Quantum technology in our lives

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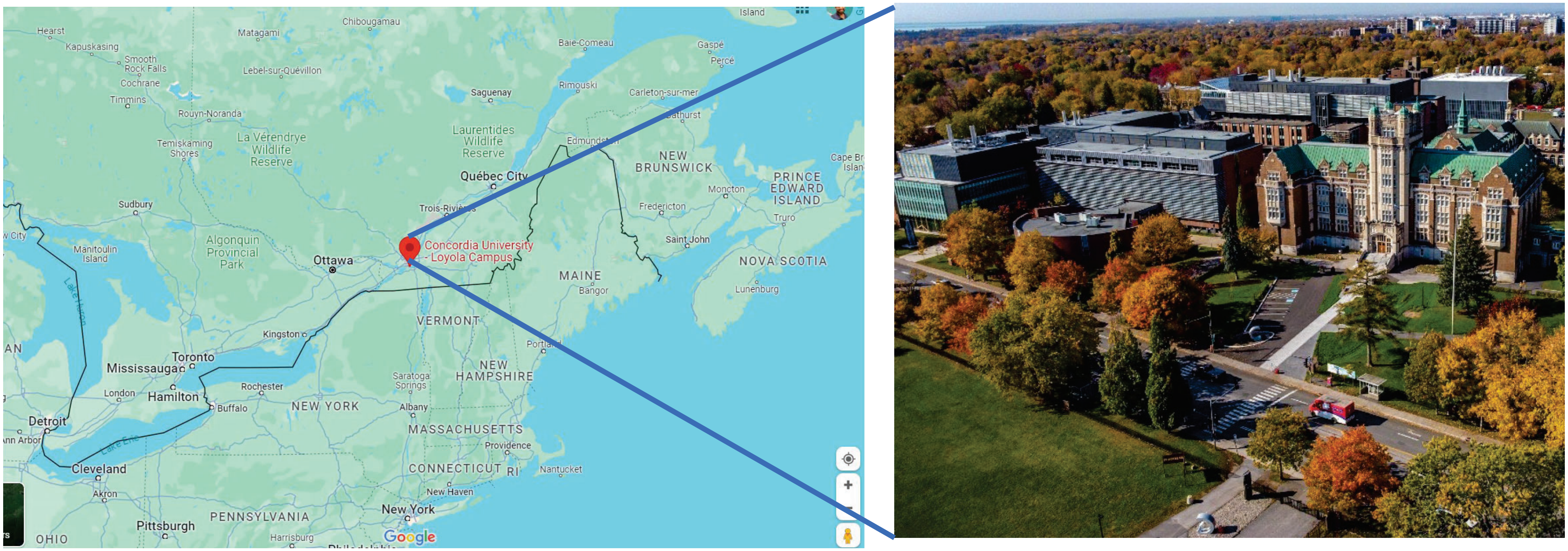
Northwest Missouri State, April 2024 [World Quantum Day]



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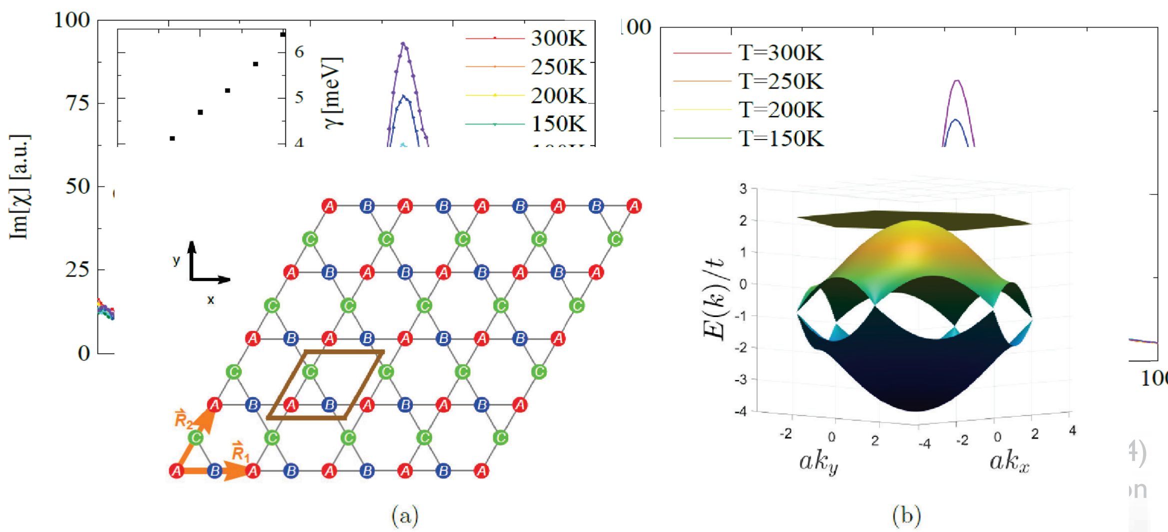
What we do?

