PHY682 Special Topics in Solid-State Physics: Quantum Information Science

Lecture time: 2:40-4:00PM Monday & Wednesday, via Zoom
Instructor: Tzu-Chieh Wei

http://insti.physics.sunysb.edu/~twei/Courses/Fall2020/PHY682/

Course description:
This is a survey of the fast-evolving field of quantum information, ranging from Bell inequality, quantum teleportation to quantum algorithms and quantum programming frameworks. It aims to cover the essential knowledge of quantum information science and helps to bridge the gap to the current research activities of the field. Emphasis will be placed on solid-state platforms of quantum computers, topological error correction codes, and applications. Other systems will be introduced when necessary. Some illustration of quantum programming will be done on IBM's transmon-type cloud quantum computers.

National Quantum Initiative Act

From Wikipedia, the free encyclopedia

The **National Quantum Initiative Act** is an Act of Congress passed on December 13, 2018 and signed into law on December 21, 2018. The law gives the United States a plan for advancing quantum technology, particularly quantum computing. It passed unanimously by United States Senate and was signed by President Donald Trump.[1][2][3][4][5][6]

References [edit]

1. ^ "President Trump has signed a $1.2 billon law to boost US quantum tech". *MIT Technology Review*. Retrieved February 11, 2019.
2. ^ "H.R.6227 - National Quantum Initiative Act". *Congress.gov*. December 21, 2018. Retrieved June 7, 2020.
3. ^ Loftus, Tom (December 20, 2018). "The Morning Download: Quantum Computing Goes to Washington". *WSJ*. Retrieved February 11, 2019.
4. ^ "Trump signs legislation to boost quantum computing research with $1.2 billion". *GeekWire*. December 22, 2018. Retrieved February 11, 2019.
5. ^ 115th Congress (2018) (June 26, 2018). "H.R. 6227 (115th)". *Legislation*. GovTrack.us. Retrieved February 11, 2019. "National Quantum Initiative Act"
6. ^ Raymer, Michael G.; Monroe, Christopher (2019). "The US National Quantum Initiative". *Quantum Science and Technology*. **4** (2): 020504. doi:10.1088/2058-9565/ab0441.

This *quantum mechanics*-related article is a *stub*. You can help Wikipedia by *expanding it*.

This *United States federal legislation* article is a *stub*. You can help Wikipedia by *expanding it*.

➔ One implication: more job opportunities in (i) research or (ii) Industry

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National Quantum Initiative Act

Long title	An Act to provide for a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States.
Enacted by	the 115th United States Congress
Effective	December 21, 2018

Citations

Public law	115-368

Legislative history

- **Introduced in the House as** H.R. 6227 by Lamar Smith (R-TX) **on** Jun 26, 2018
- **Committee consideration by** Science, Space and Technology (House) and Commerce, Science and Transportation (Senate)
- **Passed the House on** September 13, 2018 (8229-8234)
- **Passed the Senate on** December 13, 2018 ([1])
- **Signed into law by President** Donald Trump **on** December 21, 2018

Learning outcomes:

Students who have completed this course
 • Should be able to <u>understand the physical principles of quantum computation and how quantum algorithms work</u> such as Shor's factoring and Grover's searching
 • Should be able to <u>understand the basics of information theory and their relation to statistical mechanics and quantum entanglement</u>
 • Should be able to understand the <u>working principles of sold-state qubits and be able to perform simple programming on publicly available quantum computers such as IBM Q</u>
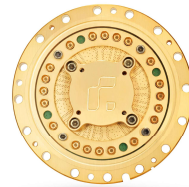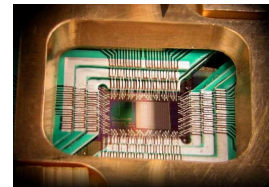
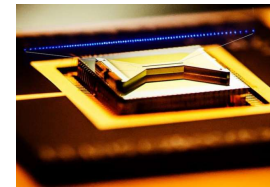IBM 50-Qubit Q Computer
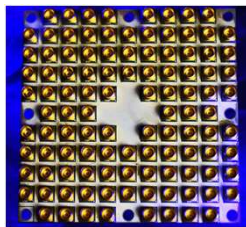
Intel 49-Qubit QC
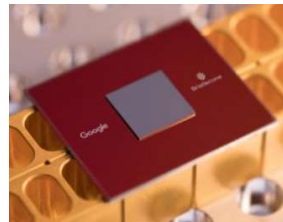
Google 72-Qubit QC

