REGINNA 4.0

Introduction to Quantum Computing

Prof. dr. Egon Pavlica

University of Nova Gorica

Supported by

eit Manufacturing

Funded by the European Union

EIT HEI Initiative
eit-hei.eu

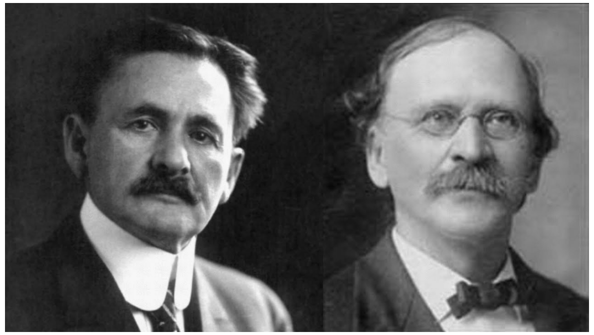
www.reginna4-0.eu

Outline

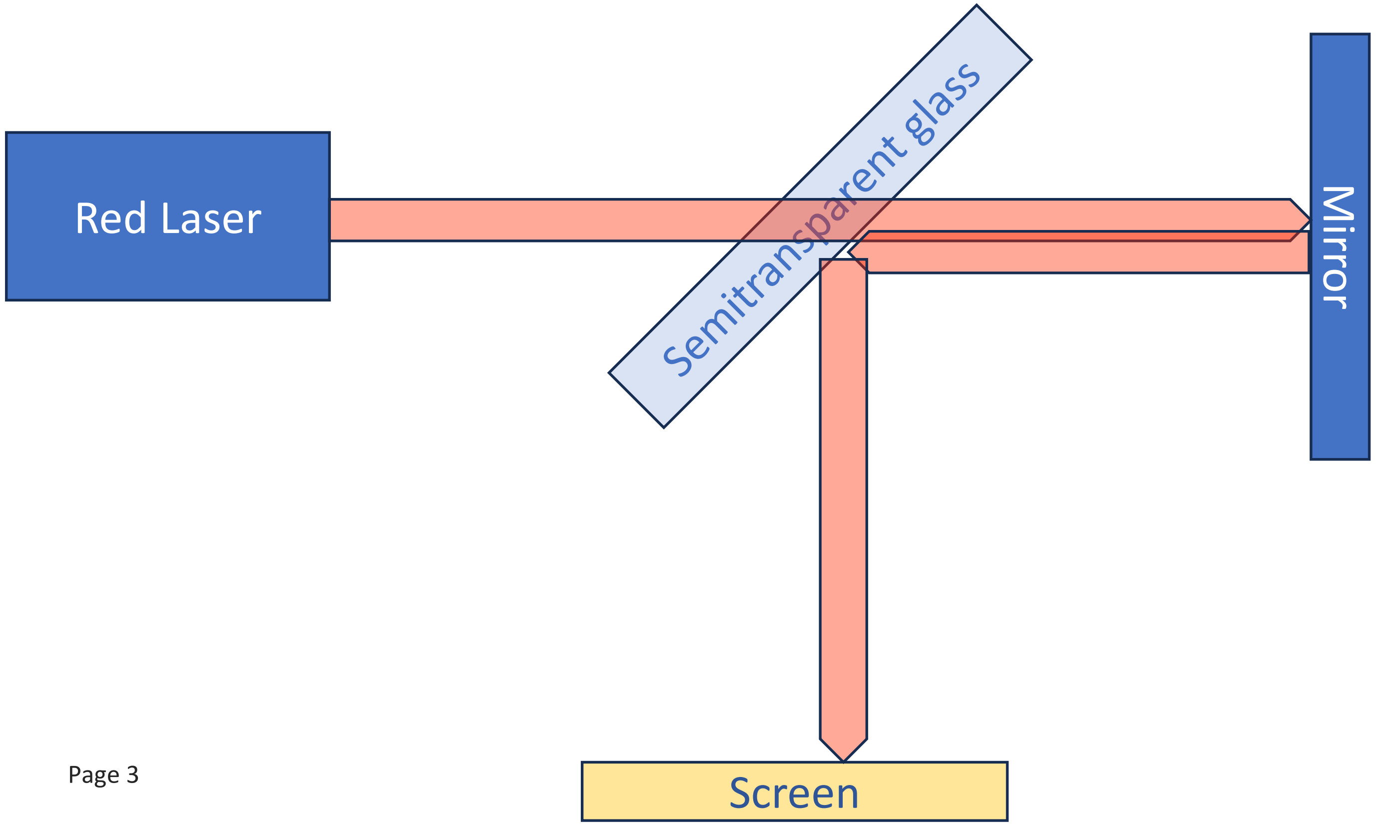
- Michelson-Morley experiment
- Two-slits experiement
- Classical computer
- Introduction to qubit
- Two beam—splitters‘ experiment
- Mathematical description of two beam-splitters‘ experiment
- Tutorial on quantum computer (Qiskit)

