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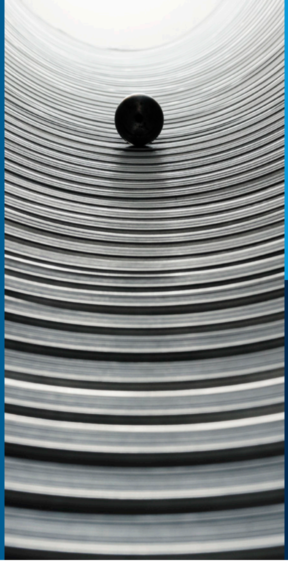

Counterpoint Global Insights

Quantum Computing

EDGE | COUNTERPOINT GLOBAL TEAM | October 2020

Quantum computing was first theorized in 1981 as a way to address a subset of exponentially complex computing problems that classical computers can't solve. It has taken more than three decades, but we are now at the cusp of moving from scientific theory to commercial reality.

Quantum computers rely on quantum mechanical properties of matter to encode data and perform calculations. These effects, which include superposition and entanglement, occur only at atomic and subatomic scales. Because quantum computers process information in a fundamentally different way than classical computers do, they can tap an exponential increase in computing power. We are likely to achieve quantum supremacy, the point at which quantum computers can solve problems that classical computers cannot, in the next few years. This will move quantum computing from the realm of science project to solving real challenges.

How It Works

Scientists including Albert Einstein, Max Planck, and Erwin Schrödinger developed the theory of quantum mechanics in the early 1900s. This new theory explained phenomena they saw in their experiments but were unable to reconcile with classical Newtonian physics. These phenomena enable quantum computing.

The fundamental building block in classical computing is the bit, which is either a 0 (the transistor is off) or a 1 (the transistor is on). Transistors, which were invented in 1947, are the building blocks of microprocessors and other computer chips. Computing power has continuously improved by shrinking the size of transistors but we are now running into physical limits.

The fundamental building block in a quantum computer is the quantum bit (qubit). As in classical computing, the qubit also takes the form of a 0 or a 1. But here is where it gets tricky. Due to the quantum phenomenon of superposition, a qubit can also be a 0 and a 1 at the same time. This enables a qubit to store more information than a bit. Quantum computers also benefit from the phenomenon of entanglement, or what Einstein called "spooky

COUNTERPOINT GLOBAL

WELCOME TO THE EDGE.

Morgan Stanley Investment Management's Counterpoint Global shares their proprietary views on a big idea that has the potential to trigger far-reaching consequences—ideas such as blockchain, autonomous vehicles, machine learning and gene editing.

Counterpoint Global's long-term ownership mindset emphasizes perspective, insight and thinking across categories, while our investment process focuses on identifying unique companies with sustainable competitive advantages. Through The EDGE, we share our framework for thinking about change and our process for recognizing patterns that may drastically alter the investment landscape over the longer term.

This work complements our team's more traditional, fundamental research to create a framework for long-term investing that is grounded in intellectual curiosity and flexibility, perspective, self-awareness and partnership.

action at a distance." When qubits become entangled, they become intrinsically linked and hence no longer act independently. Acting on one qubit effectively acts on all the entangled qubits simultaneously. Superposition and entanglement allow quantum computers to process information simultaneously. This means that they have the potential to process massive amounts of data exponentially faster than can a classical computer.

Here's why quantum computing is so groundbreaking: With classical computers, computing power doubles as the number of bits doubles. With quantum computers, computing power doubles when an incremental qubit is added. Today quantum computing is in its infancy, similar to where classical computing was in the early 1950s. And challenges remain. For example, the transistor is the standard form factor for a bit in classical computing, but there is no standardized qubit in quantum computing. Scientists are pursuing multiple methods to build qubits, including superconducting circuits, ion traps, and silicon quantum dots. The largest quantum computers today have fewer than 100 qubits and are not yet capable of performing useful tasks. However, new applications will blossom as quantum computer hardware improves.

> Quantum computing is so potentially disruptive because the computing power doubles with every incremental qubit added to the computer.

