About me…

1992 Bachelor degree in Nuclear Physics at the Peking University of Beijing, China

1995 Master degree in Particle Accelerators at the Peking University of Beijing, China

2002 PhD in Physics at Virginia Tech, Blacksburg, VA, USA

2006 Staff Scientist at Jefferson Lab, Newport News, VA, USA

Scientist at Argonne National Lab, Argonne, IL, USA

Senior Physicist at Michigan State University, East Lansing, MI, USA

Senior Scientist at Fermilab, Batavia, IL, USA

Genfa Wu
Group Leader, Cavity Prep and Assembly, SRF Material and Research Department
genfa@fnal.gov

- I was fascinated by how physics can explain how things work when I was in high school.
- My career developed around the science and technology of radio-frequency superconductivity applied to particle accelerators…
- This is a very cool field that combines the superconductivity, superfluid helium, Microwave, materials, and vacuum.
- Currently my work is focused on building the most advanced superconducting linac for the PIP-II project. My typical day is to solve problems, think creative solutions to push the scientific and technical limit.
- I love reading books (science fictions).

Silvia Zorzetti

Education

- 2012 M.Sc. In Electronics Engineering
- 2017 Ph.D. in Information Technology

Fermilab

2013-2017 Marie-Curie Fellowship

Innovative doctoral program: Improve the accuracy of alignment for the components to be installed in the next generation of particle accelerators.

Opportunities: Participate to conferences, outreaching events, trainings, industrial internships and networking

MARIE CURIE ACTIONS

2017 Bardeen Fellow
2020 Deputy Head, Quantum Computing co-design department

Hardware and software solutions to enable quantum science and applications

ONE nine cell SRF cavity + **ONE** transmon = **SQMS 100+** qubits processor

About me

EDUCATION

PhD: Northwestern University, USA:
Reconfigurable and Edgeless ROIC for Large Area Single Photon Counting Imagers without Deadtime

MBA: Open University, UK

M. Tech: University of Limerick, Ireland: Analog IC Design: **Clock and Data Recovery PLLs**

B.Tech: University of Limerick, Ireland: Information Technology & Telecommunication

WORK EXPERIENCE:

Northwestern University: 2020 – current

Adjunct Assistant Professor, Department of Electrical and Computer Engineering

Fermilab: 2009 - current

ASICs department head, Particle Physics Division

Deputy Division Head, Quantum Science: Started the Fermilab Quantum Microelectronics program

AI Project office: Initial demonstrations and seeded the Fermilab AI ASICs

ASIC Designer: *Principal designer for various Pixel detector development for BES & HEP detector program. Novel, edgeless 3D IC designs.*

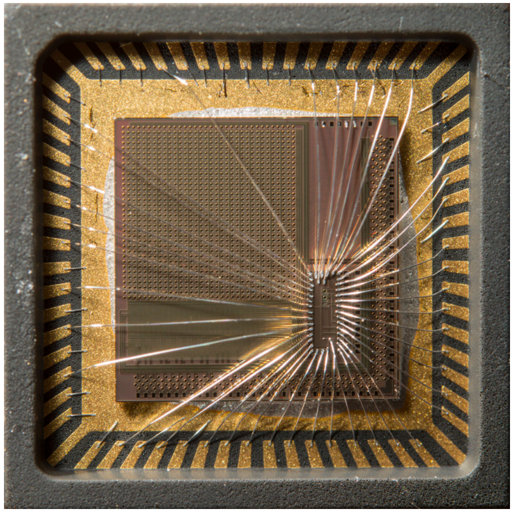
Rutherford Appleton Laboratory, UK: 2005-2009

ASIC Designer: *Custom electronics for Solar Intensity Spectrometer for BepiColumbo- ESA mission to Mercury, High throughput gas detectors, prototype electronics for European XFEL*

What do I do? I design chips! Chips

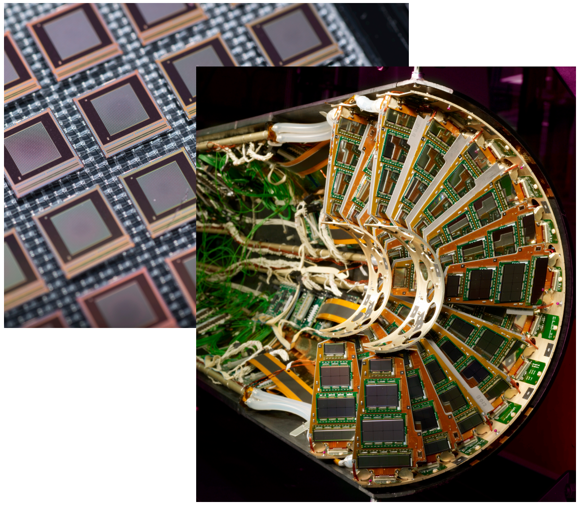
What do I do? I design chips!

ACADEMIC RESEARCH



- **Support interdisciplinary research**
- **Enables new scientific discovery and foundational engineering**
- **Novel solutions**
- **Mission: new knowledge and education of students**

NATIONAL LABS: ADVANCED SCIENTIFIC INSTRUMENTATION



- **Support scientific experiments operating in extreme environments**
- **Mid-size scaling for large experiments**
- **Mission: robust performance over several decades**

INDUSTRY – PRODUCT DRIVEN

- **Support consumer electronics**
- **Mature designs**
- **Mission: incremental product driven design**

About me…

2011 Bachelor degree in Materials Science at the University of Padua, Italy

2013 Master degree in Materials Science at the University of Padua, Italy

2014 First level master at INFN-LNL, Legnaro, Italy

2016 PhD in Physics at Illinois Institute of Technology, Chicago IL, USA

2017 Postdoctoral research associate at Fermilab, Batavia IL, USA

2017 Peoples Fellow - Associate Scientist at Fermilab, Batavia IL, USA

Mattia Checchin
Deputy Head, Quantum Materials and Qubits Department
checchin@fnal.gov

My career developed around the fundamental study of radio-frequency superconductivity applied to particle accelerators…

…currently my research is focused on QIS and I am studying materials for application in qubits and quantum devices.

Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Introduction to Quantum Computing and Qubits

Mattia Checchin

STEM Conference, Fermilab, Batavia IL, USA

1 May 2021

WHAT IS A QUANTUM COMPUTER?

Bits

0 and 1


LIBERTY
IN GOD WE TRUST
D
1996
UNITED STATES OF AMERICA
E PLURIBUS UNUM
QUARTER DOLLAR

Example: 4 bits register

0000 0001 0010 0011

0100 0101 0110 0111

1000 1001 1010 1011

1100 1101 1110 1111

Example: 4 bits register

0000 0001 0010 0011

0100 0101 0110 0111

TOTAL OF 16 numbers

(for N bits total of 2^N numbers)

