Imagine a world where particles can exist in multiple places at once, where cats can be both alive and dead until you look at them, and where particles miles apart can instantly influence each other. Welcome to the realm of quantum physics a domain so bizarre that even Albert Einstein once called some of its predictions spooky action at a distance.Quantum physics is not just strange for the sake of being strange. Its the bedrock of our modern understanding of nature at its smallest scales atoms, subatomic particles, and the very fabric of reality itself. Without quantum physics, there would be no lasers, no computers, no smartphones, and no MRI machines. Its the science that makes the impossible possible.But quantum physics has a reputation: intimidating, baffling, reserved only for genius-level physicists. Thats simply not true. Anyone with curiosity and a bit of patience can grasp its essential ideas. In this beginners guide, we will journey through the quantum world, unpack its mind-bending concepts, meet the pioneers who shaped it, and glimpse the extraordinary technologies it has inspired.Get ready: reality is about to get weird.At the dawn of the 20th century, classical physics the physics of Isaac Newton ruled supreme. Scientists believed they had almost completely understood the laws of nature. But cracks were appearing in the foundation.One major puzzle involved blackbody radiation the way objects emit light when heated. Classical physics predicted that hot objects should emit infinite amounts of energy at short wavelengths, a paradox dubbed the ultraviolet catastrophe. Experimental data clearly disagreed.In 1900, German physicist Max Planck proposed a radical idea: energy is not emitted continuously but in discrete packets he called quanta. Plancks solution matched the experimental results perfectly but seemed merely a mathematical trick at first.Then, in 1905, Albert Einstein took Plancks idea seriously. In explaining the photoelectric effect the observation that light can eject electrons from metal surfaces Einstein proposed that light itself is made of particles, later called photons. This particle nature of light was revolutionary and earned Einstein the Nobel Prize in 1921.Thus began the quantum revolution, where energy and matter were no longer continuous, but came in tiny, discrete chunks. Reality, it seemed, was quantized.One of the most bewildering concepts in quantum physics is wave-particle duality the idea that particles like electrons and photons behave sometimes like particles, sometimes like waves.This was spectacularly demonstrated in the famous double-slit experiment. When light is shone through two narrow slits, it creates an interference pattern on a screen beyond a hallmark of wave behavior. But when scientists tried to detect which slit each photon went through, the interference pattern disappeared, and the photons behaved like particles.Even more shocking, when particles like electrons (traditionally thought of as tiny billiard balls) were sent one by one through the slits, they too created an interference pattern as if each electron was simultaneously passing through both slits, interfering with itself.This experiment shattered the classical idea that particles and waves are distinct. In the quantum world, entities like electrons and photons are both particle and wave a paradoxical blend with no classical analog.In 1927, German physicist Werner Heisenberg unveiled another cornerstone of quantum physics: the uncertainty principle. Heisenberg showed that certain pairs of properties like a particles position and momentum cannot both be precisely known at the same time. The more accurately you know one, the less accurately you can know the other.This isnt just a limit of our measuring instruments its a fundamental property of nature itself. Reality at the quantum level is fuzzy and probabilistic, not sharply defined.The uncertainty principle shatters the classical idea of a clockwork universe, where knowing the present perfectly means you can predict the future perfectly. In the quantum realm, outcomes are fundamentally unpredictable. Nature does not play out like a precise script it dances to a tune of probabilities.One of the strangest features of quantum mechanics is superposition the idea that a quantum system can exist in multiple states at once.A famous thought experiment by Erwin Schrdinger illustrates this. Schrdinger imagined a cat inside a sealed box with a mechanism triggered by a quantum event say, the decay of a radioactive atom. If the atom decays, the mechanism releases poison, killing the cat. If not, the cat lives.According to quantum mechanics, until we open the box and observe it, the cat is in a superposition of being both alive and dead. Only observation collapses the superposition into one definite state.While Schrdingers cat is a metaphor, experiments on real quantum particles confirm that superposition is real. Particles can exist in multiple states or locations simultaneously until an observation forces them into a single outcome.Perhaps the most eerie aspect of quantum physics is entanglement. When two particles become entangled, their properties become linked, no matter how far apart they are.If you measure one particle and find it spin-up, the other particle, instantly and without communication, will be found spin-down even if theyre light-years apart. This instantaneous connection seemed to violate Einsteins belief that nothing can travel faster than light.Einstein, along with Podolsky and Rosen, published the EPR paradox paper in 1935, arguing that quantum mechanics must be incomplete. But decades later, experiments confirmed entanglements reality, suggesting that the quantum world allows for connections beyond classical space and time.Entanglement is not only a fascinating quirk its the basis for emerging technologies like quantum teleportation and quantum cryptography.Quantum mechanics governs the microscopic world atoms, electrons, photons. Classical mechanics governs the macroscopic world planets, tennis balls, cars.But how do the two fit together? Why dont we see cats in superpositions or cars entangled with each other?The boundary between quantum and classical is still a subject of intense research. One explanation is decoherence the idea that quantum superpositions rapidly collapse into definite states when interacting with the environment. In our messy, macroscopic world full of particles and radiation, quantum effects are washed out almost instantly.Nevertheless, experiments with larger and larger quantum systems continue to push the boundary, suggesting that the quantum weirdness is not confined to the micro-world alone.Far from being a mere curiosity, quantum mechanics powers some of the most important technologies