Leon, 3.5.2024

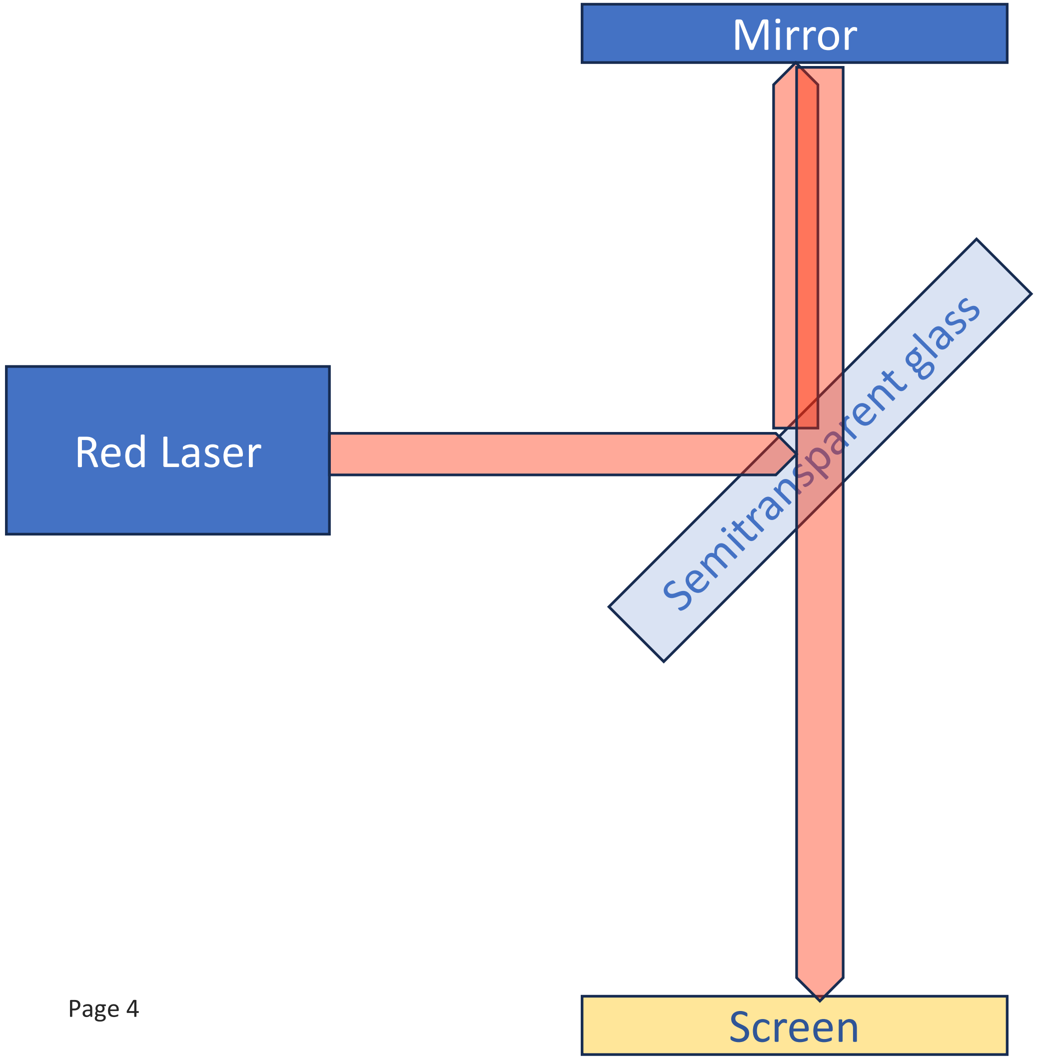
Michelson – Morley experiment



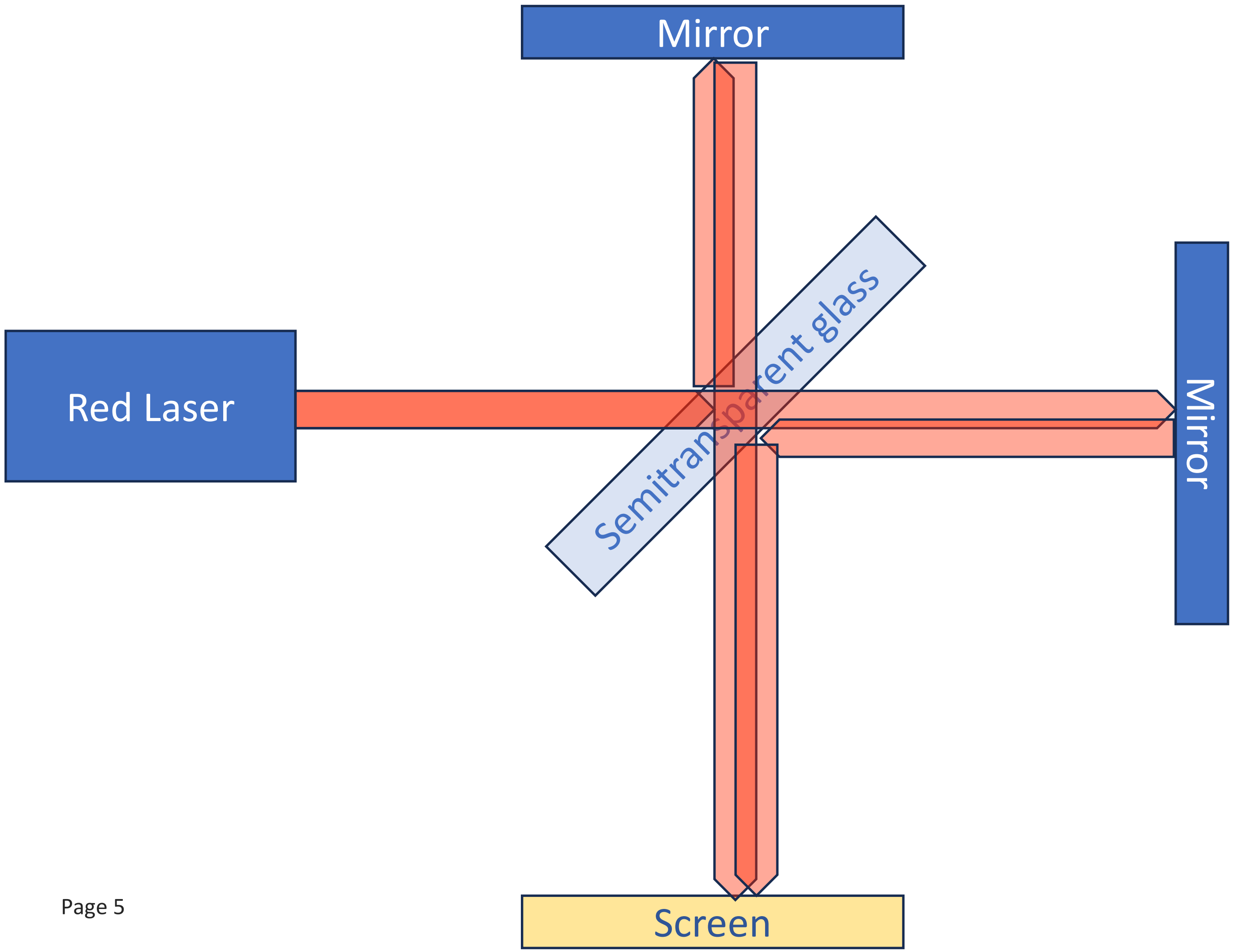
between April and July 1887



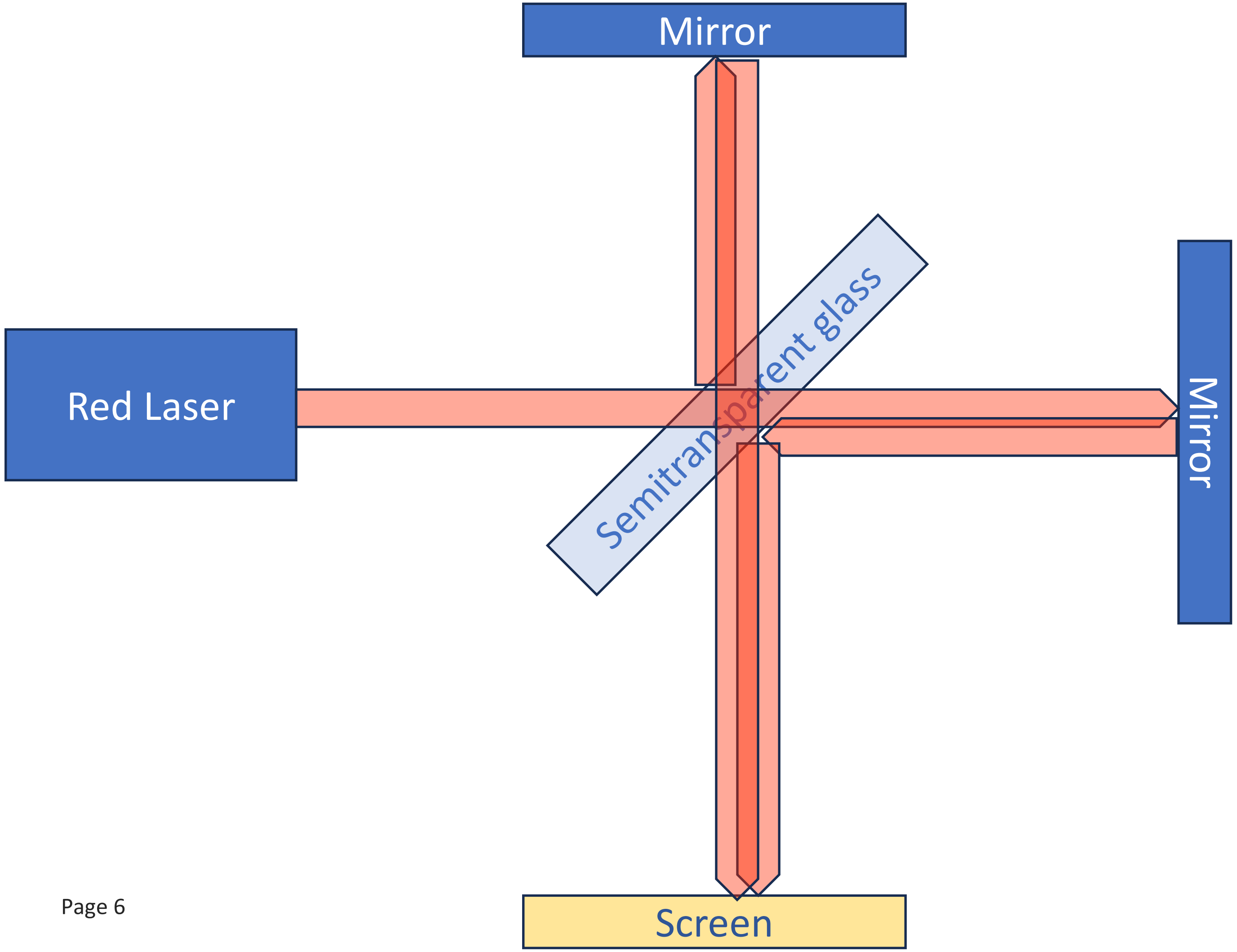
Michelson – Morley experiment

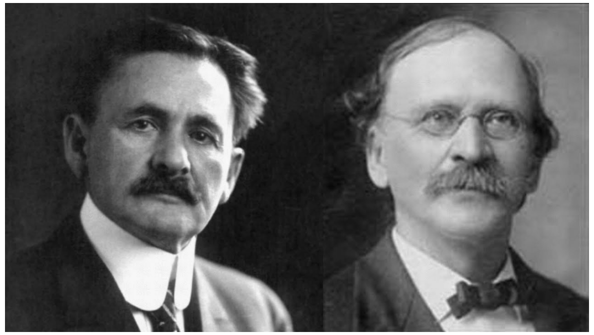


Michelson – Morley experiment

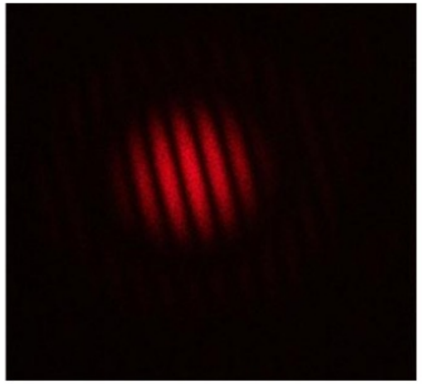


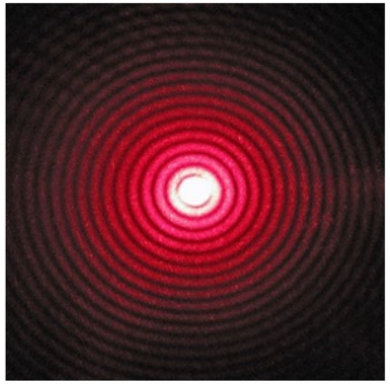
Michelson – Morley experiment



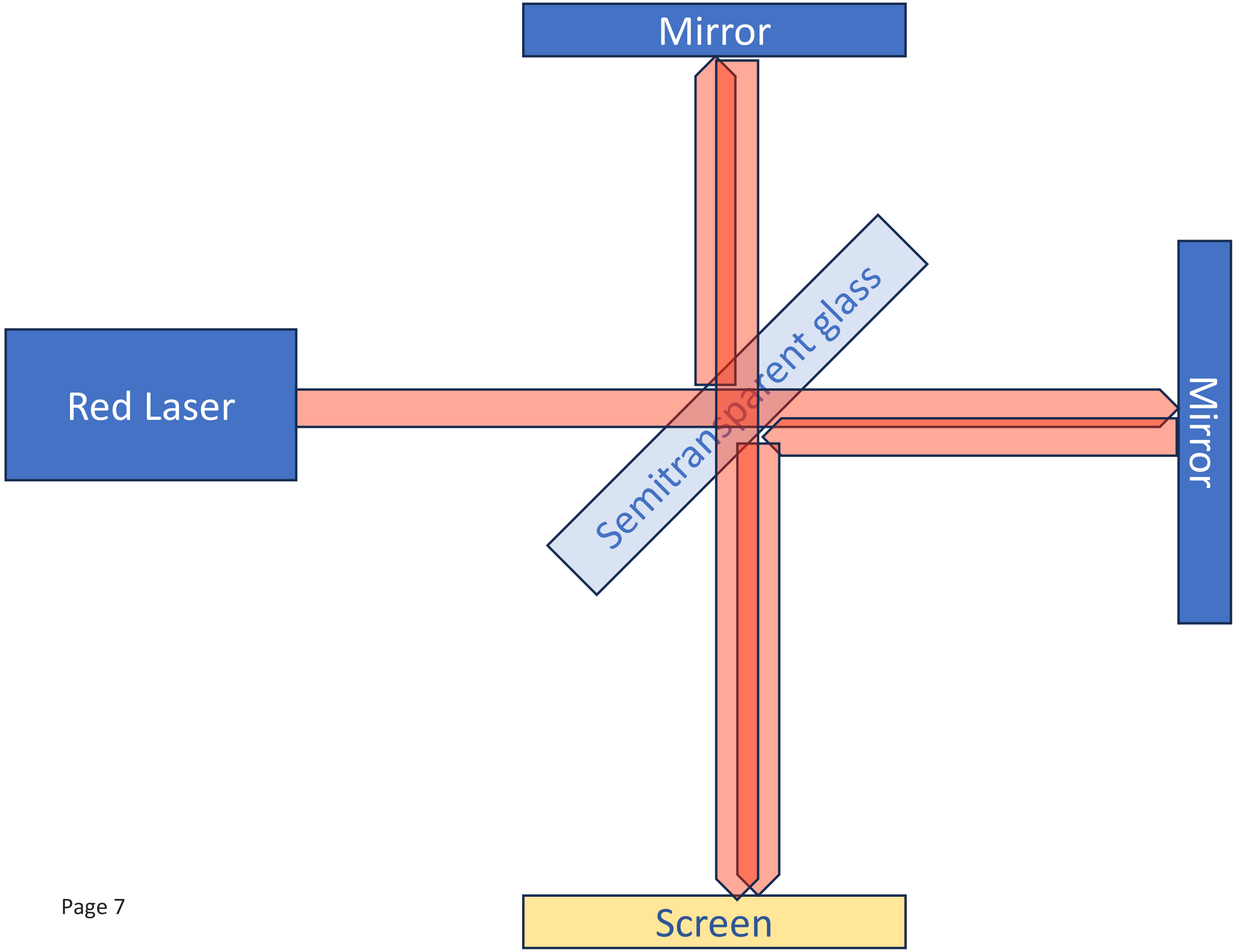


between April and July 1887

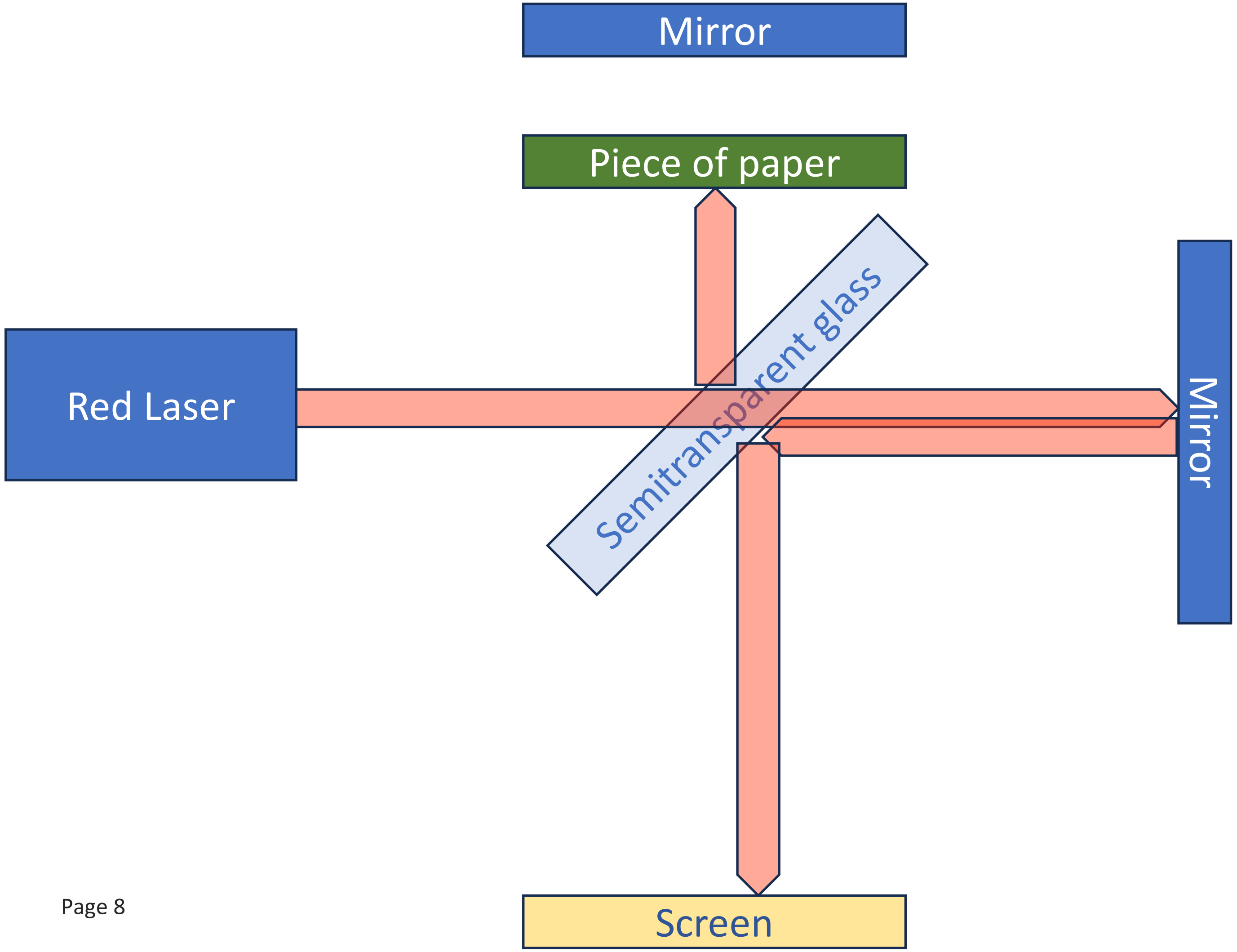




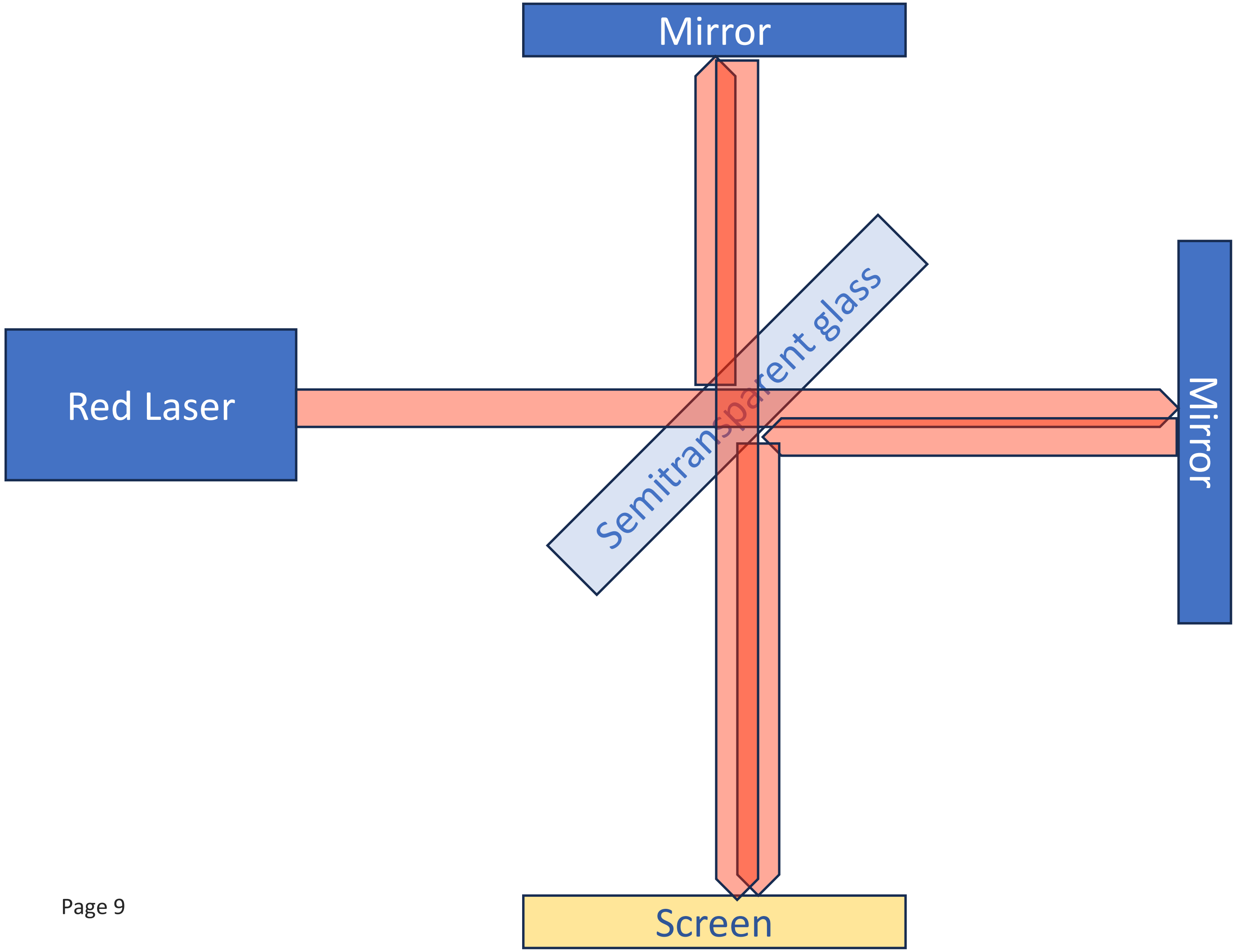
Michelson – Morley experiment



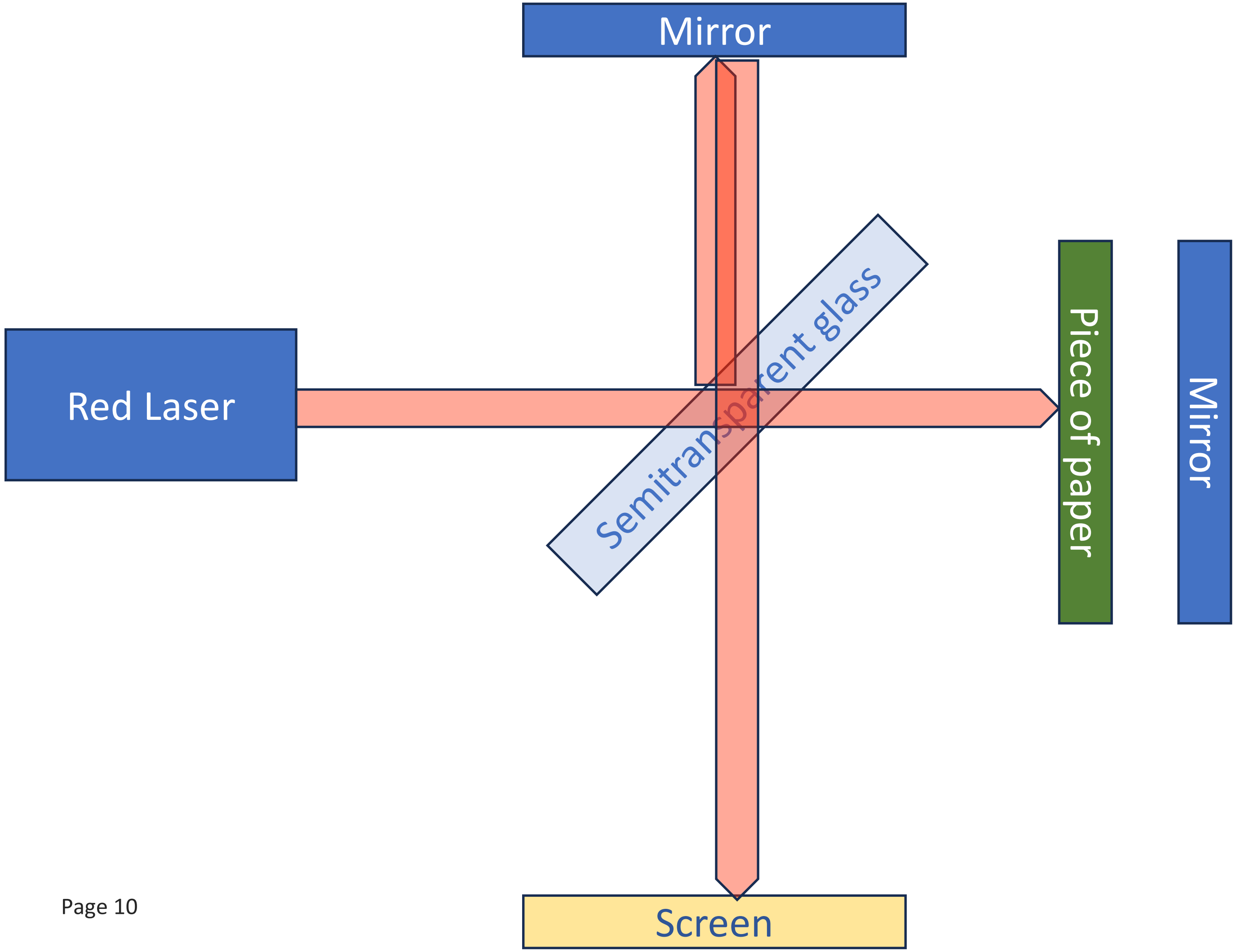
Michelson – Morley experiment



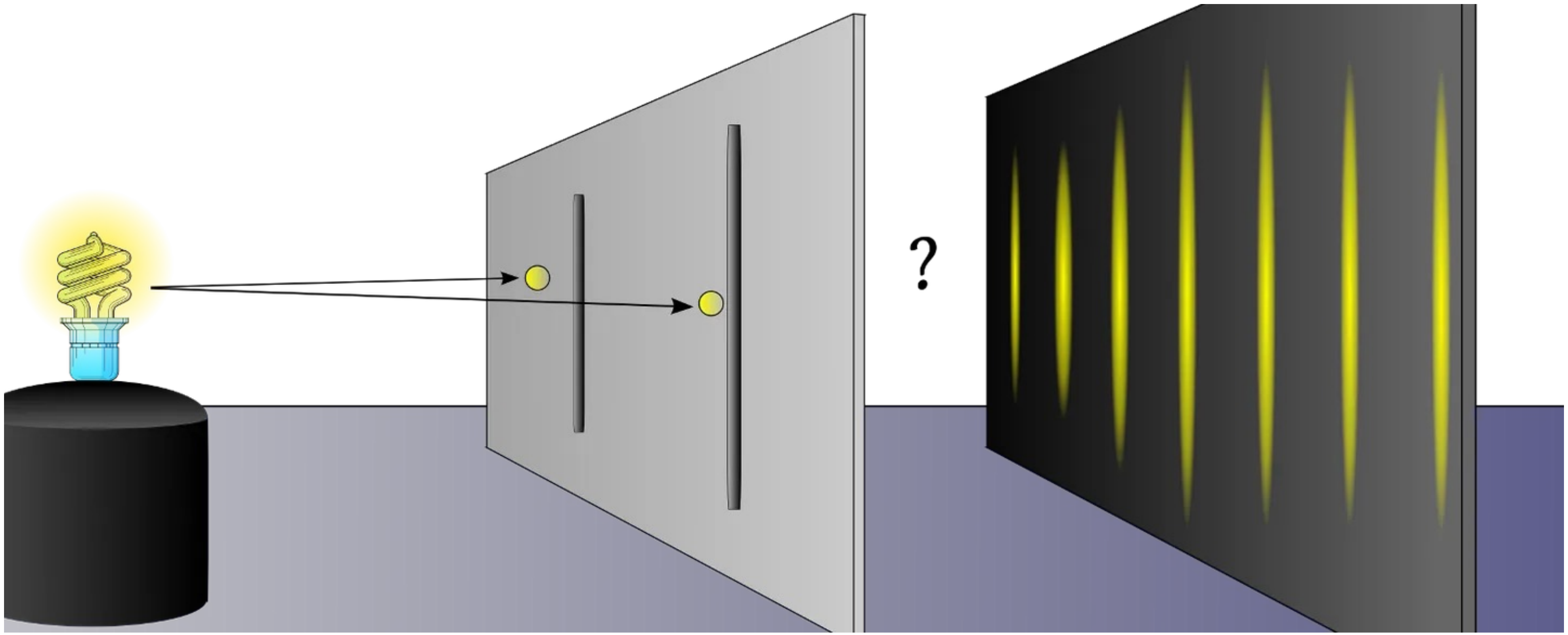
Michelson – Morley experiment



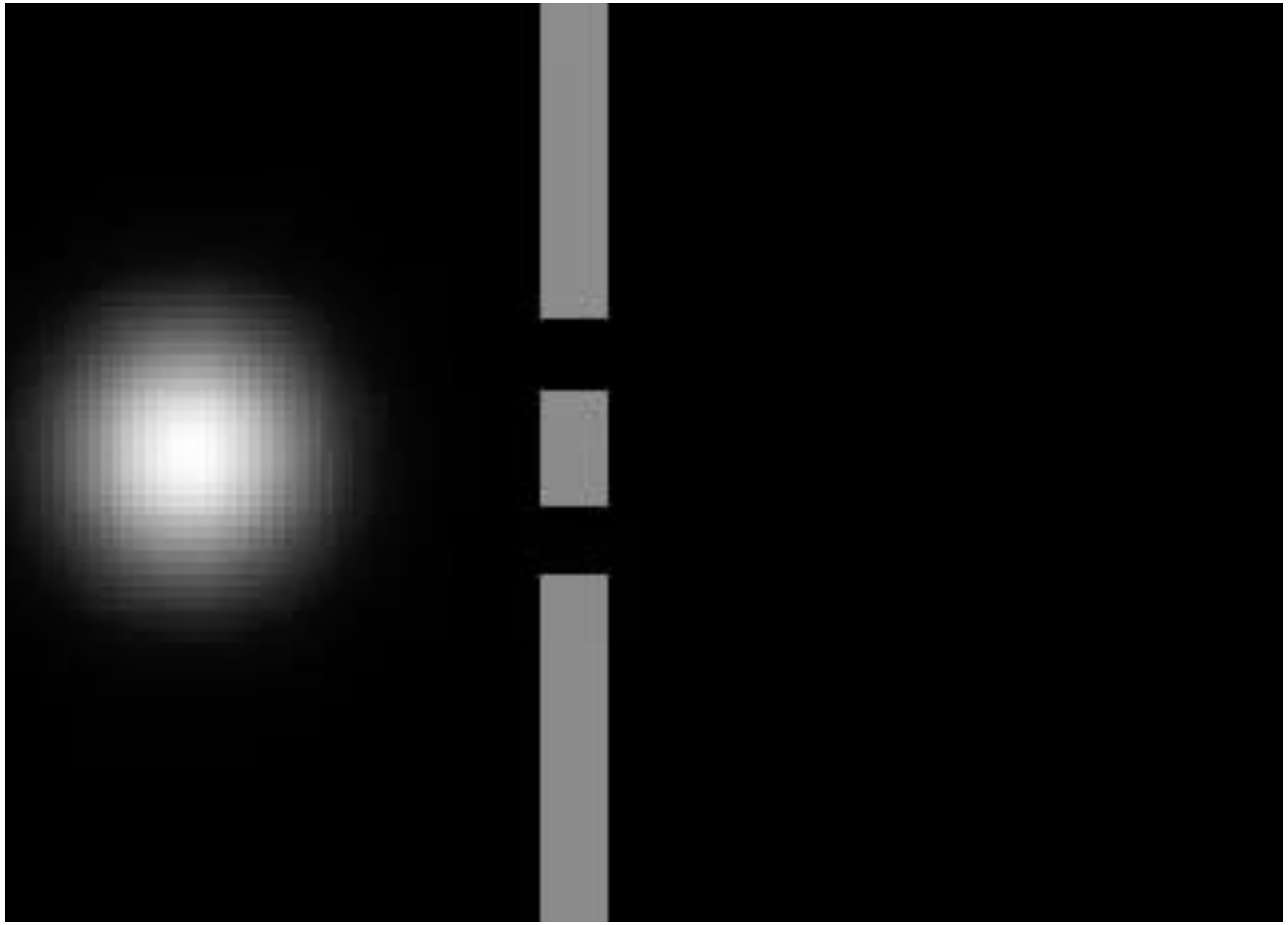
Michelson – Morley experiment