1000 1001 1010 1011

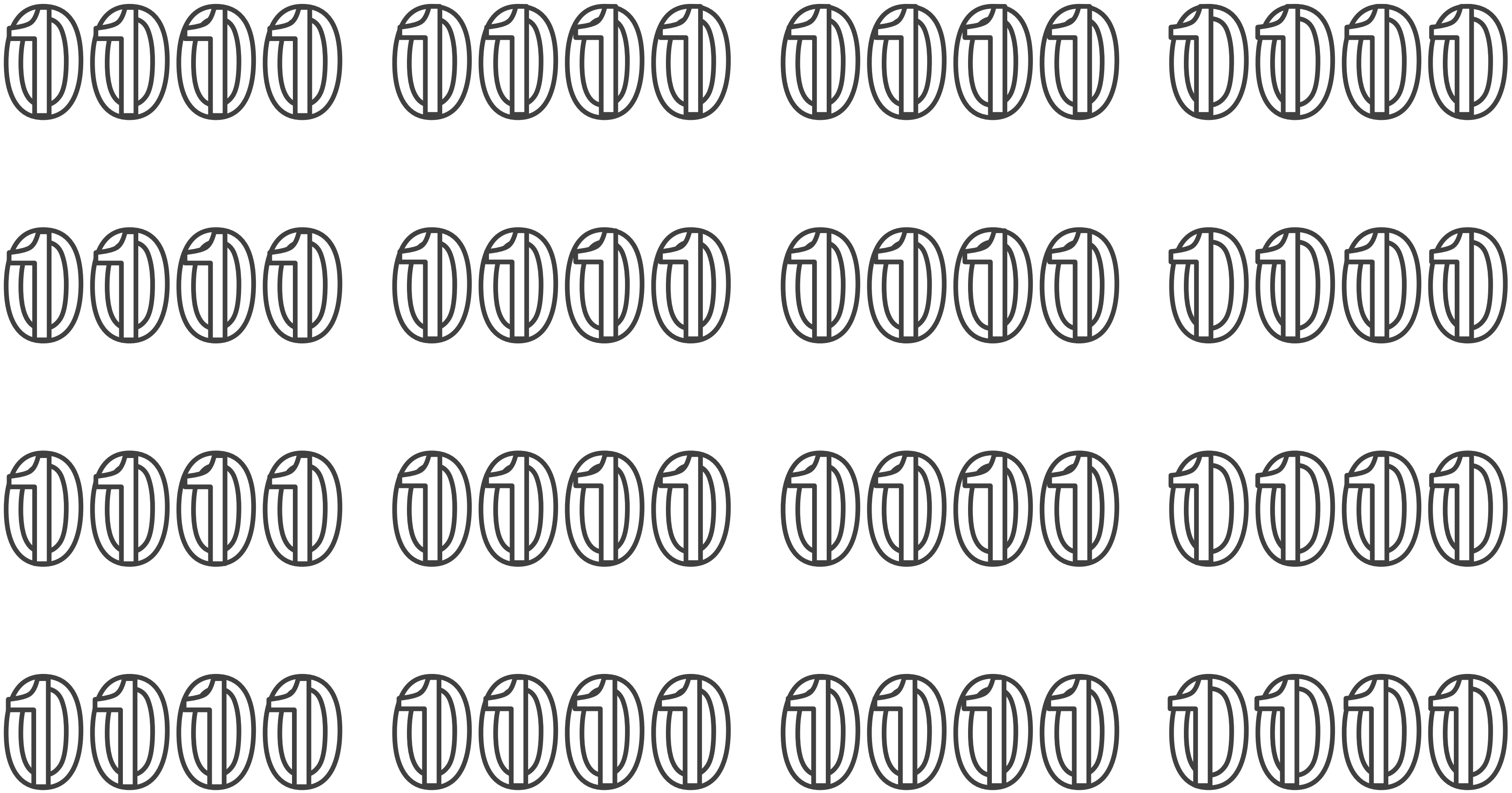
1100 1101 1110 1111

Quantum bits (Qubits)

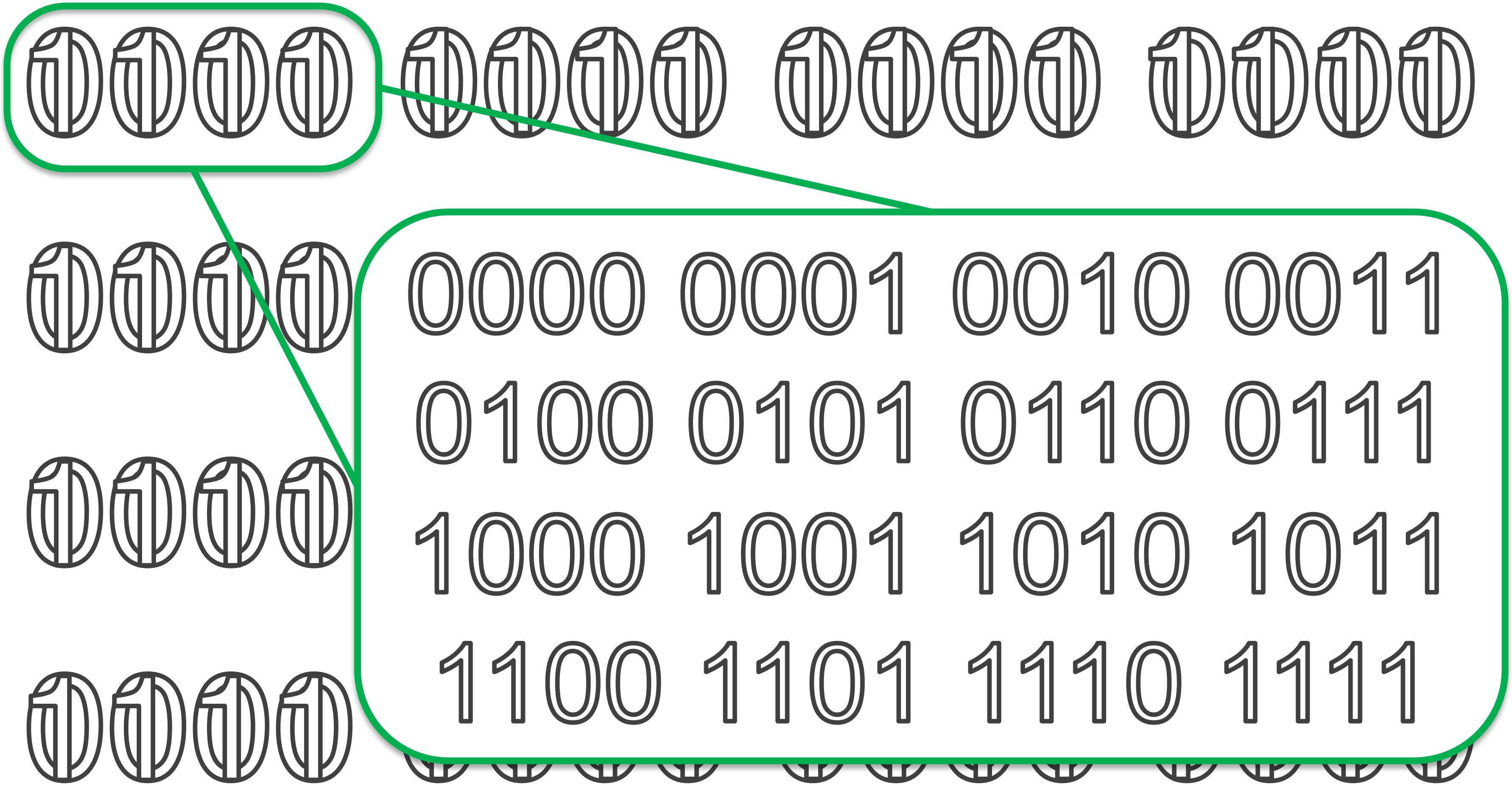
0 and 1

…but also:

Example: 4 qubits register

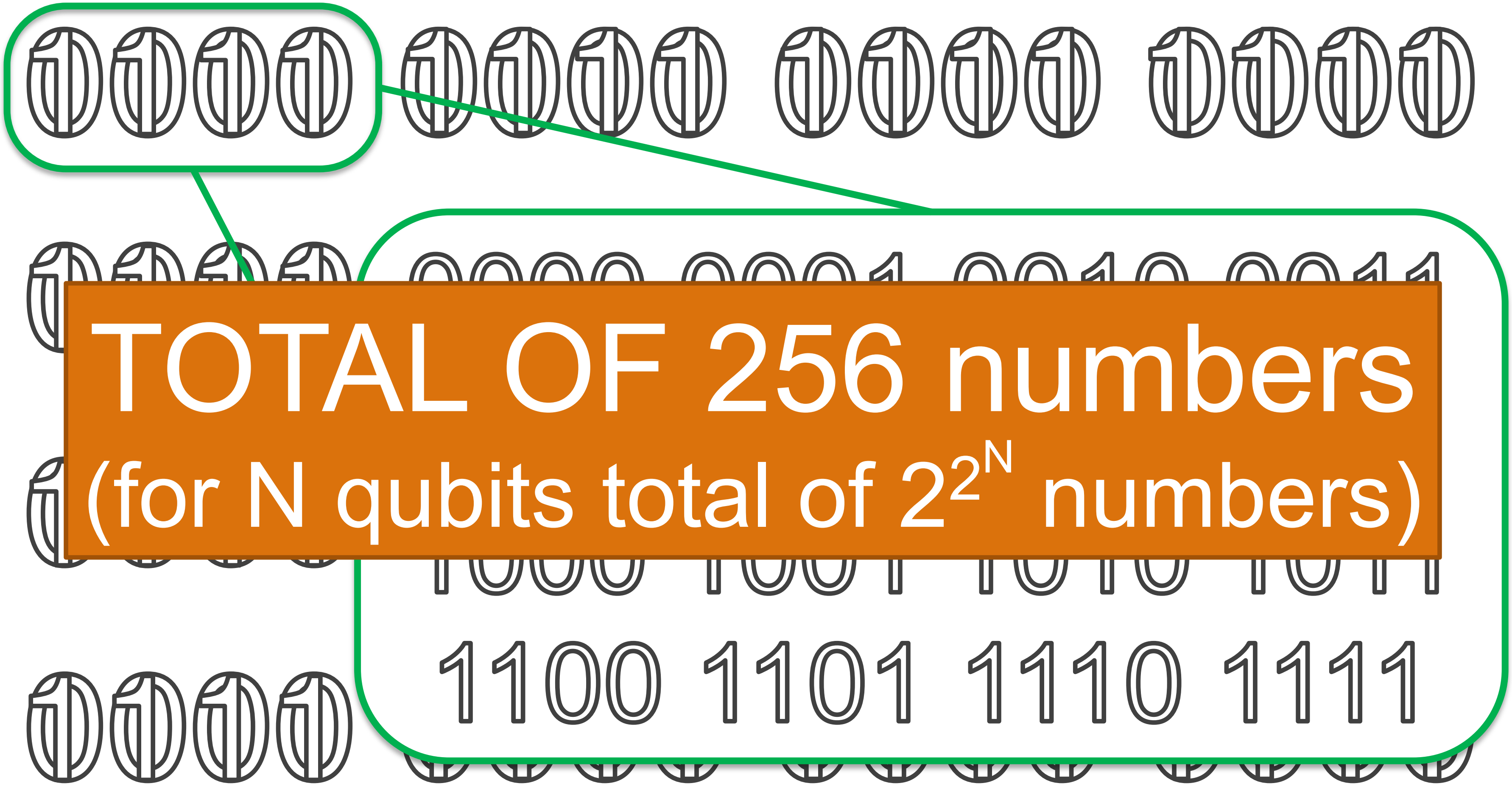


Example: 4 qubits register



0000 0001 0010 0011
0100 0101 0110 0111
1000 1001 1010 1011
1100 1101 1110 1111

Example: 4 qubits register



TOTAL OF 256 numbers

(for N qubits total of 2^{2^N} numbers)

SO WHAT?

