“Quantum dice”



Basic blocks of quantum computer



Single photon source

Slits

Single photon detector

Number “1”

Single photon detector

Number “2”

Single photon detector

Number “3”

Single photon detector

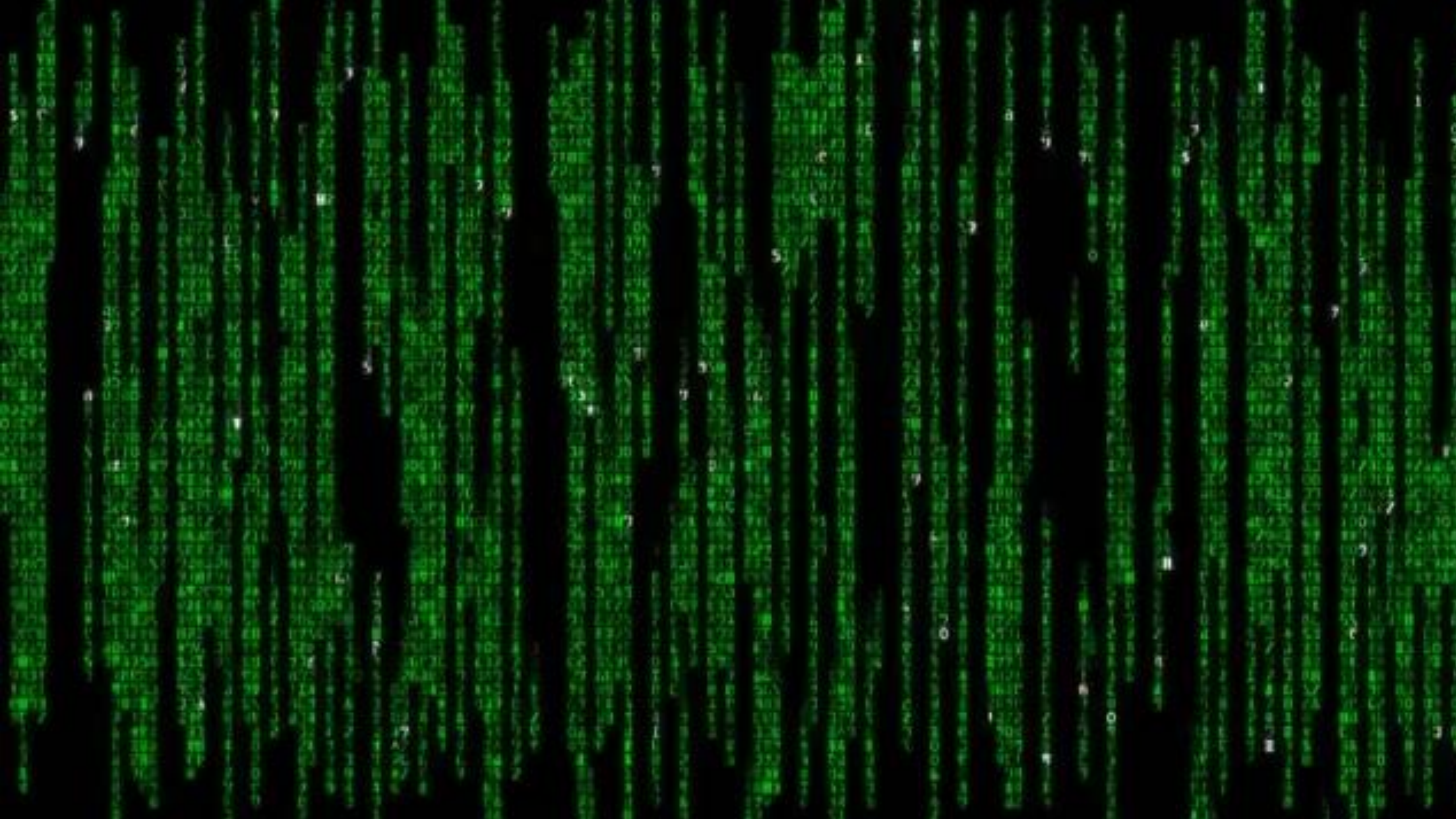
Number “6”

