

Quantum Effects and Enabling Quantum Information Science – An Analysis

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Abstract

This paper will focus primarily on quantum effects and how they enable quantum information science, The quantum effects of physics are at the atomic and subatomic level, brought to us courtesy of quantum mechanics, and hold the key to major advances — quantum leaps — in computing, communication, measurement, and sensing, known collectively as *quantum information science*. This informal paper is not intended for physicists, but for computer scientists, software developers, and other non-physicists who wish to become involved with quantum information science, particularly *quantum computing*, and have a need (or desire) to know *something* about the underlying physics, particularly enough to understand what makes quantum information science tick, but nowhere near as much as a physicist or hard-core quantum engineer might need. We need a lot more computing power to tackle much larger and much more complex computing challenges in the decades ahead. Ditto for communication, measurement, and sensing. That's where *quantum effects* come in. *Quantum information science* is the broad umbrella for the theory, science, engineering, technology, infrastructure, and applications related to exploiting quantum effects (quantum mechanics) in the areas of computing, communication, and measurement and sensing.

Quantum information science is based on any aspect of *quantum effects* which can be observed, measured, controlled, stored, or communicated in some manner. *Quantum* is essentially a reference to *quantum mechanics*, which concerns itself with atomic and subatomic particles, their energy, their motion, and their interaction.

Larger accumulations of atoms and molecules behave in more of a statistical or aggregate manner, where the quantum mechanical properties (quantum effects) get averaged away. Quantum information science and its subfields focus at the quantum mechanical level where the special features of quantum mechanics (quantum effects) are visible and can be exploited and manipulated. Quantum mechanics is the field of physics which is the theoretical foundation of quantum information science, quantum physics is the application to the principles of quantum mechanics to the many areas of physics at the subatomic, atomic, and molecular level, including the behavior of particles and waves in magnetic and electrical fields.

Key words: quantum effects, quantum mechanics, information science, magnetic, electrical, waves.

Introduction

Entanglement is the counterintuitive idea that particles can have an intrinsic connection—a connection that endures no matter the distance between them. The phenomenon remains one of the most bizarre and least understood consequences of quantum mechanics. Measure the quantum properties of one of a pair of entangled

particles, and the other changes instantaneously. Such strange phenomena typically have been relegated to the subatomic. But recently, physicists have taken entanglement and other quantum effects to new extremes by observing them in large systems including clouds of atoms, quantum drums, wires, and etched silicon chips. Device by device, they are bringing the quantum world into new territory—the macroscopic world.

This work is driving new applications. Some experimental quantum computers use loops of superconducting wire as qubits, storing quantum information. Large quantum objects have already been used to help detect gravitational waves; they could appear in next-generation devices such as ultrasensitive sensors and encryption systems. These innovations, though, reach beyond cutting-edge tech. Building bigger and bigger quantum objects even raises the possibility of exploring some of the most pervasive unsolved mysteries at the intersection between quantum and classical worlds—and between quantum mechanics and gravity. Ever since Austrian physicist Erwin Schrödinger first described wave-particle duality 90 years ago

(1), physicists have been probing the boundary between the observable, predictable macroscopic world and the one where probabilistic quantum rules dominate. In the quantum world, a particle exists as a wave representing the probabilities of its location. Once measured, however, the particle is found at a point in space.

Furthermore, a quantum particle can be in a superposition of two quantum states, with some probability of being in either one. An electron might be in a superposition of high and low energy levels, for example. When someone makes a measurement, this state collapses; the electron is observed to have one level or the other. According to quantum mechanics, the act of measurement changes the system.

So it goes with entangled pairs. Measure the properties of one, and the properties of the other, no matter how far away, are set. This all runs counter to the reliable Newtonian rules that govern our macroscopic world, in which an object can be found reliably in one place.

Quantum rules apply to single atoms and other denizens of the smallest orders of magnitude known to science, and tiny atoms make up everything, so it stands to reason that these effects should scale up. But how far?

Some people have suggested such a limit. According to what are known as wave-collapse theories, undiscovered natural laws explain these quantum mysteries without invoking the idea that observation changes a system. English mathematical physicist Roger Penrose has hypothesized that wavefunction collapse is a consequence of the force of gravity, so systems above a certain mass should never show quantum behavior

(2). The Ghirardi–Rimini–Weber theory, published in 1986, says that a particle’s wavefunction can simply collapse spontaneously

(3). It would happen rarely to each individual particle, but in a large system made of billions or more entangled particles, the collapse of one would soon cause the collapse of all.