Rigetti 20-Qubit QC

D-Wave 2000-Qubit Annealer

IonQ 160-Qubit QC

Grading: (tentative)

(1) <u>Homework</u> 50% [main purpose is to enhance understanding of lecture materials]

(2) <u>Participation</u> 10% [attendance is required; more importantly, this is to encourage active participation and learning; asking questions helps the instructor to clarify and in turn helps you and others to understand; sharing with others how you understand a particular concept is useful; you can ask questions verbally or in Zoom's chat; report technical internet problem to the instructor]

(3) <u>Mid-semester report </u>(2-3 pages) 15% [to gauge how you are doing]

(4) <u>Final presentation</u> (for suggested topics/papers, see below) & <u>end-of-semester report</u> 25% (15%+10%) [to have an in-depth understanding of a subject of your choice and a retrospect of your learning in this course]

Homework policy: <u>no late homework</u> (must be turned in on the due day by submitting it in Blackboard or email); <u>exception must be requested two days or earlier before deadline</u>

Required Textbooks:
There is no required textbook. Notes or slides will be provided when available.

Recommended Textbooks :
1. Quantum Computation and Quantum Information, M. Nielsen and I. Chuang (Cambridge University Press)
2. An Introduction to Quantum Computing, P. Kaye, R. Laflamme and M. Mosca (Oxford)
3. J. Preskill lecture notes (http://www.theory.caltech.edu/~preskill/ph229/#lecture)
4. **The Feynman Lectures on Physics, Vol. 3** (which can be read online here)
Learn Quantum Computation using Qiskit (free digital textbook)

Basic Math needed in this course:
e.g. The Mathematics of Quantum Mechanics by Dr. Martin Laforest (University of Waterloo)

Vol III

https://qiskit.org/textbook/preface.html

Qiskit

Learn   Community   Documentation
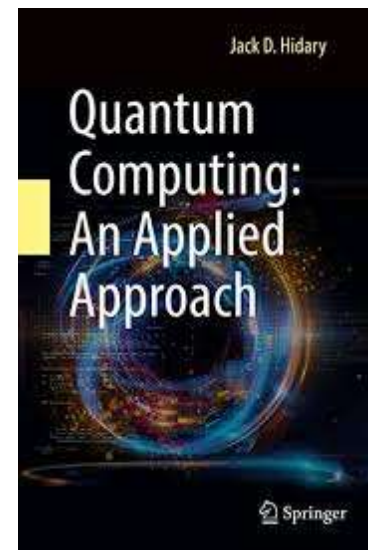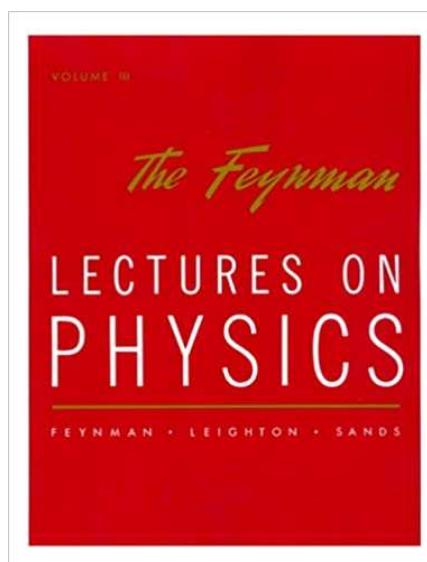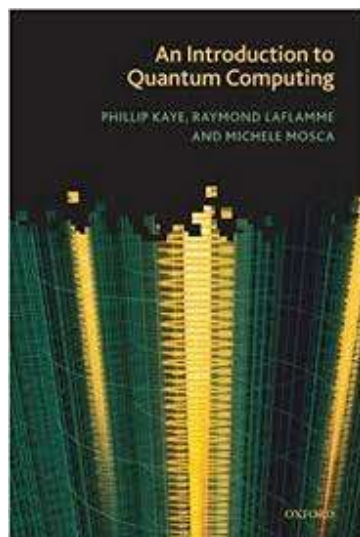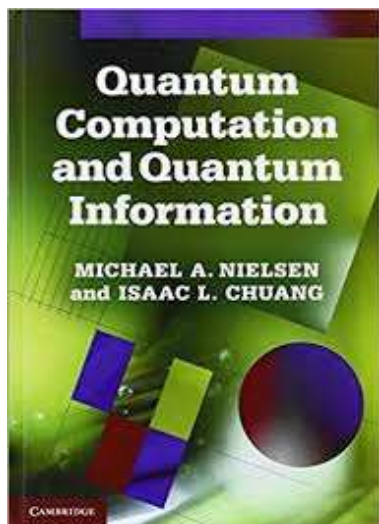
Learn Quantum Computation using Qiskit

What is Quantum?