Example: cryptography

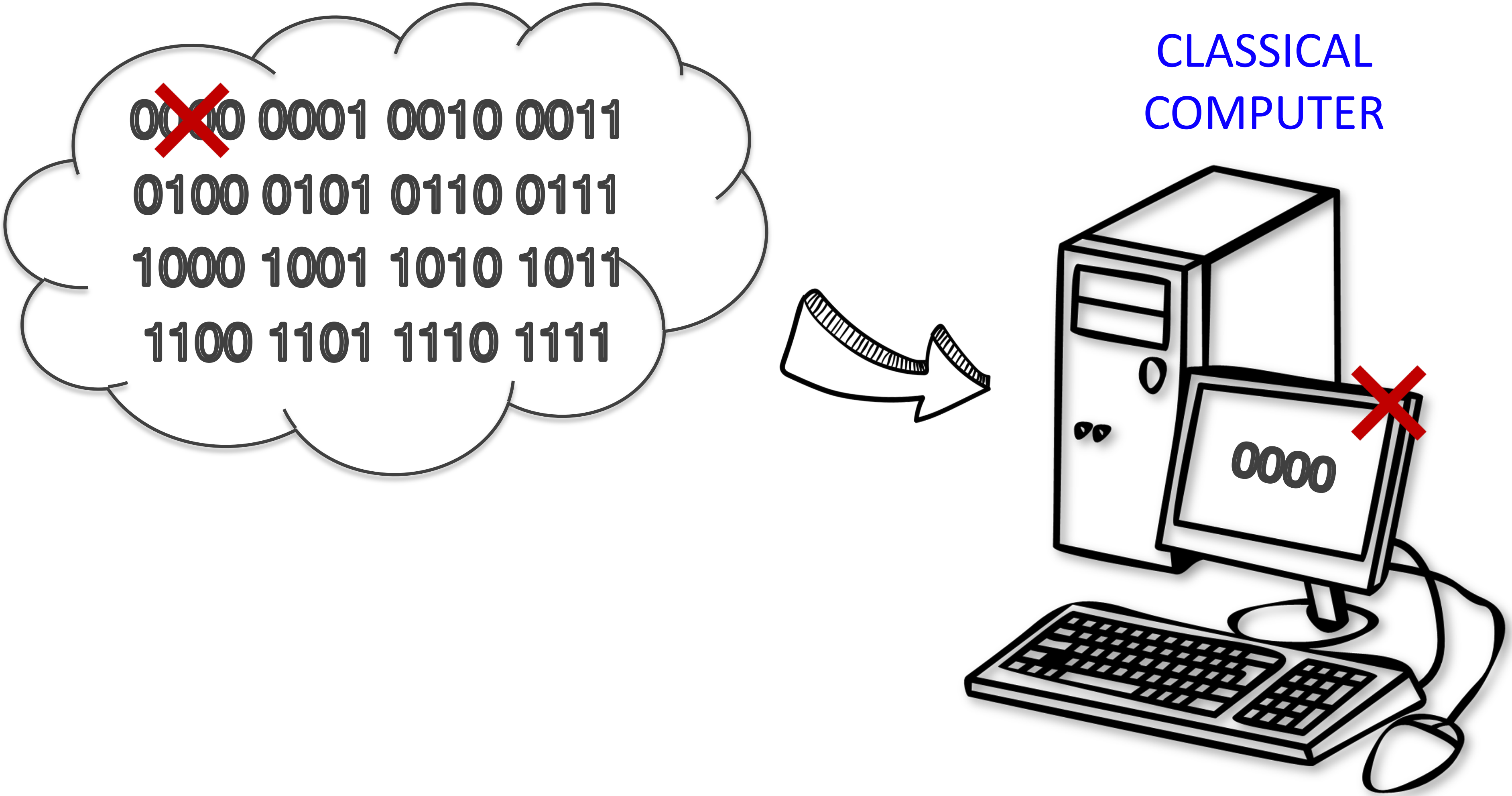
0000 0001 0010 0011

0100 0101 0110 0111

1000 1001 1010 1011

1100 1101 1110 1111

Example: cryptography



~~0000~~ 0001 0010 0011

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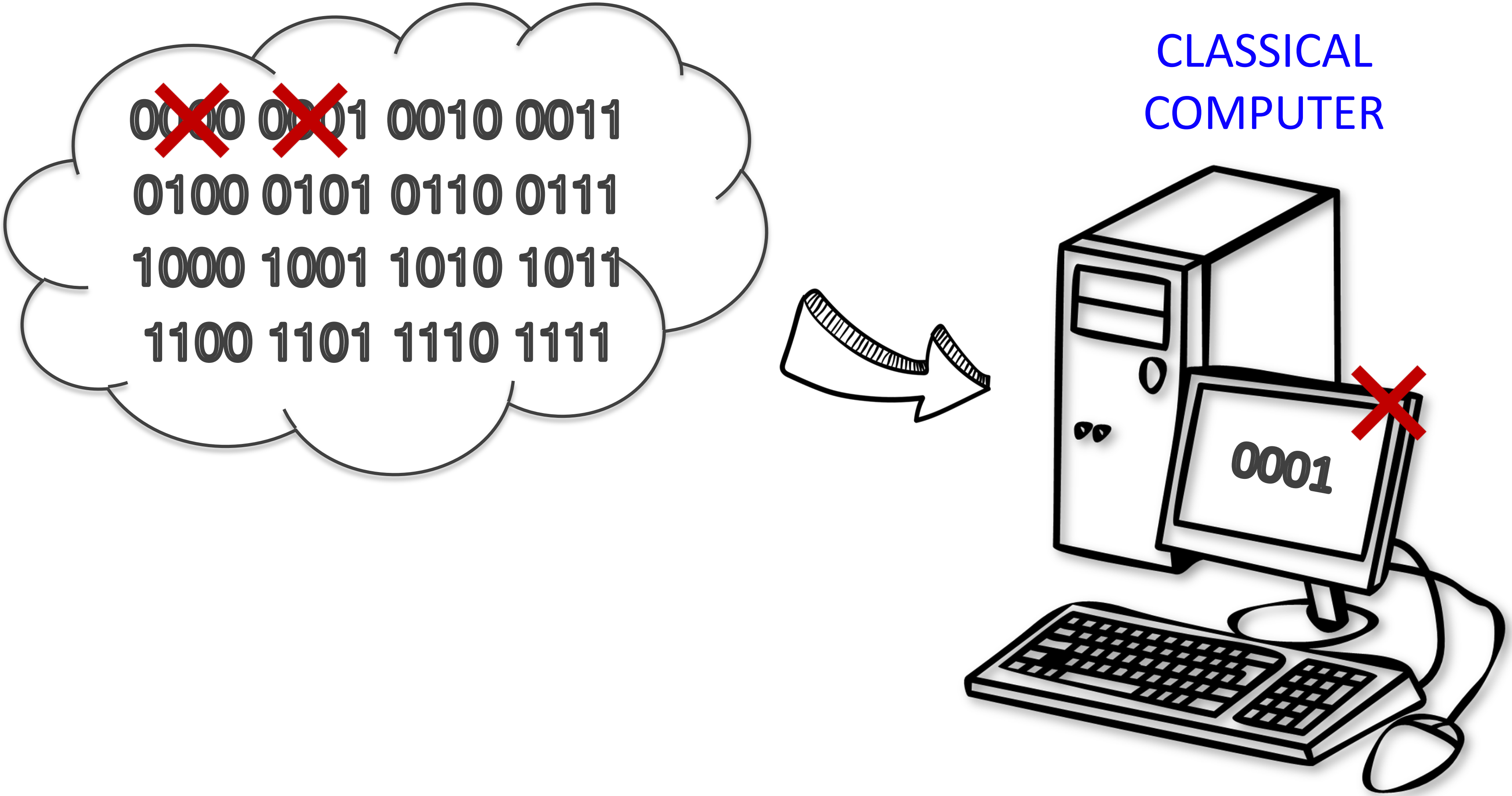
1000 1001 1010 1011

