Open-source quantum technologies

Nathan Shammah
Theoretical Quantum Physics Lab
Cluster for Pioneering Research
RIKEN, Saitama, Japan

Unitary Fund, Berkeley

MACHINE LEARNING TOKYO

Machine Learning Talks
Spaces Shinagawa
14th February 2020

AIRJ
Association of Italian
Researchers in Japan

NathanShammah.com

Association of Italian Researchers in Japan

ASSOCIAZIONE
DEI RICERCATORI
ITALIANI
IN GIAPPONE

KICK-OFF EVENT: DECEMBER 2019

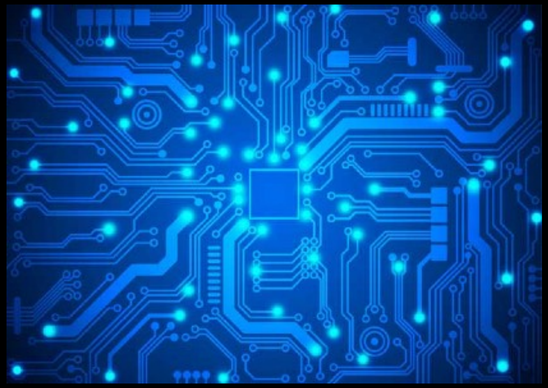
SYMPOSIUM: APRIL 2020

http://airj.info/

Quantum Technologies

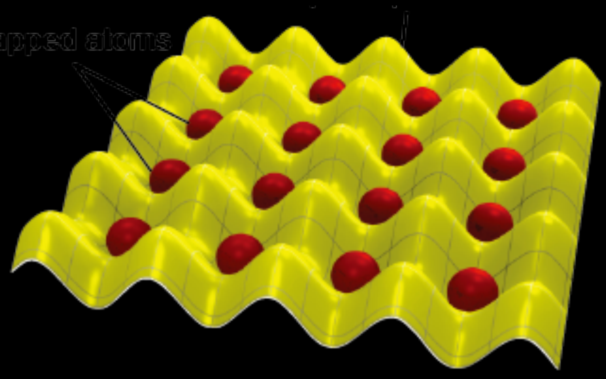
Quantum Technologies

Computing

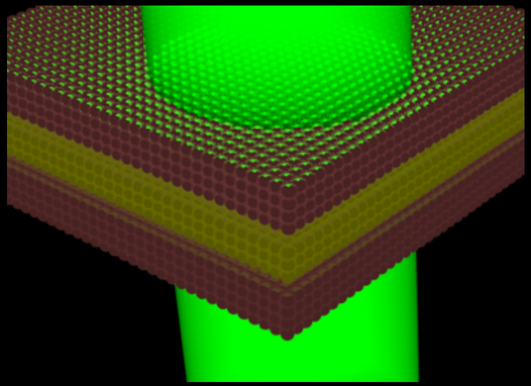


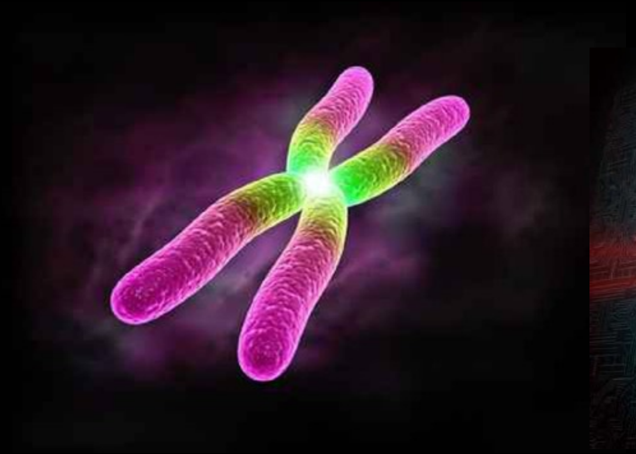
Communication

Simulation



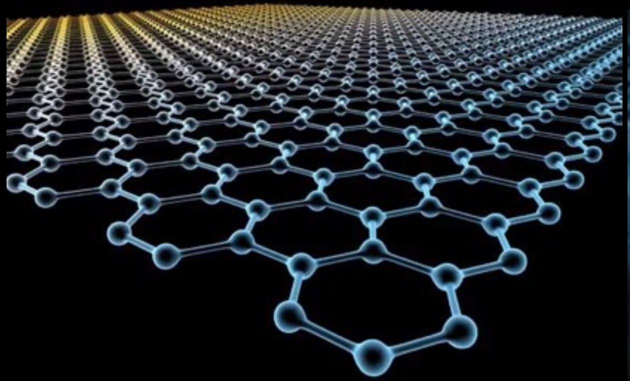
Sensors





Drug Design

Cybersecurity



Materials

Biology

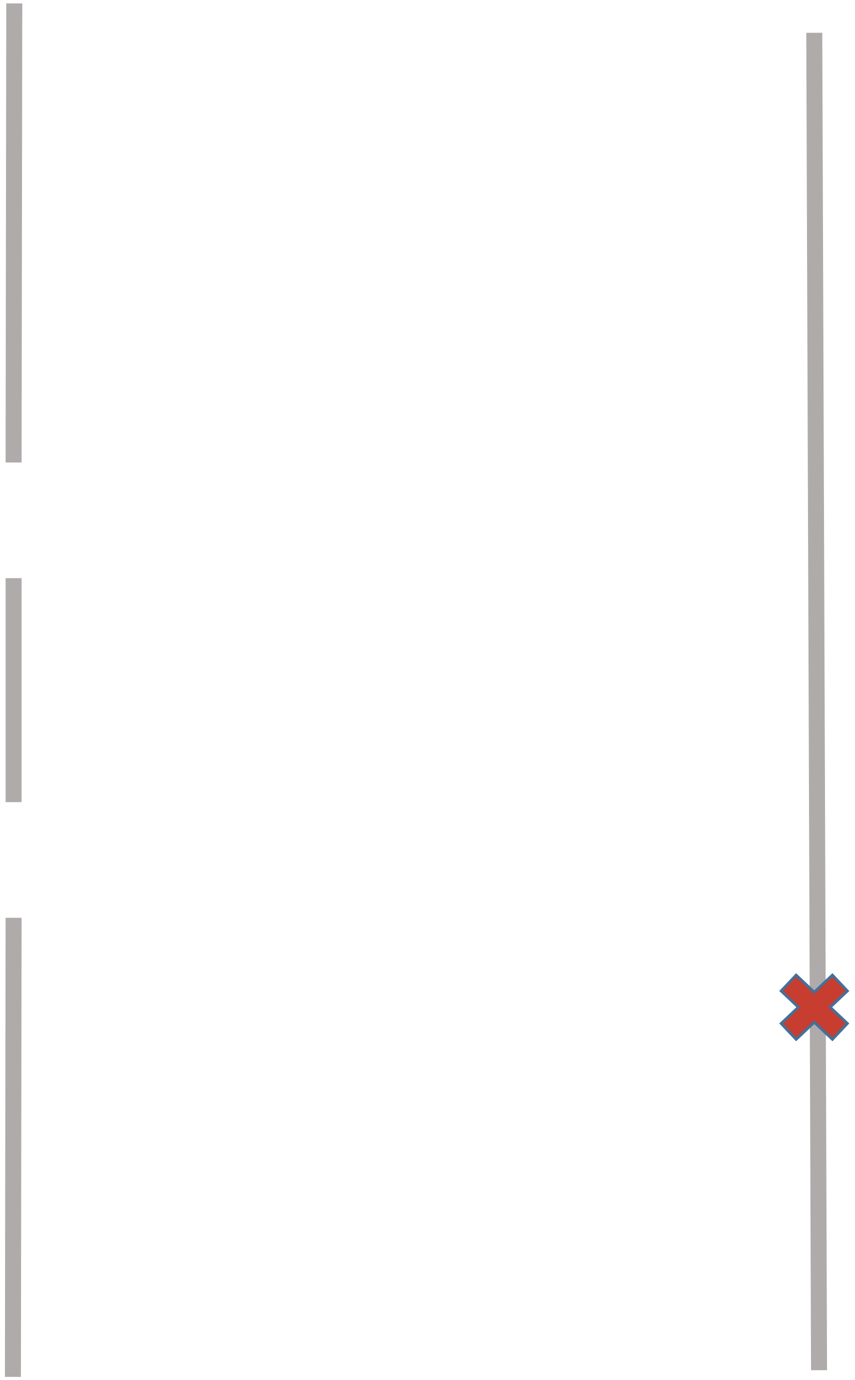
Quantum Technologies

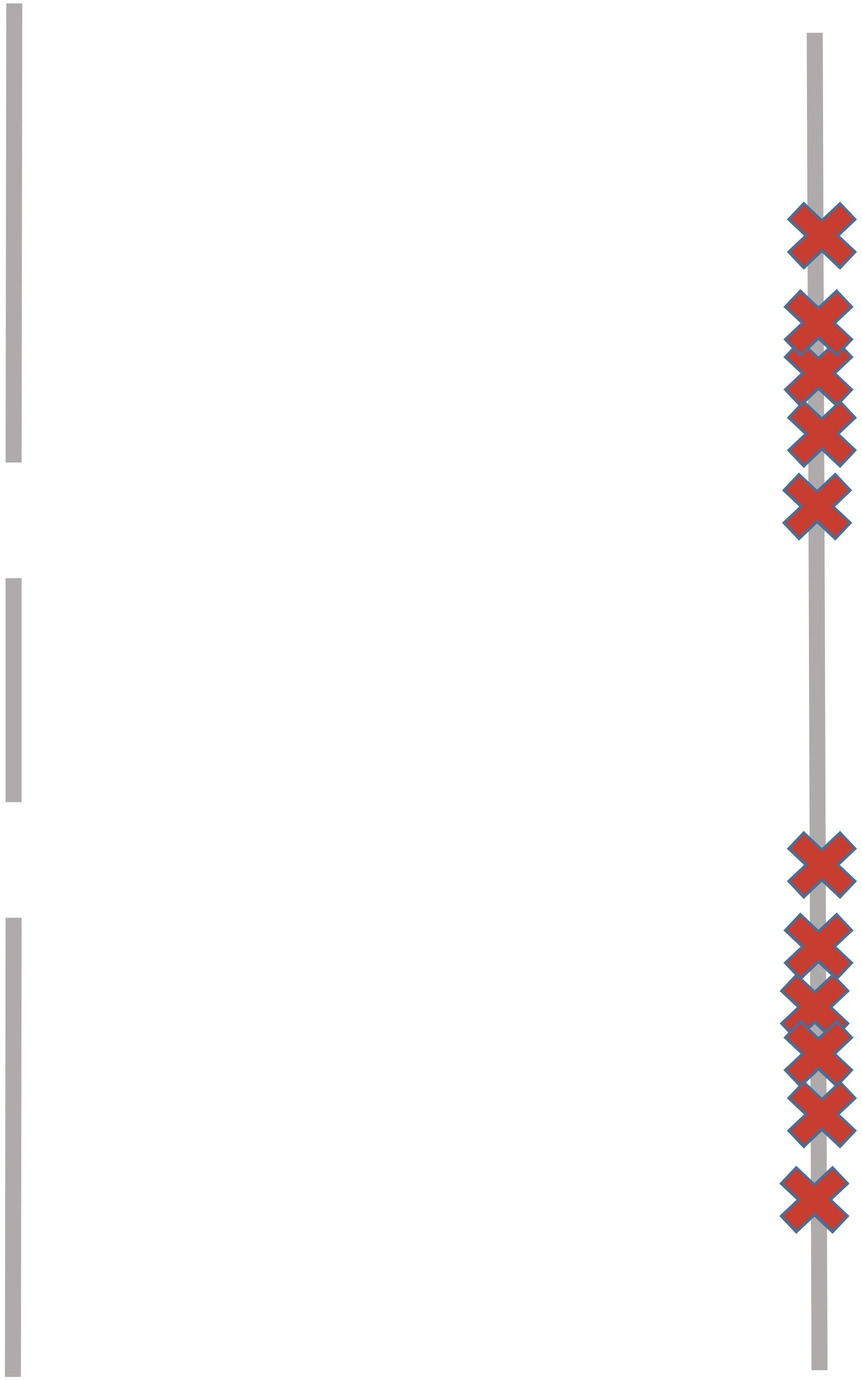
Quantum Technologies

Quantized: discrete, in ‘chunks’

Quantized: discrete, in ‘chunks’

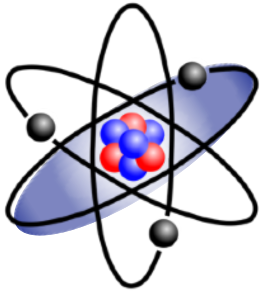
Quantized: discrete, in ‘chunks’



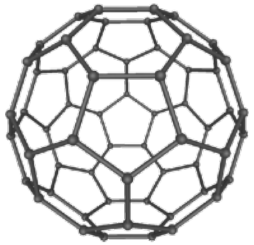


https://youtu.be/Xmq_FJd1oUQ

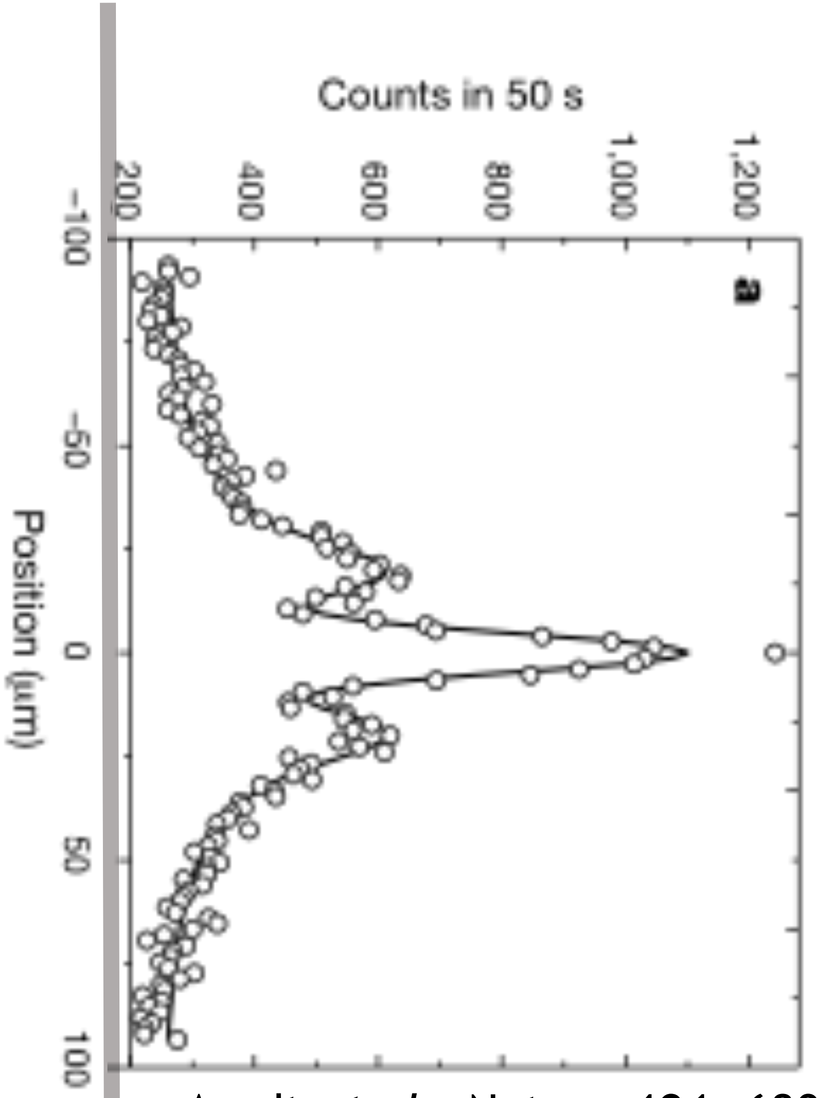
Photon



Atom

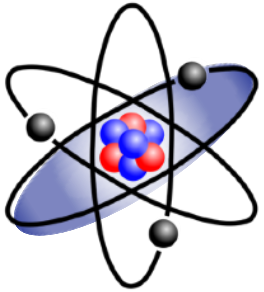


C60

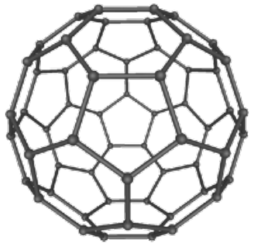


Arndt *et al.*, Nature **401**, 680 (1999)

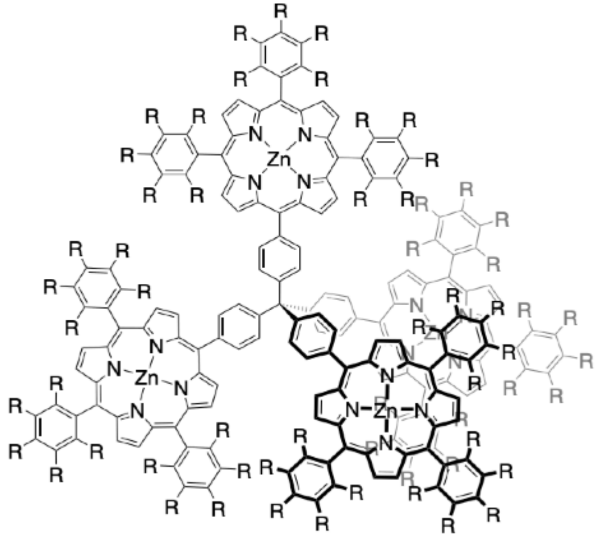
Photon



Atom



C60



R = F or $C_{10}H_4F_{17}S$

Organic molecules (oligoporphyrins)

nature physics

Letter | Published: 23 September 2019

Quantum superposition of molecules beyond 25 kDa

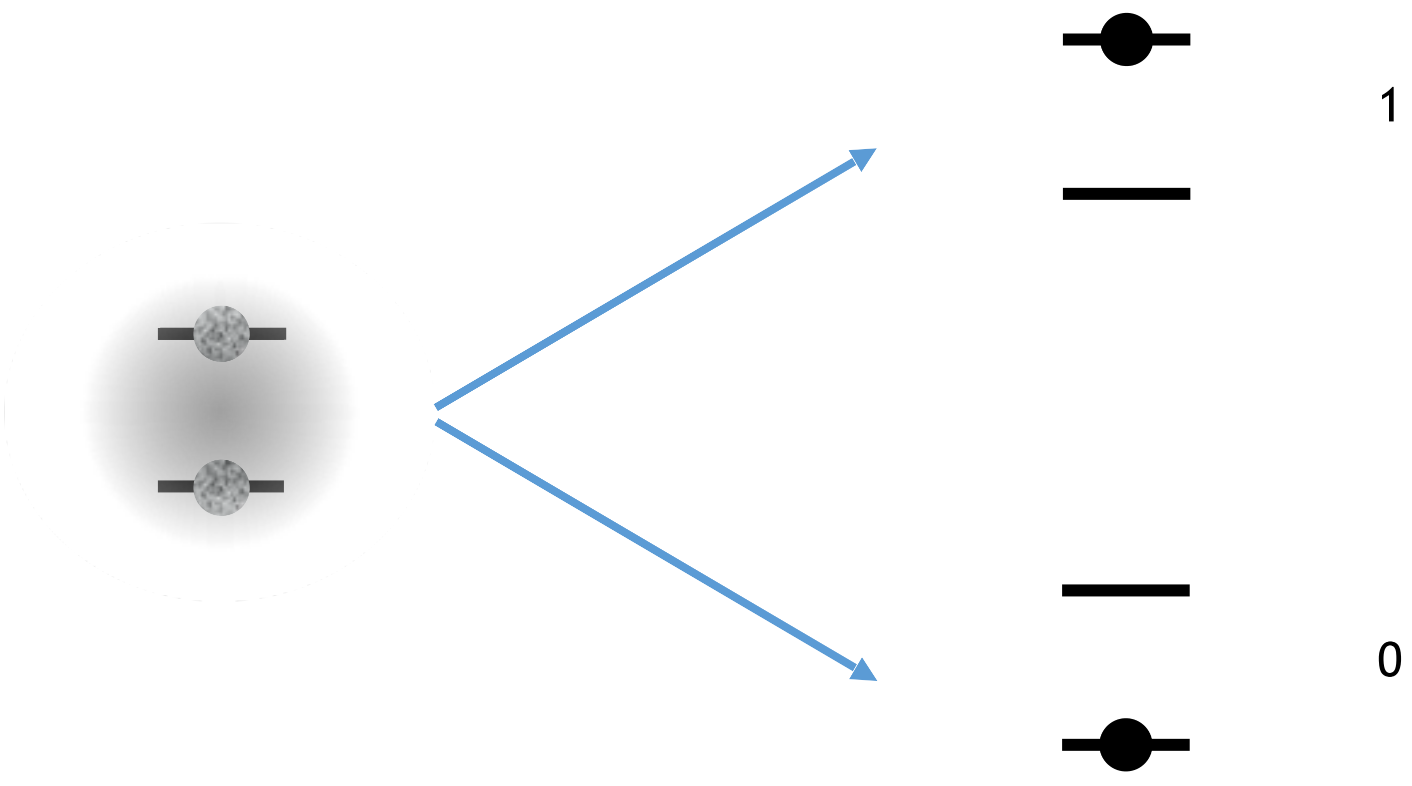
Yaakov Y. Fein, Philipp Geyer, Patrick Zwick, Filip Kiałka, Sebastian Pedalino, Marcel Mayor, Stefan Gerlich & Markus Arndt