0. Prerequisites

1. Quantum States and Qubits

1.1 Introduction

1.2 The Atoms of Computation

1.3 Representing Qubit States

1.4 Single Qubit Gates

1.5 The Case for Quantum

2. Multiple Qubits and Entanglement

2.1 Introduction

2.2 Multiple Qubits and Entangled States

2.3 Phase Kickback

2.4 More Circuit Identities

Learn Quantum Computation using Qiskit

"Quantum computing is the perfect way to dip your toes into quantum physics. It distills the core concepts from quantum physics into their simplest forms, stripping away the complications of the physical world. This page will take you on a short journey to discover (and explain!) some strange quantum phenomena, and give you a taste for what 'quantum' is."
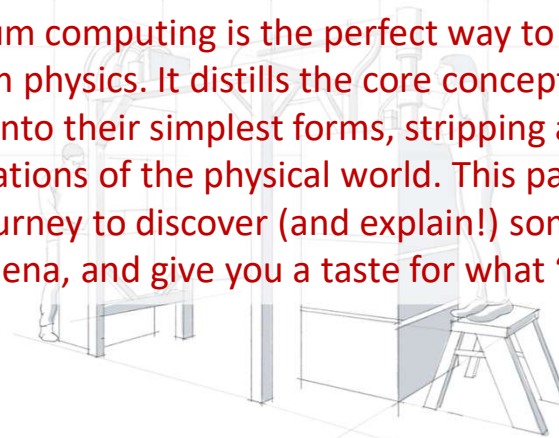
Greetings from the Qiskit Community team! This textbook is a   Cookie Prefere

Topics covered

http://insti.physics.sunysb.edu/~twei/Courses/Fall2020/PHY682/

(week 1) **The history of Q**: Overview and review of linear algebra, basics of quantum mechanics, quantum bits and mixed states.

(week 2) **From foundation to science-fiction teleportation**: Bell inequality, teleportation of states and gates, entanglement swapping, remote state preparation, superdense coding, and superdense teleportation.

(week 3) **Information is physical---**Physical systems for quantum information processing: Superconducting qubits, solid-state spin qubits, photons, trapped ions, and topological qubits

(week 4) **Grinding gates in quantum computers**: Quantum gates and circuit model of quantum computation, introduction to IBM's Qiskit, Grover's quantum search algorithm, amplitude amplification.

(week 5) **Programming through quantum clouds**: Computational complexity, Quantum programming on IBM's superconducting quantum computers, including VQE on quantum chemistry of molecules, QAOA for optimization, hybrid classical-quantum neural network.

(week 6) **Dealing with errors**: Error models, Quantum error correction, topological stabilizer codes and topological phases (including fractons), error mitigations

(week 7) **Quantum computing by braiding**: Kitaev's chain, Majorana fermions, anyons and topological quantum computation

(week 8) **More topological please**: Topological quantum computation continued, surface code and magic state distillation

(week 9) **Quantum computing by evolution and by measurement**: Other frameworks of quantum computation: adiabatic and measurement-based; D-Wave's quantum annealers

(week 10) **Quantum entangles**: Entanglement of quantum states, entanglement of formation and distillation, entanglement entropy, Schmidt decomposition, majorization, quantum Shannon theory

(week 11) **No clones in quantum**: No cloning of quantum states, non-orthogonal state discrimination, quantum tomographic tools, quantum cryptography: quantum key distribution from transmitting qubits and from shared entanglement

(week 12) **Show me your 'phase', Mr. Unitary**: Quantum Fourier Transform, quantum phase estimation, Shor's factoring algorithm, and quantum linear system (such as the HHL algorithm) and programming with IBM Qiskit

(week 13) **The quantum 'Matrix'**: Quantum simulations and quantum sensing and metrology