of the modern era.Transistors the building blocks of computers and smartphones rely on quantum tunneling, where electrons pass through barriers they classically shouldnt cross. Lasers, MRI machines, and even GPS systems depend on quantum effects.Now, a second quantum revolution is underway. Scientists are developing quantum computers, which use quantum bits (qubits) that can exist in superpositions of 0 and 1. A quantum computer could solve certain problems exponentially faster than any classical computer.Quantum cryptography promises unbreakable communication by detecting any attempt to eavesdrop via entanglement.Quantum teleportation transmitting information about a quantum state instantaneously is already being demonstrated in laboratories, hinting at future quantum networks.Quantum mechanics works spectacularly well in practice. But what it says about reality remains deeply puzzling, leading to many competing interpretations.The Copenhagen interpretation, championed by Niels Bohr, holds that quantum systems exist in superpositions until observed, at which point the wavefunction collapses.The Many Worlds Interpretation, proposed by Hugh Everett, suggests that every quantum event spawns new parallel universes, where every possible outcome happens.Pilot-wave theory, developed by Louis de Broglie and David Bohm, posits that particles are guided by deterministic hidden variables.Each interpretation offers a different vision of reality, yet none has been definitively proven or disproven. In quantum physics, understanding how the world works remains a profound and open question.In the mid-20th century, physicists developed quantum field theory (QFT), combining quantum mechanics with special relativity.In QFT, particles are excitations in underlying fields that pervade space. The photon is a ripple in the electromagnetic field. The Higgs boson famously discovered in 2012 is an excitation of the Higgs field, which gives particles mass.QFT forms the basis of the Standard Model of particle physics, which describes all known fundamental particles and forces (except gravity) with breathtaking accuracy.Yet, mysteries remain. Gravity still resists a quantum description. Dark matter and dark energy, which make up most of the universe, remain unexplained. The quest to unify quantum physics with Einsteins general relativity the so-called theory of everything continues.Quantum physics doesnt just challenge scientific ideas it forces us to rethink the very nature of reality.Are particles real before we observe them? Does the universe split into infinite branches with every quantum event? Is reality fundamentally deterministic or probabilistic? Is consciousness somehow involved in the collapse of the wavefunction?These questions bridge physics and philosophy, suggesting that understanding the quantum world may also require understanding the nature of knowledge, existence, and consciousness itself.Quantum physics is a revolution not just in science but in our very conception of what is real. It shows that the universe is far stranger, more beautiful, and more interconnected than classical physics ever imagined.From the smallest subatomic particles to the vast mysteries of the cosmos, quantum principles weave through every corner of existence. And while we have harnessed its power for technology and innovation, we are only beginning to fathom its deeper implications.For the beginner, quantum physics may seem like stepping into a dream where the rules are upside down. But as with any great journey, the more you explore, the more you realize that the quantum world, bizarre though it may be, is the foundation of everything.It is a realm where imagination meets reality, where the impossible becomes inevitable, and where the universe whispers its most profound secrets if only we are curious enough to listen.For other uses, see Quantum (disambiguation).In physics, a quantum (pl.: quanta) is the minimum amount of any physical entity (physical property) involved in an interaction. The fundamental notion that a property can be "quantized" is referred to as "the hypothesis of quantization".[1] This means that the magnitude of the physical property can take on only discrete values consisting of integer multiples of one quantum. For example, a photon is a single quantum of light of a specific frequency (or of any other form of electromagnetic radiation). Similarly, the energy of an electron bound within an atom is quantized and can exist only in certain discrete values.[2] Atoms and matter in general are stable because electrons can exist only at discrete energy levels within an atom. Quantization is one of the foundations of the much broader physics of quantum mechanics. Quantization of energy and its influence on how energy and matter interact (quantum electrodynamics) is part of the fundamental framework for understanding and describing nature.German physicist and 1918 Nobel Prize for Physics recipient Max Planck (18581947)The modern concept of the quantum in physics originates from December 14, 1900, when Max Planck reported his findings to the German Physical Society. He showed that modelling harmonic oscillators with discrete energy levels resolved a longstanding problem in the theory of blackbody radiation.[3]:15[4] In his report, Planck did not use the term quantum in the modern sense. Instead, he used the term Elementarquantum to refer to the "quantum of electricity", now known as the elementary charge. For the smallest unit of energy, he employed the term Energieelement, "energy element", rather than calling it a quantum.[5]Shortly afterwards, in a paper published in Annalen der Physik,[6] Planck introduced the constant h, which he termed the "quantum of action" (elementares Wirkungsquantum) in 1906.[5] In this paper, Planck also reported more precise values for the elementary charge and the AvogadroLoschmidt number, the number of molecules in one mole of substance.[7] The constant h is now known as the Planck constant. After his theory was validated, Planck was awarded the Nobel Prize in Physics for his discovery in 1918.[8]In 1905 Albert Einstein suggested that electromagnetic radiation exists in spatially localized packets which he called "quanta of light" (Lichtquanta).[5][9]Einstein was able to use this hypothesis to recast Planck's treatment of the blackbody problem in a form that also explained the voltages observed in Philipp Lenard's experiments on the photoelectric effect.[3]:23 Shortly thereafter, the term "energy quantum" was introduced for the quantity h.[10]Main article: Quantization (physics)While quantization was first discovered in electromagnetic radiation, it describes a fundamental aspect of energy not just restricted to photons.