

WHEN COMPUTERS BECAME “CLASSIC”

UNDERSTANDING THE
RACE TOWARDS QUANTUM

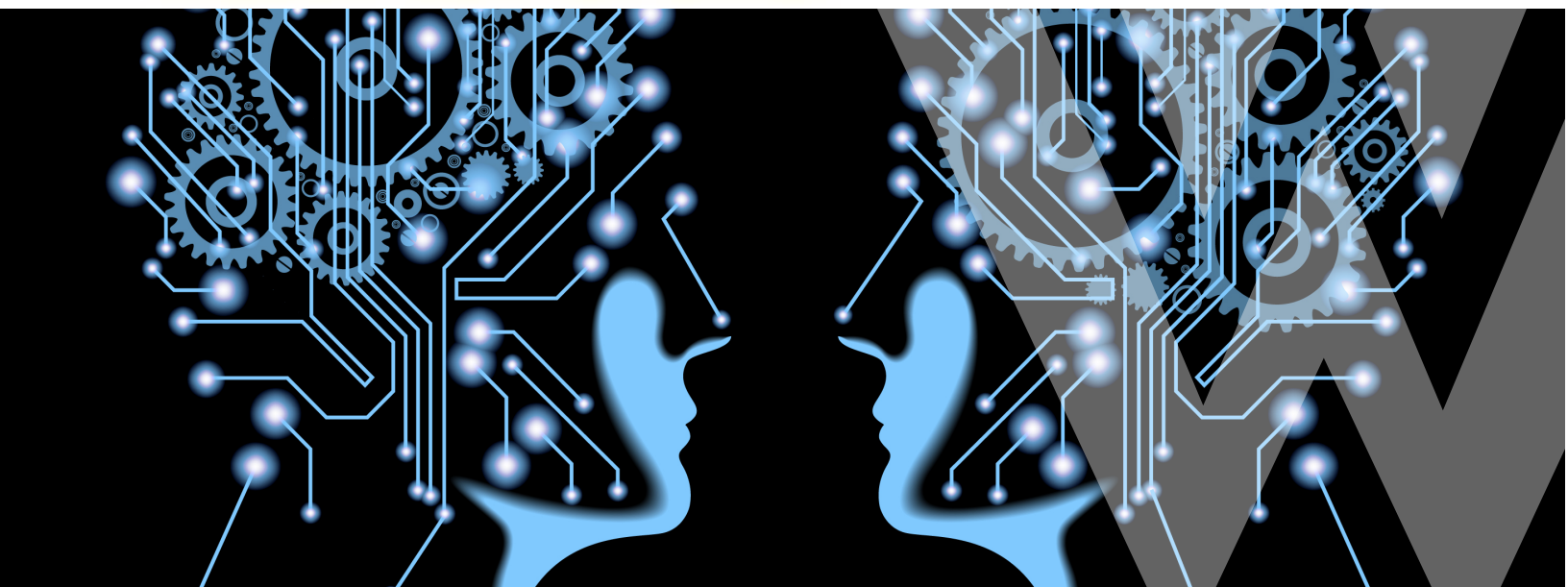
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Understanding The Race Towards Quantum Technology

The Quantum Landscape:

Quantum Physics, also referred to as quantum mechanics, is a theory that seeks to explain the behavior of particles on the universe's smallest scales—the atomic and subatomic level. Upon its emergence in the early 20th century, quantum mechanics promised to challenge long-held foundational truths of Physics that had stood since the time of Newton. As is often the case in any new field, however, the work of those who first pioneered the field raised more questions than it provided many definitive answers. Thankfully, as all good scientific inquiry ought to, research into quantum mechanics has steadily built upon itself towards a greater and more nuanced understanding of the world around us.

Today, as the underling theory has become increasingly well understood, researchers and investors are beginning to think of ways to apply lessons of quantum mechanics towards real-world endeavors.

Three prongs of research and development have come to the forefront: quantum computing, quantum communication networks (quantum internet), and quantum sensors. While one day there will likely be a nexus of these three vectors, for the purposes of this white paper it is useful to understand each in their own right.

