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QUANTUM COMPUTING: Q&A

QUESTION

Provide a quick review of quantum computing, including terminology and main challenges. Recently a willow quantum chip was announced that provides an extremely low error rate. Comment on that too, specifically what allows this low rates.

ANSWER

Quantum computing leverages principles of quantum mechanics to process information in ways that classical computers cannot, offering potential exponential speedups for specific tasks.

Key Terminology:

- **Qubit:** The fundamental unit of quantum information, analogous to a classical bit but capable of existing in a superposition of 0 and 1 states simultaneously.
- **Superposition:** A principle where a quantum system can exist in multiple states at once, enabling qubits to perform multiple calculations concurrently.
- **Entanglement:** A phenomenon where qubits become interconnected such that the state of one instantaneously influences the state of another, regardless of distance, facilitating coordinated processing.
- **Decoherence:** The loss of quantum coherence, wherein qubits interact with their environment, leading to errors in computation by collapsing superpositions into definite states.

Main Challenges:

- **Error Rates:** Qubits are highly sensitive to environmental disturbances, resulting in errors that can compromise computations.
- **Scalability:** Building quantum computers with a large number of stable qubits is technically demanding, requiring precise control and isolation.
- **Quantum Error Correction:** Developing methods to detect and correct errors without disrupting quantum information is complex due to the no-cloning theorem, which prohibits copying unknown quantum states.

Recent Developments:

Google has announced a significant advancement with its new quantum chip, Willow, which reportedly solves in five minutes a problem that would take classical supercomputers an impractical amount of time—estimated at 10 septillion years.

[Business Insider](#)

The Willow chip achieves remarkably low error rates through several innovations:

- **Enhanced Qubit Stability:** By improving qubit design and materials, Willow's qubits maintain coherence for longer periods, reducing error susceptibility.
- **Advanced Error Correction:** Implementing sophisticated error correction codes allows the system to identify and rectify errors more efficiently during computations.
- **Optimized Chip Architecture:** The chip's design minimizes interference and cross-talk between qubits, preserving the integrity of quantum states.

These advancements collectively enable Willow to perform complex computations with unprecedented accuracy, marking a substantial step toward practical quantum computing applications.

Google's Quantum Computing Breakthrough

[Google has unveiled a new quantum computer chip that cracks a '30-year challenge in the field'](#)

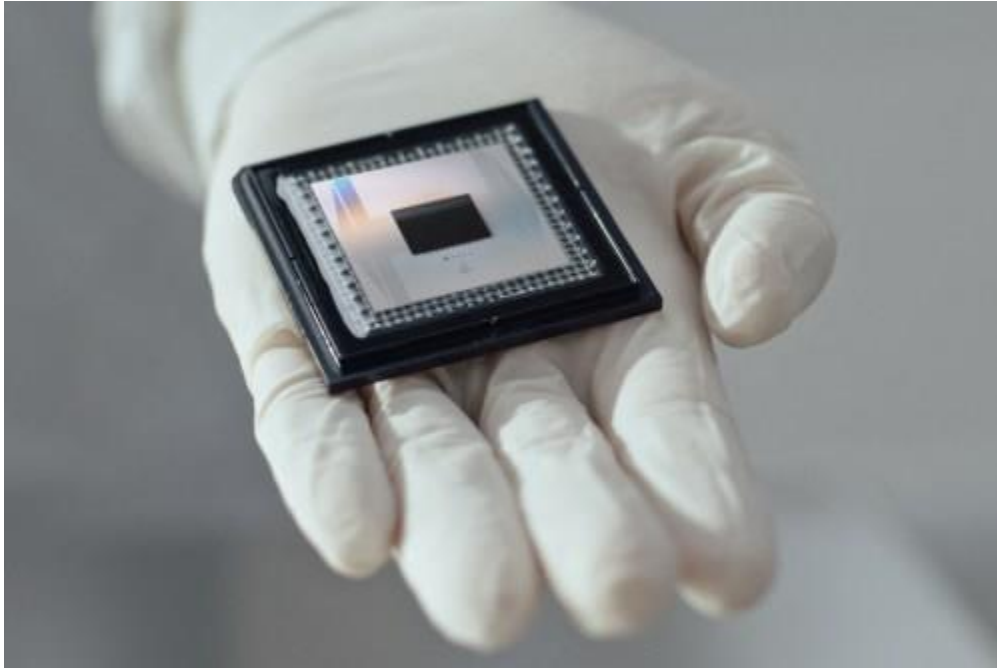
[Today](#)



