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A Case-Based Study of Quantum Mechanically Based Technologies: Their Operations, Affected Industries, and Intersections With U.S. Laws and Regulations

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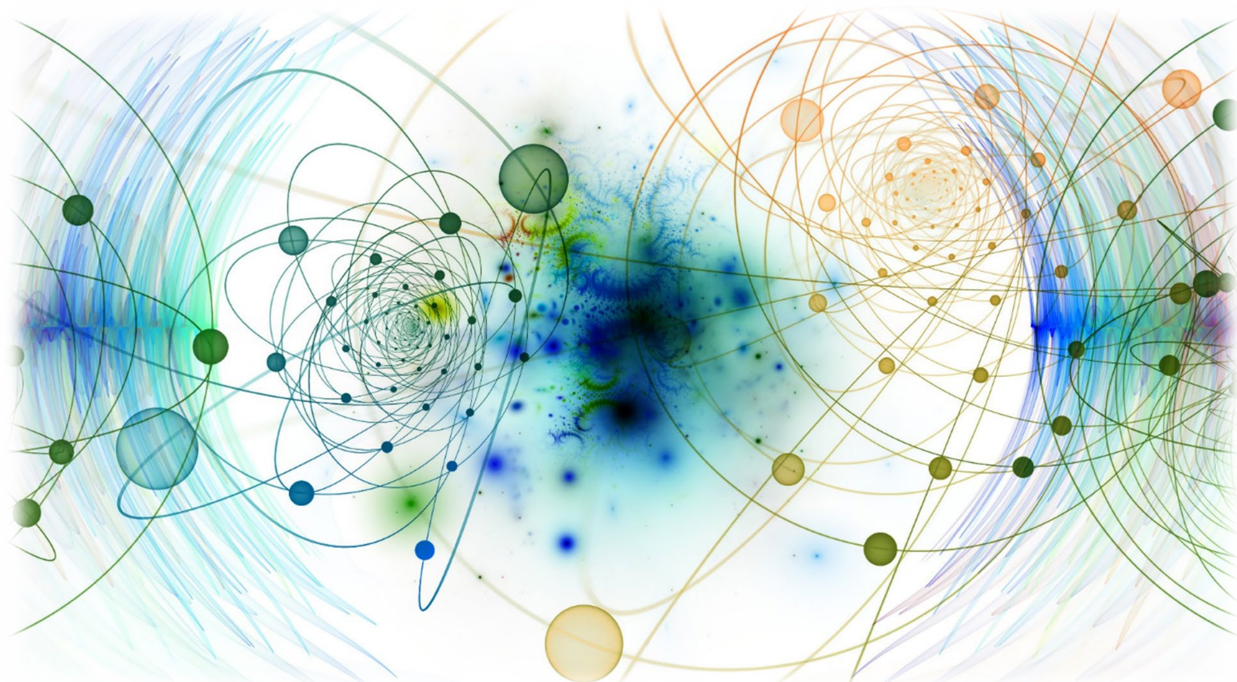

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I. Introduction

Technologies based on the principles of quantum mechanics [28] promise to catalyze significant technological and scientific progress for future societies, and with good reason. Quantum technologies possess unique advantages over their classical counterparts including dramatically improved accuracy, sensitivity, and computational power. While quantum effects cannot be directly perceived at the scale of horses and humans, they underpin our universe at its most fundamental level. As such, quantum phenomena establish intrinsic boundaries on the set of all possible measurement outcomes – the "observables" that we can see, measure, and even the extent of information that we can "know." By harnessing quantum effects, humans can design technologies that extend our capabilities for sensing and computation up to these fundamental limits. Though still an emerging field, quantum information science hints at a future where technologies based on quantum principles drive scientific discovery and innovation across multiple disciplines. Importantly, as we shall see, quantum technology provides a significantly larger state space for scientists and engineers to work in, and with continued progress, is assured to benefit society indefinitely and in unexpected ways as it heads into the future.

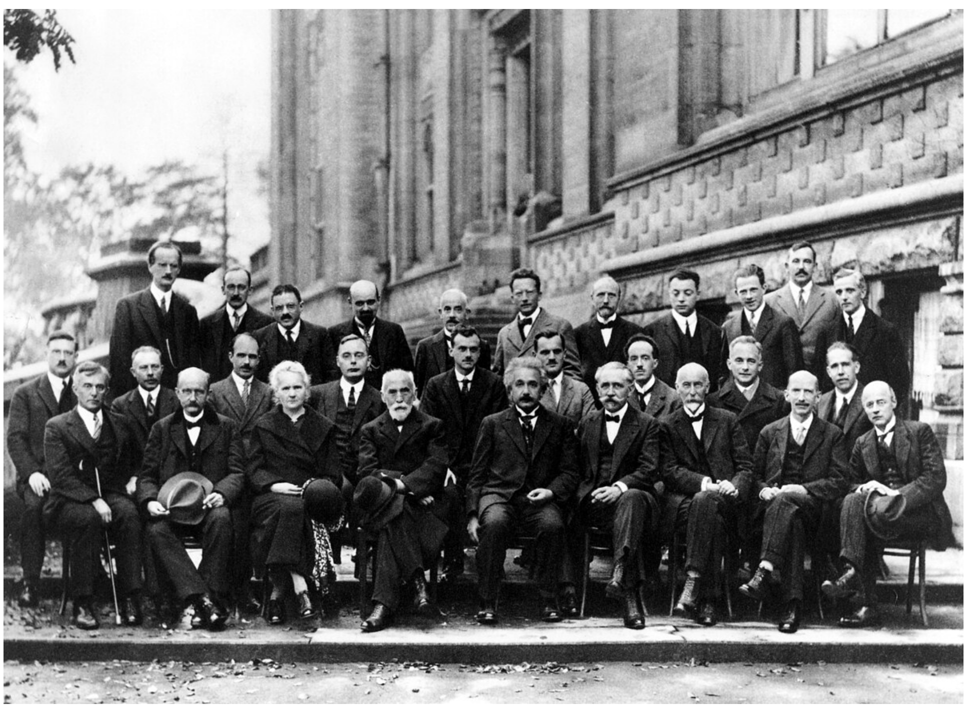


Figure 1: Fifth conference participants, 1927. Institut International de Physique Solvay in Leopold Park

Pictured: A. Piccard, E. Henriot, P. Ehrenfest, E. Herzen, Th. De Donder, E. Schrödinger, J.E. Verschaffelt, W. Pauli, W. Heisenberg, R.H. Fowler, L. Brillouin; P. Debye, M. Knudsen, W.L. Bragg, H.A. Kramers, P.A.M. Dirac, A.H. Compton, L. de Broglie, M. Born, N. Bohr; I. Langmuir, M. Planck, M. Curie, H.A. Lorentz, A. Einstein, P. Langevin, Ch. E. Guye, C.T.R. Wilson, O.W. Richardson

A. A Brief History of Quantum Mechanics

Historically, there has been a tension in physics, dating back to a 1927 dispute between Albert Einstein *et al.* and Niels Bohr *et al.* [9] over which description of the laws of nature were truly fundamental: the laws of the quantum realm [10] (which govern interactions between photons, electrons, atoms, and other elementary particles) vs. the laws of general relativity [26] (which govern gravity, cosmological expansion, and the geometry of space-time). Both presented undeniable accuracy in their own regimes but were mathematically incompatible at high energies and over short distance and time scales.

However, it has recently (since 2014) become understood that general relativity and quantum mechanics appear to be two sides of the same coin, in what has come to be known as ER = EPR [4] and are thus fundamentally inseparable [27]. More importantly, although this understanding is still incomplete, it has released the tension between the two previously incompatible explanations of the universe and generated new ideas and advancements in mathematical physics. The current understanding of nature is encompassed by the holographic principle [27], which describes the universe (including gravity) as part of a "bulk" space whose interactions are emergent properties resulting from holographic projections of interacting quantum fields on the surface of its boundary. This new understanding offers truly mind-blowing insights, but also points squarely to quantum theories as being the be-all, end-all explanations for the world, its constituents, and surroundings. This is known as the Ads/CFT [62] correspondence conjecture initially proposed by Juan Malacena and later accepted by Dr. Leonard Susskind and others, including the scientific cadre at CERN as unconditionally binding the two theories.

Classical theories [29] of physics place no fundamental limits on how precisely we can measure quantities such as time, position, energy, and other "observables." However, quantum mechanics (henceforth "QM") sets well-defined theoretical bounds on measurement precision in the form of unimaginably small Planck units. Although these boundaries technically represent restrictions over classical theories, they also provide a clear measure of the scale of the gap that exists between current technological capabilities and the potential for vastly improved devices that utilize the full fidelity and performance characteristics permitted by QM. By quantifying the boundaries of nature, QM exposes the potential to develop devices of unimaginable superiority over any technology thus conceived.

B. The Development of Quasi-Classical Quantum Devices

Technically, semiconductor circuits and devices (dating back to at least 1947 [22]) such as transistors and diodes are QM-based devices, as they do rely on QM effects such as tunneling (passing a current through a classically unpassable barrier, such as in a tunneling diode) and particle/hole creation and annihilation (the hopping of electrons into and out of atomic vacancies, creating QM currents in semiconductor devices). However, these components can only be considered "quasi-classical" because their primary utility was not the exploitation of QM phenomena (which was largely incidental), but to serve as miniaturized counterparts to those originally conceived and developed by Alan Turing in his laboratory in Bletchley Park, U.K. ca. 1939 [19], such as vacuum tubes and rectifiers.

However, due to the improved speed, efficiency, and miniscule footprint of these quasi-classical devices, computers and other electronics could finally be moved from laboratories into reasonably sized consumer products, such as the transistor radio [48], televisions, and more. With no apparent lower limit on device size, there seemed to be no limit (other than the need for new technological developments) to the number of transistors that could be fabricated onto a single circuit. This curious observation was recognized by Gordon Moore in 1965, who predicted that the number of components printed on a chip would likely double roughly every 2 years or so, a prediction known as "Moore's Law" [18].

