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 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.

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,
its 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 ($C_{8}H_{10}N_{4}O_{2}$), 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
designer 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
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 to unlock potential
applications for quantum computers
because they work completely
differently than classical computers do.

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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.

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**Global Opportunity**

Asia

**KRISTIAN HEUGH, Lead Investor**
- 6 Investors, 5 Portfolio Specialists

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