CHAPTER 1

END OF THE AGE OF SILICON

A revolution is coming.

In 2019 and 2020, two bombshells rocked the world of science. Two groups announced that they had achieved quantum supremacy, the fabled point at which a radically new type of computer, called a quantum computer, could decisively outperform an ordinary digital supercomputer on specific tasks. This heralded an upheaval that can change the entire computing landscape and overturn every aspect of our daily life.

First, Google revealed that their Sycamore quantum computer could solve a mathematical problem in 200 seconds that would take 10,000 years on the world's fastest supercomputer. According to MIT's *Technology Review,* Google called this a major breakthrough. They likened it to the launch of Sputnik or the Wright brothers' first flight. It was "the threshold of a new era of machines that would make today's mightiest computer look like an abacus."

Then the Quantum Innovation Institute at the Chinese Academy of Sciences went even further. They claimed their quantum computer was 100 trillion times faster than an ordinary supercomputer.

IBM vice president Bob Sutor, commenting on the meteoric rise of quantum computers, states flatly, "I think it's going to be the most important computing technology of this century."

Quantum computers have been called the "Ultimate Computer," a decisive leap in technology with profound implications for the entire world. Instead of computing on tiny transistors, they compute on the tiniest possible object, the atoms themselves, and hence can easily surpass the power of our greatest supercomputer. Quantum computers might usher in an entirely new age for the economy, society, and our way of life.

But quantum computers are more than just another powerful computer. They are a new type of computer that can tackle problems that digital computers can never solve, even with an infinite amount of time. For example, digital computers can never accurately calculate how atoms combine to create crucial chemical reactions, especially those that make life possible. Digital computers can only compute on digital tape, consisting of a series of 0s and 1s, which are too crude to describe the delicate waves of electrons dancing deep inside a molecule. For example, when tediously computing the paths taken by a mouse in a maze, a digital computer has to painfully analyze each possible path, one after the other. A quantum computer, however, *simultaneously* analyzes all possible paths at the same time, with lightning speed.

This in turn has heightened an intense rivalry between competing computer giants, which are all racing to create the world's most powerful quantum computer. In 2021, IBM unveiled its own quantum computer, called the Eagle, which has taken the lead, with more computing power than all previous models.

But these records are like pie crusts—they are made to be broken.

Given the profound implications of this revolution, it is not surprising that many of the world's leading corporations have invested heavily in this new technology. Google, Microsoft, Intel, IBM, Rigetti, and Honeywell are all building quantum computer prototypes. The leaders of Silicon Valley realize that they must keep pace with this revolution or be left in the dust.

IBM, Honeywell, and Rigetti Computing have put their first-generation quantum computers on the internet to whet the appetite of a curious public, so that people may gain their first direct exposure to quantum computation. One can experience this new quantum revolution firsthand by connecting to a quantum computer on the internet. For example, the "IBM Q Experience," launched in 2016, makes fifteen quantum computers available to the public via the internet for free. Samsung and JPMorgan Chase are among these users. Already, 2,000 people, from schoolchildren to professors, use them every month.

Wall Street has taken a keen interest in this technology. IonQ became the first major quantum computing company to go public, raising $600 million in its IPO in 2021. Even more startling, the rivalry is so intense that a new start-up, PsiQuantum, without any commercial prototype on the market or any track record of previous products, suddenly soared on Wall Street to a $3.1 billion valuation, with the ability to capture $665 million in funding almost overnight. Business analysts wrote that they had rarely seen anything like this, a new company riding the tide of feverish speculation and sensational headlines to such heights.

Deloitte, the consulting and accounting firm, estimates that the market for quantum computers should reach hundreds of millions of dollars in the 2020s and tens of billions of dollars in the 2030s. No one knows when quantum computers will enter the commercial marketplace and alter the economic landscape, but predictions are being revised all the time to match the unprecedented speed of scientific discovery in this field. Christopher Savoie, CEO of Zapata Computing, speaking about the meteoric rise of quantum computers, says, "It's no longer a matter of if, but when."

Even the U.S. Congress has expressed keen interest in helping jump-start this new quantum technology. Realizing that other nations have already generously funded research in quantum computers, in December 2018, Congress passed the National Quantum Initiative Act to provide seed money to help spark new research. It mandated the formation of two to five new National Quantum Information Science Research Centers, to be funded with $80 million annually.

In 2021, the U.S. government also announced an investment of $625 million in quantum technologies, to be supervised by the Department of Energy. Giant corporations like Microsoft, IBM, and Lockheed Martin also contributed an additional $340 million to this project.