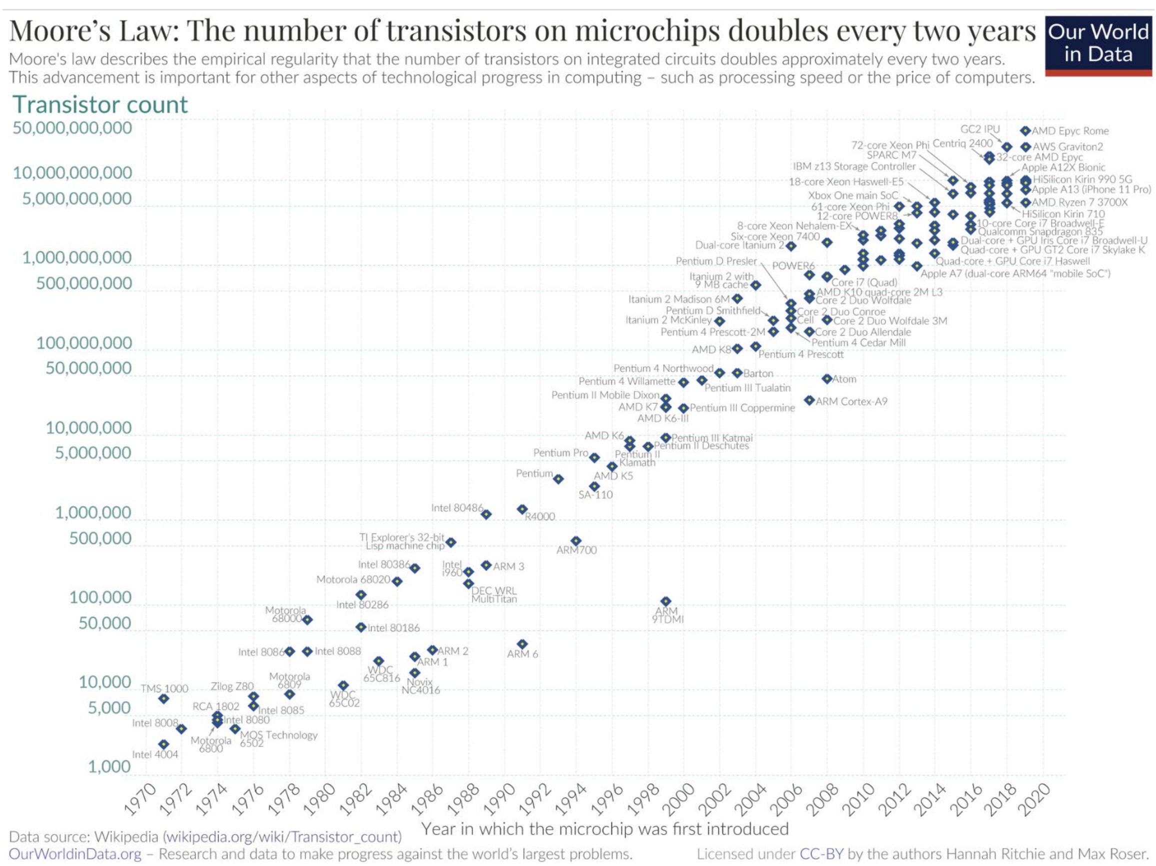


Figure 2: Moore's Law Since 1970

By the 1970's, a new technology known as CMOS [49] (complimentary metal-oxide-semiconductors) had become popular. While analog electronics continuously consumed power, CMOS circuits used logic gates to switch between two binary states (a "0" or a "1" state), and only consumed power *during the transition* between these two states, but not while in either state. This dramatically reduced the power consumption and heat of semiconductor chips, allowing for a greater density of components. Additionally, since CMOS relied on only 2 (binary) states, the component ushered in the digital age, where principles from Boolean algebra were used to build the precursors to modern-day computers, phones, and other electronics.

With ever improving circuit and component designs, Moore's law continued to hold until only recently; However, the trend has begun to flatten out [21], and as there is widespread agreement that the limit will soon be met as transistor gates approach the 5 nm scale (the 2022 AMD Zen 4 processor uses transistors with gate sizes of 7 nm [34]).

C. Scope of this Report

Quantum mechanics (QM)-based technologies remain largely nascent, with some exceptions such as quantum key distribution (QKD)[50]. As such, comprehensively analyzing their potential impacts across sectors necessarily involves some degree of speculation. However, by examining a cross-section of emerging QM technologies, how they work, and the industries they may transform, we can glean insights into how they are poised to change laws, regulations, legal practices, necessitate new oversight bodies or agencies, and otherwise shape the world.

Before exploring specific technologies, it is instructive to clarify what makes QM systems unique, demonstrating why merely enhancing classical technologies cannot replicate their potential. While QM as a scientific field confounded even renowned physicist Richard Feynman[1], two key principles underpin its promise: **entanglement** [51] and **superposition** [52]. Grasping these concepts at a basic level illuminates the innate capabilities such technologies may unlock, particularly when used in strategic combinations.

Thus, while this paper is directed towards QM technologies and their impacts on society, most quantum technologies employ only a few basic QM phenomena in various creative ways. Accordingly, the **technical** discussion of the QM phenomena underlying these technologies will be somewhat thoroughly reviewed prior to the discussion of the technologies themselves, allowing for an abridged technical description of each technology in favor of a larger discussion over the applications and impacts of each individual technology. This structure avoids repetition

[1] "If you think you understand quantum mechanics, you don't understand quantum mechanics….I think I can safely say that nobody understands quantum mechanics." – R. Feynman

and allows the reader to educate themselves beforehand, or just skip to the socio-political ramifications of each technology in later sections.

The goal here is not to lecture on QM theory, but to highlight what distinguishes these technologies, providing useful context before surveying specific applications and their prospective legal and regulatory implications across sectors. With this background established, we can proceed to examine the technologies themselves more meaningfully. This requires a dive into Quantum Information Science (QIS), the growing field of academia upon which all QM technologies are based.

II. Quantum Information science

A. Introduction

Quantum Information Science (QIS) is a recent field of interdisciplinary research that resolves the laws of **QM with information theory**. QIS presents a framework where information can be manipulated in exquisite ways completely distinct from any classical paradigm. It is the QM analog of phase space in classical mechanics. Events in QIS occur in a quantum state space [17], which is an abstract (Hilbert) space in which different "positions" do not represent literal locations, but rather quantum states of a physical system. In QM state spaces, each unit vector represents a different state that could result from a measurement. As there is no limit on the number of vectors in the space, and because the number of dimensions [62] ("Infinite-dimensional Categorical Quantum Mechanics") in the space depends on the number of vectors, quantum state spaces can grow exponentially large, offering numerous and profound applications to QM technologies. This fact is evident from the fact that some quantum mechanical operators such as momentum ($\hat{p} = -ih/2\pi(\frac{\partial}{\partial t})$) can be written succinctly as operators in calculus but require an infinite matrix representation per Dirac's identical formulization of the same operator.

QM relies on two critical phenomena. (1) **superposition** [52] (also known as parallelism), is the ability of a quantum system to exist in numerous states simultaneously- thereby allowing diverse calculations to be performed concurrently within a single system. In contrast with traditional binary systems which oscillate between discrete '0' and '1' states, quantum systems (QM bits, or qubits) can exist in a **continuous spectrum** of possible states between (and including) the '0' and '1' states.

The second component of QM is (2) quantum entanglement [51], a phenomenon that blurs the line between individual particles and collectively binds them into a shared existence, irrespective of their spatial relationship. Once entangled, it becomes meaningless to discuss either party individually; only the entangled state as a whole has meaning. Once entangled, their properties (when measured) always correlate with each other, even if they are light-years apart. Entanglement acts as a fundamental pillar for QM computing [39], teleportation [36], and several other technologies discussed in this report.

Information Theory, formalized in 1948 by Claude Shannon [35], studies the transmission, processing, extraction, and utilization of information. Abstractly, information can be thought of as the resolution of uncertainty. In the problem of communicating information over a noisy channel, the information is thought of as a set of possible messages, and the goal is to send these messages over the noisy channel such that the receiver can reconstruct the message with a low probability of error, despite channel noise. QIS is an extension of information theory that extends classical information theory to study the processing, analysis, and transmission of QM information, also known as Von Neumann entropy [53], which can be manipulated in various ways using quantum information processing techniques. QIS also investigates the limits of what can be achieved with QM information, such as dense coding and other purely QM-based information possibilities.

Dirac Notation: Henceforth, Dirac notation may be used to explain phenomena. This is appropriate, because “1 + 0 = 1” is a true statement. But the wavefunction “|ψ> = |1> + |0>” is like a spinning coin…it will be “1” or “0” once observed, but until that point it is both “1” and “0”, with the “+” sign acting as an OR operator and I’ve ignored the $\frac{1}{\sqrt{2}}$ coefficient because it is needlessly confusing. There is good reason for this…|ψ> is a wave. What’s the value of Sin(x)? You don’t know until you’ve “looked” (or observed) “x”. Sin(x) is everything from -1 to +1, depending on x. This is superposition, and will be explained later, but a heads up to any reader caught off guard by something like “|ψ> = α|x> + β|y>. α and β are the “weights” that you will observe x or y. The full story is that α and β are complex numbers, and the probability of measuring x is <x|ψ> = $|a^2|$, or y is <y|ψ> = $|b^2|$, and $\alpha^2 + \beta^2 = 1$. This information is **not necessary to understand for this paper.** It is only provided so that bra-ket (<x| is a bra, |x> is a ket) notation is not confusing.

B. State Space is a Resource

Humans live in a state space of 3 spatial dimensions and 1 time dimension, and we have made great progress in this space. QM interactions, on the other hand, produce a vastly more expansive “state spaces” [17] in which a QM-technology can operate, and in which scientists and engineers can flex their creative muscularity in far deeper and more sophisticated ways. This may seem counterintuitive: the physical size of objects like photons and electrons are miniscule, and it might seem like common sense that more could be accomplished in a large factory than in a single office space, much less at the tip of a pencil. But this notion is misguided, because the "inner space" of QM doubles with each additional qubit, leaving subtle, spellbinding possibilities for QM technologies.

So why is there so much "space" in QM land? In summary, a qubit is like a coin flipping in the air: it is both heads and tails *simultaneously* (0 and 1) until it falls to the ground and assumes one of the two possible values. This is an example of superposition: the coin is in 2 states at once. Now, consider a classical 3-bit register. The register can only take on a single value from the set: {000, 001, 010, 011, 100, 101, 110, 111}, such as 010. If it takes this value (or state), it cannot be in any of the other states. Thus, an n-bit register can take on any n-bit value, but that is all.

A 3-**qu**bit register, however, can take on each value at once until a measurement is made. Its possible values are {0/1, 0/1, 0/1}. Since each bit is a superposition of both values at once, the combined register takes on 2^n values – in this case, 8 – **each of** the possible values that the 3-bit register could take. Thus, while a 64-bit classical register represents a single 64-bit number, a 64-qubit register takes on 2^{64} = 1.8446744e+19 values *simultaneously*. This is known as the product state [15] of the qubit register, meaning the qubit states are separable (non-entangled) which we will return to later. When measured, the product state will collapse into a single 64-bit number. But until then, it assumes all possible 1.8446744e+19 values at once. This is the source of the inner space of QM, and it is *vast*.

C. Superposition is a Resource

While we have given a general description of superposition, we have yet to see how it acts as a resource. Suppose I have an electron in a superposition of two states, $\phi(t)$ = Sin(t), and $\psi(t)$ = Sin(2t). When I observe the coin, however, I only get 1 bit of information: that the coin is in state ϕ, or it is in the state ψ. For clarification, the state of the coin:"0" or "1" requires only 1-bit. Here, that bit is 1*t or 2*t ("0" or "1"). The sinusoid doesn't matter once observed: the answer will be 1 or 2. But wavefunctions allow for interference, so a cosine function is appropriate to understand the coin's "in between" state. Prior to the measurement, the coin was in a superposition of both states, representing 2 bits of information. $\rho(t) = \Phi(t) + \psi(t)$. We can see this by plotting $\Phi(t)$, $\psi(t)$, and $\rho(t)$ simultaneously (see Figs. 3-5). The $\Phi(t)$ (orange) and $\psi(t)$ (blue) curves are simple tones, because each only contains 1-bit of information: frequency. But $\rho(t)$, the sum (in green), represents their superposition, and clearly has more *structure* to it. This is because it contains more *information* (Von Neumann entropy [53]) because we need 2 bits – 2 values of frequency – to describe it. By adding more and more curves to the state $\rho(t)$, we can carry more information in this superposition of quantum states (technically each of these states requires a $\frac{1}{\sqrt{2}}$ factor for orthonormalization, but that's not important here).