Nature Physics **15**, 1242–1245(2019) | Cite this article

https://www.nature.com/articles/s41567-019-0663-9

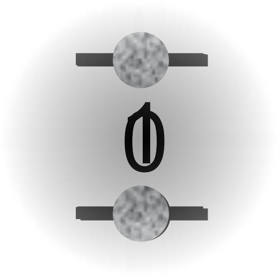
Quantum Bit

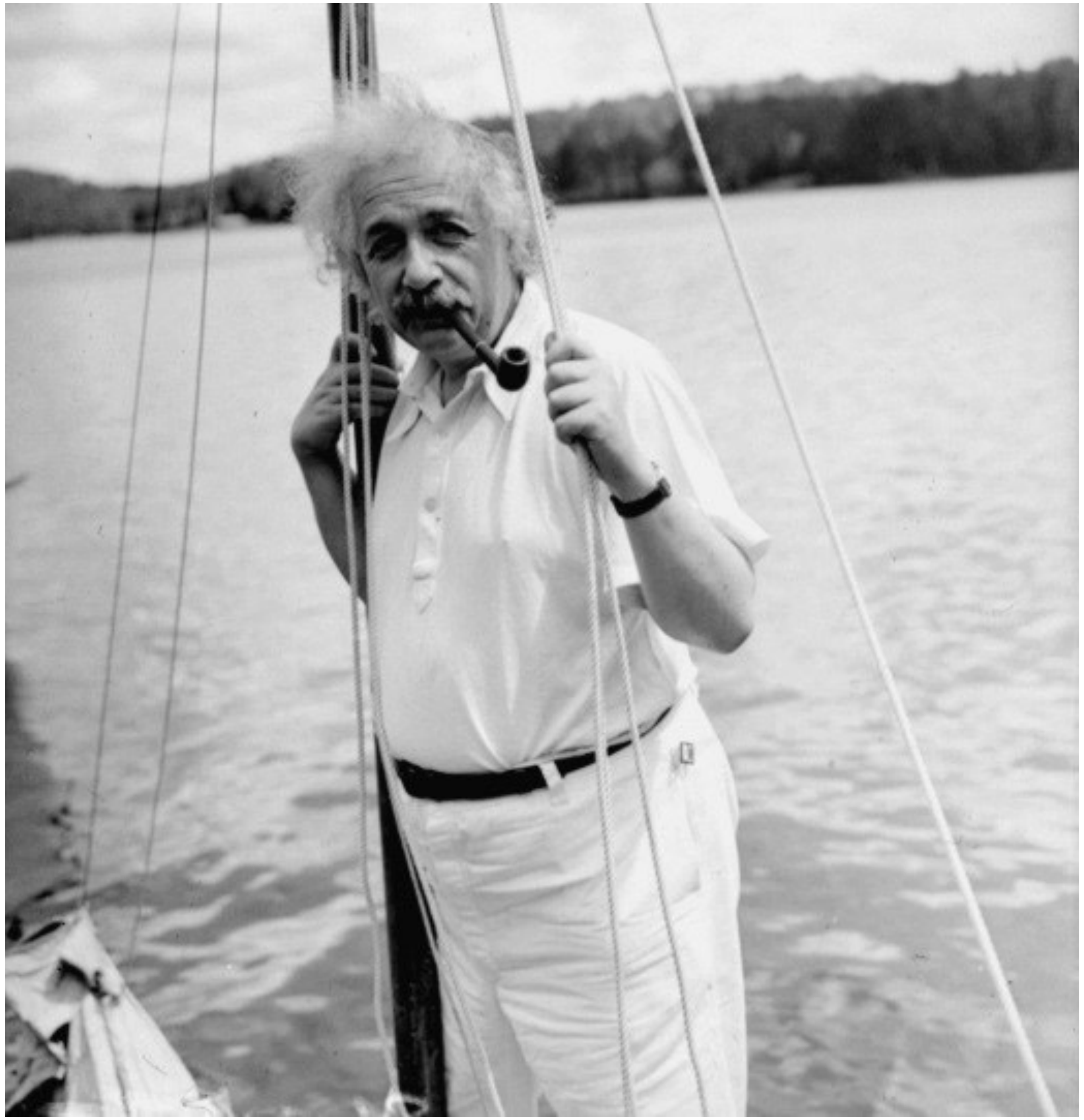
Measuring a system can modify its state



Quantum Bit

Superposition and Entanglement





Albert Einstein in 1935

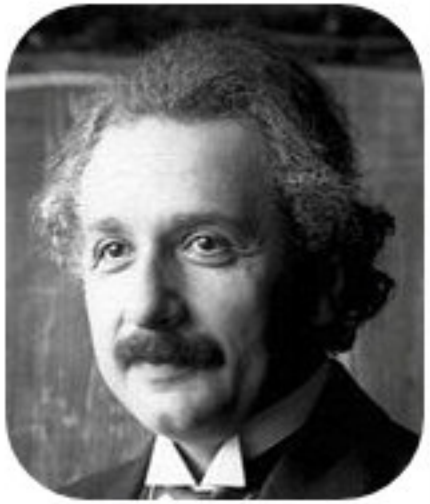
EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

The New York Times, May 4th, 1935



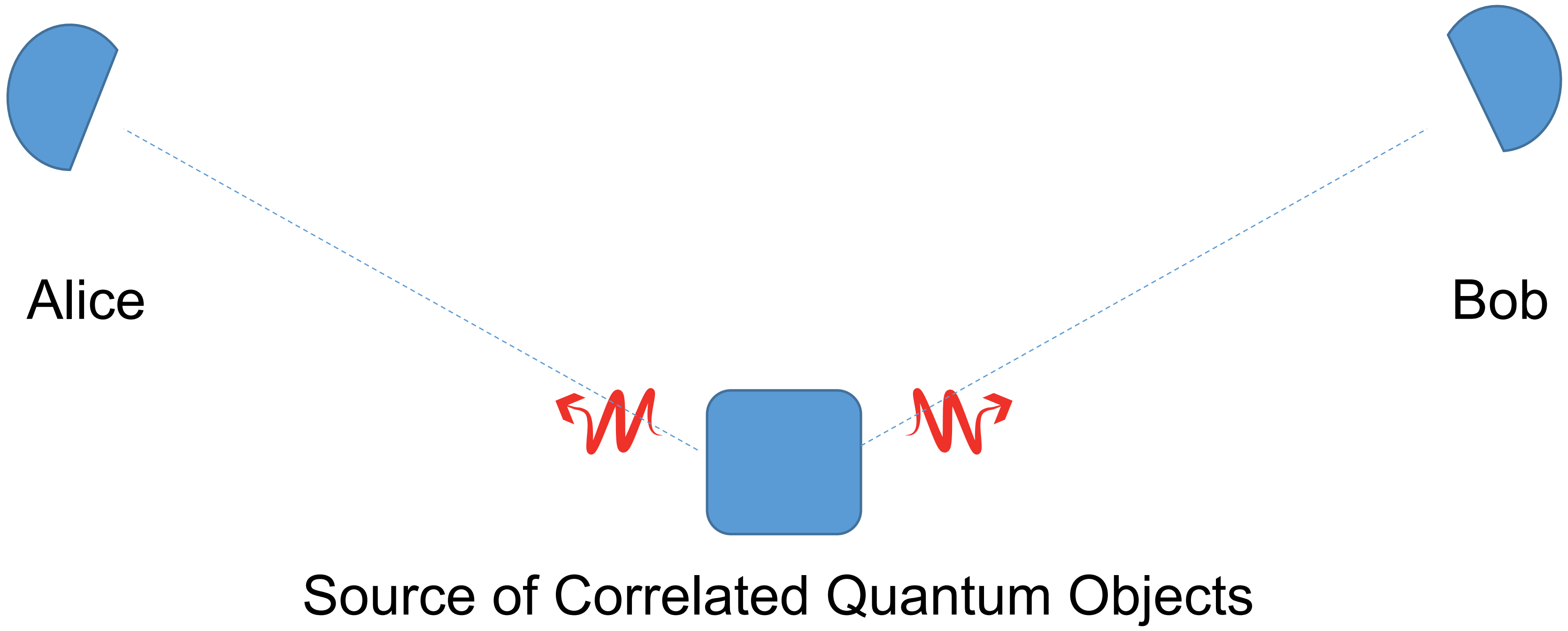
MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

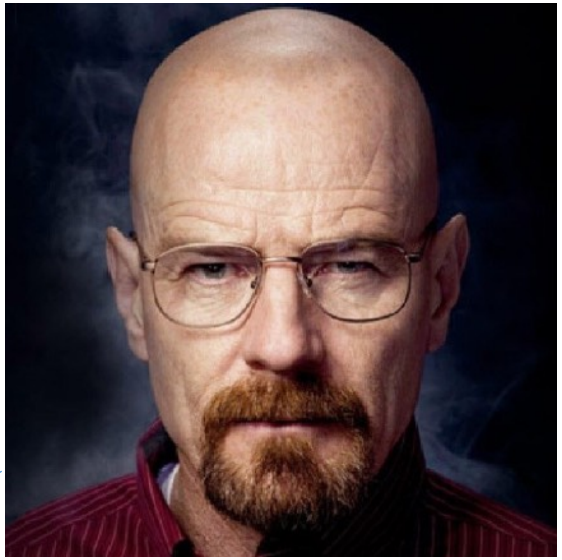
A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

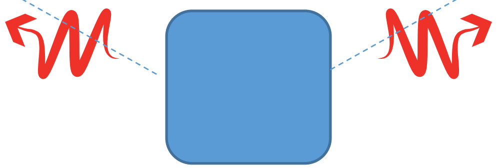
In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.


Alice
Bob
Source of Correlated Quantum Objects

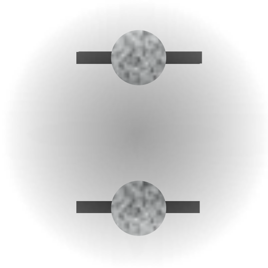
Schrodinger

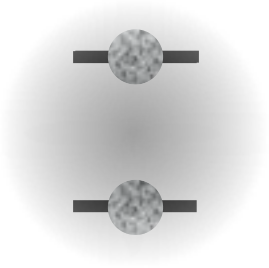


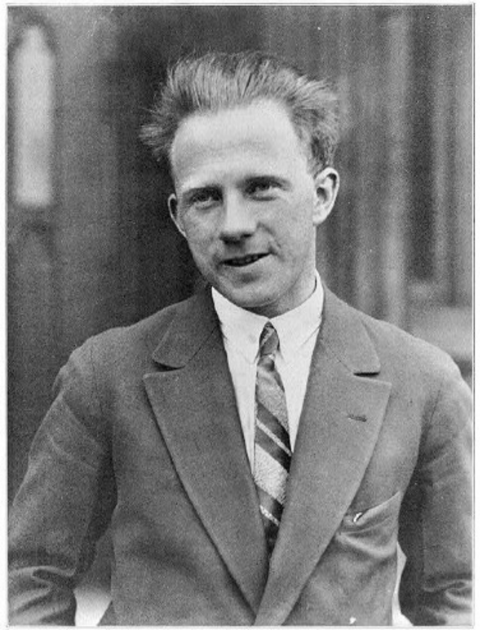
Heisenberg



Source of Correlated Quantum Objects





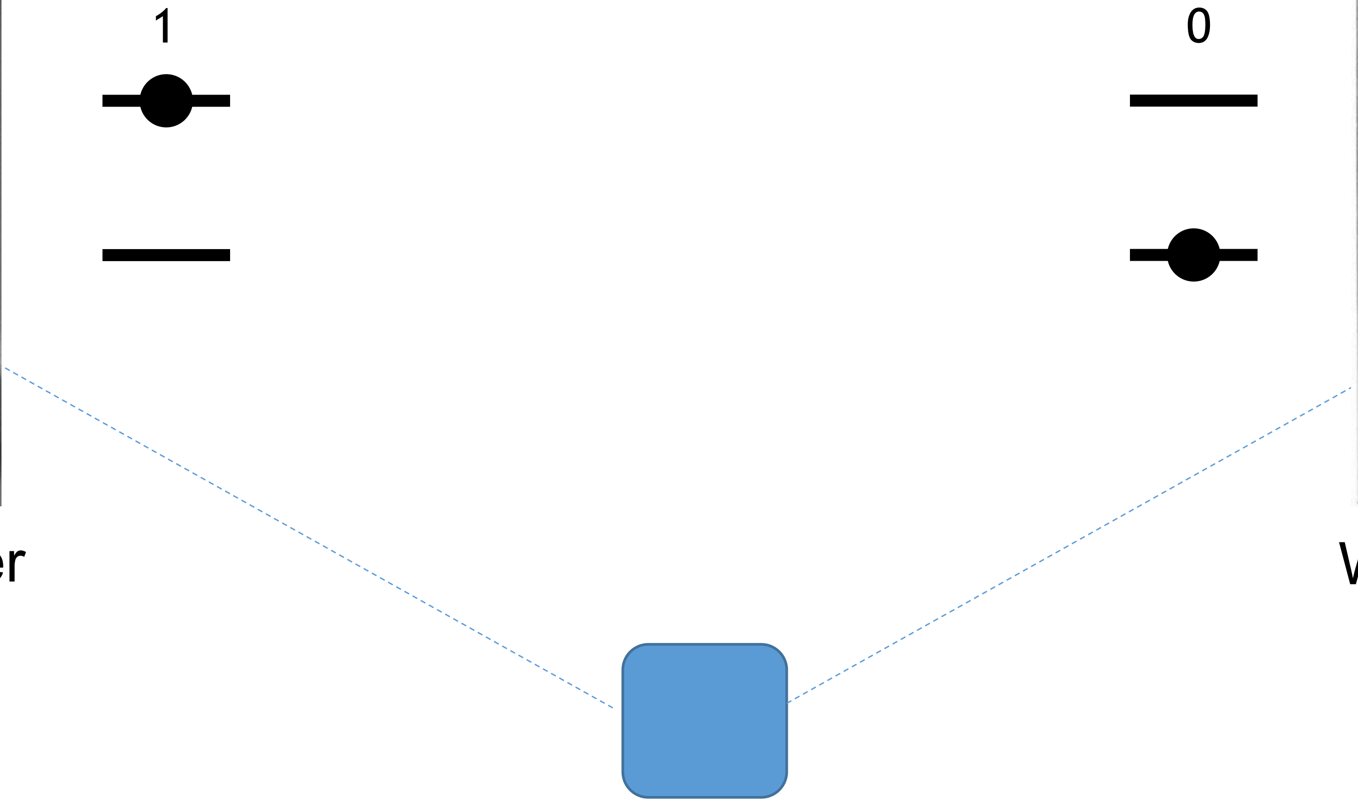


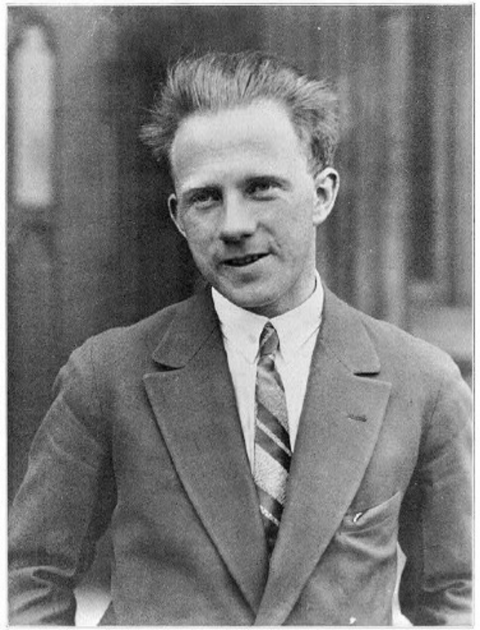
Erwin Schrodinger
(1887-1961)

Werner Heisenberg
(1901-1976)

Source of Correlated Quantum Objects

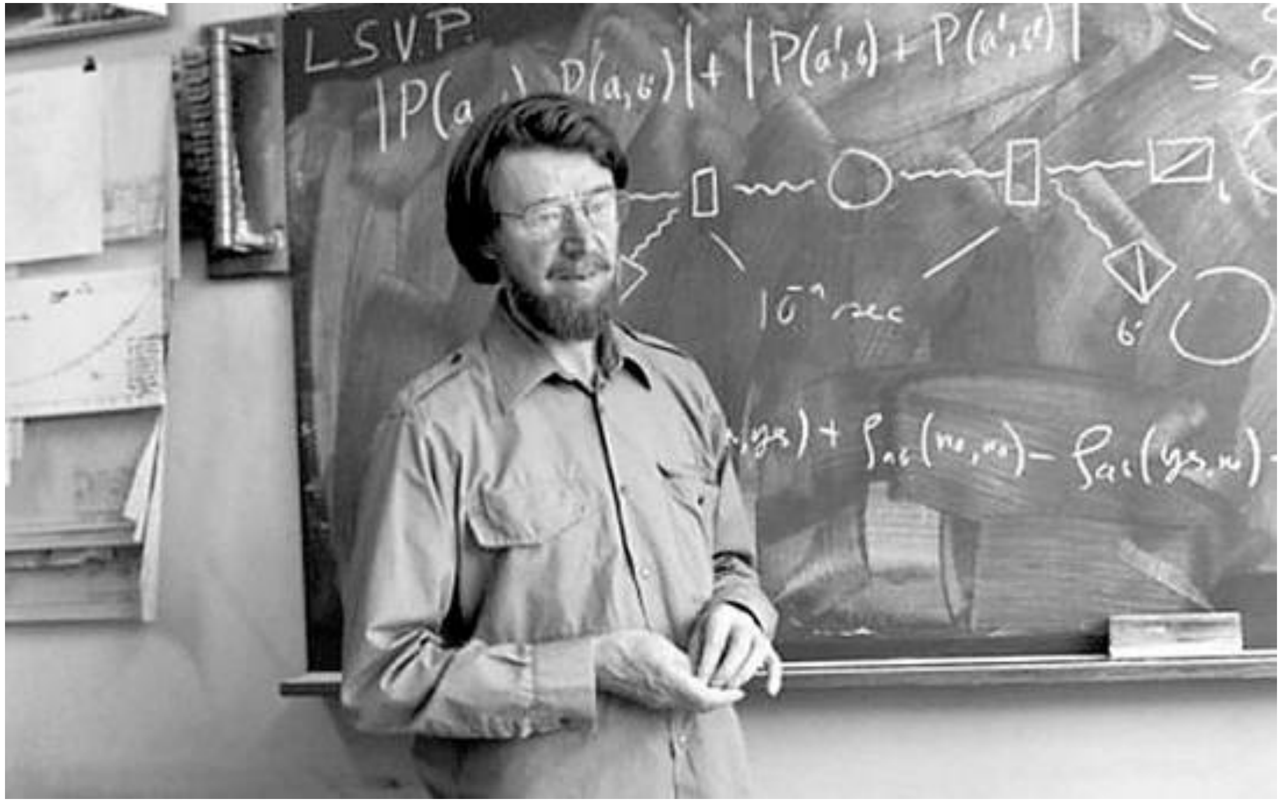
Erwin Schrodinger
(1887-1961)



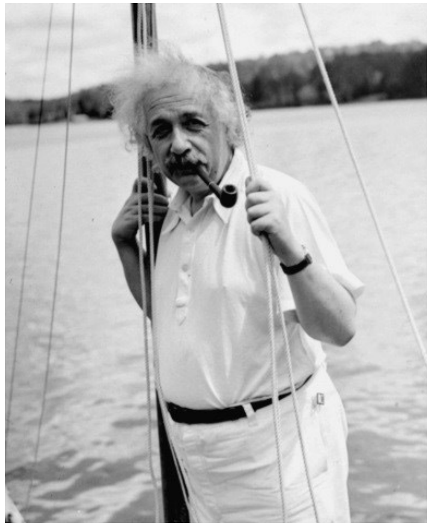


Werner Heisenberg
(1901-1976)

Source of Correlated Quantum Objects

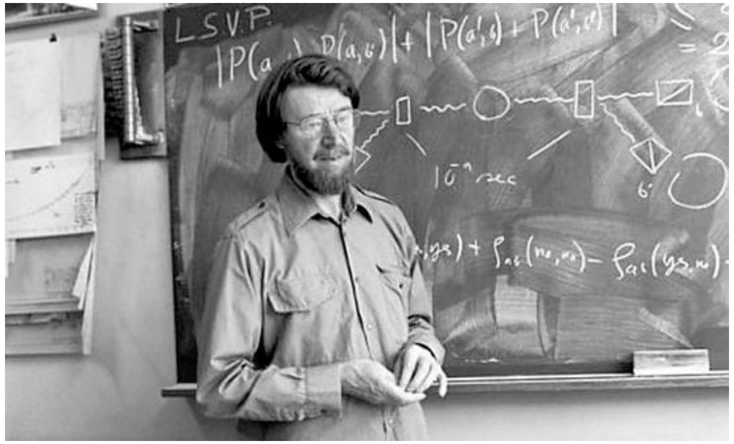


John S. Bell (1928-1991)