Physicists continue to debate at what size the microscopic world transitions into the macroscopic one and how to quantify that change.

Objective:

This paper intends to study Quantum effects both from the perspective of quantum information processing, where a major challenge is to maintain quantum coherence in systems that unavoidably interact with an environment, and lastly from the perspective of quantum biology.

Quantum effects at junctions of non-superconducting material

Experimental physicists are already demonstrating quantum effects in ever more complex domains. It's not easy. Quantum effects are fleeting, delicate, and fragile, drowned out by even the slightest vibration or thermodynamic fluctuations. To observe them at all requires experimental setups that isolate the system from the heat and noise of the outer world.

For years, researchers have been able to successfully muffle that noise to observe individual subatomic particles and even large atoms in entangled states. Isolating quantum effects is less a matter of size than of complexity. Observing any system from individual atoms up to microscopic drums means quieting the noise of all the moving parts so that the quantum effects can come out to play. The noisiest variable is usually heat: "Temperature is a form of noise, and it will mask some of those effects and signals you're looking for"

One approach uses a loop of superconducting wire, usually about a micrometer in diameter, interrupted by junctions of nonsuperconducting material. Superconductivity means electrons flow around the loop without resistance, and the current can be measured at those junctions.

Physicists can use magnetic fields to induce current to flow in both directions around the ring at the same time. That doesn't mean half go one way and half go the other; all the electrons act as one and simultaneously stream clockwise and counterclockwise. Mechanical systems also make appealing quantum targets. At Delft, Gröblacher achieved entanglement at scales approaching the macro world using membranes 1 millimeter in diameter that can vibrate for minutes with a single nudge, which makes them appealing as a playground for testing mechanical entanglement. He envisions using such a system, in the future, to put a living organism into a quantum superposition. That experiment would require an extremely small creature, like a tardigrade. "It would show that even such complex systems can behave according to quantum physics," he says.

More recently, Gröblacher's group has been conducting experiments on a device made up of two silicon chips, cooled to near absolute zero. Each chip has a tiny channel etched into it only about 10 micrometers long. Those channels act as mechanical oscillators that can translate light into motion. They expand and contract at an almost

perfectly matched frequency when struck by light. They also translate motion back into light: the oscillator produces a photon that's emitted at the same point where it entered but going in the opposite direction.

After placing the chips 20 centimeters (8 inches) apart, the researchers sent laser pulses through a beam splitter, which sent light to the oscillators. That light made one of the two oscillators vibrate. It then produced a photon, which went through another beam splitter and on to a detector.

Quantum information

Classical information (a sequence or collection of *bits*) is represented as *quantum information* in the form of a *quantum state*, one *quantum state* for each *classical bit*. *Quantum state* is the *unit of quantum information*.

To be clear, quantum information can represent more than just a 0 or 1 classical bit. Since it is a *quantum state*, it may include a superposition of both a 0 and a 1. The probabilities of 0 and 1 may differ (but they have to add up to 1.0). The probability can include a phase component, and a quantum state may be entangled or shared between two or more separate, otherwise-isolated quantum systems (particles or waves.)

The concept of quantum information applies across all subfields of quantum information science, not just quantum computing and quantum communication.

Quantum bit — qubit

A *quantum bit* or *qubit* is the *unit of storage and manipulation of quantum information (quantum states)*. Qubits are used for both quantum computing and quantum communication. Despite popular misconceptions, a qubit is not the quantum equivalent of classical information or the classical bit. Rather, a qubit is a *device for storing and manipulating quantum information*, not the quantum information itself, which is represented as the quantum state of the device. In classical computing and classical communication a bit is the abstract information, not the physical representation. A bit is either a 0 or a 1, regardless of whether that 0 or 1 is represented as a voltage level, a magnetic field, a photon, or a punched hole.

Quantum information is a 0 or a 1 or a linear combination of a 0 and a 1, regardless of the technology used to implement the qubit device which holds and manipulates that quantum information (quantum state.)

Stationary, flying, and shuttling qubits

For quantum computing, generally a qubit is a *stationary qubit*, which is a hardware device which stores and manipulates *quantum information*. It is stationary, meaning that the device does not move.

For quantum communication, a qubit is a *flying qubit*, typically a photon which gains its utility or ability to communicate by being moveable to a remote location while it is in an *entangled state* with another qubit at a different and possibly very distant location.

A *trapped-ion quantum computer* may use *shuttling* to move a qubit — an ion or atom with a net charge — a short distance so that it is easier to manipulate and measure the quantum state of the qubit, and to store more qubits than can be directly controlled or measured directly.