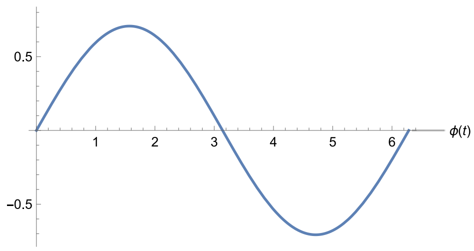


Figure 3: State Φ(t) - 1 bit of information

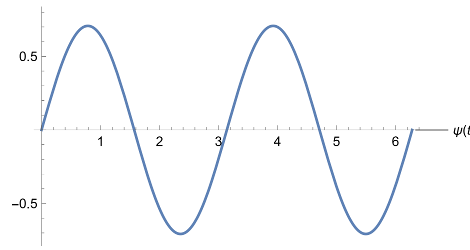


Figure 4: State ψ(t) - 1 bit of information

Φ(t) ψ(t)

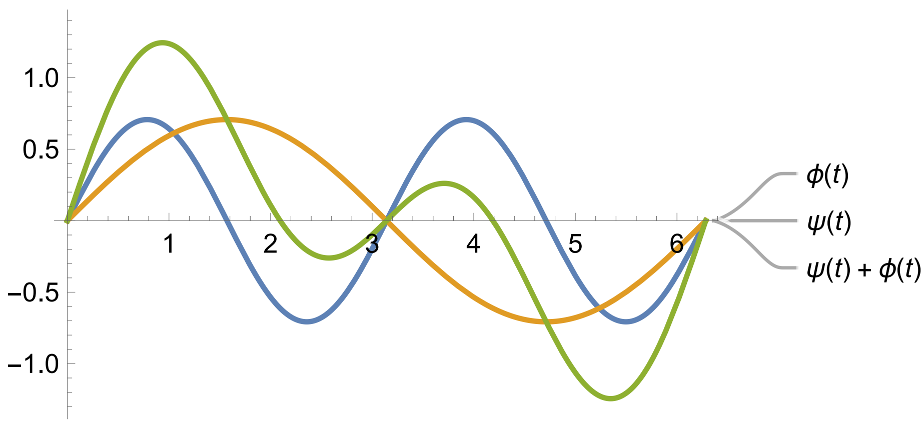


Figure 5: Φ(t), ψ(t), and ρ(t) – the superposition of the Φ(t) + ψ(t) states

Now, pure tones correspond to circles and spheres, which are common in nature; they require very little information to describe: their radius. But a square is much more complex. It doesn't seem like this would be the case at first – the information needed to make a square is just its length x height – but there are no perfect right-angles in nature, because they are discontinuous.

It would take an infinite amount of information to describe a perfect discontinuity. This can be demonstrated by looking at the number of bits required to create a Fourier approximation for a square. In the following graph, I've plotted an ideal square f(t), and successive tones containing 1, 5, 20, and 100 bits of information. It would eventually take an infinite amount of information to recreate the discontinuity at its vertices…and nothing in nature is perfectly discontinuous:

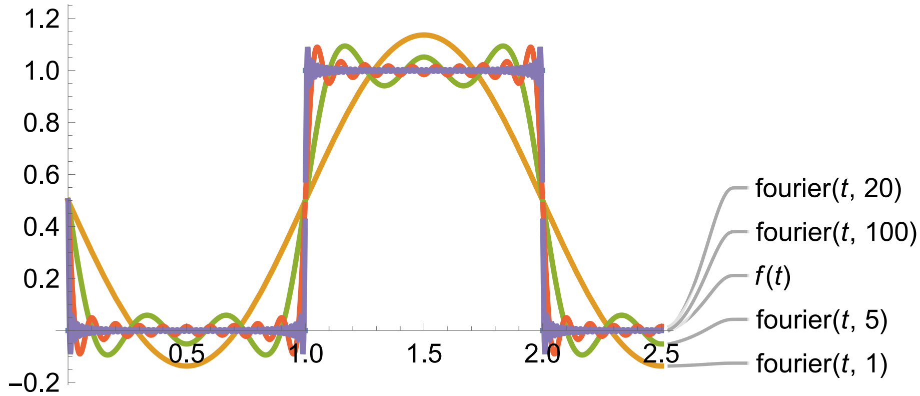


Figure 6: The amount of Information Needed to Approximate a Square

(For reference, the superposition required for the 5-bit state is ρ(t) = $\frac{1}{2} - \frac{2\text{Sin}[\pi t]}{\pi} - \frac{2\text{Sin}[3\pi t]}{3\pi} - \frac{2\text{Sin}[5\pi t]}{5\pi}$ ...0 is the 5th bit. Obviously, there is much more information in this state than in the 1-bit ϕ(t) = Sin(t) state).

So why is superposition a resource?

Parallelism [52]: In parallelism, many states are combined into a single wavefunction |ψ> via superposition. Like our 64-qubit register, the number of possible states represented by |ψ> could be enormous; however, we can perform multiple actions on |ψ> (such as shifting its phase, entangling it with |ϕ>, or any other computational operation) without destroying the superposition. This would naturally have the effect of performing the operation on each of the 2e+19 states contained in |ψ> *simultaneously*. Whereas a classical computer would have to manually perform the operation 2e+19 times, a quantum computer only needs to apply the operation once. The ability to perform such a large number of computations simultaneously is the essence of QM speedup, the characteristic that allows quantum computers to solve certain problems significantly faster than classical computers.

While superposition provides parallelism [52], one should not be fooled into thinking that *all* this information can be extracted. **This is what makes parallelism a resource**. Once an observation is made, **only one of the states will be observed** with its probability determined by the quantum state before measurement. **All other states will be "lost."** However, this is where quantum algorithms, such as Shor's algorithm [32] for factoring, and Grover's unstructured search algorithm [43] come into play.

Factorization: Shor's QM algorithm [32] substantially speeds up the process of factorization. Specifically, the algorithm finds the prime factors of a composite number in polynomial time, as opposed to classical algorithms which perform this task in superpolynomial or exponential time. While The details of how Shor's algorithm achieves this speedup are beyond the scope of this paper, the general idea involves using quantum superposition and the quantum Fourier transform to perform many calculations simultaneously (a form of quantum parallelism [52]) to quickly find the factors of the composite number. Shor's algorithm is most pronounced when the numbers to factor become very large. This is one important area where QM computers easily outperform classical computers.

The ability to factor large numbers quickly has significant implications for computer security, as many current encryption techniques rely on the difficulty of factoring large numbers to keep data safe. If large-scale quantum computers become a mainstream reality and can run Shor's algorithm effectively, these encryption techniques could become easily breakable, which is a subject of active research and discussion in the field of quantum information and cryptography.

Searching: Grover's algorithm [43] deals with searching unstructured databases. Classically, searching for a particular item in an unstructured database of N items takes N/2 queries on average, and N queries in the worst case (if the item you're looking for is the last item in the database). This is known as "linear searching" because the time complexity of the problem scales linearly with the size of the database N. Grover's algorithm provides a quantum speed up to this problem, enabling the search to be completed using only $\sqrt{N}$ queries, a significant speed-up, particularly for large values of N. It can be shown mathematically that this is the fastest possible solution to this problem. No theoretical quantum algorithm can search an unstructured database faster.

Grover's algorithm [43] performs this task by placing the system of qubits into a superposition of all possible states, which in this context corresponds to searching all elements in the database simultaneously (due to quantum parallelism [52]). It then applies a specific sequence of quantum operations known as Grover's "oracle" and the "diffusion operator" to gradually increase the amplitude of the specific state (or states) corresponding to the correct item, while diminishing the others' amplitudes. By repeating these operations $\sqrt{N}$ times, the algorithm can ensure that when a measurement is made (which collapses the superposition), the quantum system will, with high probability, fall into the state corresponding to the correct item being searched for.

An example of this utility could be an Amazon driver may be trying to optimize his route. Given 10,000 possible routes, the driver's QM computer need only make 100 queries to find the fastest route, solving the famous "postman problem" [24] using the shortest number of operations possible.

Taken together, each of these algorithms cleverly organizes the calculation of the superposition in such a way that the correct answer is obtained with high probability, effectively making use of the quantum parallelism [52] while circumventing the barriers posed by the probabilistic nature of quantum measurement. “The existence of superposition as a resource delivers significant performance gains on many information processing tasks that cannot be classically achievable.” [12] Thus, the more qubits one has in superposition, the greater their capacity to perform a large number of calculations in a single step. This makes superposition a powerful resource.

D. Entanglement is a Resource

"I would not call entanglement one but rather the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought." – Schrödinger, E.[15]. While the benefits of QM superposition, previously discussed, should be apparent to the reader, QM entanglement [51] is unquestionably the most valuable resource for all QM technologies.

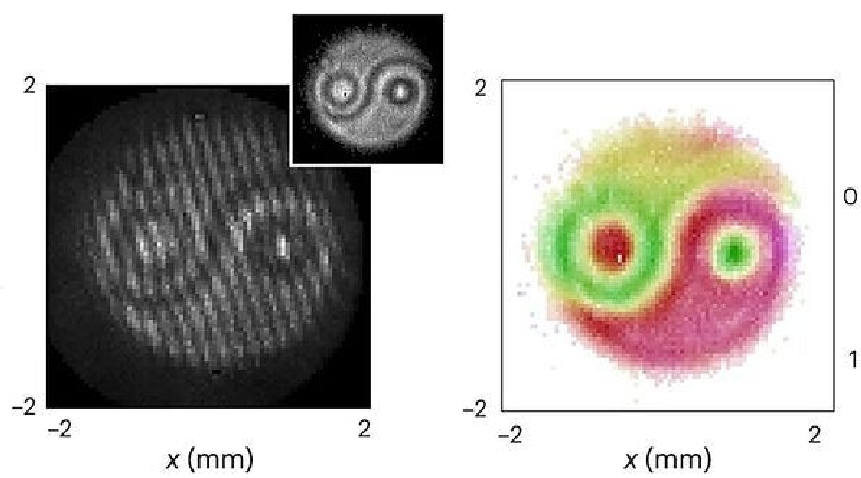


Figure 7: Entangled Photons [40]

The author of this study has remarked that “entanglement is the new oil,” and many scientists have come to believe that QM is principally defined by entanglement and nothing more. [15]. QM entanglement is the key feature of quantum mechanics, is its most counter-intuitive feature, and the one that led Einstein to call it “spooky action at a distance.” An entangled system [51] is defined to be one whose QM state cannot be factored as a product of states [15] of its local constituents.

This is a subtle but important point: in the 64-qubit register, each of the 64-qubits were in separable product states: by making an observation on a qubit the system will collapse into some 64-bit value, but the observation of a given qubit ***does not*** force a different qubit to assume an opposite state to that of the first qubit. For separable product states, it does make sense to discuss the qubits as individual entities.

$$|\Phi^+\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

$$|\Phi^-\rangle = \frac{|00\rangle - |11\rangle}{\sqrt{2}}$$

$$|\Psi^+\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

$$|\Psi^-\rangle = \frac{|01\rangle - |10\rangle}{\sqrt{2}}$$

***Figure 8**: The Four Entangled Bell States [54]*

Entangled systems [51] (see Figs. 8 and 9) are entirely different: there is a conservation of some quantity such that when one particle is found to have a definite value, like spin up, the other must become spin-down. This is why entangled states [51] are said to be inseparable; they share a property that no one particle alone possesses entirely. This makes discussing the individual particles meaningless; only the entangled state of both particles contains the state's information.

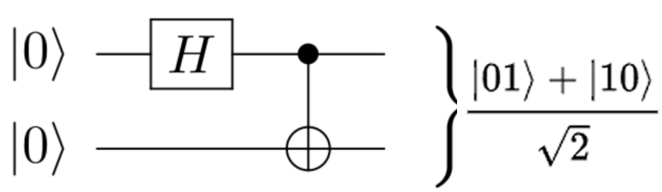


***Figure 9**: Creation of a Bell State [54] from a Hadamard Gate[65] + CNOT Gate*

There are four maximally entangled "Bell States" [54] (see Figs. 8 and 10) which form the basis for all entanglement-based technologies. Fig. 9 [64] depicts the generation of one such state from two initially separable |0>|0> states.

An important point: the Bell states [54] can easily be converted into one another with only four transformations, which correspond to the Pauli matrices [28]: (1) the identity transformation I (do nothing); (2) the q-CNOT gate "X"; (3) the q-phase-flip gate "Z"; and (4) the application of both the "X" and "Z" gates (which is equivalent to applying the i"Y" gate) – X, Y, and Z form the fundamental Pauli matrices [28]. Since these represent fundamental quantum gates, they deserve some explanation.

