The Uncertain Future of Physics and Computing

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There's no sense in being precise when you don't even know what you're talking about – John von Neumann

In the 20th century, physics became dominated by abstract mathematics, with a fundamental role for uncertainty. In contrast, computing was built on a foundation of mathematical certainty. John von Neumann was a primary source for both these foundations. I argue that both are misleading, and should be revised to reflect microscopic determinism with varying degrees of macroscopic uncertainty. I predict a future neoclassical physics without quantum entanglement, but no "theory of everything". Future computing will involve neural networks that can embody consciousness, but no quantum computing. Formal mathematical proofs of undecidability or uncomputability will have little practical impact on either computing or physics, but absolute knowledge will remain unattainable. All future predictions should be regarded with skepticism.

I. Introduction

This FQXi Essay Contest focuses on mathematical proof and implications for the foundations of physics and human knowledge. My essay focuses on the foundations and the future of physics and computing, and argues that the orthodox foundations may be incomplete or incorrect, and that mathematical proofs will not provide the answers. Physics and computing are of course distinct topics, but these are tied together by common themes of prediction and uncertainty, and by the historical presence of the 20th century polymath John von Neumann in the foundations of both physics and computing.

The essay starts by reviewing classical and modern foundations in Section II, then proceeds in Section III by suggesting a future neoclassical physics that unites relativity and quantum mechanics (QM), without quantum uncertainty or entanglement [1-5]. Section IV argues for a future of computing with artificial neural networks that can embody machine consciousness [6,7]. Section V summarizes the key points of the essay. The Appendix states the case against quantum computing (QC) [8,9].

II. Classical and Modern Foundations

The scientific revolution of the Enlightenment was based on a dual foundation of experimental observations and mathematical models, to describe both planetary orbits and the dynamics of objects on earth. Calculus was developed by Newton in parallel with mechanics, in order to quantify nature and to enable accurate predictions of trajectories. Time and space in classical physics were absolute and uniform, and the orbits were deterministic and exact. Indeed, these very orbits on the cosmic scale defined time, enabling a "clockwork universe".

Following the prediction and verification of electromagnetic (EM) waves in the 19th century, this classical synthesis of physics and mathematics seemed to be *almost* complete. These waves were believed to be carried by a medium known as the "luminiferous ether", and it was even asserted [10] that, "The real existence of this ether is one of the great events of the Victorian era". But cracks in this edifice were already present, and the entire classical foundations of both physics and mathematics would soon come crashing down.

First, observations in the 19th century showed that basic physical quantities such as velocity and energy behaved strangely in certain cases. The velocity of the earth relative to the ether was unmeasurable (Michelson and Morley, 1887), and optical spectroscopy required energy in discrete bundles, called "quanta" by Planck in 1900. The key relation is $E = h\nu$, where h is Planck's constant and ν the wave frequency. Both aspects were inconsistent with classical physics. These two classes of inconsistencies led to two divergent approaches to modern physics; relativity to address issues of velocity, and QM to address issues of discreteness. This split in the foundations of physics remains to this day.

Second, it became clear during the 19th century that mathematics was not really a description of the natural world, but rather was a distinct study of the relationships among formal logical systems, and that branches of mathematics could be constructed that had no direct correspondence in the natural world. Such abstract mathematics includes non-Euclidean geometry, linear algebra of multi-dimensional vector spaces, and even the concept of infinity. Could mathematicians prove that these various mathematical systems were consistent and complete, based only on simple axioms? German mathematician David Hilbert proposed a program to do so in the early decades of the 20th century, to establish a clear foundation for all of mathematics. This project did not succeed, and further in 1931 Kurt Gödel proved that such a consistent foundation was not possible.