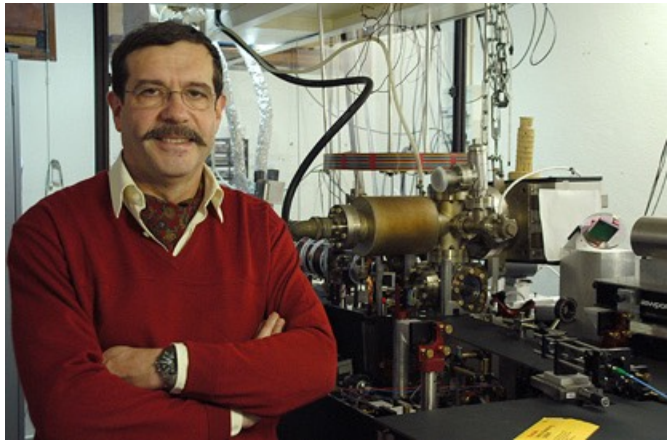
EPR Paradox
Entanglement
is *defined*

1935



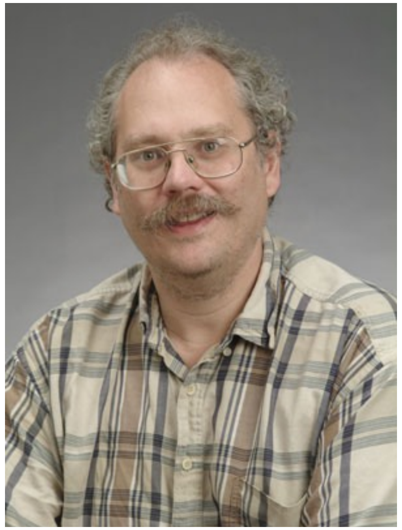
Bell's Inequalities
Entanglement
can be measured

1964



Experiments
Entanglement
is measured

1980s



Shor's Algorithm
Entanglement
is *useful*

1994

Quantum Technologies

Quantum Technologies

Quantum Technologies

- Quantum Computing
- Quantum Communication
- Quantum Simulation
- Quantum Sensing

Quantum Technologies

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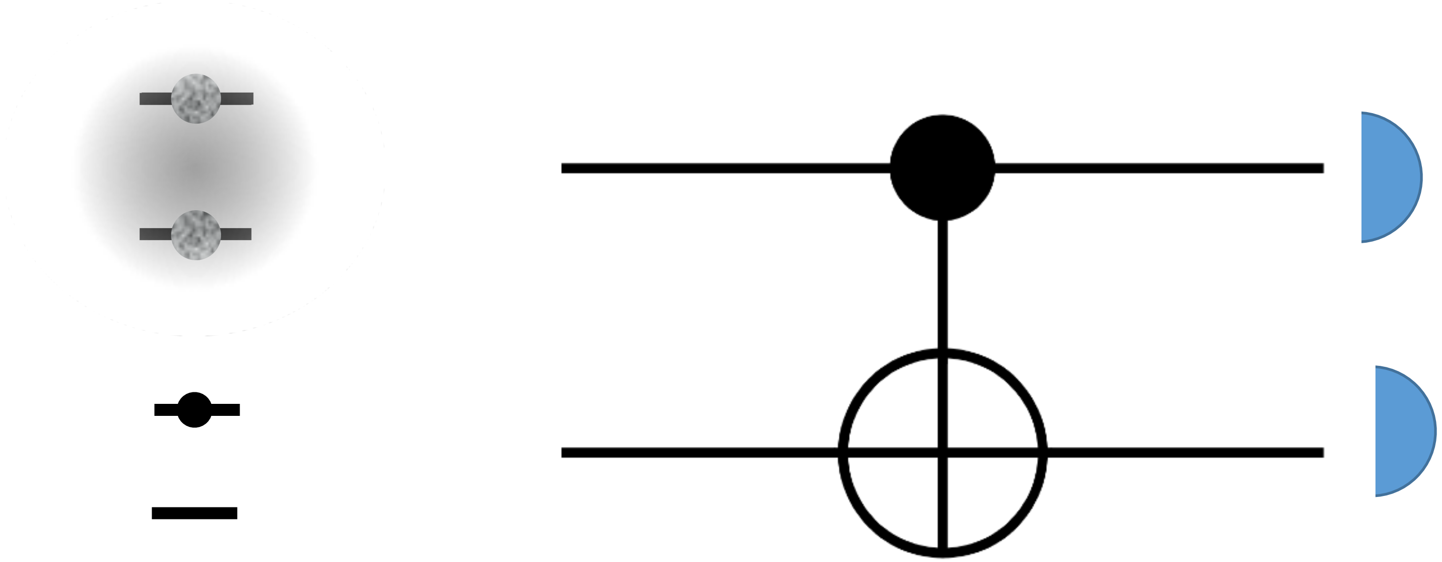
Quantum Algorithm



Quantum Computing

Shor’s Algorithm

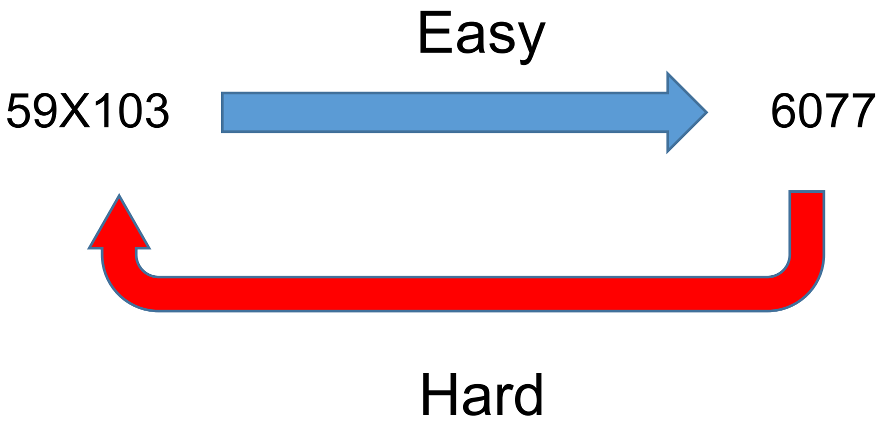
Factoring is ‘easier’ with a quantum computer

Peter Shor

Making a multiplication is easy
Making a division is hard

$$59\text{X}103 \xrightarrow{\text{Easy}} 6077$$

Making a multiplication is easy
Making a division is hard

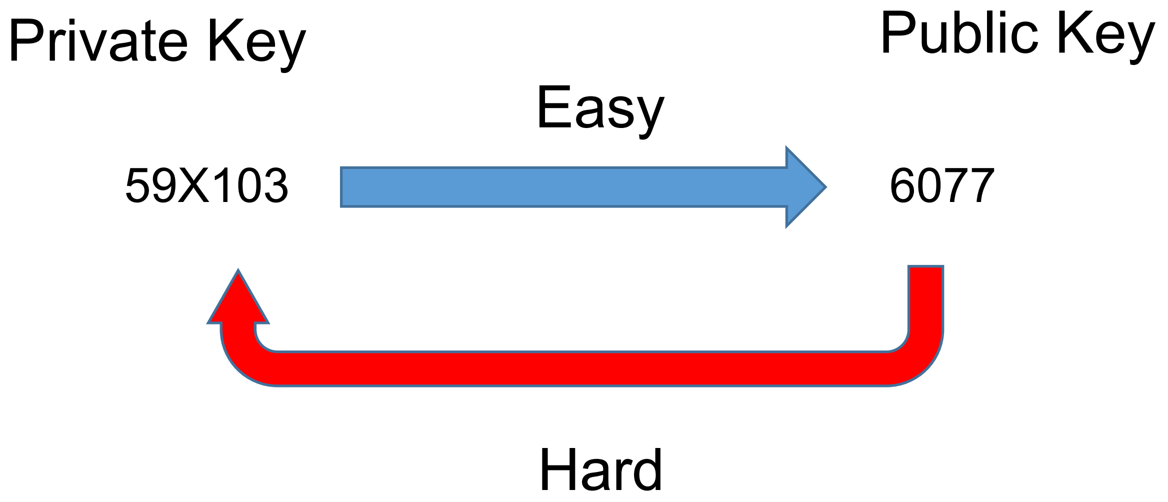


Public key distribution: Rivest, Shamir, Adelman (RSA) 1978

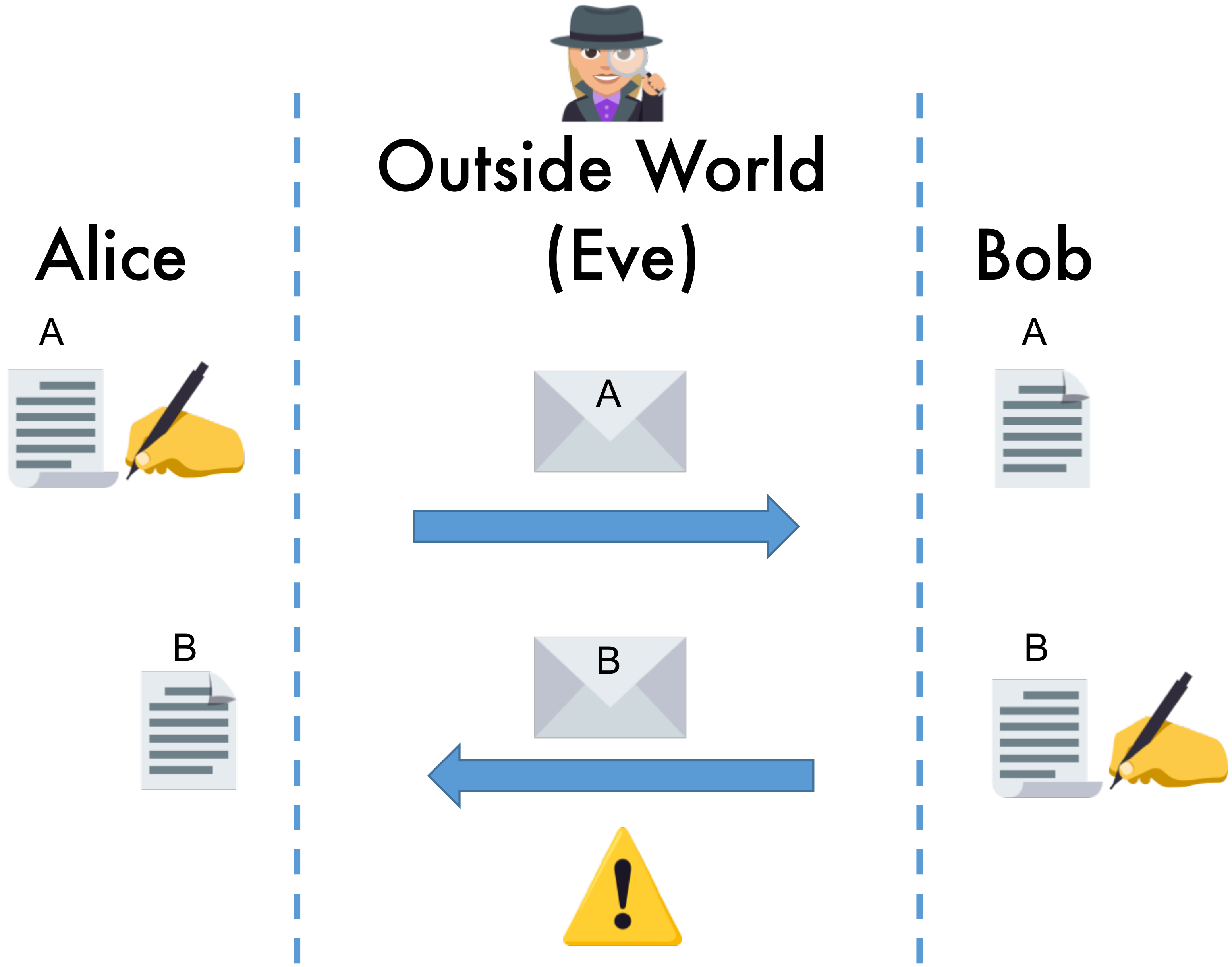
RSA

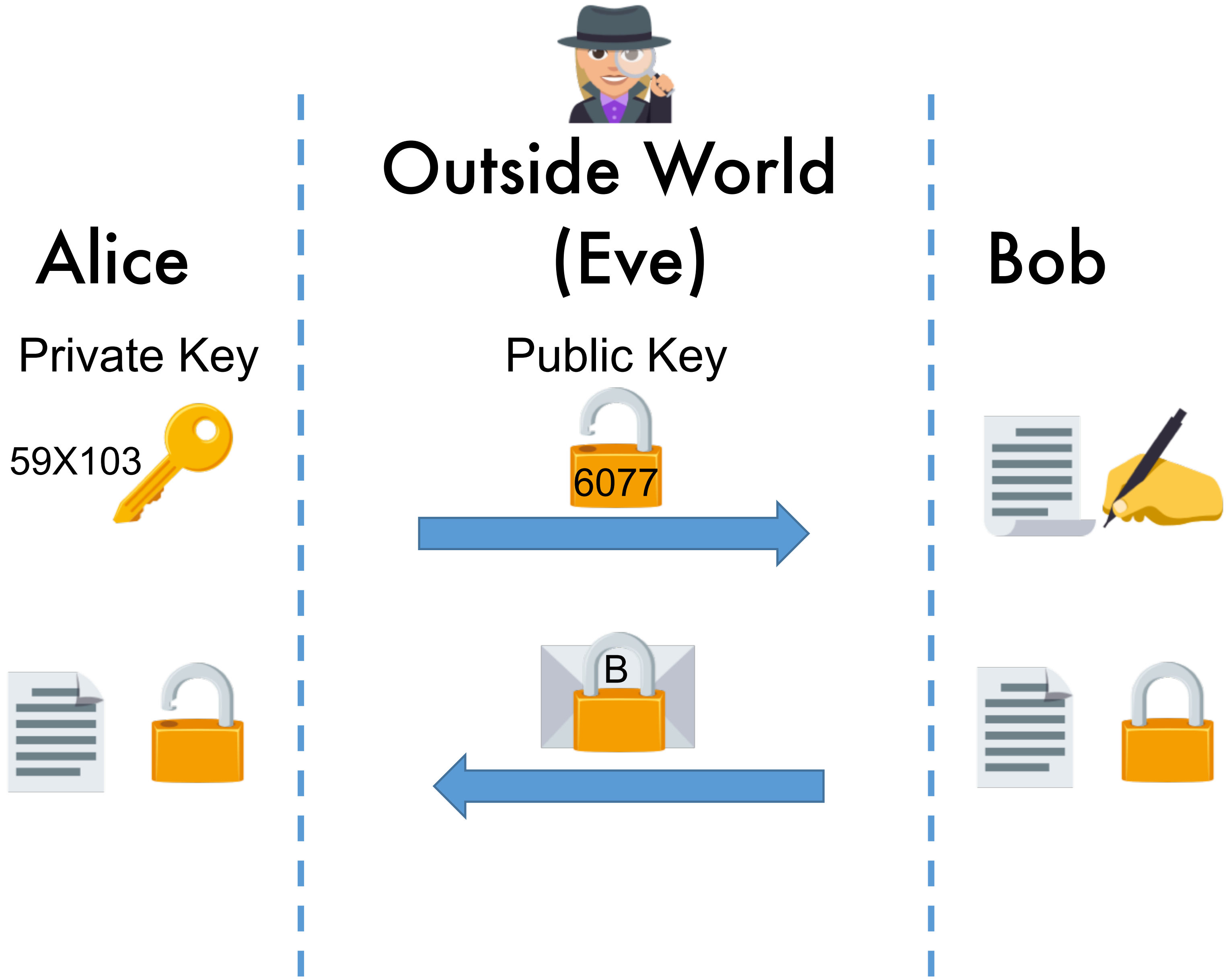
‘One-way function’ or trap-door function: Cryptography

Making a multiplication is easy
Making a division is hard

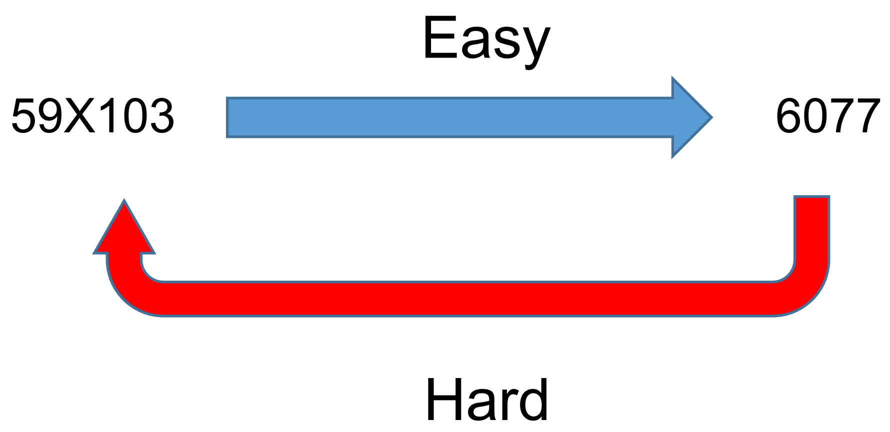


‘One-way function’ or trap-door function: Cryptography

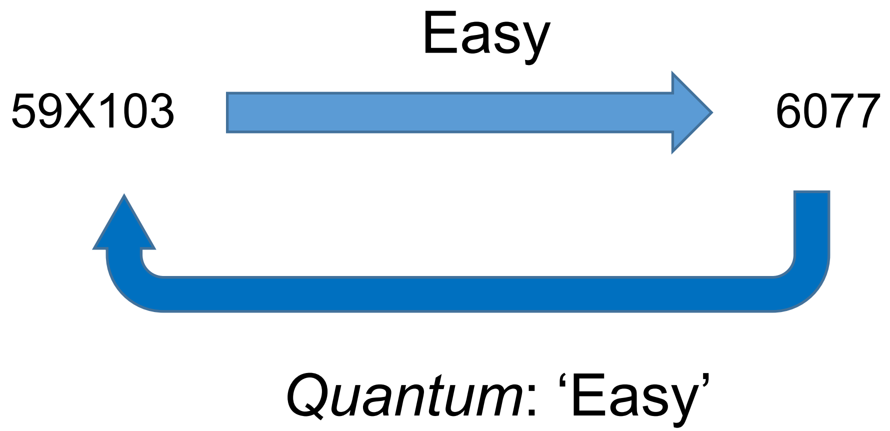

Outside World
(Eve)
Alice
Bob
A
A
A
B
B
B


Outside World
(Eve)
Alice
Bob
Private Key
Public Key
59X103
6077
B

Making a multiplication is easy
Making a division is hard



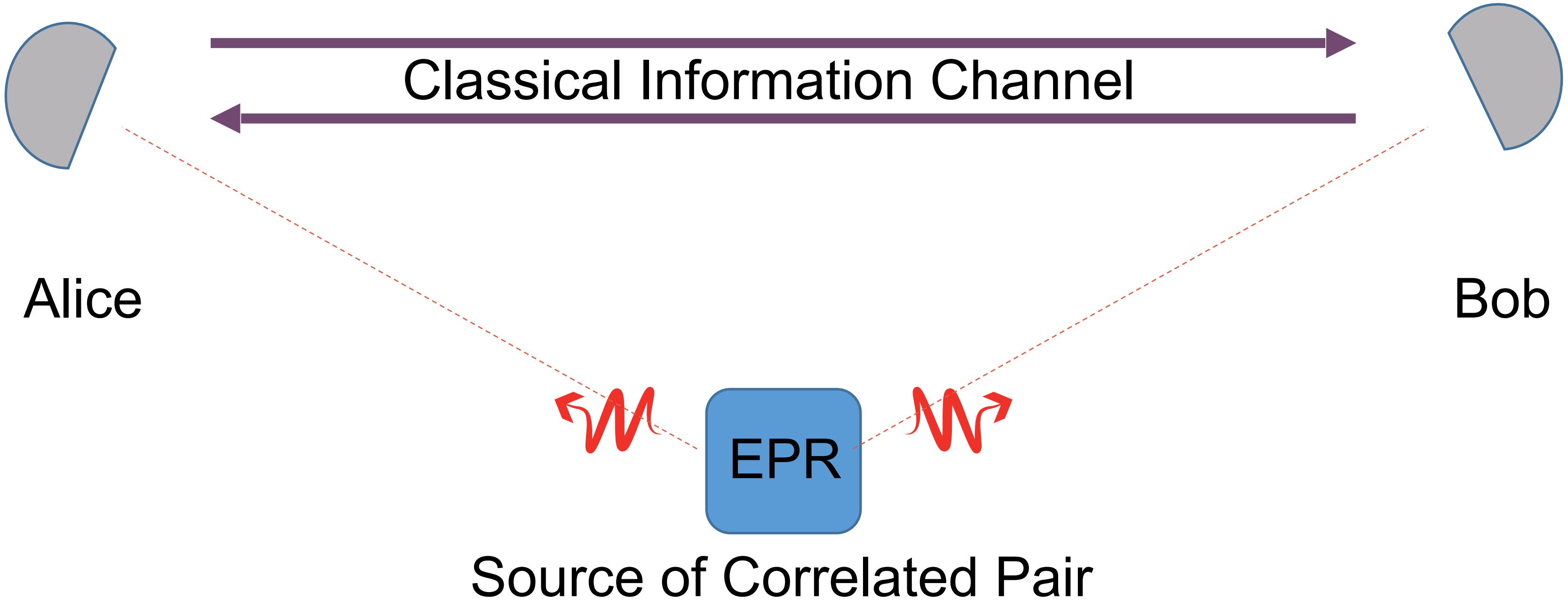
Making a multiplication is easy
Making a division is hard *classically*