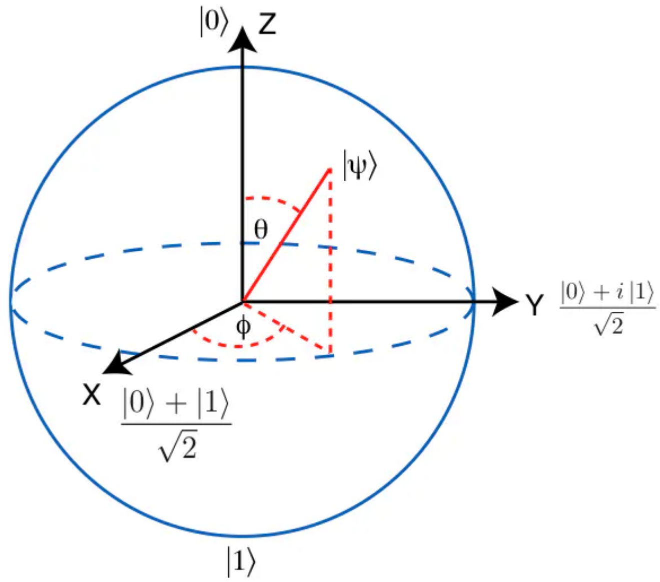


Figure 10: The Qubit Bloch Sphere and the Effect of Quantum Gates X, Y, and Z

The "X" gate is often described as the quantum equivalent of the classical NOT gate. It flips the amplitudes of the states |0⟩ and |1⟩. In **the quantum X gate**, however, the Hadamard gate [65] takes |0> → |0> + |1> (ignoring $\sqrt{2}$), and the CNOT gate acts on both states; thus, the H of |0> is |0> + |1>, And the CNOT of (|0> + |1>) with |0> creates both possibilities, causing the X operating on |00> to be $\frac{1}{\sqrt{2}}(|01> + |10>)$. ***If*** the initial bit was 1, the second will be zero, and vice versa, in superposition. It is the NOT of both potential states.

The "Z" gate is referred to as the phase-flip gate; it leaves the basis state |0⟩ unchanged but maps |1⟩ to-|1⟩. The "Y" gate is equal to 1/i times the "X" and "Z" gates. From Fig. 10 one can see how a |0> Z-gate state would transform under X and Y transformations. **The important part is that these are all merely rotations** in the complex Bloch sphere (which is a qubit) and are all 2x2 matrices known as the Pauli matrices [66]. They are identical depending on your chosen basis state.

This is depicted mathematically in Fig. 11, using only the "X" gate, consisting of a Hadamard gate [65] and a CNOT gate (**CNOT**: if the first qubit is "0", do nothing. If the first qubit is "1", flip the second qubit) on all possible inputs; equivalently I could have used I, X, Y, and Z on the same input, but that becomes more confusing because "$i = \sqrt{-1}$" comes in and is irrelevant here. The commas in Fig. 11 denote that both states are solutions, but because of **parallelism**, their sum is also a solution. It may be observed that the coefficients {00, 01, 10, 11}…correspond to the only Bell basis states [54]. This will become important when we discuss **teleportation** [36] and **superdense coding** [46], as it is ***these are the coefficients that are relevant***. When the states are passed through a second CNOT gate and second Hadamard gate [65], these coefficients will pop out.

In the entangled Bell state depicted in Fig. 9, the two qubits are in a superposition of a |01> state and a |10> state: Although there are many possible ways to create entangled Bell states through quantum circuits X, Y, and Z, not to mention other QM gates that can perform the same operation such as the Tofolli gate, but X, Y, and Z are the simplest ones. The "X" state illustrated takes a computational basis as the input, such as |0>|0>, and comprises the Hadamard gate [65] and the CNOT gate (see Fig. 9). As an example, the pictured quantum circuit of Fig. 9 takes the two-qubit input and transforms it to the third Bell state |ψ^+>. Explicitly, the Hadamard [65] and CNOT gates transform |0>|0> into a superposition of the |0> and |1> states, as mathematically verifiable as the first example in Fig. 11.

Each state has a 50/50 chance of appearing after an observation, so when either of the entangled qubits is measured, just as in our previous examples of superposition, that state becomes the "observed" state, and whichever state is observed forces the second qubit into the opposing state. Put differently, measuring the first qubit to be "0" collapses the wavefunction into the |01> state, and the second qubit comes along for the ride, taking on the "1" value. The alternative |10> state is "lost," and vice-versa if the first qubit is measured to be a "1", the |01> state is "lost." As previously noted, this will happen instantly regardless of how far the qubits may be from one another, even if that distance is 300 light-years. While we often use spin as an example, entanglement actually allows for numerous characteristics to become entangled, including charge, polarization, angular momentum, and mass. [45].

So why is entanglement a resource?

Teleportation [36]**:** Alice and Bob are given an entangled pair of qubits |A↑↓> and |B↓↑>. Alice takes her qubit |A↑↓> somewhere remote and bring in a 3rd qubit C in some state |ψ_C>. She lets |A↑↓> interact with |ψ_C>, and performs a Bell State measurement [54] on the combined qubits |A↑↓>|ψ_C>. The measurement will destroy both qubits |A↑↓> and |ψ_C> but will yield one of four possible outcomes: one of the Bell pair states, which (as we have seen from Figs. 8 and 11) can be described as {00, 01, 10, or 11}. These 2 bits give Alice the information she needs to send to Bob that will let Bob know which operations he needs to perform on his bit: (1) nothing; (2) apply "X" gate; (3) apply "Z" gate; or (4) apply "X" and "Z" gates (or equivalently iY). Whichever one of the four outcomes Alice measures, she need only transmit 2 bits classically to Bob to inform him which necessary operations (if any) to perform on |B>, which is no longer entangled. When Bob performs the operation on |B> (Say, "X"), |B> will assume the state |ψ_C>, completing the teleportation of |ψ_C>, and consuming both |A↑↓> and |B↓↑> in the process. **An important note**:

|ψ_C> has not been observed. Neither Alice nor Bob knows what state |ψ_C> is in…|ψ_C> has not been altered in any way…its information has merely been *teleported* from one qubit to another.

$$\frac{\begin{pmatrix}0\\0\end{pmatrix}_{\text{INPUT}}\begin{pmatrix}0&1\\1&0\end{pmatrix}_{H}\begin{pmatrix}1&0\\0&1\end{pmatrix}_{\text{CNOT}}}{\sqrt{2}}$$

Out[7]= $\left\{\frac{\{0\}\,\{0,1\}\,\{1,0\}}{\sqrt{2}}, \frac{\{0\}\,\{0,1\}\,\{1,0\}}{\sqrt{2}}\right\}$

$$\frac{\begin{pmatrix}0\\1\end{pmatrix}_{\text{INPUT}}\begin{pmatrix}0&1\\1&0\end{pmatrix}_{H}\begin{pmatrix}1&0\\0&1\end{pmatrix}_{\text{CNOT}}}{\sqrt{2}}$$

Out[8]= $\left\{\frac{\{0\}\,\{0,1\}\,\{1,0\}}{\sqrt{2}}, \frac{\{1\}\,\{0,1\}\,\{1,0\}}{\sqrt{2}}\right\}$

$$\frac{\begin{pmatrix}1\\0\end{pmatrix}_{\text{INPUT}}\begin{pmatrix}0&1\\1&0\end{pmatrix}_{H}\begin{pmatrix}1&0\\0&1\end{pmatrix}_{\text{CNOT}}}{\sqrt{2}}$$

Out[9]= $\left\{\frac{\{1\}\,\{0,1\}\,\{1,0\}}{\sqrt{2}}, \frac{\{0\}\,\{0,1\}\,\{1,0\}}{\sqrt{2}}\right\}$

$$\frac{\begin{pmatrix}1\\1\end{pmatrix}_{\text{INPUT}}\begin{pmatrix}0&1\\1&0\end{pmatrix}_{H}\begin{pmatrix}1&0\\0&1\end{pmatrix}_{\text{CNOT}}}{\sqrt{2}}$$

Out[10]= $\left\{\frac{\{1\}\,\{0,1\}\,\{1,0\}}{\sqrt{2}}, \frac{\{1\}\,\{0,1\}\,\{1,0\}}{\sqrt{2}}\right\}$

Figure 11: Mathematics of the "X" gate: a H + CNOT on all Possible Input States

This is an incredible outcome and demonstrates several interesting points.

a. Entanglement really is a resource. The initial entangled pair |A↑↓> and |B↓↑> are consumed during the teleportation of |ψ_C>.

b. |ψ_C> could represent any state: it could contain a pure |0>, 1-bit state, or it could contain the state of our 64-qubit register, meaning 2e+19 states…either way, only 2 classical bits are required to teleport |ψ_C> from Alice to Bob. Because of the "no cloning" theorem, |ψ_C> is necessarily annihilated from Alice, and is simultaneously created at Bob's end. But was it really? See (d.) below.

c. |ψ_C> is unaffected – the holder of |ψ_C> can perform further operations on it without collapsing |ψ_C>; if |ψ_C> were itself entangled to a fourth qubit |ψ_D>, the entanglement would not be disrupted. **This is interesting**. Suppose instead that Alice |A↑↓> has been separated from Bob |B↓↑>, but Bob also holds a second qubit |**C**←→> entangled with Carol |**D**→←>. If Bob performs a measurement on |B↑↓> and |**C**←→>, he will destroy both, and in the process gains 2 bits to send to Carol to transform |**D**> (not entangled) into |**B**↑↓> (still entangled). Now, Alice and Carol…who have never communicated, are nonetheless entangled; Alice holds |A↑↓>, and Carol holds |B↑↓>. This is "entanglement swapping."

d. In 2022, it was discovered that the teleportation of |ψ_C> is not it somehow "transmitted" through space, but instead *traverses a wormhole* [41], [36]. This means that |ψ_C> travels in a non-local way that *does not pass through space*. Despite the curiosity raised in (b.), |ψ_C> truly was annihilated at A and re-created at B. This is because, in quantum field theory, space-time is a lattice of Planck length points. As an electron passes through free space, it does not move continuously…it is annihilated and recreated at every point on the lattice. This is where uncertainty comes into play…Planck units are small…there's a chance it will be re-created at either of two closely spaced points near its annihilation point. Because the state acts as a wave, it could skip a point and be created a few points away…but nothing we would notice.

Point of interest: this is the origin of tunneling. During radioactive decay, a nucleus doesn't "let a proton go"…the proton's wave function has a probability (see Fig. 6) to be in several states (parallelism and entanglement). When radioactive decay occurs, the proton doesn't "move away" from the nucleus to which it is entangled…it's wavefunction, while tightly bound to the nucleus, has a small chance (it's half-life) to be observed by (say) thermal radiation. Up until that point, it is in a superposition of being in the nucleus and escaping the nucleus. If it is observed to be outside the nucleus, it suddenly speeds away (because the proton and nucleus are both positively charged). This is not only how radioactive decay occurs, but also how fusion occurs. Protons cannot classically fuse. They need to be in a superposition of being bound and not being bound (as their charges repel one another). The heat from the star forces them into one of the states, so on average, they occasionally fuse, releasing an enormous amount of energy. That is how stars work. As an **additional encore**, this is one reason neutron stars are so hot and magnetically active…because of Heisenberg, their location x is very well defined…they are in a tremendous gravity well. But that leaves their momentum essentially unhinged – you can say where the neutron is, but not its momentum, leaving it to dance around wildly while remaining in a fixed position, causing massive kinetic energy, and generating heat and magnetic fields (though it is electrically neutral, the neutron is composed of quarks which, in a state of high kinetic energy, reveal their fractional charges. It is completely counterintuitive, but it is how nature works.