- Collective phenomena in 2D Quantum materials for applications in technology
- Build minimal models to model experimental observations
- Suggest new material design that can host new and unconventional behavior
- Map quantum problems to real world

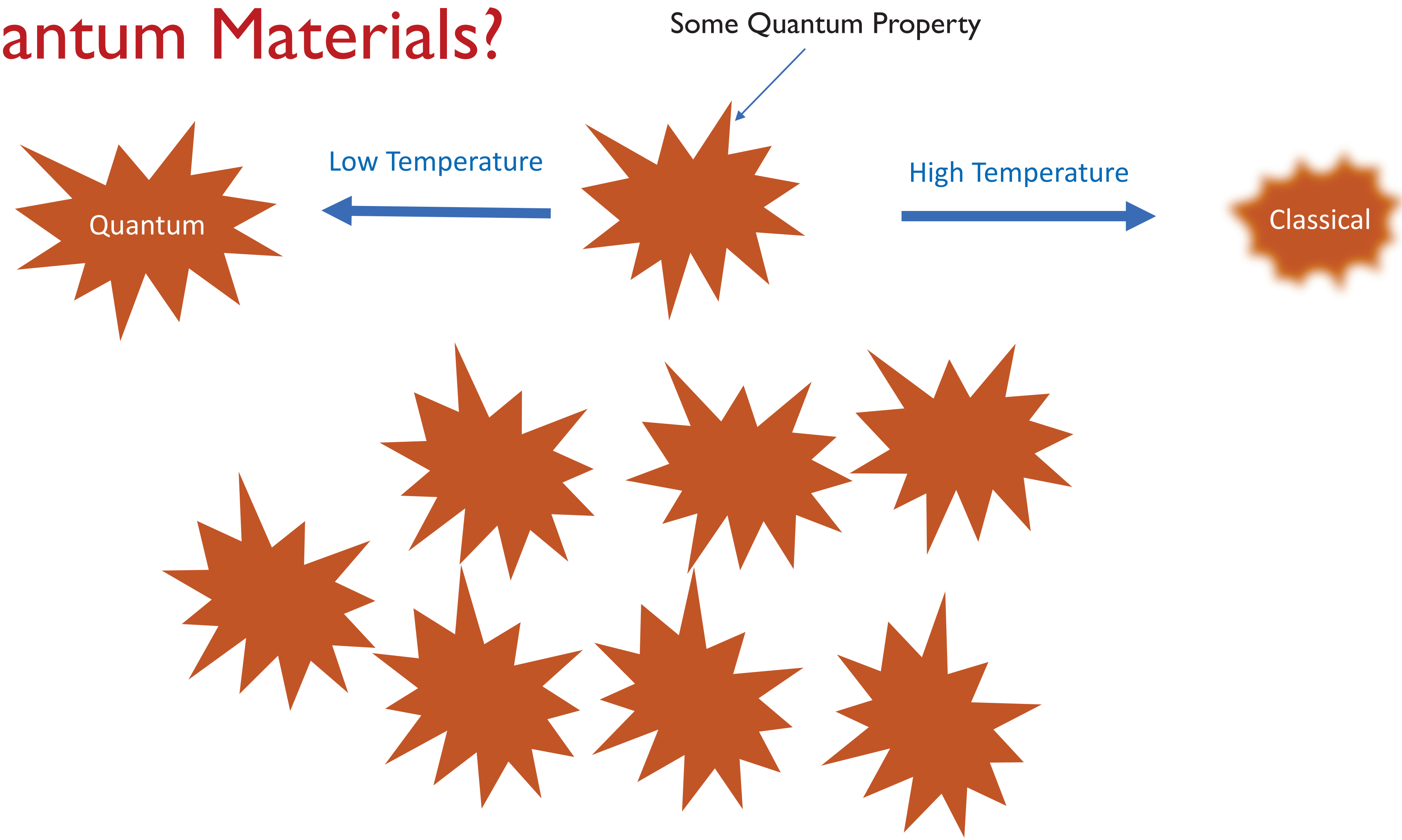


Outline

- Quantum phenomena and materials
- Quantum Technology today
- Quantum Technology for tomorrow:
- My research

- Computing
    - Classical vs Quantum

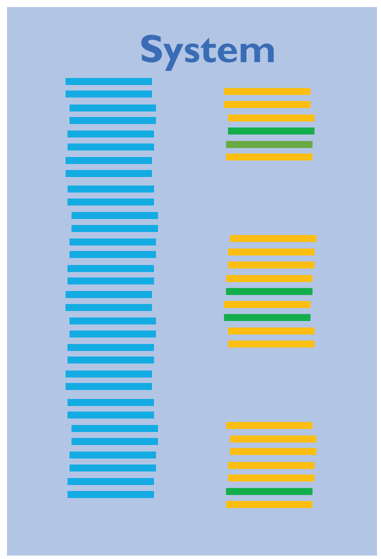
Quantum Materials?



