QUANTUM COMPUTING

what why how

About Me

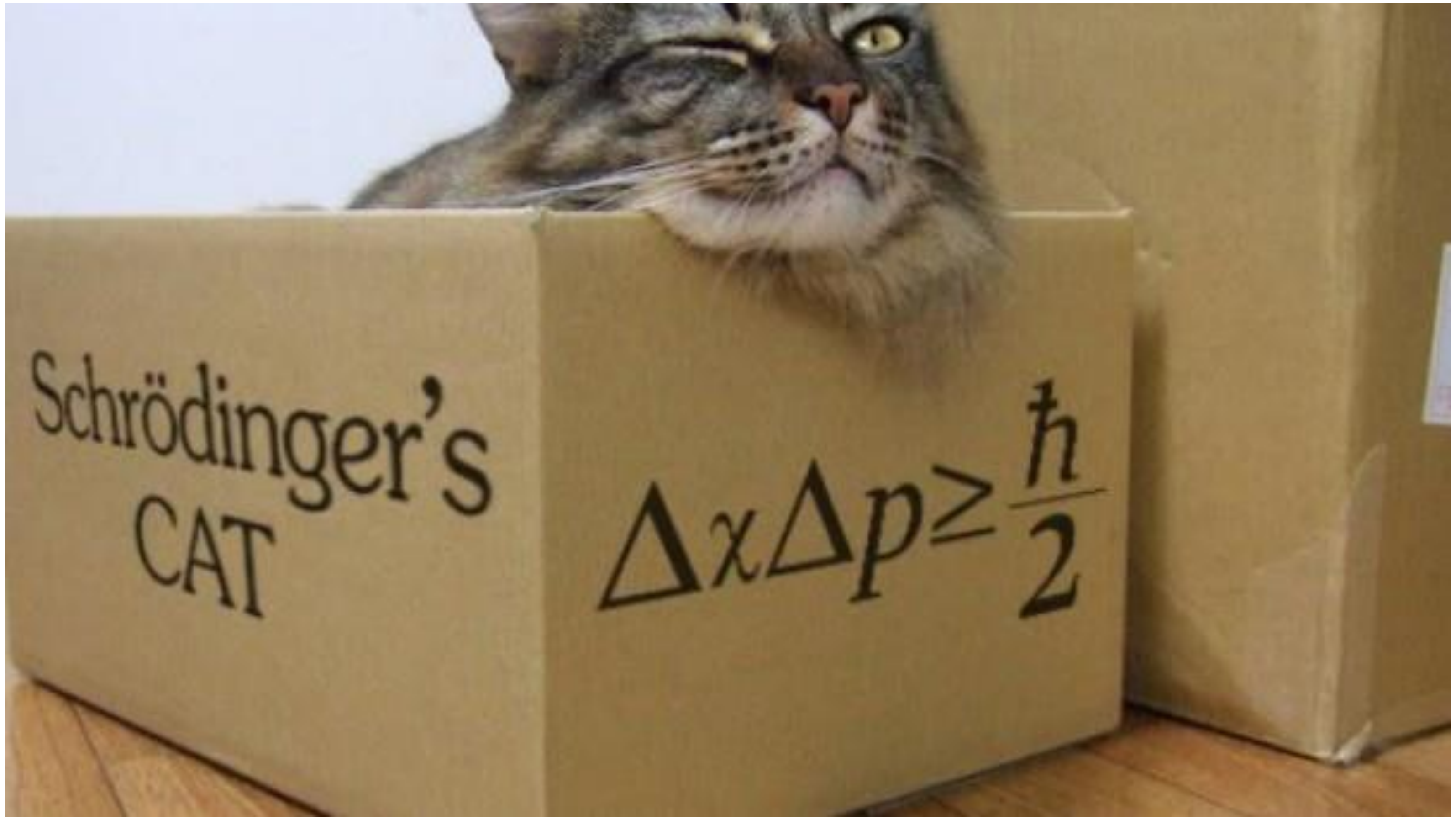
- Software Engineer
- Commercial Software Engineering @ Microsoft
- Quantum Enthusiast

@xtellurian

@rianfinnegan

Schrödinger’s Cat: Dead or Alive?

1. Schrödinger's cat: a cat, a flask of poison, and a radioactive source are placed in a sealed box.
2. If an internal monitor (e.g. Geiger counter) detects radioactivity (i.e. a single atom decaying), the flask is shattered, releasing the poison, and killing the cat.
3. The Copenhagen interpretation of quantum mechanics implies that after a while, the cat is *simultaneously* alive *and* dead. [Superposition]
4. Yet, when one looks in the box, one sees the cat *either* alive *or* dead not both alive *and* dead. [Measurement]
5. So when exactly does quantum superposition end, and when does reality collapse into one possibility or the other?

