

Qubit Technologies



Building the Hardware of the Quantum Age

Dr Khaled Mnaymneh, PEng

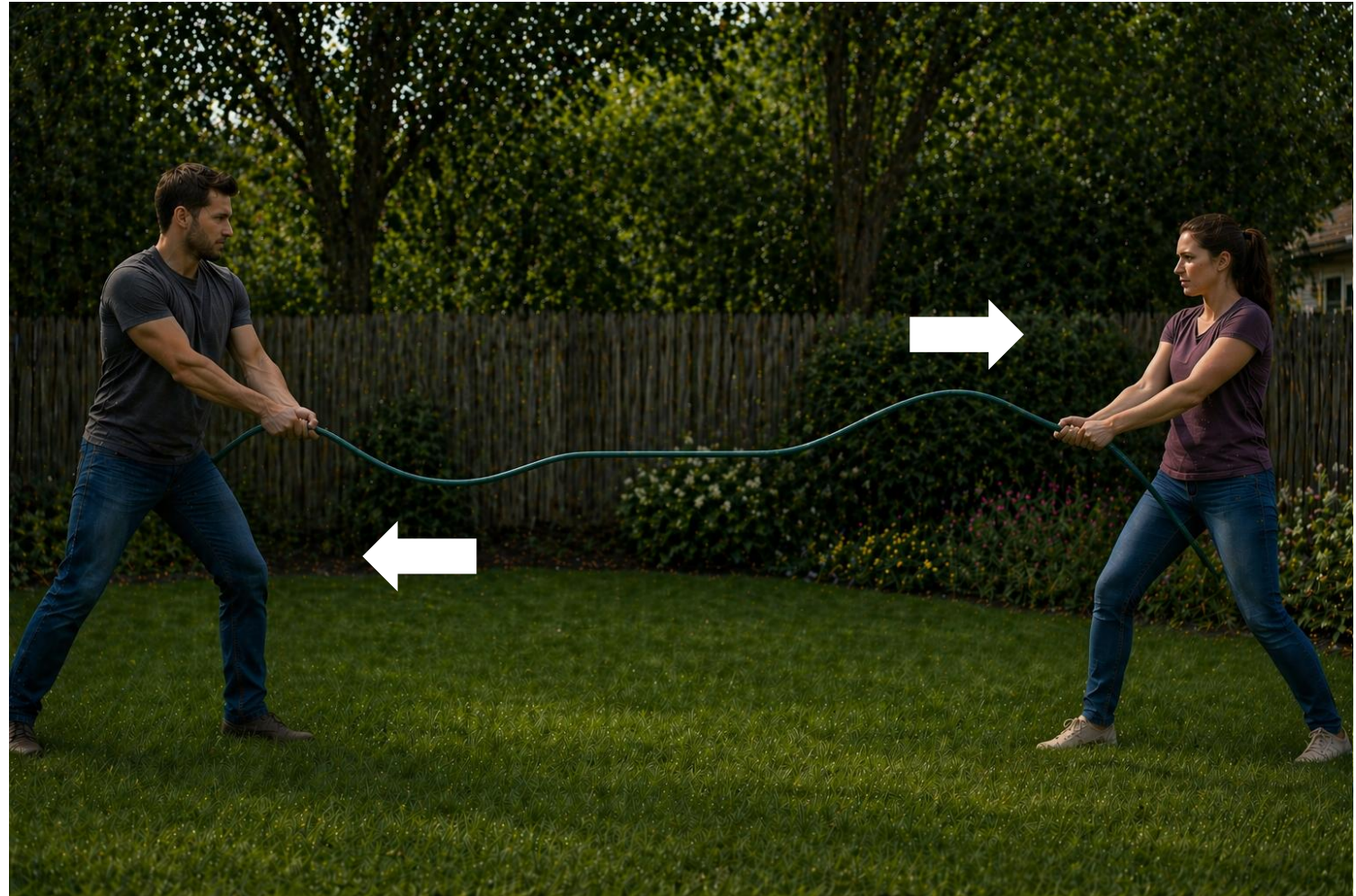
Content

- 1) What is a qubit, and how they differ from classical bits
- 2) Challenges in building stable and scalable quantum systems
- 3) Qubit Modalities
- 4) Quantum Engineering – Support structures need for the Quantum Age
- 5) Quantum Business – Opportunities



Quantum Computing – What is a Qubit?

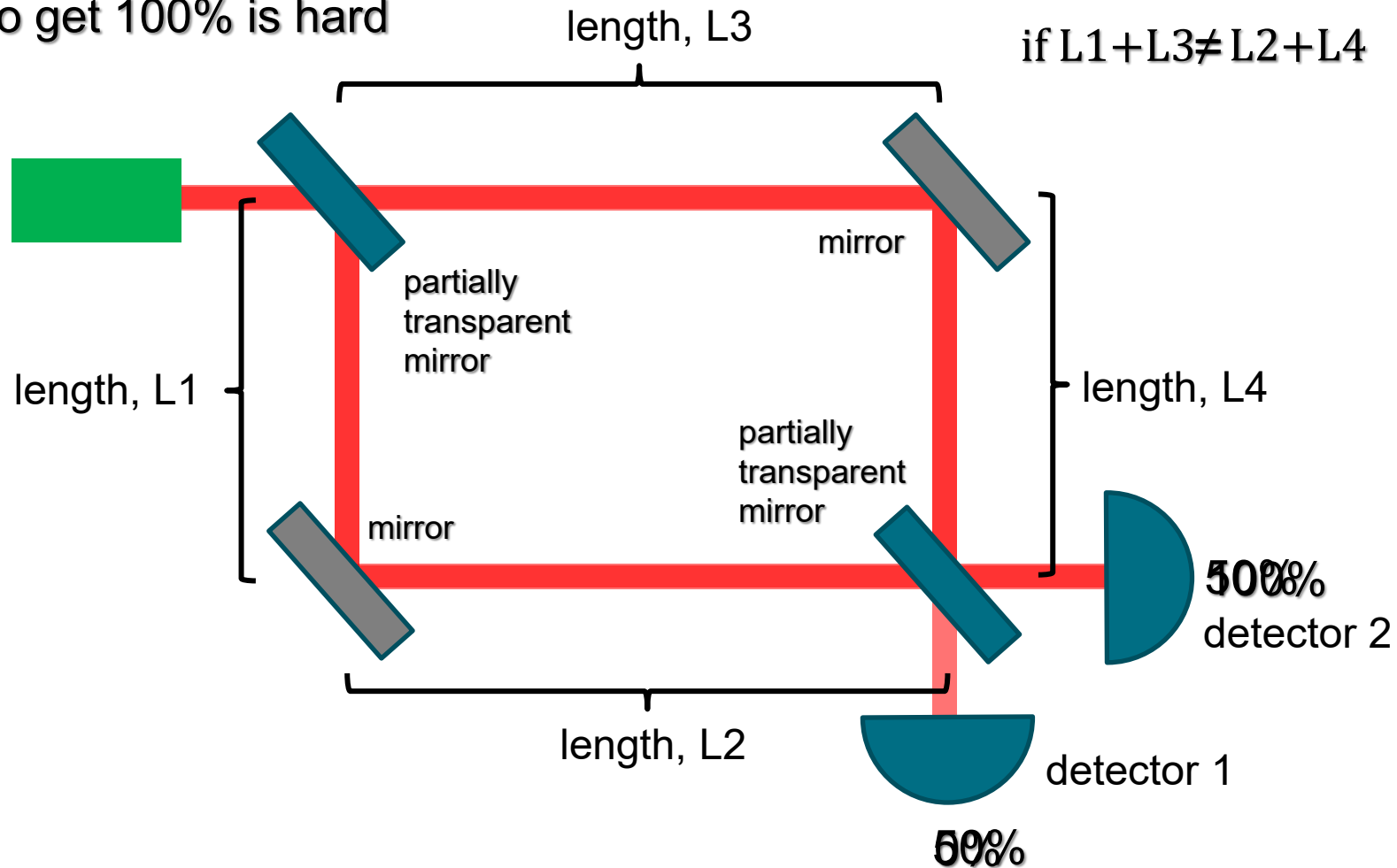
- the qubit ...