Probing Quantum Materials

High T Low T

Energy



Classical energy levels

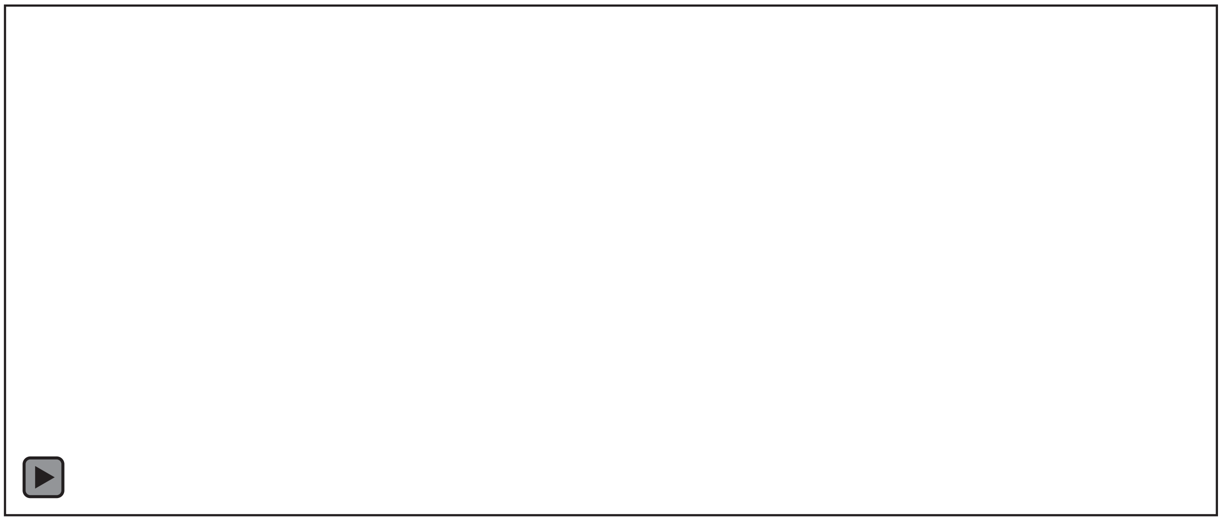
- Discrete levels
  Gaps
- Selection rules

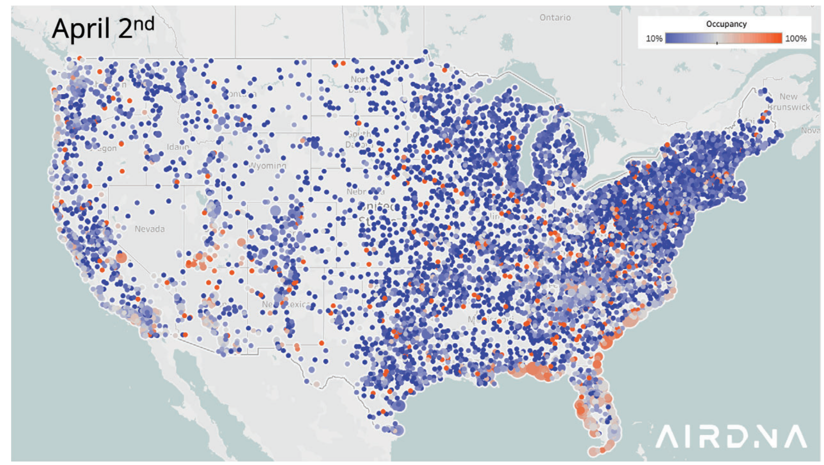
Probe

What to probe
How to probe
When to probe
Interpreting signals

Quantum energy levels

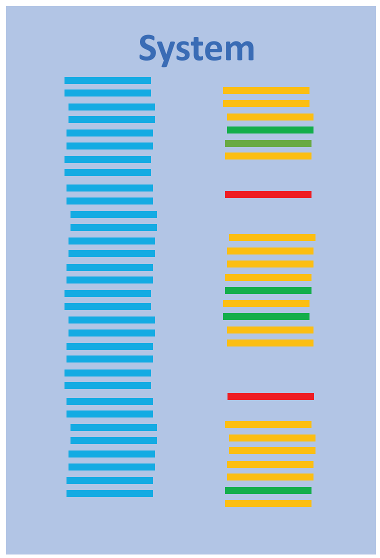
Collective phenomena?