[11]In the attempt to bring theory into agreement with experiment, Max Planck postulated that electromagnetic energy is absorbed or emitted in discrete packets, or quanta.[12]Introduction to quantum mechanicsHistory of quantum mechanics^ Wiener, N. (1966). Differential Space, Quantum Systems, and Prediction. Cambridge, Massachusetts: The Massachusetts Institute of Technology Press^ Rovelli, Carlo (January 2017). Reality is not what it seems: the elementary structure of things. Translated by Carnell, Simon; Segre, Erica (1st Americaned.). New York, New York: Riverhead Books. pp.109130. ISBN978-0-7352-1392-0.^ a b Baggott, J. E. (2013). The quantum story: a history in 40 moments (Pbked.). Oxford [England]: Oxford University Press. ISBN978-0-19-965597-7.^ Planck, M. (1901). "Ueber die Elementarquanta der Materie und der Elektricitt". Annalen der Physik (in German). 309 (3): 564566. Bibcode:1901AnP...309..564P. doi:10.1002/andp.19013090311. Archived from the original on 2023-06-24. Retrieved 2019-09-16 via Zenodo.^ a b c "Quantum". Oxford English Dictionary (Onlineed.). Oxford University Press. 2007. doi:10.1093/OED/1164299139. Retrieved 6 May 2025. (Subscription or participating institution membership required.)^ Planck, Max (1901), "Ueber das Gesetz der Energieverteilung im Normalspectrum" (PDF), Annalen der Physik (in German), 309 (3): 55363, Bibcode:1901AnP...309..553P, doi:10.1002/andp.19013090310, archived (PDF) from the original on 2012-06-10, retrieved 2008-12-15. English translations:"On the Law of Distribution of Energy in the Normal Spectrum". Archived from the original on 2008-04-18."On the Law of Distribution of Energy in the Normal Spectrum" (PDF). Archived from the original (PDF) on 2011-10-06. Retrieved 2011-10-13.^ Klein, Martin J. (1961). "Max Planck and the beginnings of the quantum theory". Archive for History of Exact Sciences. 1 (5): 459479. doi:10.1007/BF00327765. S2CID121189755.^ "Max Planck Nobel Lecture". Archived from the original on 2023-07-14. Retrieved 2023-07-14.^ Einstein, A. (1905). "ber einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt" (PDF). Annalen der Physik (in German). 17 (6): 132148. Bibcode:1905AnP...322..132E. doi:10.1002/andp.19053220607. Archived (PDF) from the original on 2015-09-24. Retrieved 2010-08-26.. A partial English translation Archived 2021-01-21 at the Wayback Machine is available from Wikisource.^ Kuhn, Thomas S. (1978). Black-body theory and the quantum discontinuity, 1894-1912. Oxford: Clarendon Press. p.201. ISBN978-0-19-502383-1.^ Parker, Will (2005-02-11). "Real-World Quantum Effects Demonstrated". ScienceAGoGo. Retrieved 2023-08-20.^ Modern Applied Physics-Tippens third edition; McGraw-Hill.Hoffmann, Banesh (1959). The Strange story of the quantum: An account for the general reader of the growth of the ideas underlying our present atomic knowledge (2ed.). New York: Dover. ISBN978-0-486-20518-2. {{cite book}}: ISBN / Date incompatibility (help)Mehra, Jagdish; Rechenberg, Helmut; Mehra, Jagdish; Rechenberg, Helmut (2001). The historical development of quantum theory. 4: Pt.1, the fundamental equations of quantum mechanics, 1925-1926 (1. softcover printed.). New York Heidelberg: Springer. ISBN978-0-387-95178-2.M. Planck, A Survey of Physical Theory, transl. by R. Jones and D.H. Williams, Methuen & Co., Limited., London 1925 (Dover edition 17 May 2003, ISBN 978-0486678672) including the Nobel lecture.Rodney, Brooks (14 December 2010) Fields of Color: The theory that escaped Einstein. Allegra Print & Imaging. ISBN 979-8373308427Retrieved from " Science Physics quantum mechanics, science dealing with the behaviour of matter and light on the atomic and subatomic scale. It attempts to describe and account for the properties of molecules and atoms and their constituentselectrons, protons, neutrons, and other more esoteric particles such as quarks and gluons. These properties include the interactions of the particles with one another and with electromagnetic radiation (i.e., light, X-rays, and gamma rays).The behaviour of matter and radiation on the atomic scale often seems peculiar, and the consequences of quantum theory are accordingly difficult to understand and to believe. Its concepts frequently conflict with common-sense notions derived from observations of the everyday world. There is no reason, however, why the behaviour of the atomic world should conform to that of the familiar, large-scale world. It is important to realize that quantum mechanics is a branch of physics and that the business of physics is to describe and account for the way the worldon both the large and the small scaleactually is and not how one imagines it or would like it to be.The study of quantum mechanics is rewarding for several reasons. First, it illustrates the essential methodology of physics. Second, it has been enormously successful in giving correct results in practically every situation to which it has been applied. There is, however, an intriguing paradox. In spite of the overwhelming practical success of quantum mechanics, the foundations of the subject contain unresolved problemsin particular, problems concerning the nature of measurement. An essential feature of quantum mechanics is that it is generally impossible, even in principle, to measure a system without disturbing it; the detailed nature of this disturbance and the exact point at which it occurs are obscure and controversial. Thus, quantum mechanics attracted some of the ablest scientists of the 20th century, and they erected what is perhaps the finest intellectual edifice of the period. At a fundamental level, both radiation and matter have characteristics of particles and waves. The gradual recognition by scientists that radiation has particle-like properties and that matter has wavelike properties provided the impetus for the development of quantum mechanics. Influenced by Newton, most physicists of the 18th century believed that light consisted of particles, which they called corpuscles. From about 1800, evidence began to accumulate for a wave theory of light. At about this time Thomas Young showed that, if monochromatic light passes through a pair of slits, the two emerging beams interfere, so that a fringe pattern of alternately bright and dark bands appears on a screen. The bands are readily explained by a wave theory of light. According to the theory, a bright band is produced when the crests (and troughs) of the waves from the two slits arrive together at the screen; a dark band is produced when the crest of one wave arrives at the same time as the trough of the other, and the effects of the two light beams cancel. Beginning in 1815, a series of experiments by Augustin-Jean Fresnel of France and others showed that, when a parallel beam of light passes through a single slit, the emerging beam is no longer parallel but starts to