Two-slits experiment setup

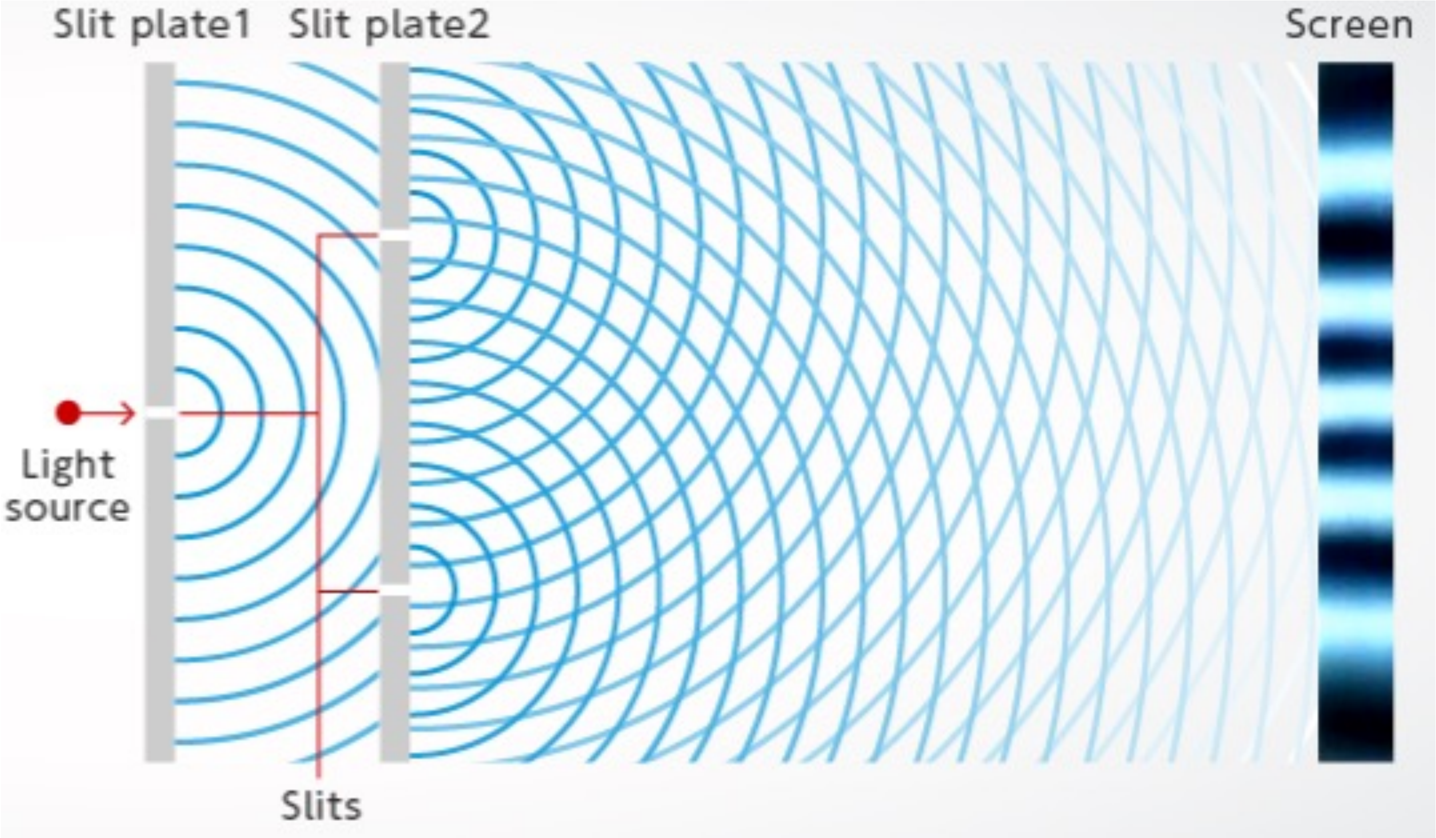


Two-slits experiment computer simulation

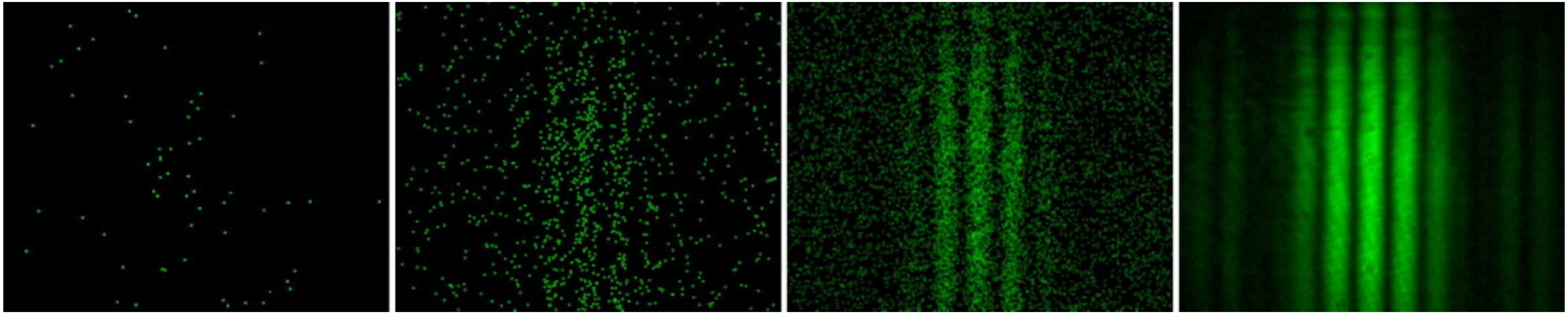


computer simulation

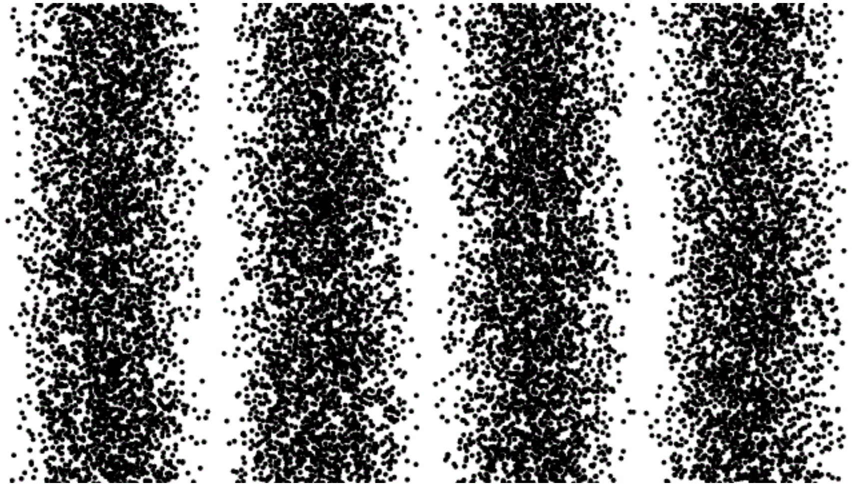
Two-slits experiment



Two-slits experiment with low light intensity

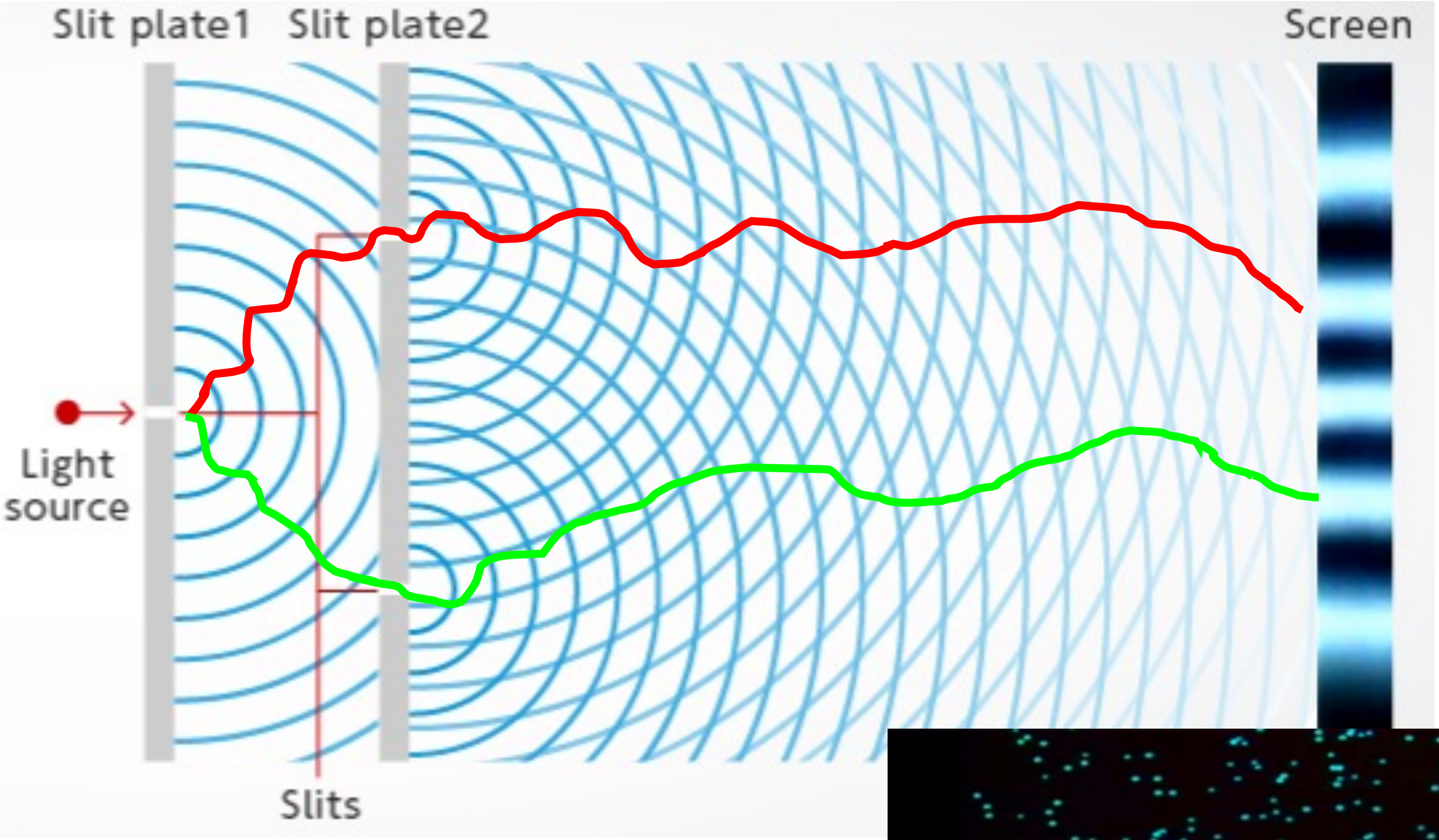


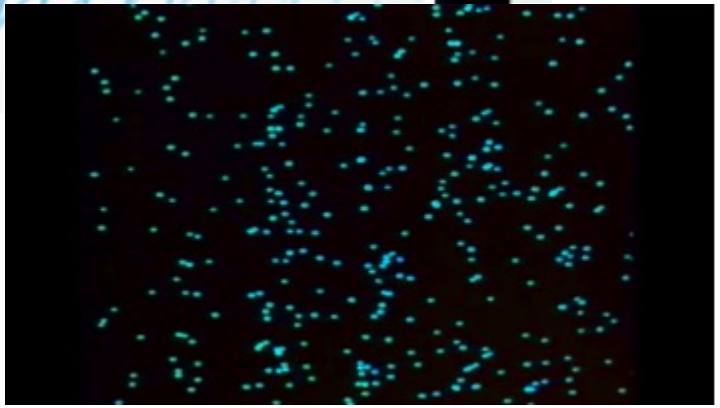
number of photons

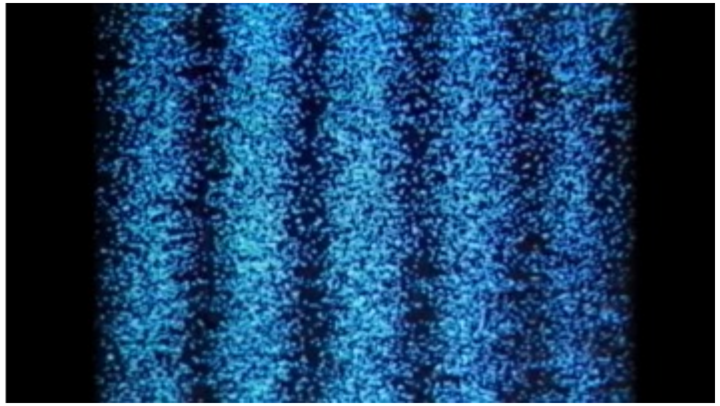


computer simulation

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

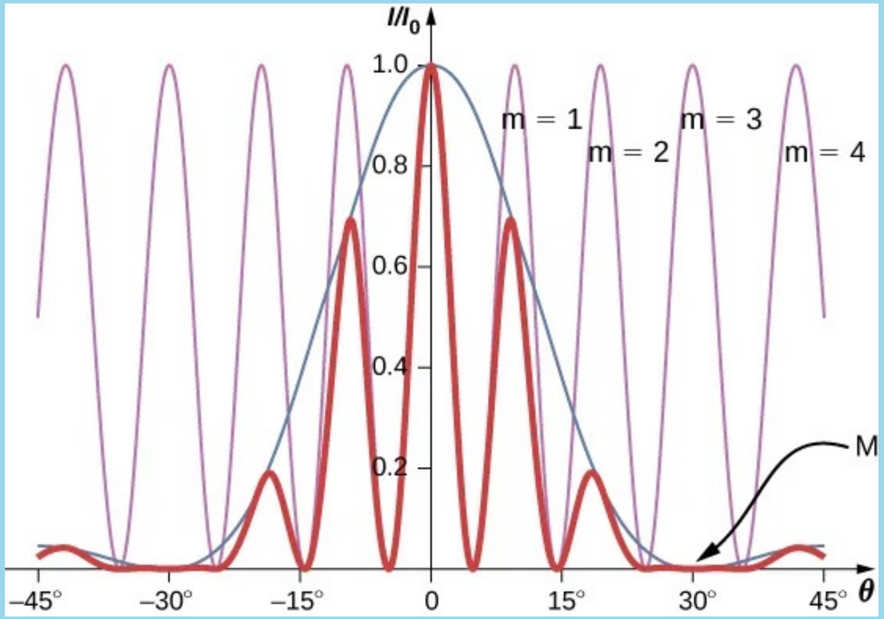






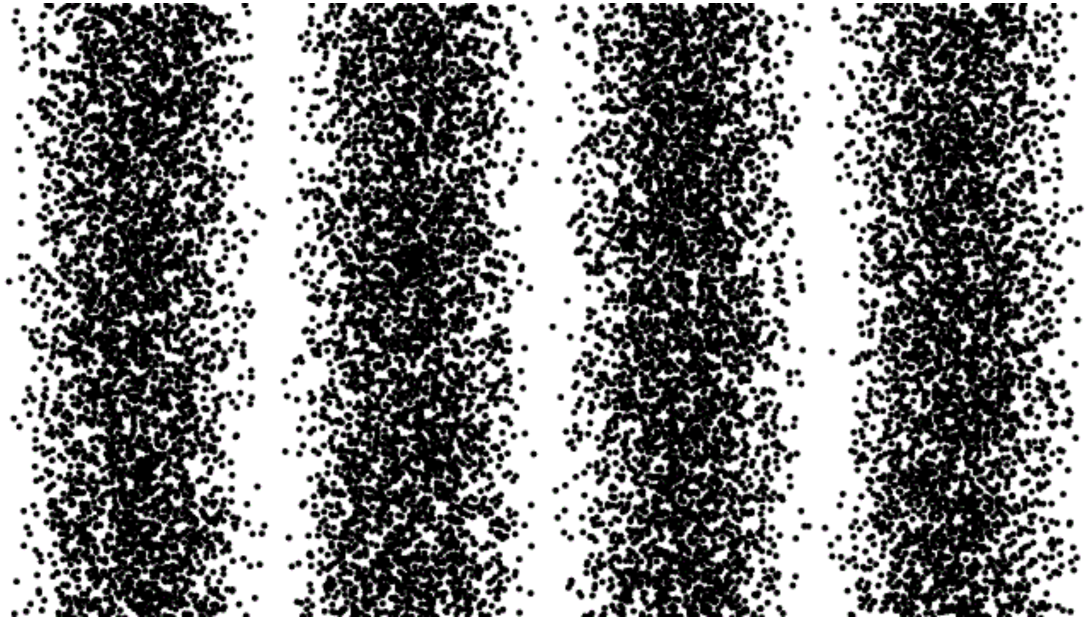
Mathematics

- 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

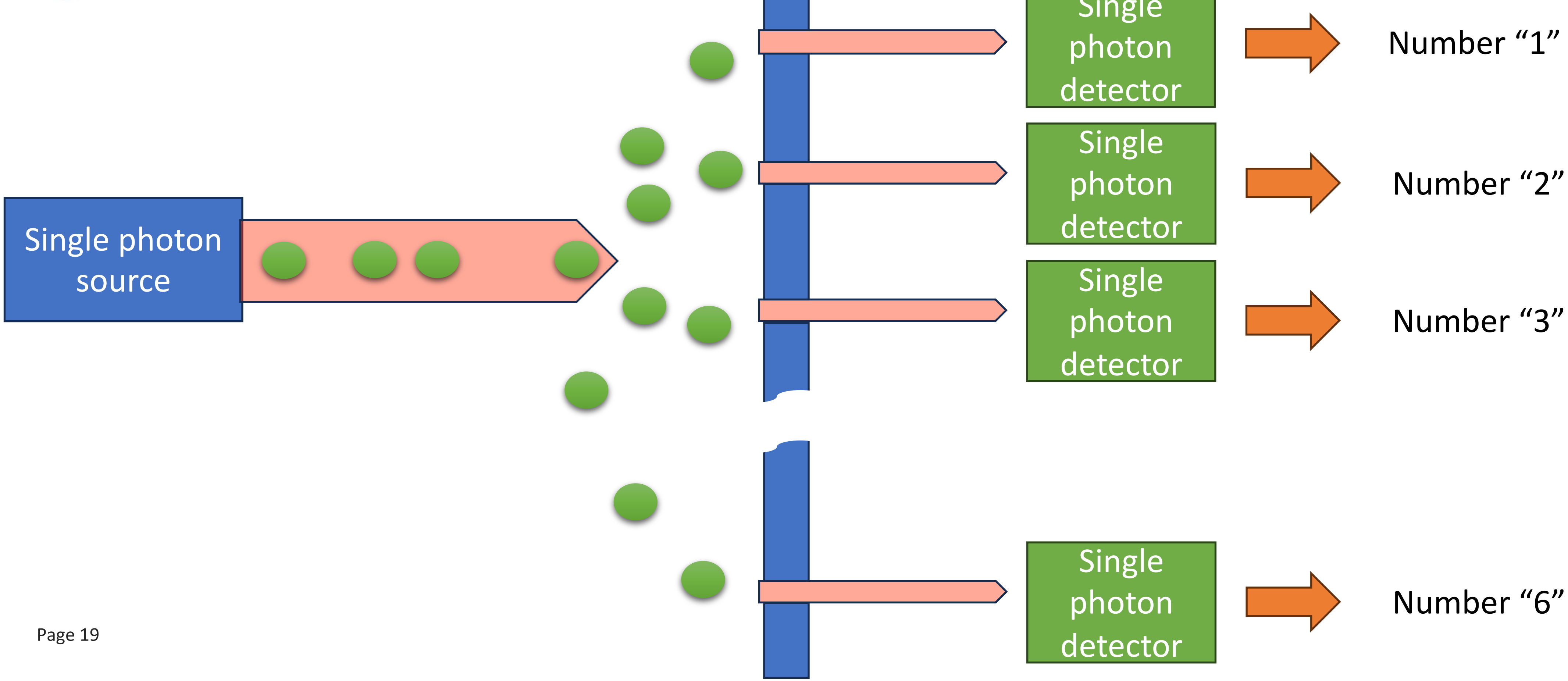
- Single photon knows where to go
- Photons interfere with each-other
- Photon obeys **quantum mechanics**