readout

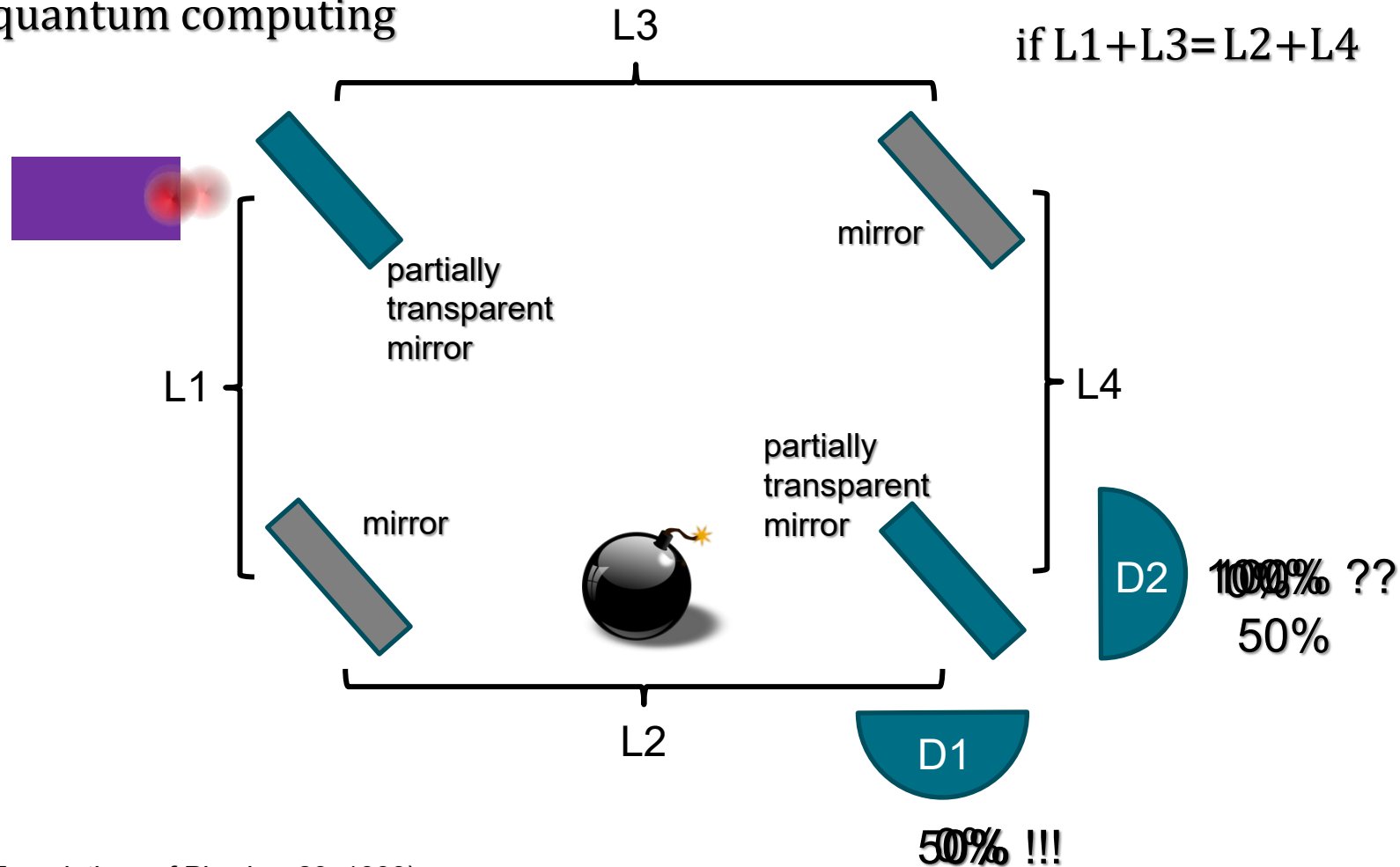
Review – Many Worlds ... Quantum Parallelism

- Mach-Zehnder Interferometer
- alignment to get 100% is hard

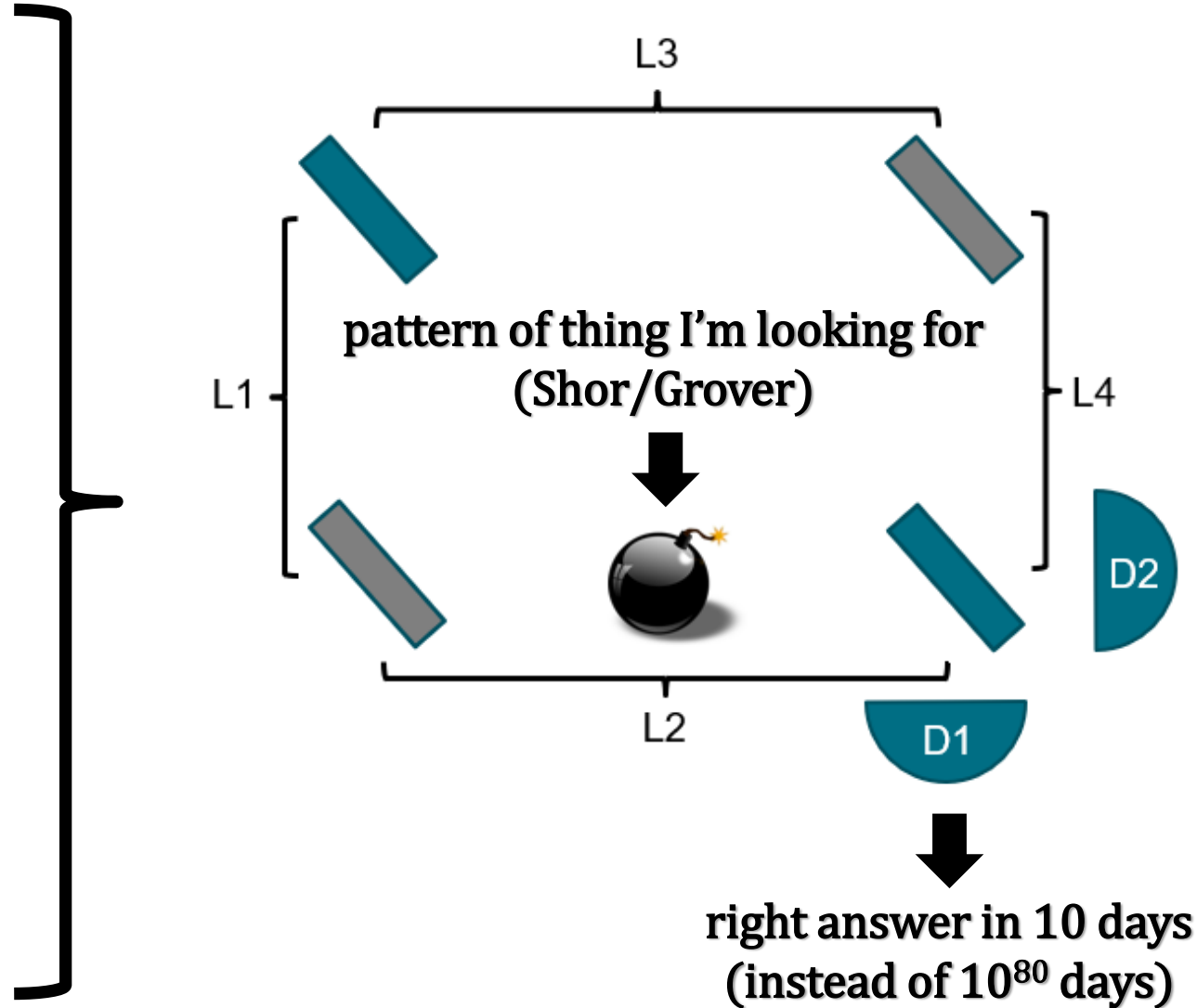


Review – Many Worlds ... Quantum Parallelism

- real access to “what ifs” [counterfactual realities]
- essence of quantum computing