Quantum Technologies

- Quantum Computing
- Quantum Communication
- Quantum Simulation
- Quantum Sensing

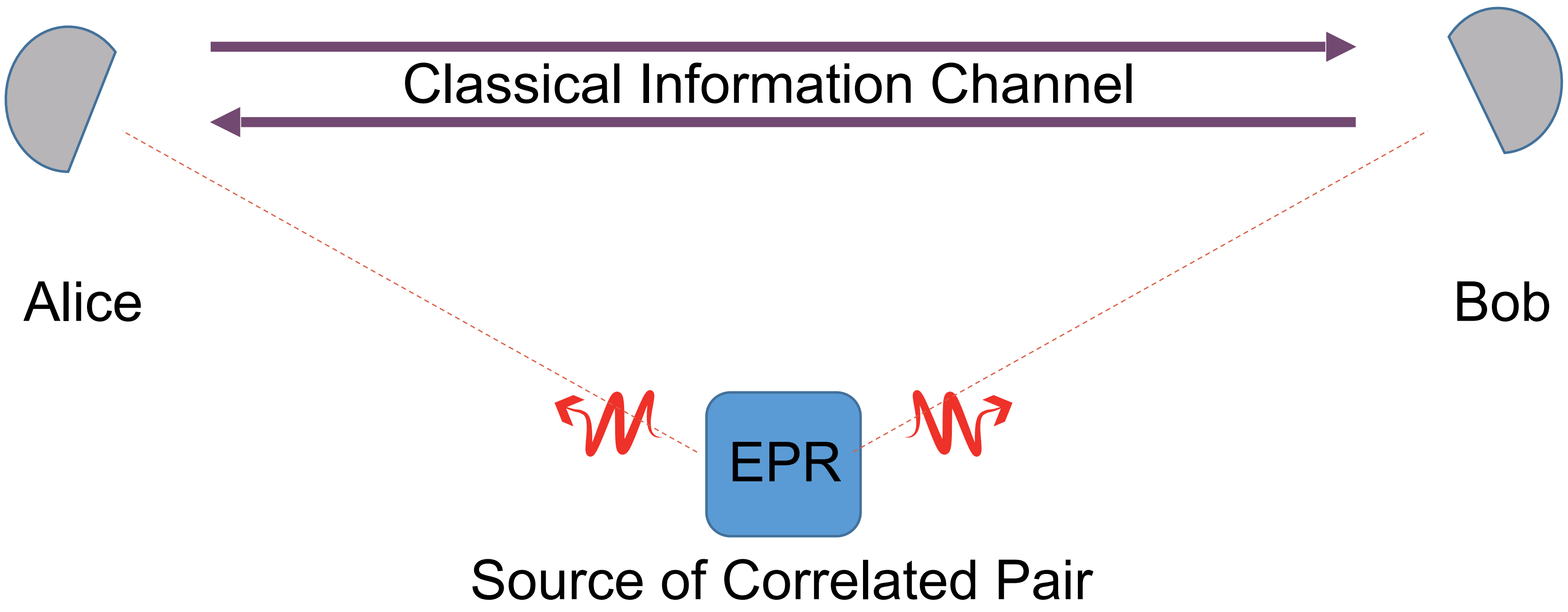
Quantum Communication



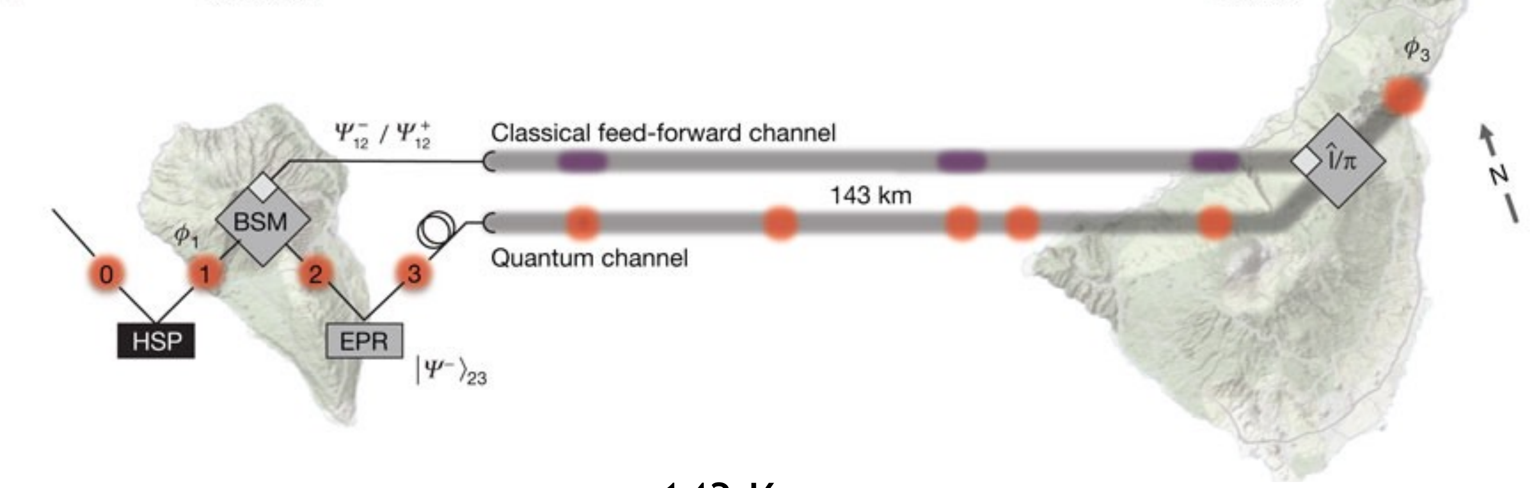
Quantum Communication

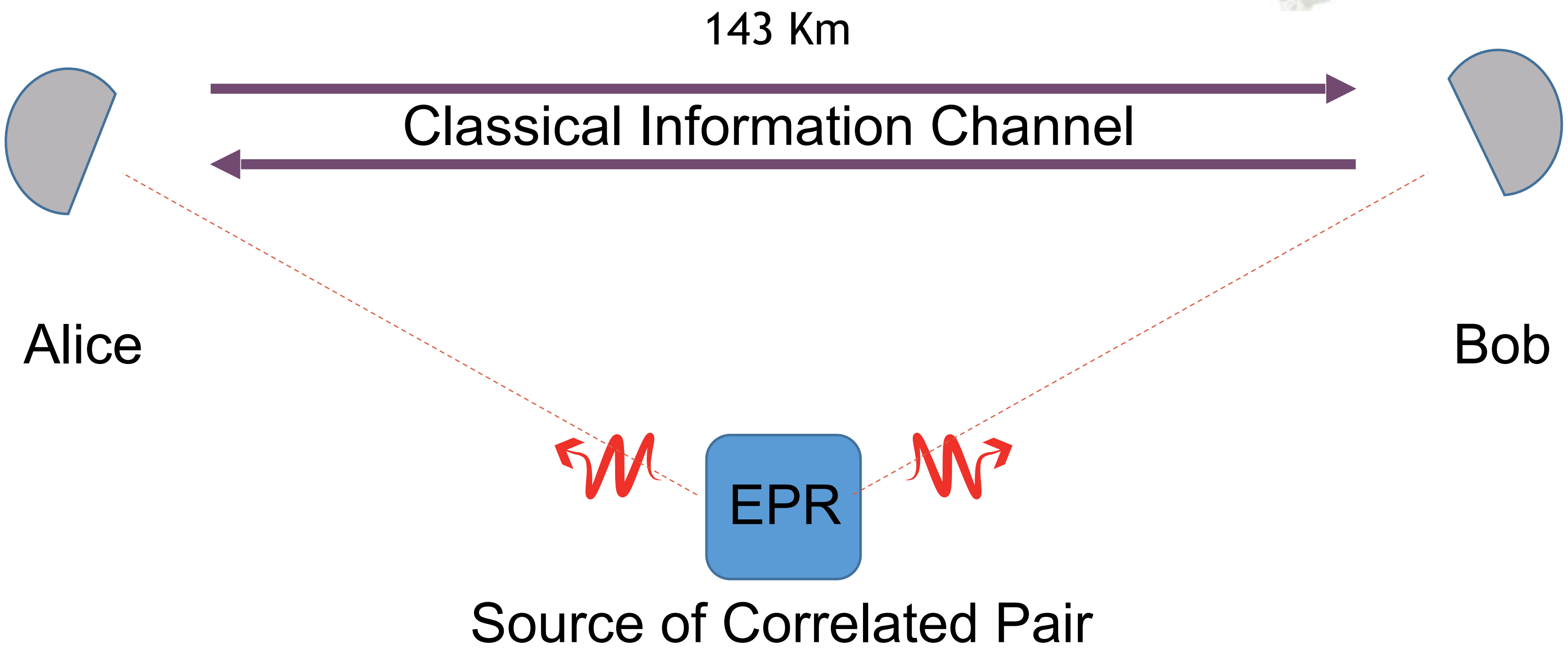
The record distance for quantum communication is …

Quantum Communication



X. Ma *et al.*, Nature **489**, 269 (2012)

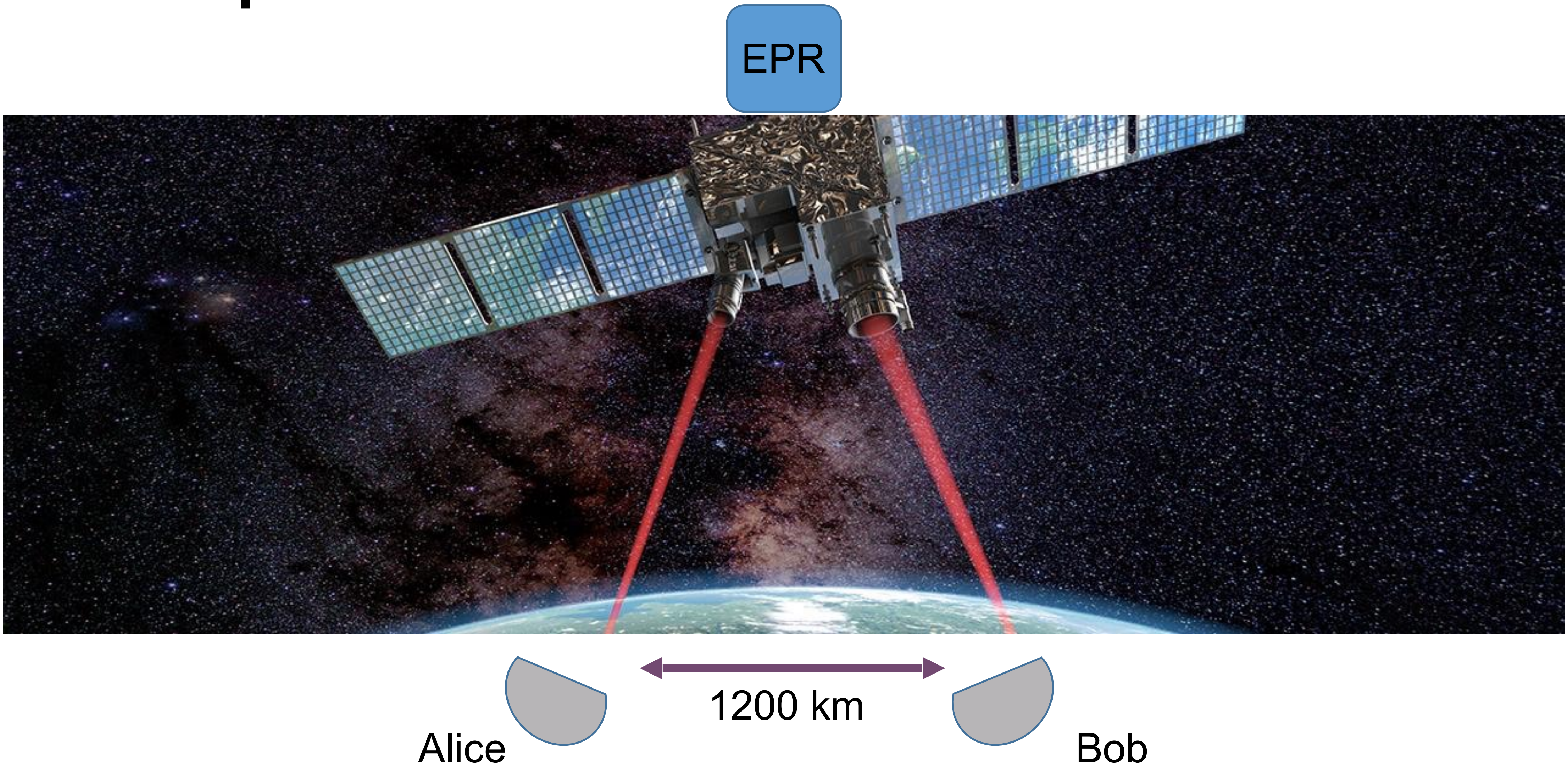




Space Quantum Communication

Micius

Space Quantum Communication



J. Yin *et al.*, Science **356**, 1140 (2017)

Quantum Technologies

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- Quantum Sensing

1994: Shor’s algorithm (prime factors)

1996: Grover’s algorithm (search a database)

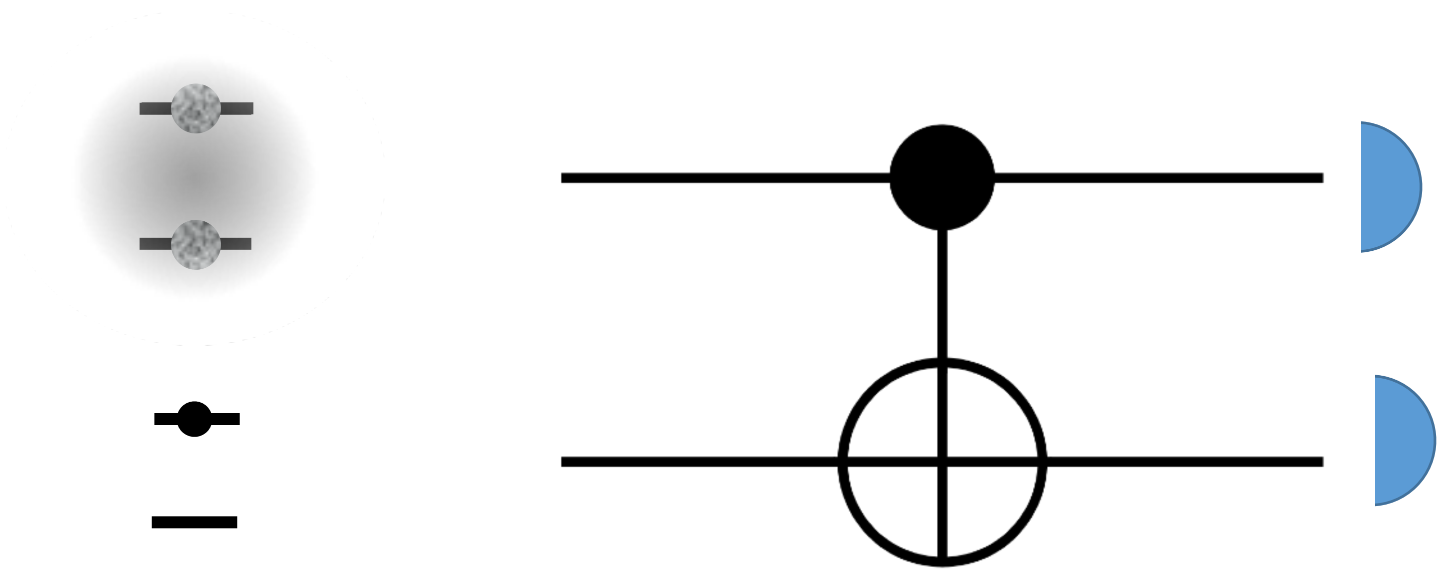
…

For more: http://math.nist.gov/quantum/zoo/

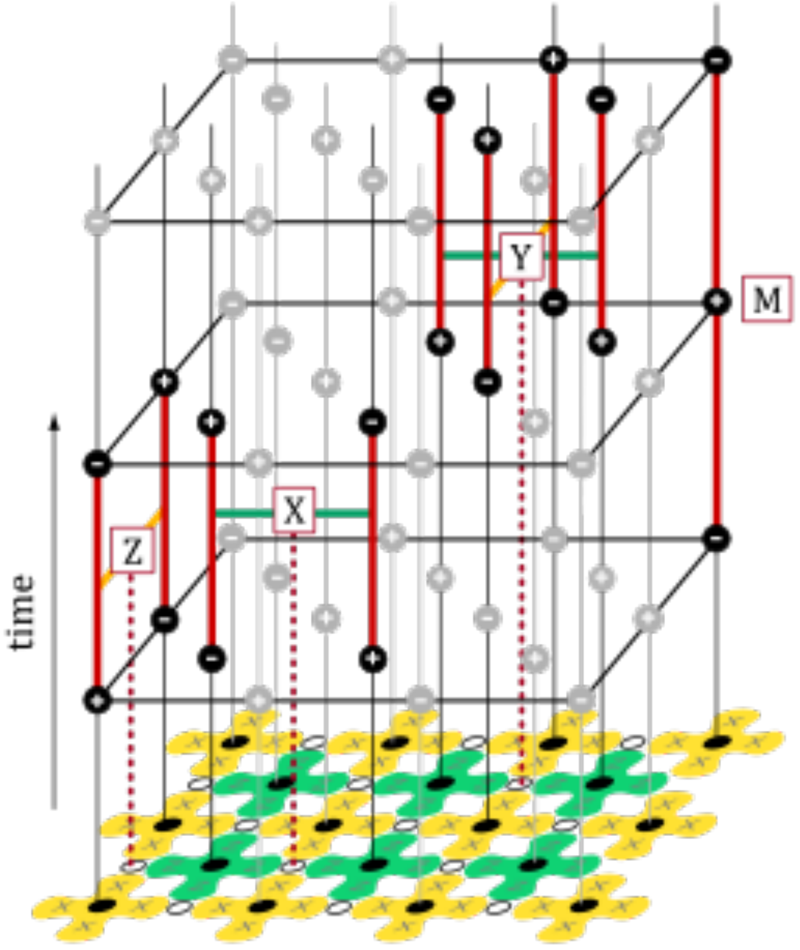
Error Correction

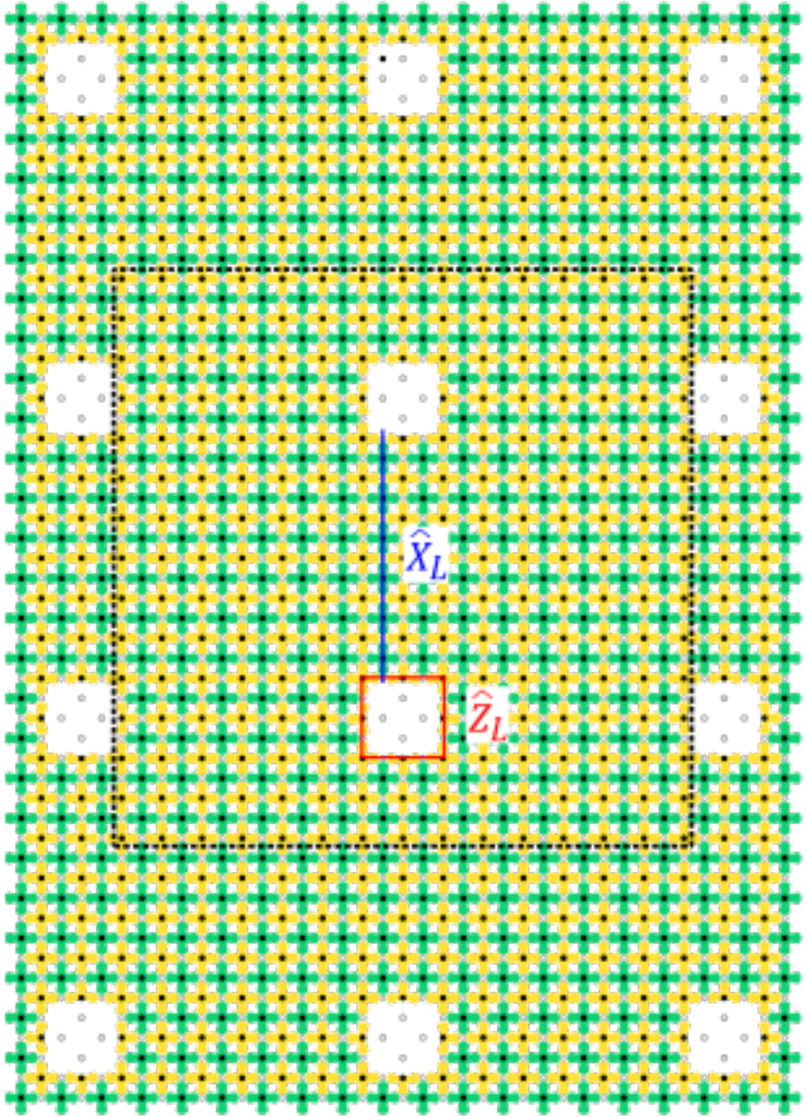
0	000
1	010
	000

Quantum Algorithm



Quantum Error Correction





A.G. Fowler *et al.*, PRA **86**, 032324 (2012)