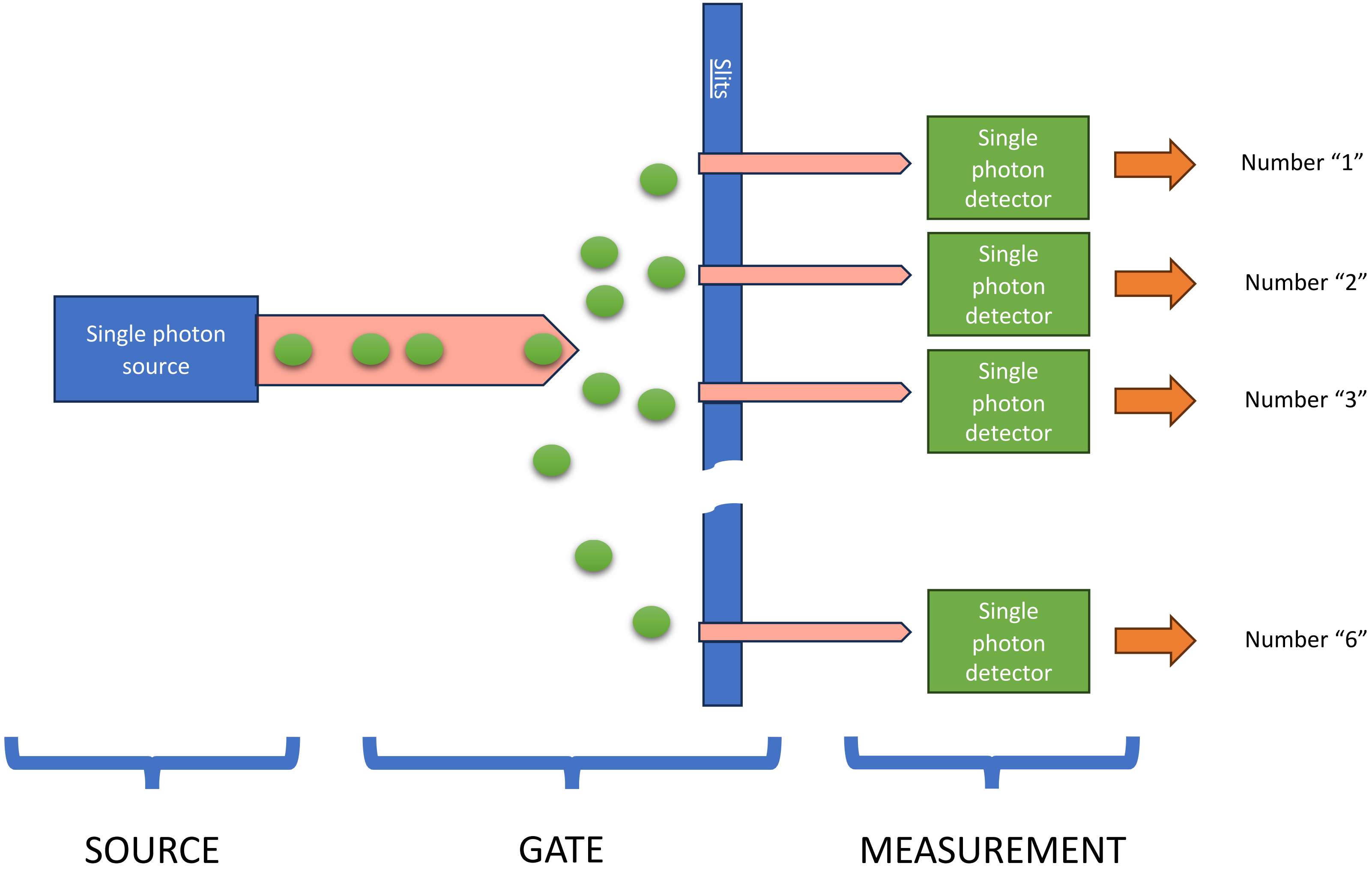
A Simple quantum computer

Task: generator of random numbers

"Quantum dice"

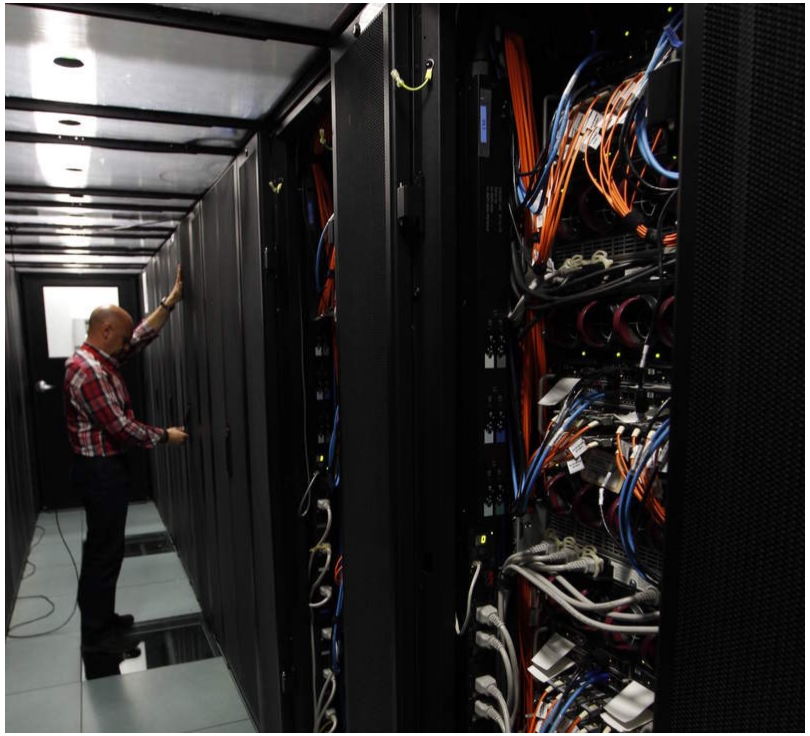


Basic blocks of quantum computer



Classical computers

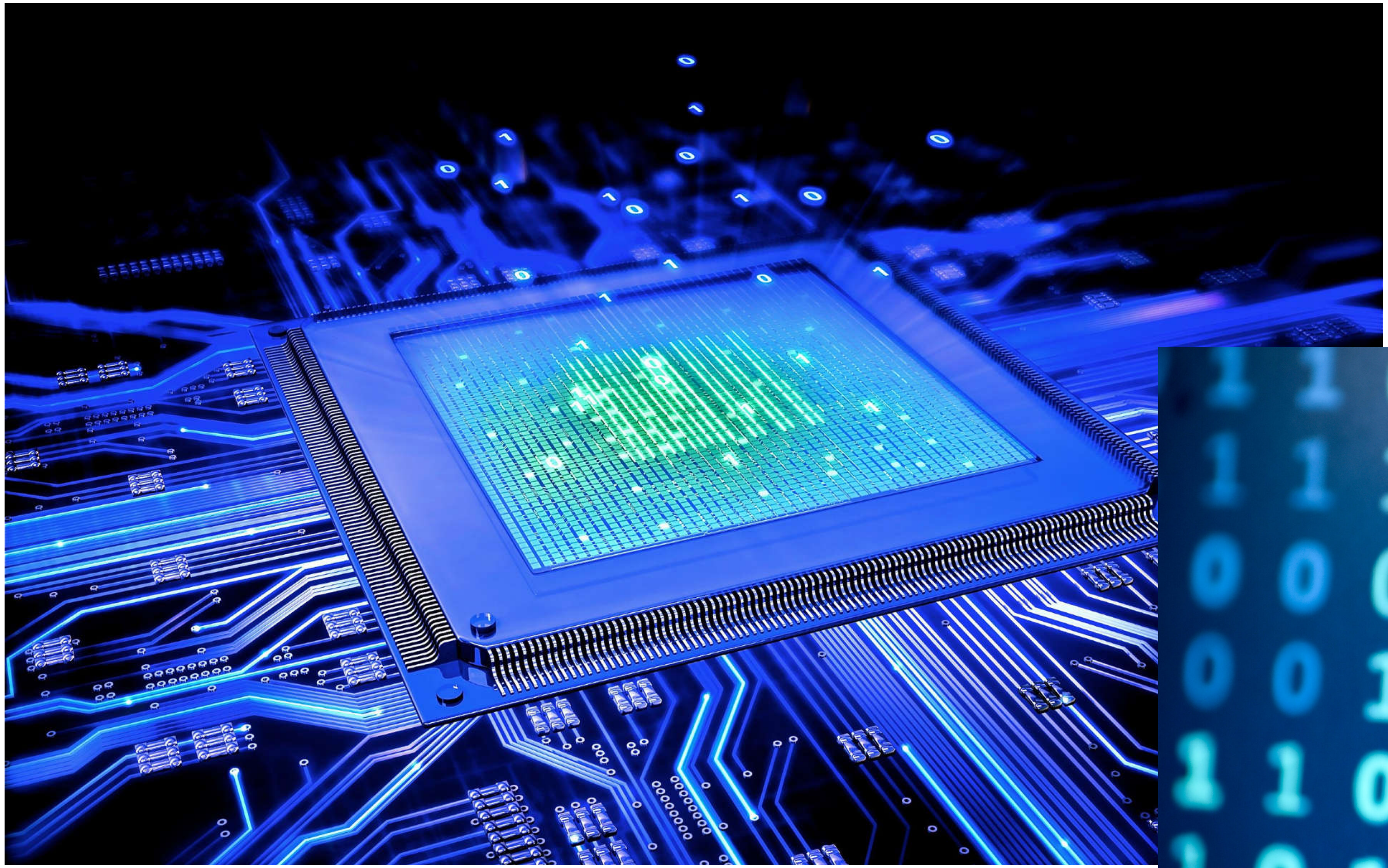
ARCTUR



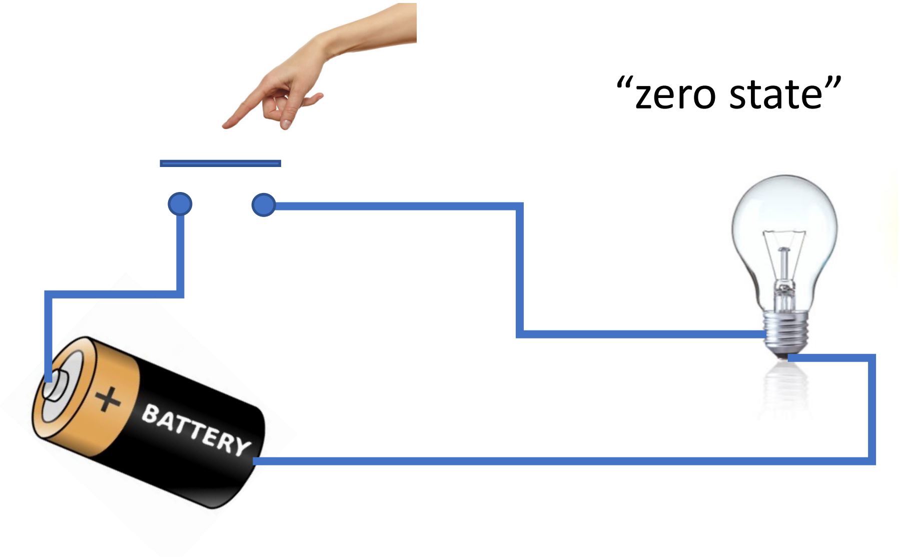
SCAYLE
SUPERCOMPUTACIÓN
CASTILLA Y LEÓN

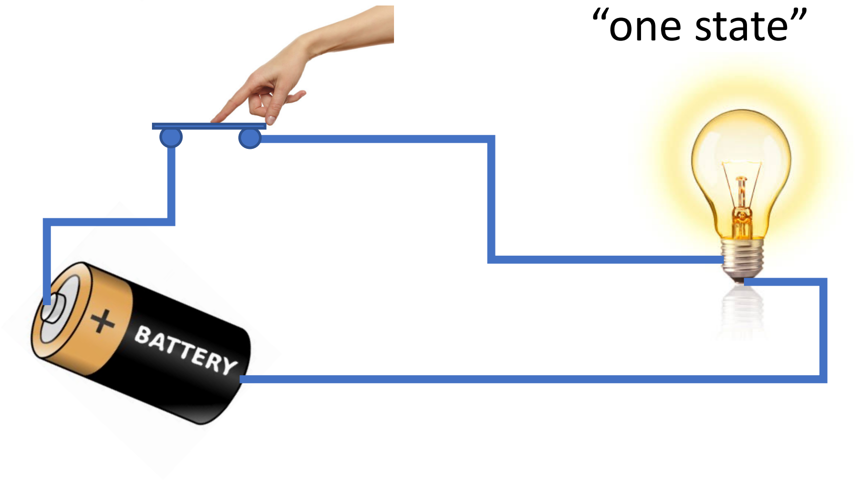
REGINNA 4.0

Classical computation is about 0 and 1

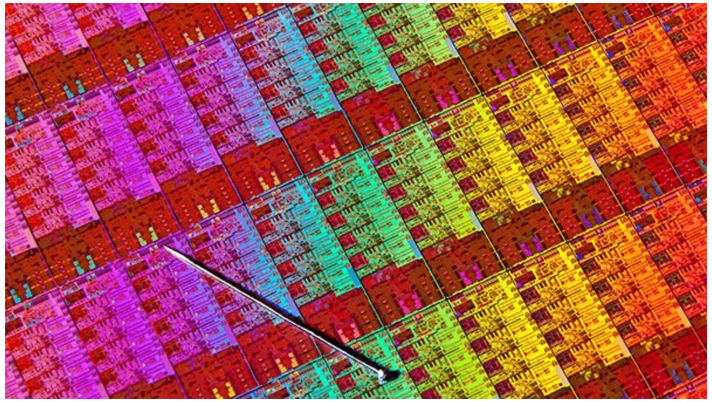


Classical computer – a box of switches



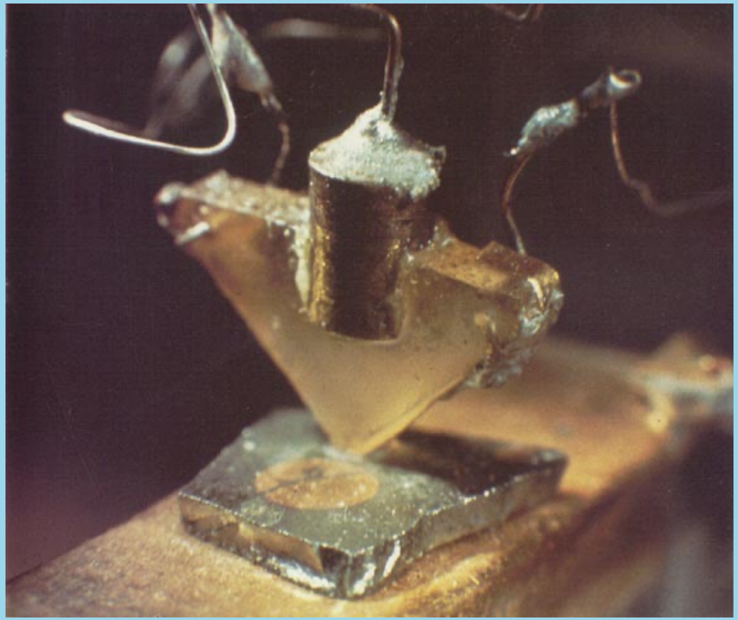


- Switch in computer is realized by a transistor
- A modern CPU has billions of transistors: e.g. Apple M2 Max - 67 billion transistors