1100 1101 1110 1111

CLASSICAL
COMPUTER

Example: cryptography



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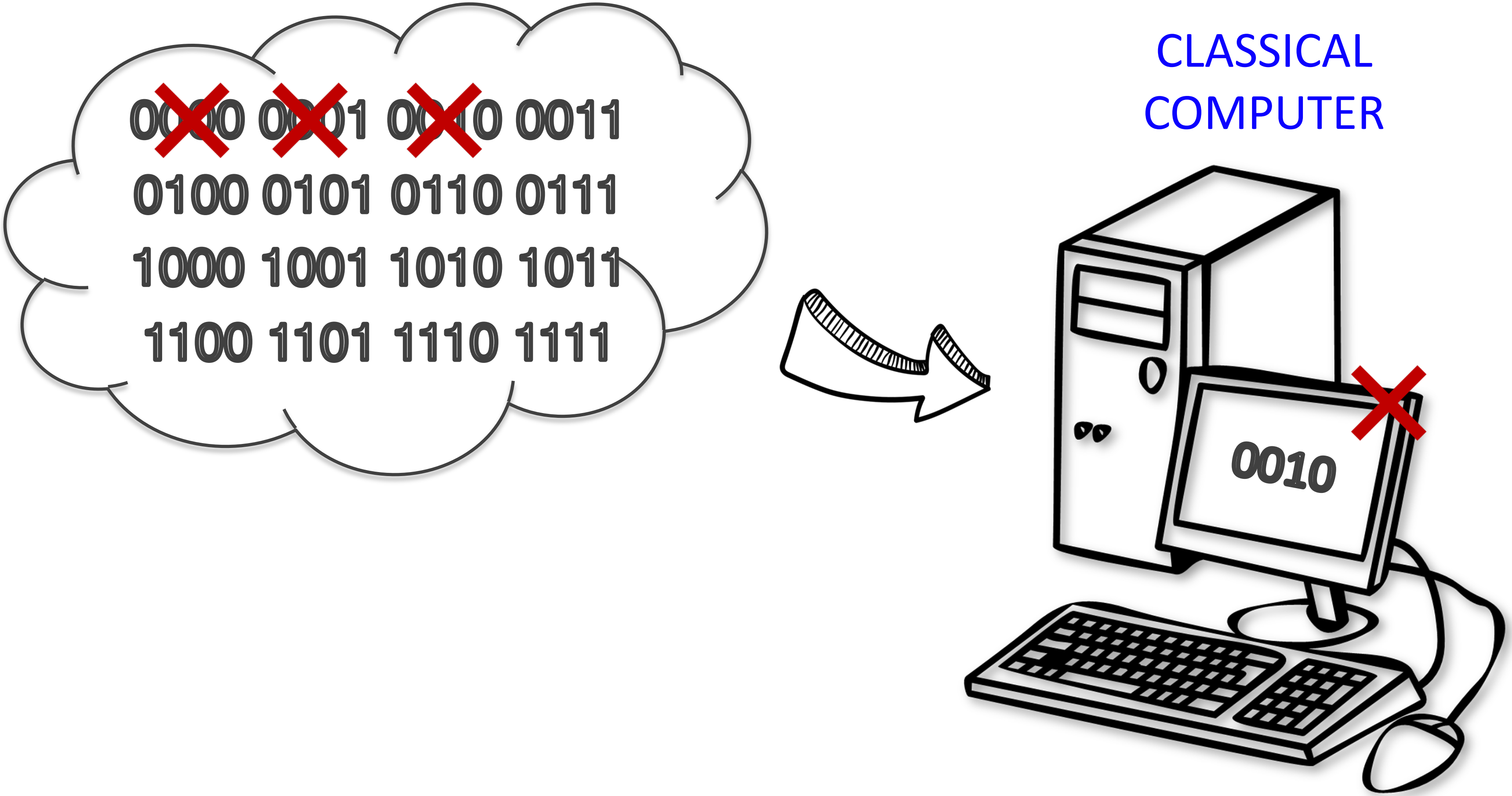
CLASSICAL
COMPUTER

Example: cryptography



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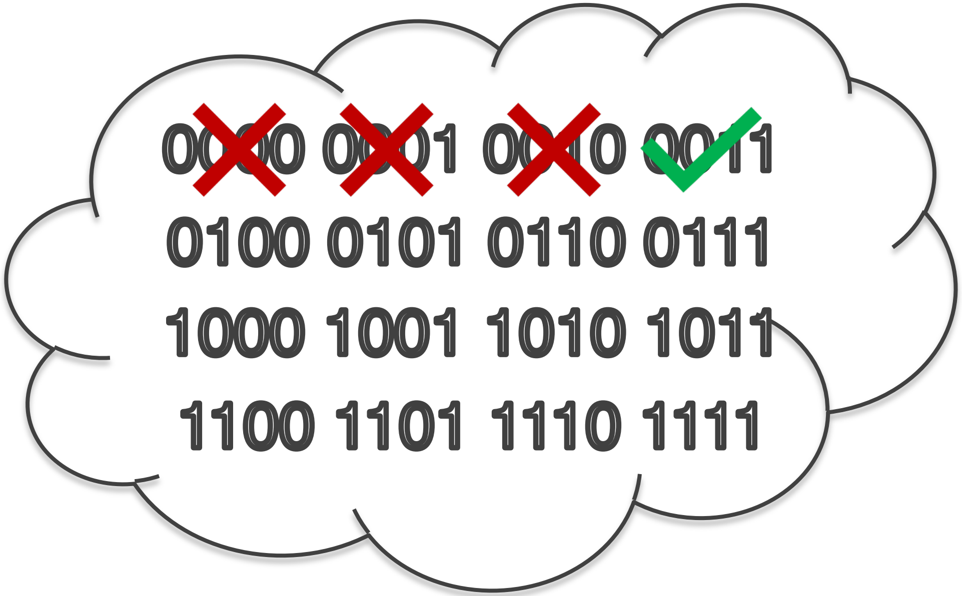
0100 0101 0110 0111
1000 1001 1010 1011
1100 1101 1110 1111

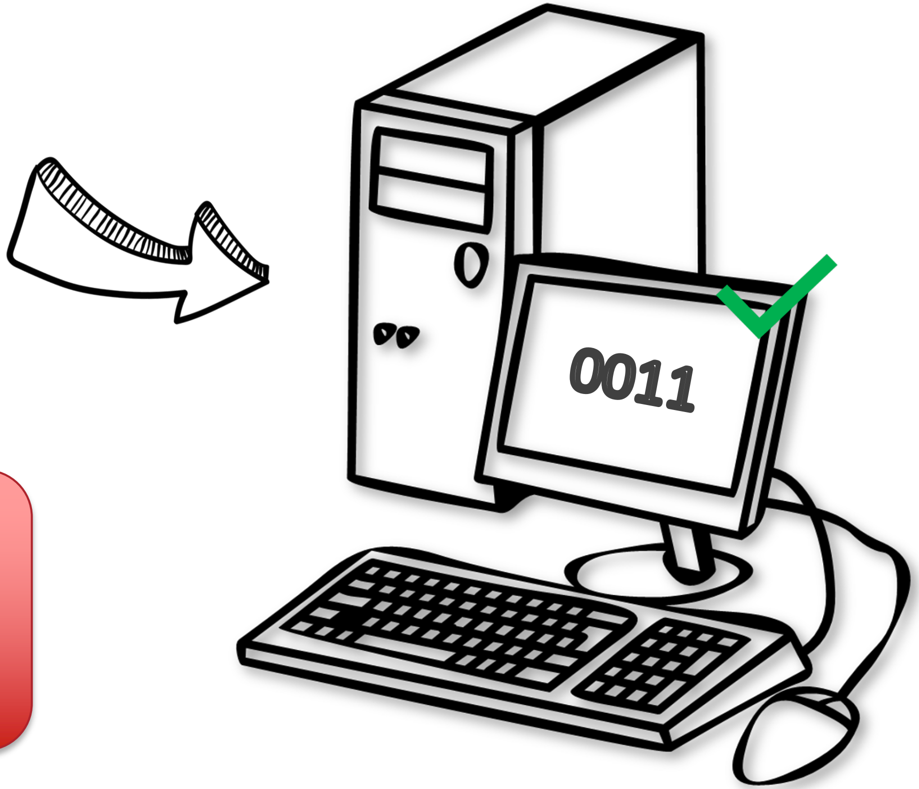
CLASSICAL
COMPUTER

Example: cryptography



~~0000~~ ~~0001~~ ~~0010~~ 0011 ✓
0100 0101 0110 0111
1000 1001 1010 1011
1100 1101 1110 1111