Returning to the foundations of physics, Einstein proposed in 1905 that the lack of detection of the ether is due to its absence; light travels in vacuum at a fixed speed c, in any inertial reference frame. This requires that time and space are not absolute as they are classically, but rather that they are tied together in a 4-dimensional space-time. In special relativity, c became the fundamental speed limit for the universe. Energy and momentum are altered, with the energy of a particle of mass m at rest given by the famous equation $E = mc^2$. By 1915, Einstein had developed general relativity (GR), which extended special relativity for the presence of gravitational fields, which bend space-time, in a way that could be described by non-Euclidean geometry for 4D space-time. The speed of light is still a universal constant, but light now follows a curved path around a source of gravity such as the sun. This curved light was verified by astronomical observations during a solar eclipse in 1919, thus confirming GR.

But relativity provided little guidance to the quantum problem, that of discreteness on the atomic level. Einstein proposed that light waves were composed of photons, quanta of light with $E = h\nu$. This wave-particle duality was a continuing theme in the early development of quantum theory, when de Broglie proposed in 1923 that an electron could also show wave effects, with wavelength $\lambda = h/p$, where p is the particle momentum. This led Schrödinger in 1926 to propose his famous wave equation for an electron in an atom, which quantitatively explained atomic spectra. The solution to this wave equation was a complex field $\Psi(r,t)$, but its nature was unclear. Schrödinger and de Broglie thought of it as a physical wave, but Bohr and Heisenberg developed the still dominant Copenhagen interpretation of QM, whereby $|\Psi|^2$ is the probability that a point electron is present in the envelope of the wave. This gave rise to the Heisenberg uncertainty principle, that the position and momentum of an electron are fundamentally uncertain.

Probability and statistics were already well known within classical physics by the 19 century; macroscopic uncertainty can arise from microscopic determinism. For example, statistical mechanics was developed by Boltzmann and others, to describe the dynamics of a large assemblage of atoms in the presence of random thermal motion. Further, it was also well known that some deterministic dynamical equations yield trajectories that are extremely sensitive to initial conditions, making them practically unpredictable. This was formalized much later into the mathematical theory of "deterministic chaos". Nonlinear equations are particularly sensitive to chaotic behavior.

Another key aspect of the quantum behavior of electrons is the exclusion principle that two electrons cannot be in the same location at the same time. This was explained in 1925 by Wolfgang Pauli using a mathematical construction that also had some odd side effects, not noticed until later: nonlocality and entanglement. Together with the Schrödinger equation, this could explain the chemistry of the Periodic Table. This was quickly accepted into the mathematical basis for QM.

This was formalized into the Mathematical Foundations of Quantum Mechanics by John von Neumann, a mathematical wunderkind who at the time was a post-doc with Hilbert, and published in 1932. This applied the mathematics of abstract linear algebra and developed the theory of Hilbert space, for an abstract vector that was later symbolized (by Paul Dirac) as $|\Psi>$. With the Nazi destruction of the German scientific community, Einstein moved to the Institute of Advanced Study in Princeton in 1933, as did von Neumann. Gödel visited IAS in 1933, and came permanently in 1939.

During this period, the orthodox mathematical foundations of QM became accepted as the unquestioned standard, due to the strong reputation of von Neumann. But Einstein and Schrödinger in 1935 identified quantum entanglement and objected to it on fundamental grounds. Einstein pointed out the EPR paradox, and Schrödinger the cat paradox, and neither accepted entanglement to the end of their lives. In a 1936 letter from von Neumann to Schrödinger, von Neumann asserted that the concerns about entanglement of both Einstein and Schrödinger were wrong [10]. But these mathematical foundations were never seriously challenged.

Quantum entanglement remained an obscure aspect of quantum theory until the 1970s, when a series of two-photon experimental tests were done, inspired by the analysis of John Bell. These Bell test experiments agreed with the predictions of orthodox quantum theory, convincing most physicists that entanglement was real and unavoidable. Recently, the first significant application of quantum entanglement is being developed: QC. Time will tell if this is achieved (see Appendix).