SOURCE

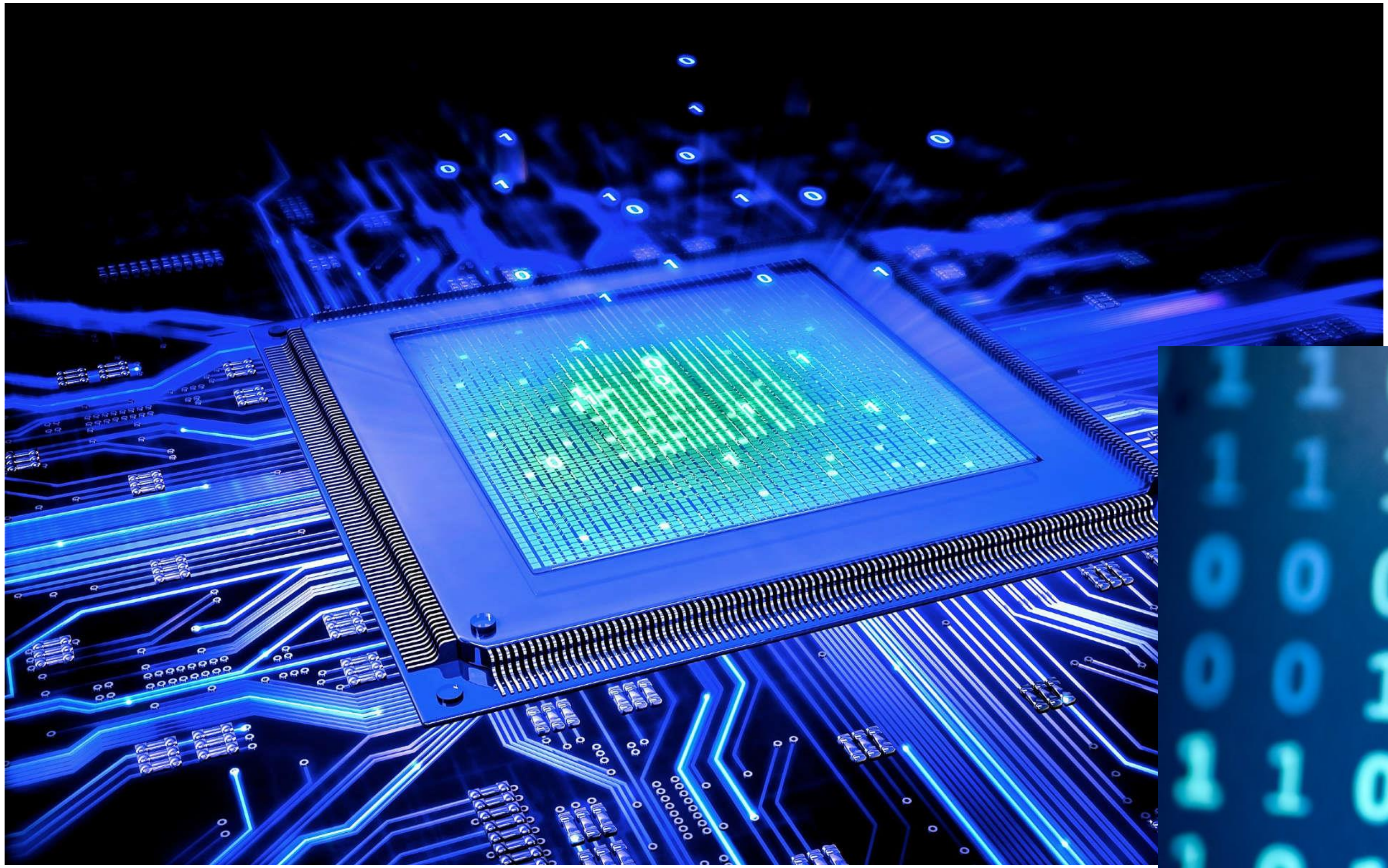
GATE

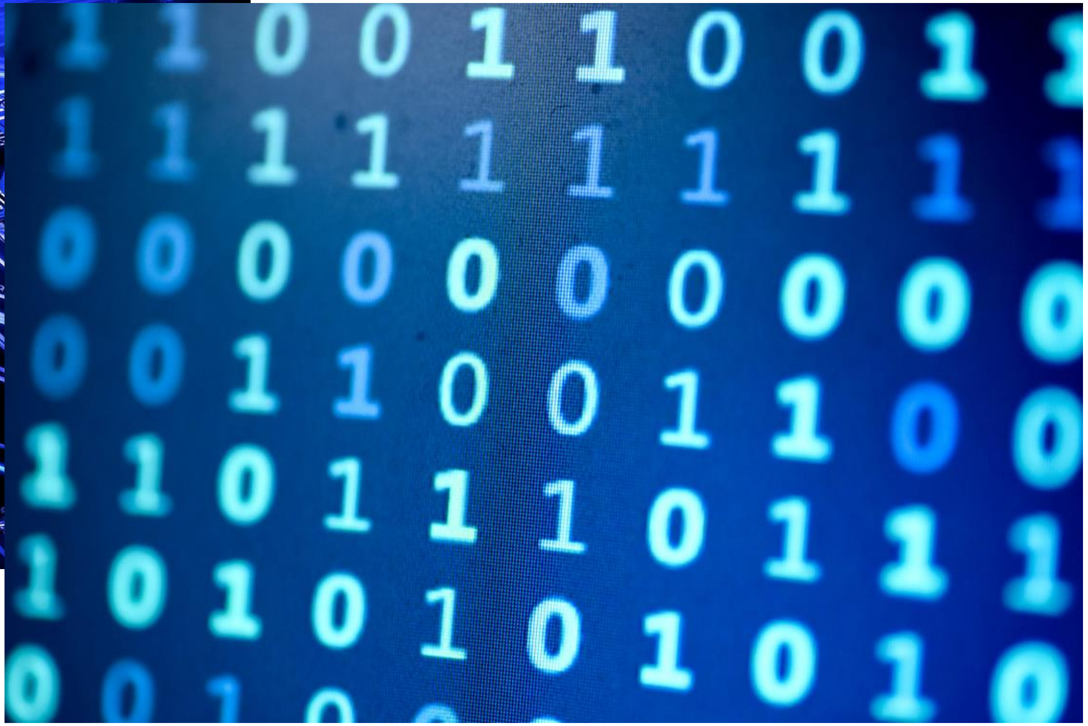
MEASUREMENT

Classical computers

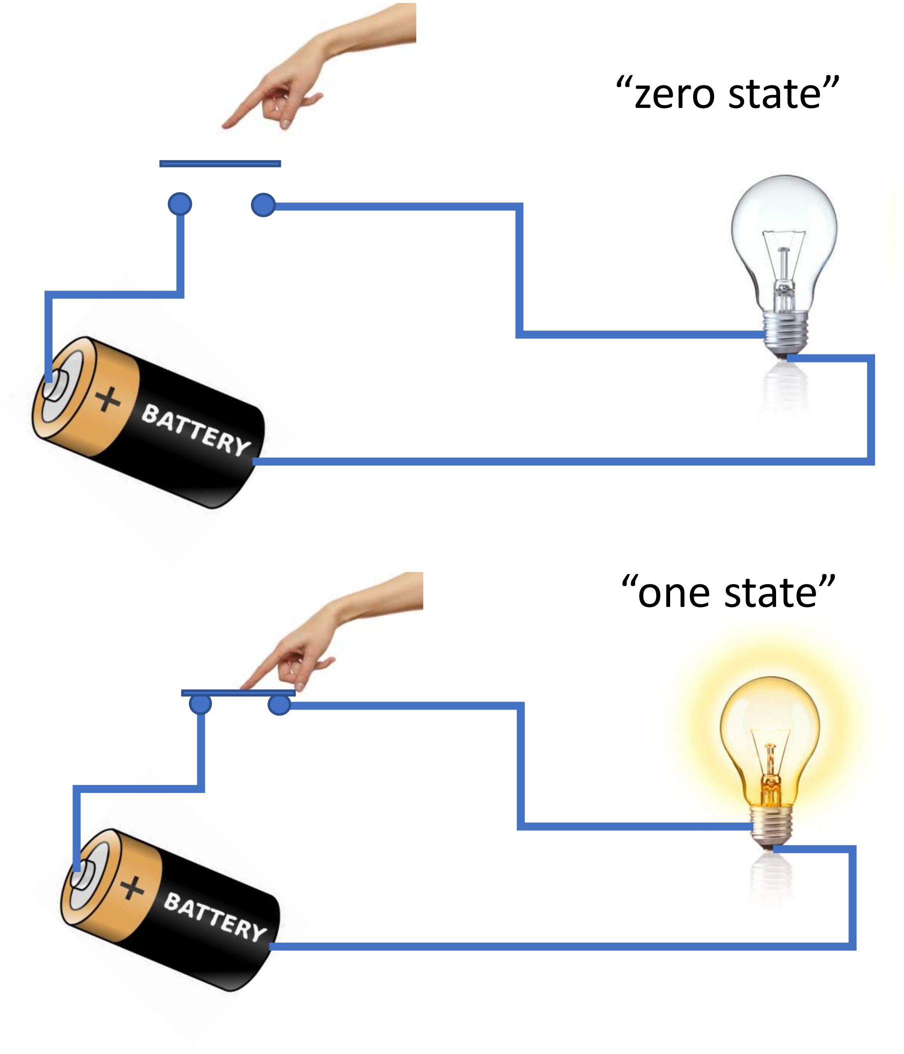


Classical computation is about 0 and 1

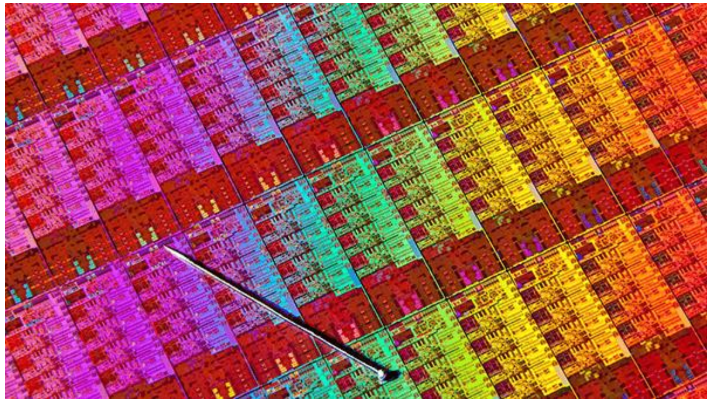




Classical computer – a box of switches

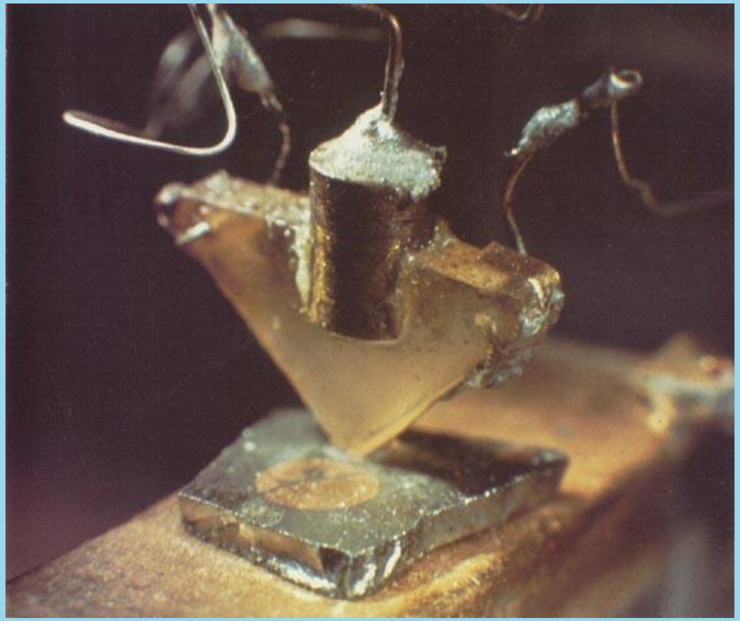


- Switch in computer is realized by a transistor
- A modern CPU has billions of transistors: e.g. Apple M2 Max - 67 billion transistors

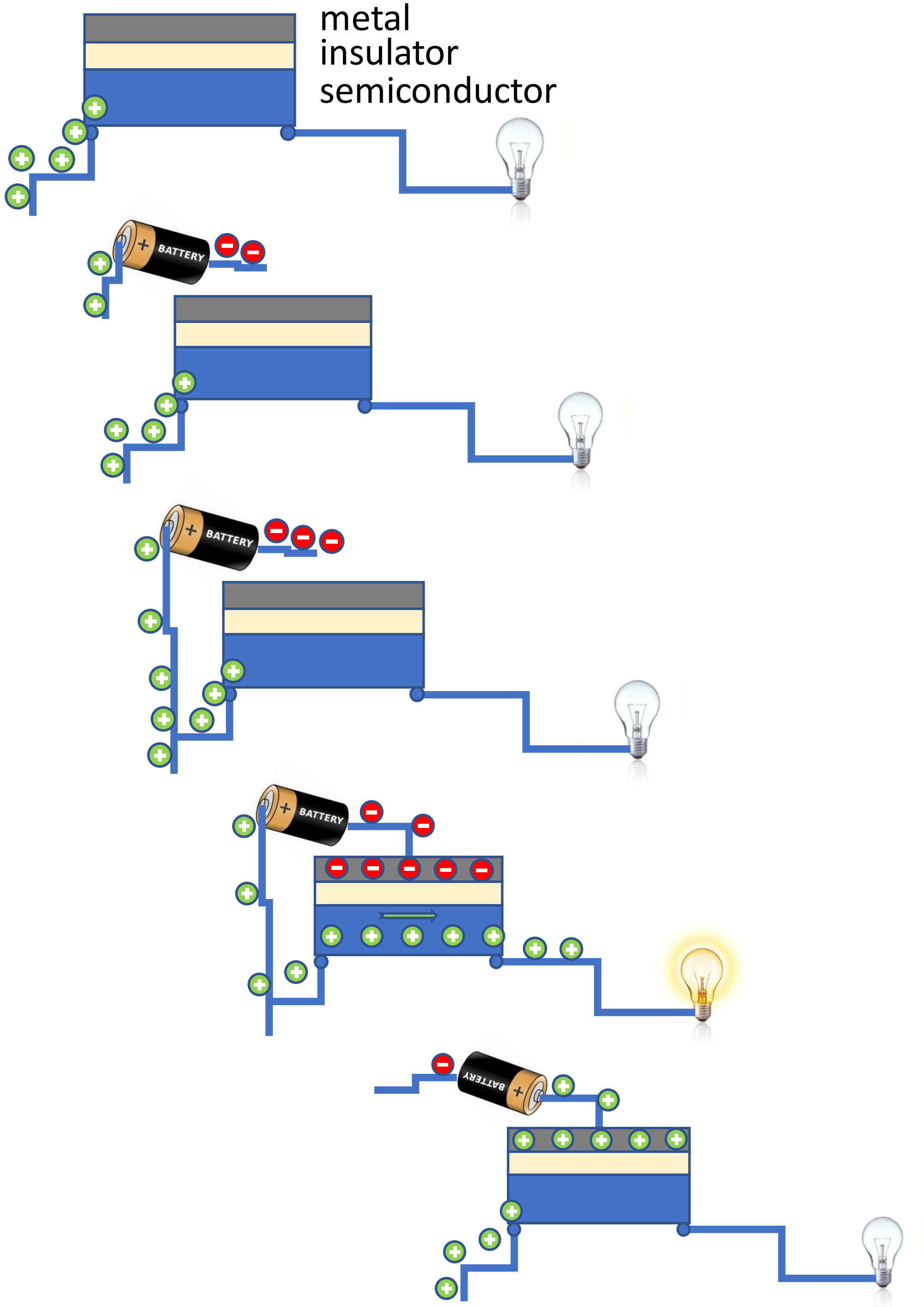


Transistor – electronic switch

- Semiconducting material enabled minituarzation of electric switches



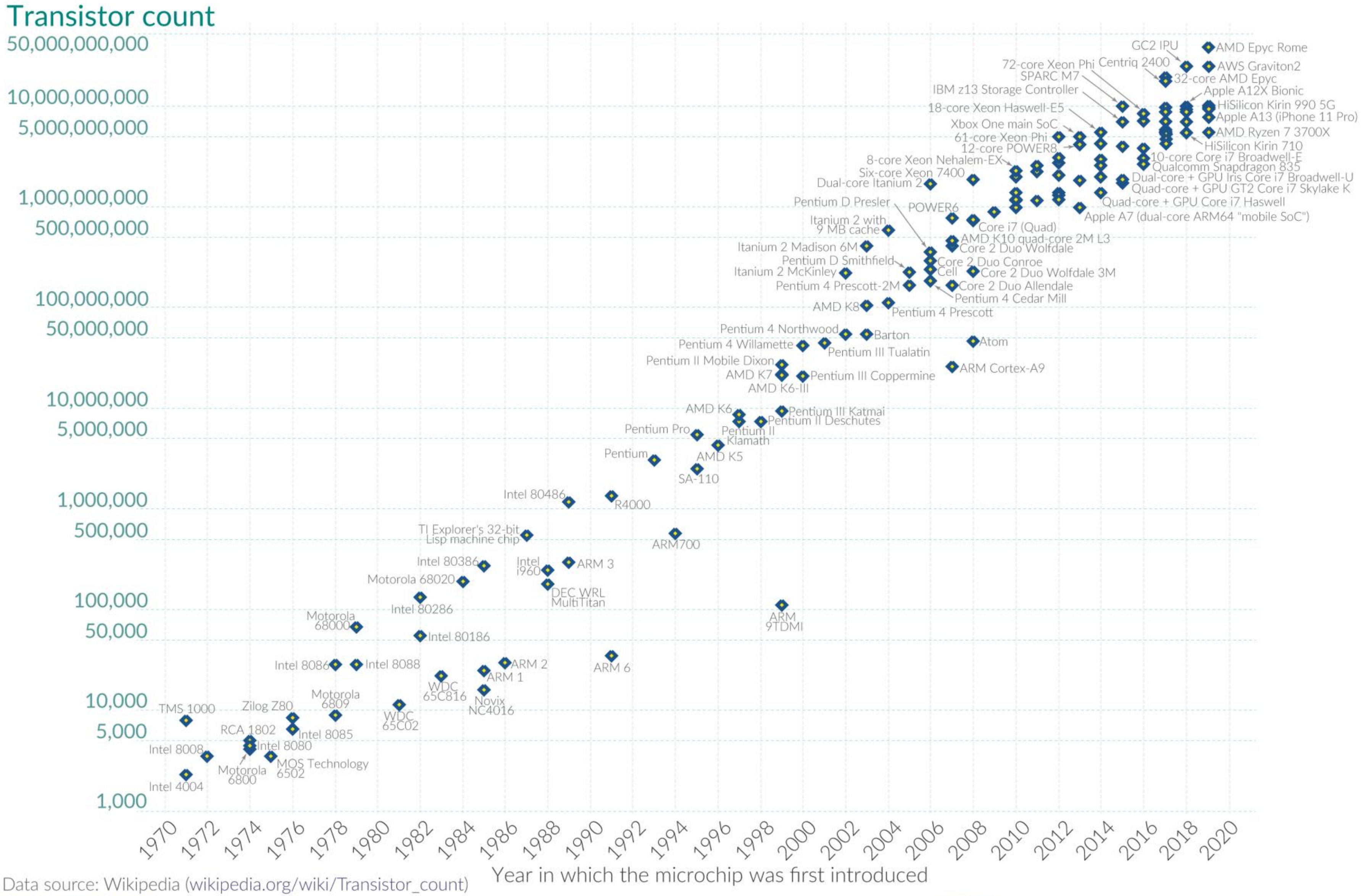
J. Bardeen, W. Brattain 1947



Moore's Law: The number of transistors on microchips doubles every two years

Our World in Data

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.