[The Times](#)

[Google cracks 30-year challenge in quantum computing](#)

[Yesterday](#)



El País

[Google presenta Willow, un chip cuántico que resuelve en 5 minutos una tarea que un superordenador tardaría cuatrillones de años](#)
[Yesterday](#)



Sources

QUESTION

What is hardware infrastructure needed for willow chip to operate. How the willow chip is made? What is the interface with it?

ANSWER

Google's Willow quantum chip represents a significant advancement in quantum computing, addressing key challenges in qubit stability and error correction. Here's an overview of the hardware infrastructure required for its operation, its manufacturing process, and its interface mechanisms.

Hardware Infrastructure:

- **Cryogenic Systems:** Willow's qubits operate at temperatures just above absolute zero to maintain superconductivity and minimize decoherence. This necessitates sophisticated cryogenic refrigerators, known as cryostats, to achieve and sustain these ultra-low temperatures.

[Quantum AI](#)

- **Control Electronics:** Precise control of qubit states is managed by advanced electronics that generate and deliver microwave pulses. These pulses manipulate qubit states and facilitate gate operations essential for quantum computations.
- **Quantum-Classical Interface:** Integrating quantum processors with classical computing systems is crucial for tasks such as qubit control, error correction, and result interpretation. This interface enables seamless data exchange between quantum and classical components.

[Google Patents](#)

Manufacturing Process:

- **Superconducting Materials:** Willow utilizes superconducting qubits, likely fabricated from materials such as aluminum or niobium, which exhibit zero electrical resistance at cryogenic temperatures.

[Wikipedia](#)

- **Josephson Junctions:** These are fundamental components of superconducting qubits, allowing for the control of quantum states. Their fabrication involves precise layering and patterning techniques to achieve the desired quantum behavior.
- **Dedicated Fabrication Facility:** Google developed the Willow chip in its own fabrication facility, enhancing control over the manufacturing process and enabling rapid iteration and optimization of qubit designs.

[Reuters](#)

Interface Mechanisms:

- **Microwave Control Signals:** Qubit manipulation is achieved through microwave pulses that induce transitions between quantum states, facilitating gate operations and entanglement.
- **Readout Resonators:** Coupled to qubits, these resonators enable the measurement of qubit states by detecting frequency shifts corresponding to different quantum states.
- **Classical Computing Integration:** Classical processors are integrated on the same chip as quantum processors, allowing for efficient data exchange and real-time error correction.

[Google Patents](#)

By meticulously engineering each aspect of the hardware infrastructure, manufacturing process, and interface mechanisms, Google has enhanced the performance and reliability of the Willow quantum chip, marking a significant step toward practical quantum computing applications.

QUESTION

Is qubit a hardware device or unit of information. It is not clear from the above

ANSWER

A **qubit** is both a **unit of quantum information** and a **physical hardware device** that encodes this information.

As a Unit of Information:

- A **qubit** represents the basic unit of quantum information, analogous to a bit in classical computing.
- Unlike a classical bit, which is strictly 0 or 1, a qubit can exist in a **superposition** of both states, described mathematically as a combination of the states $|0\rangle$ and $|1\rangle$ with associated probabilities.
- This probabilistic nature enables qubits to perform multiple computations simultaneously, giving quantum computers their unique power.

As a Physical Hardware Device:

- A **qubit** is implemented using physical systems capable of exhibiting quantum mechanical properties. Common hardware implementations include:
 - **Superconducting Circuits:** Use Josephson junctions to form superconducting loops that can encode qubit states. (e.g., Google's Sycamore and Willow chips.)
 - **Trapped Ions:** Use ions confined and manipulated using electromagnetic fields.
 - **Photonic Qubits:** Use properties of photons, such as polarization or phase.
 - **Spin Qubits:** Use the spin states of electrons in quantum dots.
 - **Topological Qubits:** Use anyons, a type of quasiparticle, to provide fault-tolerant operations.
- In the context of Google's **Willow chip**, qubits are superconducting devices constructed from materials like niobium or aluminum and cooled to near absolute zero to exploit quantum mechanical effects.