The terms "unified" and "universal" have been used repeatedly in the history of physics, to describe both established theories and future goals. Newton developed a universal theory of gravitation, with a unified formalism for motion both in the heavens and on earth. He also worked on optics, (static) electricity and magnetism (of the earth), but they were separate subjects. In the 19^{th} century, Faraday and Maxwell unified electricity, magnetism, and optics under the umbrella of Maxwell's equations. But electromagnetism (EM) was still clearly distinct from gravitation. Einstein spent the latter part of his life searching for a unified field theory of gravity and EM, but he failed completely. By the late 20th century, it became clear that there are (at least) two more fundamental forces, the strong nuclear force associated with the glue between and within nucleons (quarks and gluons), and the weak nuclear force associated with neutrinos and beta decay. Much of recent theoretical physics has been associated with attempts to develop grand unified theories that combine EM and both nuclear forces, and beyond this to theories of everything that also include gravity. But it is virtually impossible to test such theories, as that would require access to experimental regimes that are far beyond what can be presently achieved.

The foundations of computing had to wait for the 20th century, as technology developed that could implement it. The key early people in this regard were Alan Turing and John von Neumann, who overlapped at Princeton, where Turing received his Ph.D. in mathematics in 1938. Turing developed the concept of a virtual computer, the "Turing machine" (1936) that can compute an algorithm, a series of logical or arithmetic operations, according to a program. Von Neumann took this further, developing one of the first practical electronic computers at the Institute for Advanced Study [12]. This machine, first demonstrated in 1952, was secretly funded by the US Dept. of Defense to simulate nuclear weapons; the cover story was about weather and climate prediction, another computationally difficult problem. The von Neumann architecture (1945), with its central processing unit (CPU) and program in memory, provided the standard for computing architecture up to the present.

Soon after computers were first developed, they were popularly called "electronic brains", but biological brain organization was found to be quite different from that in computers. This was noticed quite early by the leading thinkers in computer science, including both von Neumann and Turing. Turing wrote an essay on "Computing Machinery and Intelligence" in 1950, and von Neumann's last (incomplete) book was "The Computer and the Brain" (1958). Turing is remembered for the "Turing test", whereby an advanced computer could exhibit artificial intelligence, which might be indistinguishable from real intelligence. Unfortunately, both Turing and von Neumann died relatively young; otherwise, the history of computing might well have been different.

The field of artificial intelligence started in the 1960s (by Marvin Minsky, John McCarthy, and others), with the advent of computers of increasing capability. When programmed with a sufficient series of rules describing a particular subject, this can create a powerful expert system. However, such a system is not good at learning new rules, something that biological systems are designed to achieve.

Biological brains are constructed from a network of neurons (NN), each connected by thousands of synapses to other neurons. There is no CPU, and no main memory, as in a classic von Neumann computer. Both processing and memory are highly parallel and highly distributed. While a von Neumann machine is a universal computer that can simulate any other type of computer, this says nothing about how efficient or fast such a simulation can be. Recent developments have shown that for certain common kinds of problems (such as pattern matching and searching), artificial neural network circuits are orders of magnitude faster and more efficient than conventional computers. Furthermore, "deep learning" with multilayer NNs has been found to be particularly efficient at machine learning (ML) without programming. However, despite IBM's Watson computer winning the game show Jeopardy, such a system could not pass the Turing test. This remains an active field of research.

III. The Future of Physics

In the early 20th century, theoretical physics broke into two distinct regimes with two contrasting mathematical approaches and philosophies: relativity with deterministic trajectories in curved space-time, and QM with uncertainty and Hilbert space. I argue that the way to reunify relativity and QM is not to come up with a new theory that incorporates these modern theories as limits. The theories are so different, that would be virtually impossible for any simple, coherent theory of nature. Instead, we need to go back to the early 20th century, and reconstruct a revised version of classical physics that can incorporate the key phenomena that relativity and QM have tried to address. This can lead to a new interpretation of relativity, and a new quantum theory that is experimentally testable, with a unified synthesis that I have called neoclassical physics [1].