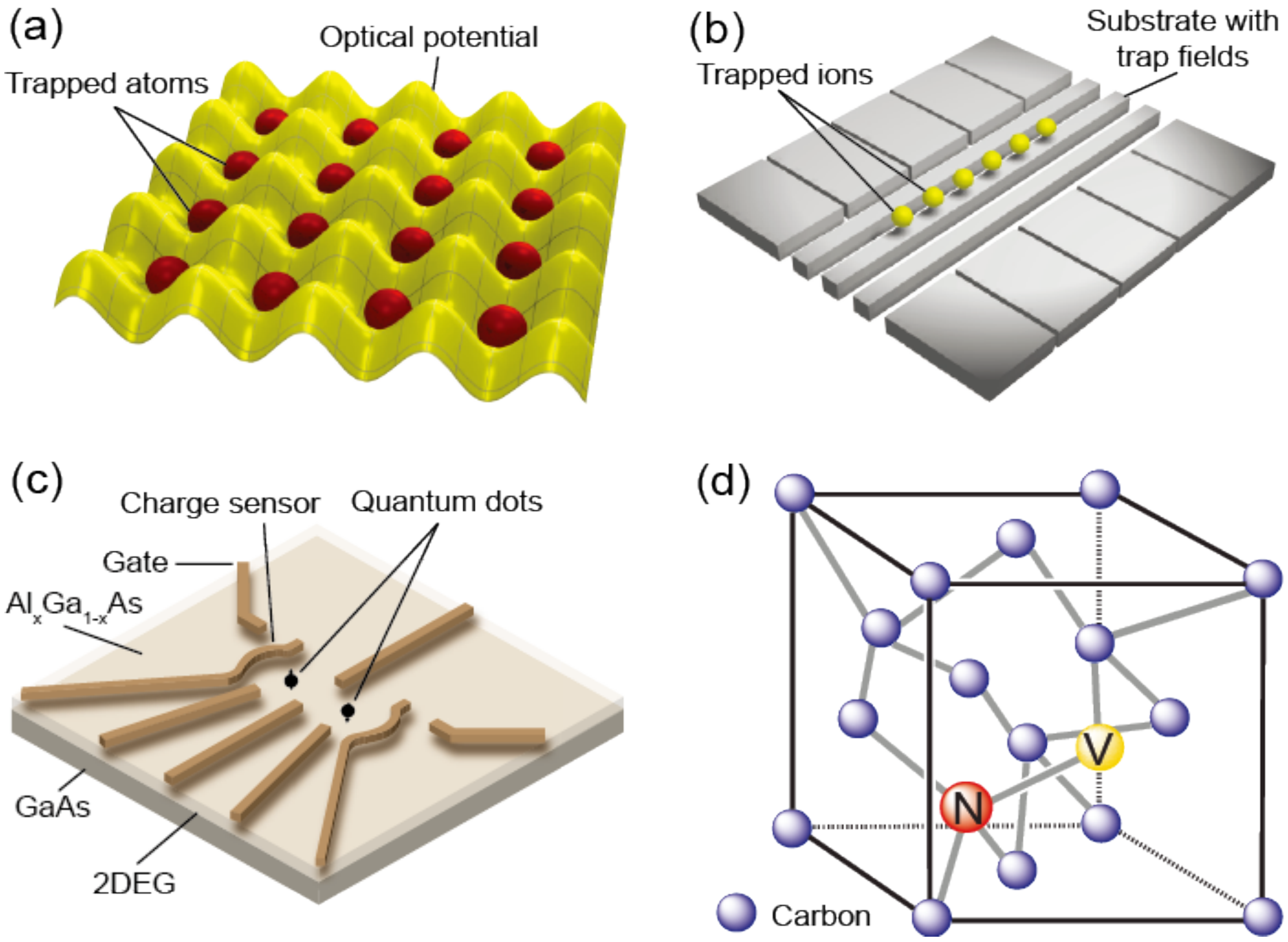
Quantum Error Correction

Logical and *physical* quantum bits

Millions of physical quantum bits

Now: 10 or so

Quantum Simulation



Y. Buluta, S. Ashhab, and F. Nori, *Reports on Progress in Physics* **74**, 104401 (2011)

Quantum Technologies

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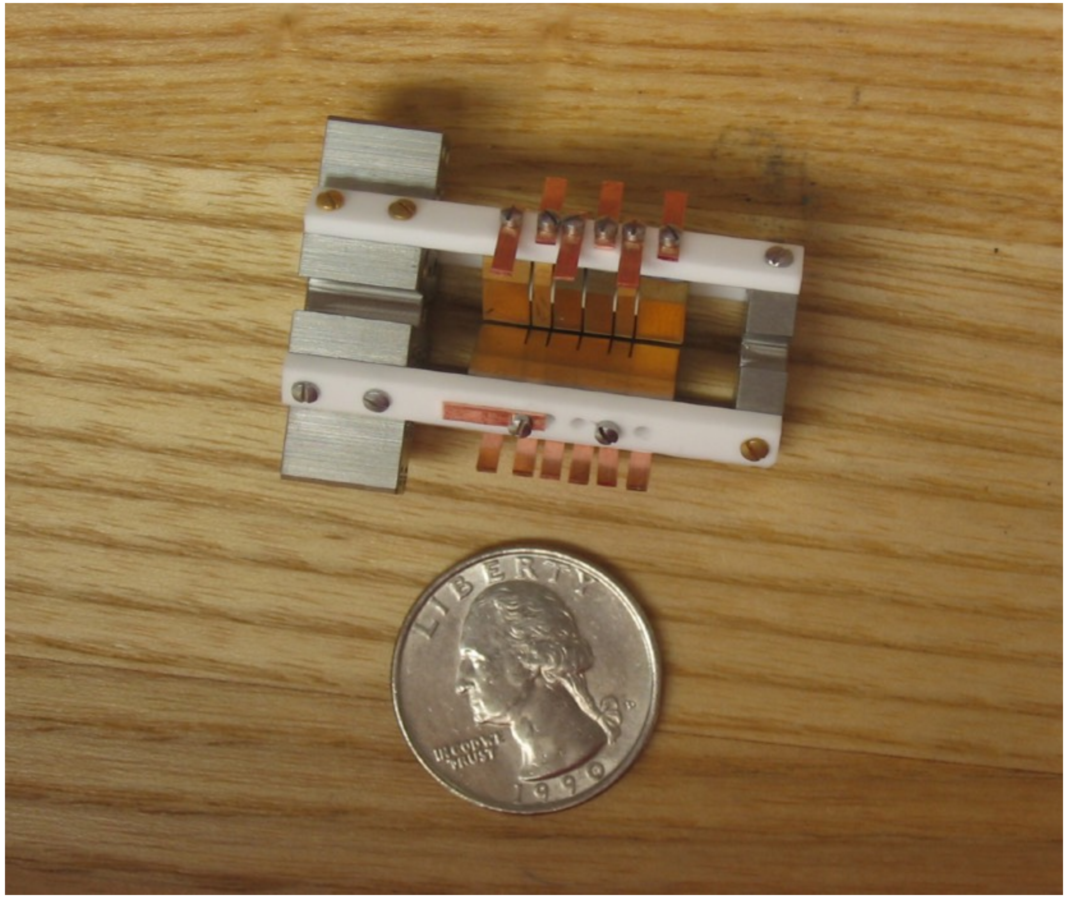
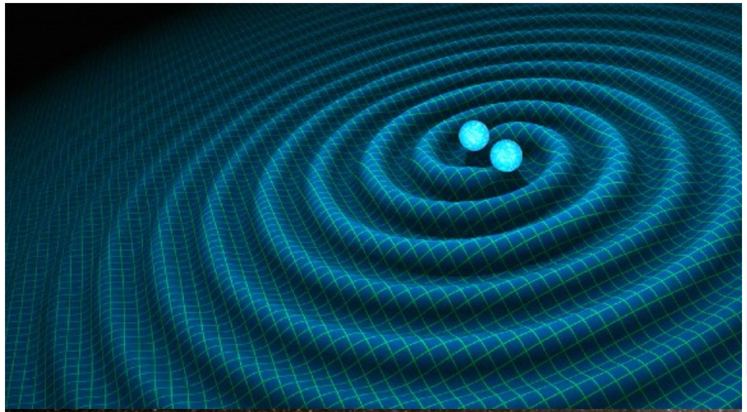
- Quantum Sensing

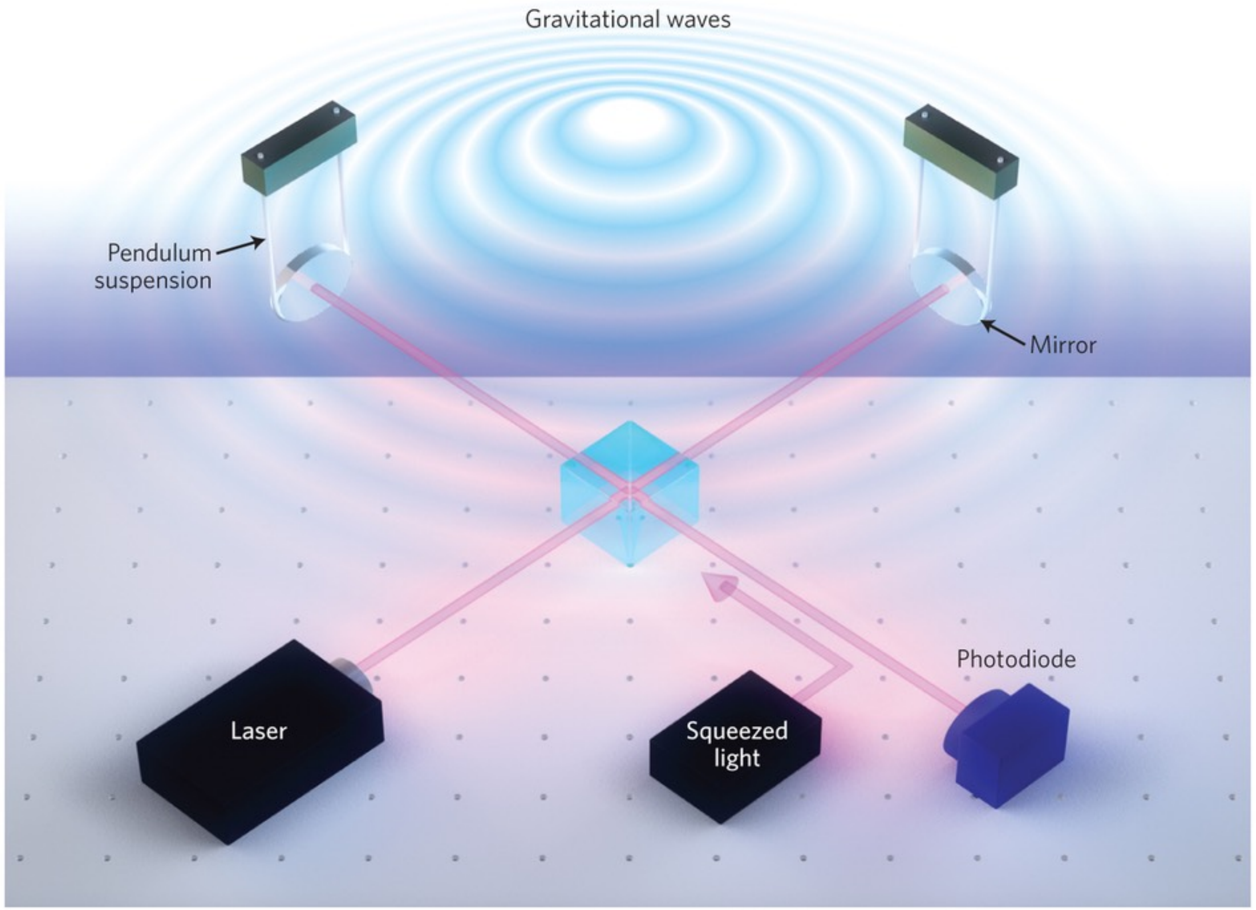
Quantum Sensors

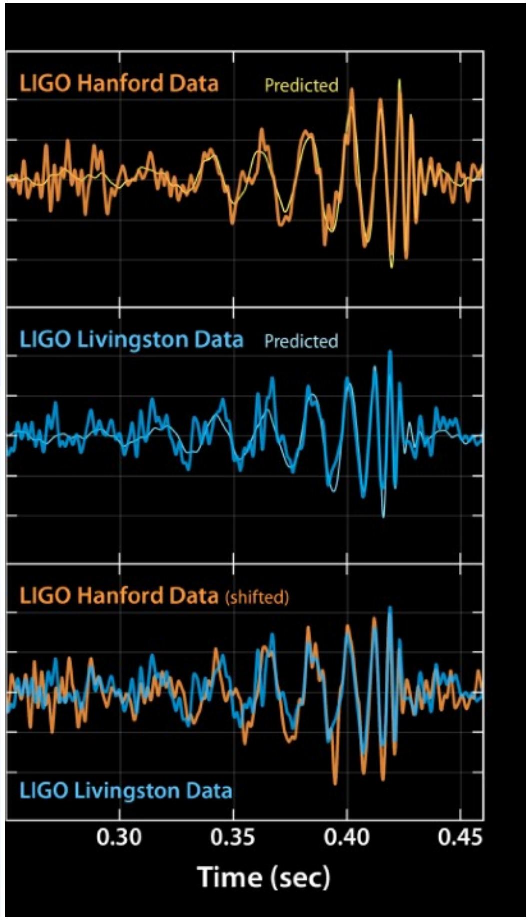


Quantum Logic Clock - Time measurement

Quantum Sensors







Interferometry using squeezed light – Position measurement
Advanced LIGO Proposal (MIT)

Quantum Sensors

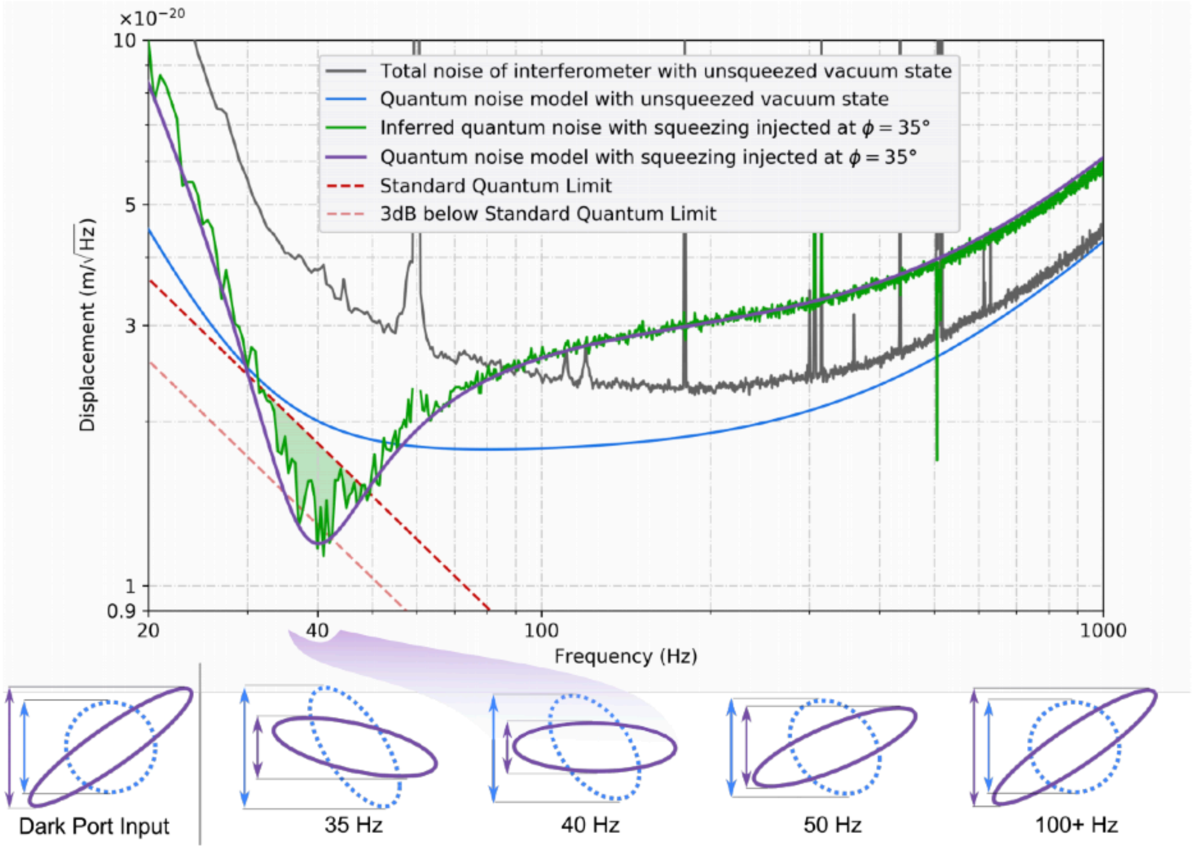
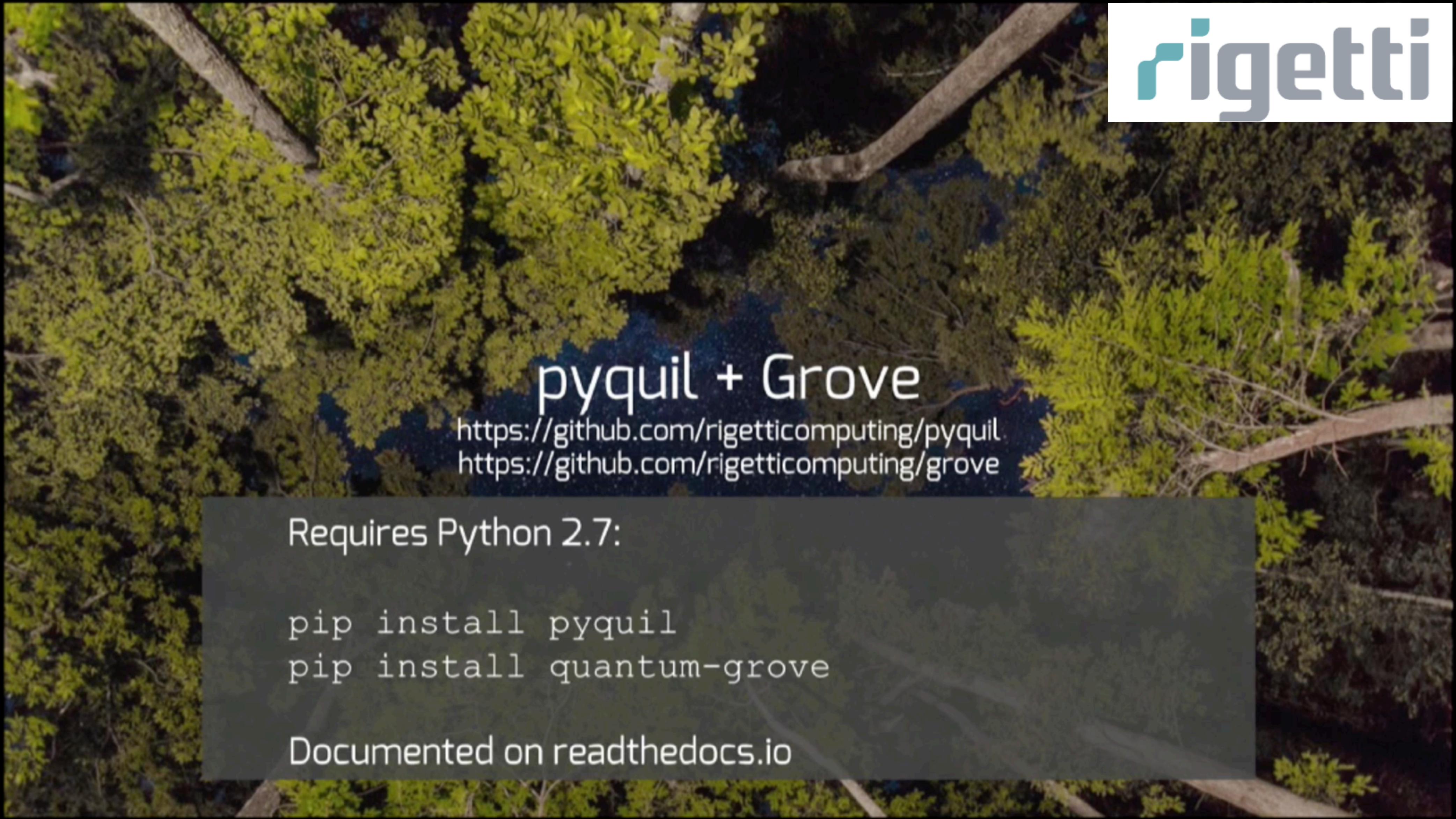


FIG. 2. **Top: Differential displacement (Δx) noise spectral density of the interferometer.** The grey trace shows the measured total noise level of the interferometer with unsqueezed vacuum state (i.e. the reference). The blue trace is the model of quantum noise during the reference measurement. The green trace shows the inferred quantum noise of the interferometer with injected squeezing at 35°, and its corresponding model is the purple trace. The notch feature, or "dip," results from the ponderomotive squeezing affecting the injected optical squeezed states. It reaches -3 dB of the free-mass SQL (red dashed trace, given by Eqn. 3) at 40 Hz. Bottom: Phase-space representation of the modeled quantum states entering through the dark port of the interferometer (left) and the output states (right), which are indexed to indicate their frequency dependence. Drawn are the unsqueezed vacuum (dotted blue) and squeezing at ϕ=35° (solid purple). In the unsqueezed vacuum case, ponderomotive squeezing distorts the ellipse for frequencies below 100 Hz, increasing QRPN in the readout quadrature (blue arrows). In the injected squeezing case, the same physical process creates a state with reduced noise at 40 Hz (purple arrows).