China and the U.S. are not the only ones using government funds to accelerate this technology. The U.K. government is now constructing the National Quantum Computing Centre, which will serve as a hub for research on quantum computing, to be built at the Harwell lab of the Science and Technology Facilities Council in Oxfordshire. Spurred on by the government, there were thirty quantum computer start-ups founded in the U.K. by the end of 2019.

Industry analysts recognize that it's a trillion-dollar gamble. There are no guarantees in this highly competitive field. Despite the impressive technical achievements made by Google and others in recent years, a workable quantum computer that can solve real-world problems is still many years in the future. A mountain of hard work still lies before us. Some critics even claim it could be a wild-goose chase. But computer companies realize that unless they have a foot in the door, it might slam shut on them.

Ivan Ostojic, a partner at consulting firm McKinsey, says, "Companies in the industries where quantum will have the greatest potential for complete disruption should get involved in quantum right now." Areas like chemistry, medicine, oil and gas, transportation, logistics, banking, pharmaceuticals, and cybersecurity are ripe for major change. He adds, "In principle, quantum will be relevant for all CIOs as it will accelerate solutions to a large range of problems. Those companies need to become owners of quantum capability."

Vern Brownell, former CEO of D-Wave Systems, a Canadian quantum computing company, remarks, "We believe we're right on the cusp of providing capabilities you can't get with classical computing."

Many scientists believe that we are now entering an entirely new era, with shock waves comparable to those created by the introduction of the transistor and the microchip. Companies without direct ties to computer production, like the automotive giant Daimler, which owns Mercedes-Benz, are already investing in this new technology, sensing that quantum computers may pave the way for new developments in their own industries. Julius Marcea, an executive with rival BMW, has written, "We are excited to investigate the transformative potential of quantum computing on the automotive industry and are committed to extending the limits of engineering performance." Other large companies, like Volkswagen and Airbus, have set up quantum computing divisions of their own to explore how this may revolutionize their business.

Pharmaceutical companies are also watching developments in this field intently, realizing that quantum computers may be able to simulate complex chemical and biological processes that are far beyond the capability of digital computers. Huge facilities devoted to testing millions of drugs may one day be replaced by "virtual laboratories" that test drugs in cyberspace. Some have feared that perhaps this might one day replace chemists. But Derek Lowe, who runs a blog about drug discovery, says, "It is not that machines are going to replace chemists. It's that the chemists who use machines will replace those that don't."

Even the Large Hadron Collider outside Geneva, Switzerland, the biggest science machine in the world, which slams protons together at 14 trillion electron volts to re-create the conditions of the early universe, now uses quantum computers to help sift through mountains of data. In one second, they can analyze up to one trillion bytes generated by about one billion particle collisions. Perhaps one day quantum computers will unravel the secrets of the creation of the universe.

Quantum Supremacy

Back in 2012, when physicist John Preskill of the California Institute of Technology first coined the term "quantum supremacy," many scientists shook their heads. It would take decades, if not centuries, they thought, before quantum computers could outperform a digital computer. After all, computing on individual atoms, rather than wafers of silicon chips, was considered fiendishly difficult. The slightest vibration or noise can disturb the delicate dance of atoms in a quantum computer. But these stunning announcements of quantum supremacy have so far shredded naysayers' gloomy predictions. Now the concern is shifting to how fast the field is developing.

The tremors caused by these remarkable achievements have also shaken boardrooms and top secret intelligence agencies around the world. Documents leaked by whistleblowers have shown that the CIA and the National Security Agency are closely following developments in the field. This is because quantum computers are so powerful that, in principle, they could break all known cybercodes. This means that the secrets carefully guarded by governments, which are their crown jewels containing their most sensitive information, are vulnerable to attack, as are the best-kept secrets of corporations and even individuals. This situation is so urgent that even the U.S. National Institute of Standards and Technology (NIST), which sets national policy and standards, recently issued guidelines to help large corporations and agencies plan for the inevitable transition to this new era. NIST has already announced they expect that by 2029 quantum computers will be able to break 128-bit AES encryption, the code used by many companies.

Writing in *Forbes* magazine, Ali El Kaafarani notes, "That's a pretty terrifying prospect for any organization with sensitive information to protect."