Consider first the nature of time. In classical physics, time is uniform and absolute, but it is calibrated by the motion of the heavenly bodies. A day is the rotation of the earth, a month is the orbit of the moon, and a year is the rotation of the earth around the sun. Then Einstein argued that we could not rely on these standards. Instead, the only absolute quantity was the speed of light, and time and space were mixed into an abstract 4D space-time.

But in the 21st century, time is operationally defined by atomic clocks, which are of course quantum, and were unknown to Einstein. One can define both time and space in terms of the de Broglie wave of the electron [13]. The characteristic electron frequency is $f_e = mc^2/h$, and the characteristic Compton wavelength is $\lambda_e = h/mc$. Their product defines the speed of light, c. However, these are not absolute; their values are modulated by speed and gravity (time dilation and length contraction). Since everything is made of electrons and atoms, everything scales in the same way. For example, in a normalized gravitational potential φ, $f_e \propto 1/(1-\varphi)$, and $\lambda_e \propto 1/(1-\varphi)$, where $\varphi = -GM/Rc^2$ a distance R from a large mass M. These modulations are normally quite small, at least within the solar system; $\varphi = -2 \times 10^{-6}$ at the surface of the sun. Taking these definitions into classical mechanics allows one to reproduce all the standard tests of GR, at least to first order in φ: gravitational red shift, bending of light, and rotation of the perihelion of Mercury. No reference to 4D space-time is necessary.

There have been no experimental tests to higher order in φ, so that we have no way of knowing the physics in this unexplored regime. For higher orders, orthodox GR predicts that time diverges as $1/\sqrt{1+2\varphi}$, corresponding to an event horizon for φ =-0.5, which seems non-physical. A non-divergent formulation of relativity [14] can produce a gravitationally condensed object with φ >>1, but it will not be a black hole. Rather, a "dim star" might be composed of a dense quark-lepton plasma similar to that in the early universe. A small amount of red-shifted radiation could still escape in a narrow angle around the vertical. This may be consistent with existing observations.

For weak φ, this alternative formulation is equivalent to GR, but it seems quite different. For example, the speed of light is not a universal constant! The speed of light scales as $c \propto (1-2\varphi)$. Within this picture, the curvature of light is due to the fact that its speed slows near a star. This change is not detectable by a local instrument, since this instrument is made from atoms, but it can be detected remotely. This variability of c is implicit in orthodox GR, but is never pointed out. In this alternative neoclassical picture, all constants are variable (including G and the charge e), except h and dimensionless ratios [13].

This has brought GR into the neoclassical synthesis, but what about QM? There are 4 main quantum phenomena that need to be explained: wave-particle duality, discrete energies, quantized spin, and the exclusion principle for electrons. I suggest that all of these can be addressed by a single ansatz based on the concept of a soliton. It is well known that certain nonlinear wave equations can give rise to localized wavepacket solutions that maintain their integrity as they move, acting like a particle moving in a linear system. The amplitude of a soliton is fixed; neither larger nor smaller wavepackets are possible. This suggests that a quantum "particle" may be more properly a "wavicle": a localized soliton-like wave packet, rather than a statistical distribution of point particles.

Furthermore, two solitons tend to repel each other; they cannot be in the same place at the same time. This seems similar to the exclusion principle, without requiring the mathematical construction of quantum entanglement. This is quite different from the behavior of linear wave equations, where the amplitude of a wavepacket is arbitrary, two wavepackets do not interact with each other, and a single wavepacket will tend to spread out, or even split, as it moves. The entire mathematical basis for orthodox QM is built around linearity, especially the Hilbert space formalism. Schrödinger's and Maxwell's equations are indeed linear. However, these may be the linear limits of the fundamental nonlinear field equations after quantized wavicles have formed.