Why It's Disruptive

Ironically, one of the first likely applications of quantum computing is to break encryption on classical computers. The secure transfer of data over the internet relies on public key cryptography, which uses a public key to encrypt data and a private key to decode it. Public key cryptography is currently based on prime number factoring. The principle is that it is very easy for a computer to multiply two prime numbers together to produce a third number, but exceedingly difficult for a computer to start with the third number and determine its prime factors. The private key is derived from the prime numbers while the public key is derived from their product. Users can make data secure by making the prime numbers so large that factoring their product through brute force is intractable for even the most powerful supercomputers.

Peter Shor, a professor of mathematics at MIT, invented his eponymous algorithm in 1994 that demonstrated that quantum computers would excel at this factoring problem. A quantum computer could crack a 2048-bit RSA encryption, the gold standard today, in as little as eight hours.[1] RSA-2048 remains secure because the quantum hardware needed to break it does not yet exist. But it could in theory be broken with a perfectly functioning quantum computer of just 4,100 qubits. Based on the present rate of progress, it is likely that a quantum computer will exist within the next decade that will be able to crack today's public key cryptography. Companies, governments, and organizations that rely on public key cryptography (i.e., anyone who sends or receives data via the internet) will therefore need to transition to security protocols that quantum computers can't crack. This change might present cybersecurity companies opportunities and risks and could provide a pathway for new entrants into the field.

While quantum computing is still in the early stage of research, it shows promise in other areas as well. It was originally proposed as a way to model quantum physics and chemistry and those remain promising applications. Classical computers have difficulty modeling the behavior of molecules accurately because a molecule's complexity increases exponentially with the number of electrons in the molecule. For example, caffeine ($C_8H_{10}N_4O_2$), is too complex to model on a classical computer even though it is not a large molecule. This complexity arises because the laws of quantum mechanics govern the behavior of electrons. Electrons are exceedingly difficult to model on classical computers as they can exist in superposition and become entangled.

Here is where quantum computing has a huge advantage. A quantum computer superposes and entangles its own qubits, which innately models the behavior of electrons in the molecule. This allows a quantum computer to process significantly more data than a classical computer can. The hope is that scientists can fundamentally understand how molecules work on a subatomic level, which will allow them to design better materials, catalysts, and drugs. For instance, bacteria convert atmospheric nitrogen into ammonia using the enzyme nitrogenase more efficiently than do humans, who use the Haber-Bosch process. Scientists know that nitrogenase catalyzes the reaction but still do not understand how. They hope that a better understanding of nitrogenase will allow them to design a more efficient process for making ammonia, the key raw material for nitrogen fertilizers. Producing ammonia more efficiently would not only lower costs but would also reduce greenhouse gas emissions. This type of modeling, made possible by quantum computers, will enable scientists to design everything from better batteries to more efficient solar panels to high-temperature superconductors.

Quantum computing has other potential applications. It could shorten the time required to perform an internet search. It could tackle all sorts of optimization problems such as scheduling, routing, and options pricing. Quantum computing may even apply to machine learning. In each of these domains, quantum computing should be significantly faster than classical computing but may not demonstrate the same exponential increase in processing speed as in cryptography and quantum simulation.

Challenges

Quantum computing is still in its infancy and there are still a lot of challenges. The incredible power of quantum computers comes from their ability to harness superposition and entanglement. But these quantum phenomena are very fragile. Decoherence (i.e., losing superposition through the quantum computer's interactions/entanglement with the external environment) causes the quantum computer to lose information to its external environment, similar to how a cooling stove loses heat to its surroundings. This introduces errors into the computer's calculations. Preventing decoherence requires extreme measures such as chilling computers to absolute zero and isolating them from all forms of electromagnetic radiation and sound.

Even with these extraordinary efforts, a quantum computer may have only milliseconds to perform calculations before decoherence renders its results useless. Scientists need to increase coherence time for quantum computers to be truly useful. Quantum computers by nature are error prone because noise can creep into the calculations even without full decoherence when qubits are exposed to the slightest perturbation. Classical computers, by contrast, are discrete and predictable. Scientists are working on error mitigation and error correction strategies simultaneously in order to make quantum computers more practical.