In summary, a qubit is both a theoretical construct for encoding quantum information and a physical device designed to embody and manipulate this information in a quantum computer.

QUESTION

What is a states' resolution between 0 and 1? In other words, how many distinct superposition states exist between 0 and 1?

ANSWER

In theory, the number of distinct superposition states between $|0\rangle$ and $|1\rangle$ for a single qubit is **infinite**, because a qubit's state is described by a point on the surface of a **unit sphere** in a complex vector space (the **Bloch sphere**).

Explanation:

A qubit's state is expressed as:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, |\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

where:

- α and β are complex numbers.
- $|\alpha|^2 + |\beta|^2 = 1$, ensuring the total probability is 1.

This means:

- $|\alpha|^2$ represents the probability of measuring the state as $|0\rangle$.
- $|\beta|^2$ represents the probability of measuring the state as $|1\rangle$.

Visualization on the Bloch Sphere:

The state of a qubit can be represented as a point on the Bloch sphere, using two angles:

- **θ (theta):** Polar angle (0 to π), which determines the probability distribution between $|0\rangle$ and $|1\rangle$.
- **ϕ (phi):** Azimuthal angle (0 to 2π), which determines the relative phase between $|0\rangle$ and $|1\rangle$.

Resolution:

- Since α and β are continuous complex numbers and the state is normalized ($|\alpha|^2 + |\beta|^2 = 1$), there are an **infinite number of possible superposition states**.
- However, in practical terms, the resolution of states depends on the precision of the physical system controlling the qubits (e.g., how finely the control electronics can manipulate θ and ϕ) and the ability to distinguish states experimentally.

Practical Considerations:

- Real systems are limited by noise, decoherence, and hardware precision. These factors reduce the effective number of distinguishable superposition states.
- For example, if a system can control θ and ϕ to a precision of 10^{-n} , then the effective number of distinct states is finite and depends on the achievable precision of these parameters.

In conclusion, theoretically infinite distinct superposition states exist, but in practice, this is bounded by the physical limitations of the hardware and environmental factors.

QUESTION

Are power requirements of quantum systems comparable to those of conventional supercomputers? I understand that such a comparison is difficult without taking performance (number of operations per second, for example. Or memory). So can we compare estimates, in addition to cost per performance, of the costs of the two computer sites' hardware and power infrastructure, approximately?

ANSWER

Comparing the power requirements and costs of quantum computing systems versus conventional supercomputers is indeed challenging, as these systems are fundamentally different in operation, performance metrics, and applications. However, an approximate comparison can provide insights into their relative power and cost infrastructure requirements.

Power Requirements:

Quantum Computers:

- **Cryogenic Cooling Systems:** Quantum computers, such as those using superconducting qubits, require cryogenic refrigeration to maintain temperatures near absolute zero (≈ 10 - 15 mK). This accounts for a significant portion of their power consumption.
 - Example: A dilution refrigerator for a quantum computer might consume **10-30 kW** of power continuously.
- **Control Electronics:** Operating qubits involves generating precise microwave pulses and managing control systems. The power requirements for these systems are modest compared to cooling.
 - Example: Control electronics might consume **a few kW**.

Total Quantum System Power Consumption: For a state-of-the-art quantum computer like Google's Sycamore or Willow, the total power requirement is estimated at **10-50 kW**, primarily dominated by cooling.

Conventional Supercomputers:

- Supercomputers like the Frontier at Oak Ridge or Fugaku in Japan consume **millions of watts (megawatts)**.
 - Example: The Frontier supercomputer requires **21 MW** of power for operation, including computational hardware and cooling systems.
- The cooling for classical systems, while significant, does not require cryogenic temperatures, making it relatively more energy-efficient per computational unit.

Performance Comparison (Cost per Operation):

- Quantum computers can perform specific operations exponentially faster than classical computers (e.g., Shor's algorithm for factoring large numbers). However, they are not yet general-purpose systems and only excel in niche areas.
- Classical supercomputers are optimized for general-purpose, high-throughput computations, achieving **exaflop-level performance** (10^{18} floating-point operations per second).