Probing Quantum Materials

High T   Low T



Classical energy levels

Collective mode levels

Quantum energy levels

- Discrete levels
  Gaps
- Selection rules

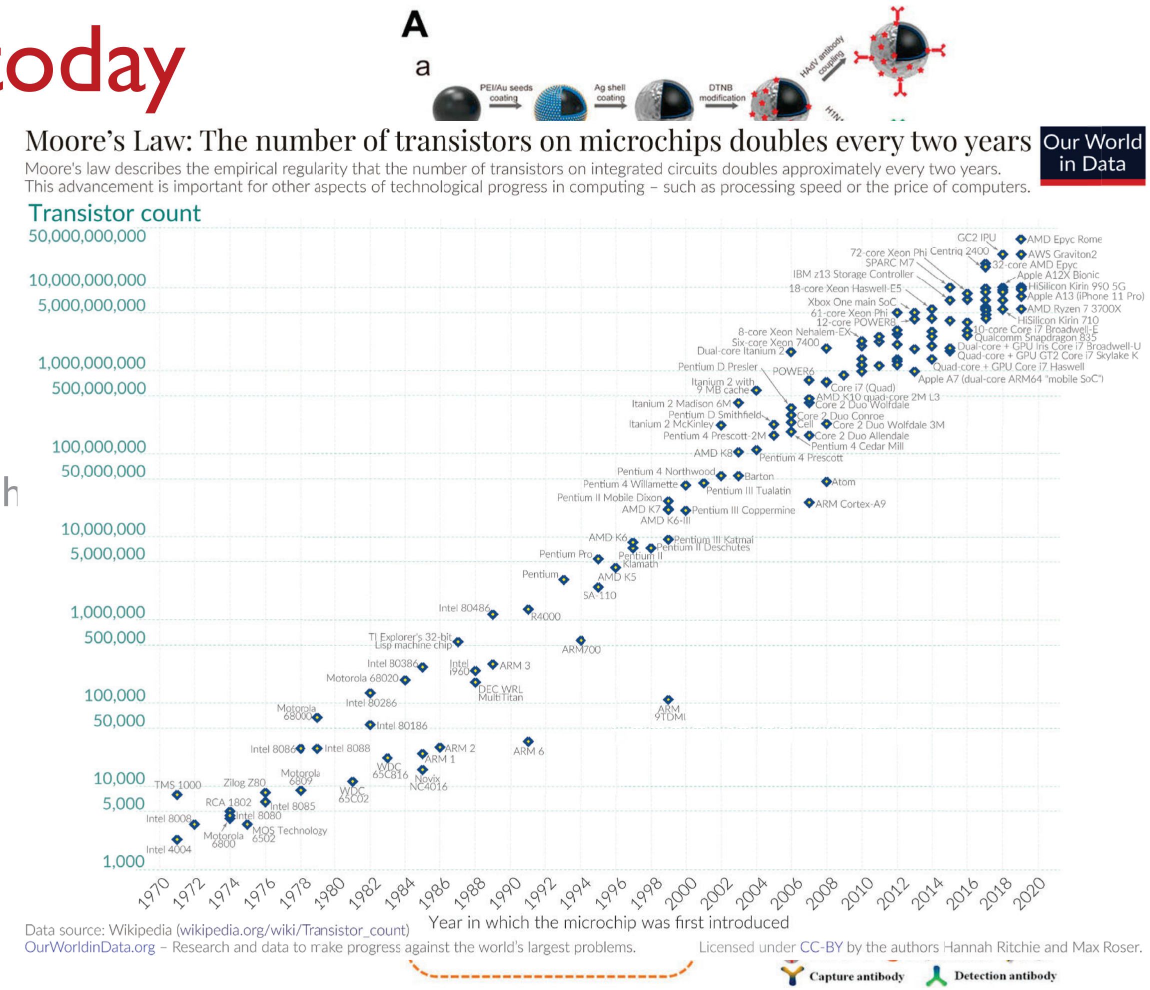
Energy

Probe

What to probe
How to probe
When to probe
Interpreting signals

Quantum technology today

- Materials purity
- Atomic Clock GPS/Data Centers
- GMR (Memory/Spintronics)
- Quantum Dots (flexible electronics)
- MRI/Superconductors
- Sensors (precession measurements, establish of standards)
- Transistors (Moore's Law)
    -
    -
    -



Quantum technology tomorrow

- Communications and Networks (Data transfer and security)
- Computing (Solving problems with exponential complexity)
- Sensors (Nano thermometers, NV-center in diamonds)
- Devices
- Materials

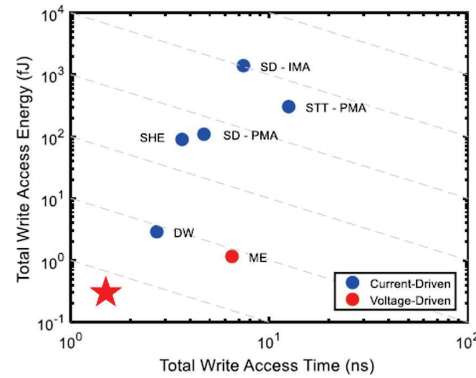
Our Research

Our Research

- Superconductors

Our Research

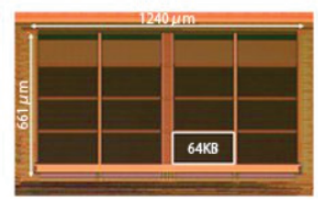
- Superconductors
- Spintronics
- Engineered 2D systems
- Look for new phenomena for applications such as
  - Spin-charge manipulation
  - Qubit design
  - New fundamentals



Communications Materials, 1, 24 (2020)

Toshiba shows a new STT-MRAM test chip that consumes about 80% less power than SRAM memory (2013)

Toshiba presented a new STT-MRAM 1-Mb test chip that provides speed performance capable of 3.3-ns access to in-cache memory. The newly developed circuit consumes about 80% less power compared to a conventional SRAM as embedded memory - and Toshiba says that this makes it the best power-performing embedded memory.