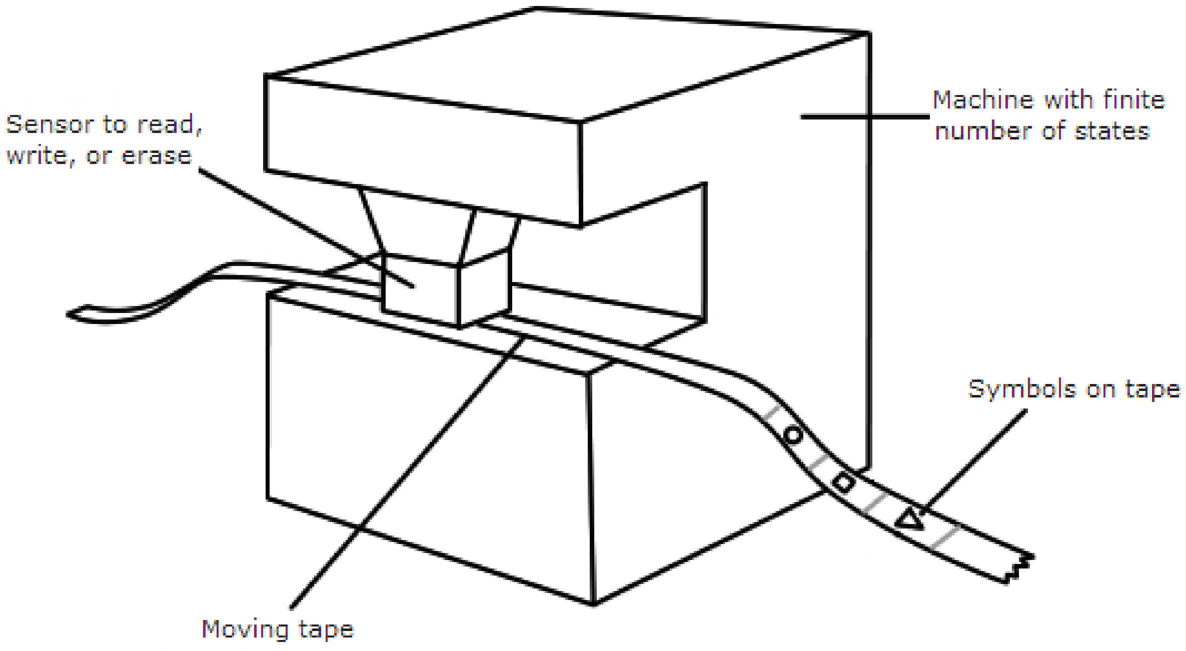

Schrödinger's
CAT
$\Delta x \Delta p \geq \frac{\hbar}{2}$

WHAT?

What is classical computing?

- Information is stored in **bits**, which take the discrete values 0 and 1.
  - *Bits are composed into larger numbers. 1001 => 9*
  - *Allowed values are discrete, rational numbers.*
- Calculations are done essentially the same way as “by hand”
  - *Everything is addition*
- Physically implemented by **transistors** and **logic gates**
  - *There are billions of transistors in your phone.*
  - *von Neumann architecture implements the Turing machine*

TURING MACHINE



A Turing Machine

Computational Complexity (Classical)

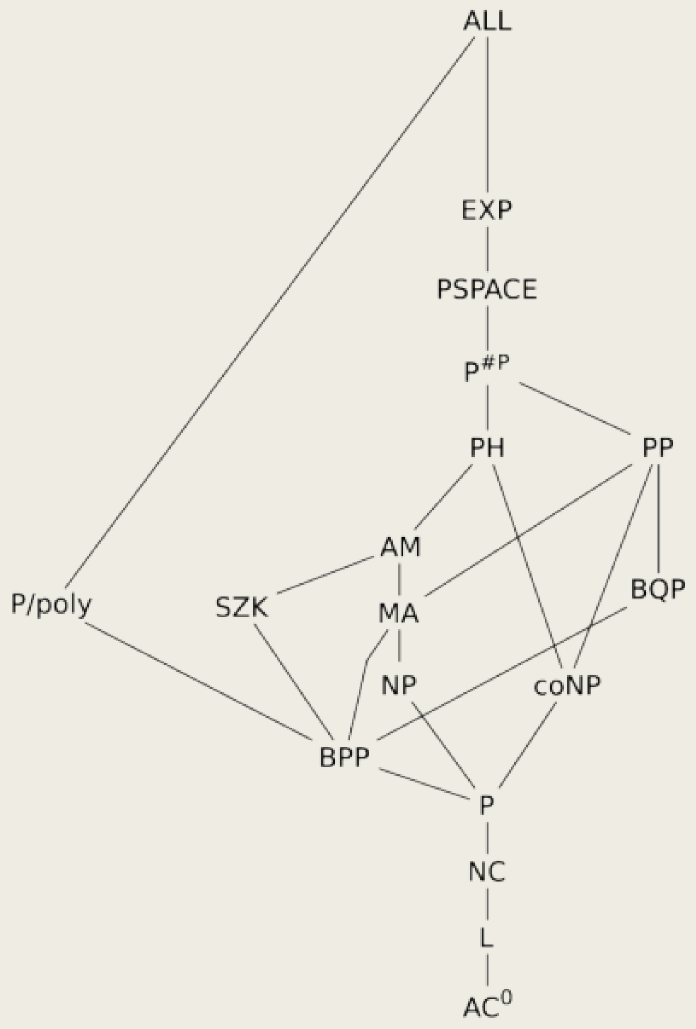
what can my computer do, and when will it be finished?

- Given some well defined problem, how hard is it to solve?
  - *Expressed as a function $n \rightarrow f(n)$, where n is the size of the input.*
  - *How much space (i.e. memory) is required?*
  - *How much time is required?*
- Classical computers (i.e. Turing machines) can solve problems in the complexity class BPP (**b**ounded-error **p**robabilistic **p**olynomial time)

Complexity Classes

Complexity classes are related to each other, and some classes are entirely contained within others.

- **P**: The class of problems which we can solve efficiently using a conventional algorithm -> class of all problems solvable by a deterministic Turing machine bounded in time by a polynomial function of the input length.
- **NP**: the set of problems such that someone can convince you of a yes answer in a reasonable amount of time.
- **BPP**: The class of problems that are solvable efficiently by randomized algorithms.
- **BQP**: The class of all problems that admit an efficient solution by quantum computers.



What is Quantum Computing?

The really short version

- A quantum computer exploits fundamental laws of the cosmos to do computational tasks
  - *Simulating quantum mechanics is hard*, so let's use quantum mechanics to perform hard* computation.*
- Physical implementations
  - *Superconducting electron qubits or topological qubits*
  - *Quantum gates and circuits*
- Information is stored as quantum bits, a.k.a. qubits