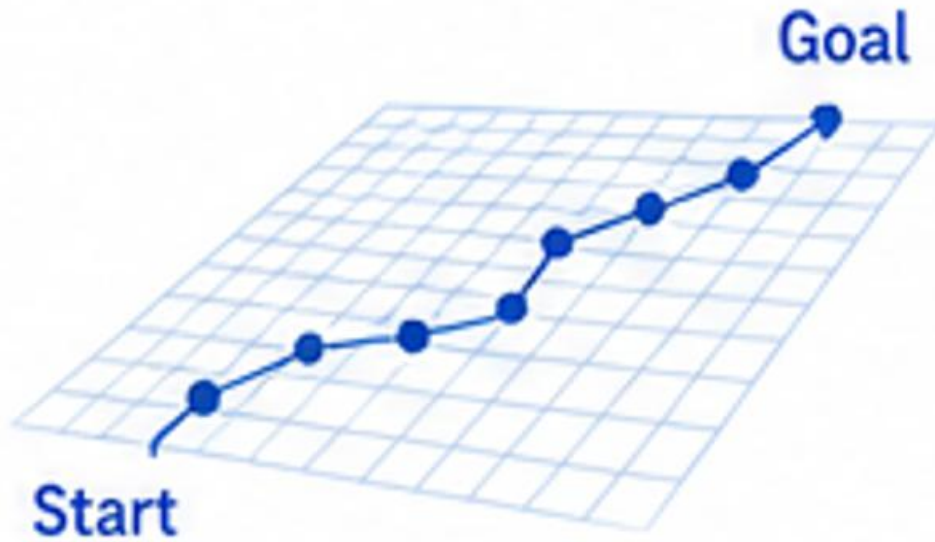
Review – Many Worlds ... Quantum Parallelism



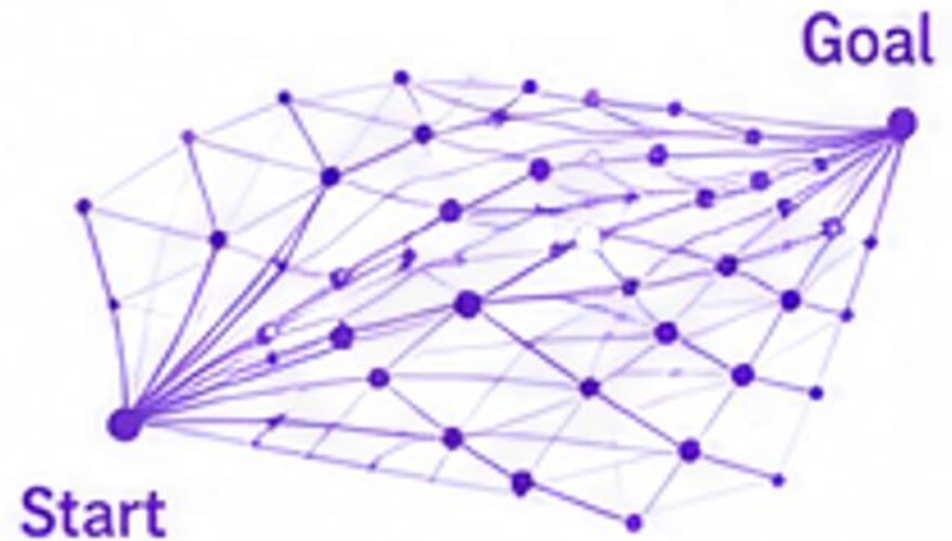
From single paths to many histories

- interference AMPLIFIES good histories and cancels bad ones

classical computation



quantum computation

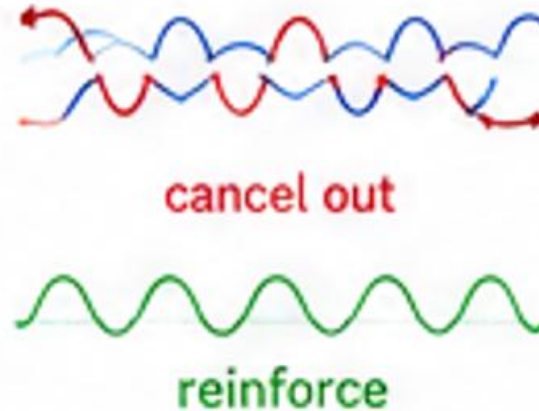


From single paths to many histories

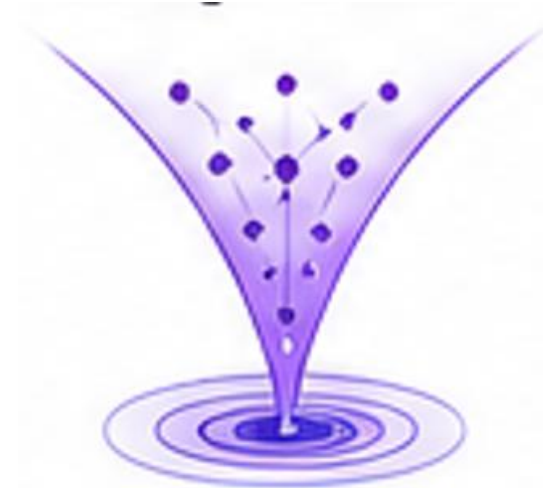
- we do not read out histories; we get ONE measurement
- power comes from **engineering interference** so that only useful histories survive
- this is why in quantum, software and hardware are “tied at the hip”, unlike classical computation