diverge; this phenomenon is known as diffraction. Given the wavelength of the light and the geometry of the apparatus (i.e., the separation and widths of the slits and the distance from the slits to the screen), one can use the wave theory to calculate the expected pattern in each case; the theory agrees precisely with the experimental data. By the end of the 19th century, physicists almost universally accepted the wave theory of light. However, though the ideas of classical physics explain interference and diffraction phenomena relating to the propagation of light, they do not account for the absorption and emission of light. All bodies radiate electromagnetic energy as heat; in fact, a body emits radiation at all wavelengths. The energy radiated at different wavelengths is a maximum at a wavelength that depends on the temperature of the body; the hotter the body, the shorter the wavelength for maximum radiation. Attempts to calculate the energy distribution for the radiation from a blackbody using classical ideas were unsuccessful. (A blackbody is a hypothetical ideal body or surface that absorbs and reemits all radiant energy falling on it.) One formula, proposed by Wilhelm Wien of Germany, did not agree with observations at long wavelengths, and another, proposed by Lord Rayleigh (John William Strutt) of England, disagreed with those at short wavelengths. In 1900 the German theoretical physicist Max Planck made a bold suggestion. He assumed that the radiation energy is emitted, not continuously, but rather in discrete packets called quanta. The energy E of the quantum is related to the frequency by E = h. The quantity h, now known as Plancks constant, is a universal constant with the approximate value of 6.62607 1034 joulesecond. Planck showed that the calculated energy spectrum then agreed with observation over the entire wavelength range. Quantum technologies have long underpinned modern foundational technologies, including lasers, atomic clocks, transistors, and semiconductor devices. Today, advancements in quantum information science and technology (QIST) are unlocking new tools for utilizing, generating, manipulating, and reading quantum states of matter, particularly quantum phenomena such as superposition and entanglementwith major potential implications on U.S. national security and economic prosperity.As a transformative platform technology, potentially on par with artificial intelligence, it is critical to understand the current state of technological development, as well as the global policy and investment landscape surrounding QIST. Research, development, and commercialization in QIST span various fields and disciplines and are progressing at varying speeds depending on the field or discipline in question.This commentary is the first in a series of three papers that explore the current state of quantum technology, the global competitive landscape as countries compete against each other to develop new QIST technologies, and considerations for U.S. quantum policy.This paper outlines five foundational areas of QISTquantum computing and quantum-centric supercomputing, quantum communication, quantum sensing, quantum materials, and quantum AI and quantum data centersand describes the technological readiness and strategic relevance of each to U.S. national security and economic prosperity.Since German physicist Werner Heisenberg formulated a type of quantum mechanics in 1925 based on matrices, scientists have made advances in these five areas. While commercial applications of QIST are currently limited, each area is evolving toward commercialization at a different pace. There is currently no globally recognized objective quantum technology readiness level (TRL) assessment.Among quantum technologies, some experts rate quantum magnetometers, for example, as more mature in their development stage compared to quantum computing and quantum networking. The most rudimentary quantum networking technology, quantum key distribution, has been available commercially for over two decades, but more general quantum networking is probably less advanced than quantum computing.1. Quantum Computing and Quantum-Centric SupercomputingQuantum computers have the potential to solve problems that are beyond the reach of classical computers. However, significant technical and engineering challenges remain, such as scaling up qubits, developing more efficient error correction codes, and integrating with high-performance computing systems.By exploiting the principles of quantum mechanics, researchers and industry aim to use quantum computers to achieve a so-called quantum advantage. It is expected that quantum computers will be able to solve complex problems that cannot currently be solved by classical high-performance computers, even those using high-performance graphics processing units.The computational power of a quantum computer increases exponentially (relative to a binary-based computer) with the addition of more qubits, highly sensitive computing units that employ superposition to encode information. Quantum computers with more qubits can accurately perform more complex calculations, helping scientists solve difficult problems in fields like chemistry and optimization challenges related to supply chains, finance, and engineering. In the midterm, the goal is to develop and commercialize intermediate-scaled quantum computers with measurement and control systems and facilitate widespread adoption of quantum computers.However, researchers are facing numerous technical challenges as they work to achieve a quantum advantage. Unlike the semiconductor industry, which has advanced through miniaturization in line with Moores Law and 3D integration, new advances in the field of quantum computing and efforts to commercialize quantum technologies will rely heavily upon a deeper understanding of the principles of quantum physics.Researchers and industry are currently using various approaches to create high-quality qubits, each with its own strengths and challenges. For example, superconducting qubits, which are made from superconducting materials operating at extremely low temperatures, are favored for their speed in performing computations and fine-tuned control. While this approach has led to the development of higher-quality qubits, physical and engineering challenges have emerged, including the need for increasingly complex wires and ever-larger cryogenic cooling systems to manage heat. Other approaches currently being developed by researchers and industry involve using photonics, neutral atoms, trapped ions, and silicon spin. There are no clear answers on the best approach for enabling utility-scale quantum computing and its commercialization, nor is there consensus on whether multiple approaches will