Do poll

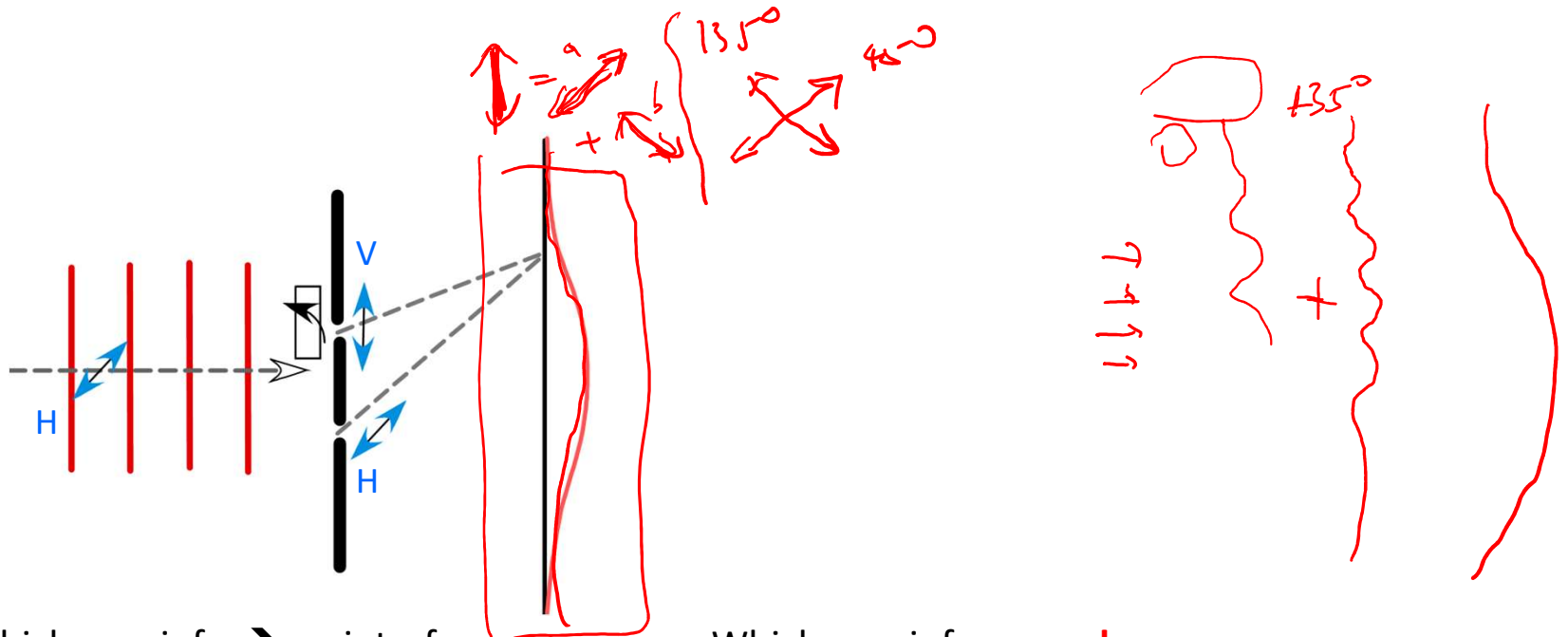# Appetizers: double-slit experiment
and Mach-Zehnder interferometer