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.123.231107 https://arxiv.org/abs/2002.01519

flickr.com/photos/ibm_research_zurich

flickr.com/photos/ibm_research_zurich



Shown at QIP 2017 – From Microsoft Research YouTube channel

FOREST

> Introducing forest.rigetti.com : Tools for experimental quantum programming

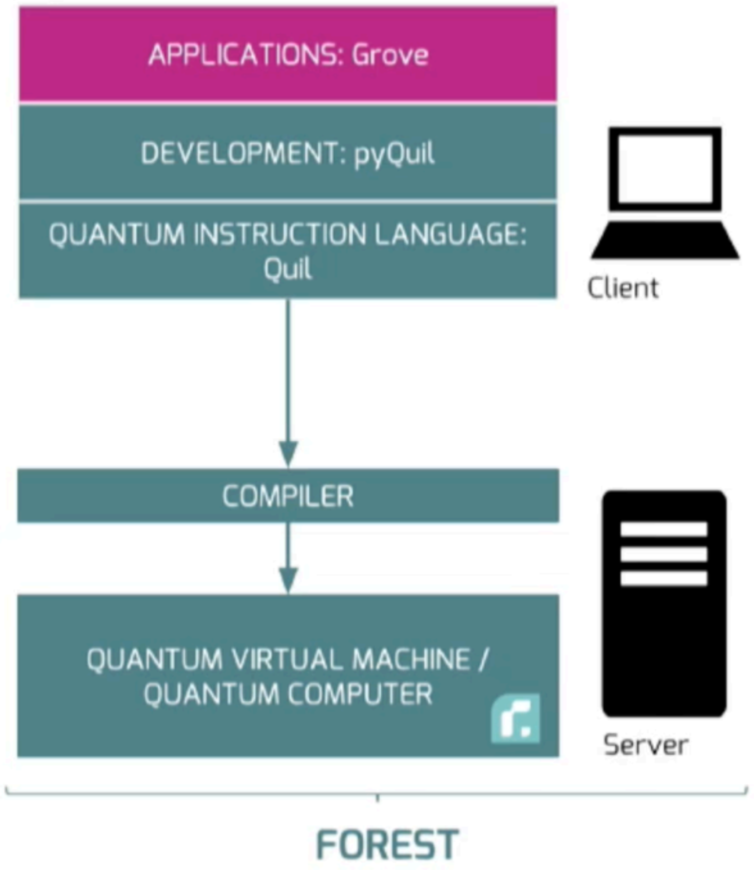
> Write applications…

> using tools…

> that build quantum programs…

> that compile onto quantum hardware…

> that execute on a real or virtual quantum processor.



Open-sourced on github under Apache v2.0 license

github.com/rigetticomputing/pyquil

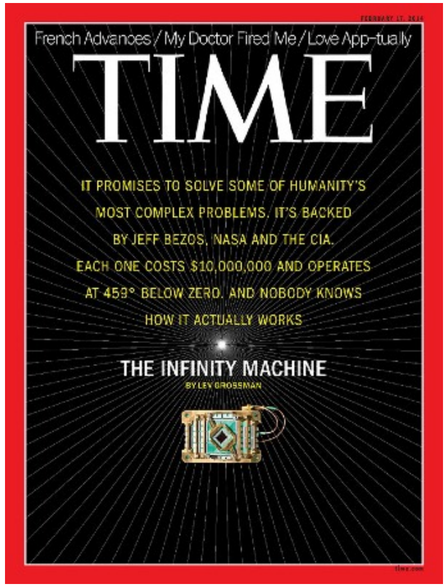
github.com/rigetticomputing/grove

Open for private-beta QVM signups

forest.rigetti.com

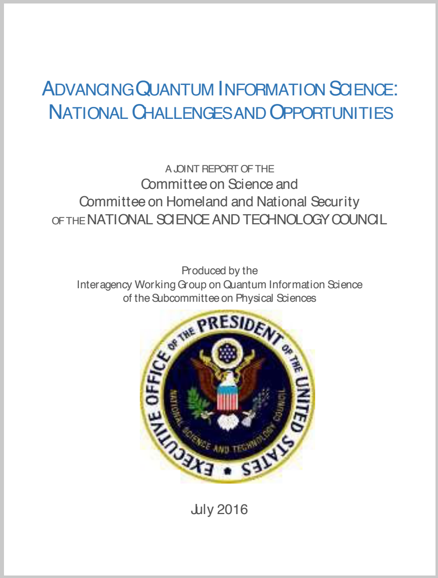
Shown at QIP 2017 – From Microsoft Research YouTube channel

The Economist, March 2017



€ 1 billion EU project (2018)

Japan R&D


ADVANCING QUANTUM INFORMATION SCIENCE: NATIONAL CHALLENGES AND OPPORTUNITIES

A JOINT REPORT OF THE
Committee on Science and
Committee on Homeland and National Security
OF THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

Produced by the
Interagency Working Group on Quantum Information Science
of the Subcommittee on Physical Sciences

July 2016

(2019)

Open Source

Quantum Tech: Quantum computing

Open-source and quantum technologies

NATURE | COMMENT

Commercialize quantum technologies in five years

Masoud Mohseni, Peter Read, Hartmut Neven, Sergio Boixo, Vasil Denchev, Ryan Babbush, Austin Fowler, Vadim Smelyanskiy & John Martinis

03 March 2017

nature International weekly journal of science

Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio & Video | Fo

Archive > Volume 549 > Issue 7671 > Comment > Article

NATURE | COMMENT

First quantum computers need smart software

Will Zeng, Blake Johnson, Robert Smith, Nick Rubin, Matt Reagor, Colm Ryan & Chad Rigetti

13 September 2017

Early devices must solve real-world problems, urge Will Zeng and colleagues.

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Subject terms: Quantum physics • Quantum information • Mathematics and computing •

IBM adds new API to quantum computing cloud service

Posted yesterday by Ron Miller (@ron_miller)

A Recent Review:

Mark Fingerhuth, Tomáš Babej, and Peter Wittek, *Open source software in quantum computing*, PLoS ONE **13** (12): e0208561 (2019).

Quantum Tech: Quantum Circuit Simulators

Open-Source Quantum Computing

	Language	Library	Quantum Compiler	Features
D-Wave	Python	qbsolv	Not a circuit-based computer	Optimization problems
IBM Q	**Python**	QISKit	20 qubits***	Thousands of experiments from the cloud by online users on the *IBM quantum experience*
Rigetti	**Python**; pyquil	Forest toolkit Grove	19 qubits*** 128 qubits*	Open to research collaborations. Proof-of-concept clustering
Google	**Python**	Cirq (simulation)	49 qubits*** 72-qubit SC chip: Bristlecone*	*Cirq*: an open-source platform for noisy quantum computing
Microsoft	**Python**; Q#	Liquid Quantum Dev Kit	NA	Topological quantum computing with Majorana particles
Alibaba	NA	NA	11-qubit SC chip* unknown architecture	Cloud computing announced

*announced only. *** limited connectivity

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For the first time theorists can run online quantum experiments

*announced only. *** limited connectivity

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Rigetti	**Python**; pyquil	Forest toolkit Grove	19 qubits*** 128 qubits*	Open to research collaborations. Proof-of-concept: clustering
Google	**Python**	Cirq (simulation)	49 qubits*** 72-qubit SC chip: Bristlecone* 53-qubit SC chip: Sycamore*	*Cirq*: an open-source platform for noisy quantum computing Quantum supremacy
Microsoft	**Python**; Q#	Liquid Quantum Dev Kit	NA	Topological quantum computing with Majorana particles
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Open-source cloud quantum labs

Extending the Open-Source Quantum Computing Paradigm

For the first time theorists can run online quantum experiments

Language	Library		Quantum Experiment	Features
		Actuators Effort $$$ Standards		Science acceleration via automation (maybe). Educational value.

Could academic institutions, physicists replicate this model?

Open Labs, Open Hardware

See: github.com/**SteeleLab**-Delft

Quantum Tech: Quantum computing

Different platforms and hardware

		Advantages	Challenges
Gate-based	Superconducting circuits	15 years of exponential improvement in extending dephasing time (x10 / 3yrs).	Artificial atoms: defects, off-resonances. Wiring leads to qubit cross-talk. Requires cooling @ micro K Temp.
	Trapped ions	‘Perfect’ qubits due to identical ions. Long coherence time even @ room Temp. Long-range interaction: Full connectivity.	Photonic link/ion shuttling needed to create entanglement between distant modules.
	Photonics	‘Flying’ qubits for quantum internet. Silicon integrated chips (CMOS industry). Very long coherence time.	Small interaction hampers two-qubit gates. Hard to have identical photons on demand. Requires interface for storing memory.
	Spins	CMOS and SiMOS integration. Long coherence time. Up to room temperature qubits.	Charge and nuclear spin noise. Weak interaction with controlling fields.
	Neutral Atoms	Atoms are identical components. Long-range interactions. Recently: two-Rydberg-atom entanglement.	Hard to trap atom and control qubit. Linear optics, low Temp required @ micro K.
Annealing	Superconducting circuits	Encode optimization problems. No error correction required.	Not a universal quantum computer. Unclear implementation of adiabatic QC. Uncertain entanglement role and scalability.

Quantum Tech: Quantum *and optical* computing

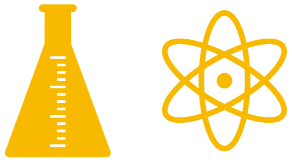
Different platforms and hardware

		Startups	Corporate	Academia (selection)
Gate-based	Superconducting circuits	rigetti, qci, IQM	IBM Q, Microsoft, Google, intel, Alibaba.com	UCSB, U Berkley Yale, ETH Zurich RIKEN, NTT Labs
	Trapped ions	IONQ, Alpine QT		U Maryland, NIST IQOQI, Oxford
	Photonics	PsiQ, XANADU		U Bristol, Paris Telecom Equs (Australia)
	Spins	SILICON QUANTUM COMPUTING	intel	QuTech, U Chicago UNSW, RIKEN
	Neutral Atoms	ATOM COMPUTING		Harvard MIT, LMU Munich NIST, U Chicago
Annealing	Superconducting circuits	D:Wave The Quantum Computing Company™		
Neuromorphic	Photonics (classical, from quantum photonics community)	LIGHTELLIGENCE, LIGHTMATTER, LightOn, LASOLV		MIT, Stanford RIKEN, JST

Open-source cloud quantum labs

Copying Open-Source Quantum Computing

Could academic institutions, physicists replicate this model?

Language	Library		Quantum Experiment	Features
		Actuators Effort $$$ Standards		Science acceleration via automation (maybe). Educational value.

Open Labs

*announced only. *** limited connectivity

Quantum Tech: Open Source Libraries

More open-source is empowering broad research in the field

Library	Year	Creators	Institution	Language	Description
QuTiP Quantum Toolbox in Python	2012	Rob Johannson Paul Nation Franco Nori	RIKEN	**Python**	Simulation of open quantum systems; quantum optics, cavity QED.
QNet	2012	Nikolas Tezak, Michael Goerz Hideo Mabuchi	Stanford	**Python**	Computer algebra package for quantum mechanics and photonic quantum networks
QuantumOptics.jl	2017	Sebastian Krämer *et al.*	U Innsbruck IQOQI	Julia	Quantum optics and open quantum systems framework inspired by the QO toolbox in Matlab and QuTiP
ProjectQ	2016	Damian S. Steiger Thomas Häner Matthias Troyer	ETH Zurich	**Python**	Hardware-agnostic framework with compiler and simulator with emulation capabilities.
OpenFermion	2017	Ryan Babbush *et al.*	Google (unofficial)	**Python**	Fermionic potential calculations for quantum chemistry
NetKet	2018	Giuseppe Carleo	The Simons Foundation	C++ **Python**	Studying many-body quantum systems with artificial neural networks and ML techniques.
STRAWBERRY FIELDS	2018	Nathan Killoran *et al.*	Xanadu Inc	**Python**	Photonic quantum computing with continuous-variable optical circuits

Checkout more open-source projects at https://qosf.github.io

Open-Source Quantum Technologies

In-house Research and Projects for the Ecosystem

Unitary Fund

1. **microgrant program**

Alphabet X

2. Own **research in-house**

Team: Will Zeng, Andrea Mari, Ryan LaRose

Checkout funded open-source projects at https://unitary.fund

Open-Source Quantum Technologies

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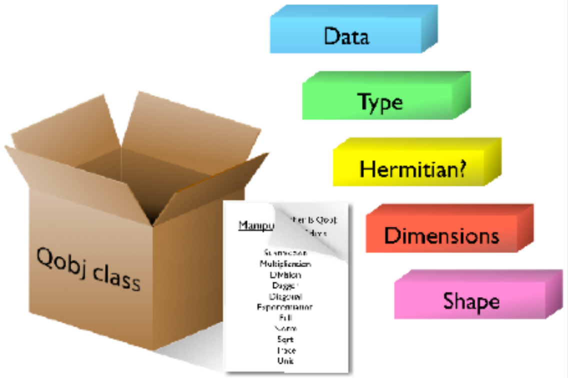
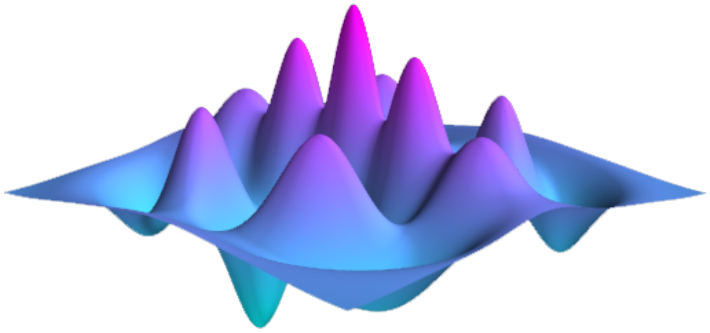
QuTiP

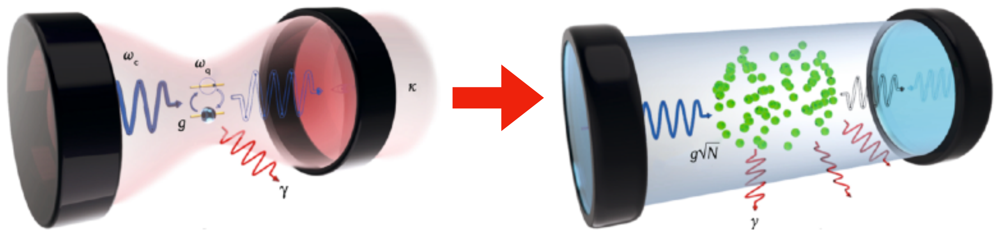
Python Classes full power

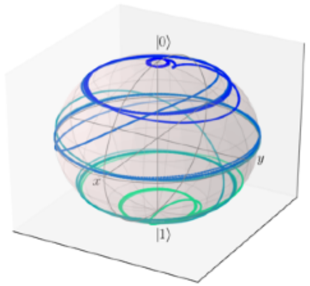




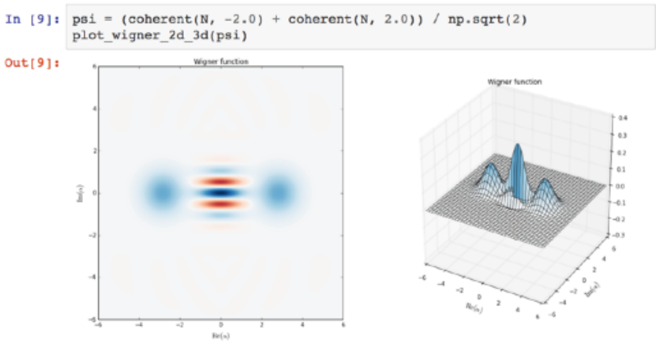
downloads 203k total

Many-body quantum dynamics



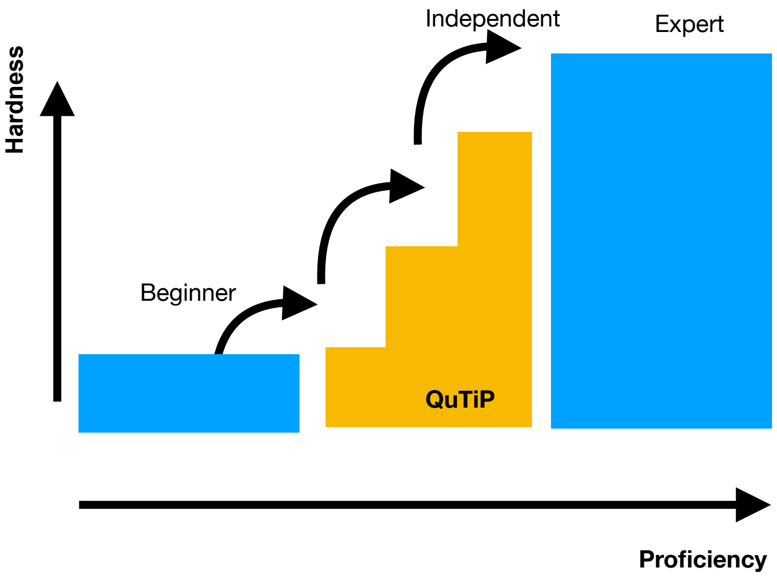


Take a snapshot

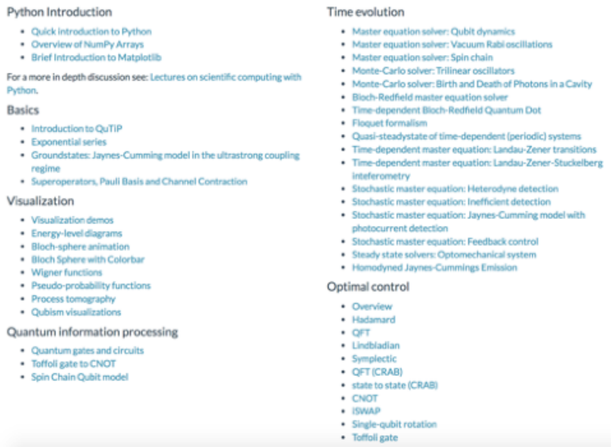


launch binder

Quantum mechanics made easy



- **Over 60** Jupyter notebook tutorials
- **Over 20** quantum mechanics lectures



Python Introduction

- Quick introduction to Python
- Overview of NumPy Arrays
- Brief Introduction to Matplotlib

For a more in depth discussion see: Lectures on scientific computing with Python.