complement each other and coexist in the future or converge on a single approach.Logical qubits, which are abstractions and encoded using a collection of physical qubits to protect against errors through quantum error correction techniques, are one meaningful indicator of quantum computing performance. Although the exact ratio depends on the approach that is used, tens of thousands of physical qubits are generally required to create 1,000 logical qubits. These logical qubits can then be used to reliably run algorithms on quantum systems. High-fidelity physical qubits at a scale and with error correction are key challenges. As of February 2024, at least eight companies have achieved logical qubits (1017), regardless of the approach used. Challenges to scale quantum computational powers include protecting qubits from external noise, mitigating and correcting errors, advancing quantum control, and adding extra qubits to encode the information to detect and correct errors.Another key challenge is performing quantum calculations. Quantum computers require users to use software on conventional computers to set up a quantum algorithm or model, configure the algorithm or model on the quantum computer to correctly find a solution, utilize the qubits on the computer to correctly output and read the results, and then return the computed results to the conventional computer. Researchers are developing optimized algorithms and readout systems to create practical quantum computing applications for both problem-specific and general-purpose uses. As quantum algorithms become more intricate, the need for error correction becomes pronounced, introducing complexity and demanding sophisticated algorithms to maintain accuracy.Integrating high-performance computing (HPC) and quantum computing is expected to significantly increase existing quantum computing capabilities. IBM has said that quantum-centric supercomputing may potentially offer exponential speedups and processing power greater than either quantum or classical computing can provide for certain problems. Integration may alleviate current limitations of classical HPC by offloading specific tasks in classical computing workflows to quantum computers, thereby enhancing precision and efficiency. It is expected that integrating HPC into the same system as the quantum device will enable real-time error correction and noise reduction, greatly improve the reliability of quantum computing, and save operational costs and computation time.HPC and quantum computing operate on completely different principles, and current challenges to integrating the two types of computing include barriers that make it difficult to establish a flexible software infrastructure framework, ensure low-latency communication interfaces between quantum and classical processors, and implement cross-disciplinary collaborative efforts.2. Quantum CommunicationsQuantum communication uses quantum properties to enable secure information transfer and distributed quantum networking. Current efforts focus on deploying post-quantum cryptography and quantum key distribution while overcoming technical barriers to large-scale quantum networking.Quantum communication makes use of physical systems that typically operate at the atomic and subatomic scale. The end goal of quantum communication is to build quantum networks through fiber-optic or free-space channels. These networks aim to connect geographically distributed quantum devices through optical qubits. Connecting distributed quantum computers can exponentially increase computing power.Even as this advanced technology is being researched and developed, simpler quantum links are already possible. As a short-term application, encoding information in a quantum state-photon and transmitting it over a distance through fiber-optic and free-space channels enables secure communication, even against powerful quantum computers. There are two methodologies for securing communication against powerful quantum computers. The first is post-quantum cryptography (PQC), which involves using cryptographic algorithms based on advanced mathematical models. The second is quantum key distribution (QKD), a hardware-based quantum cryptography approach that uses principles of quantum mechanics.The U.S. National Security Agency (NSA) has found that PQC is currently the best mitigation measure against quantum computer threats. Following the National Institute of Standards and Technology (NIST)s release of PQC standards and guidelines, PQC is expected to be implemented by federal agencies and across sectors, and, ultimately, globally. Updating existing internet software for PQC is less costly and easier to deploy on a larger scale compared to QKD, as it does not require the creation of new physical infrastructure, whereas QKD does. QKD offers reduced vulnerability to increasing quantum computational power and immediate detection of information leakage. A combination of QKD and PQC to complement their characteristics is considered by some as the best mitigation strategy against future quantum computing threats, especially for high-value links.It is expected that this long-term virtual security framework will be valuable for securing defense platforms, finance systems, and other critical infrastructure sectors against threats from malicious cyber actors who systematically exploit global telecommunications networks such as Salt Typhoon.Quantum communication is advancing through research and development in satellite technology and advanced optical components. At this time, there are a number of technical challenges to scale QKD, including reducing photon transmission loss and developing quantum repeaters and memories. This is the reason that more generalized quantum networking has a long way to go.3. Quantum SensingQuantum sensors exploit the sensitivity of qubits to measure physical quantities with unprecedented precision, promising transformative impacts across industries. However, sensors currently face challenges related to environmental interference, miniaturization, and real-world deployment.Quantum sensors utilize qubits, which are sensitive to the external environment, to create highly precise, sensitive, and responsive detection systems that are capable of making more accurate measurements than classical sensors. Quantum sensors are currently being used in the medical, finance, and defense industries. Examples include magnetic resonance imaging (MRI) machines for creating images of the body and atomic clocks for accurate timekeeping.Quantum sensors can measure temperature, pressure, frequency, acceleration, rotation, magnetic fields, images, and electric fields with unprecedented levels of precision. Quantum sensors will impact various industries, including navigation, geographic