Measurement / observation

Quantum state is not directly observable or directly measurable using normal, non-quantum methods, devices, or instruments. We can indeed measure any *quantum information* we want, but measuring a quantum state has the effect of *collapsing the wave function* of that quantum state, eliminating the truly quantum-ness of the state (e.g., superposition, entanglement, and interference or phase), leaving the quantum information in a purely classical state, such as the 0 and 1 of classical information.

These aspects of measurement apply across all of the subfields of quantum information science — quantum computing, quantum communication, and quantum metrology and sensing.

Observable

Any *quantum effect* which can be *observed* or *measured* is referred to as an *observable*. Generally, the *quantum state* is the quantum effect which is the observable.

Quantum phenomena

Quantum phenomenon is a vague term which is loosely a synonym for *quantum effect*, or any phenomenon in which a quantum effect is observable in some way, including *macroscopic quantum phenomena*.

Macroscopic quantum phenomena

A macroscopic quantum phenomenon *is any phenomenon above the level of the atomic, subatomic, and molecular level in which a quantum effect is observable in some way. Prime examples are superconductivity, superfluidity, and the quantum hall effect.*

Quantum computers might be the application most likely to benefit first from exploiting quantum effects in the macroworld. Flux qubits are being entangled to create experimental quantum computers that can do what classical computers can't.

Then there are photon detectors, such as the superconducting nanowire created in 2014 by engineers at Duke University in Durham, NC. The nanowire shows a drop in current when a photon zooms by. Bezryadin has pioneered ways to engineer similar superconducting nanowires using carbon nanotubes. A future quantum communications network, meanwhile, will require repeaters, and these devices could use large-scale quantum effects to relay entangled states. Atomic clocks gain their precision from clouds of entangled particles, and the more particles that are entangled, the more stable the clock.

A tantalizing possibility is cracking open what might be the most important question in fundamental physics: how is quantum mechanics related to gravity, the least understood of all the forces in nature? Superconducting loops aren't likely to help answer that question because current doesn't have enough heft for gravity to become significant

Recognizing these opportunities, and also aware of the growing international competition in this promising new area of science and technology, Congress passed the National Quantum Initiative Act, which became law in December 2014.

The DOE Office of Science is an integral partner in the National Quantum Initiative and has launched a range of multidisciplinary research programs in QIS. The efforts cut across the six major program offices within the Office of Science. They include efforts to develop quantum computers as testbeds, to design new algorithms for quantum computing, and to use quantum computing to model fundamental physics, chemistry, and materials phenomena. There is research relating the latest advances in string theory and black hole physics to quantum error correcting codes. There are efforts supporting quantum communication using entanglement towards the possible development of a future quantum network. There are also efforts in materials and chemical sciences to develop systems that will sustain performance, so-called “quantum coherence,” for significant periods of time—a prerequisite for effective quantum computing and information processing. In addition, there is work on sensors for next-generation detectors and the characterization tools that could enable the next round of innovations in science and engineering.

Quantum science to Quantum Biology

Biology, in its current paradigm, has had wide success in applying classical models to living systems. In most cases, subtle quantum effects on (inter)molecular scales do not play a determining role in overall biological function. Here, ‘function’ is a broad concept. For example: How do vision and photosynthesis work on a molecular level and on an ultrafast time scale? How does DNA, with stacked nucleotides separated by about 0.3 nm, deal with UV photons? How does an enzyme catalyse an essential biochemical reaction? How does our brain with neurons organized on a sub-nanometre scale deal with such an amazing amount of information? How do DNA replication and expression work? All these biological functions should, of course, be considered in the context of evolutionary fitness. The differences between a classical approximation and a quantum-mechanical model are generally thought to be negligible in these cases, even though at the basis every process is entirely governed by the laws of quantum mechanics. What happens at the ill-defined border between the quantum and classical regimes? More importantly, are there essential biological functions that ‘appear’ classical but in reality are not? The role of quantum biology is precisely to expose and unravel this connection.

Fundamentally, all matter—animate or inanimate—is quantum mechanical, being constituted of ions, atoms and/or molecules whose equilibrium properties are accurately determined by quantum theory. As a result, it could be claimed that all of biology is quantum mechanical. However, this definition does not address the dynamical

nature of biological processes, or the fact that a classical description of intermolecular dynamics seems often sufficient. Quantum biology should, therefore, be defined in terms of the physical ‘correctness’ of the models used and the consistency in the explanatory capabilities of classical versus quantum mechanical models of a particular biological process.