Quantum States

- Vector of norm 1 in n-dimensional Hilbert space
  - *Hilbert space: generalizes the notion of Euclidean space.*
  - *Complex numbers*
  - *Vector amplitudes encode probability of measurement outcomes*
- Quantum operators interact with quantum states
  - *E.g. a measurement, transformation, or time evolution*
  - *Represented as matrices in Hilbert space*
- Dirac notation
  - *a,b are complex amplitudes*
  - *and u,d are complex vectors*

$$|\psi\rangle = a|u\rangle + b|d\rangle.$$

Qubits

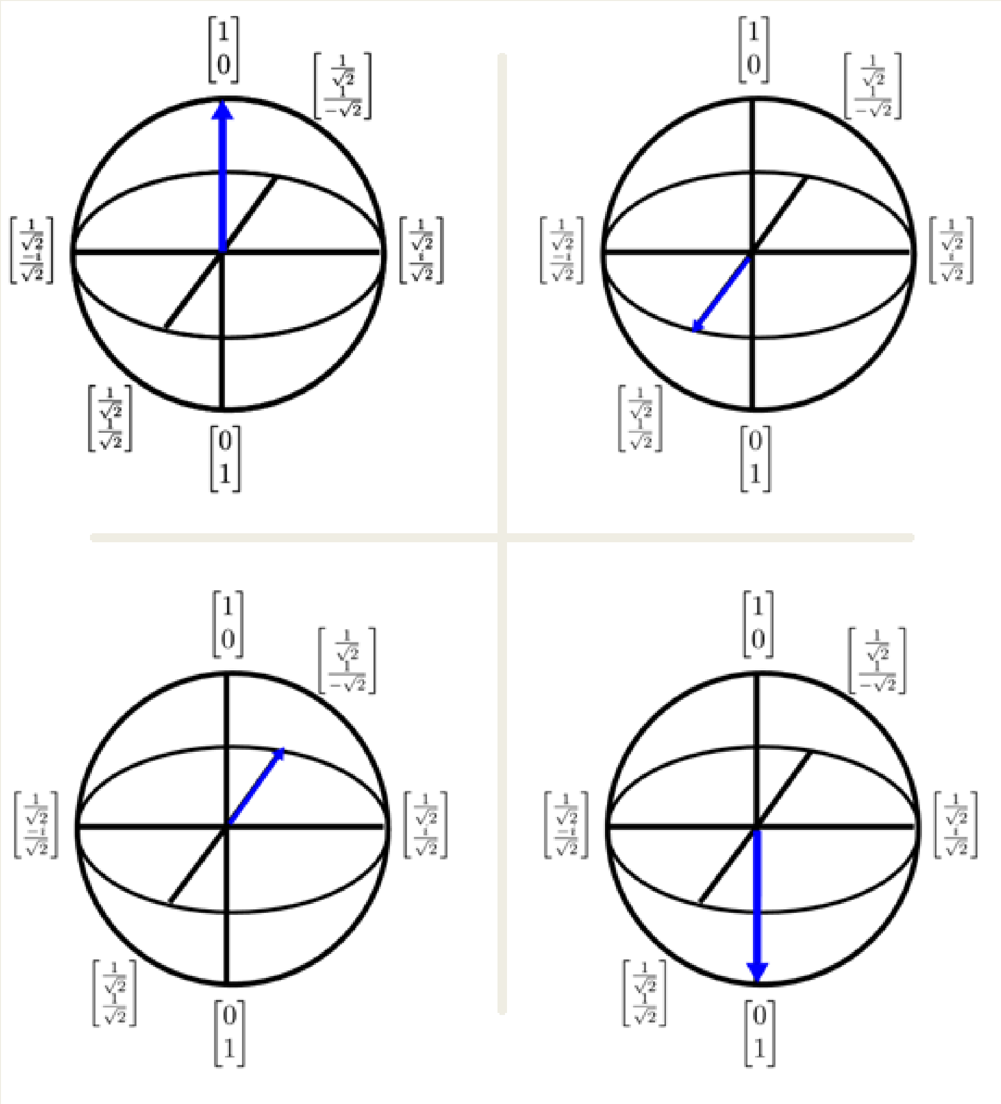
- Qubits are the simplest quantum state

- The standard basis is called the computational basis

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \qquad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}.$$

- Note that the numbers inside the *kets* $|\cdot\rangle$ are just labels. Any state of this system is thus represented as a superposition of these two basis states:

$$|\Psi\rangle = a\,|0\rangle + b\,|1\rangle$$



Bloch Sphere

Qubit Intuition

- Definitely a **One**

  $|\,x\rangle = 0|0\rangle - 1|1\rangle$

- Definitely a **Zero**

  $|\,y\rangle = 1|0\rangle + 0|1\rangle$

- A half-dead cat

  $|\,snuggles\,\rangle = 1\sqrt{2}|dead\rangle - 1\sqrt{2}|alive\rangle$

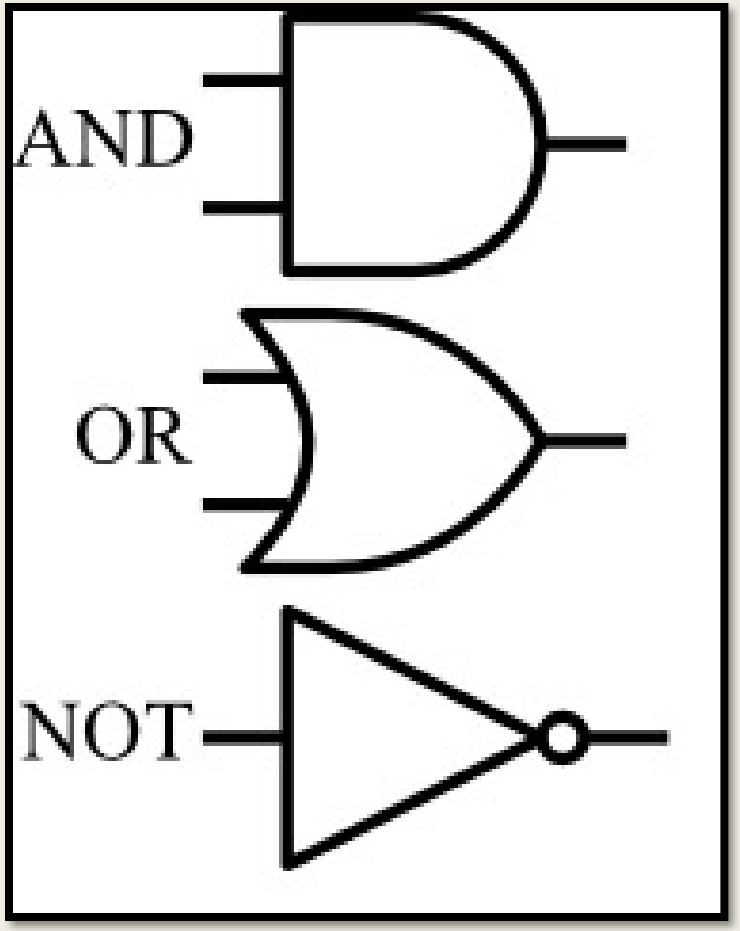
Logic Circuits

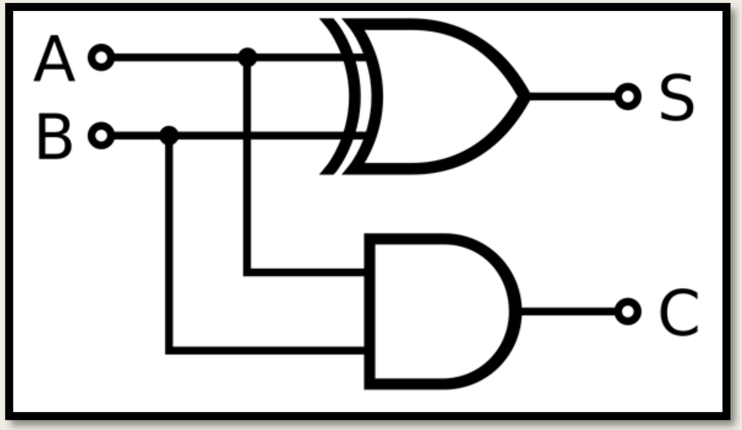
the classical version

- Logic gates take bits as input, and produce a bit as output

- Implemented in silicon via transistors
  - *All gates can be implanted by a universal logic gate i.e. the NAND and NOR gates.*

- Gates are composed to form logical circuits (e.g. the half-adder)





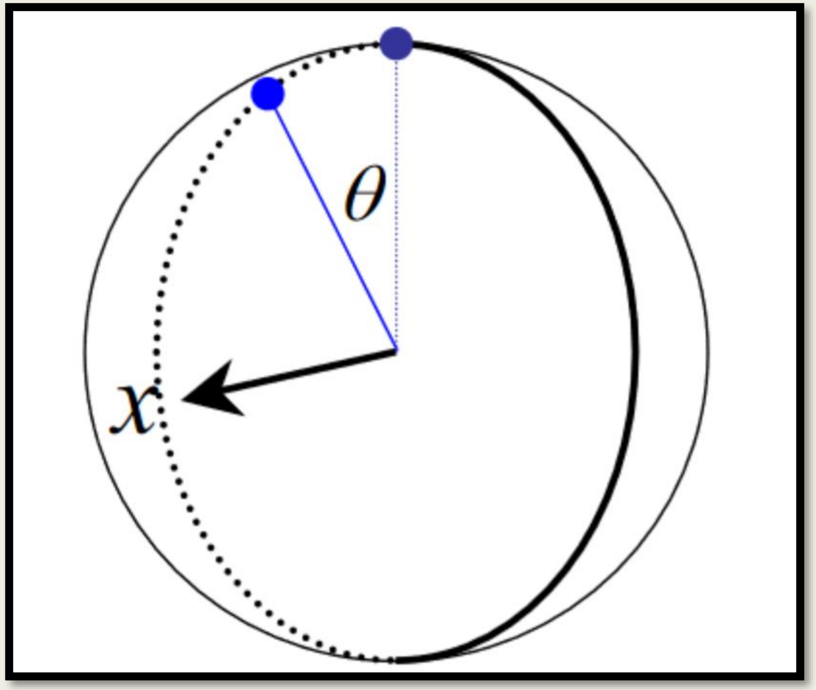
Gate	Notation	Matrix
NOT (Pauli-X)	$-\boxed{X}-$	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Z	$-\boxed{Z}-$	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard	$-\boxed{H}-$	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
CNOT (Controlled NOT)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$

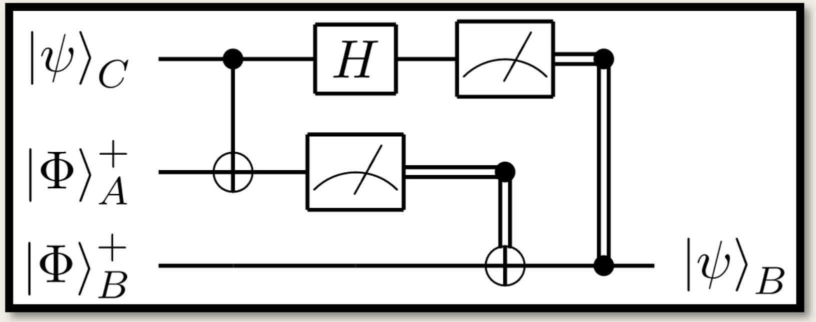
QUANTUM GATES

Logic Circuits

the quantum version

- Example: The X-Gate
  - $X = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$
  - *Names: Pauli X, X, NOT, bit flip, σ_x*
  - *Perform equivalent of NOT gate in traditional computing*
- All quantum gates are *rotations* around an axis on the Bloch sphere.
- Quantum gates are composed into quantum circuits