The Chinese have spent $10 billion on their National Laboratory for Quantum Information Sciences because they are determined to be a leader in this vital, fast-moving field. Nations spend tens of billions to jealously guard these codes. Armed with a quantum computer, a hacker might conceivably break into *any* digital computer on the planet, thereby disrupting industries and even the military. All sensitive information may become available to the highest bidder. Financial markets might also be thrown into turmoil by quantum computers breaking into the inner sanctum of Wall Street. Quantum computers might also unlock the blockchain, creating havoc in the bitcoin market as well. Deloitte has estimated that about 25 percent of bitcoins are potentially vulnerable to hacking by a quantum computer.

"Those running blockchain projects will likely be keeping a nervous eye on quantum computing advancements," concludes a report by CB Insights, a data software IT company.

So what is at stake is nothing less than the world economy, which is heavily wedded to digital technology. Wall Street banks use computers to keep track of multibillion-dollar transactions. Engineers use computers to design skyscrapers, bridges, and rockets. Artists depend on computers to animate Hollywood blockbusters. Pharmaceutical companies use computers to develop their next wonder drug. Children rely on computers to play the latest video game with their friends. And we crucially depend on cell phones to give us instantaneous news from our friends, associates, and relatives. All of us have had the experience of being thrown into a panic when we cannot find our cell phone. In fact, it is extremely difficult to name any human activity that hasn't been turned upside down by computers. We are so dependent on them that if somehow all the world's computers suddenly came to an abrupt halt, civilization would be thrown into chaos. That is why scientists are following the development of quantum computers so intently.

End of Moore's Law

What is driving all this turmoil and controversy?

The rise of quantum computers is a sign that the Age of Silicon is gradually coming to a close. For the past half-century, the explosion of computer power has been described by Moore's law, named after Intel founder Gordon Moore. Moore's law states that computer power doubles every eighteen months. This deceptively simple law has tracked the remarkable exponential increase in computer power, which is unprecedented in human history. There is no other invention which has had such a pervasive impact in such a brief period of time.

Computers have gone through many stages throughout their history, each time vastly increasing their power and causing major societal change. Moore's law, in fact, can be extended all the way back to the 1800s, to the age of mechanical computers. Back then, engineers used spinning cylinders, cogs, gears, and wheels to perform simple arithmetic operations. At the turn of the last century, these calculators began to use electricity, replacing gears with relays and cables. During World War II, computers used vast arrays of vacuum tubes to break secret government codes. In the postwar era, the transition was made from vacuum tubes to transistors, which could be miniaturized to microscopic size, facilitating continued advances in speed and power.

Back in the 1950s, mainframe computers could only be purchased by large corporations and government agencies like the Pentagon and international banks. They were powerful (for example, the ENIAC could do in thirty seconds what might take a human twenty hours). But they were expensive, bulky, and often took up an entire floor of an office building. The microchip revolutionized this entire process, decreasing in size over the decades so that a typical chip the size of your fingernail can now contain about one billion transistors. Today, cell phones used by children to play video games are more powerful than a roomful of those lumbering dinosaurs once used by the Pentagon. We take for granted that the computer in our pocket exceeds the power of the computers used during the Cold War.

All things must pass. Each transition in the development of the computer rendered the previous technology obsolete in a process of creative destruction. Moore's law is already slowing down and may eventually come to a halt. This is because microchips are so compact that the thinnest layer of transistors is about twenty atoms across. When they reach about five atoms across, the location of the electron becomes uncertain, and they can leak out and short-circuit the chip or generate so much heat that the chips melt. In other words, by the laws of physics, Moore's law must eventually collapse if we continue to use primarily silicon. We could be witnessing the end of the Age of Silicon. The next leap might be the post-Silicon or Quantum Age.

As Intel's Sanjay Natarajan has said, "We've squeezed, we believe, everything you can squeeze out of that architecture."

Silicon Valley may eventually become the next Rust Belt.

Although things seem calm now, sooner or later this new future will dawn. As Hartmut Neven, director of Google's AI lab, says, "It looks like nothing is happening, nothing is happening, and then whoops, suddenly you're in a different world."

Why Are They So Powerful?

What makes quantum computers so powerful that the nations of the world are rushing to master this new technology?

Essentially, all modern computers are based on digital information, which can be encoded in a series of 0s and 1s. The smallest unit of information, a single digit, is called a bit. This sequence of 0s and 1s is fed into a digital processor, which performs the calculation, and then produces an output. For example, your internet connection may be measured in terms of bits per second or bps, which means that one billion bits are being sent to your computer every second, giving you instant access to movies, emails, documents, etc.