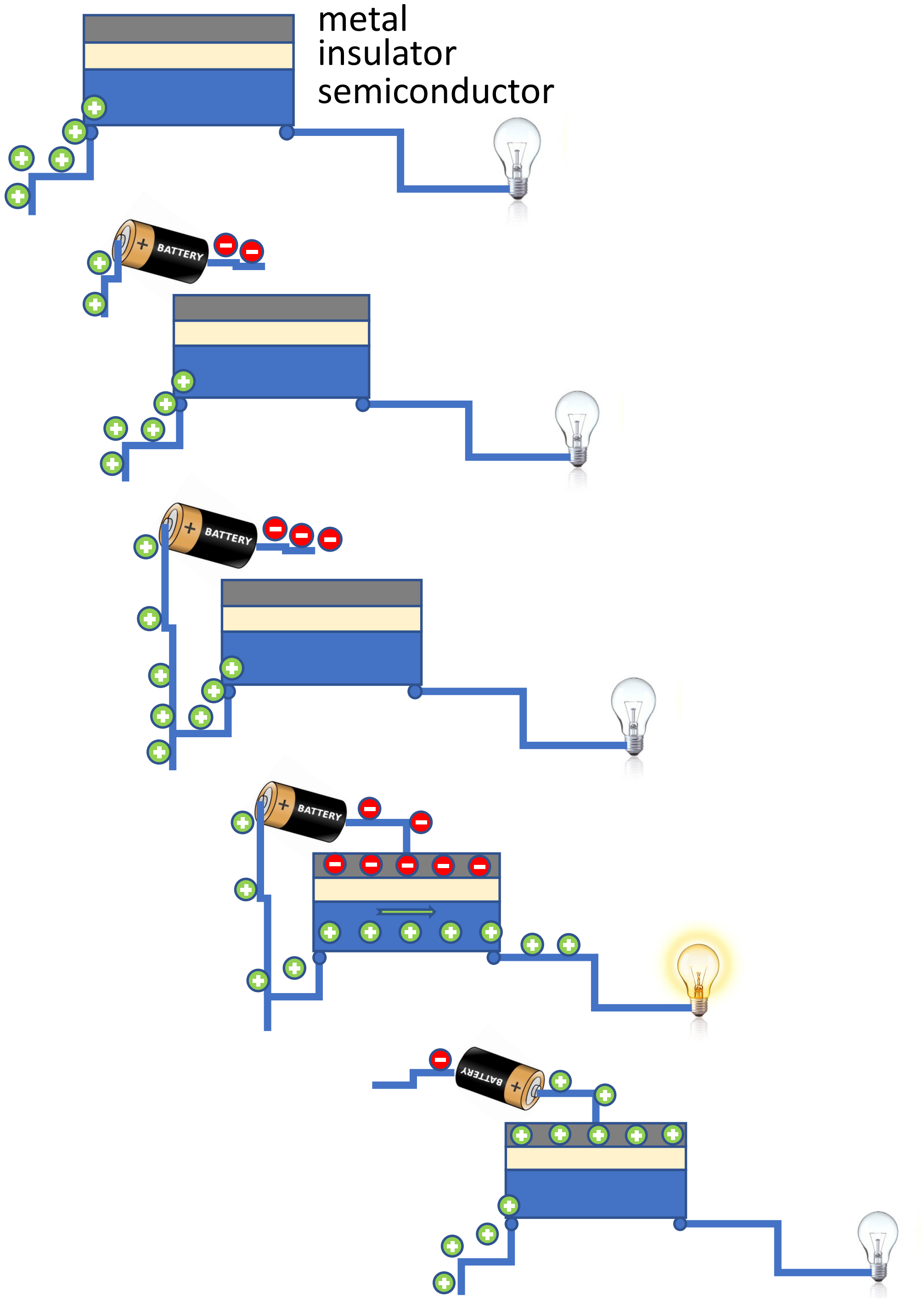


Transistor – electronic switch

- Semiconducting material enabled minituarzation of electric switches



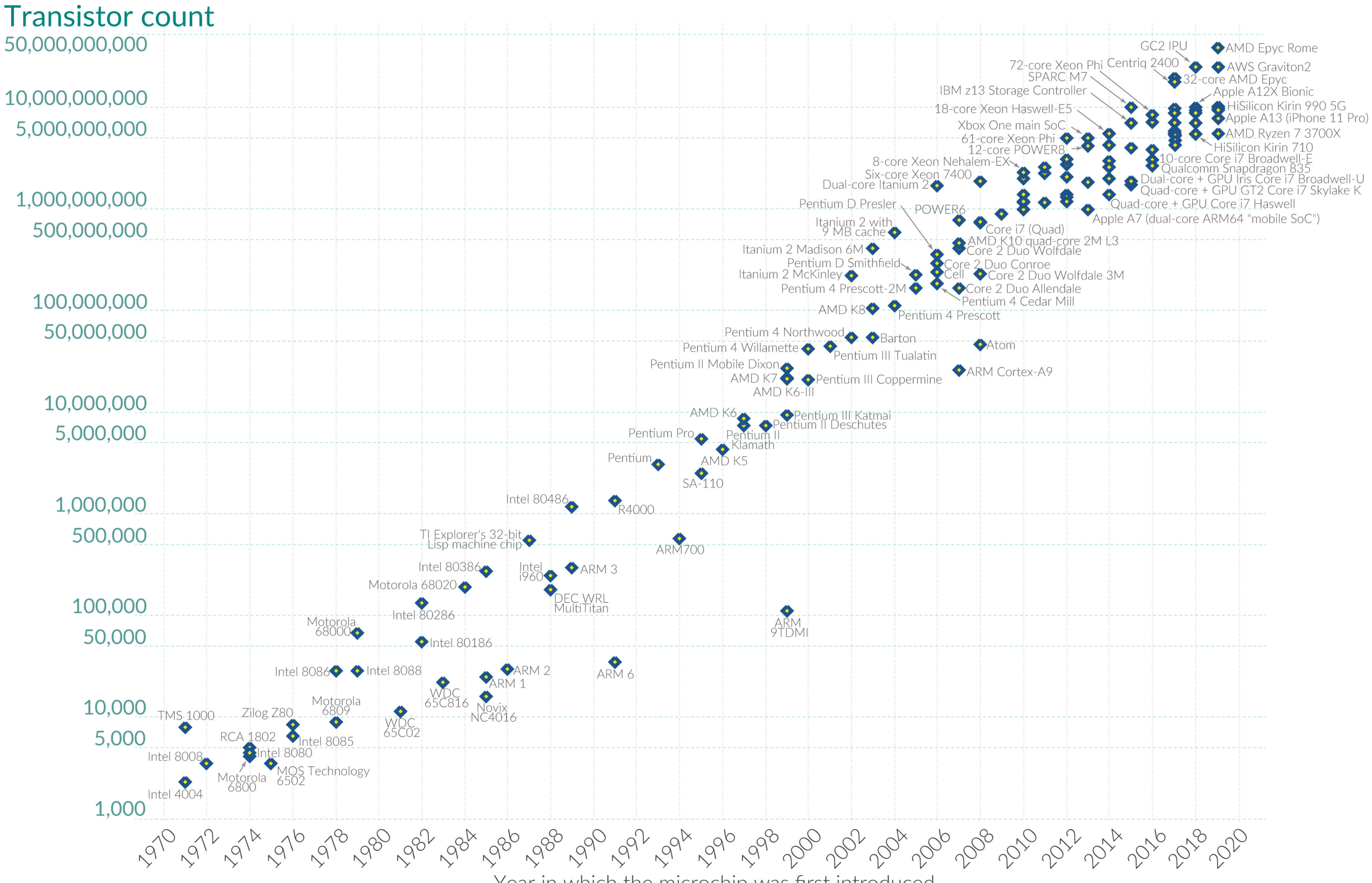
J. Bardeen, W. Brattain 1947



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

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.

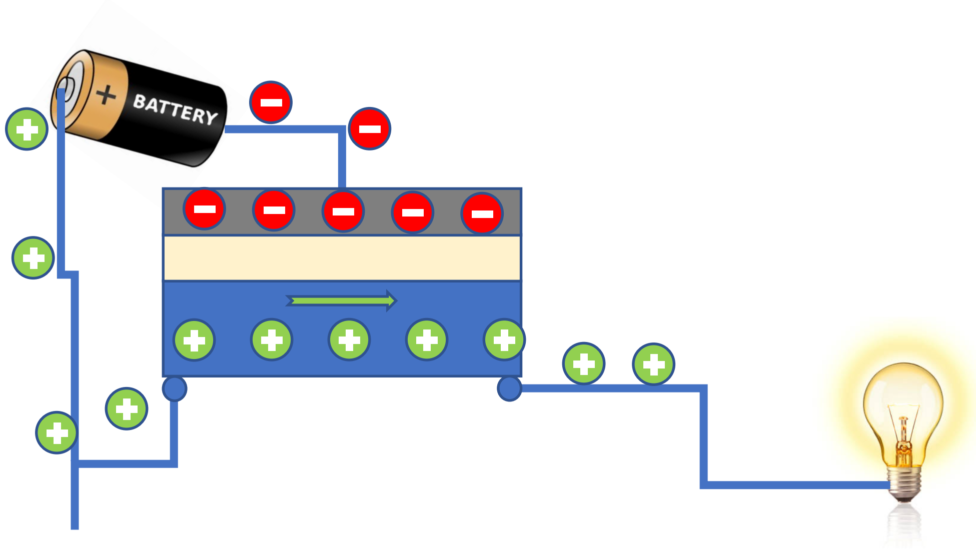
Our World in Data



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

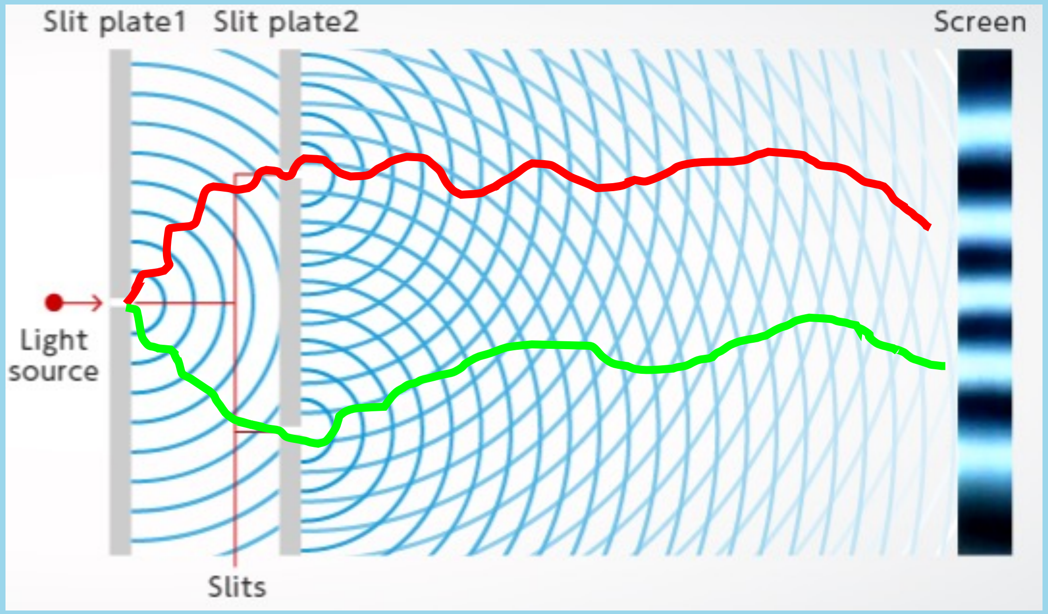
OurWorldinData.org – Research and data to make progress against the world's largest problems.

- Minituarization reduced insulator thickness to 2 -5 nm in 2024.
- Still number of electrons is large
- as a result the quantum phenomena averages out



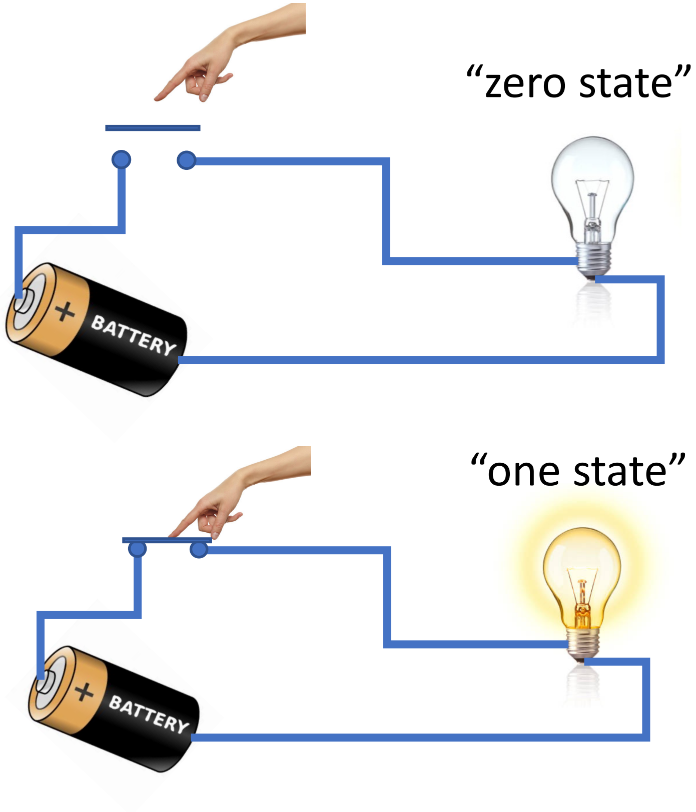
Quantum state

- 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“.



REGINNA 4.0

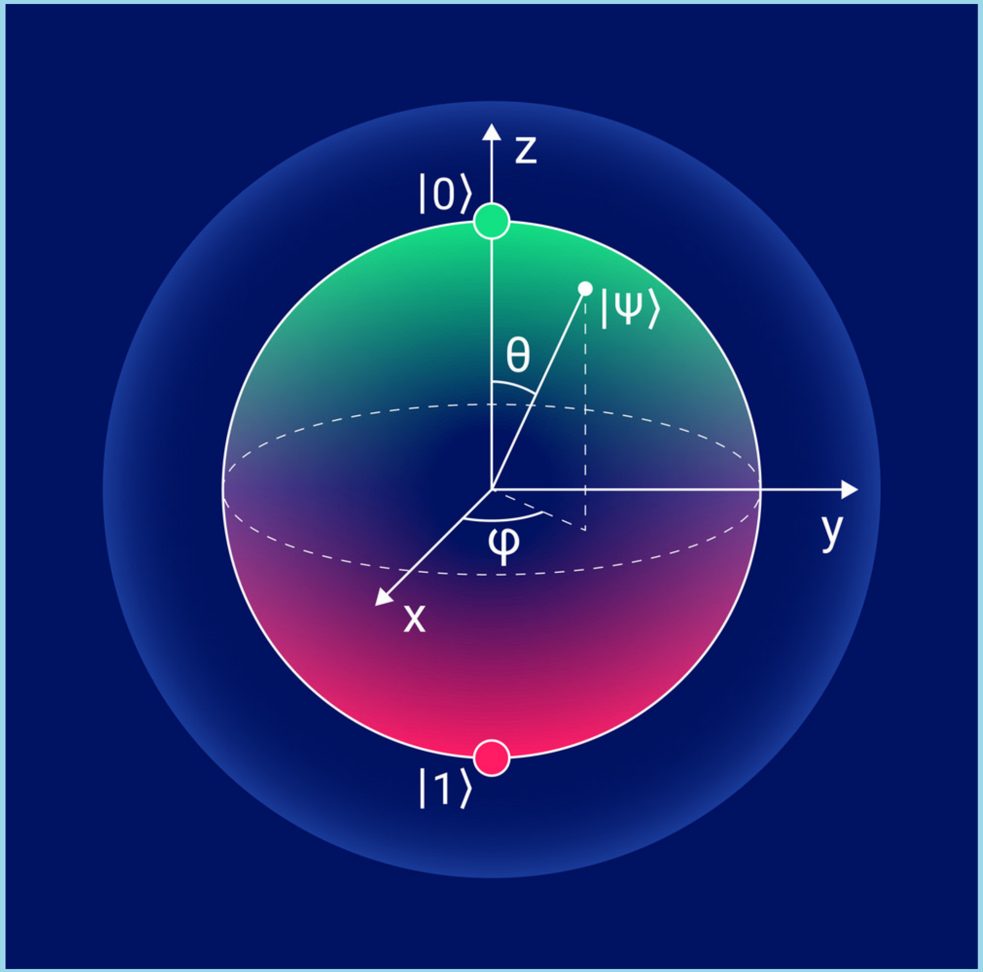
Introduction of quantum bit - qubit

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

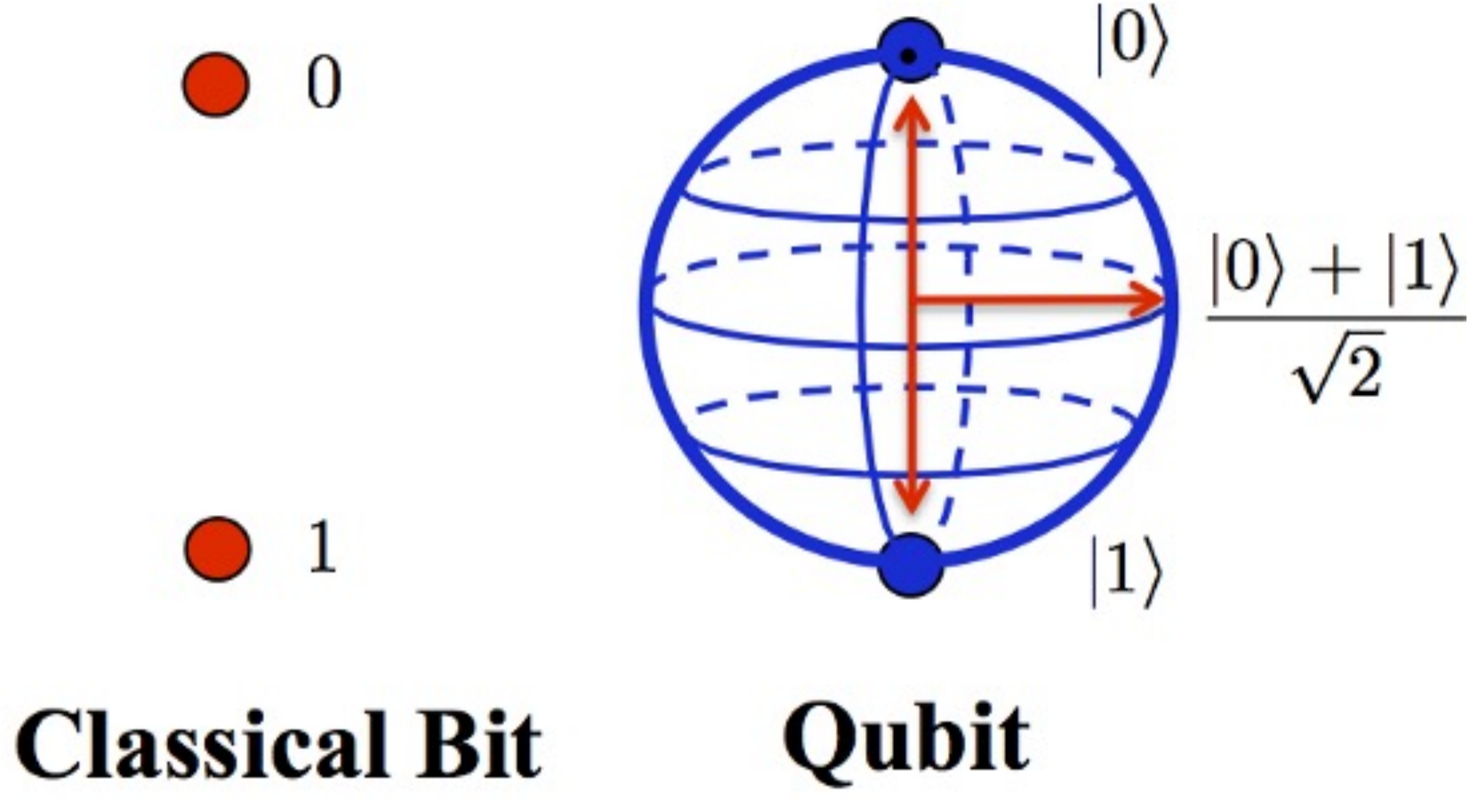
to be in “0” and “1” must be 1

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

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

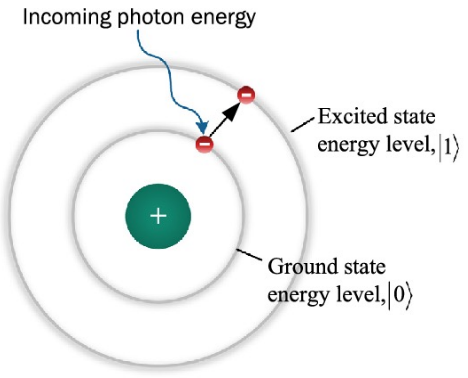
REGINNA 4.0

Classical vs Quantum bit

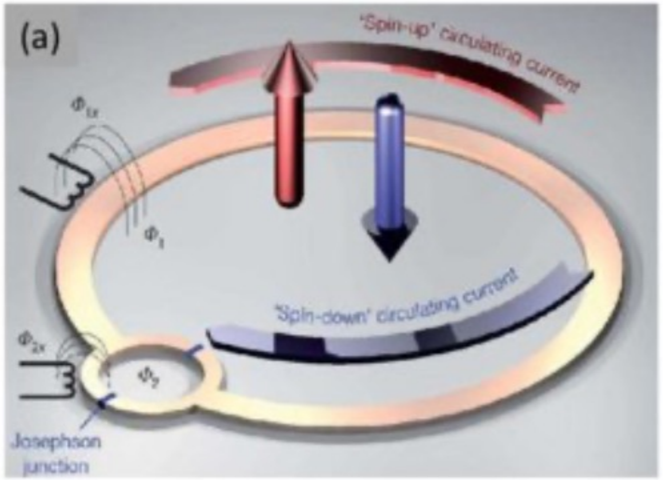


QuBit physical support

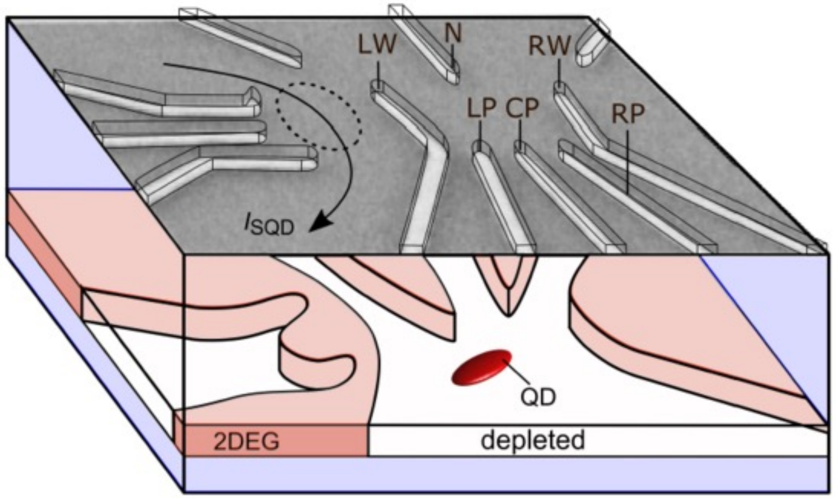
Any system with two quantum states:



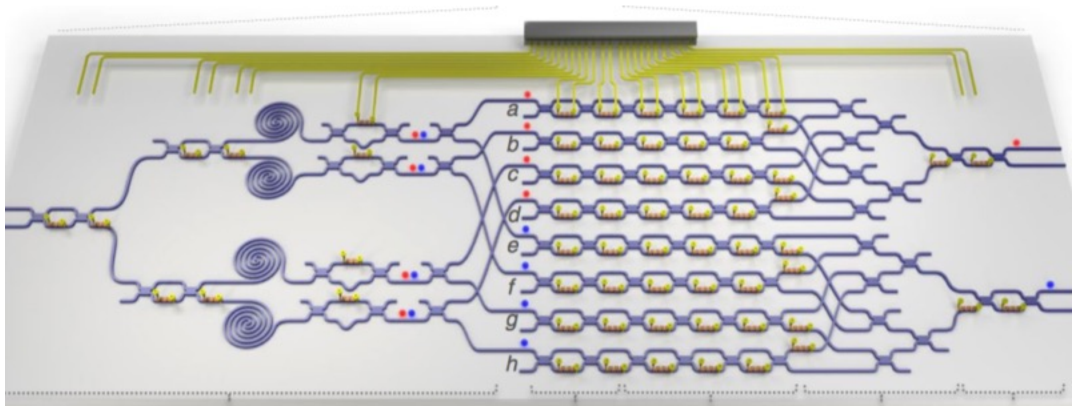
Excited atoms & ions



Superconducting loops **(image by W. Macready)**



Spin of electron



Photon polarization

Wikipedia
The Free Encyclopedia

QuBIT systems

Physical support	Name	Information support	$\vert 0\rangle$	$\vert 1\rangle$
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	$\vert 01\rangle$ superposition	$\vert 10\rangle$ superposition
van der Waals heterostructure[16]	Electron localization	Charge	Electron on bottom sheet	Electron on top sheet

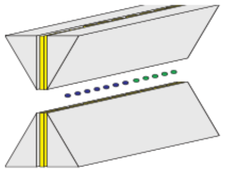
REGINNA 4.0

QuBit Processing units Vendors

QPU vendors collected by Olivier Ezratty (see www.oezratty.net for more):

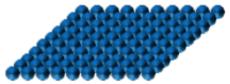
atoms

trapped ions



- Quantinuum
- IonQ
- AQT
- UQ
- oxford ionics
- eleQtron
- Foxconn
- Quantum Art
- Crystal Quantum Computing
- NEQXT
- Qudora Technologies

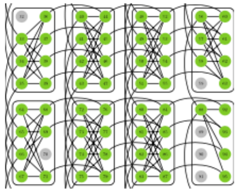
cold atoms



- Pasqal
- QuEra
- Infleqtion
- atom computing
- planqc
- QuanTier
- NanoQT Nanofiber Quantum Technologies

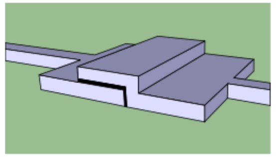
electron *superconducting loops & controlled spin*

annealing



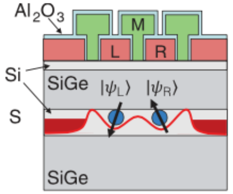
- D-Wave The Quantum Computing Company
- Qilimanjaro Quantum Tech
- NEC

super-conducting



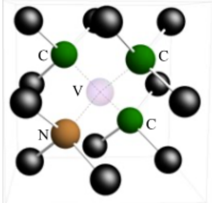
- IBM
- rigetti
- amazon
- Google
- qci
- Nord Quantique
- OQC
- IQM
- Alice & Bob
- 本源量子 Origin Quantum
- Anyon
- Atlantic Quantum
- bleximo
- Fujitsu

silicon



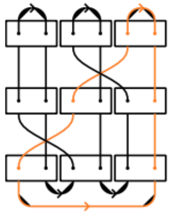
- intel
- quobly
- Quantum Motion
- Silicon Quantum Computing
- diraq
- EeroQ
- equal1.labs
- C12
- ARQUE
- QπAI
- Archer

vacancies



- Quantum Brilliance
- SaxonQ
- Turing
- photonic
- NTT
- XEED
- Quantum Transistors

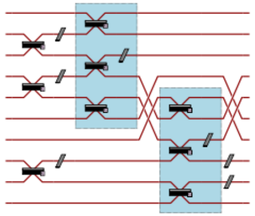
topological



- Microsoft
- Quoherent
- Quantum Gravity Research

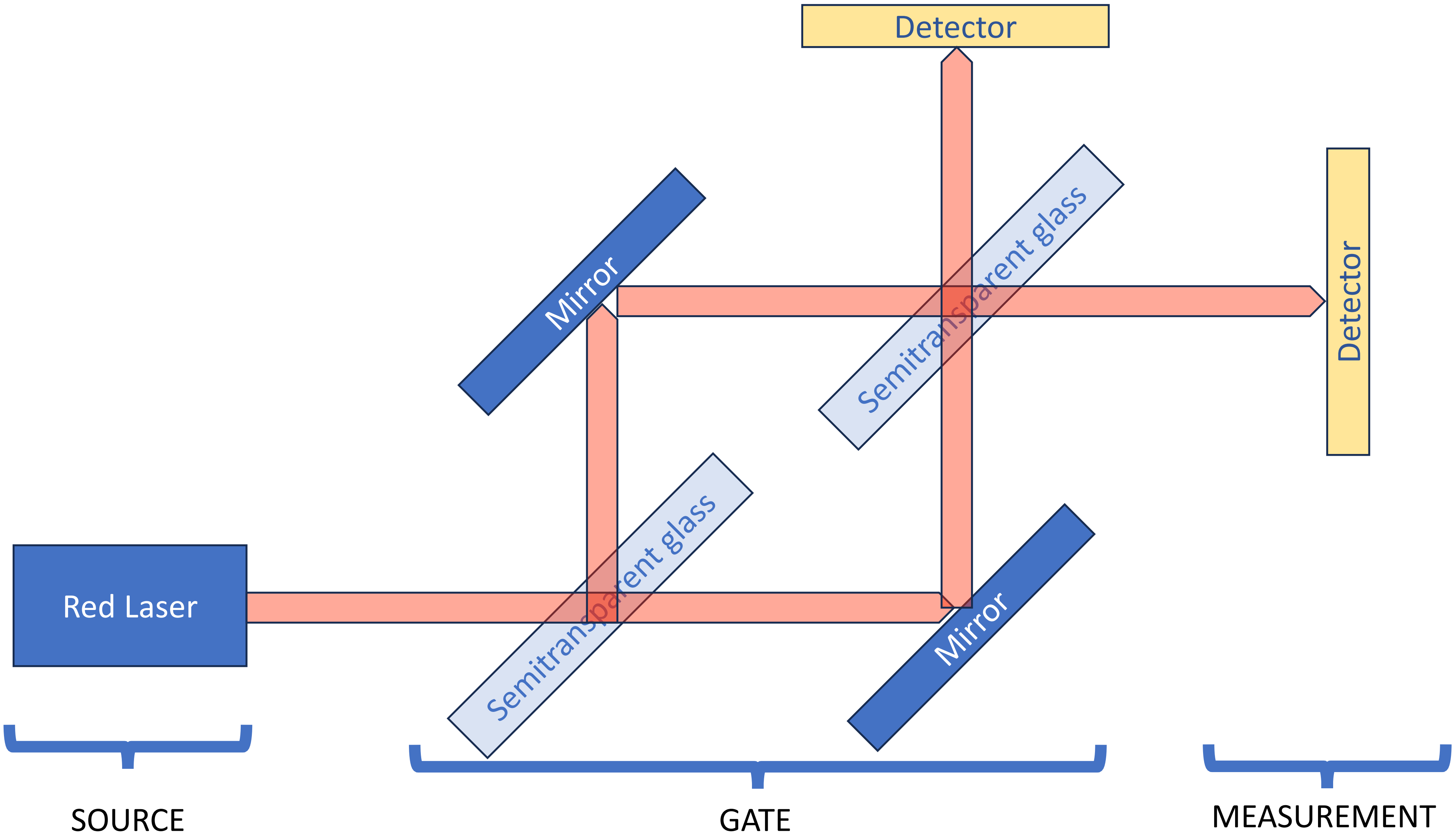
photons

photons



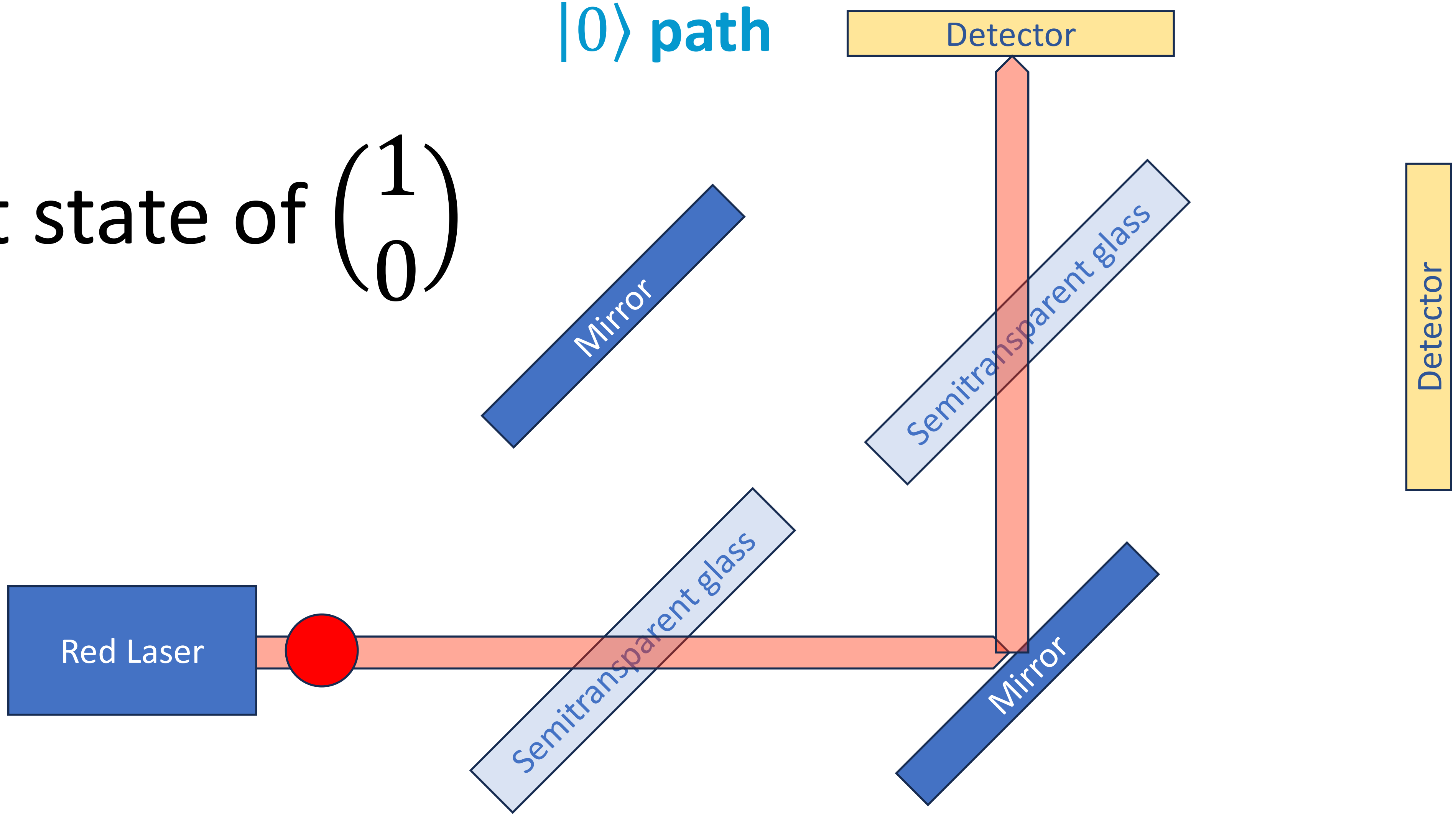
- PsiQuantum
- Quandela
- Orca Computing
- Xanadu
- Duality Quantum Photonics
- QuiX Quantum
- BardeenQ Labs
- QBoson
- QCi
- photonicsQ
- QuanFluence
- Tundra Systems Global Ltd