Superdense Coding [46]: Superdense coding allows the transmission of 2 classical bits by a single quantum bit, and in many ways can be thought of as the reverse of QM teleportation. In this communication protocol, Alice and Bob each hold one of a pair of entangled qubits. For example, $|\psi\rangle = |0_A0_B\rangle + |1_A1_B\rangle$, where subscripts indicate which qubit is sent to Alice and which to Bob. Now, the process is simple. If Alice wants to send "00" to Bob, she does nothing (applies the identity operator) so $|\psi_{00}\rangle = |0_A0_B\rangle + |1_A1_B\rangle$. If she wants to send "01", she applies the "X" gate: $|\psi_{01}\rangle = |1_A0_B\rangle + |0_A1_B\rangle$. If she wants to send "10", she applies the "Z" gate: $|\psi_{10}\rangle = |0_A0_B\rangle - |1_A1_B\rangle$. Finally, to send "11" she applies both the "Z" and "X" gates: $|\psi_{11}\rangle = |0_A1_B\rangle + |1_A0_B\rangle$. Alice then transmits her qubit back to Bob, who can tell which operations she performed on the original bit based on the new bit state and receives 2 classical bits from 1 qubit. As before, the measurement destroys both Alice's and Bob's qubits, but Alice has squeezed twice the amount of classical information into a single qubit.

An interesting point of note is that Superdense coding is a form of secure quantum communication. If an eavesdropper, commonly called Eve, intercepts Alice's qubit en route to Bob, all that is obtained by Eve is part of an entangled state. Without access to Bob's qubit, Eve is unable to get any information from Alice's qubit. A third party is unable to eavesdrop on information being communicated through superdense coding and an attempt to measure either qubit would collapse the state of that qubit and alert Bob and Alice. Such an alert could come from a variety of means, but the simplest would be to establish a quantum interferometer (see Section V. A.) to establish an interference pattern between Alice and Bob (much like LIGO [8] detects 3rd party gravitational waves) and monitor for any changes in their interference pattern during their communication.

These two examples merely illustrate a few of the applications QM permits for use in technology.

III. Quantum Computing

A. Technological Operation

Why can quantum computers [39] outshine their classical counterparts? As we've learned, the hand waving answer is that some combination of superposition and entanglement allows a quantum computer to out-perform classical computers by harnessing phenomena such as teleportation and superdense coding; but that doesn't give a precise answer as to "how" this can be accomplished.

The artistry of QM computing is creating circuits consisting of quantum gates [39] that cleverly perform QM algorithms such as Shor's [32] factorization algorithm or Grover's [43] search algorithm. An example of such a circuit is provided in Fig. 12 below:

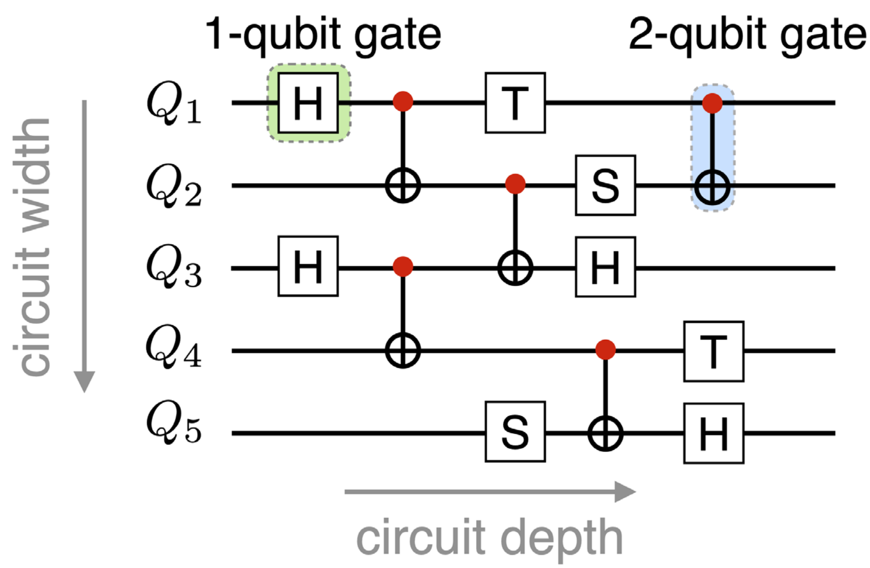
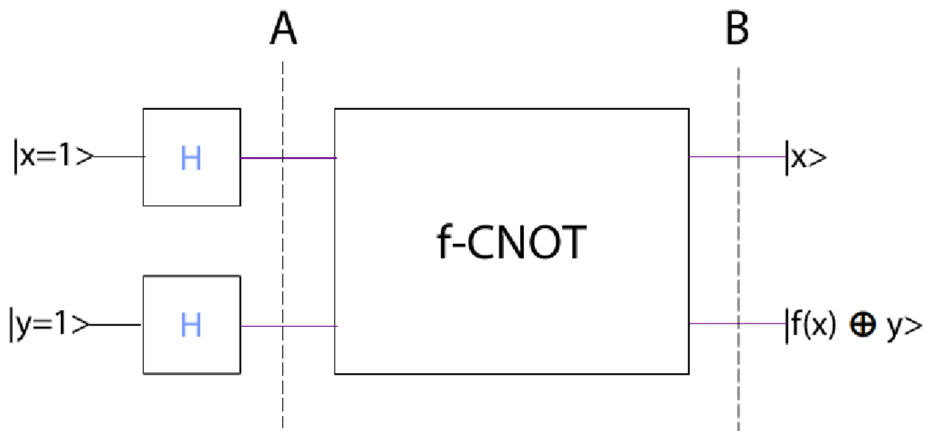


Figure 12: A 5-qubit Quantum Circuit

Here, the T-gate is a rotation represented by $T = \begin{pmatrix} 1 & 0 \\ 0 & e^{\frac{\pi i}{4}} \end{pmatrix}$, and S is the rotation $S = \begin{pmatrix} 1 & 0 \\ 0 & -i \end{pmatrix}$. This circuit is presented only to show the impressiveness of some quantum circuits. However, the simplest quantum algorithm was discovered by David Deutch in 1970, and is known as Deutsch's problem [38]. Deutsch imagined a binary function ***f*** which could take a 0 or a 1 as an input and output a 0 or a 1. ***F*** would be **constant** if its input equaled its output (***f(0) = f(1))*** and would be **balanced** if ***f(0)≠f(1).*** For this demonstration, we can say ***f*** will be balanced if ***f(0)= $\hat{f}$(1)*** where the "hat" denotes the "NOT" operation; the two statements are equivalent. **Classically**, this would require two separate operations: inputting a "1" to find ***f(1)*** and then inputting a "0" to find ***f(0);*** if the two values are equal ***f*** is constant; otherwise, it is balanced. Deutsch realized this could be condensed into a single operation with a QM computer [39]. While the setup is not simple, it is not particularly complex either. Two bits in the "1" state are each passed through a Hadamard gate (See Fig. 9) which turns a pure |1> or |0> state into a superposition of the |1> and |0> states. Although represented separately in the diagram, the initial input can be written as |x>|y> = |1>|1> and passed through a single "H" gate rather than the two "H" gates depicted below; the resulting wavefunction at "A" in Fig. 11 below is the input, which contains every possible combination of input/output pairs in a superposition. The trick now is to operate on the collective states at once (parallelism [52]) to determine whether ***f*** is constant or balanced. This is a *global* problem: it is not computing a number or a function; it is determining the value of an operation, like deciding if ***f*** represents multiplication or division. Once you know that it is (say) multiplication, you can input any two numbers in and know the output. This is much more powerful than calculating "3*9 = 27"…it's determining whether there is an "*" or a "/" between the "3" and the "9", allowing us to calculate *any* number "a*b".



$$|\psi_A> \; = \; \frac{1}{2}\,(\,|0_1 \times 0_2> - \,|1_1 \times 0_2> - \,|0_1 \times 1_2> + \,|1_1 \times 1_2>)$$

$$|\psi_B> \; = \; \frac{1}{2}\left(\left|0_1\, f(0)_2\right> - \left|1_1\, f(1)_2\right> - \left|0_1\, f(\hat{0})_2\right> + \left|1_1\, f(\hat{1})_2\right>\right)$$

Now, if f(0) = f(1), we can factor B's wavefunction as: $|\psi_B> \; = \; \frac{1}{2}\,(\,|0_1> - \,|1_1>)\left(\left|f(0)_2\right> + \left|f(\hat{0})_2\right>\right)$

But, if f(0) ≠ f(1), we can factor B's wavefunction as: $|\psi_B> \; = \; \frac{1}{2}\,(\,|0_1> + \,|1_1>)\left(\left|f(0)_2\right> + \left|f(\hat{0})_2\right>\right)$

By passing $|\psi_B>$ through another "H" gate followed by an X-register, we will get a "1" if f(0) = f(1), or "0" if f(0) ≠ f(1).

Accordingly, we have determined whether ***f*** is constant or balanced in a single operation.

Figure 13:*Deutsch's Problem*

While the input is |1>|1>, the output is |x>|*f*(x) ⊕ y> where ⊕ is the Boolean XOR operator. As described in the figure, that's all there is to it. The wavefunction at "B" carries all the information – it need only be passed through an additional "H" gate (to undo the original "H" gate(s), (because $H^2|1> = |1>$), and then a "$-1/1_1$" register which evaluates only the "1" state, and will return a value of "0" if ***f is*** balanced and a "1" if ***f*** is constant. The intermediary equations with the red oval are simplifications of the overall wavefunction; one assuming ***f*** is balanced and one assuming it is not; the oval merely highlights the change in sign depending on which of these possibilities is realized by ***f***.

This covers the basic operation of a QM computer. Although this was a simple example, it demonstrates how QM computers thrive on more highly entangled quantum states that come with greater quantum complexity, which makes QM computers formidable tools in solving certain complex problems.

To conclude with a side note, it turns out that **teleportation** [36] is also extraordinarily important in the operation of a quantum computer because of the "no cloning" theorem (which is just a re-statement of the Heisenberg uncertainty principle). This principle prohibits the copying of qubits. This is a severe limitation; we routinely copy and paste sentences, files, and folders without batting an eye. But if we could copy a qubit, we would violate the uncertainty principle, because we could measure any 2 non-commutative properties of the qubit (like position and velocity) with arbitrary precision by measuring property with perfect fidelity on the first qubit and measure a second non-commutative property with equal precision on the second. This means we need a means of moving qubits around in a quantum computer without copying them. The only way to do this is via *teleportation* [36]: we must teleport qubits to move them about. This illustrates the importance of the resource of entanglement because we will need an entangled pair each time we move the qubit, which is an unfortunate reality.

B. Industries Primarily Affected

Quantum computing is guaranteed to touch on every industry under the sun. However, a brief list of those that may see the greatest changes is provided below:

National Security and Defense: The transition from bits to qubits will undoubtedly pose new risks to the U.S. while simultaneously providing it the tools to combat such risks. QM computers are exponentially more powerful than conventional computers, and can crack traditional encryption methods using algorithms such as Shor's algorithm[32] in conjunction with other strategies – for example, one can imagine systems of communication that use entanglement swapping to rapidly "hop" around geographically (similar to frequency hopping). This would alert users of an intrusion into their communications channel but would also make it incredibly difficult for an eavesdropper to intrude in the first place: a combination of security and deterrence.

Finance: High-frequency trading firms rely on advanced algorithms and fast processing speeds. Quantum computing could potentially process, analyze, and act on market data more quickly and accurately, leading to a potential arms race among these firms to harness quantum technology first. QM algorithms could possibly analyze risks and rewards of various trading strategies more accurately than traditional models.

Climate and Environmental Science: QM computers have the potential to advance climate modeling, helping scientists better understand how climate change is developing and how it can be mitigated. Quantum computers could improve the forecasting precision of natural disasters such as hurricanes and earthquakes, leading to better disaster response efforts.

Information Technology and Internet: Given its processing power, QM computing can also have a significant impact on data analysis and the handling of large datasets. Data centers could leverage

QM computing to speed up their data operations or solve complex problems faster than is currently possible.

Legal Profession and Privacy: QM computing's potential ability to crack conventional encryption poses an existential threat to individual data privacy. Governments, businesses, and individuals will need legal guidance on how to navigate this new privacy landscape. Additionally, patent law might need to evolve to handle new inventions derived from or related to QM computing.