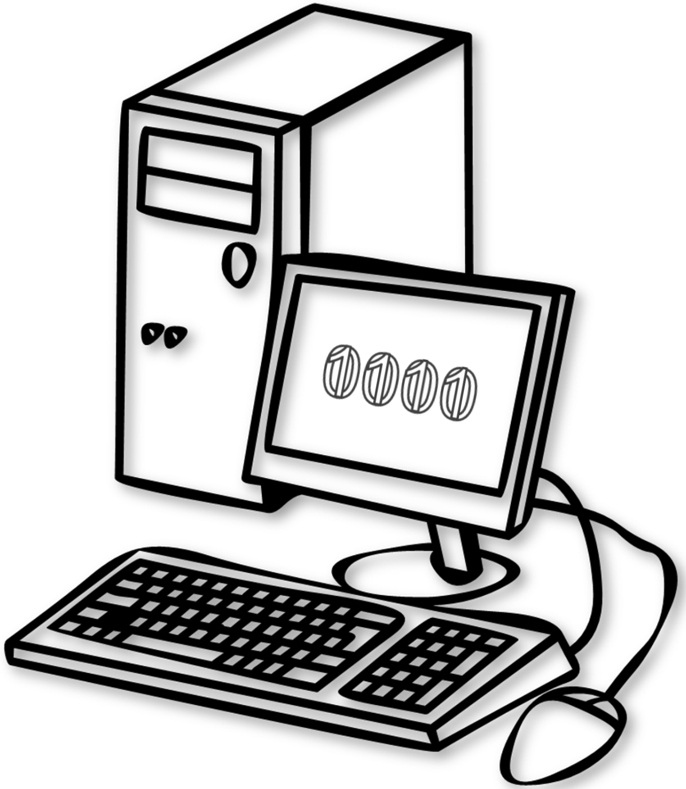
CLASSICAL
COMPUTER



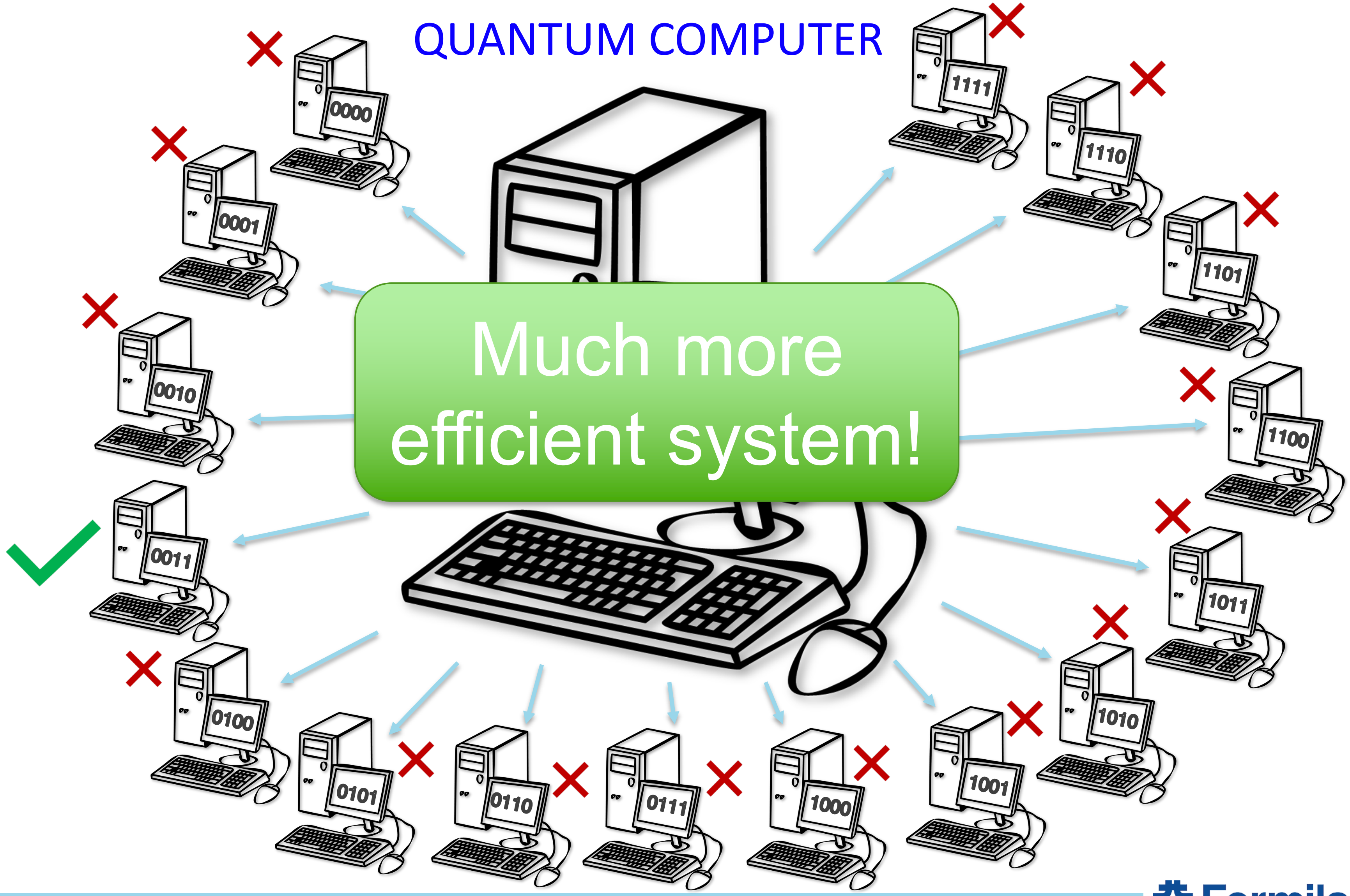
It takes very long time!

Example: cryptography

QUANTUM COMPUTER



Example: cryptography

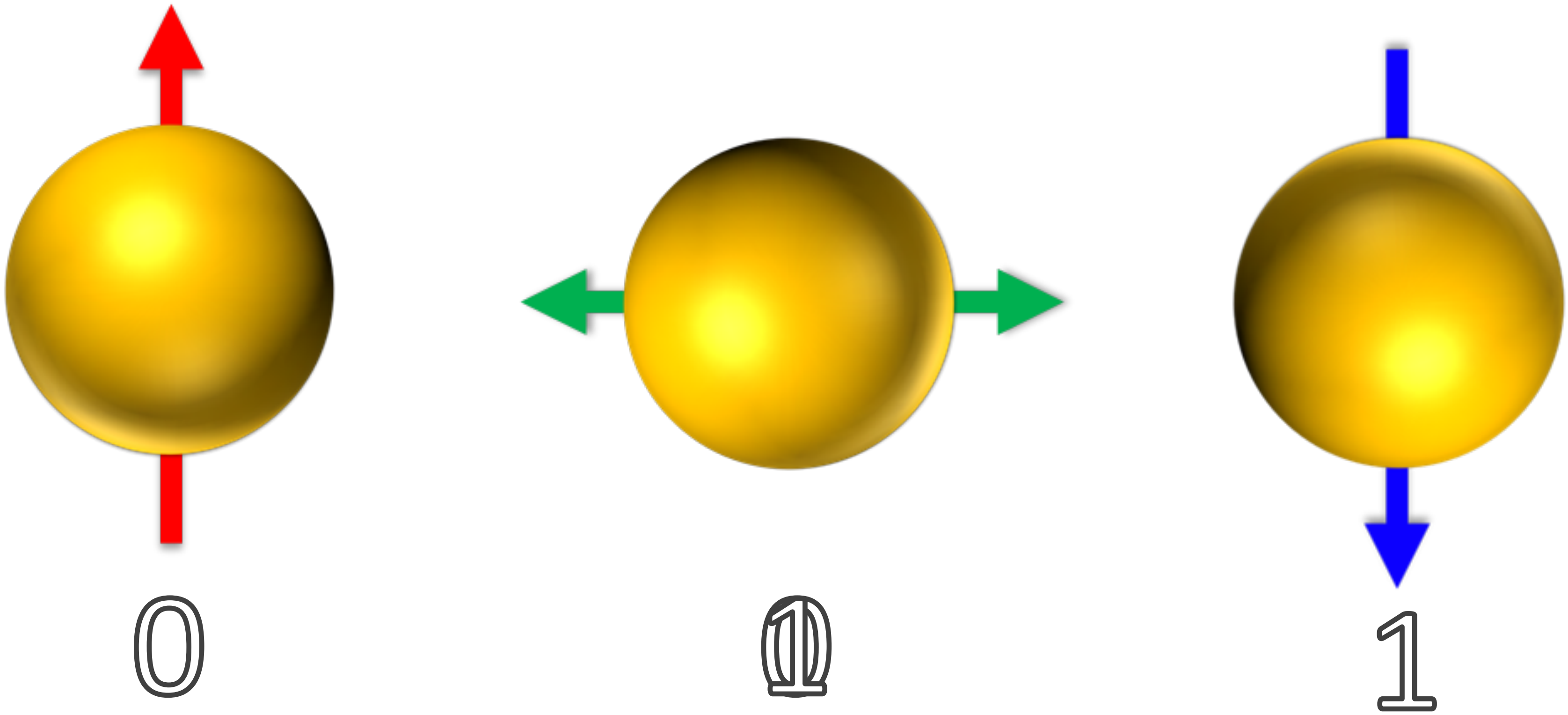


Much more efficient system!

HOW DO WE MAKE A QUBIT?

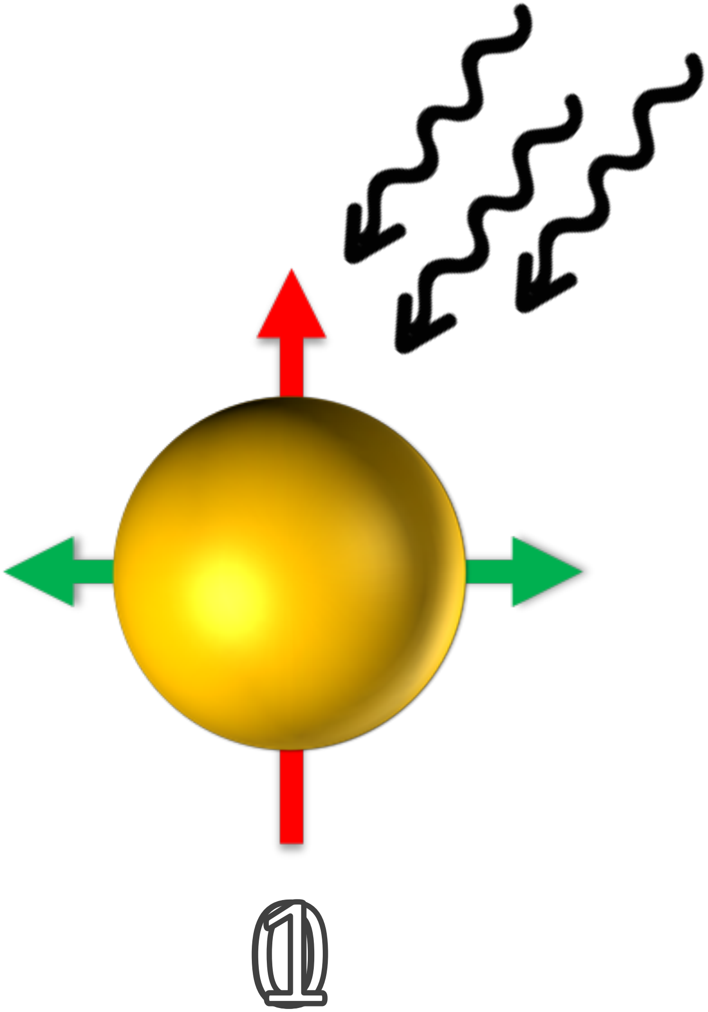
What is a qubit?