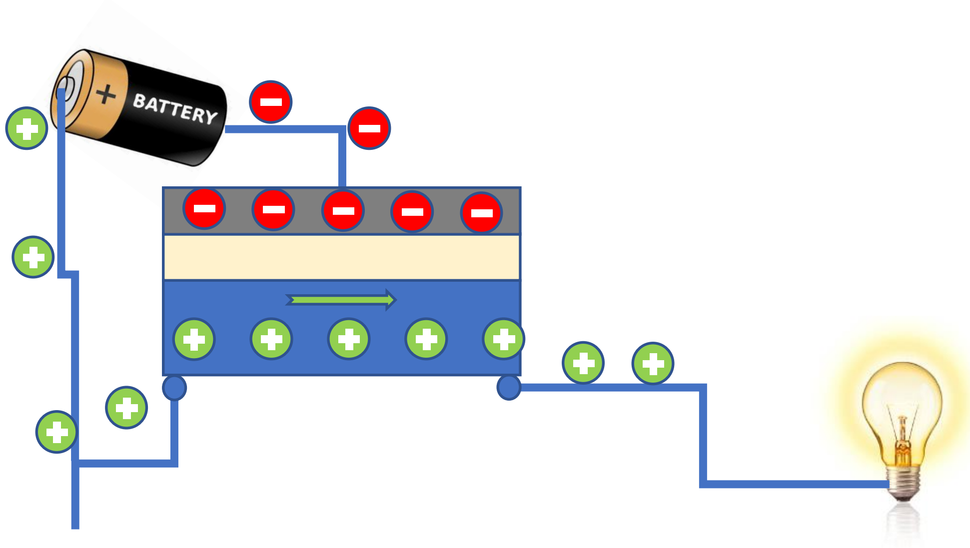
Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)

OurWorldinData.org – Research and data to make progress against the world's largest problems.

Minituarization reduced insulator thickness to 2 -5 nm in 2024.

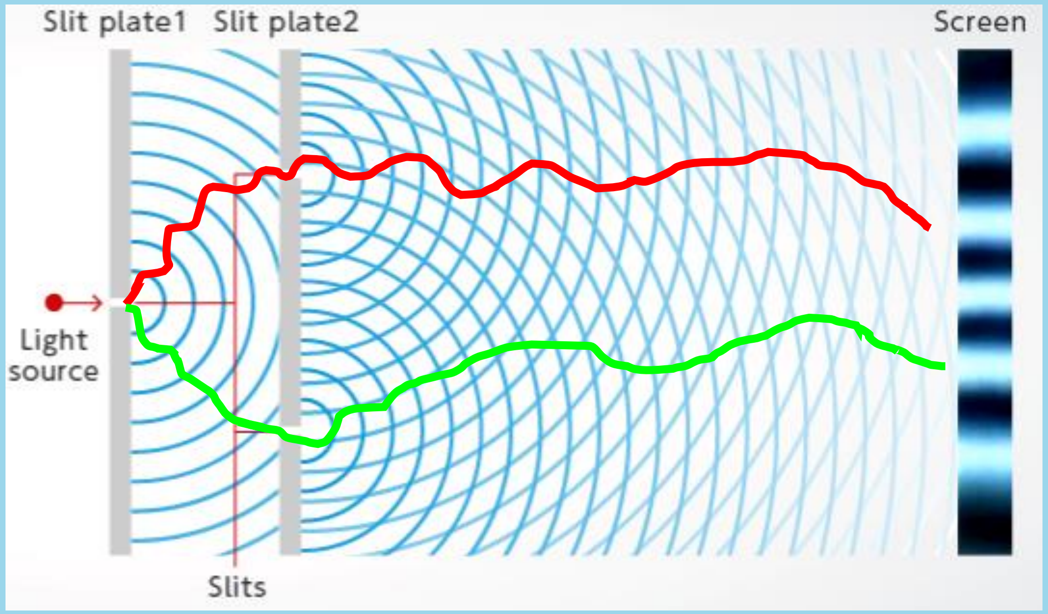
Still number of electrons is large

as a result the quantum phenomena averages out



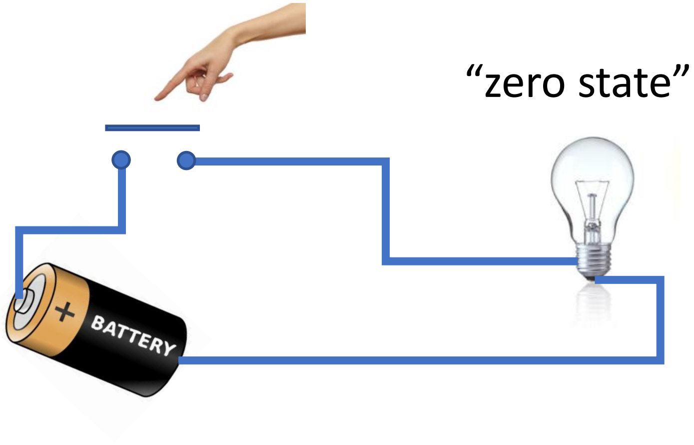
Quantum state

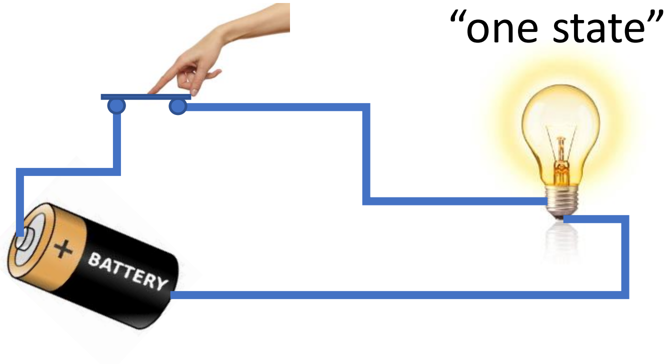
- Single photon can hold the information
- Single photon hold more than just „0“ or „1“



Classical state

- Semiconductor can be conducting or non-conducting
- semiconductor can hold the information of „0“ or “1“.


“zero state”


“one state”

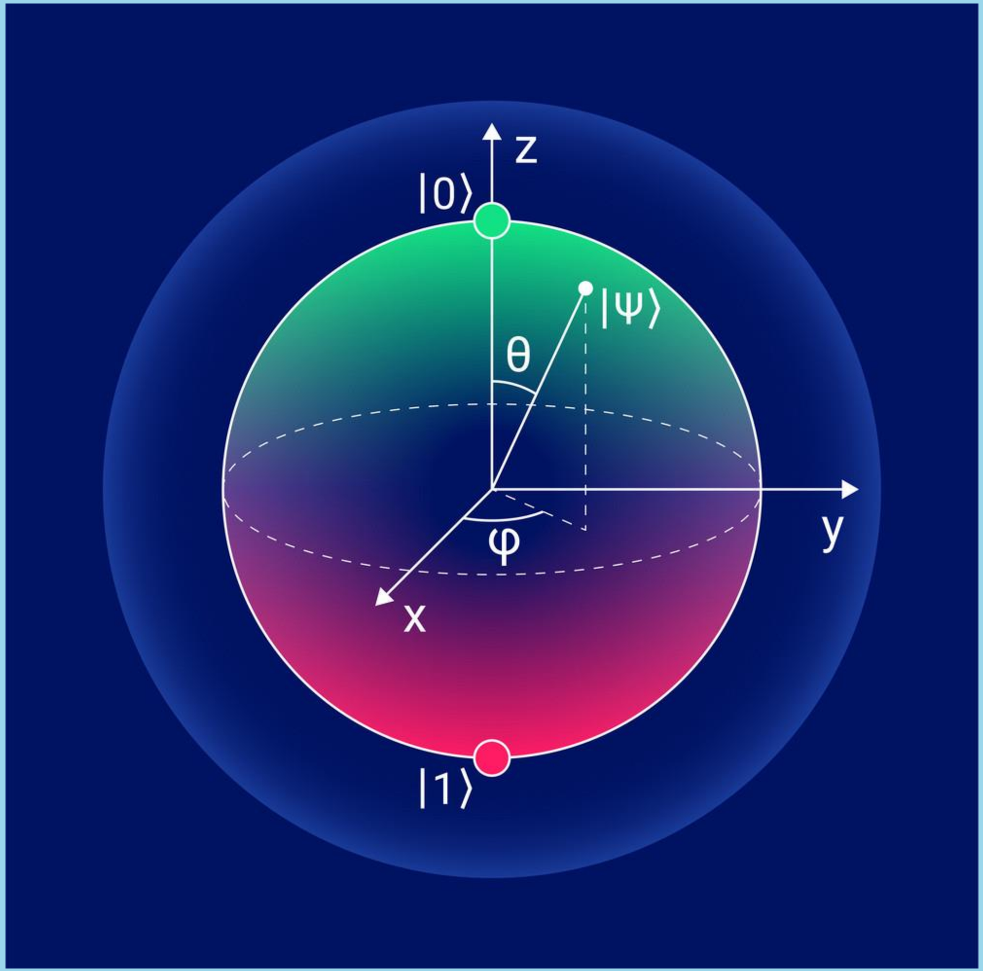
Introduction of quantum bit - qubit

Classical bit is “0” or “1”

$$BIT = |0\rangle \quad or \quad BIT = |1\rangle$$

Quantum bit – **superposition** of both states – “0” and “1”