Progress on all three fronts is contingent upon successfully discovering a consistent method of controlling particles known as quantum bits, or *qubits*, that are the most basic unit of quantum mechanics; all that differs is the intended ends to which such a discovery will be applied. Because of the commonalities undergirding the various threads of quantum research, before jumping into a discussion of the contemporary race in innovation, it is important to first understand the underlying logic that dictates quantum mechanics as a whole.

Quantum Mechanics 101

At the core of quantum theory are two central phenomenon known as *superposition* and *entanglement*. The principle of superposition dictates that on the most fundamental level quantum particles appear to occupy more than one state at the same time. That is, unlike any physical object we might interact with in our daily lives, quantum particles are neither here nor there at any given moment, but rather both here and there at once—a superposition of all possible locations. Because the exact location of a qubit is not known, quantum mechanics works in probabilities rather than absolutes in describing the whereabouts of the qubits in question. Meanwhile, the principle of entanglement dictates that pairs of qubits, if manipulated in a certain way, are able to interact in a highly correlated manner with one another regardless of how far apart they might be. In such a case, the pair of qubits are said to be entangled with one another.

Thanks to the aforementioned phenomena, quantum mechanics “has a well-earned reputation for weirdness.”¹ The technical challenges inherent in trying to impose order and control on this “weirdness” are great. The potential of such an achievement is even greater. Doing so will not only allow us to make upgrades to existing technologies, improving their performance by orders of magnitude, but will inspire the creation of new ones all together.

Quantum Computing:

As one might infer from the name, quantum computing attempts to harness these seemingly other-worldly quantum phenomena—superposition and entanglement—to process information in a novel and promising way.

IBM’s quantum computing division explains:

“Classical computers encode information in bits. Each bit can take the value of 1 or 0. These 1s and 0s act as on/off switches that ultimately drive computer functions. Quantum computers, on the other hand, are based on qubits, which operate according to two key principles of quantum physics: superposition and entanglement. Superposition means that each qubit can represent both a 1 and a 0 at the same time. Entanglement means that qubits in a superposition can be correlated with each other; that is, the state of one (whether it is a 1 or a 0) can depend on the state of another. Using these two principles, qubits can act as more sophisticated switches, enabling quantum computers to function in ways that allow them to solve difficult problems that are intractable using today’s computers.”²

As with other projects dealing with quantum mechanics, the quantum computing industry is in a relatively nascent stage and still faces many challenges ahead. At the top the list of difficulties facing researchers is the ability to efficiently control the underlying network of qubits that make up quantum computers. Since computations in a quantum computer occur when these qubits interact with one another, for a quantum computer to function usefully—outperforming a classical computer—it must maintain a large quantity of qubits. As one might suspect, the more qubits involved, the harder the task of making them perform as desired is. Any such method needs to not only work on a consistent basis, but ideally must also be scalable so as to meet the demands of the eagerly awaiting marketplace.³

Researchers have begun to tackle the first of these issues—stabilizing an increasing number of qubits—by using high-intensity cooling systems that slow everything down to a more controllable speed. According to D-Wave Systems, an industry leader in quantum computer development, their systems require that internal temperatures be roughly 180 times colder than interstellar space in order for their processors to function.⁴ As one might suspect, such cooling systems are expensive and not readily available to the greater public, which gets to the second issue mentioned above—scalability. Until this issue is solved, quantum computers, however primitive, will remain mostly relegated to the expensive and hi-tech laboratories of certain government agencies and ambitious industry giants such as D-Wave Systems, Google, IBM, and Microsoft.

While achieving the industrial or commercial scale that many aspire for has yet to be realized, there is still great optimism that the quantum computing industry is quickly approaching such a point. In recent months Google has begun offering developers early access to its quantum processors over the internet—to envision this think of how it offers cloud-based services to consumers across the world today. As reported by *Bloomberg News*, “The goal is to spur development of tools and applications for the technology, and ultimately turn it into a faster, more powerful cloud-computing service, according to people pitched on the plan.”⁵ IBM has conducted a similar program and has even begun to offer limited quantum computing services, mostly relating to matters of optimization, to interested online consumers.