Double-slit experiment

$$\left|\psi_1(r) + \psi_2(r)\right|^2$$

Wave-like

$$\left|\psi_1(r)\right|^2 + \left|\psi_2(r)\right|^2$$

Particle-like
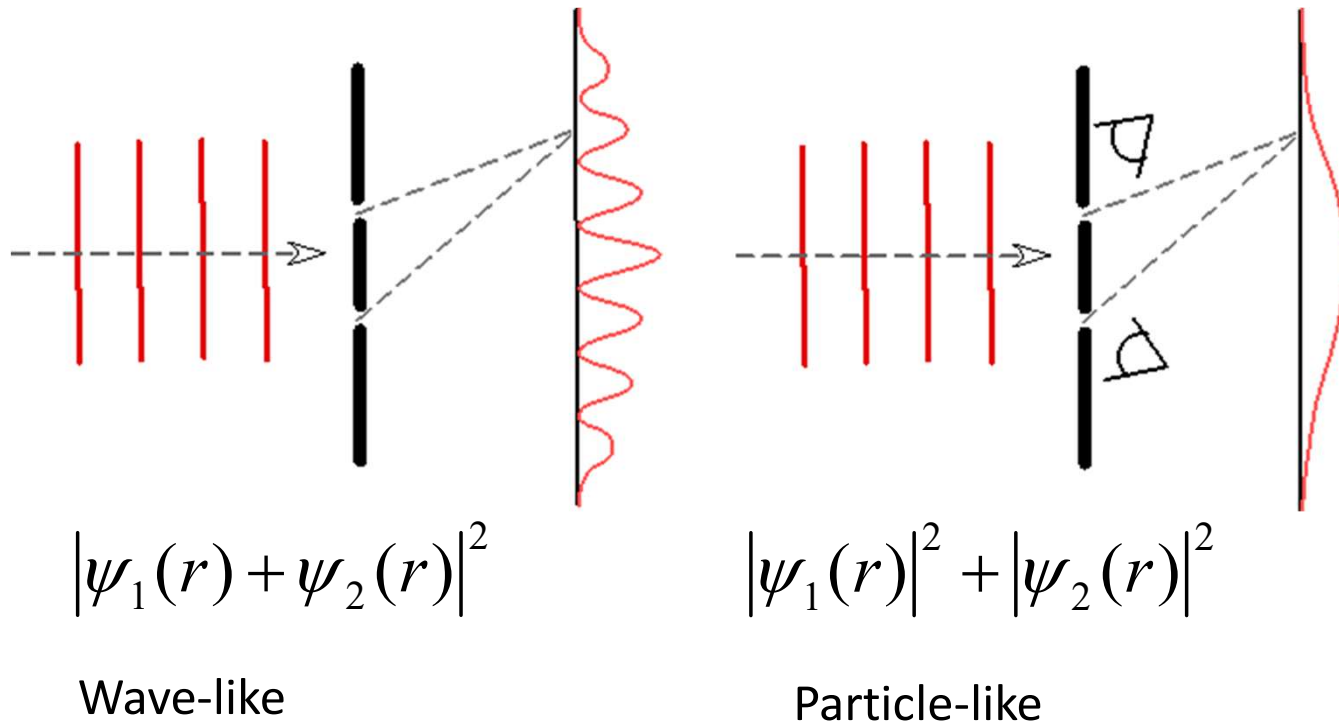
➔ Interference (or 'superposition'): no which-way info;
if you know the light comes from a specific slit, no interference (only adding probabilities)

Which-way information and quantum erasure

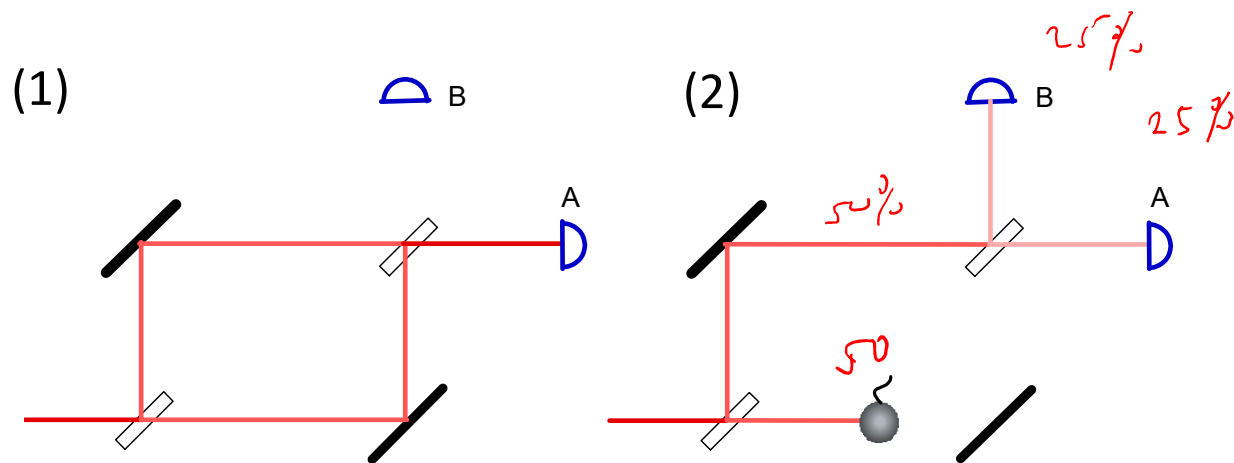Which-way info. ➔ no interference

Which-way info. **erased**
➔ interference recovered

❑ Polarization can be a WW marker $\Psi(r) = \psi_1(r)|\theta_1\rangle + \psi_2(r)|\theta_2\rangle,$

➔ $|\Psi(r)|^2 = |\psi_1(r)|^2 + |\psi_2(r)|^2 + 2\operatorname{Re}\psi_1^*(r)\psi_2(r)\langle\theta_1|\theta_2\rangle$

Mach-Zehnder interferometer and interaction-free measurement

(1)

B

A

D

(2)