Mach-Zehnder interferometer



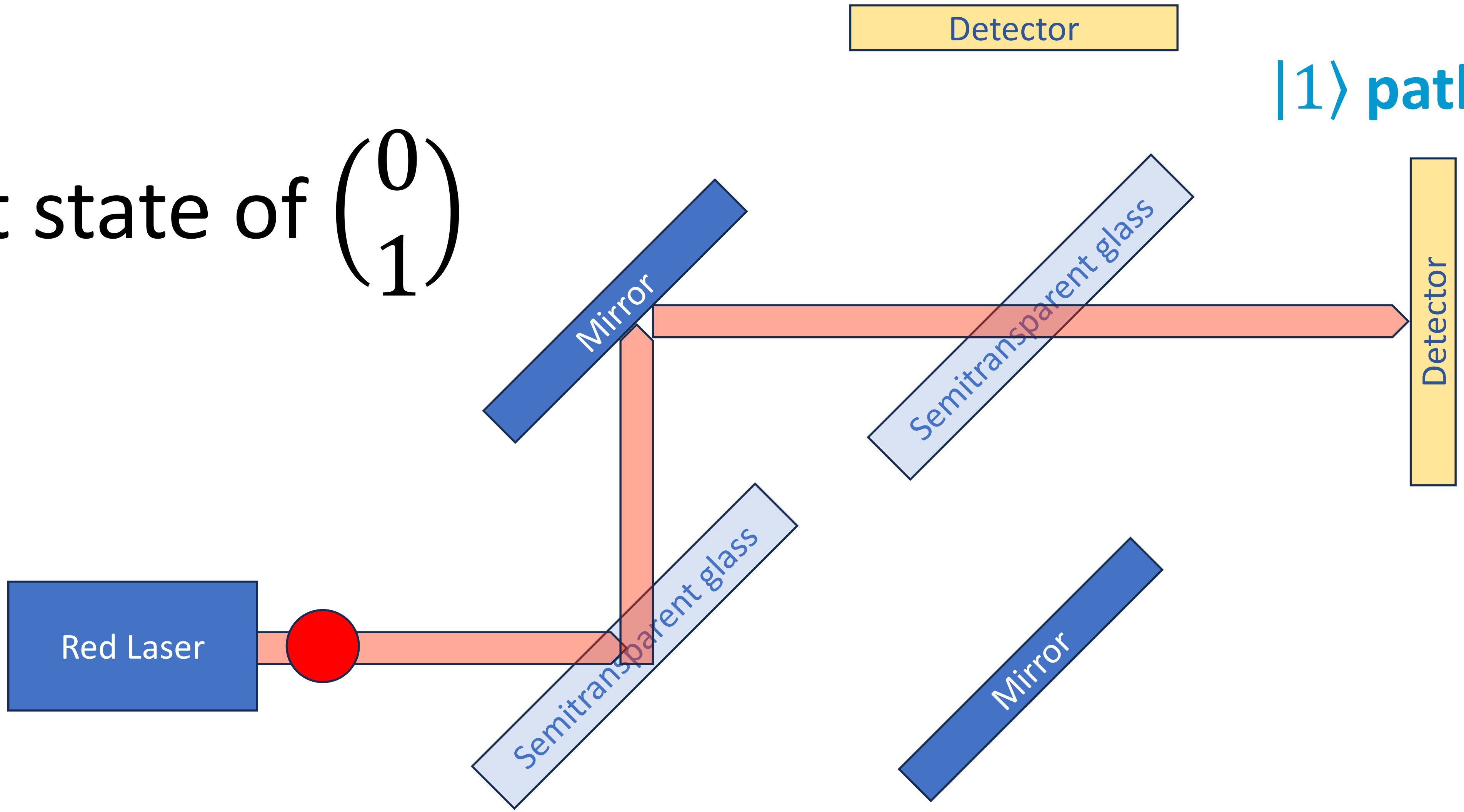
$|0\rangle$ **path**

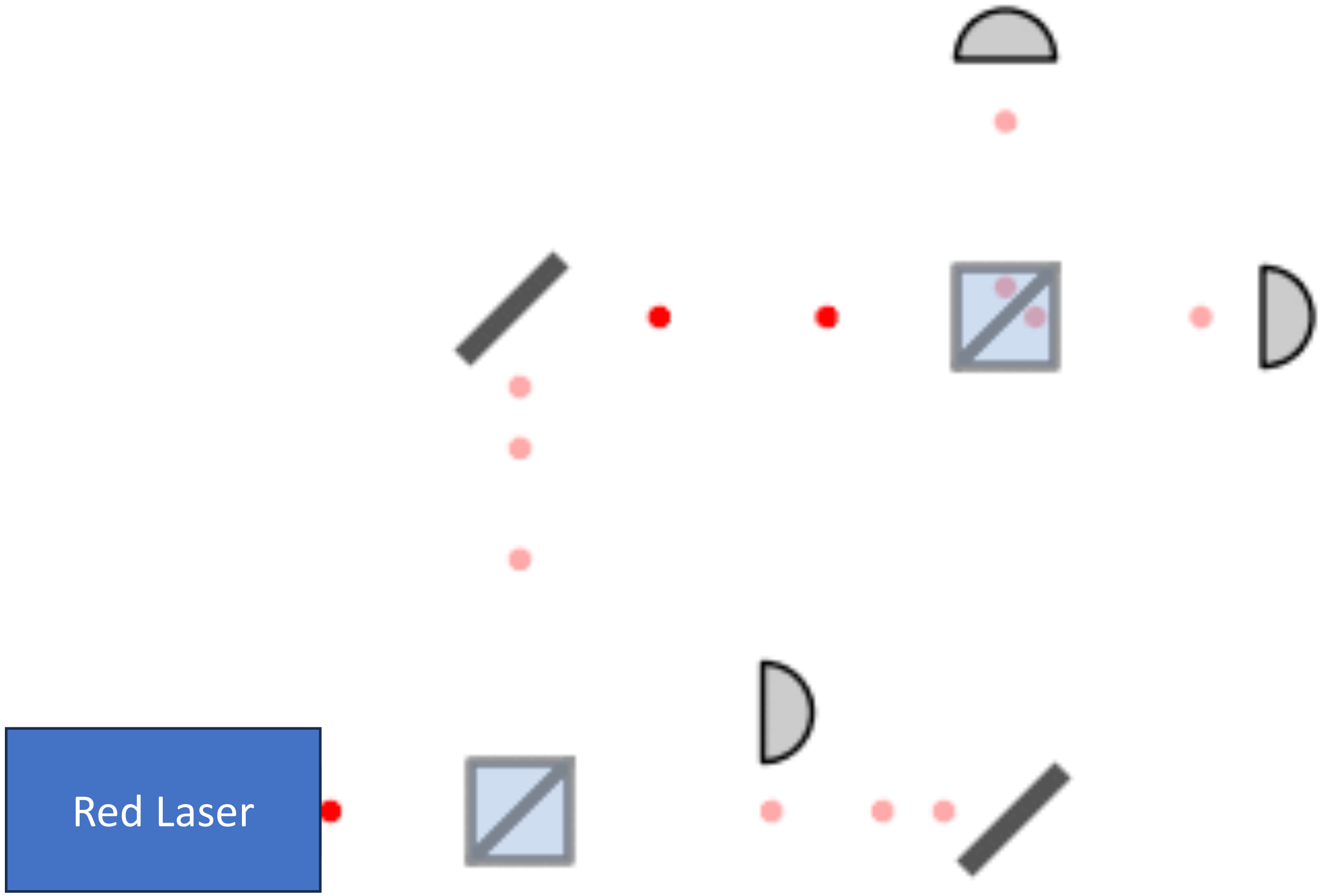
Qubit state of $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$



Qubit state of $\binom{0}{1}$

$|1\rangle$ **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: $\alpha\begin{pmatrix}1\\0\end{pmatrix} + \beta\begin{pmatrix}0\\1\end{pmatrix} = \begin{pmatrix}\alpha\\\beta\end{pmatrix}$

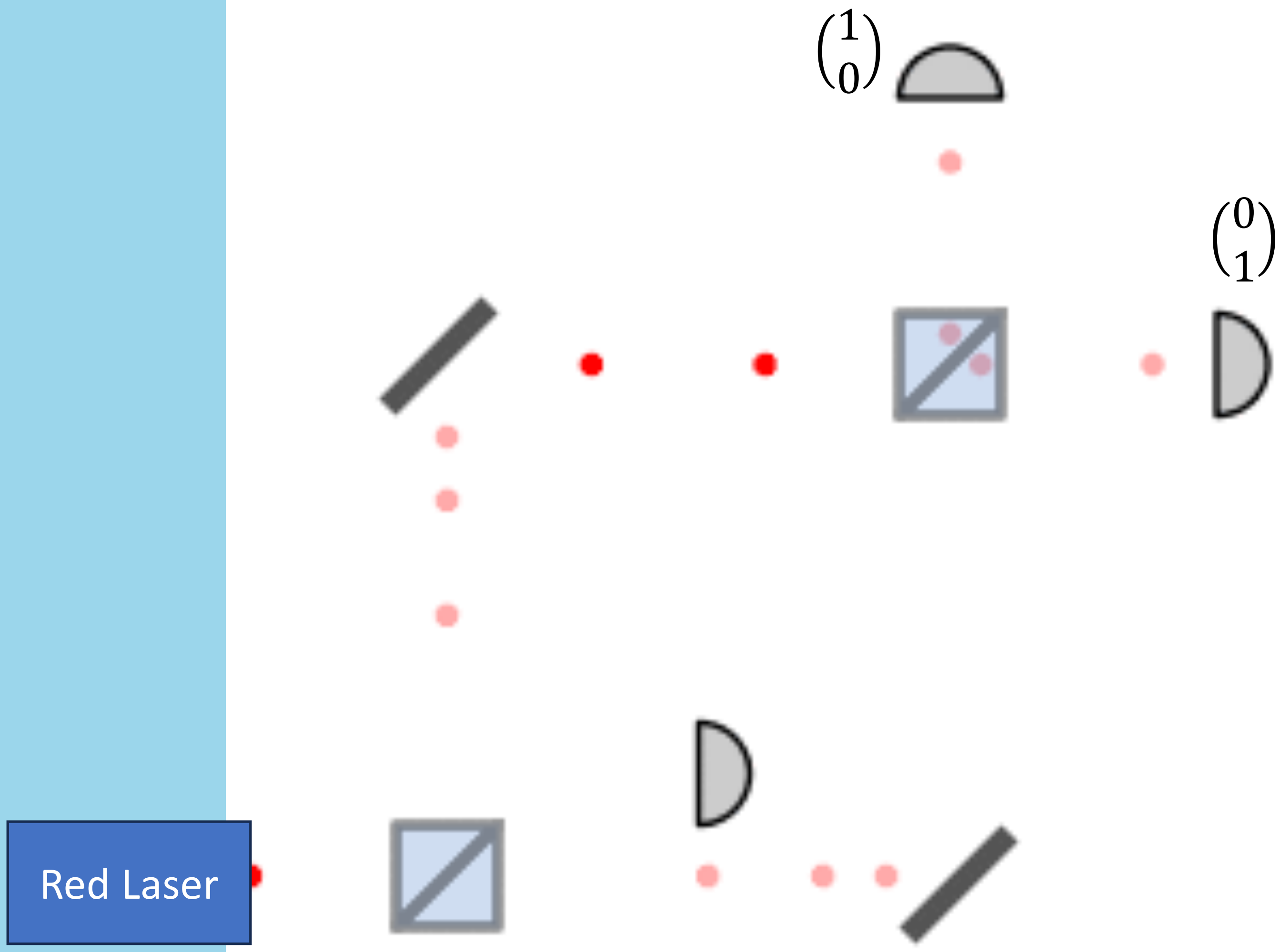
Beam-splitter operation: $A = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & i\\ i & 1\end{bmatrix}$

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:

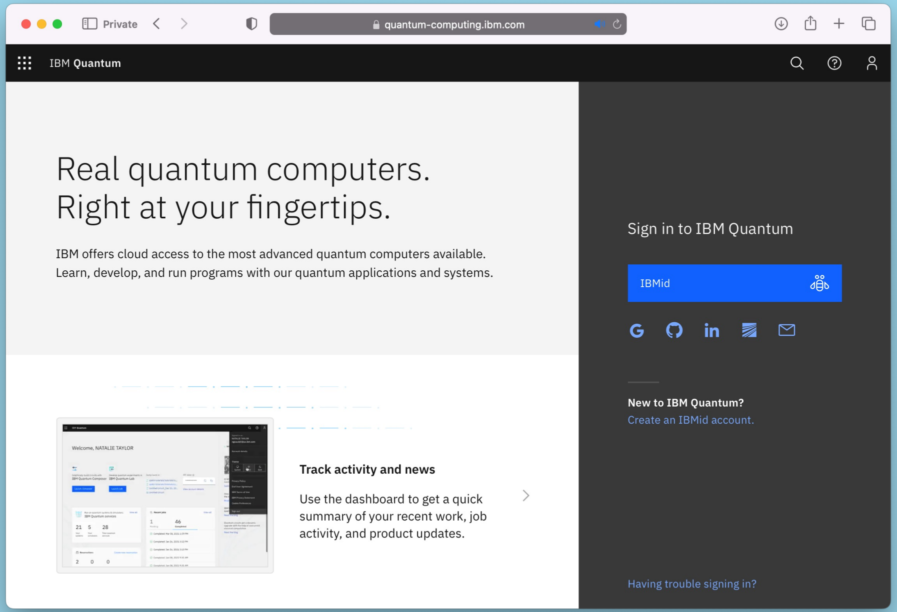
$$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & i\\ i & 1\end{bmatrix}\cdot\frac{1}{\sqrt{2}}\begin{pmatrix}1\\i\end{pmatrix} = i\begin{pmatrix}0\\1\end{pmatrix}$$