<STT-MRAM test chipt>

Some Highlights

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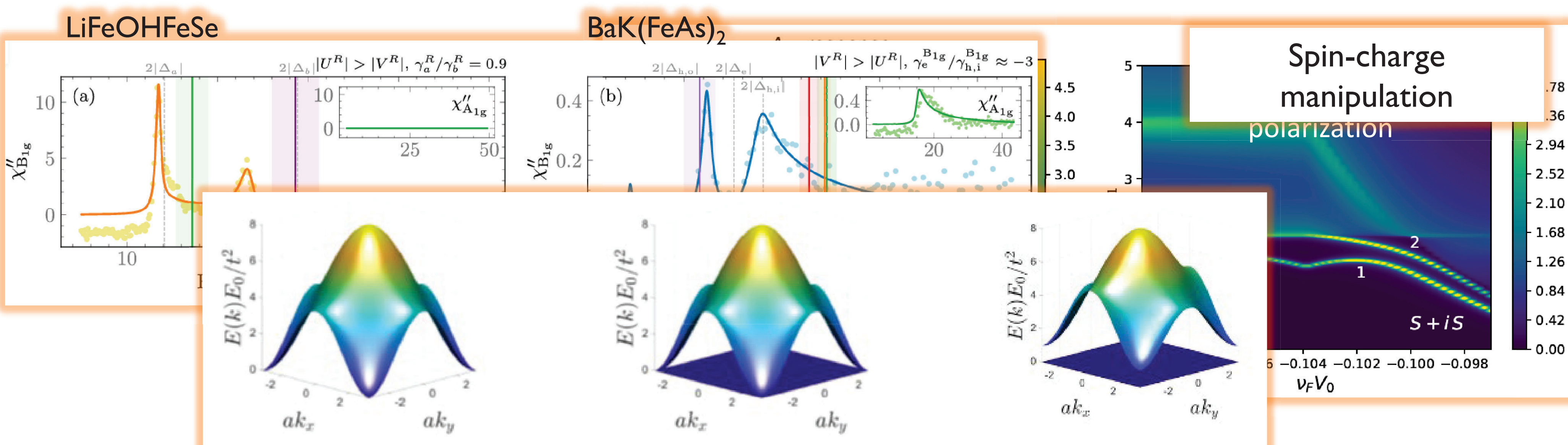
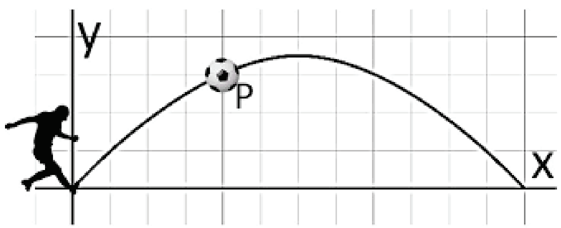


~~Quantum~~ Computing

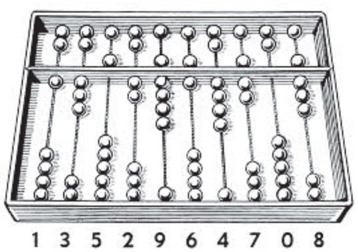
Following a prescription
to find/calculate something new

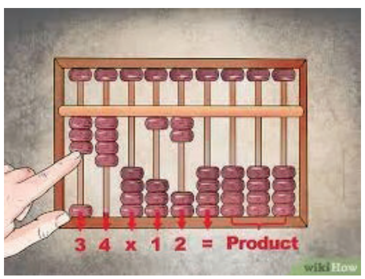


~~Quantum~~ Computing

Following a prescription
to find/calculate something new

Following a prescription, with the aid of a device,
to find/calculate something new





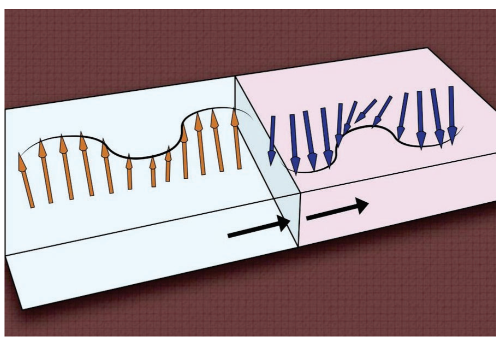
- Map your parameters to the states of the device
- Find ways to manipulate the states of the device
- Design algorithms create a sequence of manipulations to perform the computations we need.

Analog ~~Quantum~~ Computing

Following a prescription
to find/calculate something new

Following a prescription, with the aid of a device,
to find/calculate something new

Magnetic waves for
addition (MIT, 2019)



Issue: New problem needs a new device design

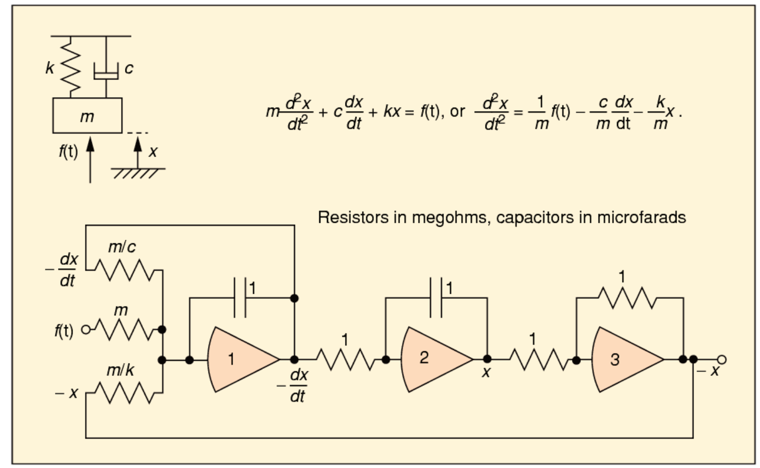
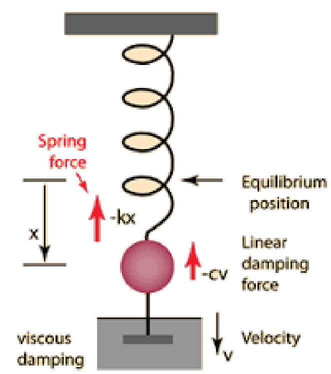