exploration, chemical and material analysis, intelligence, and defense.As researchers work to develop reliable quantum sensors, they are facing technical challenges related to the size, weight, power consumption, and cost of quantum hardware components. For example, quantum sensors are impacted by minuscule noises on moving platforms and environmental interference. The performance of quantum sensors degrades once a sensor is placed on moving platforms, due to electric and magnetic fields, field gradients, and system vibrations. The Department of Defense seeks to overcome these challenges through innovative physics approaches to quantum sensing.Different types of quantum sensors are at various stages of development. For example, quantum magnetometerswhich measure both the strength and direction of magnetic fieldsand quantum gravimeterswhich detect subtle variations in gravityare already being deployed to carry out mineral exploration and geological surveys.Microwave atomic clocks run GPS systems, and optical atomic clocks have been on sea trials.Quantum navigation uses quantum states to provide highly precise and reliable measurements of time, acceleration, and magnetic fields, surpassing the capabilities of conventional satellite-based navigation methods. It is expected that improvements in this area will solve current signal jamming and spoofing threats, with over 1,000 flights per day now disrupted by GPS jamming incidents. According to a report in 2023, the accuracy of quantum kinematics and timing sensors is still undergoing early empirical validation, with a number of publications reporting on trials or demonstrations of these sensors.4. Quantum MaterialsQuantum materials exhibit unique quantum properties that could revolutionize electronics and quantum devices. Quantum materials enable quantum mechanical functions that differ from the properties of conventional metals and materials. These materials, which go beyond classical physics, can potentially form the basis of technologies that will redefine our daily lives. Research is underway to stabilize and control these materials for practical use.One example of a quantum material that exhibits unique quantum mechanical properties is the topological insulator. Unlike traditional metals, semiconductors, and insulators, topological insulators serve as conductors on their surfaces while functioning as insulators internally. In the future, topological insulators could be used to create new transistors that consume far less power than existing ones. At the present moment, quantum materials are unstable and easily affected by ambient thermal noise.Researchers have demonstrated that certain devices can be used to control the quantum states of electrons and spins.Researchers aim to create devices that can more precisely control the quantum properties of quantum materials.On February 19, 2025, researchers at Microsoft formed a quasiparticle (a particle-like collective electronic state) that can function as a topological qubit. Quasiparticles are expected to enable a new approach to quantum computing.5. Quantum AI and Quantum Data CentersResearchers are exploring how quantum technologies and AI can complement each other to enhance computational efficiency and advance AI capabilities. Experts have expressed interest in exploring new quantum technologies that can provide more efficient solutions for data-intensive tasks by enhancing existing AI applications, such as machine learning and deep learning. As AI becomes more widely used and the volume of data used in AI models grows, these subsets of AI will require large amounts of data processing and computing power. Quantum machine learning (QML) is an area of research that explores how quantum technology can enhance the speed, efficiency, and accuracy of machine learning (a subset of AI).Commercial applications of QML have not yet been developed because of current technical challenges in the field of quantum computing. Recently, developments in Hybrid Quantum-Classical Machine Learning (QCML) have been driving progress in research aimed at addressing these technical challenges. Hybrid QCML is a process that involves performing calculations on a quantum computer and then optimizing the parameters of those calculations by using machine learning on a classical computer.On the other hand, AI could also help speed up the development of quantum technologies, including by improving quantum hardware development and design, helping researchers create more effective algorithms for controlling and optimizing quantum devices, mitigating and correcting computational errors, and analyzing outputs.Researchers are also exploring the idea of building a quantum data center, which would integrate quantum machines into a data center or high-performance computing facility to perform large-scale quantum computation and data processing. Patrick P. Gelsinger, former Intel CEO, mentioned, When we go into a data center in 2030, were [going to] have a quantum corner, AI corner, the general purpose corner, and they are all going to be operating in combination.ConclusionThe future potential impact of quantum technology on industry and national security cannot be overstated. The five areas of QIST discussed in this paper are at various stages of research and development, each with its own unique set of technical challenges and opportunities, and commercialization of each area is advancing at a different pace. The United States should closely monitor technological challenges and emerging applications in each of these areas to ensure effective and efficient quantum innovation policy, given the strategic importance of QIST technologies for the U.S. national security and economic prosperity.The CSISs Renewing American Innovation program is undertaking a review of the U.S. Quantum Opportunity, as requested by the National Institute of Standards and Technology and in cooperation with the Quantum Economic Development Consortium.Hideki Tomoshige is an associate fellow with Renewing American Innovation at the Center for Strategic and International Studies in Washington, D.C. Phillip Singerman is a senior adviser (non-resident) with Renewing American Innovation at CSIS. A quantum, the singular form of quanta, is the smallest discrete unit of any physical entity. For example, a quantum of light is a photon, and a quantum of electricity is an electron. Quantum comes from Latin, meaning an amount or how much. If something is quantifiable, it can be measured. German physicist Max Planck introduced the modern concept of quantum in physics in 1901. He was trying to explain blackbody radiation and how objects changed color after being heated. Instead of assuming that the energy from heat was emitted in a constant wave, he posed that