A qubit is a quantum system that can be prepared in two distinct states, or in a superposition of them.



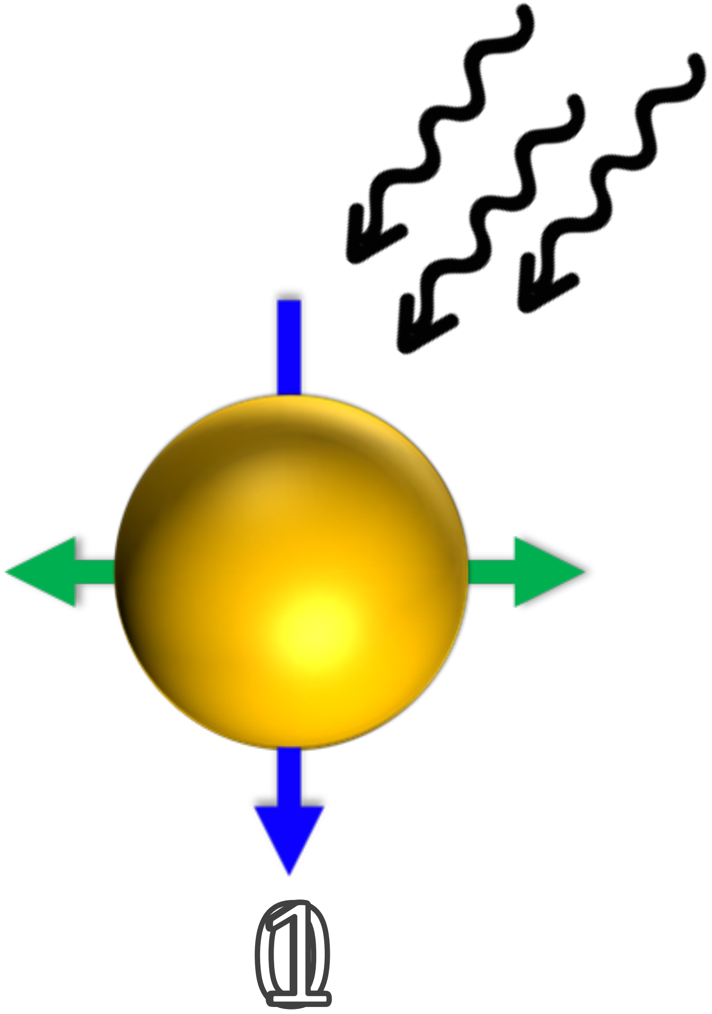
A qubit can be controlled

Apply perturbation



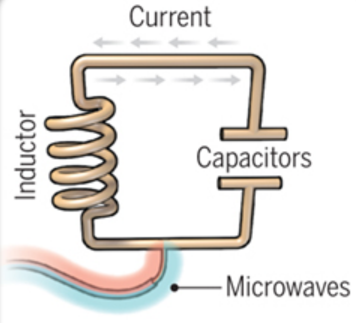
A qubit can be controlled

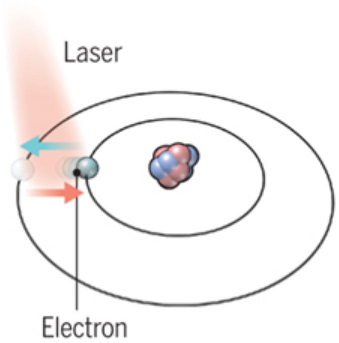
Continue applying perturbation

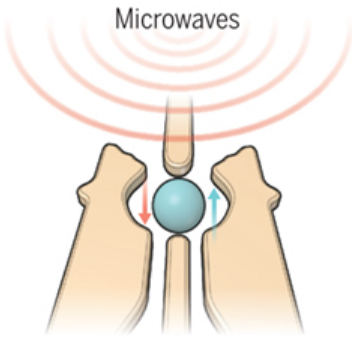


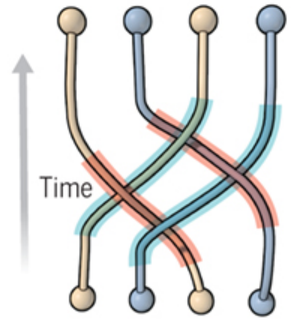
A bit of the action

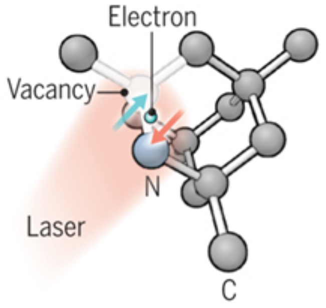
In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.









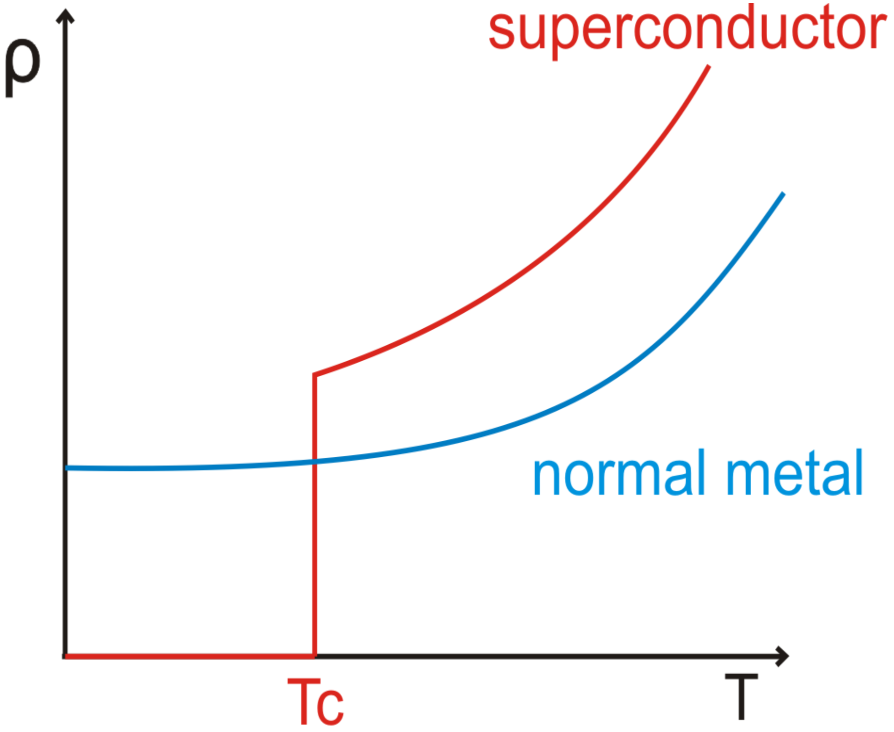


	Superconducting loops	**Trapped ions**	**Silicon quantum dots**	**Topological qubits**	**Diamond vacancies**
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
⊕ **Pros**	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
⊖ **Cons**	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