As we investigate biological systems on nanoscales and larger, we find that there exist processes in biological organisms, detailed in this article, for which it is currently thought that a quantum mechanical description is necessary to fully characterize the behaviour of the relevant subsystem. While quantum effects are difficult to observe on macroscopic time and length scales, processes necessary for the overall function and therefore survival of the organism seem to rely on dynamical quantum-mechanical effects at the intermolecular scale. It is precisely the interplay between these time and length scales that quantum biology investigates with the aim to build a consistent physical picture.

Grand hopes for quantum biology may include a contribution to a definition and understanding of life, or to an understanding of the brain and consciousness. However, these problems are as old as science itself, and a better approach is to ask whether quantum biology can contribute to a framework in which we can repose these questions in such a way as to get new answers. The study of biological processes operating efficiently at the boundary between the realms of quantum and classical physics is already contributing to improved physical descriptions of this quantum-to-classical transition.

More immediately, quantum biology promises to give rise to design principles for biologically inspired quantum nanotechnologies, with the ability to perform efficiently at a fundamental level in noisy environments at room temperature and even make use of these ‘noisy environments’ to preserve or even enhance the quantum properties. Through engineering such systems, it may be possible to test and quantify the extent to which quantum effects can enhance processes and functions found in biology, and ultimately answer whether these quantum effects may have been purposefully selected in the design of the systems. Importantly, however, quantum bioinspired technologies can also be intrinsically useful independently from the organisms that inspired them.

Even low-intensity light of a suitable frequency will lead to electrons being emitted whereas high-intensity light below this threshold frequency will have no effect. Einstein explained this by proposing that in this instance light behaves as a particle rather than a wave, with discrete energies $h\nu$ that can be transferred to the electrons in a material. Bohr’s 1913 model of the hydrogen atom, with its discrete energy states, and Compton’s 1923 work with X-rays all contributed to the beginning of a new era in modern physics. These ways of explaining blackbody radiation and the photoelectric effect, as well as atomic stability and spectroscopy, led to the development of quantum mechanics, a theory that has proved extremely successful in predicting and describing microphysical systems

Quantum biology and complexity

Whereas Planck and Einstein began the quantum revolution by postulating that radiation also demonstrates particle-like behaviour, de Broglie, in 1923, made the complementary suggestion that matter itself has wave-like properties, with a wavelength related to its momentum through Planck's constant. This hypothesis suggested that matter waves should undergo diffraction, which was subsequently proved by experiments that demonstrated that particles such as electrons showed interference patterns. Schrödinger built on this observation in his formulation of quantum mechanics, which describes the dynamics of microscopic systems through the use of wave mechanics. The formulation of quantum mechanics allows for the investigation of a number of important facets of a quantum state: its mathematical description at any time t , how to calculate different physical quantities associated with this state and how to describe the evolution of the state in time.

Quantum mechanics is a mathematical framework that identifies an isolated physical system with quantum state that completely characterizes the system and is denoted by $|\psi\rangle$, and a Hilbert space \mathcal{H} that contains all states available to the system. The time evolution of a system described by a state vector $|\psi\rangle$ obeys the Schrödinger equation,

$$i\hbar \frac{d}{dt} |\psi\rangle = H(t) |\psi\rangle,$$

where \hbar is the reduced Planck constant and $H(t)$ is the Hamiltonian, which represents the energy levels of the system and the interaction between parts of the system.

Conclusion

Quantum information science is based on any aspect of *quantum effects* which can be observed, measured, controlled, stored, or communicated in some manner. Quantum effects enable the capabilities of quantum computing, quantum communication, and quantum sensing and measurement.

Since the mid-1960s, we have been living in a world governed by Moore's Law. In 1965, Intel co-founder Gordon Moore predicted that the number of transistors on computer chips would double every year—a trend that implied a yearly doubling of computer power. Later the predicted interval was amended to eighteen months. That prediction has held true for better than five decades as millions and eventually billions of transistors were crammed onto the most advanced computer chips. But given the sheer physical limits of miniaturization, Moore's Law is now slowing down, and it has long been recognized that eventually Moore's Law will come to an end.

That is one major development that has driven the growing interest in quantum information science (QIS)—forms of computing and information processing that might get around these “classical” physical limitations by relying on exotic quantum effects.

Such effects include “superposition”—whereby a quantum system can exist in all possible states until it is observed—and “entanglement”—whereby measurement of one member of a paired system causes the other member immediately to assume a related value, no matter how distant they are in space.

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