$$QuBIT = \alpha \cdot |0\rangle + \beta \cdot |1\rangle$$



Bloch sphere representation of qubit

$$|\Psi\rangle = \alpha \cdot |0\rangle + \beta \cdot |1\rangle$$

$$\alpha = \cos\frac{\theta}{2} \quad \beta = e^{i\varphi}\sin\frac{\theta}{2}$$

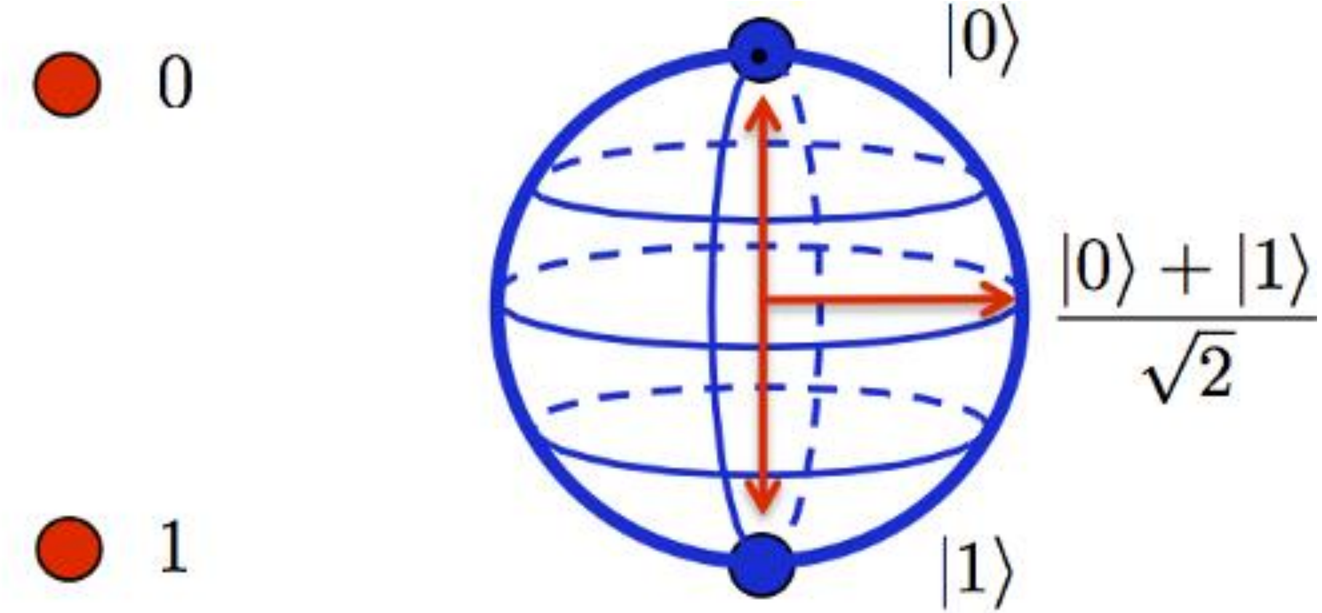
Probability

to be in “0” and “1” must be 1

$$QuBIT = \alpha \cdot |0\rangle + \beta \cdot |1\rangle$$

$$P(QuBIT) = \alpha^2 + \beta^2 = 1$$

Classical vs Quantum bit



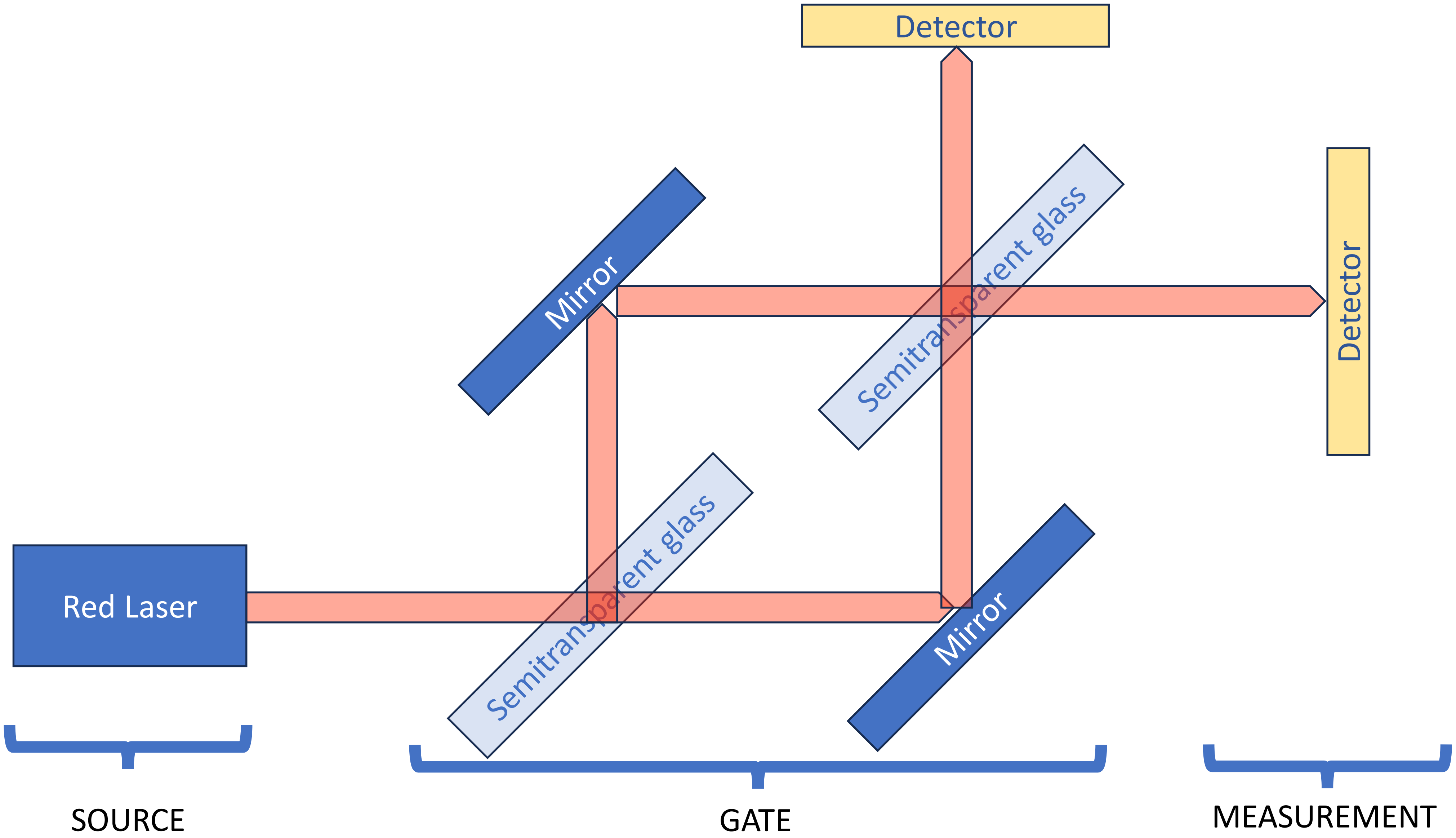
Classical Bit **Qubit**

QuBIT systems

Wikipedia
The Free Encyclopedia

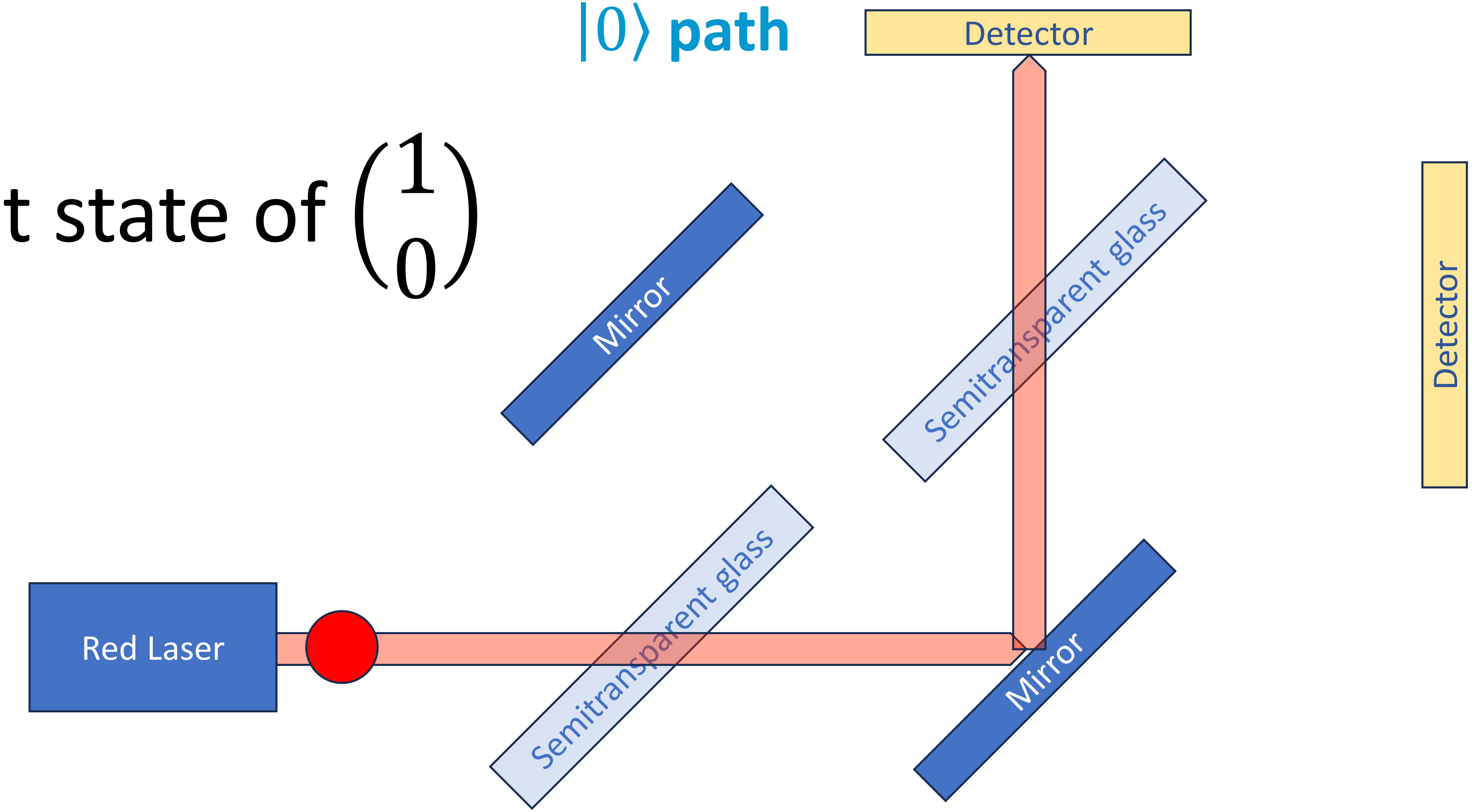
Physical support	Name	Information support	$\lvert 0\rangle$	$\lvert 1\rangle$
Photon	Polarization encoding	Polarization of light	Horizontal	Vertical
	Number of photons	Fock state	Vacuum	Single photon state
	Time-bin encoding	Time of arrival	Early	Late
Coherent state of light	Squeezed light	Quadrature	Amplitude-squeezed state	Phase-squeezed state
Electrons	Electronic spin	Spin	Up	Down
	Electron number	Charge	No electron	One electron
Nucleus	Nuclear spin addressed through NMR	Spin	Up	Down
Optical lattices	Atomic spin	Spin	Up	Down
Josephson junction	Superconducting charge qubit	Charge	Uncharged superconducting island (Q=0)	Charged superconducting island (Q=2e, one extra Cooper pair)
	Superconducting flux qubit	Current	Clockwise current	Counterclockwise current
	Superconducting phase qubit	Energy	Ground state	First excited state
Singly charged quantum dot pair	Electron localization	Charge	Electron on left dot	Electron on right dot
Quantum dot	Dot spin	Spin	Down	Up
Gapped topological system	Non-abelian anyons	Braiding of Excitations	Depends on specific topological system	Depends on specific topological system
Vibrational qubit[15]	Vibrational states	Phonon/vibron	$\lvert 01\rangle$ superposition	$\lvert 10\rangle$ superposition
van der Waals heterostructure[16]	Electron localization	Charge	Electron on bottom sheet	Electron on top sheet

Mach-Zehnder interferometer



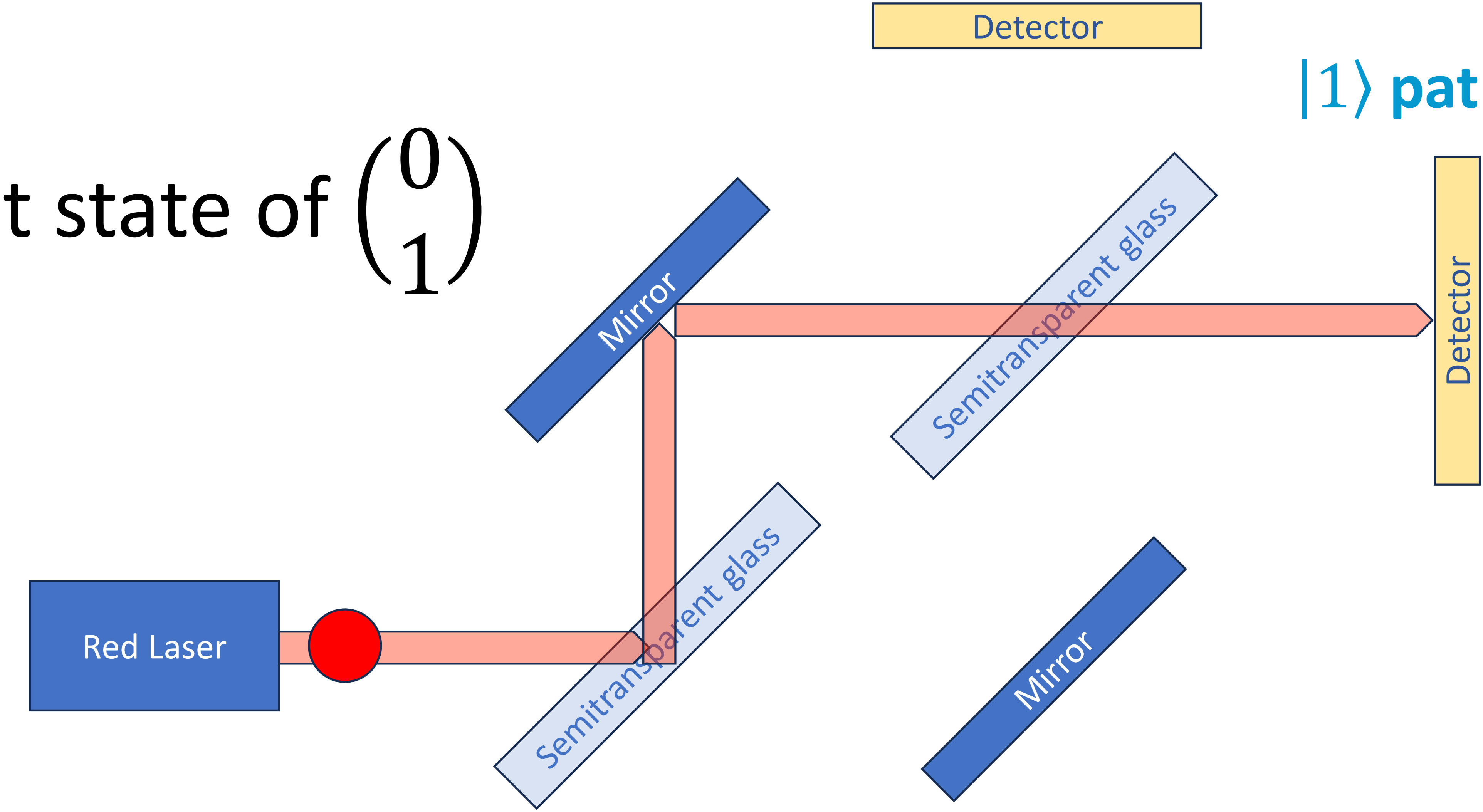
Qubit state of $\begin{pmatrix}1\\0\end{pmatrix}$