25%

B

25%

50%

A

D

50
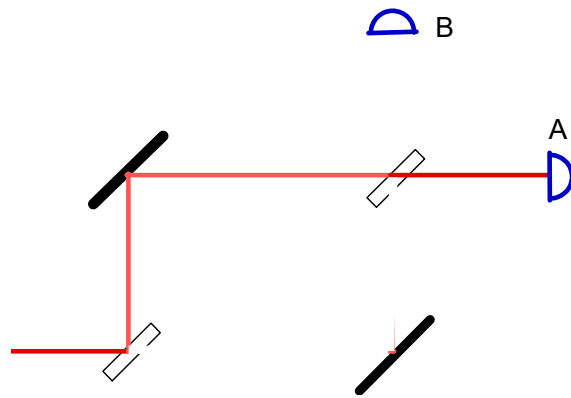
In fig. (2)

Q: What is the probability that bomb explodes?   50%

Q: What is the probability that detector A/B clicks?   25%, 25%
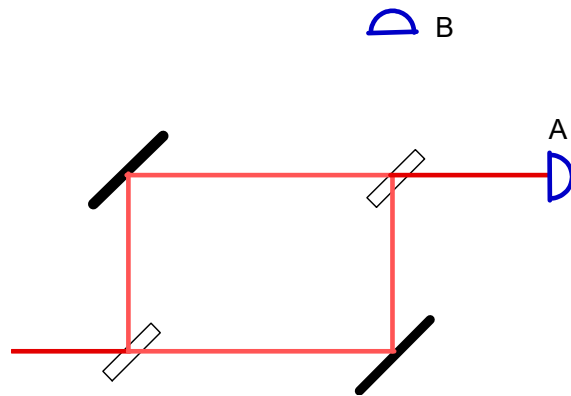
Classical 'pinballs'

$$|\psi_1(r)|^2 + |\psi_2(r)|^2$$

Suppose the "transparent flippers" allow a pinball to go thru or deflect each with probability 1/2

(1) Q: What is the probability that a pinball gets to A?

$$\frac{1}{2} \times \frac{1}{2} + \frac{1}{2} \times \frac{1}{2} = \frac{1}{2}$$

(2) Q: What is the probability that a pinball gets to B?

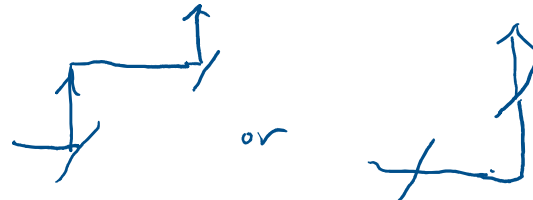$$\frac{1}{2} \times \frac{1}{2} + \frac{1}{2} \times \frac{1}{2} = \frac{1}{2}$$

Quantum 'pinballs'

$$\left|\psi_1(r) + \psi_2(r)\right|^2$$

B

A

D

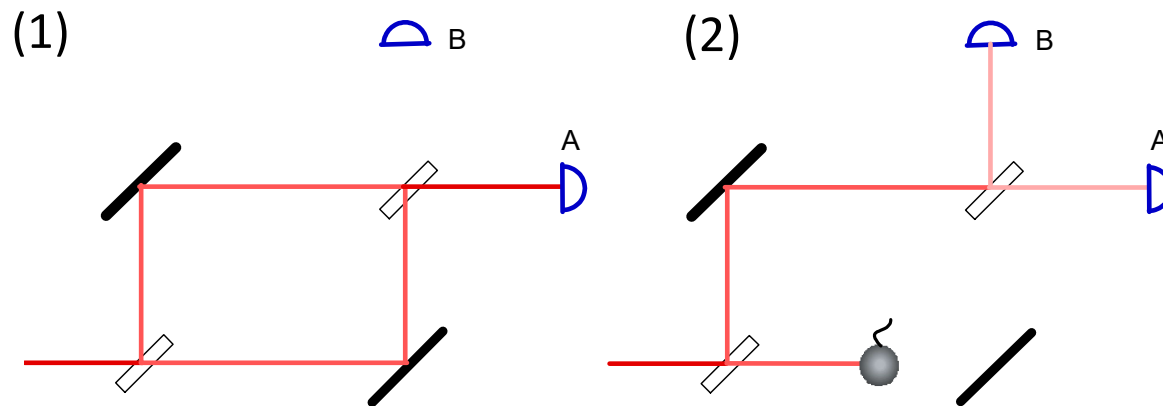Special rule: "pinball going thru acquires amplitude $1/\sqrt{2}$; being deflected acquires $i/\sqrt{2}$

$$i = \sqrt{-1}$$

(1) Q: What is the probability that a pinball gets to A?

$$\left|\frac{i}{\sqrt{2}} \times \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}} \times \frac{i}{\sqrt{2}}\right|^2 = 1$$

(2) Q: What is the probability that a pinball gets to B?

or

$$\left|\frac{i}{\sqrt{2}} \times \frac{i}{\sqrt{2}} + \frac{1}{\sqrt{2}} \times \frac{1}{\sqrt{2}}\right|^2 = 0$$

Mach-Zehnder interferometer and interaction-free measurement

(1)

B

A

(2)

B

A

In fig. (2)

Q: What is the probability that bomb explodes?