Scaling is a related obstacle. Adding more qubits to a computer increases challenges with decoherence and can add errors into calculations. Figuring out how to increase the number of qubits while reducing errors is a huge focus of research. Finally, scientists need to develop new algorithms

[1] Emerging Technology from the arVix. (May 30, 2019). How a quantum computer could break 2048-bit RSA encryption in 8 hours. Retrieved from https://www.technologyreview.com/s/613596/how-a-quantum-computer-could-break-2048-bit-rsa-encryption-in-8-hours/.this.

to unlock potential applications for quantum computers because they work completely differently than classical computers do.

Conclusion

The notion that Moore's Law, the idea that classical computing capability doubles every two years, is dead has gained traction in recent years. Quantum computing offers a possible path to continue the improvement in computing. While still nascent, quantum computing has the potential to improve much faster than the rate suggested by Moore's Law. In fact, quantum computing is said to follow Neven's Law, which states, "Quantum computing is experiencing doubly exponential growth relative to conventional computing." If Neven's Law proves true, we can expect to see huge advances in quantum computing over the next decade. Quantum computing offers the potential to improve our lives by enabling everything from better renewable energy technologies to new drugs to cure complex diseases. Quantum computing could become a foundational technology in the decades ahead.

Other Disruptors

Other themes the team is currently researching include

- Blockchain
- Autonomous vehicles
- Machine learning
- Automation/robotics

Counterpoint Global

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SAM CHAINANI	Head of Counterpoint Global ~ New York, Technology	29	29	25
JASON YEUNG	Health Care	28	23	21
ARMISTEAD NASH	Business Services, Software	25	23	21
DAVID COHEN	Consumer	37	32	26
ALEX NORTON	Consumer, Industrials, Technology (ex Software)	30	25	25
MANAS GAUTAM	Head of Global Endurance, Generalist	13	10	10
ANNE EDELSTEIN	Co-Head of Vitality, Health Care	14	7	7
JENNY LEEDS	Co-Head of Vitality, Health Care	9	6	6
ABHIK KUMAR	Software, Media	16	6	6
JOSHUA JARRETT	Director of Research, Generalist	20	5	5
RUOBING CHANG	Internet	13	9	5
ALEKS SAMETS	Payments	5	5	5
BETH FIFER	Health Care	13	4	4
MUHAMMADRAZA PANJU	Internet	6	4	4
PETE STOVELL	Generalist	31	4	4
MICHAEL MORITZ	Generalist	7	3	3
GINO GRAZIADIO	Generalist	1	1	1
CONSILIENT RESEARCH				
MICHAEL MAUBOUSSIN	Head of Consilient Research	39	5	5
DAN CALLAHAN	Consilient Research	20	5	5
DISRUPTIVE CHANGE RESEARCH				
STAN DELANEY	Big Ideas, Emerging Themes	24	24	21
SASHA COHEN	Big Ideas, Emerging Themes	8	8	8
JUSTIN AMEZQUITA	Big Ideas, Emerging Themes	5	5	5
SUSTAINABILITY RESEARCH				
THOMAS KAMEI	Head of Sustainability Research, Tailwinds	13	13	13
DERRICK MAYO	Sustainability Research	20	11	4
CLIENT RELATIONSHIP & BUSINESS MANAGEMENT				
MARK TODTFELD	Chief Operating Officer	30	20	6
KERRY ANN JAMES	Head of Client Relations, Portfolio Specialist	28	8	4
PRAJAKTA NADKARNI	Portfolio Specialist	21	18	14
MICK MORAN	Portfolio Specialist	11	11	3
MCKENZIE BURKHARDT	Portfolio Specialist	22	22	22
XAVIER SALAZAR	Portfolio Analyst	7	7	3
KATHRYNE HORAN	Portfolio Specialist ~ Global Endurance	13	13	3
EARL PRYCE	Portfolio Administrator	25	25	18
CHAYSE MORGAN	Portfolio Administrator	5	5	5
ERICA CASARENO	Portfolio Administrator	3	3	3
AMBER YANG	Business Management	15	7	4

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Years of Experience, Years with Firm and Years with Team are as of February 2025.

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For important information about the investment managers, please refer to Form ADV Part 2.

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