Figure 2. *Analog circuit for simulating a mass-spring-damper system. Amplifier 1 sums*



Digital
~~Quantum~~ Computing

- Map your parameters to the states of the device
- Find ways to manipulate the states of the device
- Design algorithms create a sequence of manipulations to perform the computations we need.

1 0

$\begin{pmatrix} 0 \\ 1 \end{pmatrix}$ $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$

Possibilities

State space vector: $\begin{pmatrix} w_0 \\ w_1 \end{pmatrix}$ $\begin{array}{l} \text{Wt of state 0} \\ \text{Wt of state 1} \end{array}$

Action on State

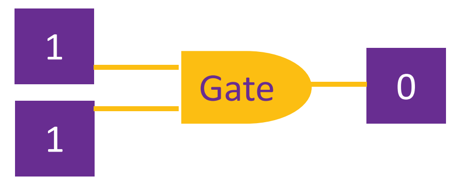
$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Change of State

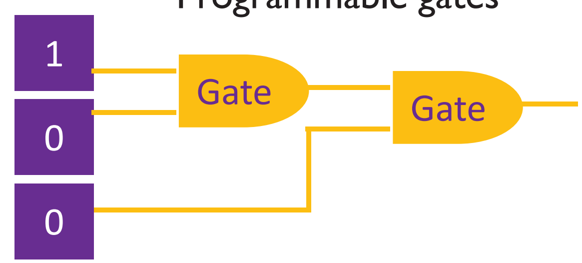
0/1 0/1 $\begin{pmatrix} w_{00} \\ w_{10} \\ w_{01} \\ w_{11} \end{pmatrix}$

$\begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$ $\begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}$ $\begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}$ $\begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$

Possibilities



Programmable gates

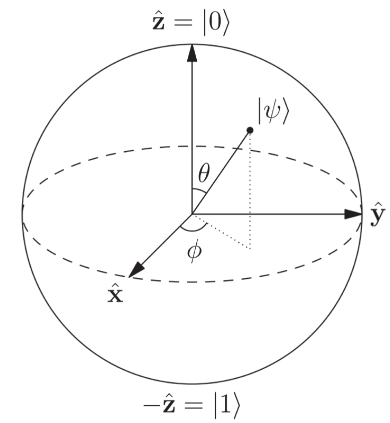


Quantum Computing

Qubit 1 0

$\begin{pmatrix} 0 \\ 1 \end{pmatrix}$ $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$

State space vector: $\begin{array}{l} \text{Wt of state 0} \\ \begin{pmatrix} w_0 \\ w_1 \end{pmatrix} \\ \text{Wt of state 1} \end{array}$



Qubit States on a Bloch sphere

Qubits are quantum systems. Hence they evolve:

$$\begin{pmatrix} U_{11} & U_{12} \\ U_{21} & U_{22} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} \alpha \\ \beta \end{pmatrix} \rightarrow \alpha \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \beta \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Quantum Action on State

Arbitrary superposition of two states

Multiple Measurements

$|\alpha|^2$ % in 0 $|\beta|^2$ % in 1

$\alpha = \cos\theta$ z-component

$\beta = e^{i\Phi}\sin\theta = \cos\phi\sin\theta + i\,\sin\phi\sin\theta$

x+iy components

X Gate
Bit–flip, Not

$$\boxed{X} \equiv \begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}\begin{bmatrix}\alpha\\ \beta\end{bmatrix} = \beta|0\rangle + \alpha|1\rangle$$

Z Gate
Phase–flip

$$\boxed{Z} \equiv \begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}\begin{bmatrix}\alpha\\ \beta\end{bmatrix} = \alpha|0\rangle - \beta|1\rangle$$

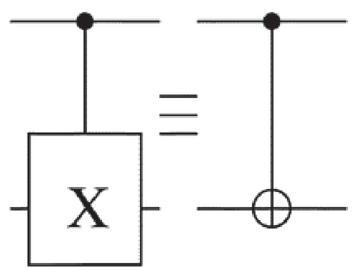
H Gate
Hadamard

$$\boxed{H} \equiv \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}\begin{bmatrix}\alpha\\ \beta\end{bmatrix} = \frac{\alpha+\beta|0\rangle + \alpha-\beta|1\rangle}{\sqrt{2}}$$

T Gate

$$\boxed{T} \equiv \begin{bmatrix}1 & 0\\ 0 & e^{i\pi/4}\end{bmatrix}\begin{bmatrix}\alpha\\ \beta\end{bmatrix} = \alpha|0\rangle + e^{i\pi/4}\beta|1\rangle$$