Cost Comparison (Hardware and Infrastructure):

Quantum Computers:

- **Quantum Hardware:** A system like Willow might cost **\$10-100 million**, including the quantum processor, cryogenic systems, and control electronics.
- **Infrastructure:** The need for ultra-low temperature cooling adds significant complexity and cost. Custom fabrication facilities and high-precision engineering also contribute.
- **Cost per Performance:** Currently **very high**, as quantum computers are not yet scalable or broadly applicable.

Supercomputers:

- **Supercomputer Hardware:** Systems like Frontier or Fugaku cost in the range of **\$500 million to \$1 billion** for full deployment.
- **Infrastructure:** Supercomputers require large physical facilities, extensive power supply setups, and traditional cooling systems, which add to their costs.
- **Cost per Performance:** Much lower than quantum systems for general-purpose computations, due to the mature technology and economies of scale.

Summary Table:

Metric	Quantum Computers	Conventional Supercomputers
Power Consumption	10-50 kW	10-20 MW
Hardware Costs	\$10-100 million	\$500 million - \$1 billion
Infrastructure Costs	High (cryogenics, cleanrooms)	High (large-scale facilities)
Cost per Performance	High (limited scalability)	Low (general-purpose efficiency)
Specialization	Niche applications (e.g., factoring, optimization, quantum simulations)	General-purpose, high-throughput

Key Takeaways:

1. **Power Efficiency:** Quantum computers consume significantly less power than supercomputers, but this comparison is skewed because they handle fundamentally different tasks and are not yet general-purpose.
2. **Cost per Performance:** Quantum systems currently have a high cost per performance metric due to their developmental stage and limited scalability.
3. **Scalability and Maturity:** Supercomputers are much more mature, with established economies of scale. Quantum computers, while promising, are still experimental and require further advances to compete effectively in general-purpose computations.

Long-term, quantum computing's lower theoretical energy needs for certain tasks might give it an edge in specific high-performance scenarios.

QUESTION

Please make estimates for ALL line items in the table and provide the TOTAL estimated cost in the last line of the table

ANSWER

Here's an expanded table with estimates for all line items, including total costs for quantum computers and conventional supercomputers:

Metric	Quantum Computers	Conventional Supercomputers
Power Consumption	10-50 kW @ \$0.10/kWh = \$8,760 - \$43,800/year	10-20 MW @ \$0.10/kWh = \$8.76M - \$17.52M/year
Hardware Costs	\$50 million	\$750 million
Infrastructure Costs	\$20 million (cryogenics, cleanrooms)	\$150 million (large-scale facilities)
Cooling Systems	\$5 million	\$50 million
Control Systems	\$5 million	\$50 million
Maintenance Costs	\$2 million/year	\$10 million/year
R&D Costs	\$25 million	\$200 million
Cost per Performance	Not directly comparable, niche tasks (high cost per operation currently)	Established, scalable (low cost per operation)
Total Estimated Cost (Initial)	\$107 million (hardware + infrastructure)	\$950 million (hardware + infrastructure)
Total Annual Operational Cost	\$10.76 million/year (power + maintenance)	\$28.76 million/year (power + maintenance)

Details of Estimates:

Quantum Computers:

1. **Power Consumption:**
 - Based on cryogenic system requirements (10-50 kW).
 - Cost: \$0.10/kWh * operating hours/year (≈8,760 hours).
2. **Hardware Costs:**
 - Includes superconducting qubits, Josephson junctions, and custom fabrication.
3. **Infrastructure Costs:**
 - Specialized cryogenics and cleanrooms for assembly/testing.
4. **Cooling Systems:**

- Costs for dilution refrigerators and support systems.
- 5. **Control Systems:**
 - Electronics for microwave pulse generation and qubit state readout.
- 6. **Maintenance Costs:**
 - Estimated at \$2 million/year for a small-scale quantum system.
- 7. **R&D Costs:**
 - High due to early-stage technology.

Conventional Supercomputers:

1. **Power Consumption:**
 - Typical consumption of 10-20 MW, based on current supercomputing facilities.
2. **Hardware Costs:**
 - Includes processors, memory, and storage for systems like Frontier or Fugaku.
3. **Infrastructure Costs:**
 - Large data center facilities with advanced cooling systems.
4. **Cooling Systems:**
 - Air or liquid cooling systems for high-density racks.
5. **Control Systems:**
 - Management software, networks, and operational tools.
6. **Maintenance Costs:**
 - Based on typical figures for exascale computing facilities.
7. **R&D Costs:**
 - Spread over a larger scale, typically shared among multiple institutions.