Q: What is the probability that detector A/B clicks?

Quantum task: Shor factoring
→ exponential speedup

18070820886874048059516561644059055662781025167
69401349170127021450056662540244048387341127590
81230337178188796656318201321488055 7
=(????....?) x (????...?)

=(396859994595974542901611261628837
86067576449112810064832555157243)
x
(455344986467359721884036868972744 0
88643563012632050696009990 44599)

superposition + unitary evolution + measurement

→ Can break RSA (Rivest-Shamir-Aldeman) encryption
exponentially faster than classical computers

IBM offers cloud Quantum Computers

➢ If you do not have an IBM Q account, please create one at

https://auth.quantum-computing.ibm.com/auth/idaas

Hardware-efficient variational quantum eigensolver for small molecules and quantum magnets
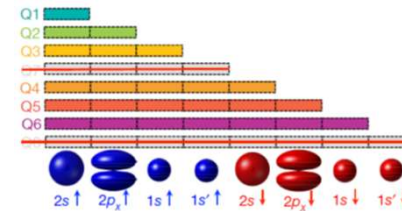
Abhinav Kandala ✉, Antonio Mezzacapo ✉, Kristan Temme, Maika Takita, Markus Brink, Jerry M. Chow & Jay M. Gambetta

Quantum simulation Qubits

Superconducting properties and materials
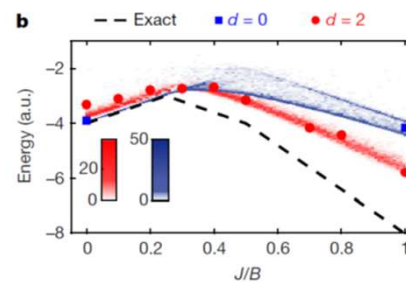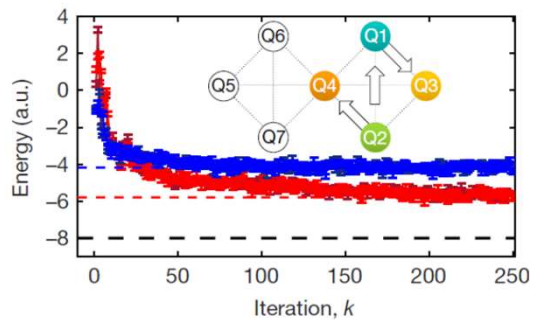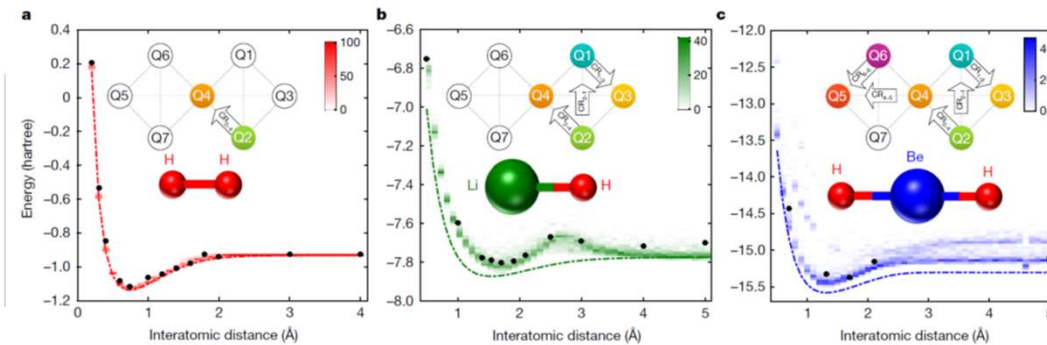
What mathematics do I need?

Mostly, linear algebra (vectors and matrices) is needed.
We will review the very basics in the next few slides; if
you know all of them, you are all set to go.

Other mathematics can be learned along the way.