the energy was emitted in discrete packets or bundles. These were termed quanta of energy. This led to him discovering Planck's constant, which is a fundamental universal value. Planck's constant is symbolized as h and relates the energy in one photon to the frequency of the photon. Further units were derived from Planck's constant: Planck's distance and Planck's time, which describe the shortest meaningful unit of distance and the shortest meaningful unit of time. For anything smaller than a unit, such as a particle variable, physicist Werner Heisenberg's uncertainty principle postulated that variables of a particle had inherent uncertainty in position and momentum when measured, so these variables couldn't be definitively measured. The discovery of quanta and the quantum nature of subatomic particles led to a revolution in physics, and to the birth of quantum physics. Before the quantum discovery, the physics world revolved around Albert Einstein's theory of relativity, which described the behavior of macroscopic things. In contrast, quantum theory described the behavior of microscopic particles, which became known as quantum theory, or quantum mechanics. Einstein's theory of relativity and the microscopic focus of quantum theory became the two theories underpinning modern physics. Unfortunately, they deal with different domains, leaving physicists seeking a unified theory of everything. The double-slit experiment showed that light behaves as both a wave and a particle. In 1801, English physicist Thomas Young revealed the quantum nature of light in his double-slit experiment. In his experiment, a wave was split into two separate waves and projected upon a screen, demonstrating that light behaves as both a wave and a particle. Subatomic particles behave in ways that are counterintuitive. A single photon quantum of light can simultaneously go through two slits in a piece of material, as shown in the double-slit experiment. Schrdinger's cat is a famous thought experiment that describes a quantum particle in superposition, or the state where the probability waveform hasn't collapsed, and where multiple states or probabilities can exist simultaneously. Particles can also become quantumly entangled, causing them to interact instantly over a distance. Quantum technology uses the nature of subatomic particles to perform calculations instead of electrical signals like classical computing. Quantum computers use quantum bits or qubits instead of binary bits. By programming the initial conditions of the qubit, quantum computing can solve a real-world problem when the superposition state collapses and where multiple coexisting probabilities resolve into a single outcome. This enables the processing of complex artificial intelligence (AI) algorithms that are too numerically intensive for the electrical processing workflows of classical computing power to undertake. The forefront of quantum computer research is linking greater numbers of qubits to solve larger, more complex problems. Quantum computing uses the nature of subatomic particles to execute calculations as an alternative to the electrical signals used in classical computing. Quantum systems from Google, IBM, Microsoft and others benchmark quantum computer performance by measuring factors such as volume, which in quantum computing means the amount of computational space a circuit can process while still being able to return an accurate result. It's already been ascertained that quantum computers can perform certain calculations much faster than classical computers because they must go through each processing option one at a time. It can take a long time to go through all the options for some types of problems. Quantum computers don't need to try each option; they resolve the answer almost instantly. Some problems that quantum computers can solve quicker than classical computers are factoring for prime numbers and the traveling salesman problem, which involves processing an algorithm to find the shortest route between a set of points and locations that must be visited. Once quantum computers demonstrate the ability to solve these problems faster than classical computers, quantum supremacy will be achieved. Market.us reports that the global market for quantum computing will reach $8.28 billion by 2032. Quantum computing is rapidly growing, driven by public and private sector investments. Industries are realizing its potential in areas that require immense computational capabilities not even possible with the largest supercomputers. The following highlights potential advancements in the field of quantum computing across various industries and sectors: Healthcare and pharmaceuticals. Quantum computing has the potential to accelerate drug development, and quantum-enhanced AI models could enable earlier disease detection. Cybersecurity. Quantum cybersecurity uses quantum computing and the laws of quantum mechanics and computer science to develop modern cryptography systems that secure digital communication. Experts expect quantum computers to render existing cryptographic systems insecure and obsolete. Efforts to develop post-quantum cryptography are underway to create algorithms resistant to quantum attacks but can still be used by classical computers. Eventually, full quantum cryptography will be available for quantum computers. Supply chain and logistics. Quantum computing can potentially speed up the loading and shipping of goods from one place. Optimizing routes could help reduce fuel consumption. Finance. Quantum technology could help optimize financial portfolios and detect fraudulent transactions. Climate forecasting. Quantum technology, combined with machine learning, has the potential to enable more accurate weather predictions, helping provide better preparedness for extreme weather events. Quantum computing has many potential uses. Learn which areas organizations could apply quantum computing technology to increase efficiency and reduce costs. Quantum physics is the study of matter and energy at the most fundamental level. It aims to uncover the properties and behaviors of the very building blocks of nature. While many quantum experiments examine very small objects, such as electrons and photons, quantum phenomena are all around us, acting on every scale. However, we may not be able to detect them easily in larger objects. This may give the wrong impression that quantum phenomena are bizarre or otherworldly. In fact, quantum science closes gaps in our knowledge of physics to give us a more complete picture of our everyday lives.Quantum discoveries have been incorporated into our foundational understanding of materials, chemistry, biology, and astronomy. These discoveries are a valuable resource for innovation, giving rise to devices