Basics

- Introduction to QuTiP
- Exponential series
- Groundstates: Jaynes-Cumming model in the ultrastrong coupling regime
- Superoperators, Pauli Basis and Channel Contraction

Visualization

- Visualization demos
- Energy-level diagrams
- Bloch-sphere animation
- Bloch Sphere with Colorbar
- Wigner functions
- Pseudo-probability functions
- Process tomography
- Qubism visualizations

Quantum information processing

- Quantum gates and circuits
- Toffoli gate to CNOT
- Spin Chain Qubit model

Time evolution

- Master equation solver: Qubit dynamics
- Master equation solver: Vacuum Rabi oscillations
- Master equation solver: Spin chain
- Monte-Carlo solver: Trilinear oscillators
- Monte-Carlo solver: Birth and Death of Photons in a Cavity
- Bloch-Redfield master equation solver
- Time-dependent Bloch-Redfield Quantum Dot
- Floquet formalism
- Quasi-steadystate of time-dependent (periodic) systems
- Time-dependent master equation: Landau-Zener transitions
- Time-dependent master equation: Landau-Zener-Stuckelberg inteferometry
- Stochastic master equation: Heterodyne detection
- Stochastic master equation: Inefficient detection
- Stochastic master equation: Jaynes-Cumming model with photocurrent detection
- Stochastic master equation: Feedback control
- Steady state solvers: Optomechanical system
- Homodyned Jaynes-Cummings Emission

Optimal control

- Overview
- Hadamard
- QFT
- Lindbladian
- Symplectic
- QFT (CRAB)
- state to state (CRAB)
- CNOT
- ISWAP
- Single-qubit rotation
- Toffoli gate

QuTiP: Empowering scientific research

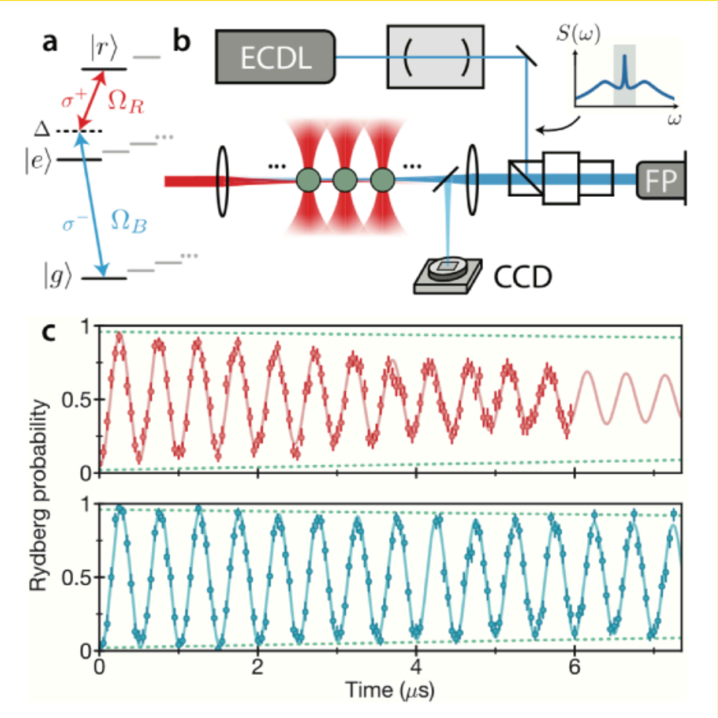
The **Qu**antum **T**oolbox **i**n **P**ython

Experimental Research

arXiv:1806.04682v1 [quant-ph] 12 Jun 2018

High-fidelity control and entanglement of Rydberg atom qubits

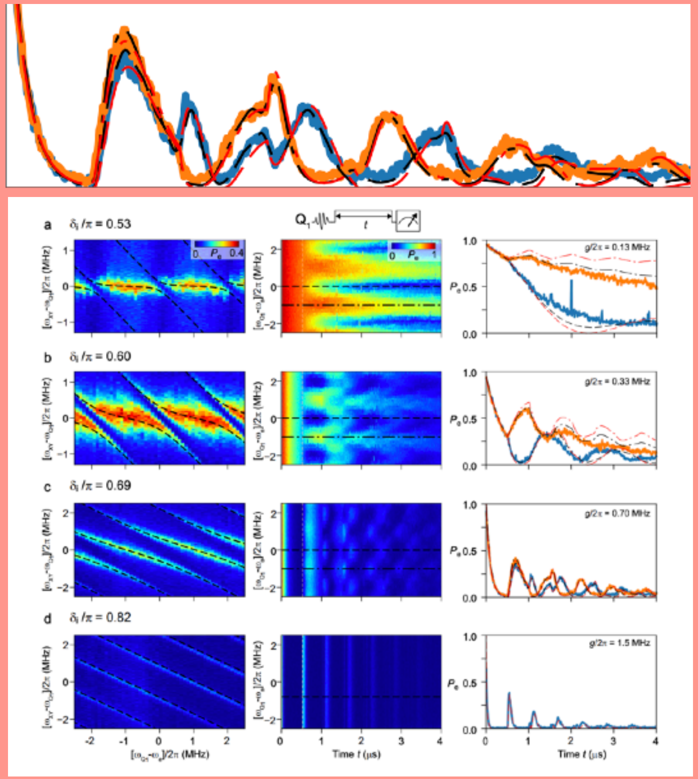
H. Levine, [...] and M.D. Lukin Phys. Rev. Lett (2018)



arXiv:1903.05672 [quant-ph] 13 Mar 2019

Phonon-mediated quantum state transfer and remote qubit entanglement

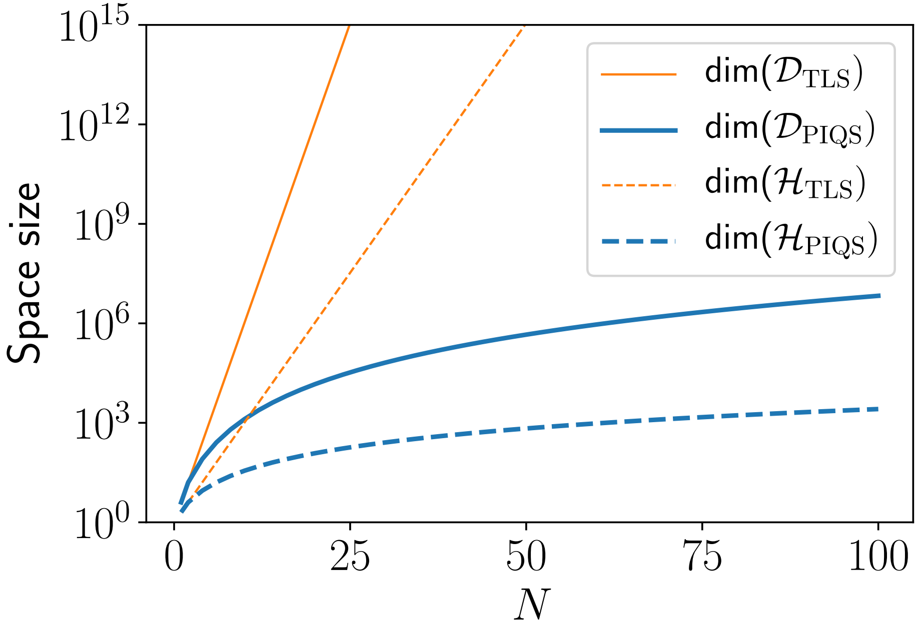
A. Bienfait, [...] and A.N. Cleland, Science **10**, 1126 (2019)



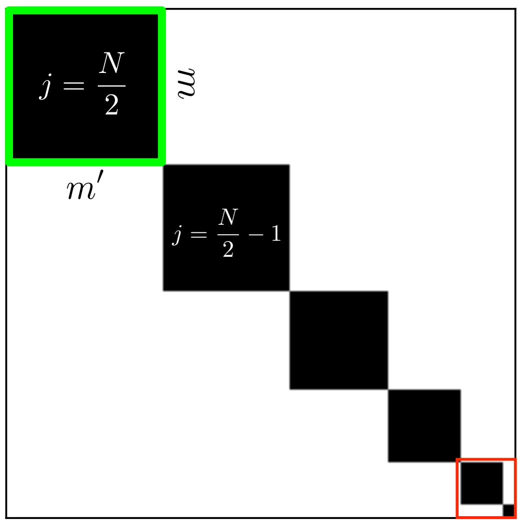
Permutational symmetric method in the Dicke space

Homogeneous local dissipation can be included in the dynamical model

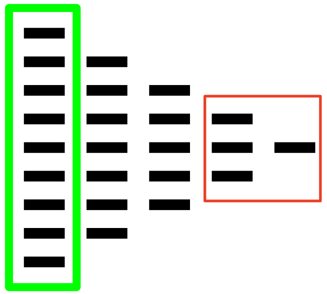
Exponential Space Reduction



Block-Diagonal Density Matrix



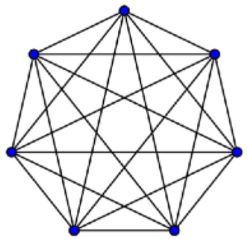
Dicke space visualization



Number of Dicke States

$$n_{\mathrm{DS}}(N) = \sum_{j=0}^{N/2}(2j+1) = \left(\frac{N}{2}+1\right)^2$$

B. A. Chase and J. M. Geremia, Phys. Rev. A **78**, 052101 (2008)
F. Damanet, D. Braun, and J. Martin, Rev. A **94**, 033838 (2016)
N. Shammah et al. Phys. Rev. A (2017)



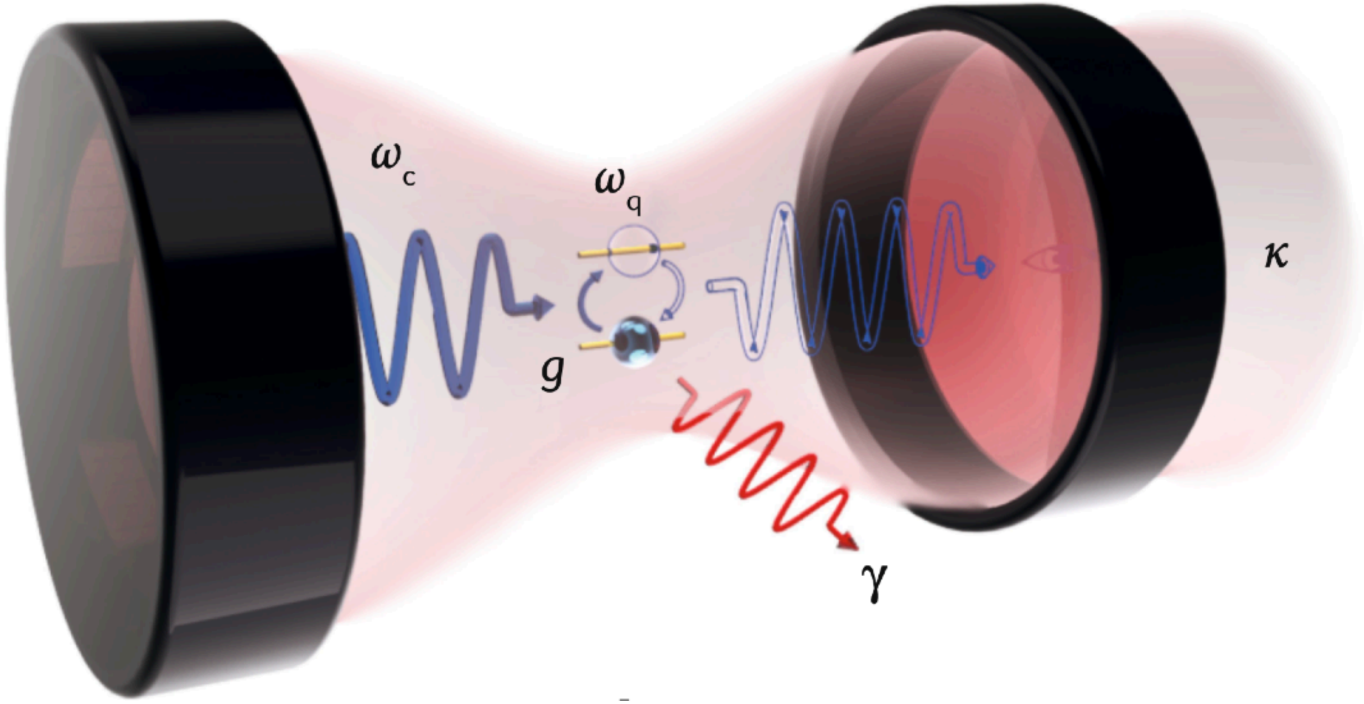
Hamiltonian
Collective spin operators only
Complete graph (fully connected).
Constant edges weight: no lattice distance.

Dissipation
Homogeneous local couplings.

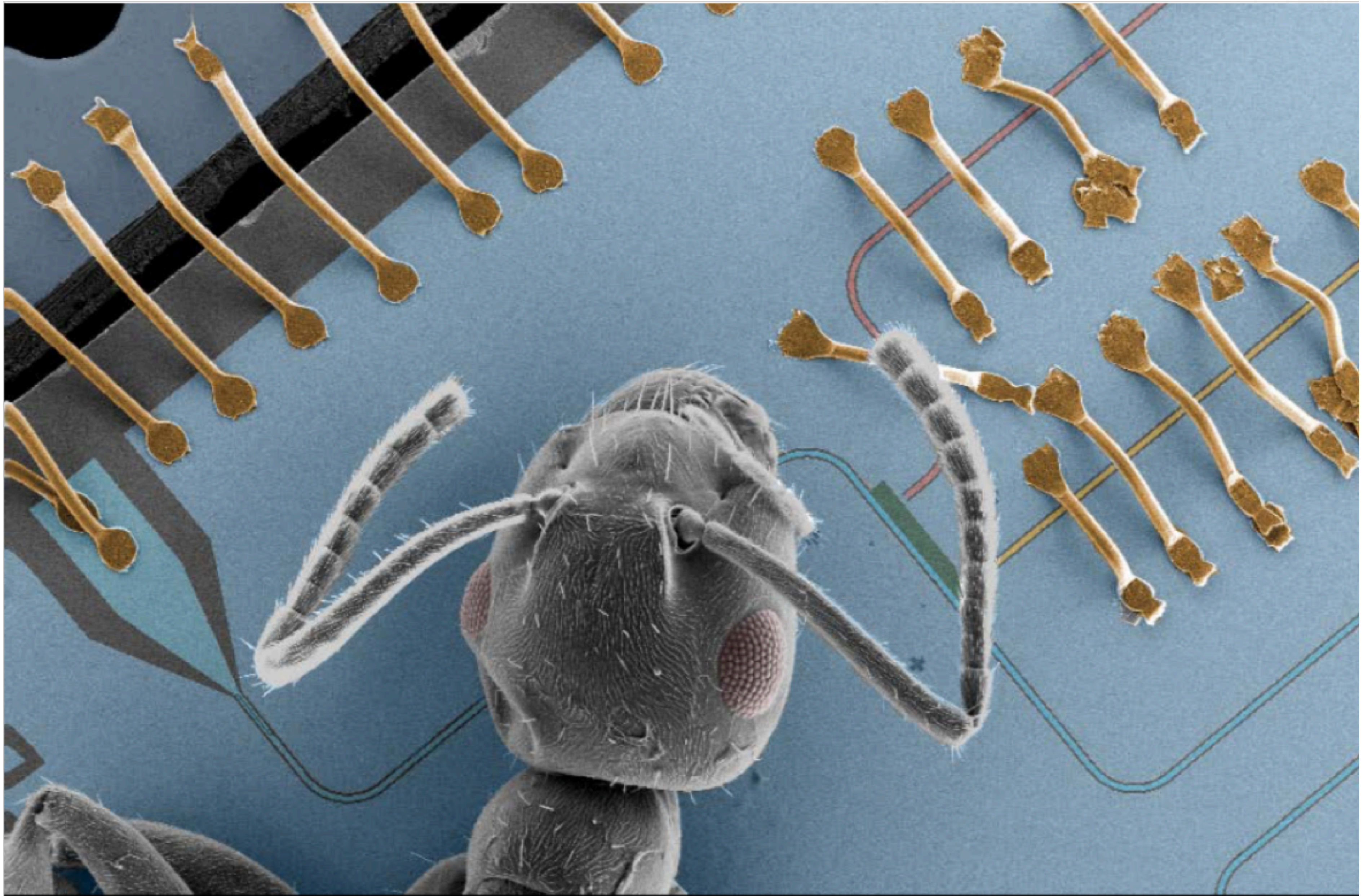
States
Limited to identical qubit states.

Cavity Quantum Electrodynamics (Cavity QED)

Using the **Qu**antum **T**oolbox **in** **P**ython to study physics



A. F. Kockum, A. Miranowicz, S. De Liberato, S. Savasta & Franco Nori, Nature Reviews Physics, **1** 19 (2019)



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

J. Mlynek *et al.*, Quantum Device Lab, ETH Zurich (2012)

QuTiP: A Growing Ecosystem for Quantum Physics

What's going on

- 2018: Joined NumFOCUS, foundation for scientific code (NumPy)

NUMFOCUS
OPEN CODE = BETTER SCIENCE

- 2019: Participating to Google Summer of Code 2019:

Student Applications opened March 26th. Closed April 9th. 3 students working on summer projects.

Google
Summer of Code

2019: Applied to 1st Google Season of Docs 2019: Technical writers projects for documentation.

downloads 203k total (conda forge)

- 2018-2019: Reaching out to the sci-dev community.

EuroScipy 2018
July 2018
Trento, Italy

PyData 2018
November 2018
Warsaw, Poland

FOSDEM'19 (Quantum Computing)
February 2, 2019,
Brussels, Belgium

1st QuTiP developers workshop
February 19-21, 2019
RIKEN, Wako, Japan

EuroScipy 2019
September 2019
Bilbao, Spain

- 2018-2019: A growing QuTiP ecosystem of satellite libraries:

`piqs`
QuTiP library
Now a qutip module

`krotov`
QuTiP-based quantum
optimal control library

`matsubara`
A qutip plugin for
non-Markovian dynamics

QuTiP ecosystem:
Like AstroPy,
but for Quantum

New in QuTiP 4.5.0 (2020): Noisy Quantum Circuits

qutip.nisq

Model noise in quantum information processing (QIP)

QuTiP's QIP module represents ideal quantum circuits.

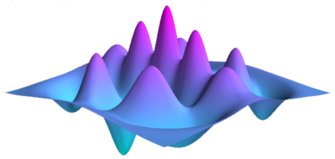
Student: Boxi Li (ETH Zurich)

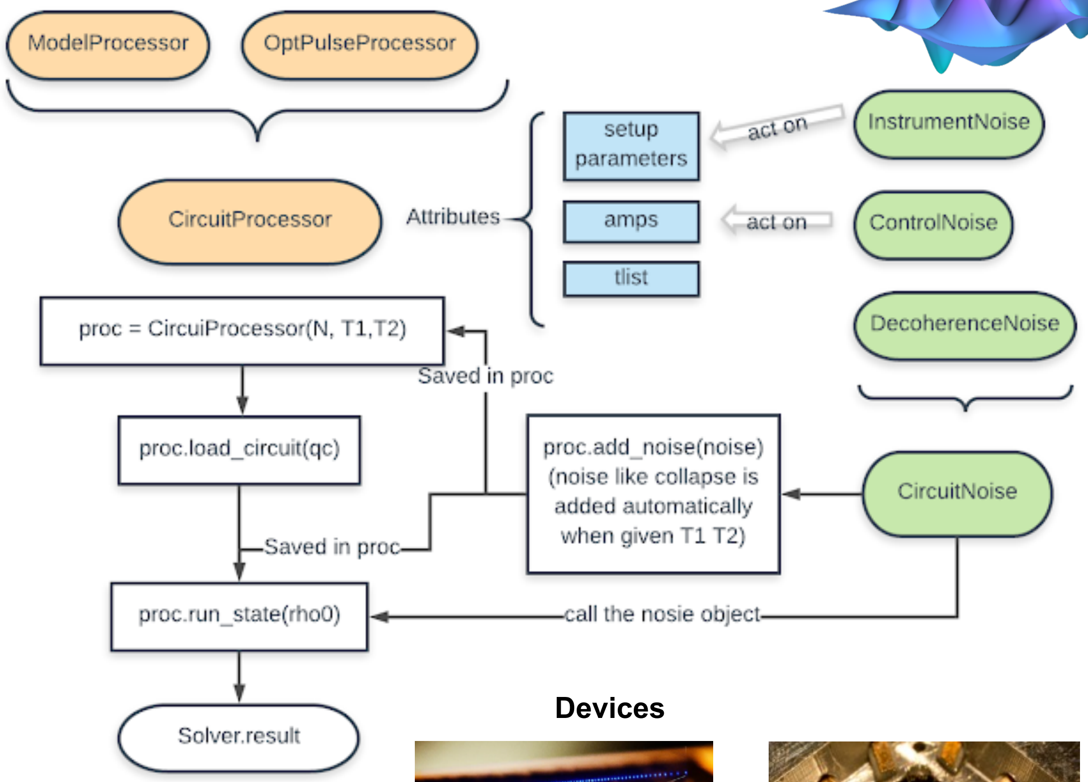
Objectives:
- Go beyond gates as instantaneous unitary transformation
- Noise model for realistic devices
- Noise model for dissipative dynamics

Deployed results:
- Added Mølmer-Sørensen gate
- Allowed user-defined gates
- Added optical pulses for gate shaping

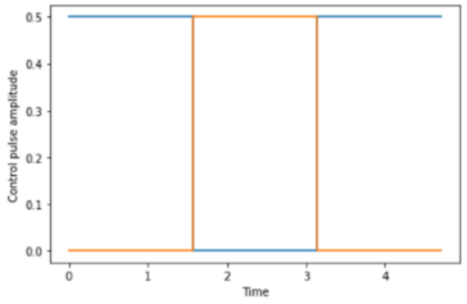
Code: Boxi Li. Github: BoxiLi
Mentors: Alex Pitchford,
Neill Lambert,
Shahnawaz Ahmed,
Nathan Shammah

Google
Summer of Code

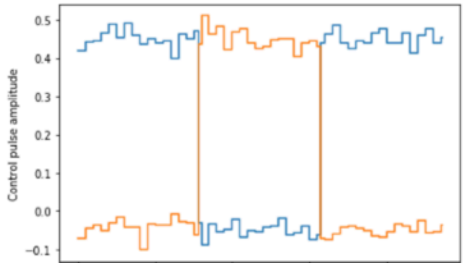




Perfect Unitary

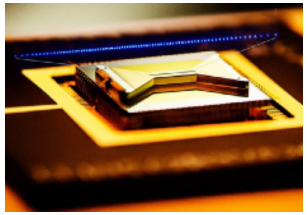


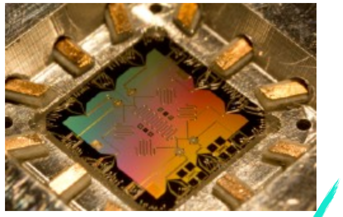

```
[20]: processor_white.plot_pulses(noisy=True)
[20]: (<Figure size 432x288 with 1 Axes>,
       <matplotlib.axes._subplots.AxesSubplot at 0x269999bb710>)
```



Noisy pulses

Devices





piqs
QuTiP library
Now a qutip module

krotov
QuTiP-based quantum optimal control library

matsubara
A qutip plugin for non-Markovian dynamics

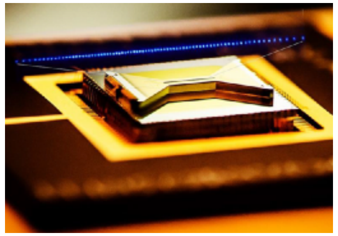
qutip.noise
Noisy quantum circuits using QuTiP solvers

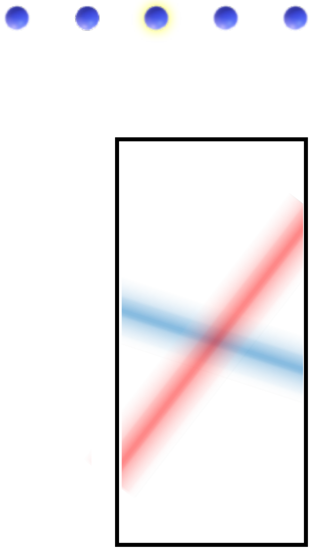
...