Intellectual Property Rights: Much like AI-generated patentable subject matter, a similar conundrum faces inventions devised using QM computers. An obvious initial argument is that an AI system is not a person, so cannot be an inventor, whereas a human working on (any) computer can be. But if I optimize some device or process using a computer "optimize" routine (like a button command: "optimize"), and my computer stores more states than there are particles in the observable universe…**am I still the inventor?** That is superhuman and does not necessarily require me to provide much input other than "make an optimal ____," and the machine fathoms 10^{80} possibilities at the same time to give me the right answer. This is a subtle but important point: **AI uses reasoning and logic…that's not what's happening here**. What I've requested is that my computer find a needle in a haystack, but the haystack is enormous, and the computer can process each piece of hay at the same time – **it has not exercised any logic** or decision making (unlike AI). It has simply "boiled down" 10^{80} numbers to find the smallest one…something inventors routinely do – simulate circuits, run optimization routines to find the ideal load resistance, and file. Based on these and other considerations It is possible that **new categories of patents** could be established specifically for QM-based technologies.

Education and Workforce: QM computing is still an emerging field and calls for specific, currently rare, skills. The need for QM-educated workers will grow in the coming years, creating a demand for specialized education programs in universities and colleges. This is a particularly interesting area: as bright as our modern-day circuit designers may be, they design circuits and algorithms for classical machines. It makes sense to read in data to fill up a buffer, process the data, and fill the buffer again…it's common sense. Designers of QM circuits will have a much more difficult task, because no human can "think" like an entangled photon. However, advances in QM computing software, and significantly, the addition of QM computing to advanced artificial intelligence (AI) systems (discussed below) may help overcome this hurdle.

Artificial Intelligence (AI) [56]: QM computing could significantly alter both the AI and ML sectors because they rely heavily on high-speed computing and the processing of large amounts of data — the precise areas where QM computers excel. Some potential advancements in the field may include:

- **Increased Processing Speeds**: QM parallelism could give AI systems the ability to analyze and process data exponentially faster. Because AI requires processing vast amounts of data to be trained, QM computers may be able to carry out the processes much faster, leading to quicker realization of AI/ML potential.

- **Solving Complex Problems**: Machine learning involves dealing with high-dimensional data and requires modeling complex, intricate systems. Techniques such as clustering, classification, and regression models require finding optimal solutions in large search spaces. QM computers rely on vast state spaces and have the potential to navigate this space more efficiently, potentially leading to more effective and sophisticated AI models.

- **Optimization Problems**: Optimization issues are important in machine learning (frequently referred to as "gradient descent"). These problems involve finding the best solution among a sea of variables that create nightmarish multidimensional landscapes which quickly become intractable for modern computers to minimize efficiently or accurately. QM computers, with their potential for complex calculations and simultaneous analysis of multiple options, could enable faster and more effective solutions to optimization problems.

- **Quantum Machine Learning (QML)**: QM machine learning, a combination of QM physics and machine learning, explores how machine learning algorithms can be improved with QM computing. It examines how QM algorithms can be used to speed up classical machine learning algorithms and provide solutions to complex problems, potentially opening new avenues for AI development.

- **Enhanced creativity**: Modern AI systems are already wildly creative: they can make up stories and songs, tell jokes, and come up with creative solutions to problems. Given a modern AI state space of "x," QM enhancements would raise that space to 2^x (as discussed with our 64-qubit register model). This would open up an unimaginable…and possibly terrifying amount of creativity in AI systems. While it's just a guess, the author believes this would quickly and definitively outdo humans in every area of thought, reasoning, planning, etc.

C. Quantum Simulation

QM simulation [39] is a subset of QM computing, but it deserves its own section. In fact, the idea behind QM computing came from Richard Feynman who was looking for a way to simulate QM systems. While he recognized computers of the day weren't up to the task (except for some niche areas that were trivial), he also had the foresight to guess that no future classical computer would be able to perform accurate simulations, either, because inherently deterministic. A frequently used term in computer science is "pseudo-random," and that's accurate. "Random number generators" use highly nonlinear algorithms to generate what appear to be random numbers, but they are not. Even if a classical computer used inputs such as room temperature or variations in its power consumption as kernels for such generators, they would still follow statistical patterns (even if those patterns were imperceptible to humans) – only a QM system could accurately simulate another QM system, because it would act in absolute accordance with QM theory…something that no classical system can do.

QM simulations can encompass anything from the interaction of molecules, the properties of materials, and possibly even cosmic events. So how do QM simulations work?

1. **Initialization**: During the initialization stage, the QM computer is set to a simple initial state that can be easily prepared.

2. **Encoding**: The QM system must be encoded onto the QM computer (in other words, program the qubits to represent the QM system we want to simulate). This essentially involves preparing the qubits to reflect the state of the QM system we wish to simulate.

3. **Simulation**: Once the QM system is encoded, we perform a QM simulation, which involves applying a series of QM gates (i.e., operations) to the qubits to simulate the evolution of the QM state over time.

4. **Measurement**: At the end, we perform QM measurements to gain information about the resulting QM state, which, ideally, should tell us something about the behavior of the QM system we are simulating.

5. **Repeat**: The simulation is not a one-and-done deal. It would likely need to be repeated many times to get a reliable outcome, due to the probabilistic nature of QM mechanics.

D. Industries Primarily Affected (by Q-Simulation)

Healthcare and Biotechnology: QM simulation could revolutionize the healthcare and drug discovery process. Simulating molecules on traditional computers is extremely challenging due to the sheer complexity of biological systems. QM simulations, however, could model and analyze biological systems in unprecedented detail, leading to breakthroughs in drug discovery, personalized medicine, and understanding diseases at a fundamental level. In pharmaceutical research, QM computers could simulate the interactions between molecules, atoms, and particles to not only discover new drugs but also to test their potential impacts before laboratory testing, all at unprecedented speeds. This could drastically cut down the time and costs associated with bringing new medications to market, providing faster remedies for emerging diseases.

Photosynthesis and Chemical Reactions: In nature, photosynthesis is a QM process. QM computers could simulate this process accurately, helping us understand its efficiency and possibly guiding us to mimic or enhance this technique for sustainable energy production. Moreover, they can help break down complex chemical reactions at a granular level, something that's nearly impossible to do with classical computers due to the complexity of QM interactions.

This could revolutionize fields like biochemistry, aiding in the design of better catalysts, predicting reaction outcomes, and even creating new synthetic routes for chemicals.

Material Science: QM simulations could play a significant role in material science by enabling the exploration of new phases of matter and the design of new materials with desired properties. For instance, they could help in designing superconductors that work at room temperature, leading to significant energy savings.

Technological & Economic Sectors: QM simulations can run complex simulations far more efficiently than classical computers. This can be vital in multiple other industries such as aviation and energy, leading to improved aerodynamics, optimized power grids, and more. The financial industry could also significantly benefit, for instance, by optimizing trading strategies, portfolio management, and risk modeling.

Government Sector: In addition to improvements in logistics and operations, the government could employ QM simulations to enhance national security. QM cryptography breakthroughs may revolutionize secure communications, protecting critical information from potential adversaries. Governments could also leverage QM simulations to combat climate change, by modeling the environment and understanding changes at a level of detail that is challenging for today's supercomputers.

Social Sector: With advances in medicine, energy, and climate control, there could be considerable, albeit indirect, impacts on the social sector as well. For instance, advances in healthcare owing to QM-enhanced drug discovery could lead to social improvements through better wellness and lifespan. The QM revolution could also generate new jobs requiring greater levels of expertise, necessitating an educated workforce motivated by new education policies and programs.

E. Intersection with US Laws, Regulations, and other Legal Practices & Procedures

QM Computing, and QM technologies intersection with the law is vast. See:

- [58] ("How to regulate quantum technology before everyone understands how it works"),
- [57] ("Establishing the Legal Framework to Regulate Quantum Computing Technology",
- [59] ("Towards responsible quantum technology, safeguarding, engaging and advancing Quantum R&D"),
- [2] ("The Legal Implications of Quantum Computing"),

- [60] ("Law and Governance of Quantum Technologies,")
- [61] ("Quantum Law: Navigating the Legal Challenges and Opportunities in the Age")

Below are a few select examples from these works([2] and [57]-[61]), each of which is mentioned as being of primary legal significance.

Data Protection and Privacy Laws: QM computing has the potential to disrupt current data encryption methods and would likely require significant strengthening of current data protection and privacy laws to respond to these new threats. QM computers may even lead to the need for regulations on their use and ownership.

Intellectual Property Laws: The development and application of new QM technologies could lead to a surge in patent applications, creating a need for training and guidelines for patent examiners to ensure the flood of applications are properly evaluated. This would be similar to the situation seen during the initial boom in computer and internet technologies, which required patent laws and interpretations to evolve in order to properly protect these new types of invention. Similarly, trade secrets laws may need to be re-evaluated given the high value and unique properties of QM technologies.

Criminal Law and Procedure : Law enforcement and the courts may need to grapple with the implications of QM technology. For example, the potential breach of encrypted systems could impact the conduct of investigations and trials if previously secure evidence becomes accessible. This could result in changes in legal procedures, such as processes for obtaining and using digital evidence.

National Security: The advanced capabilities of QM technologies would likely present national security concerns, particularly when it comes to cryptography. This was echoed in the National Quantum Initiative Act [11], signed into law by President Donald Trump in 2018, which among other things, establishes a 10-year plan to speed development of QM information science and technology applications in the United States.

Regulatory Infrastructure: Given the revolutionary aspects of QM computing and the inherent potential risks, QM computing could lead to the need for a new regulatory agency or the expansion of the mandates of existing agencies like the Federal Communications Commission (FCC), the National Institute of Standards and Technology (NIST), or the Department of Commerce.

IV. Quantum Cryptography & Quantum Key Distribution (QKD)

A. Technological Operation

QM cryptography is a fascinating intersection of QM physics and computer science that aims to dramatically enhance the security of digital communication. In traditional cryptography, secret keys are used to encrypt and decrypt messages. If Alice wants to send a secure message to Bob, for instance, she will encrypt the message using a secret key, send it over a potentially insecure channel (like the internet), and then Bob would decrypt it on the other end using the same secret key. This method of encryption is generally secure unless the key gets intercepted or is cracked through sheer computational power.

QM cryptography, and more specifically QM Key Distribution (QKD), offers a way to combat the vulnerabilities of classical cryptographic systems. In QM Key Distribution (QKD), two parties (let's call them Alice and Bob) can generate a shared, random secret key. In one of the best-known protocols, BB84, Alice sends photons (light particles) to Bob in random orientations. Then, Bob randomly chooses an orientation to measure these photons. Bob has a 50% chance of guessing the orientation correctly. Bob then tells Alice which orientations he chose (but not the results of his measurements), and Alice tells Bob when he chose the correct orientation. The measurements where Bob chose the right orientation are then used to make up the key. If an eavesdropper tries to intercept the quantum key by measuring the photons, their shared quantum state will decohere, informing Alice and Bob of the third party, forcing them to discard the key and repeat process until they generate one that's secure.

While quantum cryptography leverages the principles of QM to provide a high degree of security, it has limitations relating to signal attenuation and noise in the transmission channels. While it is unbreakable in principle, real-world constraints require allowable error rates. Recall that entangled systems are extraordinarily fragile, so some approaches may use multiple parallel or regenerating QM channels, some of which may decohere without triggering a full breach in communication. This is less of a problem over fiber optic networks, which are less susceptible to attenuation and noise, but much of our modern communication relies on free-space propagation (such as cell phones), which introduces detrimental environmental factors.

B. Industries Primarily Affected

QM cryptography and Quantum Key Distribution (QKD) have already been employed in several spaces where secrecy is of the highest order. As the cost of these technologies continues to decline, however, their potential in nearly every application is desirable. The first comers are (or will likely be) social commercialization (cell phones), secure economic transactions, technological secrecy/R&D projects, and governmental (all over).