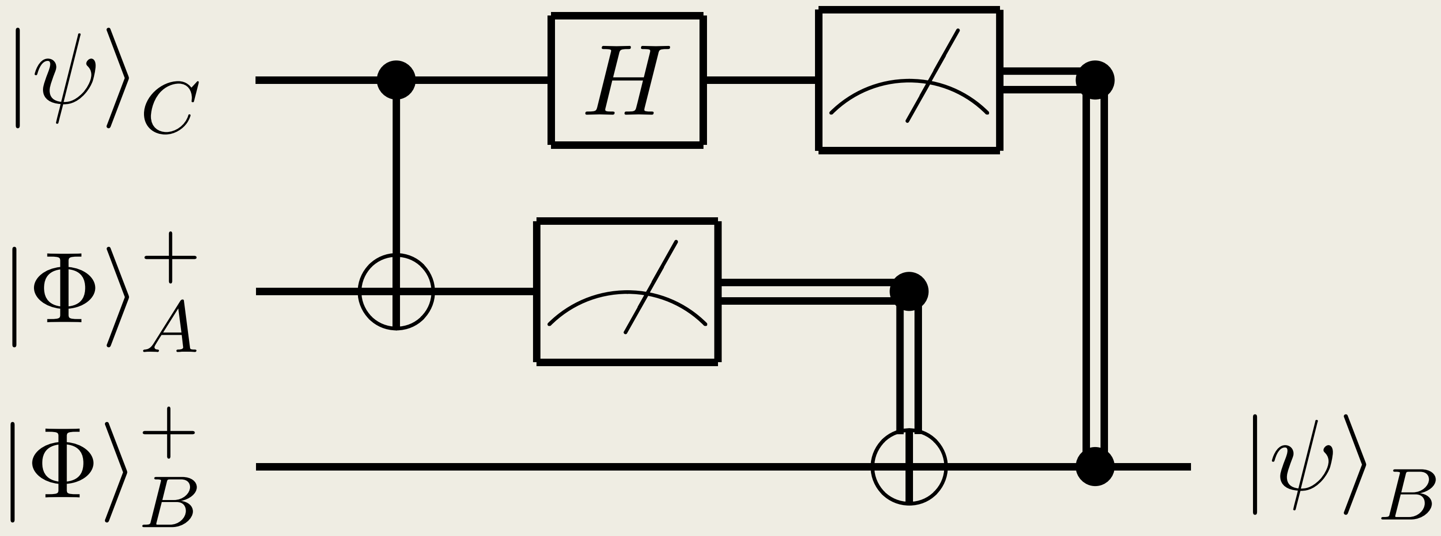




Entanglement

- Two qubits with correlated measurement outcomes

- We can create entangled qubits!
- Used for **control** and **execution** of quantum **operations**



What is Quantum Computing?

Again

- Implements quantum circuits
  - *From universal quantum gates we can approximate any quantum gate.*
- Model any quantum system
  - *with less effort than the equivalent simulation on a classical computer.*
- Quantum circuits implement quantum algorithms
  - *Some class of problems (BQP) are much easier to solve.*
- Solves hard* problems

What Quantum Computing is NOT

- NOT a really fast computer
- NOT a massively parallel computer
- NOT, for most problems, better than classical computers
- NOT cheap
- NOT magic

WHY?