Controlled Not
Controlled X
CNot



$$\equiv \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}a\\ b\\ c\\ d\end{bmatrix} = a|00\rangle + b|01\rangle + d|10\rangle + c|11\rangle$$

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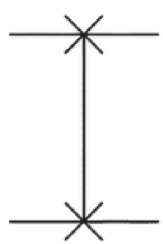
Swap



$$\equiv \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}a\\ b\\ c\\ d\end{bmatrix} = a|00\rangle + c|01\rangle + b|10\rangle + d|11\rangle$$

Following a prescription, with the aid of a device, to find/calculate something new

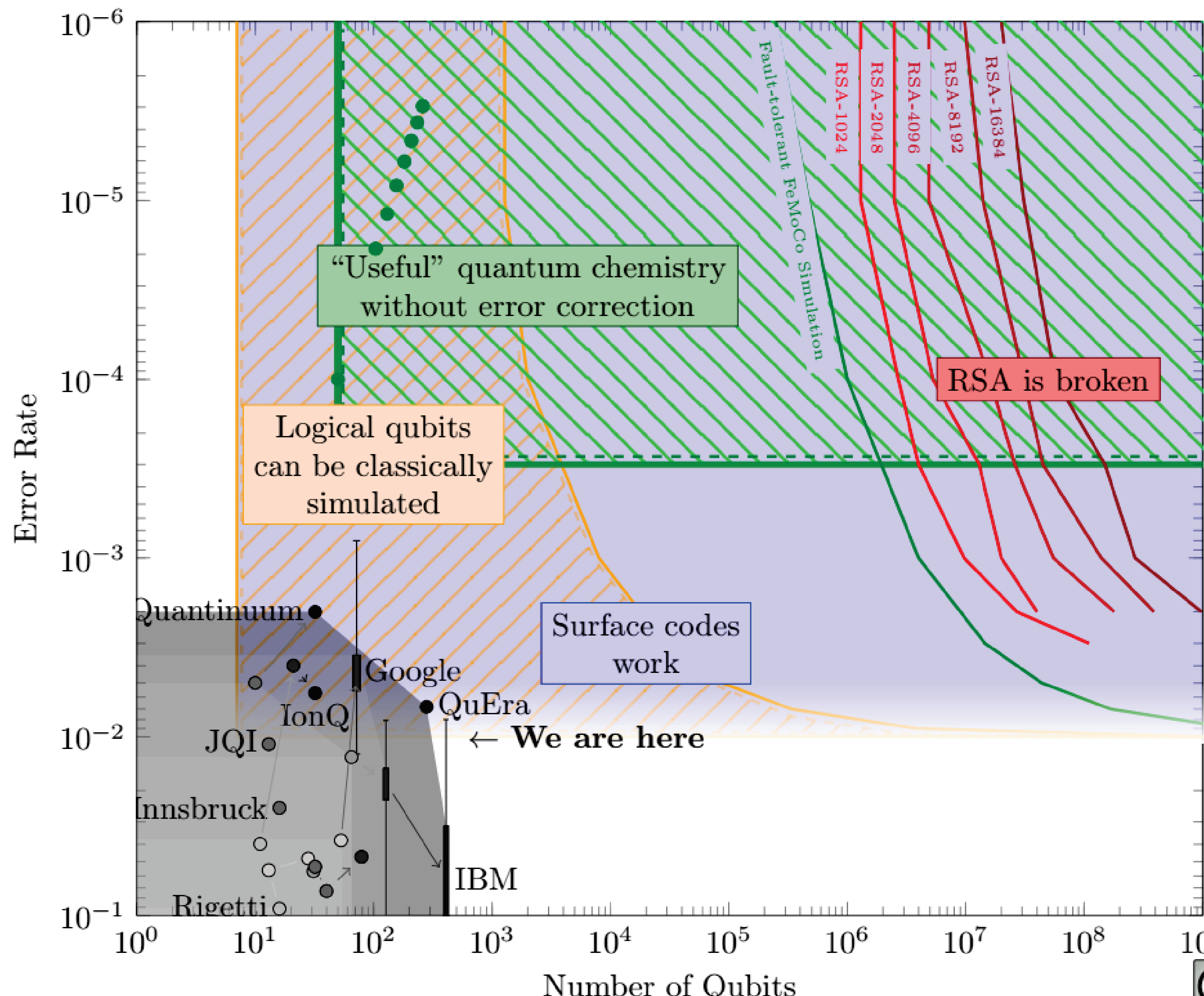
- Map your parameters to the states of the device
- Find ways to manipulate the states of the device
- Design algorithms create a sequence of manipulations to perform the computations we need.