Government and National Security: QM cryptography and QKD can be used to protect classified information and secure communication channels in intelligence, military, and national security sectors. They are largely tamper-proof, and ideally any interception or eavesdropping attempts would be immediately noticeable, deterring espionage and information theft. If it hasn't already, the U.S. government should leverage these technologies to enhance its cyber-defense and data protection capabilities.

Finance and Banking: Financial transactions and banking systems require high levels of security to prevent data breaches and fraud. The use of QM cryptography here could potentially revolutionize the level of security, enabling safe online transactions and protecting against any form of data breach, contributing to the overall stability of the financial sector and economy.

Healthcare: Confidentiality of patient records and other sensitive data is a crucial aspect of the healthcare industry. The incorporation of QM cryptography could ensure this data is protected, enhancing privacy standards.

Telecommunications and Internet: The increasing volume of digital traffic requires secure lines of communication, especially in the emerging era of IoT devices, where billions of devices are connected and exchanging private information. QKD and QM cryptography would ensure secure exchanges of this information, leading to more robust networks and more secure online environments.

Social Impact: As these technologies become more mainstream, they may also shift societal expectations about privacy and security. As people become more accustomed to a greater sense of security and privacy offered by these technologies, this could elevate public standards, demanding more secure and private digital systems across various other sectors.

Legislation and Regulation: The emergence of QM cryptography also poses questions regarding current laws and regulations pertaining to data protection and privacy. Legislation will likely need to catch up, creating new frameworks that mandate the advanced protections provided by QM cryptographic technologies.

C. Intersection with US Laws, Regulations, and other Legal Practices & Procedures

The integration of QM cryptography and QKD technologies into the existing legal landscape could have numerous implications, requiring an evolution of many existing U.S laws, regulations, and legal practices. Some examples include:

Data Privacy Laws: Because the implementation of QKD would enhance the security of data transmitted over networks, the legal system could see a reduction in the incidences of data breaches, potentially leading to fewer lawsuits. **However**, the interpretation of data protection obligations could also change. Currently, laws like the **California Consumer Privacy Act (CCPA)** require businesses to implement **reasonable** security procedures and practices. If QKD becomes commercially available and affordable, it may raise the question of whether **not** using QKD could be seen as failing to implement reasonable security measures.

Electronic Communications Privacy Act (ECPA): The ECPA updated the Federal Wiretap Act of 1968, which addressed interception of conversations using "hard" telephone lines but did not apply to interception of computer and other digital and electronic communications. Several subsequent pieces of legislation, including The USA PATRIOT Act, clarify and update the ECPA to keep pace with the evolution of new communications technologies and methods, including easing restrictions on law enforcement access to stored communications in some cases. In general, the ECPA regulates government access to personal electronic communications and data. **Theoretically, QKD could make unauthorized access technically impossible, which could lead to a redefinition of the boundaries between surveillance capabilities and privacy rights**.

Criminal Law and Procedure: Forensics and the handling of digital evidence may change as QKD could make it more difficult for law enforcement to gather digital evidence. This potentially raises Fourth Amendment considerations. A crucial aspect of these cases hinges on **the "reasonable expectation of privacy,"** which **could be redefined** with advances in QM cryptography.

Regulations and the role of regulatory bodies: Integration of QM cryptography into critical infrastructures like power grids, military communication systems, or banking **could lead to new standards** for these industries. Current regulatory bodies like the Federal Communications Commission (FCC), and NIST would likely be involved. There could be the need for a **new regulatory body specifically for QM technologies**.

International Law and Jurisdiction: With this technology, the physical location of data could become irrelevant, raising questions about jurisdiction and data sovereignty. Laws such as the U.S. CLOUD Act. The CLOUD Act, which primarily amends the Stored Communications Act (SCA) of 1986 to allow federal law enforcement to compel U.S.-based technology companies via warrant or subpoena to provide requested data stored on servers, regardless of whether the data are stored in the U.S. or on foreign soil, could become too complex to enforce or possibly even moot. If information is held between separate locations sharing a common quantum state, where is it? An even more creative bad actor may use teleportation and teleportation swapping to continually re-locate the information: recall, because of the “no cloning” theorem, there would literally be no trace of the information once it was moved – its previous state is annihilated.

It is evident that the deployment of QM cryptography can create shifts and expansions in various legal fields. It is crucial that policymakers and stakeholders engage in active dialogue as this technology continues to materialize to ensure the laws are accommodative and supportive of these advancements.

V. Quantum Metrology (Sensors and Imaging)

A. Technological Operation

QM metrology, or QM sensing, is a rapidly developing field that leverages principles of quantum mechanics to improve precision measurement technology. QM metrology uses superposition and entanglement to develop sensors that can measure phenomena such as gravitational fields, magnetic fields, or time, with unprecedented precision.

An example of a QM sensor is a **quantum interferometer** (a much smaller version as the one used at the laser interferometer gravitational observatory, or LIGO [8]). In this device, a QM state—like a group of atoms—is split into two separate paths in superposition with one another. These paths create a characteristic interference pattern (like the ρ(t) state from Fig. 5). When one of the paths interacts with some phenomenon we wish to measure, the interference pattern displays a measurable change.

One of the ways QM metrology improves upon classical methods is by **circumventing** the standard quantum limit (SQL). This is possible by performing repeated measures on entangled (and thus correlated) EPR (entangled Bell state) pairs. Classically, the uncertainty in a measurement decreases as the square root of the number of repeated measurements (known as the Standard Quantum Limit). However, with entangled states, this uncertainty can decrease linearly with the number of measurements, allowing us to one to reach the so-called Heisenberg limit, (which cannot be circumvented) improving the interferometer's precision by leaps and bounds.

Quantum RADAR's [55] make use of QM interferometry and quantum illumination (discussed below with reference to a different type of sensor), and rely on entanglement and the uncertainty principle to outperform their classical counterparts. The basic concept is to create a stream of entangled visible-frequency photons and split it in half. One half, the "signal beam", goes through a conversion to microwave frequencies in a way that preserves the original QM state. The microwave signal is then sent and received as in a normal radar system. When the reflected signal is received it is converted back into visible photons and compared with the other half of the original entangled beam, the "idler beam". While most of the original entanglement will be lost due to QM decoherence as the microwaves travel to the target objects and back, enough QM correlations will remain between the reflected-signal and the idler beams. By using interferometric detectors, the number of returning photons that can be detected is dramatically increased. This scheme allows the system to pick out just those photons that were originally sent by the radar, completely filtering out any other sources and leading to a much greater target resolution.

Another advantage of a QM RADAR [55] is that, traditionally, the enemy could defeat a conventional radar system by broadcasting signals on the same frequencies used by the radar, making it impossible for the receiver to distinguish between their own broadcasts and the spoofing signal (or "jamming"). However, such systems cannot know, even in theory, what the original QM state of the radar's internal signal is. Lacking such information, their broadcasts will not match the original signal and will be filtered out in the correlator. Environmental sources, like ground clutter and aurorae, will similarly be filtered out.

Yet another QM-based sensor is a quantum magnetometer.[47]. This technology uses a quite simple technique to sense extremely small magnetic fields. In 2019, scientists at MIT began using tiny defects in diamonds called nitrogen-vacancy (NV) centers. These defects consist of two adjacent places in the diamond's orderly lattice of carbon atoms where carbon atoms are missing; one of them is replaced by a nitrogen atom, and the other is left empty. This leaves missing bonds in the structure, with electrons that are extremely sensitive to tiny variations in their environment, be they electrical, magnetic, or light-based.

Quantum imaging is yet another sub-field of QM metrology, as it manipulates QM states via superposition and entanglement to create images with properties that cannot be achieved by conventional means. Specifically, QM imaging utilizes a method known as quantum illumination, which relies on correlations between entangled photons. In quantum illumination, a laser fires a stream of entangled photon pairs, where one photon is detected immediately, but the second photon is sent towards the object of interest. The reflected photons from the object are then collected and detected. The detected photons are then compared and matched with the first set of detected photons to eliminate unwanted 'noisy' photons that weren't part of the original entangled pairs.

One **variant** of QM imaging is known as ghost imaging. To understand ghost imaging, a simple example should suffice: Imagine two transparent boxes: one that is empty and one that has an object within it. The back wall of the empty box contains a grid of many pixels (i.e., a camera), while the back wall of the box with the object is just a large single pixel (a bucket detector) that registers an “on” or “off” signal if it is struck by a photon but otherwise has no resolution. Next, shine laser light into a beam splitter and reflect the two resulting beams such that each pass through the same part of its respective box at the same time. For example, while the first beam passes through the empty box to hit the pixel in the top-left corner at the back of the box, the second beam passes through the filled box to hit the top-left corner of the bucket detector.

Now imagine moving the laser beam around to hit each of the pixels at the back of the **empty** box, **meanwhile** moving the corresponding beam **around the box with the object**. While the first light beam will always hit a pixel at the back of the empty box, the second light beam will **sometimes be blocked** by the object and **will not reach the bucket detector**. A processor receiving a signal from both light detectors **only records a pixel of an image when light hits both detectors at the same time**. In this way, a **silhouette image** can be constructed from the camera in the empty box, even though the light going towards the multi-pixel camera did not touch the object.

In either case, by narrowing down the data to only include photons that were part of an entangled pair, the resulting image is significantly clearer and has less noise compared to traditional imaging methods. This process can be used to obtain images in low-light conditions, or to view objects obscured by highly scattering mediums (like fog or biological tissue). There are many other types of sensors that utilize QM phenomena to detect things like temperature, mass, angular momentum, and more, all with extreme precision. Unfortunately, there are too many to discuss in this paper.

B. Industries Primarily Affected

QM metrology, including QM sensing and imaging technologies, has the potential to revolutionize various sectors across the U.S., from healthcare and environmental protection to defense and security.

Healthcare sector: QM sensing and imaging may greatly impact the medical field by offering highly sensitive diagnostic tools. The ability to detect subtle differences in biological samples, such as a forming tumor through minute magnetic fields or temperature differences could lead to the development of medical diagnostic devices that can pick up on early-stage diseases with far greater accuracy. QM imaging can also significantly improve the clarity and resolution of medical imaging technologies such as MRI and CT scans, enabling more precise visualization of diseases and internal injury.

Environmental sector: QM sensing can also have a profound impact on environmental monitoring. As we have seen, detectors based on QM entanglement can accomplish highly sensitive measurements of magnetic fields, electric fields, and light, parameters that are crucial in tracking and understanding changes in environmental conditions. This could, in turn, help in creating better environmental protection policies and strategies.

Technological sector: QM metrology could significantly improve the precision of various navigational systems, and consequently, all technologies relying on Global Positioning Systems (GPS). These could include autonomous vehicles, cell phones trackers, aircraft and naval vessels. Additionally, QM sensors (such as nuclear clocks) could enhance the accuracy of time-keeping systems, essential for data centers, telecommunications, and complex scientific experiments that rely on extremely precise time measurements.

Government and Defense: QM imaging, such as QM radar and QM lidar, could significantly boost surveillance capabilities by providing clearer images in almost any environmental conditions, potentially revealing obscured or hidden objects. Besides, QM metrology could also play a pivotal role in secure communications. Through the use of QM key distribution (QKD), secure keys could be created and distributed for secure communication, crucial in areas concerning national security.

Economic sector: As QM metrology advances, it's expected to fuel the growth of new industries; the need to detect dangerous chemicals or pathogens in trace amounts of air, or provide greater accuracy in determining concentrations of chemicals in water or other fluids, will undoubtedly create numerous employment opportunities. These developments could force policymakers to consider new workforce demands created by these needs and spurn more proactive approaches in their efforts to invest in education and training.