Challenges and Opportunities

NITROGEN FIXATION

CARBON SEQUESTRATION

ANTIBIOTIC RESISTANCE

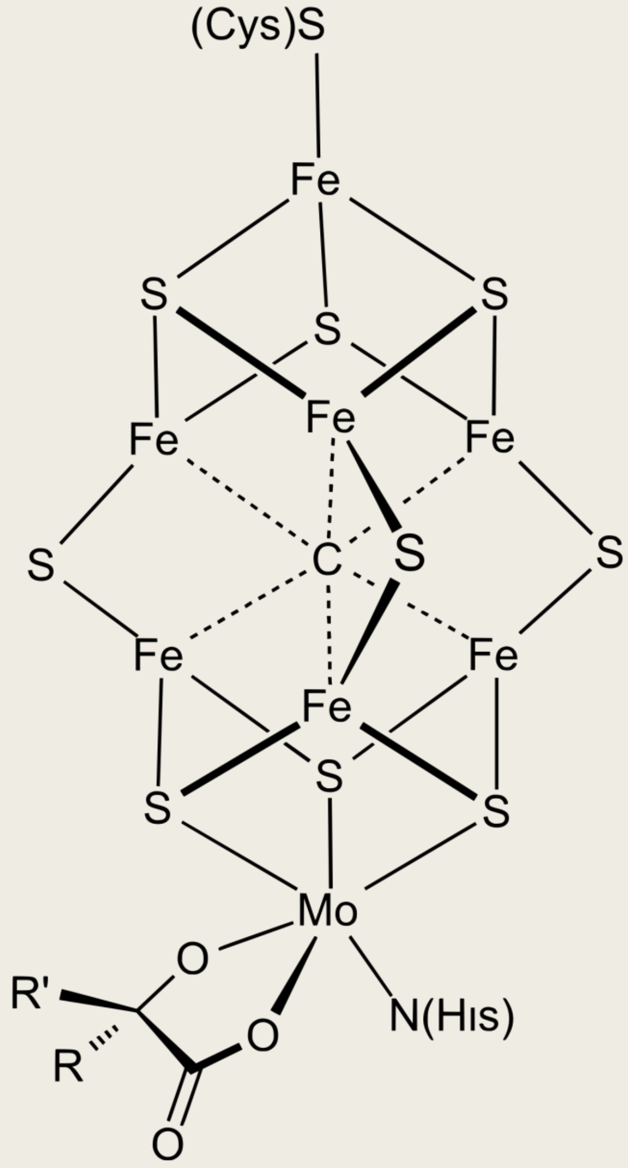
CRYPTOGRAPHY

ARTIFICIAL INTELLIGENCE

Nitrogen Fixation

or how to feed the world

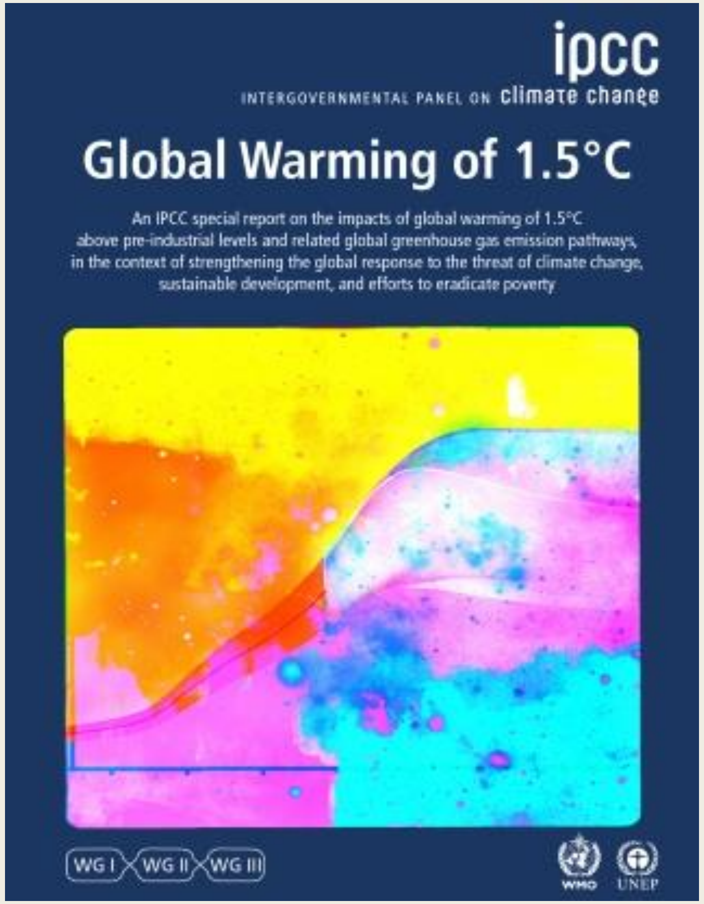
- Crops consume nitrogen as fertiliser
- The Haber-Bosch process
  - *Converts atmospheric nitrogen (N2) to ammonia (NH3)*
  - *Uses 1-2% of global annual energy supply*
- FeMoco
  - *Catalyses the conversion of atmospheric N2 into ammonia (NH3) a.k.a. nitrogen fixation.*
  - *200 qubits can simulate FeMoco*



Carbon sequestration

combat climate change

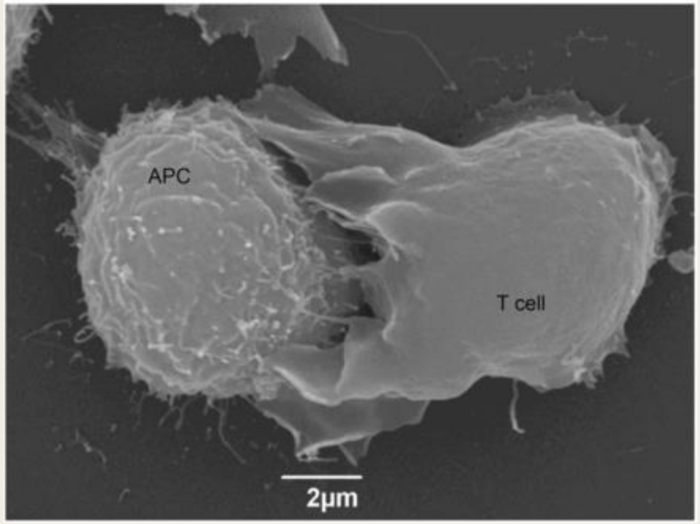
- Current State of the Art in carbon sequestration is ineffective and inefficient
- Can we find a low energy catalyst for carbon sequestration?
  - *Capture atmospheric or oceanic carbon*



Antibiotic Resistance

molecular modelling

- Antigens are important molecules for fighting disease
  - *Usually proteins, peptides (amino acid chains) and polysaccharides*
  - *Vaccines are examples of antigens*
  - *Antigens bind to foreign/ infected cells*
  - *T cells selectively recognize the antigens, based on HLA proteins*
- Can we model antigen/ pathogen interaction?
  - *Potentially thousands of atoms*
  - *We can do it (with enough qubits)*



Quantum Cryptography

Perfectly Private Communication

- Quantum Key Exchange
  - *enables two parties to produce a shared random secret key known only to them.*
- Alice and Bob can detect the presence of any third party attempting to intercept comms
- Exploits quantum *entanglement*
  - *“spooky action at a distance” – Einstein*
  - *Two quantum states that, when measured, will have correlated outcomes* ***regardless of distance.***

Artificial Intelligence

optimising machine learning

Quantum software to enable machine learning that is faster than that of classical computers.

- Grover’s Search
- Linear algebra simulation with quantum amplitudes
- Enhanced reinforcement learning
- Fast sampling from generic probabilistic models

Quantum Supremacy

- Quantum supremacy means:
  - *Solving a really hard* problem on a **quantum** computer*
  - *Not solving that same problem on a **classical** computer*
  - *Some confidence that the problem is **classically not solvable.***

HOW?

Quantum Hardware

- Superconducting Qubits (Rigetti, Google, IBM)
- Topological Qubits (Microsoft)
- Advantages of a topological qubit
  - *Longer decoherence time*
  - *Robust to noise = scale with fewer resources*
  - *Information is stored non-locally, meaning fewer errors*
  - *Less overhead on long (i.e. useful) computations*
- Quantum Compute Stack
  - *Quantum Processor*
  - *Cryogenic Control Machine*
  - *Application Computer*

Quantum Software

Cirq - Python library for writing, manipulating, and optimizing quantum circuits

Qiskit - for developing quantum computing applications and working with NISQ (Noisy-Intermediate Scale Quantum) computers such as IBM Q.