such as lasers and transistors, and enabling real progress on technologies once considered purely speculative, such as quantum computers. Physicists are exploring the potential of quantum science to transform our view of gravity and its connection to space and time. Quantum science may even reveal how everything in the universe (or in multiple universes) is connected to everything else through higher dimensions that our senses cannot comprehend. The field of quantum physics arose in the late 1800s and early 1900s from a series of experimental observations of atoms that didn't make intuitive sense in the context of classical physics. Among the basic discoveries was the realization that matter and energy can be thought of as discrete packets, or quanta, that have a minimum value associated with them. For example, light of a fixed frequency will deliver energy in quanta called "photons." Each photon at this frequency will have the same amount of energy, and this energy can't be broken down into smaller units. In fact, the word "quantum" has Latin roots and means "how much."Knowledge of quantum principles transformed our conceptualization of the atom, which consists of a nucleus surrounded by electrons. Early models depicted electrons as particles that orbited the nucleus, much like the way satellites orbit Earth. Modern quantum physics instead understands electrons as being distributed within orbitals, mathematical descriptions that represent the probability of the electrons' existence in more than one location within a given range at any given time. Electrons can jump from one orbital to another as they gain or lose energy, but they cannot be found between orbitals.Other central concepts helped to establish the foundations of quantum physics:Wave-particle duality: This principle dates back to the earliest days of quantum science. It describes the outcomes of experiments that showed that light and matter had the properties of particles or waves, depending on how they were measured. Today, we understand that these different forms of energy are actually neither particle nor wave. They are distinct quantum objects that we cannot easily conceptualize.Superposition: This is a term used to describe an object as a combination of multiple possible states at the same time. A superposed object is analogous to a ripple on the surface of a pond that is a combination of two waves overlapping. In a mathematical sense, an object in superposition can be represented by an equation that has more than one solution or outcome.Uncertainty principle: This is a mathematical concept that represents a trade-off between complementary points of view. In physics, this means that two properties of an object, such as its position and velocity, cannot both be precisely known at the same time. If we precisely measure the position of an electron, for example, we will be limited in how precisely we can know its speed.Entanglement: This is a phenomenon that occurs when two or more objects are connected in such a way that they can be thought of as a single system, even if they are very far apart. The state of one object in that system can't be fully described without information on the state of the other object. Likewise, learning information about one object automatically tells you something about the other and vice versa. Because many of the concepts of quantum physics are difficult if not impossible for us to visualize, mathematics is essential to the field. Equations are used to describe or help predict quantum objects and phenomena in ways that are more exact than what our imaginations can conjure.Mathematics is also necessary to represent the probabilistic nature of quantum phenomena. For example, the position of an electron may not be known exactly. Instead, it may be described as being in a range of possible locations (such as within an orbital), with each location associated with a probability of finding the electron there.Given their probabilistic nature, quantum objects are often described using mathematical "wave functions," which are solutions to what is known as the Schrdinger equation. Waves in water can be characterized by the changing height of the water as the wave moves past a set point. Similarly, sound waves can be characterized by the changing compression or expansion of air molecules as they move past a point. Wave functions don't track with a physical property in this way. The solutions to the wave functions provide the likelihoods of where an observer might find a particular object over a range of potential options. However, just as a ripple in a pond or a note played on a trumpet are spread out and not confined to one location, quantum objects can also be in multiple placesand take on different states, as in the case of superpositionat once. The act of observation is a topic of considerable discussion in quantum physics. Early in the field, scientists were baffled to find that simply observing an experiment influenced the outcome. For example, an electron acted like a wave when not observed, but the act of observing it caused the wave to collapse (or, more accurately, "decohere") and the electron to behave instead like a particle. Scientists now appreciate that the term "observation" is misleading in this context, suggesting that consciousness is involved. Instead, "measurement" better describes the effect, in which a change in outcome may be caused by the interaction between the quantum phenomenon and the external environment, including the device used to measure the phenomenon. Even this connection has caveats, though, and a full understanding of the relationship between measurement and outcome is still needed. Credit: Joel Caswell for Caltech Science Exchange Perhaps the most definitive experiment in the field of quantum physics is the double-slit experiment. This experiment, which involves shooting particles such as photons or electrons through a barrier with two slits, was originally used in 1801 to show that light is made up of waves. Since then, numerous incarnations of the experiment have been used to demonstrate that matter can also behave like a wave and to demonstrate the principles of superposition, entanglement, and the observer effect.The field of quantum science may seem mysterious or illogical, but it describes everything around us, whether we realize it or not. Harnessing the power of quantum physics gives rise to new technologies, both for applications we use today and for those that may be available in the future.

What is the simplest quantum field theory. Is quantum field theory hard. Quantum field theory simplified. What is quantum field theory. Quantum field theory explained simply. Quantum fiels theory. Quantum field theory explained. Quantum field theory simple explanation.