The other key issues are quantization of spin and energy. Conventionally, spin is the quantized angular momentum associated with a point quantum particle, with no classical limit, and that nothing is really spinning. However, this becomes much clearer if one considers the example of a classical circularly polarized (CP) EM wavepacket [16]. This corresponds to a vector field $\vec{E}$ of fixed amplitude, rotating at frequency f = $2\pi\omega$, which is indeed spinning, and it carries angular momentum distributed across its volume. Such a wavepacket has an energy density $\mathcal{E}$ and an angular momentum density $\mathcal{S}$, both proportional to the field intensity $\propto |\vec{E}|^2$, related to each other by $\mathcal{E} = \mathcal{S}\omega$. So if we associate this distributed wavepacket with a single photon that is known to have spin S = $h/2\pi = \hbar$, then if one integrates over the volume of the photon, the relation E = $\hbar\omega$ follows as a direct consequence. Similarly, an electron may also be represented by a vector field rotating about a fixed spin axis, where the integrated spin is S = $\hbar/2$. Further, all fundamental quantum particles are really localized wavepackets with quantized spin, corresponding to the coherent rotation of a vector field around a spin axis. Spin is no longer mysterious.

The rotation of a real vector initially seems quite different from the complex scalar of Schrodinger's equation, but they are mathematically equivalent. Schrödinger's equation can be derived from real vector solutions of the relativistic Klein-Gordon wave equation, assuming only rotation about a fixed axis [15]. If the solution to the Schrodinger equation is $\Psi = |\Psi|\exp(i\theta)$, θ represents the real rotation angle of the rotating vector field, with the relativistic "carrier wave" at f = mc^2/h suppressed.

This neoclassical synthesis is not complete – what is needed are the full nonlinear wave equations for the electron and photon, which should lead spontaneously to spin quantization and the exclusion principle. Still, this represents a consistent picture, based on local reality without the need for any fundamental uncertainty. The phase angle of a rotating vector field would not normally be known or controlled, so that there is plenty of statistical uncertainty on a macroscopic level.

This alternative quantum model makes predictions that are sharply different from those of the orthodox quantum theory [17]. For example, the two-stage Stern-Gerlach experiment may test superposition in electron spins, and a measurement of polarization of single photons may test whether the entanglement experiments are really valid. Further, this alternative model predicts that QC should be impossible (see Appendix). If indeed QC fails in the next few years, the physics community may be more willing to consider an alternative model such as this.

Finally, this view of physics removes most of the "magic" that has been at the heart of modern science fiction. There should be no time travel, no warp drive, no wormholes, no parallel universes, no subspace communication, no extra dimensions, no mysterious energy sources. But a reality-based foundation for physics will provide a firmer basis for addressing future issues in physics, such as the nature of dark matter and simulating the properties of matter here on earth.

IV. The Future of Computing

Computers have been growing exponentially in the 21st century, both in performance and in proliferation of systems. This has been enabled by Moore's Law of transistor scaling, which is coming to an end, so a different approach will be needed to ensure continued progress into the future. Two novel approaches have recently been getting attention, quantum computing (QC) and artificial intelligence (AI). I address in the Appendix why QC is unlikely to be practical, so this section focuses on AI, which I believe will provide the predominant source of growth in computing capability in the next several decades.

Until recently, virtually all computers were based on universal von Neumann machines with precise digital arithmetic engines. These are built with integrated circuits of billions of identical transistors, operating at fast gigahertz speeds, with no errors allowed. This should be contrasted with biological brains, built with billions of non-identical neurons and synapses, operating at slow kilohertz speeds, performing analog operations that are tolerant of errors and noise. But they are structured as multilayer neural networks (NNs) rather than arithmetic engines, which enables much greater parallelism, as well as learning and adaptation. NNs are particularly fast and efficient at matching patterns, which does not require precision. Artificial NNs have been developed in a variety of device technologies, and are increasingly being applied to AI.

One area of AI that is not yet a major focus is conscious computing, in part because consciousness is not properly defined or understood. Human consciousness is perceived through our own internal sense of self, which makes it seem fundamental and even mystical. Indeed, this internal sense provides the foundation for religious beliefs in the disembodied human soul. But consciousness is not some mysterious property that emerges from brains of a critical mass, but rather a specific organized structure that can be emulated in technology.