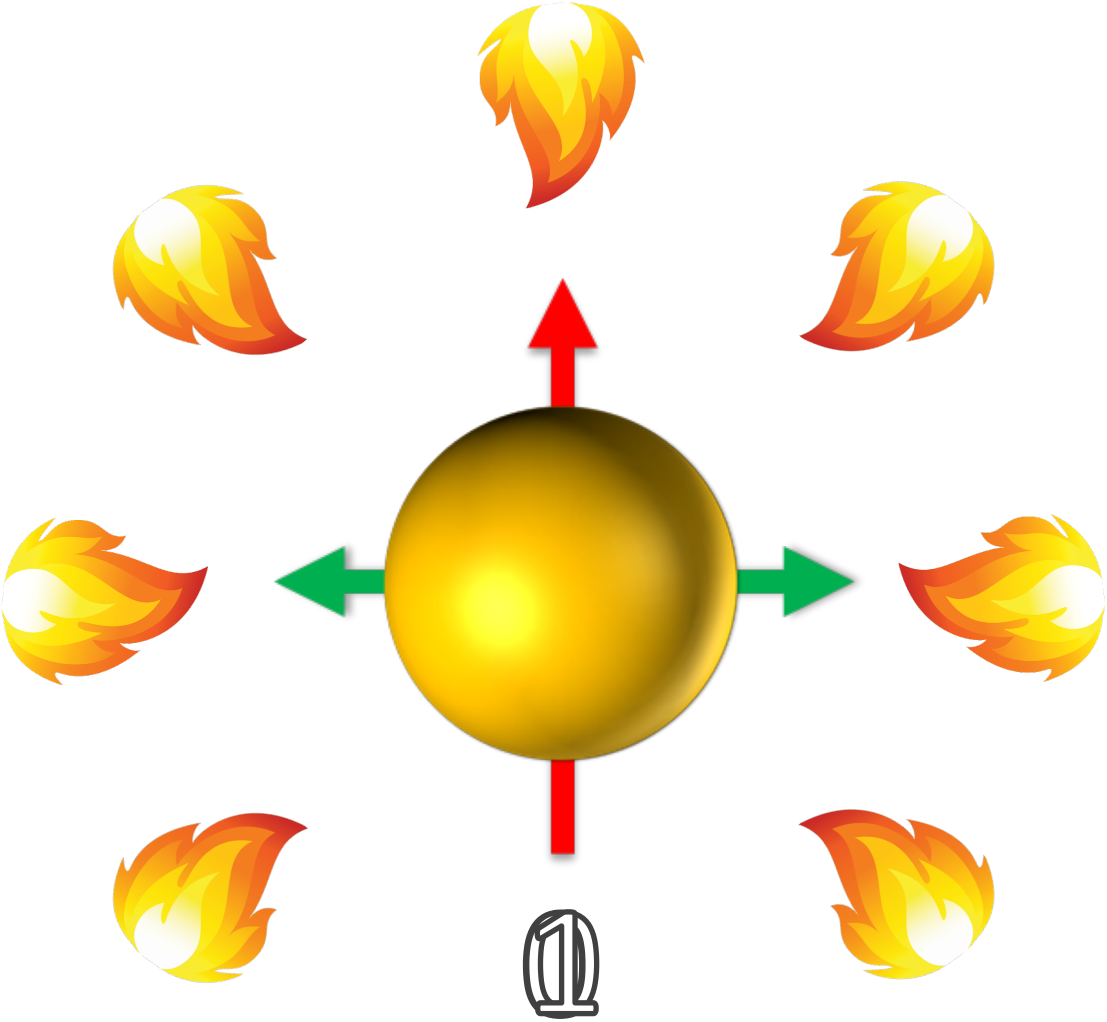
Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

Superconductivity needs low temperature

- Superconducting materials have ZERO resistance at low T
- Niobium T_c=9.25 K (– 443 °F)
- Aluminum T_c=1.2 K (– 458 °F)
- We need to cool these devices to low temperature



Temperature can change the qubit state



Temperature can change the qubit state

We do not want this to happen!

Superconducting qubits need very low temperatures

- Qubits operate at T~10 mK (– 460 °F)!

  COLDER THAN OUTER SPACE!

- Outer space temperature is ~ 2.7 K (–454.81 °F)

- Dilution refrigerators are used to maintain such low temperatures

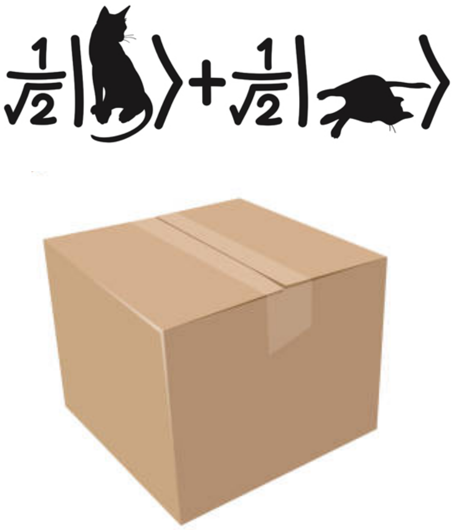
HOW DO WE MEASURE THE STATE OF A QUBIT?

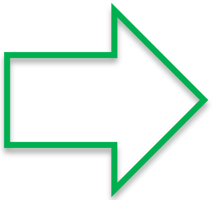
The Schrödinger cat

Superposition of states

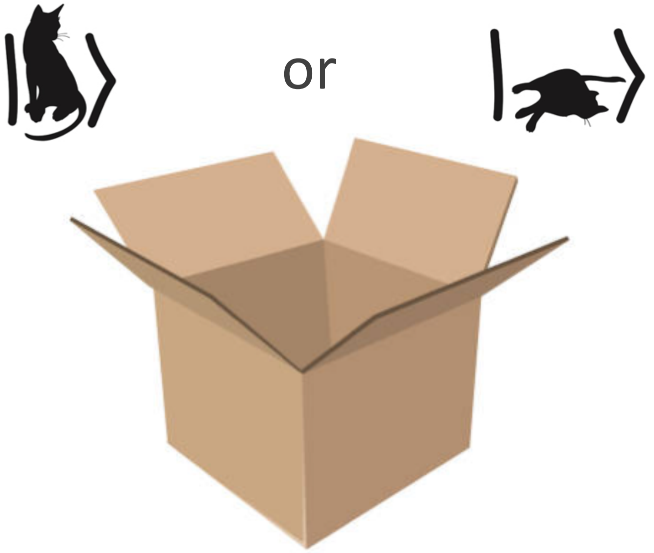
The cat is alive

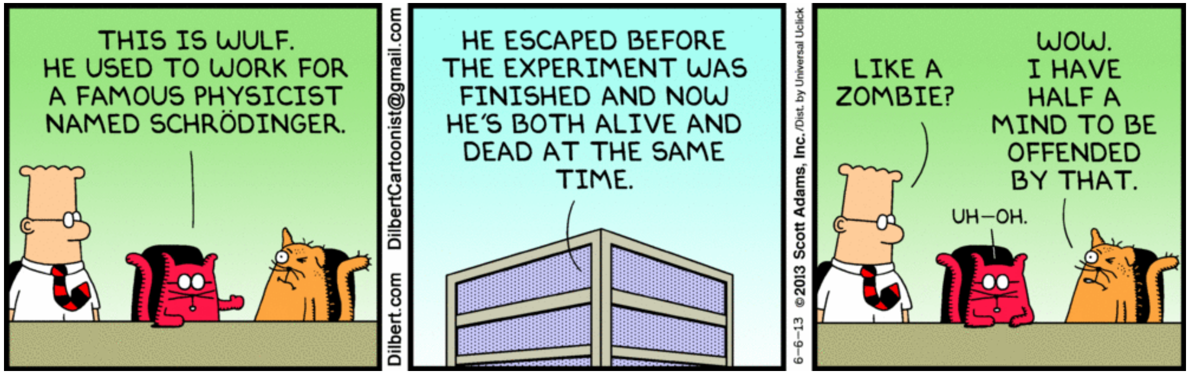
The cat is dead





Measurement





Dilbert.com DilbertCartoonist@gmail.com

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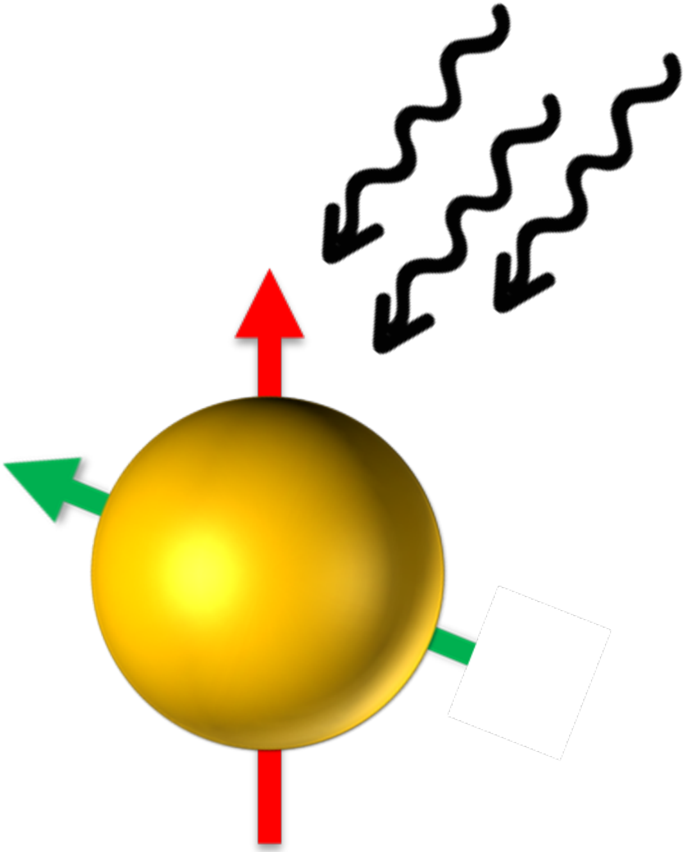
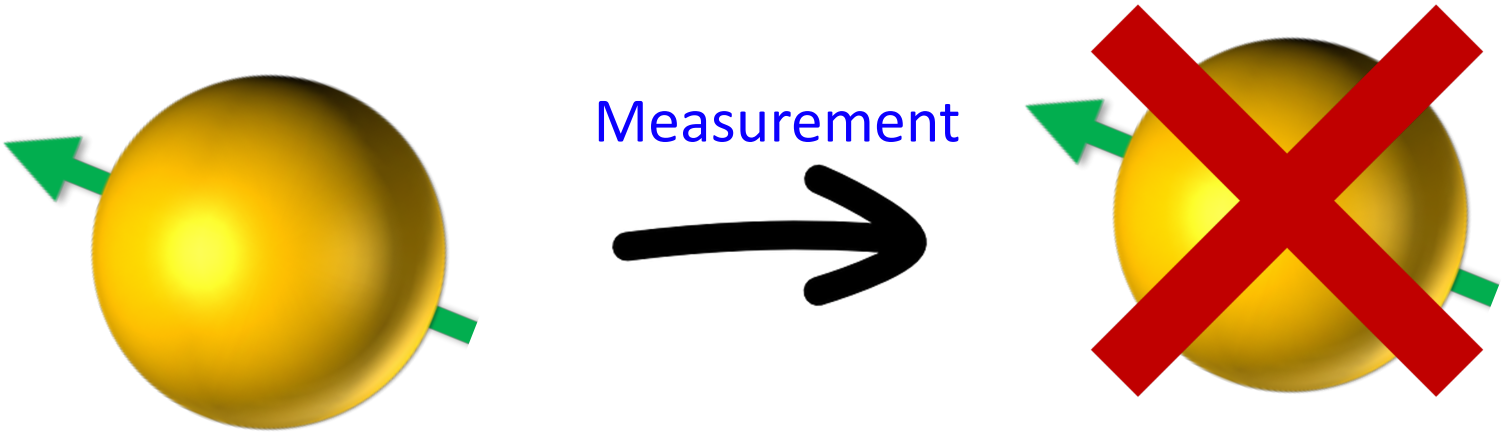
State preparation