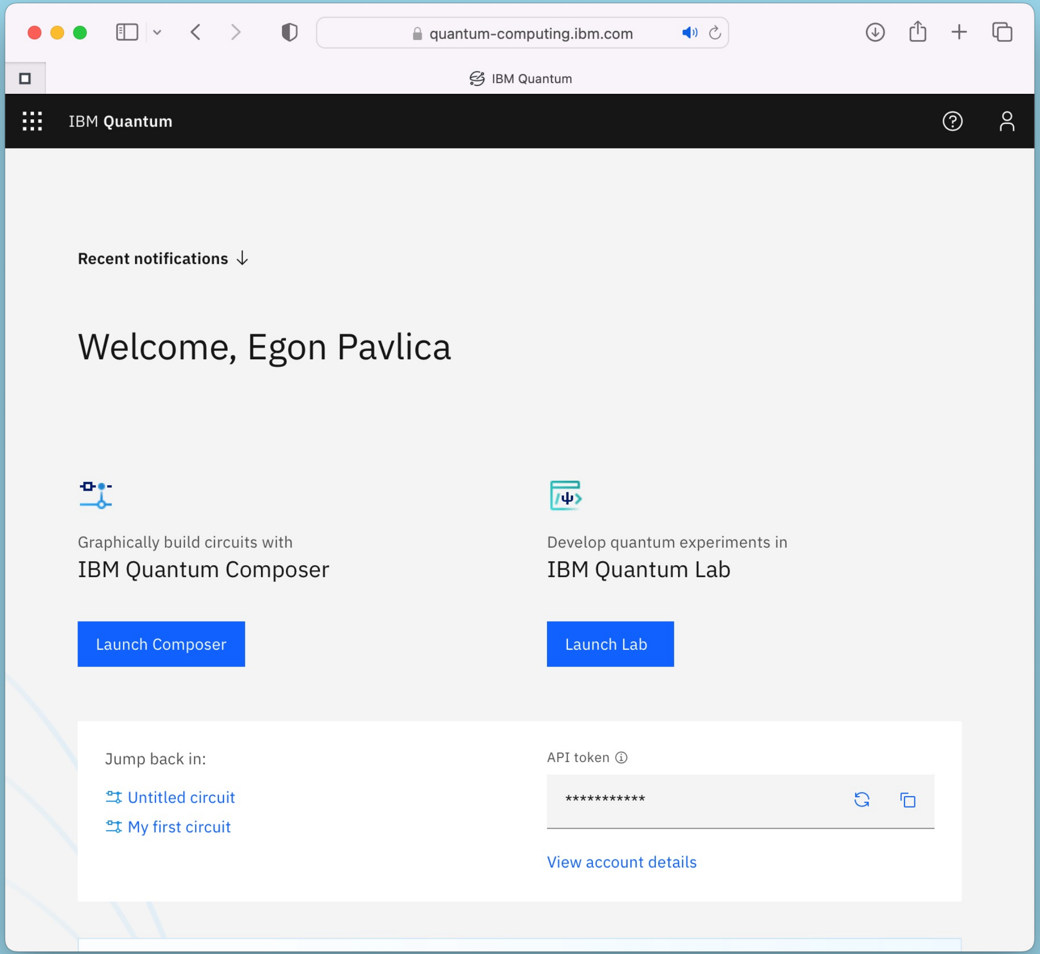


Qiskit

1. Create an account:

https://quantum-computing.ibm.com

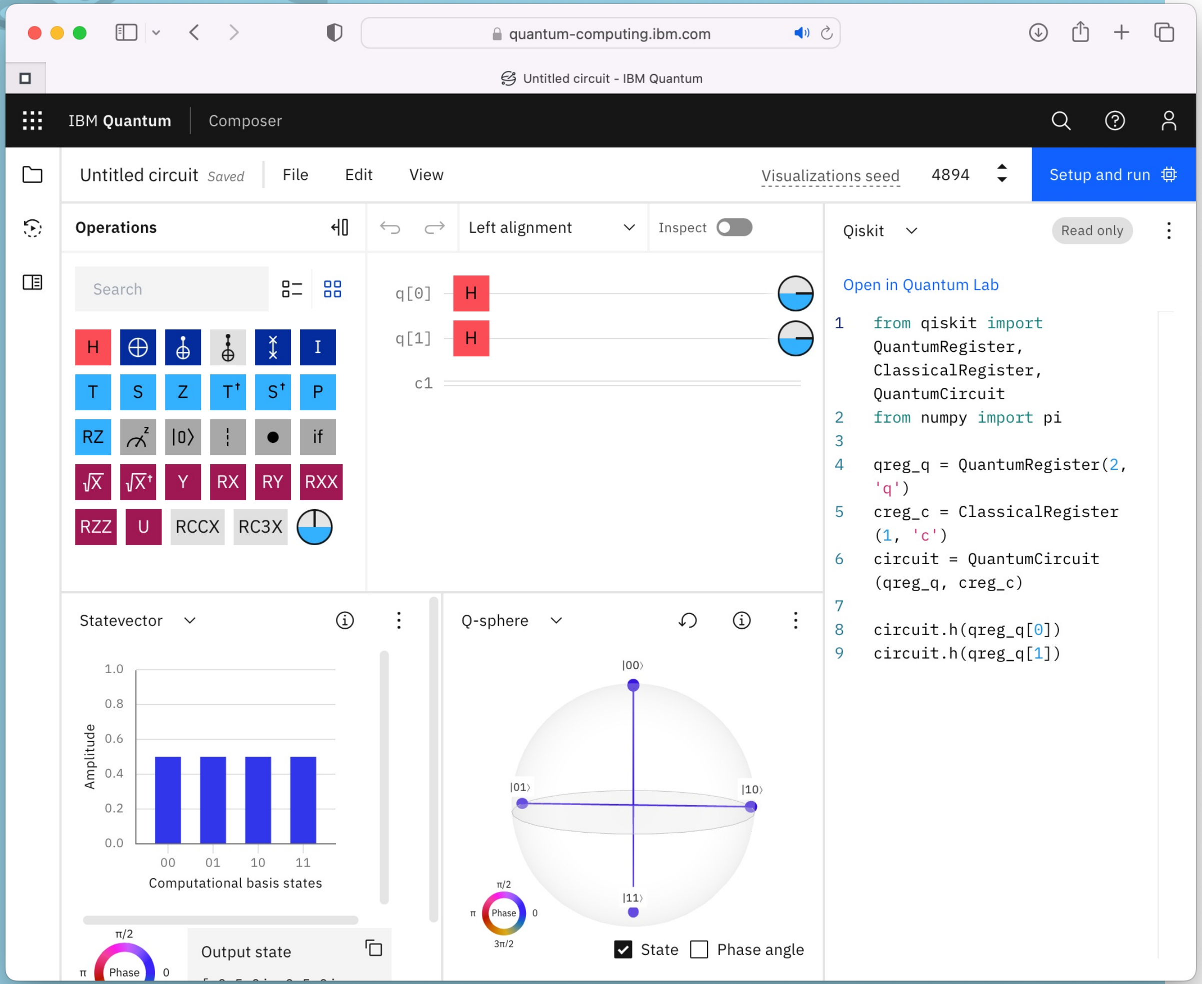




1. Create an account:

https://quantum-computing.ibm.com

2. Launch IBM Quantum Composer

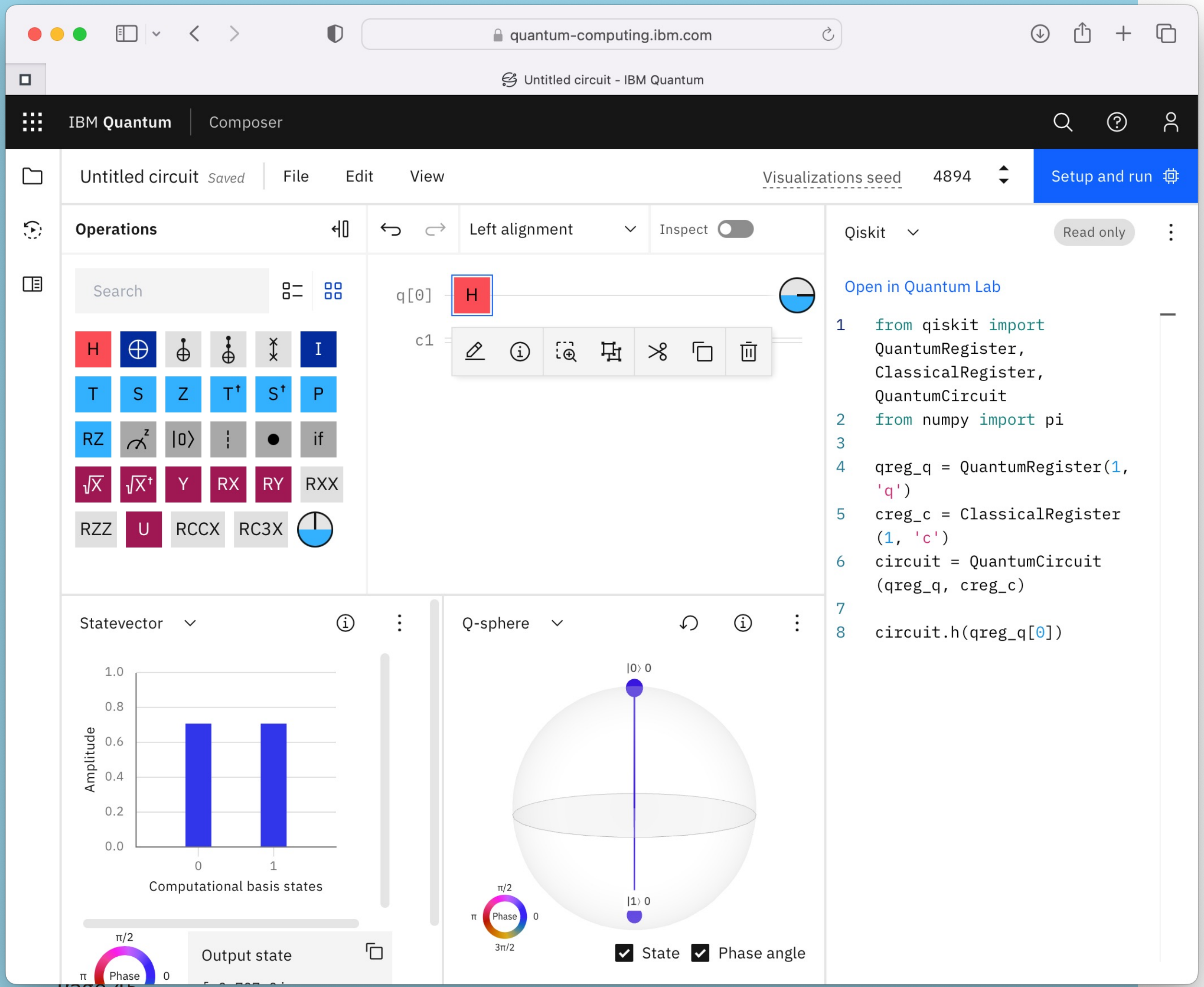


1. Create an account:

https://quantum-computing.ibm.com

2. Launch IBM Quantum Composer

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



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

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

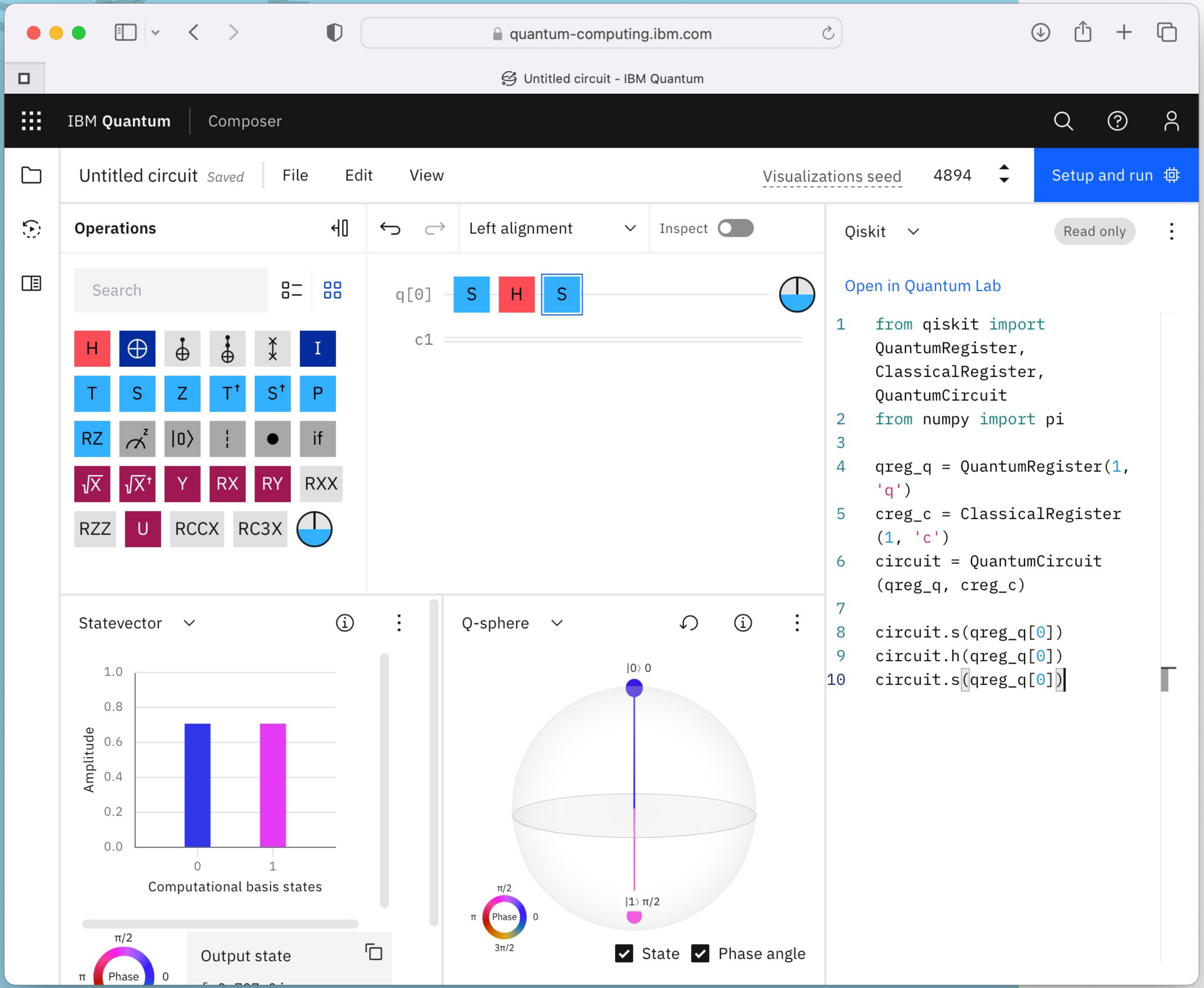
$$= \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\0 & i\end{bmatrix}\cdot\begin{bmatrix}1 & i\\1 & -i\end{bmatrix}\begin{bmatrix}1\\0\end{bmatrix} =$$

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

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

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

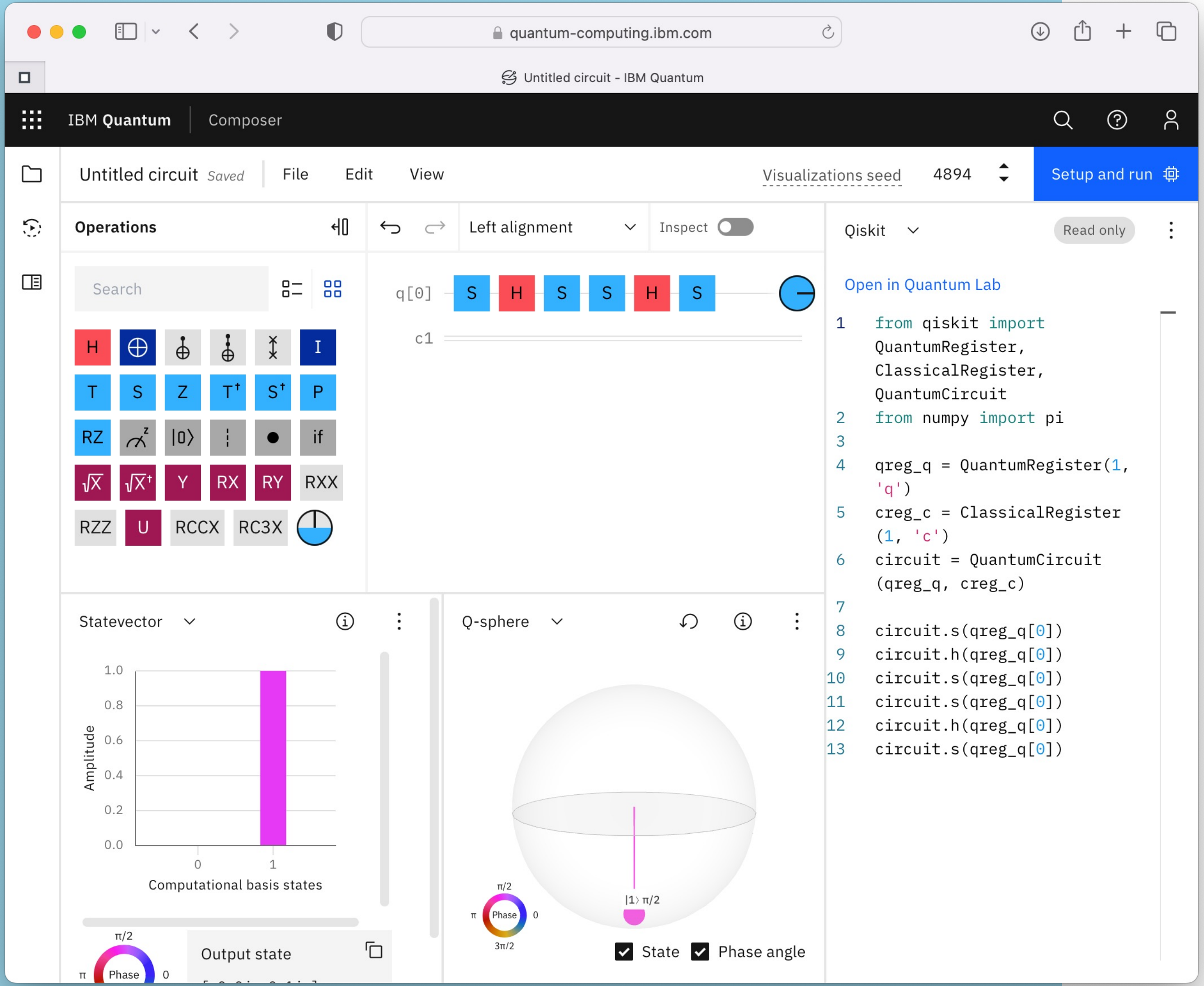
1st Beam spliter



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

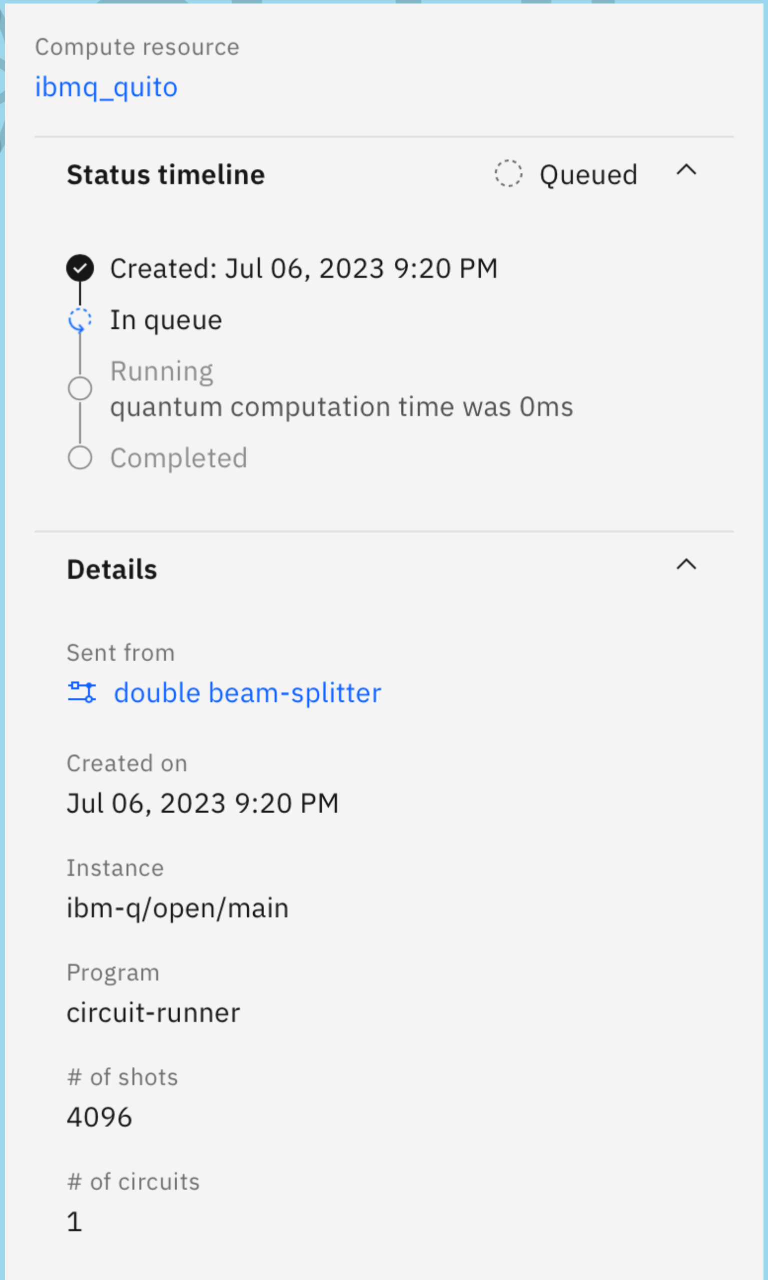
$$= \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ i \end{bmatrix}$$

2nd Beam spliter

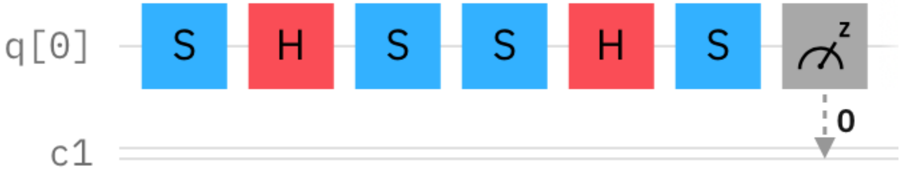


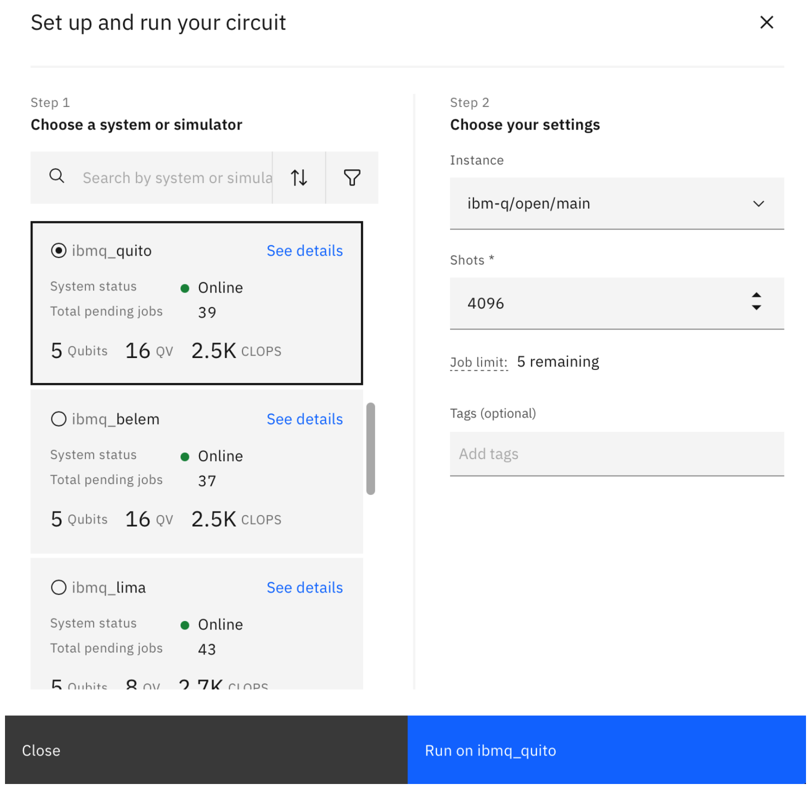
$$(S\cdot H\cdot S)\cdot(S\cdot H\cdot S)\begin{bmatrix}1\\0\end{bmatrix}=$$

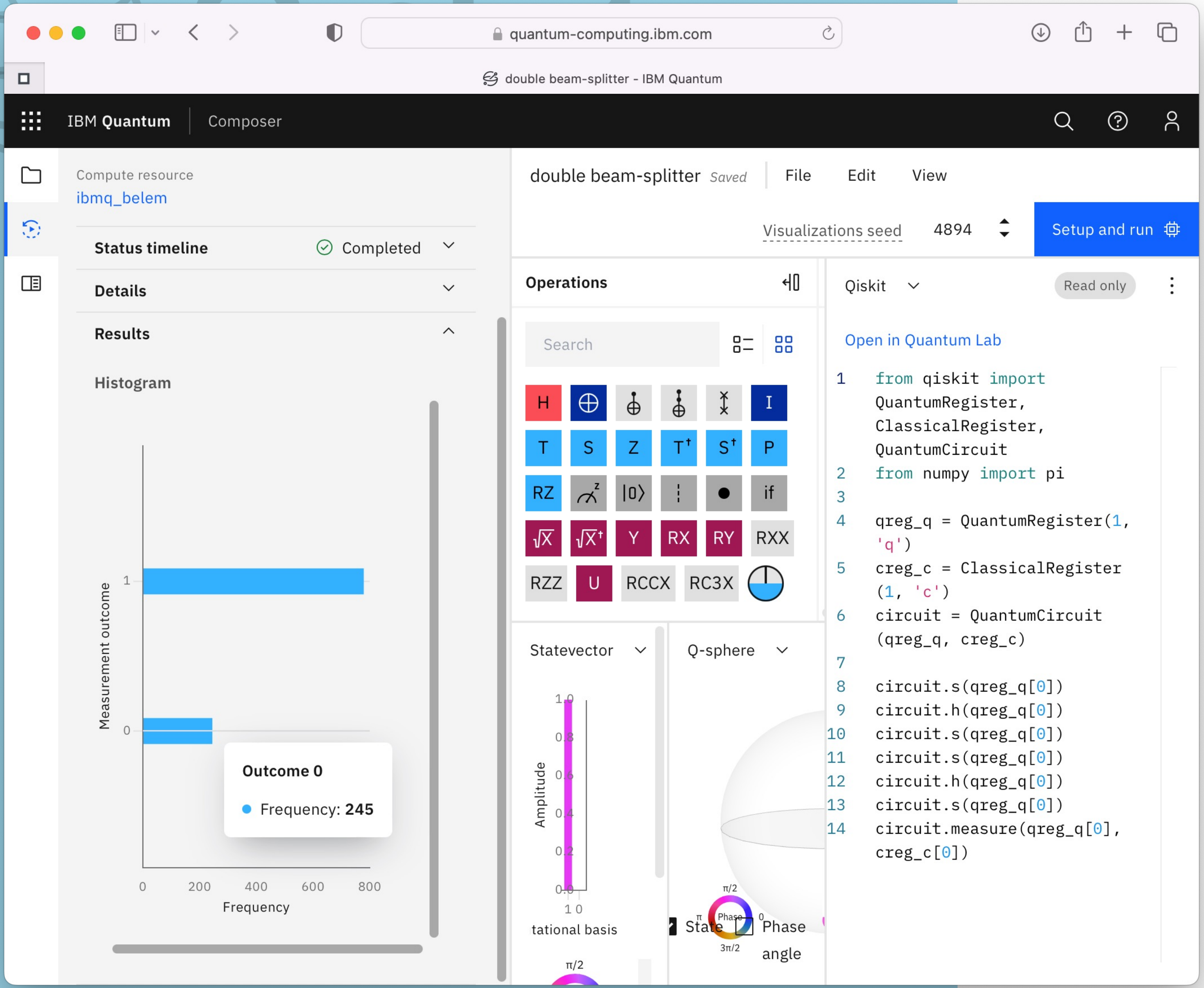
$$=\begin{bmatrix}0\\i\end{bmatrix}$$



Add a measure and run the quantum program!







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)

UNIVERZA V NOVI GORICI
SCIENTIA 1995 VINCES

Supported by
eit Manufacturing
Funded by the European Union
INNOVATION CAPACITY BUILDING FOR HIGHER EDUCATION
PART OF
EIT HEI Initiative
eit-hei.eu