Google has publicly claimed that they believe that companies will begin to see return on their investments in quantum computing within the next

five years. Whether or not their timeline holds true, it seems as if quantum computers will at some point become a reality—what will their impact be?

A team of scientists working for a research consortium that includes Google and NASA found that a relatively rudimentary quantum computer they were testing proved to be “100 million times faster than a conventional computer.”⁶ Such a leap in efficiency would obviously be an attractive sell to all sorts of businesses and consumers. Beyond just speed, however, quantum computing could offer solutions to problems that are currently intractable for even the world’s most advanced supercomputers. Practically speaking, functioning quantum computers could one day be able to aid in drug discovery and the development of personalized medicines, create more efficient fertilizers, produce better financial models, and increase the power of artificial intelligence through more nuanced machine learning, to name but a few potential applications.^{7 8}

When the day of quantum computers arrives they will unleash a fury of efficiency and optimization that will leave few industries untouched in some form.

Quantum Communication Networks:

In search of a Quantum Internet

Scientists have long flirted with the idea that the physical laws of quantum mechanics could be utilized to create a hyper-secure communication network that would be theoretically impervious to outside interference. The thinking goes that “long strings of entangled photons, shared between distant locations, can be ‘quantum keys’ that secure communications.”⁹ The secure nature of such communication would be thanks to a phenomenon known as the “observer effect”

in which the action of observing a quantum particle actually alters its physical state. This would mean that anyone trying to eavesdrop on a quantum-encrypted message—“observe” it—would instantly disrupt the shared key, alerting all involved to a compromised channel. As a result, it is believed that quantum-based communication networks would be virtually “hack-proof.”¹⁰ The hope is to one day create a worldwide quantum-based internet that would mitigate, if not remove, the dangers faced by today’s users.

The first known efforts at creating such a network were attempted by a team at DARPA in collaboration with researchers at Harvard and Boston University. In 2004, the researchers used a web of fiber optic cables to successfully send and receive quantum-encrypted communications between the three locations.¹¹ While this was a huge advance in the field, the technology was relatively rudimentary in that it could only support point-to-point connections over a single length of fiber—a ways away from any sort of viable global “internet.”

There has been incremental progress on this front since the launch of the DARPA network, notably the work done by scientists at Los Alamos National Labs, where there has supposedly been an internal, multi-nodal network up and running for several years.¹² That said, any such operation to this point has yet to create a truly robust network, one that could service any number of users spread out across the globe, as the internet does today.

But thanks to two recent space-based experiments conducted by a team of Chinese scientists, the creation of “ultrasecure communications networks, and, eventually, a space-based quantum internet,” suddenly seems more feasible than ever before.¹³

Quantum Satellites & the Chinese Advantage

In August of 2016, China launched a satellite known as the Quantum Experiments at Space Scale (QUESS), often referred to as “Micius” This marked the world’s first and only deployment of a satellite designed with the specific capacity for, and stated purpose of, conducting quantum experiments. Two such experiments are of particular note:

In June, 2017 the first experiment conducted by the QUESS aimed to push the known limits of how far apart two entangled particles could remain in a linked quantum state. While theoretically two particles should remain entangled over any distance, in practice results had been modest at best due primarily to the limits presented by today’s terrestrial fiber-optics networks. By using the vacuum of space as the medium for transportation, the QUESS team was able to achieve a far greater distance of observable quantum entanglement.

As described by *Nature*, an international journal of science, “At the heart of [the Micius] satellite is a crystal that produces pairs of entangled photons, whose properties remain entwined however far apart they are separated.”¹⁴ These entangled photons were funneled into two onboard telescopes and beamed down to two ground stations located 1,200 kilometers apart. The photons were observed at each station and it was determined that they were in a linked quantum state with one another. This successful result by the Chinese scientists easily broke the previous distance record of 144 kilometers from similar experiments.¹⁵

In a second experiment just one month later—July 2017— the QUESS team successfully “teleported” a photon from a ground station located in the Gobi desert up to the Micius satellite, which was orbiting

roughly five hundred kilometers above Earth at the time.¹⁶ Similar to the first experiment, the ability for this “quantum teleportation” to occur stems from the effects of quantum entanglement. The notion of “teleportation” is a slight misnomer, as the photon is not physically moving through space. Rather, the information it carries, such as its spin or polarization, is instantly replicated on its entangled pair, appearing as if the qubit was beamed from point A to point B without any physical movement or the passage of any time.