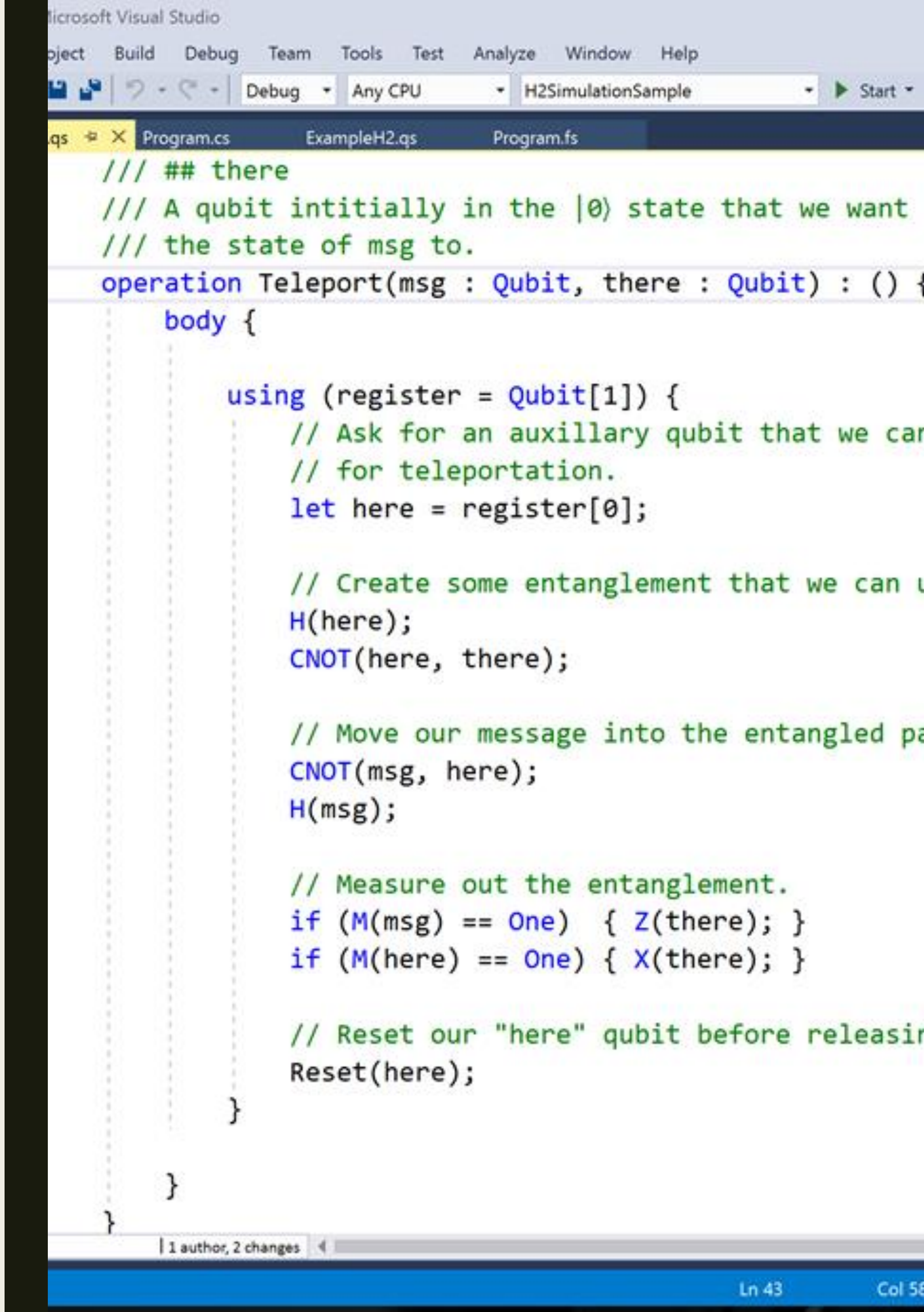
pyQuil - library for easily generating Quil programs to be executed using the Rigetti Forest platform.

QDK – Quantum Development Kit including Q# language, simulators and libraries

Q#

Quantum-focused Programming Language

- Built ground-up for Quantum
- Native type system
- Windows, MacOS and Linux
- Fully integrated into Visual Studio and VS Code
- Python interoperability



Quantum Simulator

Run locally or in the cloud

Local simulator

Simulate a 30 qubit computer

Visual Studio and VS Code integration

Full debugging support

Azure simulator

Available for up to 40 qubits – with 16TB of memory!

QDK

Libraries and Samples

New Features

New chemical simulation library

Q# language improvements

Improved developer experience

Samples

Database search and integer factorisation

H2 molecular simulation

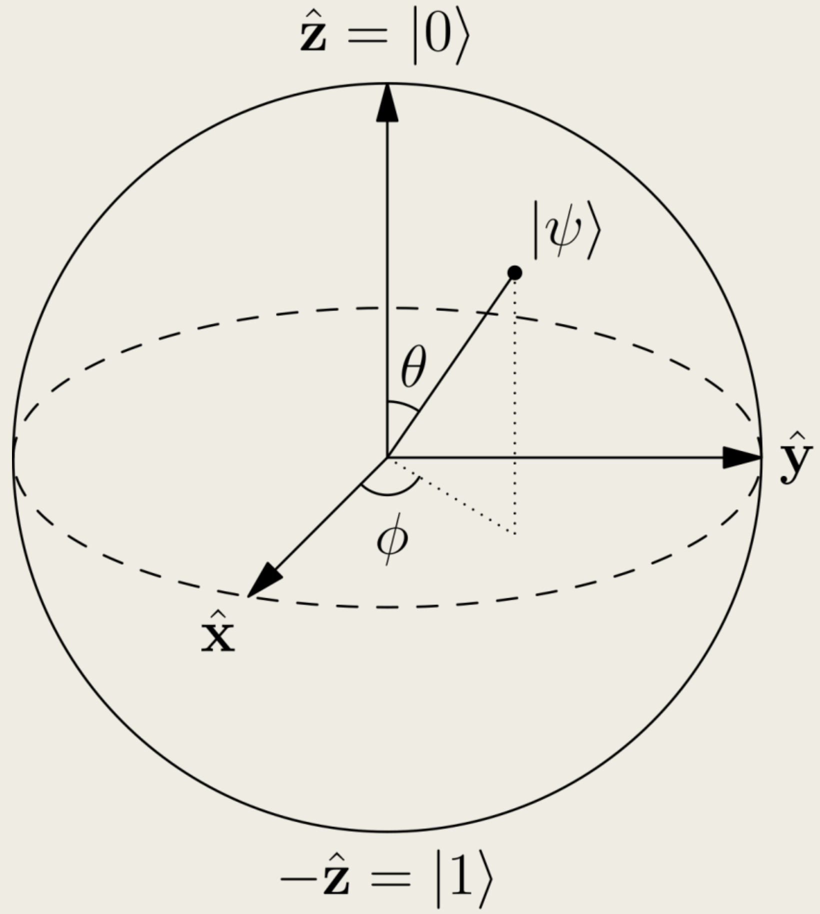
Ferromagnetic simulation

Interop with Qiskit and OpenQasm

Quantum as a Service

- Quantum computing will be provided as an auxiliary service, similar to:
  - *FPGA's (Project Brainwave)*
  - *Graphics Cards*
  - *Cognitive Services*