Apply perturbation



60%: 0 0 40%: 1

Qubit measurement is a probabilistic result



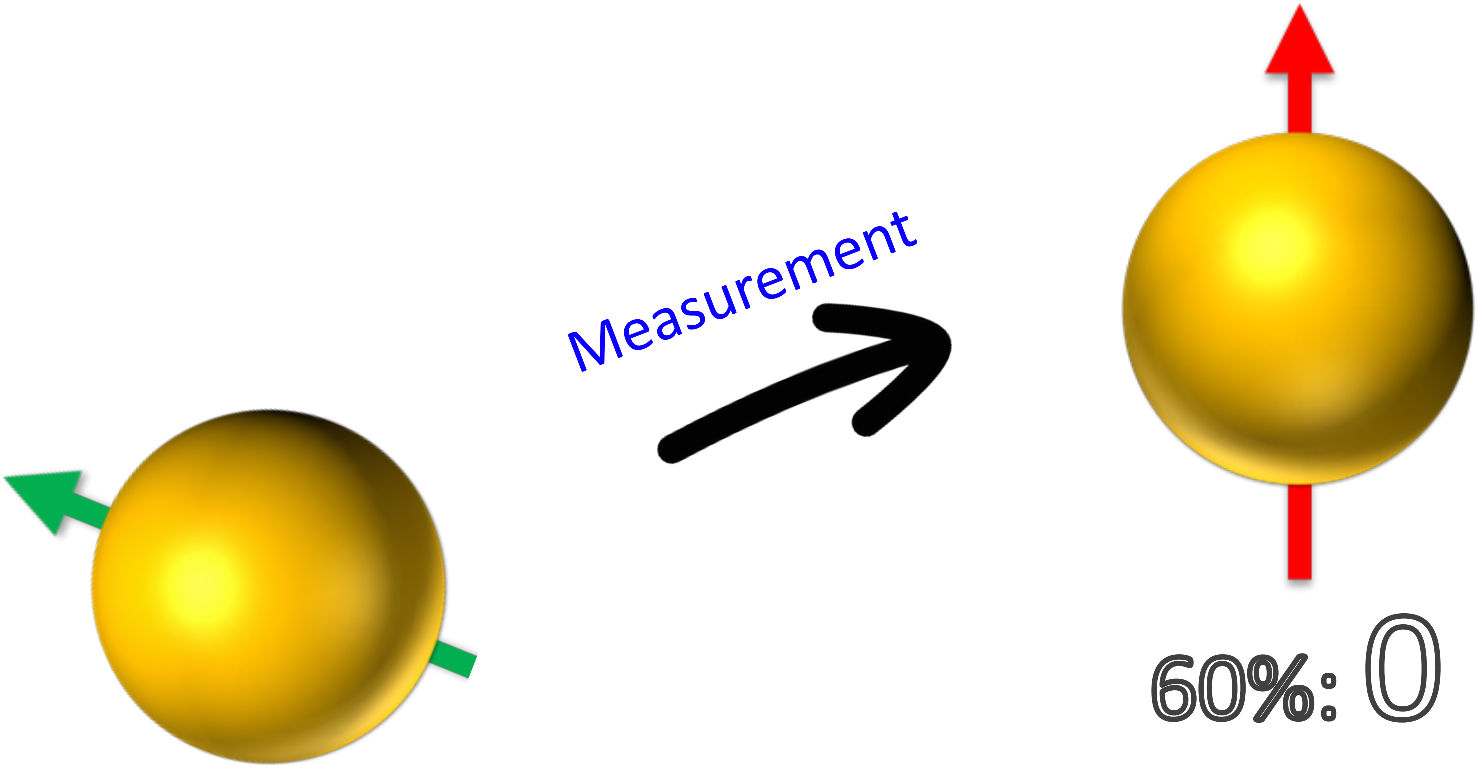
Measurement

Not possible

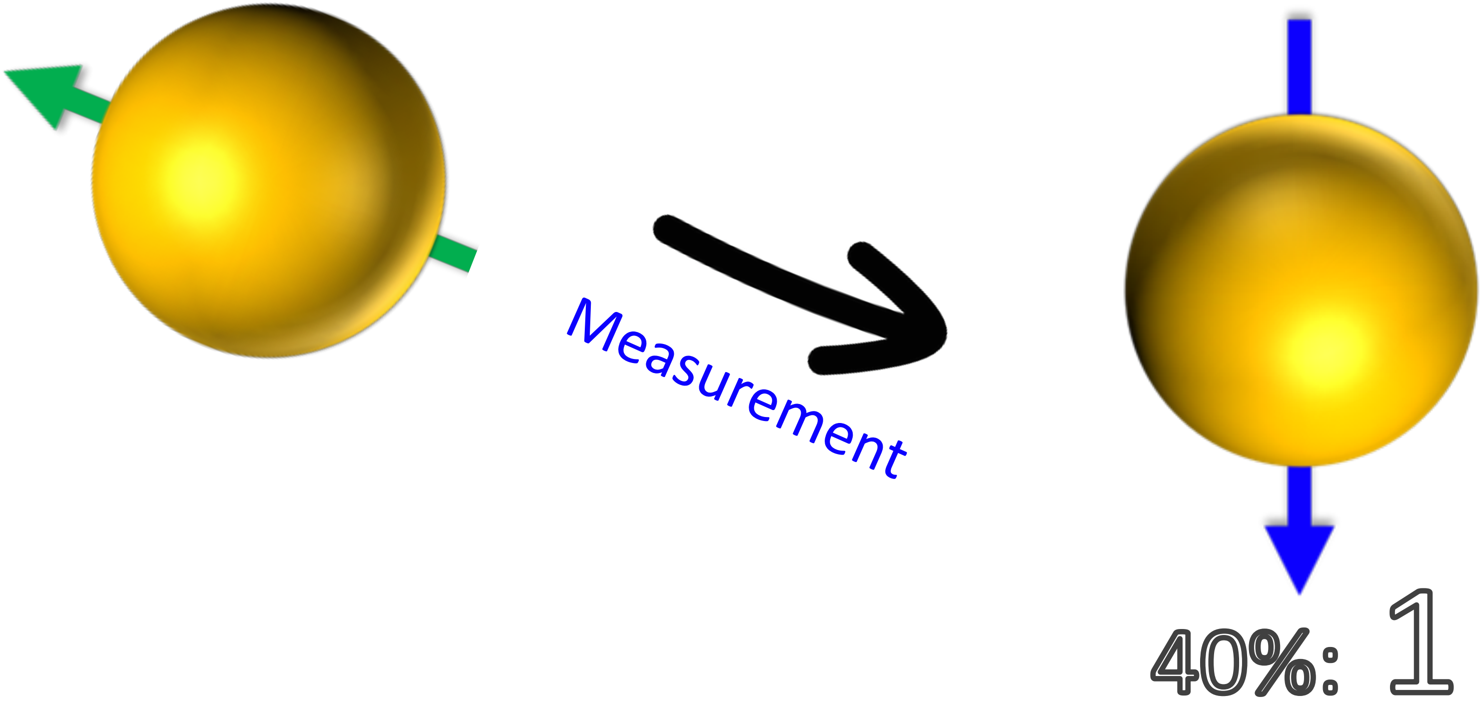
60%: 0

40%: 1

Qubit measurement is a probabilistic result



Qubit measurement is a probabilistic result



CONCLUSIONS

Conclusions

- A quantum computer is composed by quantum bits (qubits)
  - Take advantage of quantum mechanics
  - Qubits can be 0, 1 or a superposition of the two
- A quantum computer can solve complicated problems not solvable by classical computers
- The qubit state can be controlled by perturbing it with some type of signal (microwaves, light, …)
  - Superconductors need low T to operate
  - Temperature might disrupt the state of the qubit
  - Qubits must be cooled to ultra-low temperatures
- Outcome of a qubit measurement is probabilistic
  - Quantum computers returns probabilistic results