Much of this internal sense of consciousness is illusory; the conscious mind is not actually in control of most of the mind. As discussed in the 2011 book, "Thinking Fast and Slow" by the Princeton psychologist Daniel Kahneman, the conscious mind is like the CEO who thinks he runs his company single-handedly, taking credit for the work done by his underlings (the unconscious mind). The conscious mind is actually quite slow and limited to one task at a time, and addresses only those decisions that cannot be done, quickly and invisibly, by the unconscious mind. Further, many animals (such as horses or dogs) may be as conscious as we are, even if they cannot tell us so. But can we create a conscious machine [6,7], and will it be useful?

Biological consciousness evolved in order to make rapid decisions in complex, unpredictable environments, with incomplete information, extrapolating from past experience. Similar capabilities may also be useful for autonomous vehicles, robotic assistants, and autonomous agents in computer networks. While a conscious computer would work closely with unconscious modules, consciousness is likely to offer some advantages in terms of flexibility and adaptability.

But what fundamentally is consciousness[6]? I suggest that the internal perception of consciousness provides a major clue – it is primarily about temporal pattern recognition, identifying correlations in video and other sensory sequences. This permits a conscious system to partition the environment into objects, agents, and self, and to correlate those with previous experiences in memory. The sense of consciousness is largely the continuing recognition of oneself in the environment, mapping onto previous incarnations of the self. The second key feature of consciousness is the creation of a narrative, a coherent story of oneself in the environment. This narrative continues from the past and projects to the future, and includes decision points. Note that these features do not necessarily include linguistic competence or intelligent thinking.

I do not believe that there have been any AI systems thus far that incorporate these principles to demonstrate machine consciousness at any level. However, artificial NN technology has reached a stage where a primitive conscious machine can be constructed, perhaps in the next decade [7].

A prevailing concern in science fiction has been that super-intelligent robots will take over the world from humans. And indeed, one can envision systems that combine the high speed of electronics with the architecture of brains, challenging the very notion of human uniqueness. But more likely, conscious robots will increase the digital divide between those humans in control of the robots, and those who are left outside the system. Future AI will provide challenges to human societies, but hopefully we can ensure that it is applied to protect networks and benefit mankind. The future is uncertain.

V. Conclusions

1) No Quantum Uncertainty or Entanglement

These are mathematical artifacts of the abstract Hilbert space model developed by von Neumann, but are inapplicable to the real world.

2) Real physical fields in real space define the foundations of physics

Future physics will be guided by a neoclassical model that reunifies relativistic and quantum phenomena, in which real wavicles (soliton-like wave packets) define time and space, without the need for the abstract mathematics of space-time or complex Hilbert space.

3) No Quantum Computing

Quantum computing is unachievable for both fundamental and practical reasons, and will not be the future of computing; the experimental evidence thus far has been misinterpreted.

4) Neural networks for artificial intelligence.

The future of computing will be based not on the precise arithmetic of classic von Neumann machines, but rather on neural networks, which are capable of adaptive learning and massively parallel approximate computations, mostly to match patterns.

5) Machine Consciousness from Temporal Pattern Recognition

Neural networks configured to match patterns in temporal sequences will enable identification of objects, agents, and the self in a perceived model environment. This will provide the basis for machine consciousness, which will find near-term application in autonomous vehicles.

6) No absolute knowledge or predictability

This goes beyond formal mathematical proofs. Our understanding will always be approximate and limited to what we can observe. We can make predictions about the future, but they are likely to be wrong.

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Appendix: Why We Should Be Skeptical About Quantum Computing [8]

Extraordinary claims require extraordinary evidence – [Carl Sagan]

As of 2020, quantum computing (QC) has become a very hot field of research and technology. Governments, corporations, and investors around the world are competing with each other to pour billions of dollars into development projects that promise revolutionary breakthroughs in computer performance. Articles in the popular and scientific press are reporting claims of "quantum supremacy", that a QC can outperform any conceivable classical computer. And some are projecting that within a few years, quantum computers will make all conventional computers obsolete.

In sharp contrast, I suggest that all of this is hype, and I predict that the entire field will collapse, likely within a few years, with nothing to show for it.