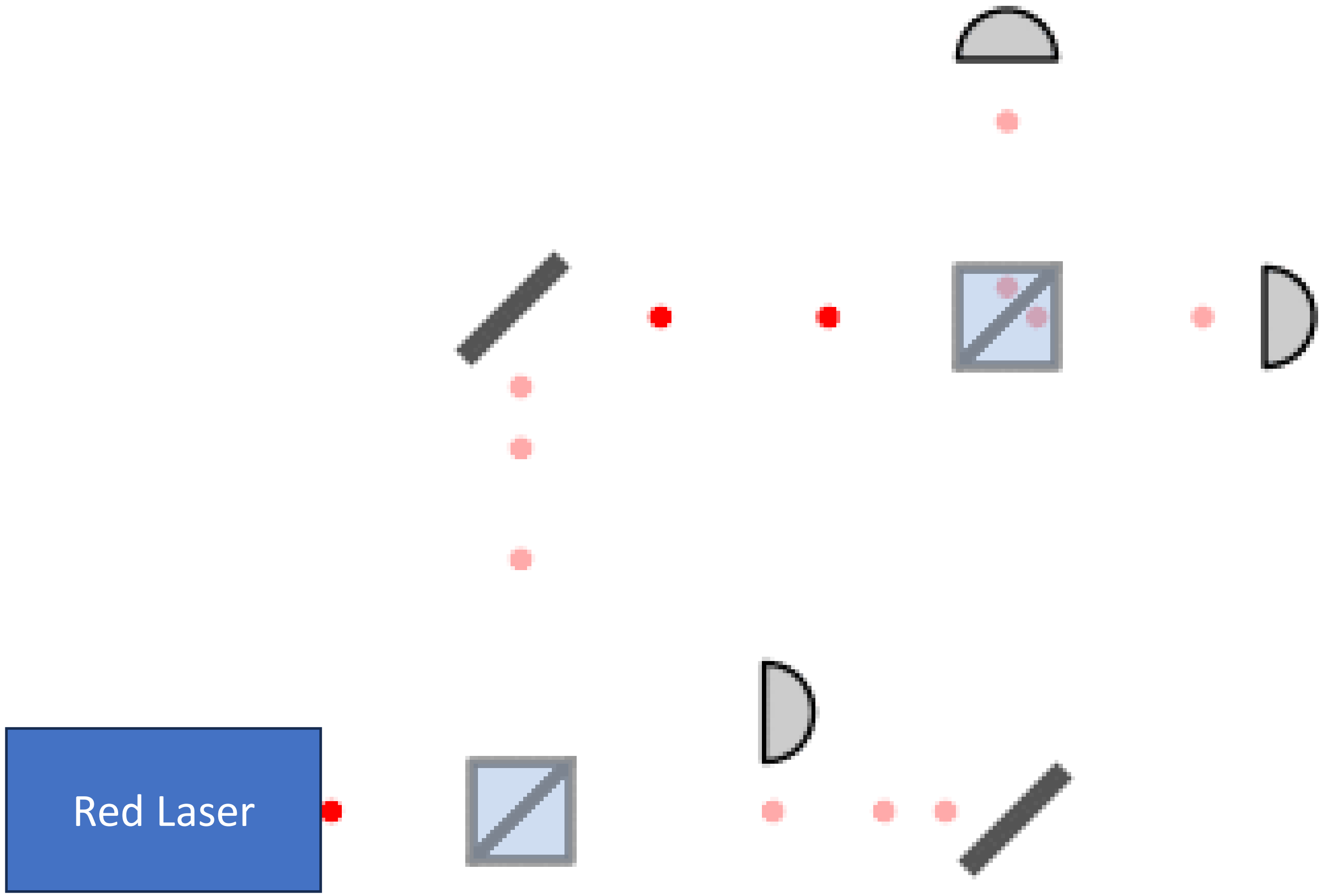
$|0\rangle$ **path**



Qubit state of $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$

$|1\rangle$ **path**





Experiment shows that photons travel only to path $|1\rangle$

Mathematical description

Qubit at the exit of the laser: $\begin{pmatrix}1\\0\end{pmatrix}$

After BS: $\alpha\begin{pmatrix}1\\0\end{pmatrix}+\beta\begin{pmatrix}0\\1\end{pmatrix}=\begin{pmatrix}\alpha\\\beta\end{pmatrix}$

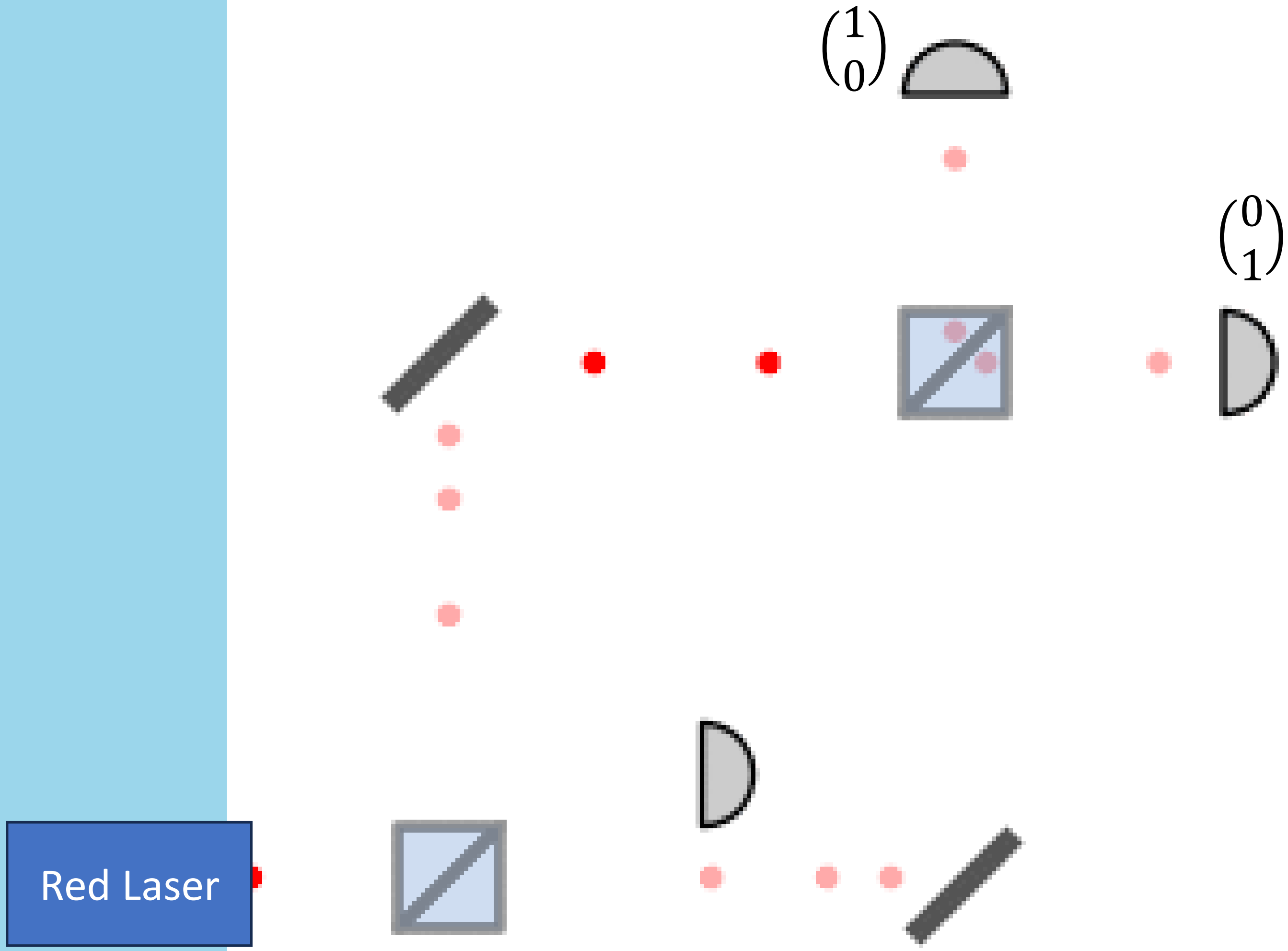
Beam-splitter operation: $A=\frac{1}{\sqrt{2}}\begin{bmatrix}1 & i\\ i & 1\end{bmatrix}$

After first beam-splitter:

$$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & i\\ i & 1\end{bmatrix}\cdot\begin{pmatrix}1\\0\end{pmatrix}=\frac{1}{\sqrt{2}}\begin{pmatrix}1\\i\end{pmatrix}$$

After second beam-splitter:

$$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & i\\ i & 1\end{bmatrix}\cdot\frac{1}{\sqrt{2}}\begin{pmatrix}1\\i\end{pmatrix}=i\begin{pmatrix}0\\1\end{pmatrix}$$



Qiskit

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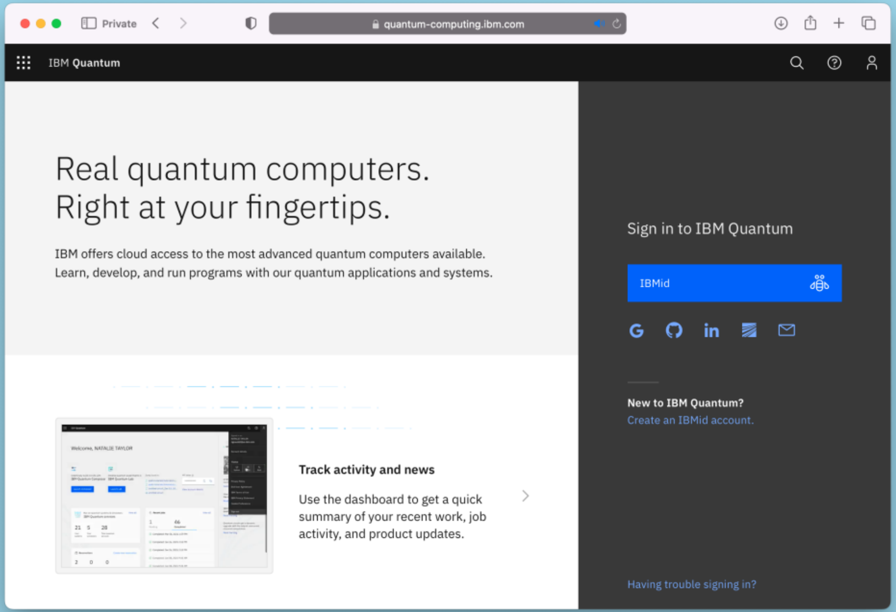