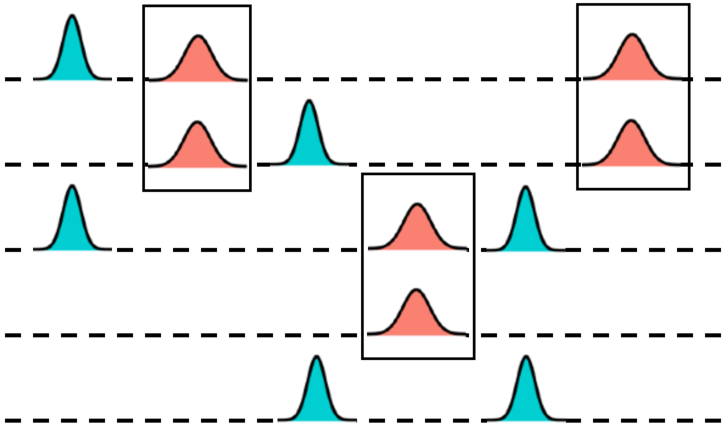
New in QuTiP 4.5.0 (2020): Noisy Quantum Circuits

Boxi Li (ETH Zurich)

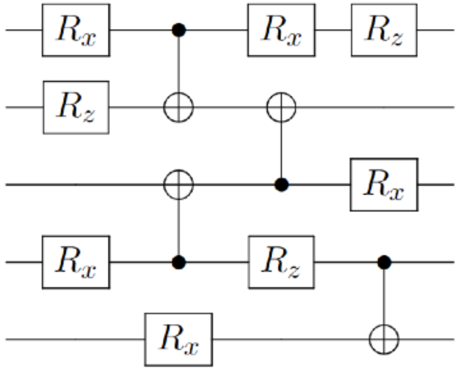
Back-end







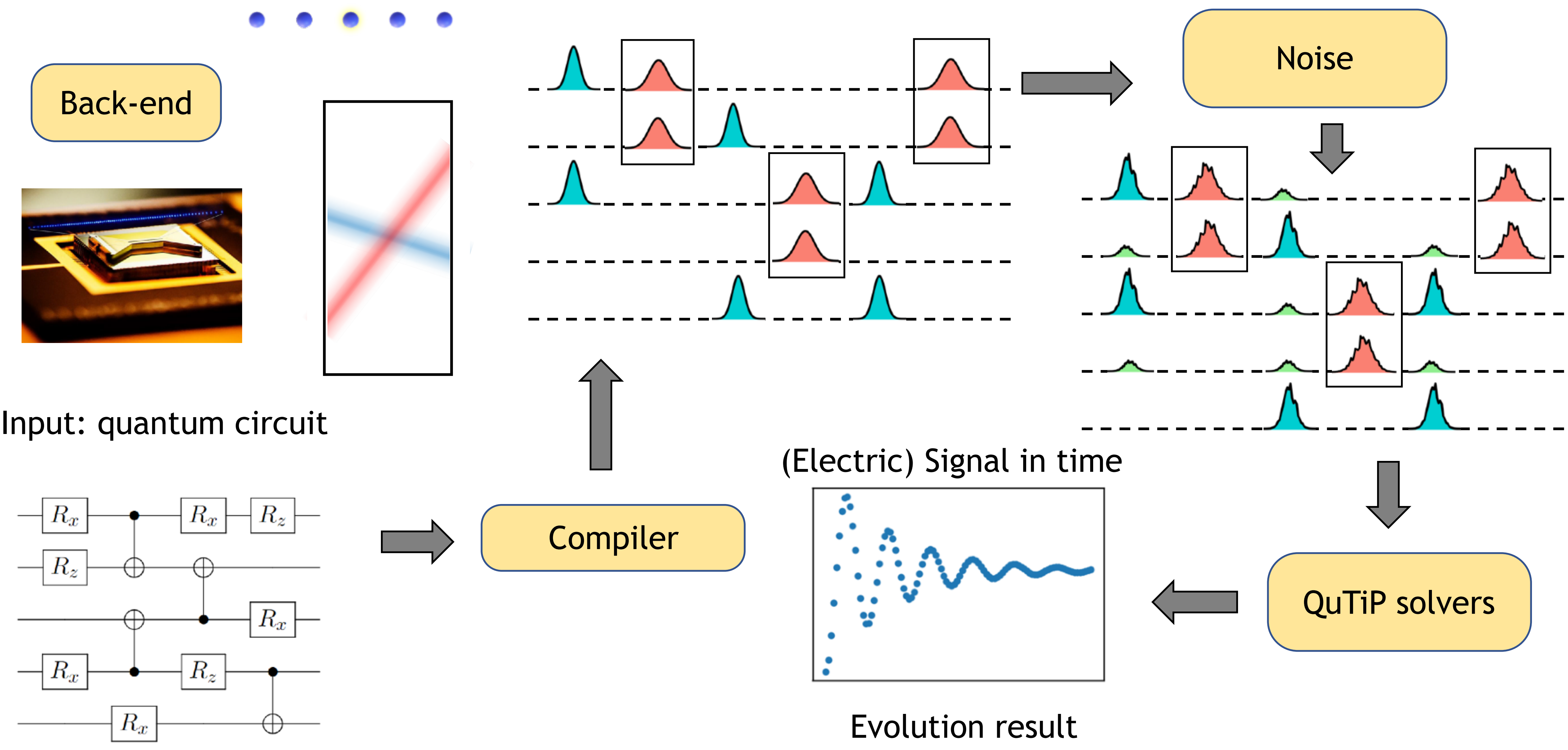
Input: quantum circuit



Compiler

New in QuTiP 4.5.0 (2020): Noisy Quantum Circuits

Boxi Li (ETH Zurich)



QuTiP project


Paul Nation


Robert Johansson

Johansson, J. Robert, P. D. Nation, and Franco Nori. "QuTiP: An open-source Python framework for the dynamics of open quantum systems." *Computer Physics Communications* 183.8 (2012): 1760-1772.

Johansson, J. Robert, Paul D. Nation, and Franco Nori. "QuTiP 2: A Python framework for the dynamics of open quantum systems." *Computer Physics Communications* 184.4 (2013): 1234-1240.

Chris Granade, Arne Grimsmo, +60 contributors


Shahnawaz Ahmed
Chalmers, Sweden


Alex Pitchford
Aberystwyth University
United Kingdom


Eric Giguère
U. de Sherbrooke
Canada


Neill Lambert
RIKEN, Japan


Nathan Shammah
RIKEN, Japan
Unitary Fund, USA


Franco Nori
RIKEN, Japan
U. of Michigan (USA)

日本学術振興会
Japan Society for the Promotion of Science

Japan Science and Technology Agency
Q-LEAP

Franco Nori's Group

NUMFOCUS
OPEN CODE = BETTER SCIENCE

Google
Summer of Code

UNIVERSITÉ DE
SHERBROOKE

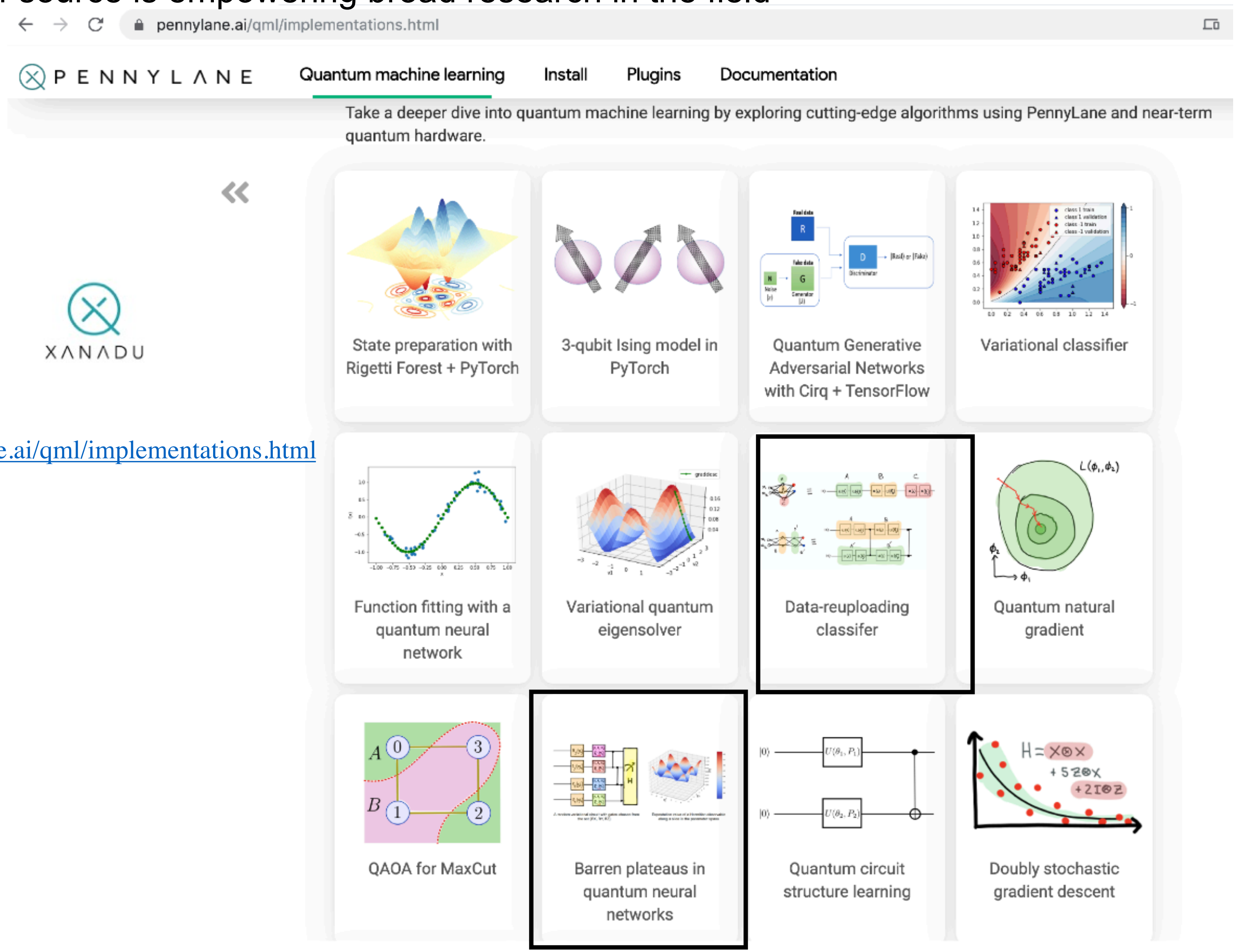
PRIFYSGOL
ABERYSTWYTH
UNIVERSITY

Machine Learning

Quantum Technologies

Quantum Tech: Open Source Libraries

More open-source is empowering broad research in the field



https://pennylane.ai/qml/implementations.html

Machine Learning and Quantum do not commute

Define: Commutator

$$[A, B] = AB - BA$$

$$[\mathbf{ML}, Quantum] \neq 0$$

MLQ

Machine Learning of Quantum Systems

Apply “standard” Machine Learning to
Study Quantum Physics Systems

J. Carrasquilla & R. Melko, *Nature Phys.* (2017)

QML

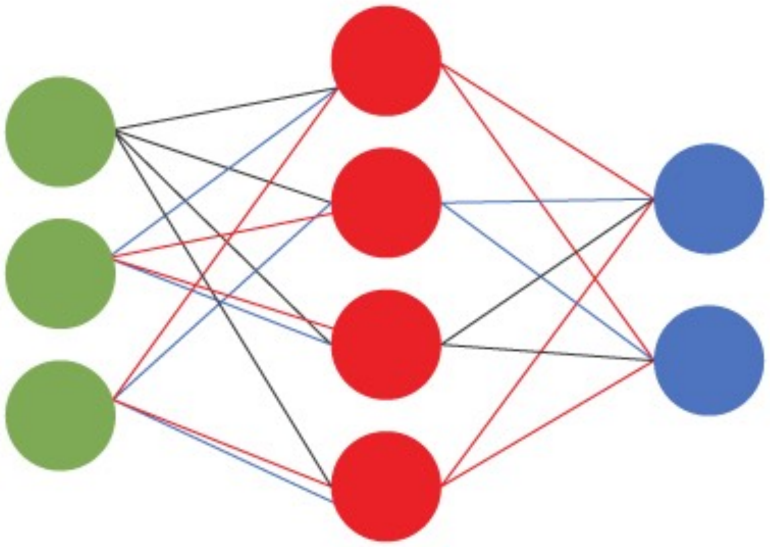
Quantum-enhanced Machine Learning

Exploit quantum correlations
for new algorithms and frameworks (QNN)

J. Biamonte, …, S. Loyd, *Nature* (2017)

Deep Neural Networks

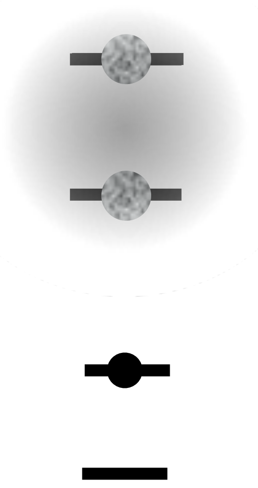
Feed-Forward basics

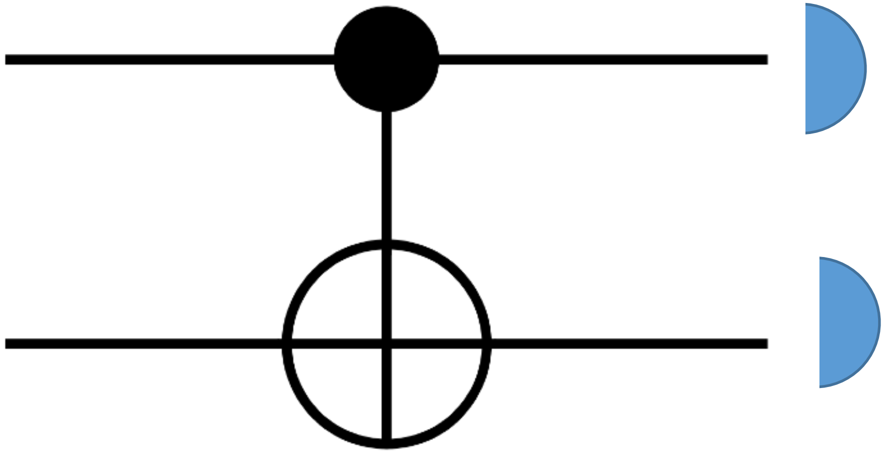


$\mathrm{L}(n0 \rightarrow n1)$: $\quad \mathbf{x} \rightarrow \mathbf{y} = \phi(W\mathbf{x} + \mathbf{b})$

Quantum Circuit

Basics

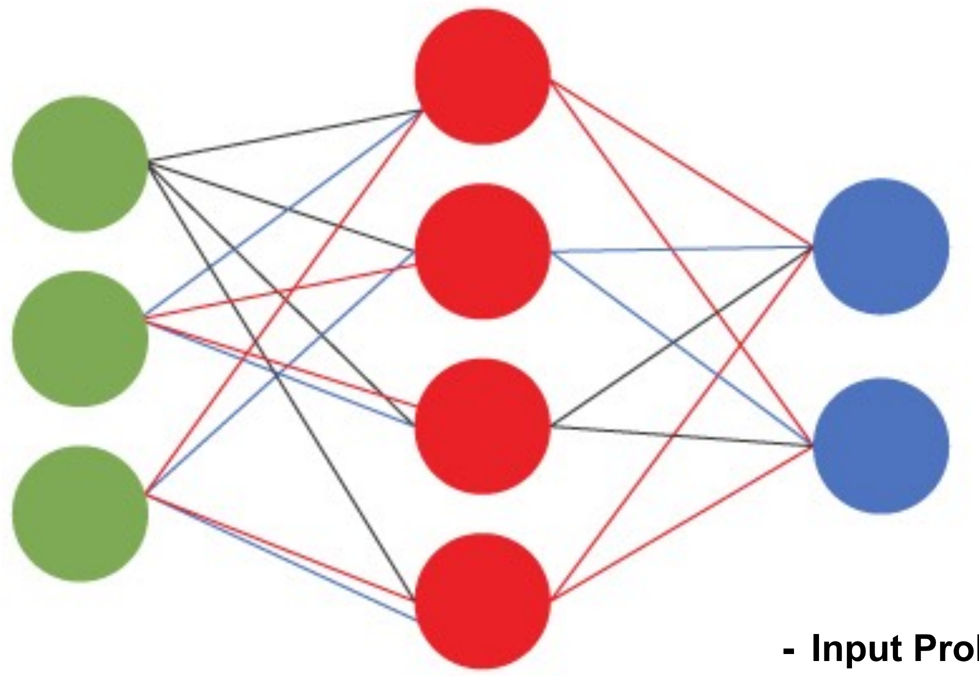


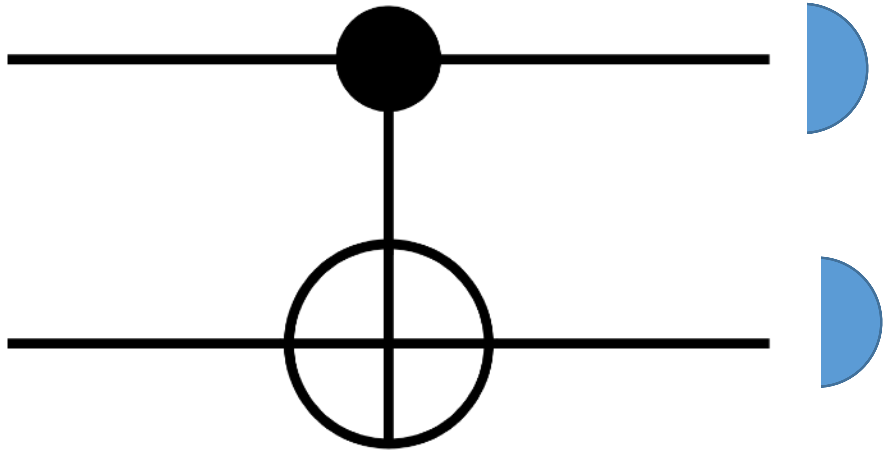


$$\mathbf{x} \rightarrow \mathbf{y} = W\mathbf{x}$$

Quantum Machine Learning

Basic example





- **Input Problem**
- **Output Problem**
- **Costing Problem**
- **Benchmarking Problem**

J. Biamonte, …, S. Loyd, *Nature* (2017)