- many possible histories
- computation explores many trajectories

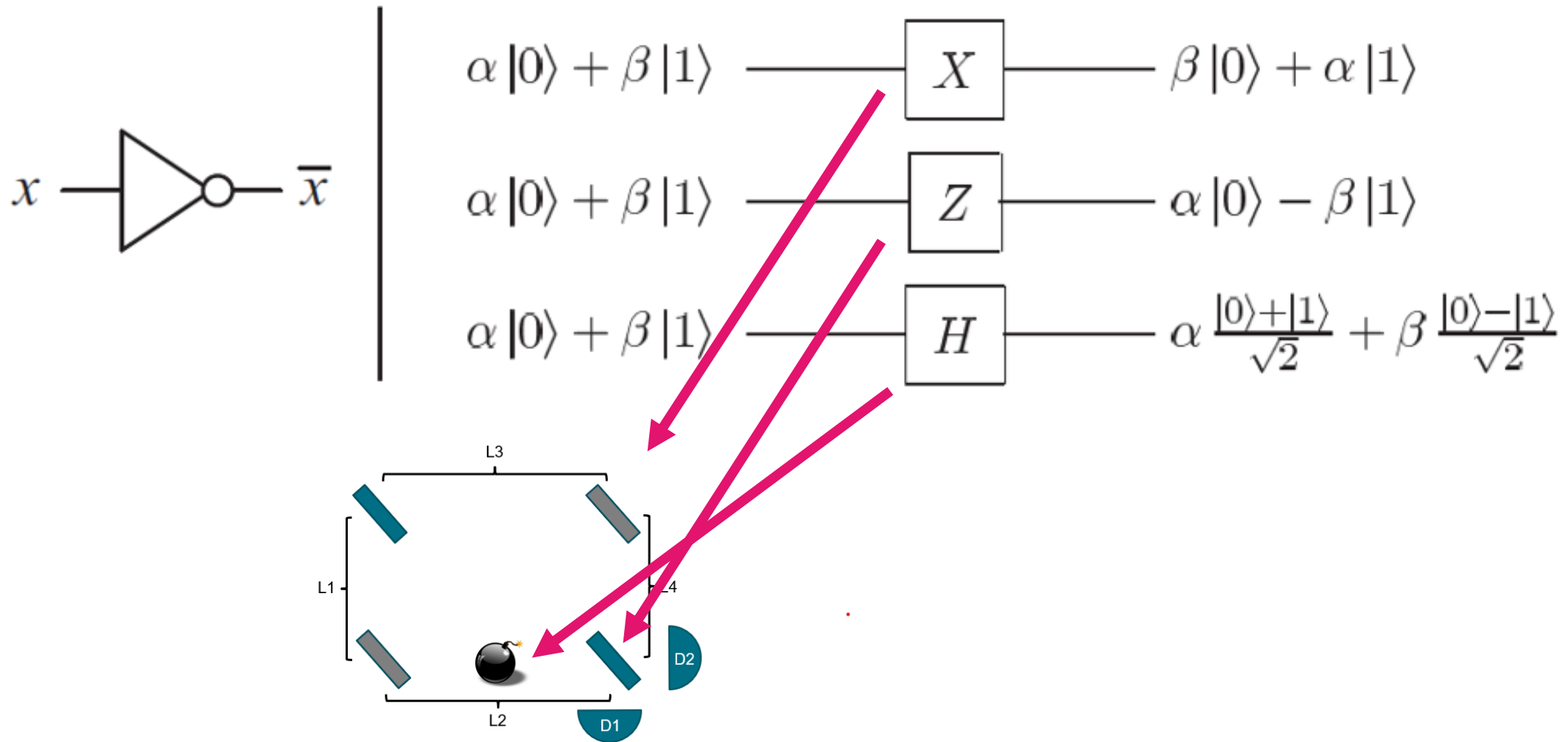


- phase cause destructive and constructive interference

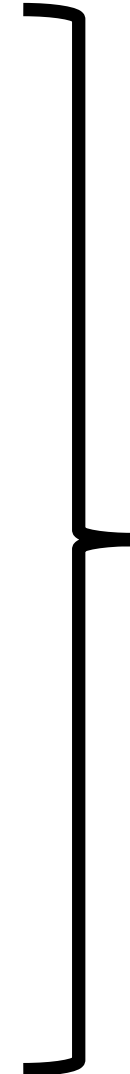


- probability concentrates on right answers

Qubit vs Bit

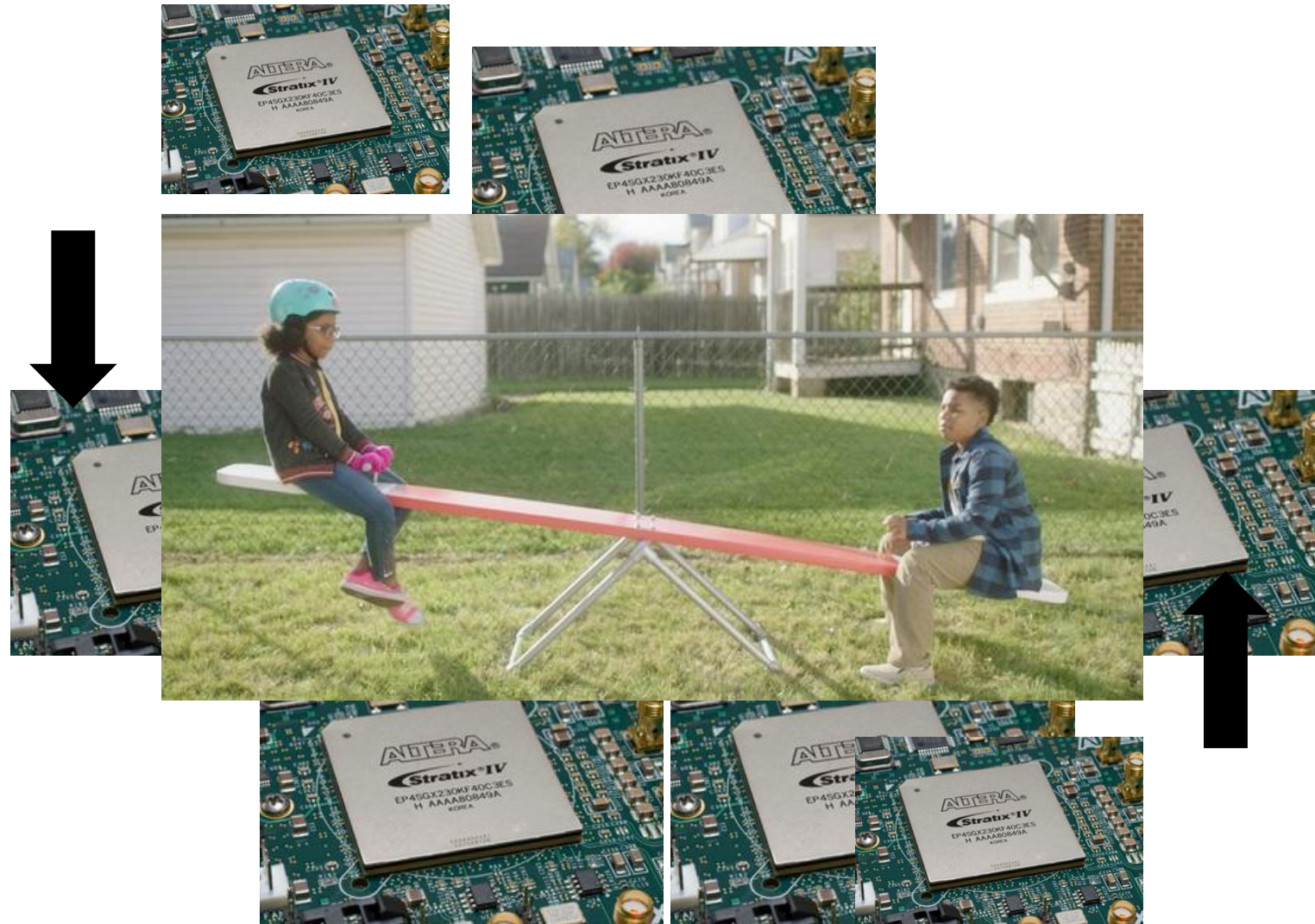


Error Correction / Fault Tolerance



**TO
GATES**

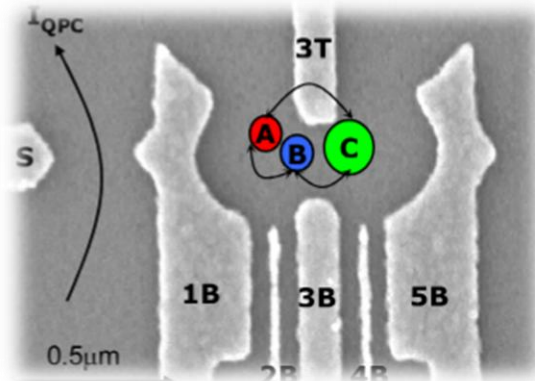
Classical Electronics to the Rescue!



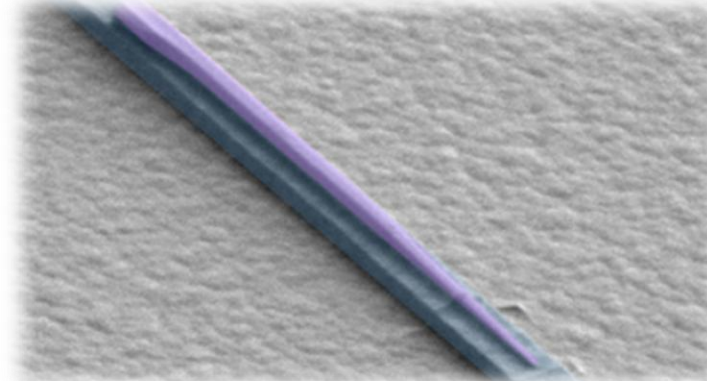
Qubit Modalities



NRC's Spin Qubit



NRC's Photon Qubit



Challenges

Quantum hardware platforms are advancing steadily, but no one knows when quantum computers will run applications that broadly benefit society.

The path from NISQ to FASQ is likely to be arduous, expensive, and prolonged.

We seek applications that are quantumly easy, classically hard, and practically useful.

Light road

An error-corrected quantum machine will actually be a hybrid system requiring substantial classical processing power to decode error syndromes.

2,3 and John Preskill

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

Systems, Freie Universität Berlin, 14195 Berlin, Germany

Materialien und
Hertz Institute

Quantum Computing, Pasadena, CA 91129, USA

Yet substantial gaps separate today's noisy intermediate-scale

quantum (NISQ) devices from tomorrow's fault-tolerant application-scale quantum (FASQ) machines. We

identify four related hurdles along the road ahead: (i) from error mitigation to active error detection and correction, (ii) from rudimentary error correction to scalable fault tolerance, (iii) from early heuristics to mature, verifiable algorithms, and (iv) from exploratory simulators to credible advantage in quantum simulation. Targeting these transitions will accelerate progress toward broadly useful quantum computing.