Recent developments

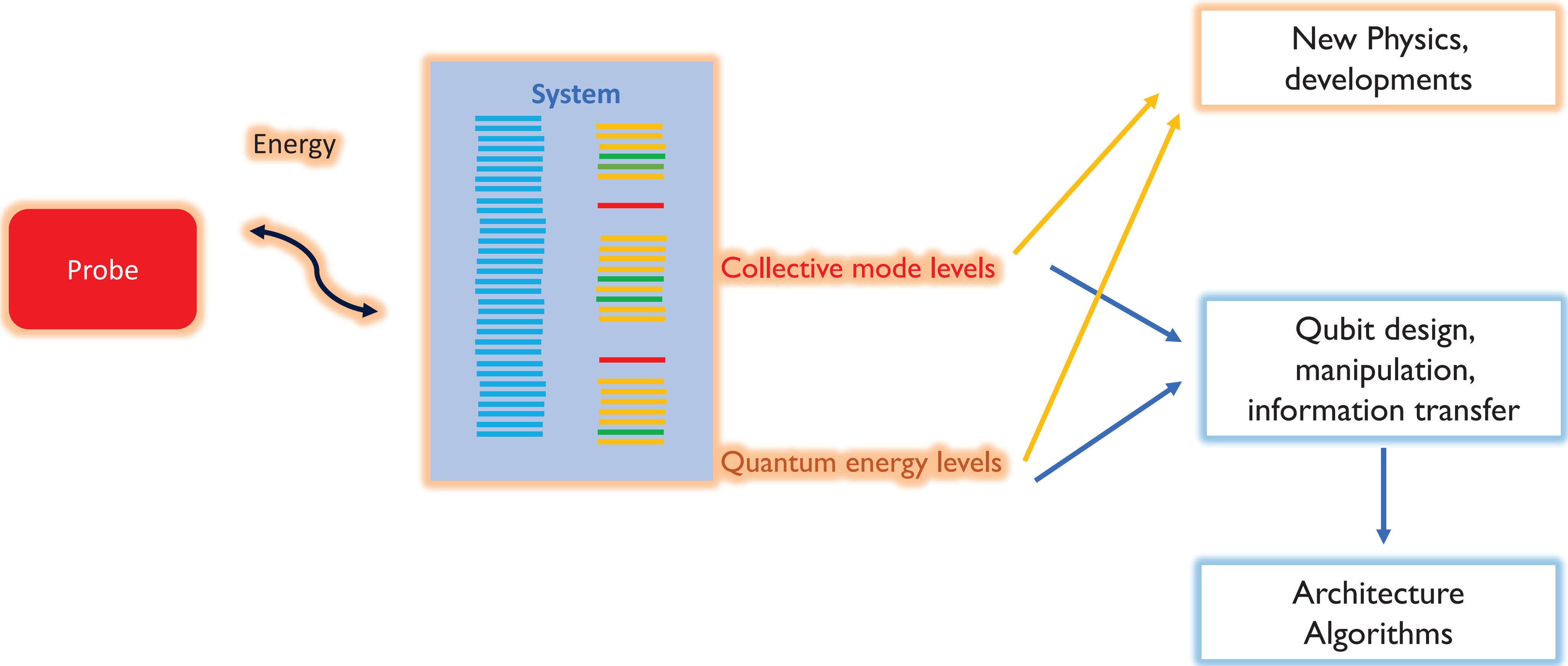
- Largest number factored:
  - Quantum Hardware (Shor's Algorithm): 21
  - Quantum Hardware (general method): 249919 (18 bits)
  - Classical Quantum Hybrid: 261980999226229 (48 bits)

- Quantum algorithm superior to classical in finding local minima

arXiv:2309.16596 (2023)



Error Rate
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Number of Qubits
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
"Useful" quantum chemistry without error correction
Logical qubits can be classically simulated
Surface codes work
RSA is broken
Fault-tolerant FeMoCo Simulation
RSA-1024
RSA-2048
RSA-4096
RSA-8192
RSA-16384
Quantinuum
Google
QuEra
IonQ
JQI
Innsbruck
Rigetti
IBM
← **We are here**

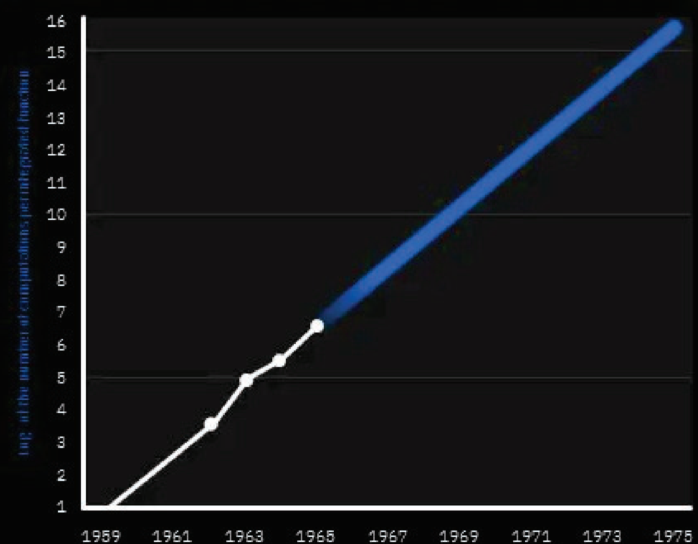


Probe
Energy
System
Collective mode levels
Quantum energy levels
New Physics, developments
Qubit design, manipulation, information transfer
Architecture Algorithms

We are in the early stages of a rapidly advancing new computing technology

IBM **Quantum**

Moore’s law



Quantum Volume: The New Moore’s Law