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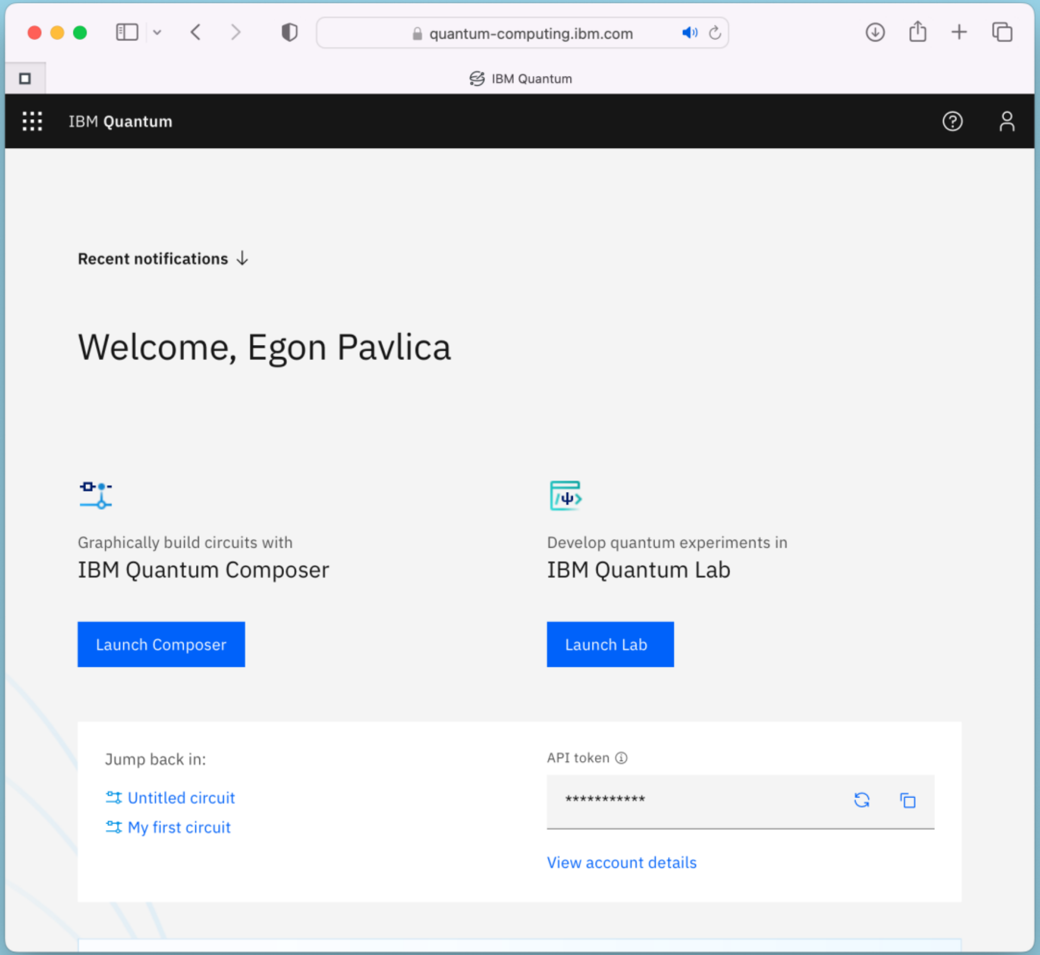


Welcome, Egon Pavlica

Graphically build circuits with
IBM Quantum Composer

Develop quantum experiments in
IBM Quantum Lab

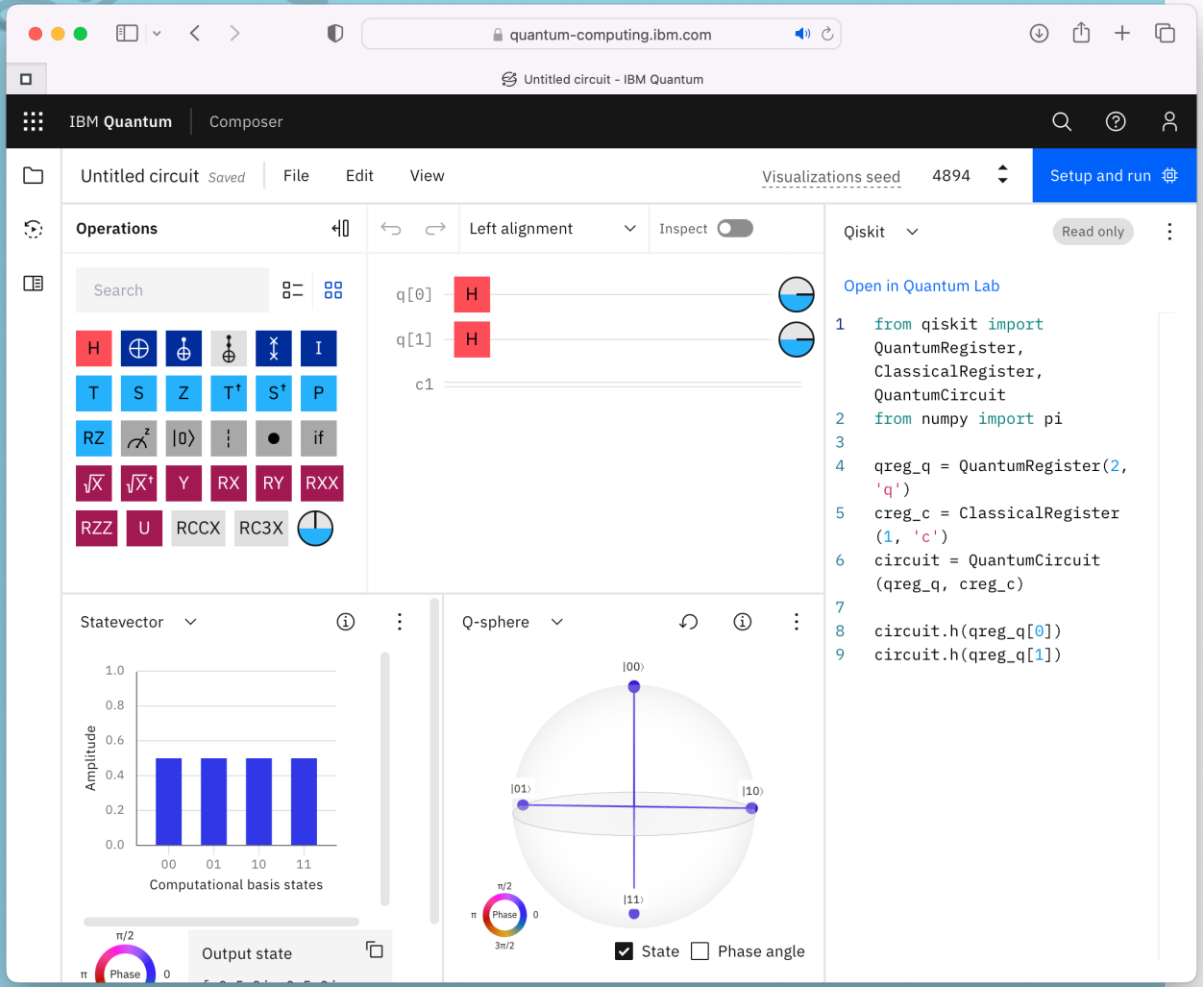
Jump back in:

API token: ***********

1. Create an account:

https://quantum-computing.ibm.com

2. Launch IBM Quantum Composer



Visualizations seed 4894

Left alignment

☑ State ☐ Phase angle

```
from qiskit import QuantumRegister, ClassicalRegister, QuantumCircuit
from numpy import pi

qreg_q = QuantumRegister(2, 'q')
creg_c = ClassicalRegister(1, 'c')
circuit = QuantumCircuit(qreg_q, creg_c)

circuit.h(qreg_q[0])
circuit.h(qreg_q[1])
```

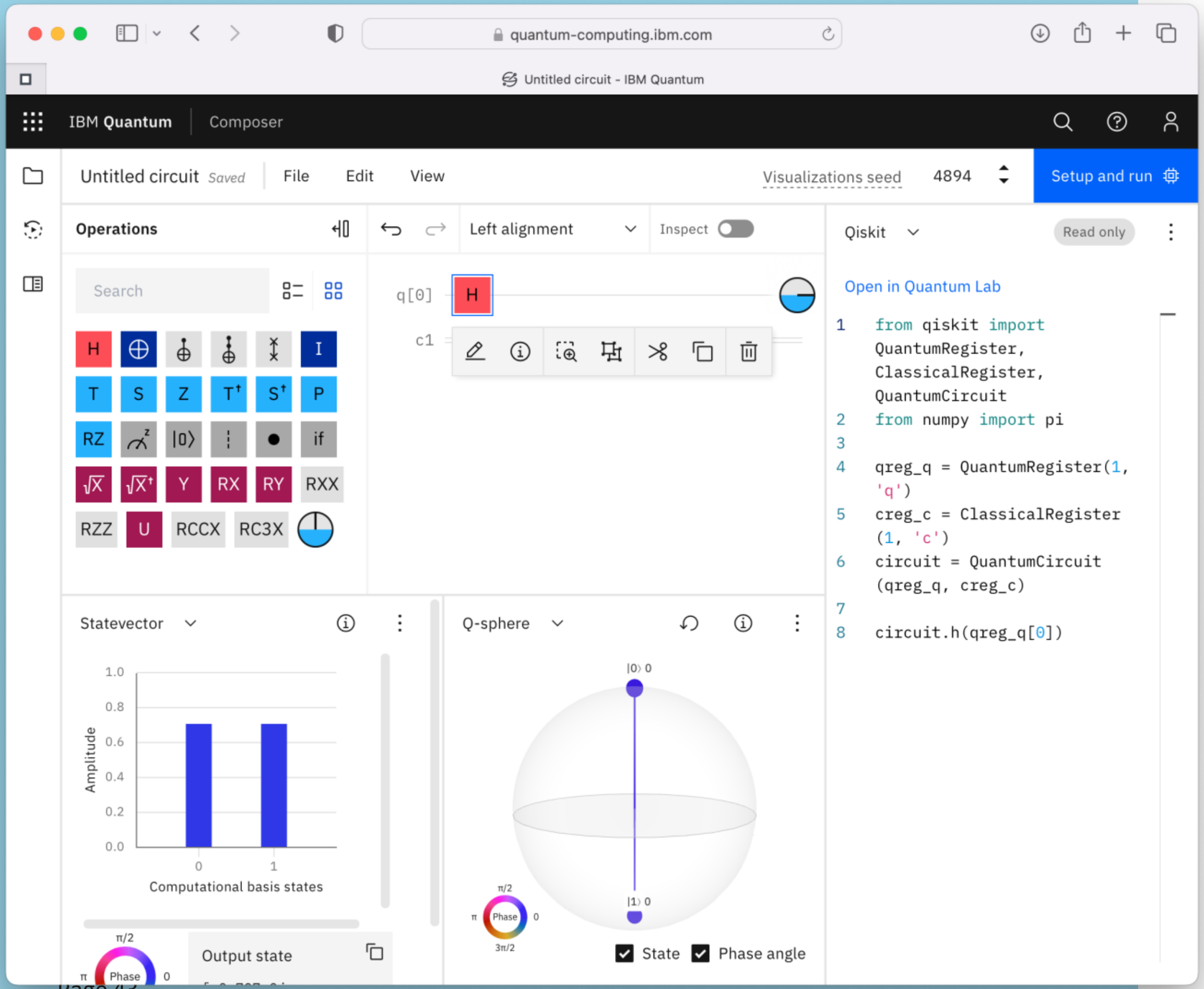
1. Create an account:

https://quantum-computing.ibm.com

2. Launch IBM Quantum Composer

3. Modify to have one, two or three qubits -> study the changes

Qiskit



```
from qiskit import QuantumRegister, ClassicalRegister, QuantumCircuit
from numpy import pi

qreg_q = QuantumRegister(1, 'q')
creg_c = ClassicalRegister(1, 'c')
circuit = QuantumCircuit(qreg_q, creg_c)

circuit.h(qreg_q[0])
```