“Despite our best efforts to predict the important applications, tomorrow's quantum computers are sure to delight and benefit us in ways we cannot currently anticipate. Before that happens, we have a lot of work to do.”

Qubit Modalities

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

Platform: Superconducting - Transmons

Superconducting Qubit
Example: Transmon Qubit

Physical principle
The qubit is a nonlinear LC oscillator. The Josephson junction provides nonlinearity (anharmonicity), allowing us to use the two lowest energy levels $|0\rangle$ and $|1\rangle$ as a quantum bit.

Qubit states
 $|0\rangle$ = ground state
 $|1\rangle$ = excited state

Typical parameters
 $\omega_{01}/2\pi \sim 4 - 7$ GHz
Anharmonicity $\alpha/2\pi \sim -200$ to -300 MHz
Coherence time $T_1 \sim 10 - 100$ μ s
Dephasing time $T_2 \sim 10 - 100$ μ s

Qubit energy levels

Anharmonic spectrum ($\omega_{12} \neq \omega_{01}$)



Qubit Modalities

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

Platform: Trapped Ion

Trapped Ion Qubits

Qubits encoded in the internal states of ions confined and controlled by electromagnetic fields

Radiofrequency (RF) electrode

Endcap electrode

Trapped ions (typically $^{40}\text{Ca}^+$, $^{171}\text{Yb}^+$, $^{25}\text{Mg}^+$)

DC control electrode

State preparation and measurement (laser)

Laser beams for quantum gates

Qubit energy levels (example: $^{40}\text{Ca}^+$)

Energy

$|e\rangle$ Excited state

Laser excitation (qubit operations)

Spontaneous emission

$|1\rangle$ $D_{5/2}, m_J = \frac{1}{2}$ (logical $|1\rangle$)

ω_{01} (qubit transition) $\sim 3-5$ THz

$|0\rangle$ $S_{1/2}, m_J = -\frac{1}{2}$ (logical $|0\rangle$)

Key advantages

- Very high coherence times (seconds to minutes)
- High-fidelity gates and readout
- All-to-all connectivity
- Excellent qubit uniformity and control

Challenges

- Complex and expensive laser systems
- Scaling to large numbers of qubits

Physical principle

Individual ions are confined in free space using electromagnetic fields.

Qubits are encoded in long-lived internal electronic states.

Laser or microwave fields are used for state preparation, coherent control, and readout.

Coupling between ions is mediated by their collective motion (phonons), enabling high-fidelity two-qubit gates.

Qubit encoding
Example: $^{40}\text{Ca}^+$

$|0\rangle = S_{1/2}, m_J = -\frac{1}{2}$

$|1\rangle = D_{5/2}, m_J = \frac{1}{2}$

Bloch sphere representation

How entangling gates work

A laser drives the collective motion (phonons), which couples the ions. The motion is then used to entangle the qubit states.

The shared motion acts as a "bus" that mediates interactions between distant ions, allowing high-fidelity entangling gates.

Typical parameters (state of the art)

- ω_{01} Qubit transition frequency $\omega_{01}/2\pi \sim 1-10$ THz (optical)
- Single-qubit gate time $\sim 1-10$ μs
- Two-qubit (entangling) gate time $\sim 10-100$ μs
- Single-qubit gate fidelity $> 99.99\%$
- Two-qubit gate fidelity $> 99.5\%$
- Qubit connectivity All-to-all (in principle)



Qubit Modalities

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

Platform: Neutral Atom

Neutral Atom Qubits

Qubits encoded in the internal states of ultracold neutral atoms trapped in an optical tweezer array.

Optical tweezers (focused laser beams)

Individual atom trapped in the ground state of motion

Qubit states encoded in hyperfine ground states

$|1\rangle$

$|0\rangle$

Qubit energy levels (example: ^{87}Rb)

Energy

$|r\rangle$ Rydberg state (nS, nP, \dots)

Laser excitation (Raman / Rydberg)

$|1\rangle \equiv |F=2, m_F=0\rangle$

$|0\rangle \equiv |F=1, m_F=0\rangle$

Hyperfine ground states

$\omega_{01}/2\pi \sim 6.8 \text{ GHz}$

Global control lasers (Raman / microwave)

Cooling lasers (Doppler + sub-Doppler)

High-NA objective

Key advantages

- Scalable 2D/3D arrays (thousands of qubits)
- High-fidelity, fast entangling gates
- Reconfigurable connectivity
- Long coherence times (seconds)
- All-to-all interactions (in principle)

Challenges

- Technical complexity (lasers, optics)
- Atom loss and heating
- Crosstalk and addressing errors
- Vacuum and stability requirements

Physical principle

Neutral atoms are cooled to $\sim \mu\text{K}$ and trapped in an optical tweezer array.

Qubits are encoded in long-lived hyperfine ground states.

Entanglement is generated via state-dependent interactions, typically by exciting atoms to Rydberg states that interact strongly with each other.

Typical atoms: ^{87}Rb , ^{133}Cs , ^{171}Yb , ^7Li , ^{40}K , ^{88}Sr , ...

Qubit encoding

Example: ^{87}Rb

$|0\rangle \equiv |F=1, m_F=0\rangle$

$|1\rangle \equiv |F=2, m_F=0\rangle$

$F=2$

$F=1$

6.8 GHz

$m_F = -2 \quad -1 \quad 0 \quad +1 \quad +2$

How entangling gates work

1. Excite atoms to Rydberg state
2. Strong Rydberg interaction (V_{ij})
3. De-excite to complete gate

Rydberg blockade prevents simultaneous excitation within a radius R_b , implementing a controlled phase gate between atoms i and j . Combined with single-qubit rotations \rightarrow universal gates.

Interaction potential (van der Waals)

$V(r) = \frac{C_6}{r^6}$ Blockade radius: $V(R_b) = \hbar\Omega$

Typical parameters (state of the art)

Coherence time T_2	$\sim 1 - 100 \text{ s}$
Single-qubit gate time	$\sim 10 - 100 \text{ ns}$
Two-qubit gate time	$\sim 0.5 - 5 \mu\text{s}$
Single-qubit gate fidelity	$> 99.9\%$
Two-qubit gate fidelity	$> 99\%$
Typical array size	$10^2 - 10^3+$
Connectivity	Reconfigurable, all-to-all (in principle)

Infleqtion

QuEra

Putting Quantum to Work



Pasqal



NanoQNT

Nanofiber Quantum Technologies

Qubit Modalities

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

Platform: Photonics

Photonic Qubits

Qubits encoded in the quantum states of single photons, manipulated using integrated optical circuits.

Single-photon source

- SPDC
- Quantum dots
- Atom-cavity
- Heralded source

Typical integrated platform

Single-photon detectors ("click" / "no click")

Qubit encodings (examples)

Polarization (path-encoded equivalent)

$|0\rangle = |H\rangle$
 $|1\rangle = |V\rangle$

Horizontal (H) / Vertical (V)

Path

$|0\rangle$
 $|1\rangle$

Photon in upper / lower path

Time-bin

Early ($|0\rangle$)
Late ($|1\rangle$)

Early / late arrival time separated by Δt

Many other encodings: frequency-bin, orbital angular momentum, continuous-variable (quadrature), etc.

Key advantages

- Low decoherence and long coherence times
- Room-temperature operation
- High-speed operation (ps–ns scale)
- Easy transmission over optical fiber
- Scalable with integrated photonics

Challenges

- Probabilistic two-qubit gates (usually require measurement)
- Photon loss and detector inefficiency
- On-demand single-photon sources
- Scaling to large, deterministic circuits

1. Physical principle

Information is encoded in discrete degrees of freedom of single photons.

Two-qubit entanglement is generated using linear optical networks and measurement-induced nonlinearity.

Detection events ("clicks") project the photonic state, enabling entanglement and gate operations.