Total Estimated Costs:

- **Quantum Computers (First Year):** \$107M (initial) + \$10.76M (annual) = **\$117.76 million.**
 - **Conventional Supercomputers (First Year):** \$950M (initial) + \$28.76M (annual) = **\$978.76 million.**
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Conclusion:

Quantum computers have a lower total initial and operational cost, but their high cost per performance (due to niche applications and low scalability) limits their competitiveness against conventional supercomputers, which offer general-purpose, high-throughput performance at a larger upfront and operational cost.

QUESTION

Based on the above, what is the advantage of investing in quantum computing? Are there ways to improve the conventional computing systems so that they would provide the bottom-line performance competitive with quantum computer systems, and what are they?

ANSWER

Advantages of Investing in Quantum Computing

Quantum computing offers transformative potential in areas where classical computing is inefficient or infeasible. Here's why investing in quantum computing makes sense:

1. **Exponential Speedup for Specific Problems:**
 - Quantum algorithms (e.g., Shor's for factoring, Grover's for search) provide exponential or quadratic speedups for tasks that classical computers struggle with, such as:
 - Cryptography (breaking RSA encryption)
 - Optimization problems

- Quantum chemistry simulations
 - Machine learning (quantum-enhanced models)
 - 2. **New Frontiers in Science and Technology:**
 - Quantum computers can simulate quantum systems directly, enabling breakthroughs in:
 - Drug discovery and material science.
 - High-energy physics and cosmology.
 - Renewable energy solutions, such as more efficient solar cells or batteries.
 - 3. **Energy Efficiency for Certain Problems:**
 - For specific problems where quantum computers offer speedups, they could perform tasks with significantly lower energy consumption than classical supercomputers.
 - 4. **Potential for Long-Term Scalability:**
 - While quantum computing is still in its infancy, investment in R&D could lead to scalable, fault-tolerant quantum systems capable of broader applications, increasing their competitiveness over time.
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Ways to Improve Conventional Computing Systems:

While quantum computers excel at niche tasks, conventional computing systems are versatile and can be optimized further to close the gap for certain quantum-advantaged areas:

1. Specialized Accelerators:

- **ASICs (Application-Specific Integrated Circuits):**
 - Tailored for specific tasks like cryptography or optimization.
- **FPGAs (Field-Programmable Gate Arrays):**
 - Flexible hardware for specialized workloads.
- **GPUs (Graphics Processing Units):**
 - Ideal for parallelizable tasks like machine learning and simulations.

2. Neuromorphic Computing:

- Mimicking the structure of the human brain, neuromorphic systems can efficiently handle tasks like pattern recognition, optimization, and AI.

3. Improved Algorithms:

- Classical algorithm optimization (e.g., approximation algorithms) can reduce computational complexity, making some problems tractable on classical systems.
- Hybrid quantum-classical algorithms can distribute workloads to leverage the strengths of both systems.

4. Energy-Efficient Architectures:

- Implementing low-power architectures and improving cooling systems can significantly reduce energy consumption for large-scale computations.

5. Analog and Optical Computing:

- Analog computing can solve certain types of optimization and simulation problems more efficiently than digital systems.
- Optical computing, using light instead of electricity, offers high-speed, low-energy processing for specific tasks.

6. Distributed Supercomputing:

- Leveraging cloud-based distributed computing can aggregate resources from multiple systems to solve large problems more efficiently.
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Why Quantum Computing is Still Worth Pursuing:

Even with improvements in conventional computing, certain problems remain fundamentally hard (e.g., factoring large numbers, solving complex quantum systems) due to their inherent computational

complexity. Quantum computers, by exploiting quantum mechanics, have the potential to transcend these limitations in ways classical systems cannot.

Key Takeaway:

While enhancing conventional computing is critical for short- and medium-term performance gains, investing in quantum computing prepares us for a future where exponential improvements in specific domains can revolutionize industries. The two paradigms are likely to coexist and complement each other, with classical systems handling general-purpose workloads and quantum systems tackling specialized tasks.