Overall, the wide array of applications and the significant advancements offered by QM metrology means that its impact will likely be substantial across various sectors. Nonetheless, as with all QM technologies, it's important to consider information security and the potential ethical implications alongside this technological growth.

C. Intersection with US Laws, Regulations, and other Legal Practices & Procedures

QM metrology, which includes QM sensors and QM imaging, has numerous potential impacts on U.S. laws, regulations, and legal practices and procedures. Its intersections can be numerous and far-reaching, affecting everything from privacy rights to intellectual property laws to national security. For example:

Legal concerns: As with any emerging technology, QM metrology may prompt new legal and ethical questions. The heightened detection abilities of QM sensors might interfere with privacy rights. At the same time, QM imaging could develop into a tool that significantly fights against forgery and counterfeiting by enabling an unprecedented level of detail and authentication in imaging.

Privacy Rights and Fourth Amendment Issues: QM imaging can potentially enable new forms of surveillance due to its unique ability to capture highly detailed images or data without high levels of light or other traditional requirements. This could pose new challenges to the existing Fourth Amendment interpretations regarding unreasonable searches and seizures. The **U.S Supreme Court in Kyllo v. United States (2001)** [67] already dealt with a scenario where **thermal imaging was used to infer activities inside a home**, which was deemed a search under the Fourth Amendment. Legal precedence such as this will likely need to be re-evaluated or re-interpreted for QM technologies.

Legal Standards for Evidence Collection and Authentication: The enhanced measurement capabilities from QM sensors could alter standards for evidence collection and authentication. Their increased precision and reliability may alter evidentiary admissibility rules. For example, advanced QM sensors might be able to provide more accurate drug or substance detection or provide advanced detection of specific banned substances in sporting events.

Intellectual Property Laws: The development of QM metrology technologies is expected to build upon itself, creating ever smaller and more sensitive devices building off of their predecessors causing a potential cascade of extensive patenting. This could lead to potentially complex patent landscapes. Both patent laws and competition laws would need to be adapted to deal with this new technological scenario, which could potentially be monopolized by a few powerful corporations or countries. Trade secret laws may also come into play as companies strive to protect their innovations within this sector.

National Security and Defense: The application of QM metrology in national defense and security could raise complex legal and ethical issues. The U.S. government, through agencies such as the Defense Advanced Research Projects Agency (DARPA) or the Department of Energy (DOE), typically regulates the use and dissemination of such technologies for national security purposes. However, **the emergence of these technologies could necessitate the establishment of new regulatory bodies or standards to ensure responsible use**.

Regulatory Standards and Bodies: As with any emerging technology, there is **a need for** both technical and ethical standards alongside **appropriate regulatory bodies**. NIST could play a role in setting technical standards for QM sensors and QM imaging technologies. Furthermore, we might see the emergence of institutions like the Federal Communications Commission (FCC) for the telecommunication sector.

International Laws and Agreements: On the international front, the emergence of QM metrology could lead to new forms of international treaties or agreements. **It's conceivable that future arms treaties might include provisions about QM technologies**. Moreover, as these technologies advance, there could be a necessity for international intellectual property agreements to mitigate potential disputes.

In summary, the intersection of QM metrology and U.S. law and regulations is a rapidly evolving field. As technology advances, more complex and nuanced legal, ethical, and societal issues will likely arise, requiring innovative legal and regulatory solutions.

VI. Quantum Networks (Quantum Internet)

A. Technological Operation

A QM network interconnects multiple QM computers, users, or nodes, enabling the transmission of QM information between them. This is done through QM channels, which typically involve sending individual photons (light particles) through optical fibers.

The core of a QM network can be divided mainly into three components:

- **Quantum Repeaters**: These are devices used to extend the distance over which QM information can be sent. QM information cannot be amplified like classical information due to the no-cloning theorem. Therefore, QM repeaters are used.

- **Quantum Routers**: Just like classical routers, these devices route the QM information to the correct paths.

- **End Nodes**: The user devices that generate, manipulate, and measure QM information.

QM entanglement holds the promise to create ultra-fast, long-distance, secure networks. A QM network operates by transferring information via teleportation rather than the direct propagation of the information itself (although as we have seen, classical information must also be transmitted during teleportation to correctly decode the teleported QM states. Performing network-scale information transfer through the QM states of entangled qubits would truly and fundamentally diverge from the operation of classical networks and will present numerous obstacles to overcome. But on the optimistic side, most of these obstacles have been overcome on smaller scales, and it appears that the biggest challenge will be scaling those technologies up to suit the needs of the world. It is worth noting that one of the key applications previously discussed is tailor-made for QM networks: QM key distribution (QKD).

B. Industries Primarily Affected

Because QM Networks, or a QM Internet, allows for such extremely secure communication while simultaneously processing vast amounts of data, they will have the potential to revolutionize numerous sectors, from economics to national security. Some industries that may experience the most significant impacts include:

Telecommunications and Information Technology: QM networks could revolutionize the digital communication space due to their unique properties. QM key distribution (QKD) could help organizations to transmit and receive data with strong encryption, drastically improving cybersecurity practices and data privacy. Furthermore, QM networks' potential to process vast amounts of data at incredible speeds would revolutionize data processing and handling. This could lead to improvements across industries that rely heavily on data, such as **finance and healthcare**.

Government and National Security: QM networks could significantly improve national security due in part to their ability to provide high security, high volume data transmission. While traditional methods of encryption could be rendered obsolete by QM computers, QM networks could equally help protect sensitive government, military, and financial data. QM networks' high-speed processing capabilities could also aid in rapid real-time situational awareness assessment and decision-making in defense operations or disaster responses, enhancing national security and resiliency.

Research and Development: Across most scientific fields, the ability to process and analyze large data sets at unprecedented speeds would expedite research and development efforts. This could catalyze innovation in sectors such as genetic research, climate modelling, drug discovery, and much more.

Economic Sector: Commercial industries that require large and fast data-processing capabilities, ranging from finance to logistics, would benefit greatly. For instance, in the finance sector, QM computing networks could optimize trading models by analyzing vast amounts of data at speeds not currently possible, resulting in more efficient markets. Meanwhile, businesses involved in supply chain, logistics, and transportation could optimize their routes and plans based on real-time data analysis, improving efficiency, and reducing costs.

Healthcare: QM networks could significantly speed up the analysis of large sets of healthcare and genomic data. This could transform personalized medicine, advance our understanding of genetic diseases, and improve healthcare delivery performance.

Despite this numerosity of positive benefits, such a powerful technology would undoubtedly bear significant societal and regulatory implications. In terms of privacy, while QM networks can enable secure transmission, the counterpart is the potential misuse through QM-enabled breaches, where encryption of classic data would be rendered ineffective. Thus, a major challenge for lawmakers and society at large would be to regulate the use and misuse of such a technology, a task that's already challenging in our current digital age.

Another societal implication could be a further increase in the disparities between different societal groups. Those who can afford to access and use this technology could further advance, leaving those who cannot behind, thereby increasing both income and information inequality. Policymakers would need to focus on equitable access to such advanced technologies.

Lastly, while various industries would benefit from QM networks' processing power, this could also lead to job displacement in areas where human data analysts are replaced by QM systems. This technology therefore presents opportunities and challenges alike for the workforce, potentially requiring a significant shift in skills and training.

In conclusion, while the QM Internet could bring about great advancements, it also raises significant ethical, societal, and economic questions that need addressing from a policy perspective to ensure its benefits are broadly shared and potential downsides mitigated.

C. Intersection with US Laws, Regulations, and other Legal Practices & Procedures

QM networks promise various benefits, from highly secure communication to greatly enhanced computation power. However, like any advancement in technology, they will also likely raise a host of legal and regulatory challenges. I will categorize the impacts into several aspects: data privacy & security, intellectual property law, criminal law, and regulatory/standards development.

Data Privacy & Security: QM networks are predicted to enhance communication security exponentially, thanks to the principles of quantum physics and the 'no-cloning theorem'. This level of security **could augment data privacy protections**, modifying the interpretations and implementation of relevant laws like the U.S. **Electronic Communications Privacy Act (ECPA)**, **Stored Communications Act (SCA)**, and various state privacy laws. It could also **necessitate new legislation or amendments** to existing legislation, to account for QM encryption's potential, both proactively (in protecting consumer privacy) and reactively (in the event of a QM encryption failure).

Intellectual Property (IP) Law: Emerging QM technologies often need cutting-edge, proprietary technology. Therefore, robust patent protection will likely play a vital role in fostering an innovative and competitive market. **These technologies could press for a re-evaluation of the patentability of QM-based innovations**, as happened with software and digital technologies. Current patent laws might have to be revised to consider the specific dynamics of QM paradigms.

Criminal Law: Since QM technologies bring heightened security, they could also potentially fortify malicious cyber activities. An unauthorized third party could potentially use QM cryptography for concealed illegal activities, causing enforcement issues for authorities like the Federal Bureau of Investigation (FBI) or Department of Homeland Security (DHS). **A re-evaluation of search and seizure laws might be necessary**, as conventional means of digital forensics might not be applicable in a world of QM-encrypted data.

Regulatory/Standards Development: It's necessary to emphasize the development of national and international standards for QM technologies, which are fundamental for uniformity and competitiveness. Currently, NIST is working to develop new cryptographic standards to resist QM computing attacks. In this context, **the current standards might be insufficient for QM communications**, **requiring new mandatory protocols** that might be dictated by a national body or a consortium of industry players.

In conclusion, QM networks or QM internet, though an exciting prospect, could have massive implications across various legal domains, prompting a need for careful investigations and legislative adjustments. As such technologies are still at an embryonic stage, it's both an opportunity and a challenge for the legal system to adapt and be ready for the promises and perils they bring along.

VII. Conclusion

In summary, QM technologies represent a revolutionary step in the evolution of computing and information processing, harnessing the strange and counterintuitive principles of QM mechanics—such as superposition and entanglement—to perform tasks that are beyond the capabilities of classical computers. The potential societal impacts of these technologies are profound. QM computing promises to solve complex mathematical problems much faster than current supercomputers, potentially leading to breakthroughs in drug discovery, materials science, and optimization problems in logistics and manufacturing. QM cryptography, on the other hand, can provide unprecedented security for data transmission, based on the principle that observing a QM state inherently alters it, thus enabling the detection of eavesdropping.

As QM technologies continue to mature, they will significantly affect the legal system. For example, as previously mentioned, QM cryptography could pose challenges to the law enforcement and national security agencies' methods for wiretapping and surveillance, protected under acts like the USA Patriot Act. The balance between individual privacy and collective security may need reevaluation if QM encryption makes it practically impossible for agencies to intercept communications without detection. This could lead to new legislation or amendments to existing laws to address these changes.

Moreover, as previously touched upon, the development of QM technologies will make them exponentially significant because the economics of these technologies are assured to lower with widespread adoption, new fabrication techniques, and government funding subsidies.

Intellectual property, and patent law in particular, will likely be a critical area of legal expansion and contestation. IP associated with QM algorithms, QM communication systems, and other QM-driven innovations will be likely to be hotly debated and litigated. Companies investing in these technologies will seek to protect their innovations through patents, which could lead to a surge in patent-related lawsuits and a consequent need for the legal system to better understand the complexities of QM technologies.

Additionally, there may be calls for international regulations and norms governing the use of QM technologies, particularly in areas such as cyber warfare and espionage, given the potential for QM computing to break conventional encryption. This aspect could lead to new international treaties and laws, thus requiring legal professionals to become conversant not only in traditional law but in the nuanced specifics of technological applications that were previously the province of scientists and engineers.

The intersection of QM technologies with the U.S. legal system will necessitate an evolution of current laws and legal procedures to keep pace with advancements that could surpass the underlying assumptions of existing regulations. Legal practitioners will need to collaborate closely with QM physicists and related experts to properly interpret and apply the law considering these novel and rapidly advancing technologies. This interdisciplinary approach will be essential to navigate the legal implications of a world where QM technologies are commonplace.

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