2. Qubit encoding (examples)

Polarization qubit

$|0\rangle = |H\rangle$
 $|1\rangle = |V\rangle$

Path qubit

$|0\rangle$
 $|1\rangle$

3. Two-qubit gate (example)

Probabilistic entangling gate (KLM / linear optics)

When specific detector patterns click, the output is projected onto an entangled state (e.g., Bell state).

4. Entanglement generation

Example: Hong–Ou–Mandel (HOM) interference

Indistinguishable photons bunch together → zero coincidence counts.

Resource for building larger entangled states (cluster states, graph states, GHZ, ...)

5. Typical parameters (state of the art)

- ⌚ Single-photon duration ~ 10 – 100 ps
- ⊕ Two-photon gate time ~ 100 ps – 1 ns (heralded)
- ⊕ Two-qubit gate success ~ 1% – 10% (typical) probability
- ⊕ Single-qubit gate fidelity > 99.9%
- ⊕ Entanglement generation > 90% (typical) fidelity
- ⊖ Photonic loss (on-chip) ~ 0.1 – 1 dB/cm
- 🌡 Operating temperature Room temperature

Where photonic qubits excel

- 🌀 Long-distance quantum communication
- 🔌 Scalable quantum interconnects
- 📡 Boson sampling & quantum advantage
- 🔗 Measurement-based quantum computing
- 🔒 Quantum key distribution (QKD)



Qubit Modalities

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

Platform: Quantum Dots

Quantum Dot Spin Qubits

Qubits encoded in the spin state of a single electron confined in a semiconductor quantum dot.

Gate electrodes

- Define quantum dot
- Control tunnel barriers
- Tune interactions

Charge sensor (QPC/SET)

- Readout of spin state via spin-to-charge conversion

2DEG in GaAs/SiGe (or Si/SiGe) (electron gas)

Qubit states (spin states)
Electron spin-1/2 in a quantum dot

$|0\rangle \equiv |\downarrow\rangle$ (spin down) $|1\rangle \equiv |\uparrow\rangle$ (spin up)

Energy

$\Delta E = g\mu_B B_{ext}$

Typical parameters:
 $g^* \sim -0.4$ (GaAs), $\mu_B = 9.27 \times 10^{-24}$ J/T
 $\Delta E/h \sim 5 - 20$ GHz for $B_{ext} = 0.1 - 1$ T

Control and readout

ESR or EDSR for spin rotations

Spin-to-charge conversion for readout

Spin state $|\uparrow\rangle$ or $|\downarrow\rangle$ Tunnel selectively Charge sensor

Spin information is inferred from the sensor current.

Physical principle

Electrons are confined in a semiconductor quantum dot using electrostatic gates.

The two spin states ($|\downarrow\rangle, |\uparrow\rangle$) form a natural two-level system that is long-lived and can be coherently controlled.

Electric and magnetic fields control the qubit, while nearby charge sensors enable fast, high-fidelity readout.

Qubit control

Single-qubit rotation (X or Y gate)

Microwave drive (ESR: B_1 field) or (EDSR: electric field)

Two-qubit gate (exchange coupling)

Bring dots close \rightarrow tunable exchange J

Gate time $\sim 10 - 100$ ns
Fidelity $> 99\%$ (state of the art)

Qubit connectivity

Nearest-neighbor on a 2D array

Key advantages

- Compatibility with CMOS and semiconductor industry
- Fast gates (ns scale)
- Potential for high density
- Operation at mK temperatures (dilution refrigerator)

Challenges

- Charge noise and decoherence
- Precise fabrication and tuning
- Cross-talk between qubits
- Scalability of control lines

Typical parameters (state of the art)

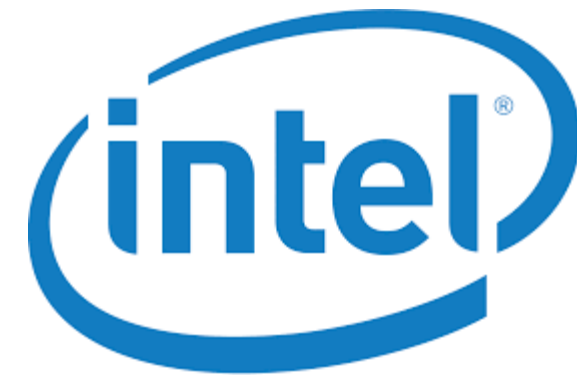
Coherence time T_2^* $\sim 0.1 - 10$ μ s	Single-qubit gate time $\sim 1 - 50$ ns	Single-qubit gate fidelity $> 99.9\%$	Operating temperature $\sim 10 - 100$ mK	Qubit count (2024) $\sim 10 - 100$ (lab devices)
Echo coherence time T_2 $\sim 10 - 1,000$ μ s	Two-qubit gate time $\sim 10 - 100$ ns	Two-qubit gate fidelity $> 99\%$	Magnetic field $0.1 - 1$ T (typical)	Roadmap $> 10^4$ (with scaling)

Example materials

- GaAs/AlGaAs
- Si/SiGe
- Ge/SiGe
- Si/SiO₂ (MOS dots)

Where quantum dot spin qubits excel

- Integration with semiconductor technology
- Fast, scalable qubit operations
- Operation in standard dilution refrigerators
- High qubit density potential
- Natural for modular architectures



Qubit Modalities

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

Platform: Spin defects

Spin Defect Qubits

Qubits encoded in the electron spin of point defects in solids (e.g., NV centers in diamond, SiC divacancies).

Optical initialization and readout

- Spin-dependent fluorescence

Microwave control

- Drives spin transitions

Example: NV center in diamond (N substitutional next to a vacancy)

Qubit energy levels (NV center)

Spin readout

Bright state $|0\rangle$ → High fluorescence

Dark state $|1\rangle$ → Low fluorescence

Measure fluorescence to infer spin state.

Coherence (example: NV in ^{12}C diamond)

T_2^* (Ramsey) $\sim 1 - 10 \mu\text{s}$

T_2 (Hahn echo) $\sim 10 - 1,000 \mu\text{s}$

T_1 (relaxation) $\sim 1 - 10 \text{ms}$

Improved with isotopic purification (^{12}C enrichment) and dynamical decoupling.

Key advantages

- Room-temperature operation (in many materials)
- Long coherence times
- All-optical initialization and readout
- Nanoscale localization → high spatial density
- Compatibility with semiconductor / photonic platforms

Challenges

- Spin bath from surrounding nuclear/paramagnetic spins
- Spectral diffusion and charge noise
- Inhomogeneous broadening
- Integration with fast control and scaling

1. Physical principle

A point defect in a crystal creates localized electronic states. The unpaired electron spin serves as a two-level system.

Crystal field splits spin levels via zero-field splitting D .

External fields (microwave, strain, E-field) enable coherent control.

2. Qubit states (spin-1 system)

We encode a qubit in $|0\rangle$ and $|±1\rangle$.

Qubit subspace: $\{|0\rangle, |±1\rangle\}$ (robust to some noise sources)

3. Control

Microwave driving

Coherent rotations between $|0\rangle$ and $|±1\rangle$.

Strain / electric field

Tune energy levels via Stark / spin-orbit coupling.

4. Two-qubit gates

Mediated by dipolar or exchange interaction between nearby defects.

Examples:

- Dipolar coupling $H_{dd} \propto \frac{1-3\cos^2\theta}{r^3}$
- Exchange via tunneling (engineered)
- Cavity/photonic interconnects

Typical gate time: 10 ns – 10 μs

Fidelity: > 99% (state of the art)

5. Host materials and defects

Diamond

- NV center (N-V)
- Silicon vacancy (SiV)
- Germanium vacancy (GeV)

Silicon carbide (SiC)

- Divacancy (VV)
- Silicon vacancy (V_{Si})
- Carbon vacancy (V_{C})

Other materials

- hBN: V_{N} , V_{B}
- Al_2O_3 : V_{Al}
- 4H-SiC, GaN, ...