Complex numbers

$$i = \sqrt{-1}, \ \ i^2 = -1, \ \ |i| = |\sqrt{-1}| = 1$$

$$|a + b\,i|^2 = a^2 + b^2, \ \ \ \text{for } a, b \text{ real}$$

$$z \equiv a + b\,i, \ \ \ \text{for } a, b \text{ real} \ \ \ \ \ \text{Re}(z) = a, \ \ \text{Im}(z) = b$$

$$i^* = -i, \ \ (a + b\,i)^* = \overline{a + b\,i} = a - b\,i, \ \ \text{for } a, b \text{ real}$$

$$e^{i\theta} = cos\theta + i\sin\theta \ \ \ \ \ \ \ \ \overline{e^{i\theta}} = cos\theta - i\sin\theta \ \ \ \ \ \ \ \ e^{i\pi} = -1, \ e^{i\pi/2} = i$$

Linear algebra: vectors and matrices

$$\vec{v}_1 = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} =: |'1'\rangle \qquad \vec{v}_2 = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} =: |'2'\rangle \qquad \vec{v}_3 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} =: |'3'\rangle$$

$\vec{v}'s$ form an orthogonal basis: $\vec{v}_i^{*T} \cdot \vec{v}_j = \vec{v}_i^{\dagger} \vec{v}_j = \delta_{ij}$ \qquad Bra-ket notation $\langle'i'|'j'\rangle = \delta_{ij}$

A unitary matrix U satisfies $U^{\dagger}U = UU^{\dagger} = I$, for example,

$$U = \begin{pmatrix} \cos\theta & i\sin\theta & 0 \\ i\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad U^{\dagger} = \begin{pmatrix} \cos\theta & -i\sin\theta & 0 \\ -i\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Bra-ket notation: $U = \sum_{ij} U_{ij}|'i'\rangle\langle'j'|$, thus $\langle'i'|U|'j'\rangle = U_{ij}$

$(U\vec{v})_i = \sum_{ij} U_{ij}v_j = \langle'i'|U|v\rangle$ \qquad $n \times n$ identity matrix: $I = \sum_{i=1}^{n} |'i'\rangle\langle'i'|$

Trace of a square matrix: $\text{Tr}(U) = \sum_{i=1}^{n} U_{ii}$

Projectors and tensor (or Kronecker) product

$$\vec{v}_1 = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} =: |'1'\rangle \qquad \vec{v}_2 = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} =: |'2'\rangle$$

$$P_1 \equiv \vec{v}_1 \vec{v}_1^{\dagger} = |'1'\rangle\langle'1'| = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \text{ projects to the subspace spanned by}$$

the vector $\vec{v}_1$. $\qquad P_1$ is hermitian and $P_1^2 = P_1$.

$$\vec{v}_1 \otimes \vec{v}_2 = \begin{pmatrix} 1 \times \vec{v}_2 \\ 0 \times \vec{v}_2 \\ 0 \times \vec{v}_2 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = |'1'\rangle \otimes |'2'\rangle \qquad A \otimes B = \begin{pmatrix} a_{11}B & a_{12}B & a_{13}B \\ a_{21}B & a_{22}B & a_{23}B \\ a_{31}B & a_{32}B & a_{33}B \end{pmatrix}$$

Eigenvalue equation for a Hermitian matrix

H is an $n \times n$ Hermitian matrix (i.e. $H^\dagger = H$), the eigenvalue equation: $H\vec{v} = \lambda \vec{v}$ (or in bra-ket notation: $H|v\rangle = \lambda |v\rangle$).

There are n indepdent solutions $\vec{v_i}$ (eigenvectors) and λ_i (eigenvalues); we have that λ_i's are real and eigenvectors can be made orthonormal: $\vec{v_i}^\dagger \vec{v_j} = \delta_{ij}$ (or in bra-ket notation: $\langle v_i | v_j \rangle = \delta_{ij}$).

If some λ_i's are the same, they are degenerate.

For example, the following three Pauli matrices each have two eigenvalues and eigenvectors (what are they?).

$$\sigma_x = X \equiv \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = Y \equiv \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = Z \equiv \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Do poll

For more about Linear Algebra see any textbook on it or

1. Appendix in Qiskit book
https://qiskit.org/textbook/ch-appendix/linear_algebra.html

2. The Mathematics of Quantum Mechanics by Dr. Martin Laforest
(University of Waterloo)
<http://dl.icdst.org/pdfs/files3/8950b72535591b7bf7217e2bb5f650a1.pdf>

Office hour?

- Discussion board is set up in Blackboard.
  Peer discussions are encouraged.

- Maybe use a Doodle poll to find a one-hour slot
  (on a day other than Monday and Wednesday)