Taken together, the QUESS team’s newfound abilities to up-beam a quantum particle from Earth to an orbiting satellite (teleportation) and to entangle such particles over large distances, have rightly grabbed the attention of the world. Their efforts mark by far the most significant progress to-date in the quest to create a quantum internet and have left the rest of the world playing catch-up to the Chinese on this front.

Quantum Sensors:

A final area of quantum research that is likely to be of increasing significance in the years to come focuses on using quantum mechanical properties to create highly calibrated sensors that will dramatically improve the accuracy and capacity of measurement taking. This field of inquiry, known as quantum metrology, has a more established background than quantum computing or quantum communication, having already produced such revolutionary devices as the atomic clock.

The clock, which depending on the model calculates time based on measurements of superimposed or entangled particles, is considered the first-ever quantum device to escape the confines of the lab and be brought to market. It improved mankind’s

ability to measure time with a precision never seen before. Researchers today have not only improved upon the capabilities of the original atomic clock, but have started applying its ability for collecting highly accurate measurements towards other uses. Clocks, it turns out, are good for more than just keeping time.

Thanks to Einstein’s discoveries about the theory of relativity, we know that time actually elapses at slightly different rates depending on how close to Earth one measures it. Due to the unique relationship between gravity and time, a watch ticking on the surface of the planet actually measures time somewhat slower than an identical watch in outer space. Such discrepancies are imperceptible to a standard clock, but can be easily seen on today’s atomic devices.

What could one do with such a honed ability to sense gravitational differences? As *The Economist* hypothesized in a report on quantum metrology, quantum sensors could make “ultra-precise height measurements,” which could help enhance satellite imaging and GPS devices. Additionally, “at a fixed height, [they] could sense the gravitational attraction of what is below; solid bedrock would give a different reading from an oil-and-gas pocket.”¹⁷ The military sees potential use here as well, believing that such quantum gravity sensors could help them “spot moving masses underwater, such as submarines or torpedoes.”¹⁸ The potential doesn’t end there as quantum sensors could spell big things for the ongoing push towards self-driving cars: “these high-precision devices will be of great interest to carmakers, and in particular to the autonomous-vehicle industry, the success of which will depend on accurate sensing of the movements of cars and their surroundings.”¹⁹

Unlike quantum computers, which once they reach market-readiness will likely operate behind the scenes and out of view of most consumers, quantum sensors are primed to find their way into the devices we use on a daily basis.

Looking Forward:

Although there may be little to show for it to the average consumer just yet, progress in the development of quantum-based technologies is proceeding at breakneck speed. When the day arrives that quantum properties can be more regularly controlled, the implications for our society could be on the scale of the introduction of the classical computer or the internet.

Governments and businesses alike have ideas of what they believe quantum technology could mean for their individual agendas. These ambitious predictions and potential applications would substantively impact all sectors of the global economy if they were to come to fruition. In all likelihood, however, these outlooks are too myopic in their scope.

In the early days of the internet, researchers believed they were merely creating an advanced communication network that would help the government coordinate its operations more efficiently. Today, the Internet's domain far outstrips the intent or even comprehension of its original creators. The same is likely to be true for quantum. As the technology advances and becomes more democratized, the full force of the market will eventually take over and quantum-based technologies will take on applications not yet even considered. In doing so, they will disrupt existing industries and create new ones.

The remaining hurdles facing developers today are primarily engineering in their nature, not scientific. As history has proven before in analogous technological quandaries—developing the nuclear bomb or putting a man on the moon—if the underlying science is relatively understood, and if motivation is great enough, the engineering knowhow will eventually follow. This means that with enough time, trial and error, and investment, the challenges standing in the way of a true quantum leap will likely one day be solved. The potential that functioning quantum technologies hold is too great not to demand such an effort.

Endnotes

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