6. Typical performance (examples)

NV center in ^{12}C diamond (Isotopically purified sample)

T_1	3 – 10 ms
T_2 (echo)	100 – 1,000 μs
Gate time	20 – 200 ns
Fidelity (1-qubit)	> 99.9%
Fidelity (2-qubit)	> 99%

SiV center in diamond

T_1	up to 1 s
T_2 (echo)	up to 1 ms
Narrow optical line	< 100 MHz

(Values vary with material and environment)

Applications

- Quantum sensing (magnetometry, thermometry, electric-field sensing)
- Quantum networks (quantum repeaters, interfaces)
- Scalable quantum computing (nanoscale qubit arrays with optical I/O)
- Hybrid quantum systems (cavity QED, mechanics, superconducting circuits)

Outlook

Defect spin qubits combine long coherence with optical access and solid-state scalability, making them a leading platform for practical quantum technologies.

Challenges & Opportunities

REVIEW

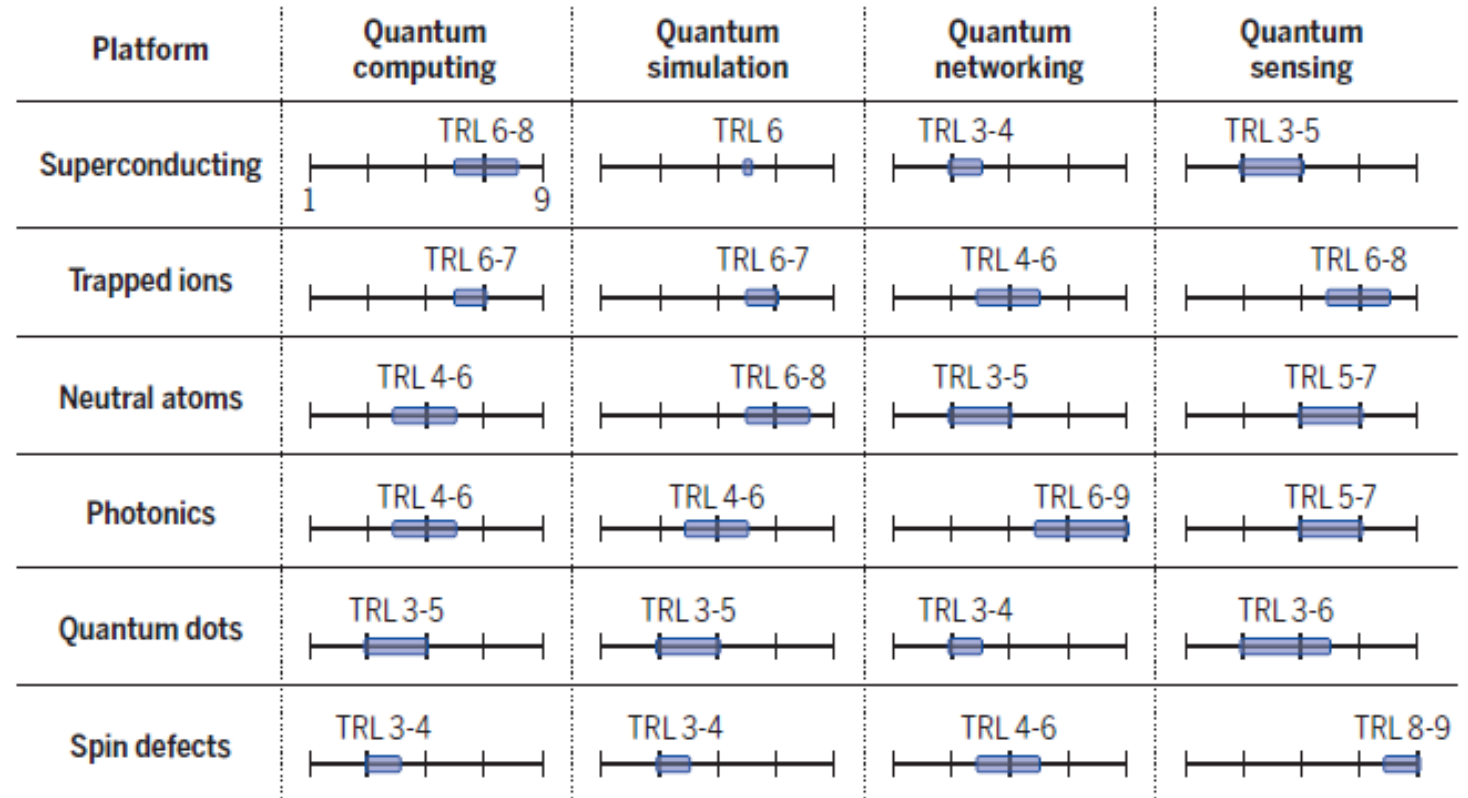
vQR/ QI review

A QUANTUM WORLD

REVIEW

Challenges and opportunities for quantum information hardware

David D. Awschalom^{1,2*}, Hannes Bernien^{1,3,4}, Ronald Hanson^{5,6},
William D. Oliver^{7,8,9}, Jelena Vučković^{10,11}



Silicon Nitride for Quantum Technologies

REVIEW

vQR/ QI review

A QUANTUM WORLD

REVIEW

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Prof. Connor Kupchak
(Quantum Tech.)
Carleton U



Dr. Abubaker Tareki
(SiN Materials)

Thanks to NRC's Quantum Sensing Program

ADVANCED QUANTUM TECHNOLOGIES

Communication | [Full Access](#)

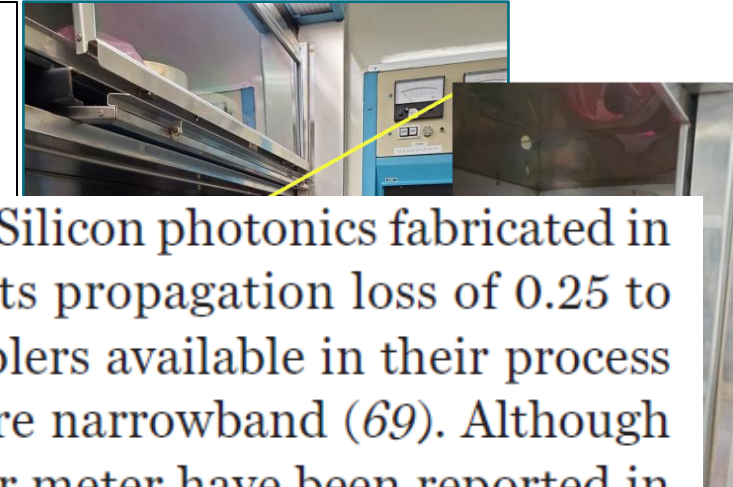
On-Chip Integration of Single Photon Sources via Evanescent

Photonics exemplifies the challenge: Silicon photonics fabricated in commercial foundries typically exhibits propagation loss of 0.25 to 1 dB/cm, and fiber-to-chip grating couplers available in their process design kits exhibit >3 dB of loss and are narrowband (69). Although lower propagation losses of decibels per meter have been reported in research-grade silicon nitride, lithium niobate, or silicon carbide photonics (73, 79, 80), these processes have not yet become widely available in a foundry environment. Moreover, state-of-the-art spatial light modulators have limited resolution and speed for scaling tweezer arrays (81), and solutions are needed at shorter wavelengths, with smaller pixel sizes and higher speed for trapping more atoms, reducing their separation, and controlling and moving atoms faster.