It may be helpful to review the theoretical basis for the promised QC performance, which is due to virtual parallelism on an exponential scale. In classical computing, certain kinds of problems are amenable to speedup via parallel processing. One may have parallelism at the level of multiple processors (as in supercomputers), or at the level of individual devices (as in neural networks). So one may reasonably project to a parallel enhancement of up to about a billion.

The power of QC depends on the entanglement of interacting quantum bits (qubits), which expands the Hilbert space exponentially. For a system with N qubits, the effective parallelism of the entangled state is 2^N. If N = 300, $2^N = 10^{300*\log 2} = 10^{90}$, which is greater than the number of atoms in the known universe. This provides exponentially large virtual parallelism from a very modest hardware parallelism. Furthermore, this would seem to provide a roadmap for continuing exponential enhancement of computer performance, to surpass Moore's Law which is ending. If for example, one could add an additional qubit every year, one could then double in performance every year.

If such a system with massive virtual parallelism existed, it could be used to solve problems that are completely unsolvable by any foreseeable classical computer, such as factoring large integers that are central to standard Internet encryption protocols. This was the initial reason that certain government agencies became interested in QC.

But this is a truly extraordinary claim, with little or nothing to back it up. Quantum entanglement entered quantum theory early on, but there is no evidence for many-body entanglement effects. The well-established aspects of QM, such as atomic orbitals and energy bands, are really based on single-electron physics. I question whether any of the von Neumann quantum formalism is correct, which may be testable by straightforward experiments [9].

But even if this formalism is correct, such highly entangled states are expected to be exponentially sensitive to noise and fluctuations. It has been suggested that "quantum error correction" can use qubits to correct other qubits, so that one might require hundreds of physical qubits correcting each logical qubit. Some researchers have suggested that this is an insurmountable problem, so that QC will be impossible to achieve at a scale which is useful [18].

A second confusing aspect of the present situation is that one company is already selling commercial "quantum computers" based on superconducting integrated circuits at temperatures << 1 K, which verifiably solve difficult optimization problems. So doesn't this prove that quantum computers work? No, because this system is more properly a "quantum annealer", an analog computer that is completely different from the digital quantum gate computer that other companies are developing. Further, this system is deliberately designed to function in the same way in the classical limit, by mapping onto the 2D Ising model. While it is claimed that this system has a quantum advantage, this is not at all clear.

In fact, there is also a commercial "Digital Annealer"chip, which maps onto the same 2D Ising model, and uses "quantum inspired" algorithms to solve the same optimization problems. This chip is based on standard silicon technology operating at room temperature, and is not quantum at all. This is a custom chip that uses parallelism and distributed memory to achieve dramatic speedups compared to a conventional von Neumann computer architecture.

In contrast, the QC prototypes based on the digital qubit gate model do not operate at all in the classical limit. But there is also little evidence that they have performed any useful calculations. Still, there have been many careful experimental measurements on arrays of qubits in these systems. They claim to be seeing quantum entanglement, but is there an alternative explanation?

I suggest that what is being seen in these coupled qubit systems is really just coupled oscillators. A qubit is essentially a highly resonant system, with little or no loss. For qubits to entangle, they must interact. But an array of classical coupled oscillators will form a band of collective modes throughout the system, at slightly different frequencies. The same is true for coupled electronic states in solids – they form energy bands. But this does not increase the phase space of the system; N oscillators give rise to N delocalized modes, without the exponential increase from entanglement needed for QC. Researchers in this field should be trying to prove that QC models may be incorrect, rather than trying to verify them. A coupled-mode model may provide an alternative to evaluate the same measurements.

Finally, QC provides the first real application of the von Neumann quantum formalism. Given how much money is being invested in the field, it should be clear within a few years if this is working. If QC is successful, this will prove the robustness of this theory. But if QC fails, physicists will want to understand why. This will open up the field to alternative models for quantum foundations. I remain skeptical of QC, but let's see what happens.