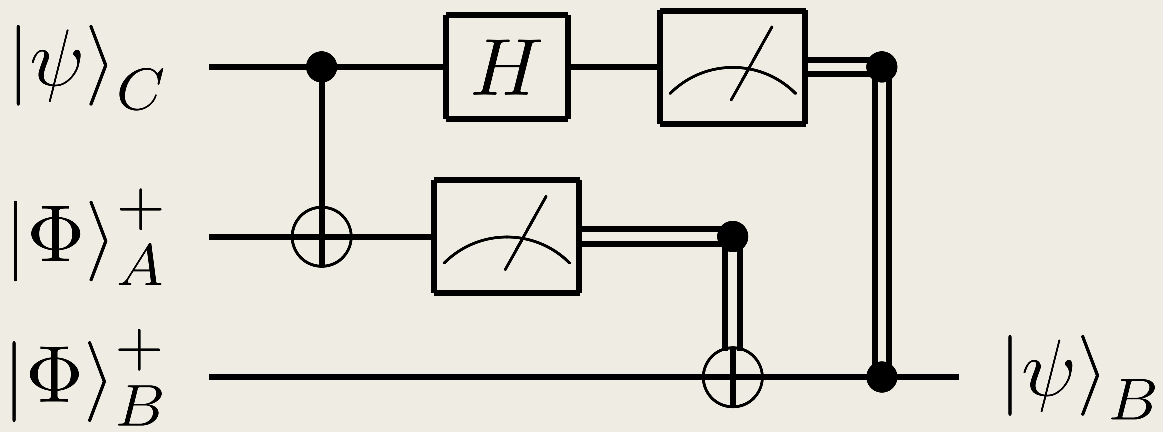
- It's a 'back-end' service
  - *You won't have a quantum computer in your pocket!*



DEMO

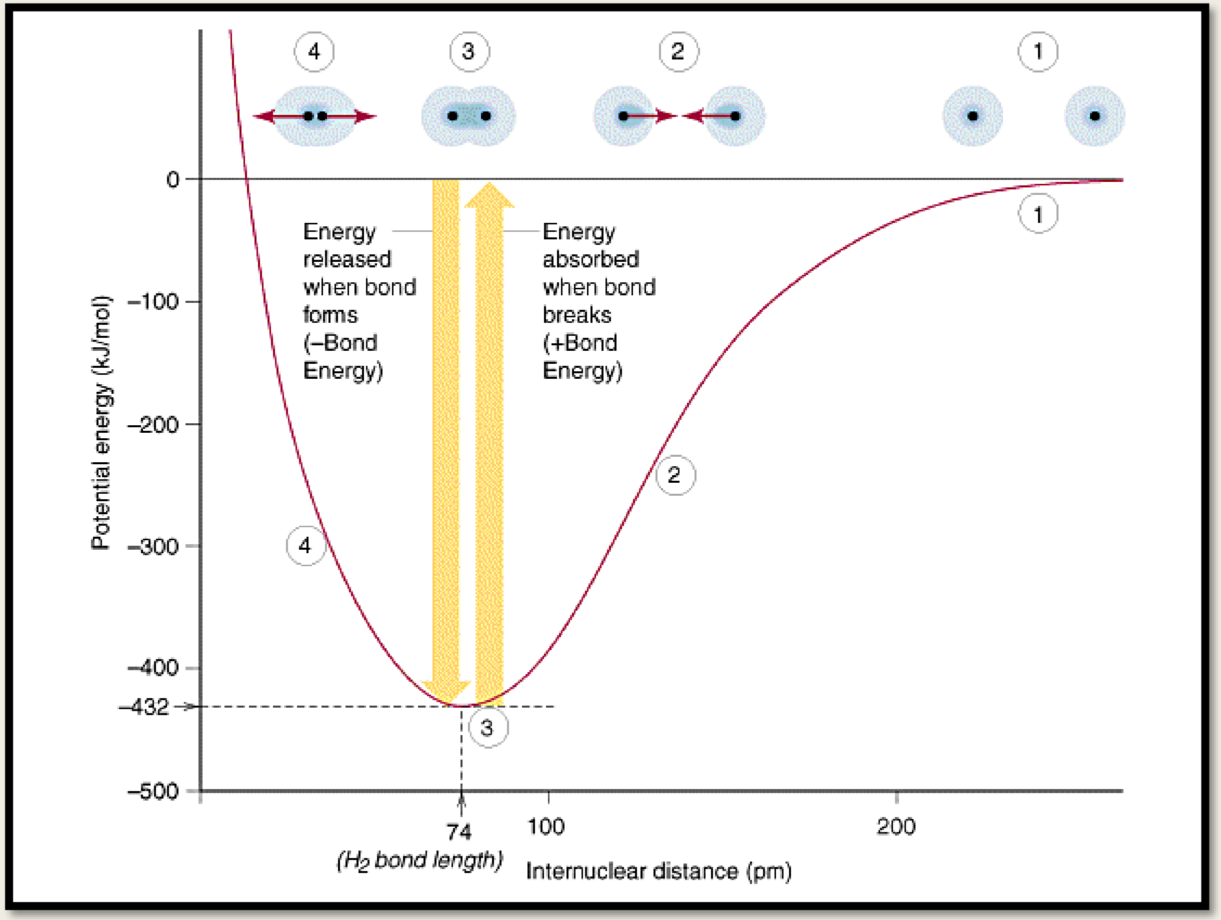
MEASUREMENT

Hadamard transformation: 180 degree rotation around the diagonal X+Z axis of the Bloch sphere.



DEMO

TELEPORTATION



DEMO

H2 BOND ENERGY


Rian.Finnegan@Microsoft.com
@RianFinnegan
aka.ms/LearnQuantum