NRC 1.5kV 13.5mm x100k 12/1/2022 10:53 500nm

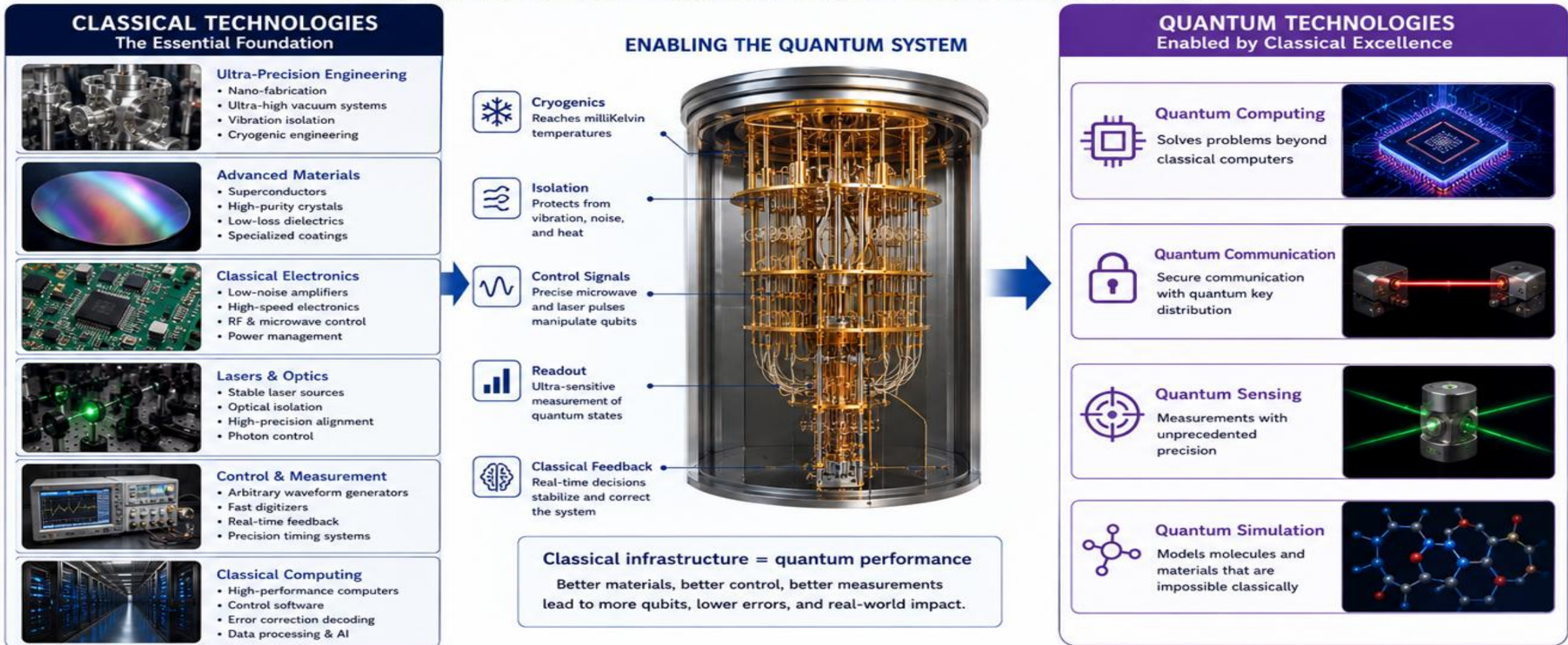
bulk losses < 0.1 dB/cm

NRC 1.5kV 21.1mm x150 3/29/2021 12:55 300um



CLASSICAL TECHNOLOGIES ARE THE KEY TO MAKING QUANTUM TECHNOLOGIES SUCCESSFUL

Quantum advantages come from quantum physics, but quantum technologies are built, controlled, and scaled by classical technologies.



NRC's supports the National Quantum Strategy



- NRC Quantum R&D Initiative (\$9.0M)
- NRC Challenge Programs (\$50.0M)

“Funding, de-risking and creating supportive policy frameworks for emerging technologies, convening and coordinating, procuring goods and services, and serving as a research partner.”

The NRC supports all Canadian strategies on quantum

NRC funded initiatives

National Metrology Institute Initiatives

nmiQ

Canadian Quantum Strategies



NRC Quantum + Portfolio

COLLABORATION R&D PROGRAMS



- Small teams and Ideation projects
- High-throughput and Secure Networks
- Quantum Sensors
- Applied Quantum Computing
- Quantum InterNetworking (NEW)

RESEARCH CENTRES



- Quantum & Nanotechnologies Research Centre
- Metrology Research Centre
- Digital Technologies

BUSINESS INNOVATION



- Canadian Photonics Fabrication Centre
- Industrial Research Assistance Program

COLLABORATION CENTRE



- Joint Centre for Extreme Photonics

NRC QUANTUM

Bringing technical expertise to collaborations

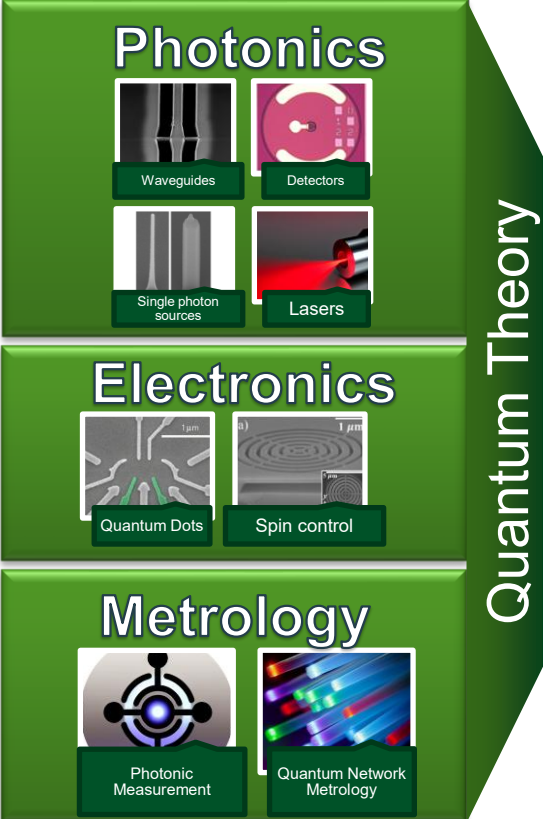

NRC has a diversity of quantum expertise



Essential ingredients for heterogeneous quantum networking



Canada has world-class quantum talent and expertise



Photonics

- Waveguides
- Detectors
- Single photon sources
- Lasers

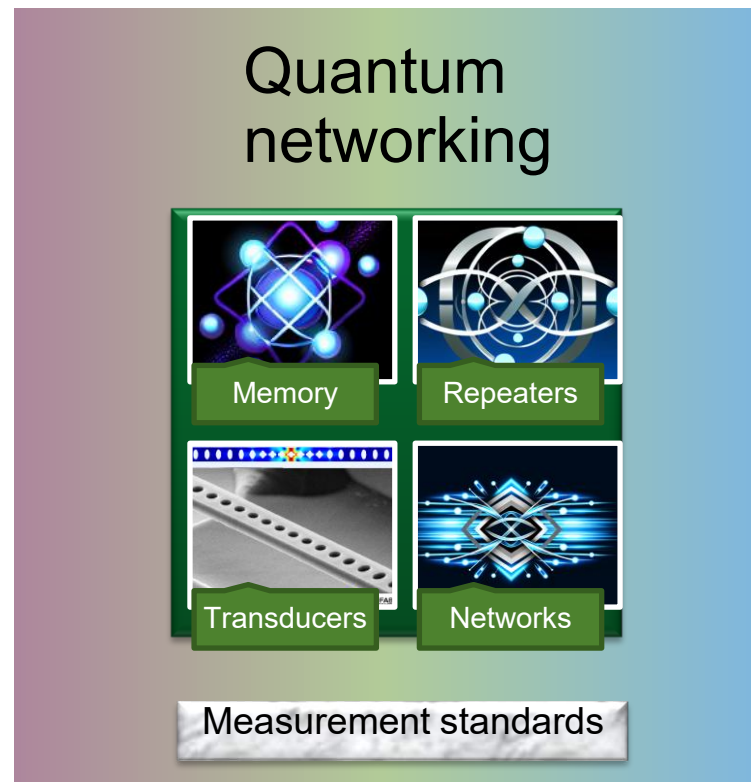
Electronics

- Quantum Dots
- Spin control

Metrology

- Photonic Measurement
- Quantum Network Metrology

Quantum Theory



Quantum networking

- Memory
- Repeaters
- Transducers
- Networks
- Measurement standards



Quantum Industry

- Quantum Valley Ideas Lab
- Quantum Bridge
- Nord Quantique
- photonics
- XANADU
- DREAM PHOTONICS
- SBOQuantum
- + many more

Academic Hubs

- Vancouver
- Montréal
- Sherbrooke
- Calgary
- Ottawa
- Toronto
- Waterloo
- Edmonton
- + many more

Thank You!