1. Create an account:

https://quantum-computing.ibm.com

2. Launch IBM Quantum Composer

3. Modify to have one, two or three qubits -> **study the changes**

4. Leave only one qubit, and study **H and S operations**

Hadamard operation: $H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

Phase change: $S = \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$

Setup Beam-splitter gate

1st Beam-splitter: $A\begin{bmatrix}1\\0\end{bmatrix}=\frac{1}{\sqrt{2}}\begin{bmatrix}1 & i\\ i & 1\end{bmatrix}\begin{bmatrix}1\\0\end{bmatrix}=\frac{1}{\sqrt{2}}\begin{bmatrix}1\\i\end{bmatrix}$

$$S\cdot H\cdot S\begin{bmatrix}1\\0\end{bmatrix}=\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\ 0 & i\end{bmatrix}\cdot\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}\cdot\begin{bmatrix}1 & 0\\ 0 & i\end{bmatrix}\begin{bmatrix}1\\0\end{bmatrix}=$$

$$=\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\ 0 & i\end{bmatrix}\cdot\begin{bmatrix}1 & i\\ 1 & -i\end{bmatrix}\begin{bmatrix}1\\0\end{bmatrix}=$$

$$=\frac{1}{\sqrt{2}}\begin{bmatrix}1 & i\\ i & 1\end{bmatrix}\begin{bmatrix}1\\0\end{bmatrix}=\frac{1}{\sqrt{2}}\begin{bmatrix}1\\i\end{bmatrix}$$

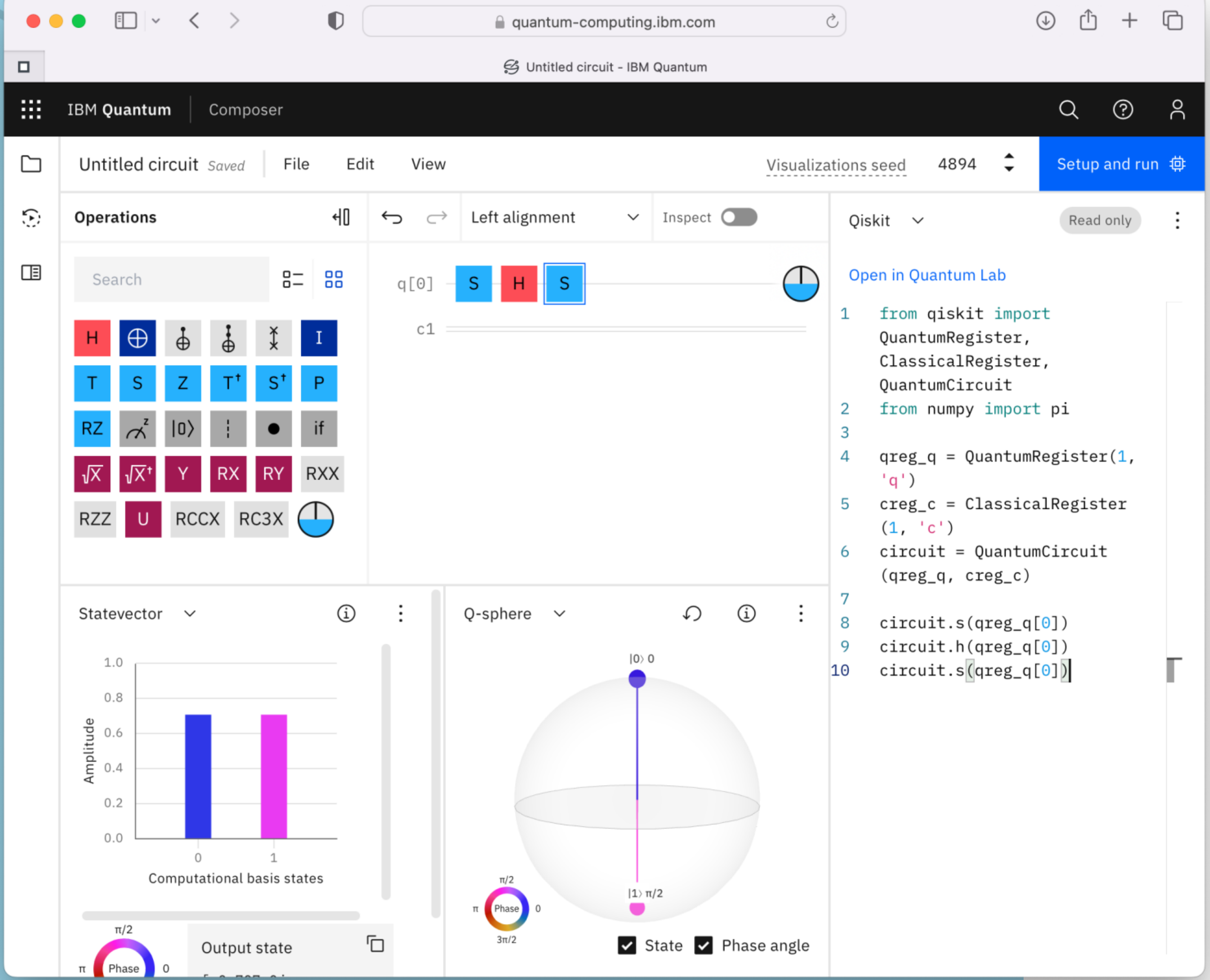
1st+2nd Beam-splitter: $A\cdot A\begin{bmatrix}1\\0\end{bmatrix}=\begin{bmatrix}0\\i\end{bmatrix}$

$$(S\cdot H\cdot S)\cdot(S\cdot H\cdot S)\begin{bmatrix}1\\0\end{bmatrix}=\begin{bmatrix}0\\i\end{bmatrix}$$

1st Beam spliter

$$S \cdot H \cdot S \begin{bmatrix} 1 \\ 0 \end{bmatrix} =$$

$$= \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ i \end{bmatrix}$$



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from numpy import pi

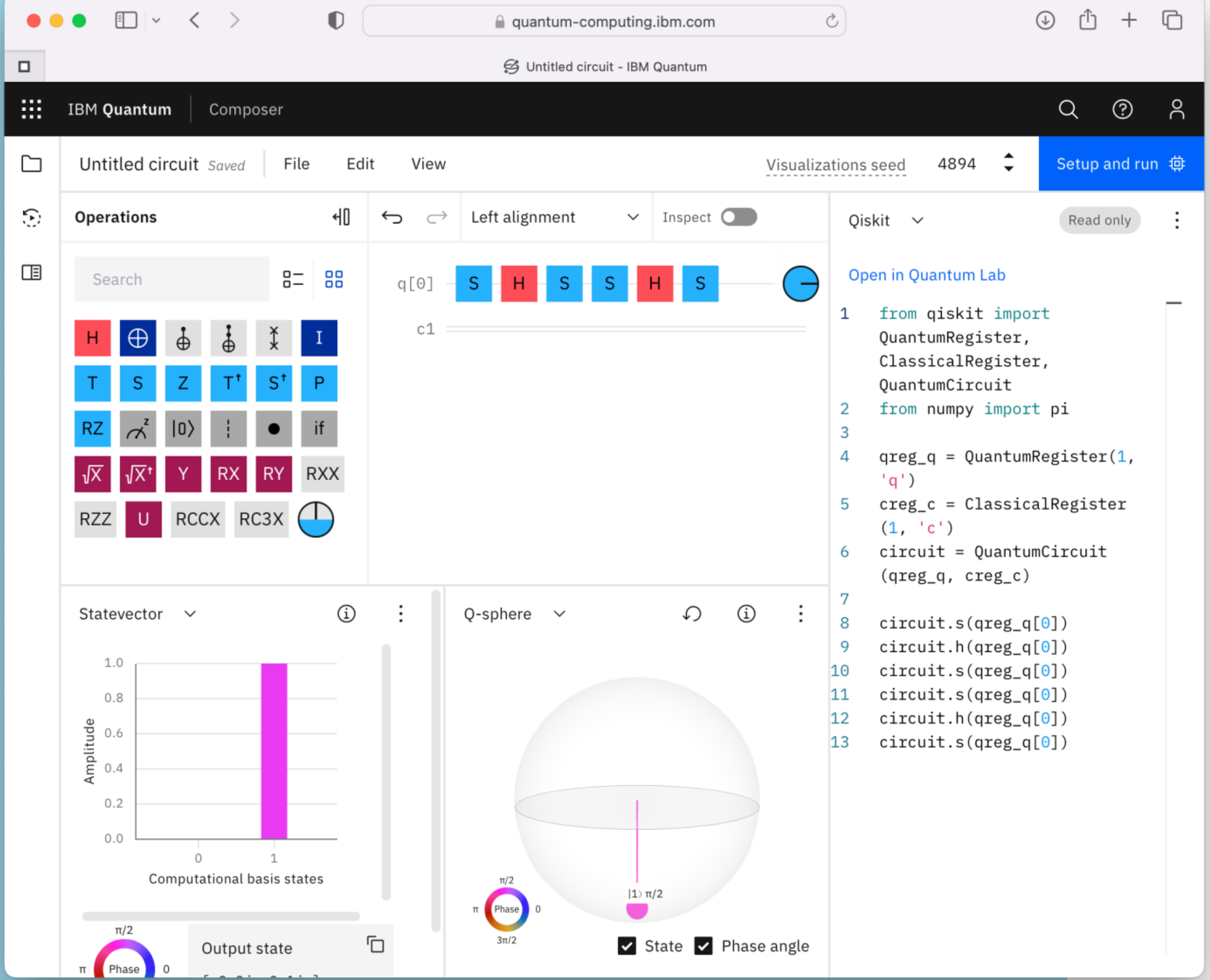
qreg_q = QuantumRegister(1, 'q')
creg_c = ClassicalRegister(1, 'c')
circuit = QuantumCircuit(qreg_q, creg_c)

circuit.s(qreg_q[0])
circuit.h(qreg_q[0])
circuit.s(qreg_q[0])
```

2nd Beam spliter

$$(S \cdot H \cdot S) \cdot (S \cdot H \cdot S) \begin{bmatrix} 1 \\ 0 \end{bmatrix} =$$

$$= \begin{bmatrix} 0 \\ i \end{bmatrix}$$



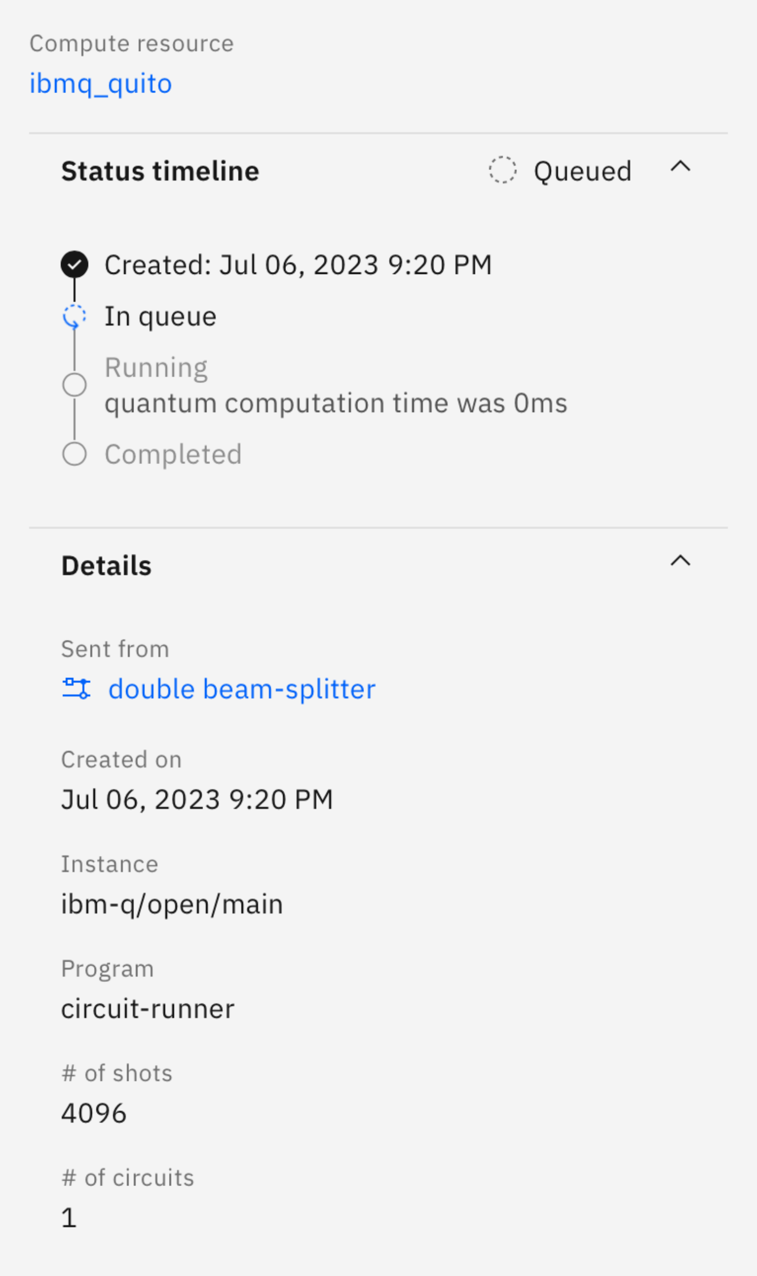
Left alignment

Visualizations seed 4894

```
from qiskit import QuantumRegister, ClassicalRegister, QuantumCircuit
from numpy import pi

qreg_q = QuantumRegister(1, 'q')
creg_c = ClassicalRegister(1, 'c')
circuit = QuantumCircuit(qreg_q, creg_c)

circuit.s(qreg_q[0])
circuit.h(qreg_q[0])
circuit.s(qreg_q[0])
circuit.s(qreg_q[0])
circuit.h(qreg_q[0])
circuit.s(qreg_q[0])
```



Compute resource

ibmq_quito

Status timeline ◌ Queued

- ● Created: Jul 06, 2023 9:20 PM
- ◌ In queue
- ○ Running
  quantum computation time was 0ms
- ○ Completed

Details

Sent from

double beam-splitter

Created on

Jul 06, 2023 9:20 PM

Instance

ibm-q/open/main

Program

circuit-runner

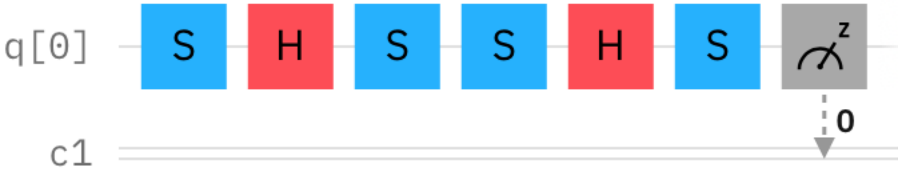
# of shots

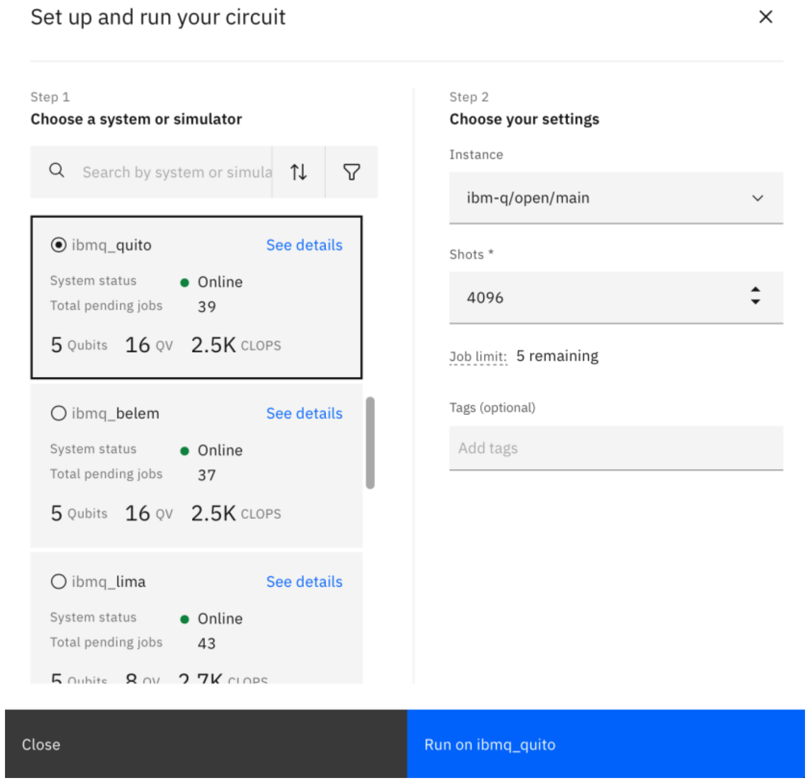
4096

# of circuits

1

Add a measure and run the quantum program!





Set up and run your circuit

Step 1

Choose a system or simulator

Search by system or simula

● ibmq_quito — See details

System status: Online

Total pending jobs: 39

5 Qubits 16 QV 2.5K CLOPS

○ ibmq_belem — See details

System status: Online

Total pending jobs: 37

5 Qubits 16 QV 2.5K CLOPS

○ ibmq_lima — See details

System status: Online

Total pending jobs: 43

5 Qubits 8 QV 2.7K CLOPS

Step 2

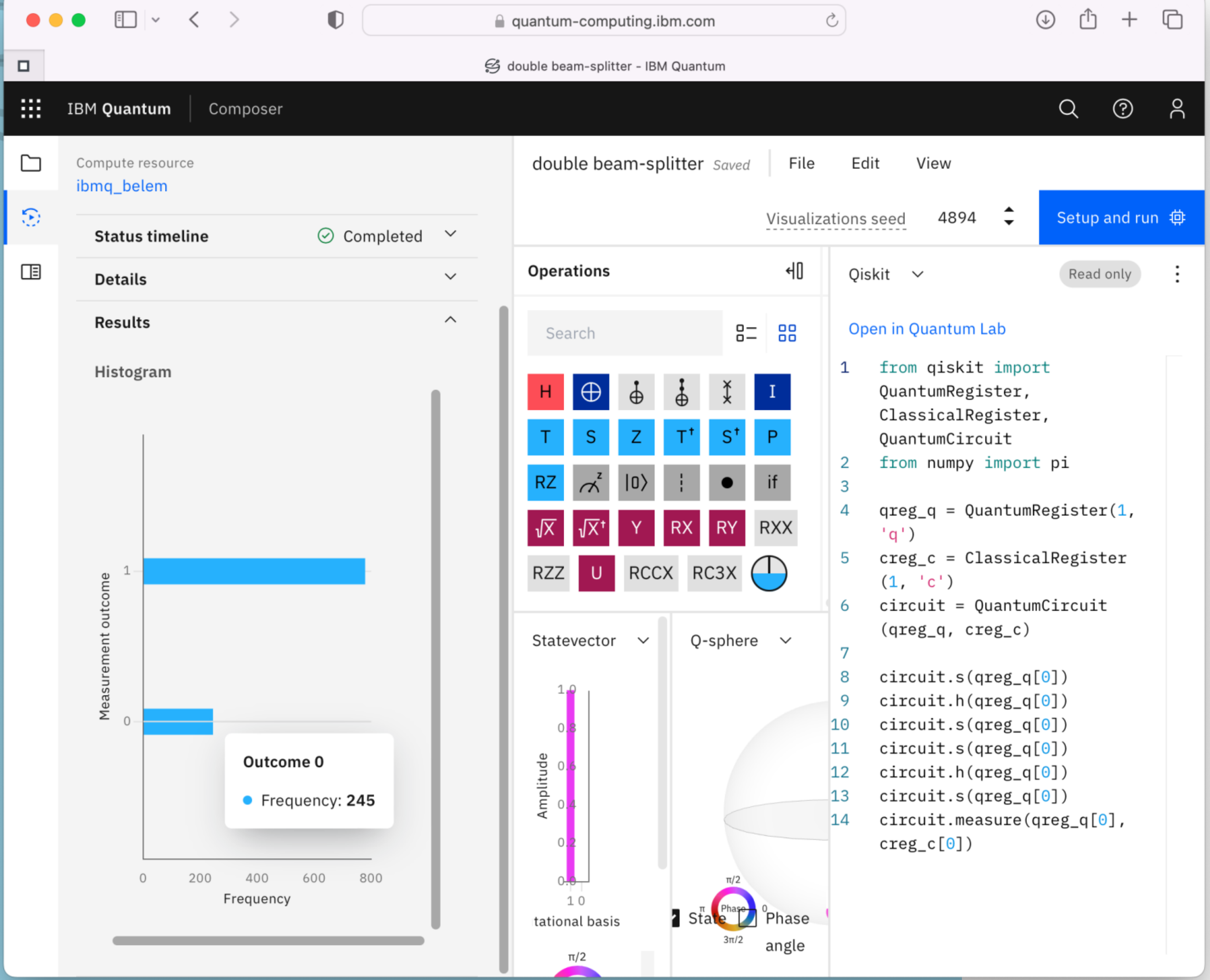
Choose your settings

Instance: ibm-q/open/main

Shots *: 4096

Job limit: 5 remaining

Tags (optional): Add tags



Compute resource: ibmq_belem

double beam-splitter *Saved*

Visualizations seed: 4894

Outcome 0
Frequency: 245

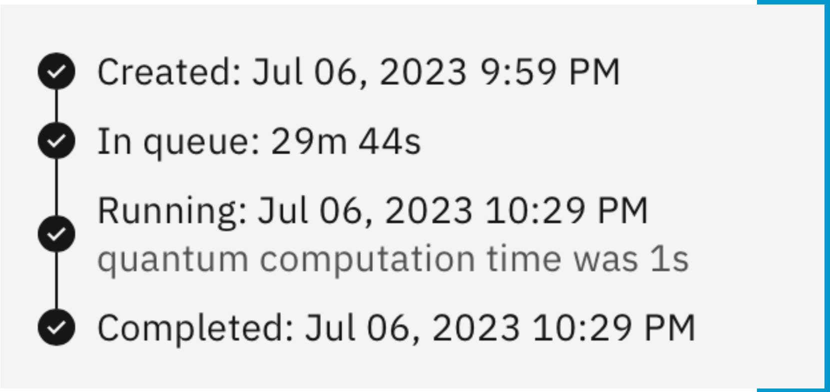
```
from qiskit import QuantumRegister, ClassicalRegister, QuantumCircuit
from numpy import pi

qreg_q = QuantumRegister(1, 'q')
creg_c = ClassicalRegister(1, 'c')
circuit = QuantumCircuit(qreg_q, creg_c)

circuit.s(qreg_q[0])
circuit.h(qreg_q[0])
circuit.s(qreg_q[0])
circuit.s(qreg_q[0])
circuit.h(qreg_q[0])
circuit.s(qreg_q[0])
circuit.measure(qreg_q[0], creg_c[0])
```

Check the number of |0> and |1>

Note: *Real quantum computers have also errors!*



- ✓ Created: Jul 06, 2023 9:59 PM
- ✓ In queue: 29m 44s
- ✓ Running: Jul 06, 2023 10:29 PM
  quantum computation time was 1s
- ✓ Completed: Jul 06, 2023 10:29 PM

REGINNA 4.0

Want more? Take the red pill ;)

Egon Pavlica (mailto:egon.pavlica@ung.si)

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