However, Nobel laureate Richard Feynman in 1959 saw a different approach to digital information. In a prophetic, pathbreaking essay titled "There's Plenty of Room at the Bottom" and subsequent articles, he asked: Why not replace this sequence of 0s and 1s with states of atoms, making an atomic computer? Why not replace transistors with the smallest possible object, the atom?

Atoms are like spinning tops. In a magnetic field, they can align either up or down with respect to the magnetic field, which can correspond to a 0 or a 1. The power of a digital computer is related to the number of states (the 0s or 1s) you have in your computer.

But due to the weird rules of the subatomic world, atoms can also spin in any combination of the two. For example, you can have a state in which the atom spins up 10 percent of the time and spins down 90 percent of the time. Or it spins up 65 percent of the time and spins down 35 percent of the time. In fact, there are an infinite number of ways that you can have an atom spin. This vastly increases the number of states that are possible. So the atom can carry much more information, not just in a bit, but a qubit, i.e., a simultaneous mixture of the up and down states. Digital bits can only carry one bit of information at a time, which limits their power, but qubits, or quantum bits, have almost unlimited power. The fact that, at the atomic level, objects can exist simultaneously in multiple states is called superposition. (This also means the familiar laws of common sense are routinely violated at the atomic level. At that scale, electrons can be in two places at the same time, which is not true for large objects.)

In addition, these qubits can interact with each other, which is not possible for ordinary bits. This is called entanglement. Whereas digital bits have independent states, each time you add another qubit, it interacts with all the previous qubits, so you double the number of possible interactions. Hence, quantum computers are inherently exponentially more powerful than digital computers, because you double the number of interactions every time you add an additional qubit.

For example, today quantum computers can have over 100 qubits. This means that they are 2^{100} times more powerful than a supercomputer with just one qubit.

Google's Sycamore quantum computer, which was the first to achieve quantum supremacy, has the power to process 72 billion billion bytes of memory with its fifty-three qubits. So a quantum computer like Sycamore dwarfs any conventional computer.

The commercial and scientific implications of this are enormous. As we transition from a digital world economy to a quantum economy, the stakes are extraordinarily high.

Speed Bumps to Quantum Computers

The next key question is: What prevents us from marketing powerful quantum computers today? Why doesn't some enterprising inventor unveil a quantum computer that can break any known code?

The problem facing quantum computers was also foreseen by Richard Feynman when he first proposed the concept. In order for quantum computers to work, atoms have to be arranged precisely so that they vibrate in unison. This is called coherence. But atoms are incredibly small and sensitive objects. The smallest impurity or disturbance from the outside world can cause this array of atoms to fall out of coherence, ruining the entire calculation. This fragility is the main problem facing quantum computers. So the trillion-dollar question is: Can we control decoherence?

In order to minimize the contamination coming from the outside world, scientists use special equipment to drop the temperature to near absolute zero, where unwanted vibrations are at a minimum. But this requires expensive, special pumps and tubing to reach those temperatures.

But we are faced with a mystery. Mother Nature uses quantum mechanics at room temperature without a problem. For example, the miracle of photosynthesis, one of the most important processes on earth, is a quantum process, yet it takes place at normal temperatures. Mother Nature does not use a roomful of exotic devices operating at near absolute zero to execute photosynthesis. For reasons that are not well understood, in the natural world coherence can be maintained even on a warm, sunny day, when disturbances from the outside world should create chaos at the atomic level. If we could one day figure out how Mother Nature performs her magic at room temperature, then we might become masters of the quantum and even life itself.

Revolutionizing the Economy

Although quantum computers pose a threat to the cybersecurity of nations in the short term, they also have vast practical implications in the long term, with the power to revolutionize the world economy, create a more sustainable future, and usher in an era of quantum medicine to help cure previously incurable diseases.

There are many areas where quantum computers can overtake conventional digital computers:

1. Search engines

In the past, wealth might be measured in terms of oil or gold.

Now, increasingly it is measured in data. Companies used to throw their own financial data away, but now this information is being recognized as more valuable than precious metals. But sifting through mountains of data may overwhelm a conventional digital computer. This is where quantum computers come in, by finding the needle in the haystack. Quantum computers may be able to analyze a company's finances in order to isolate the handful of factors that are preventing it from growing.

In fact, JPMorgan Chase has recently partnered with IBM and Honeywell in order to analyze its data to make better predictions of financial risk and uncertainty and increase the efficiency of their operations.

2. Optimization

Once quantum computers have used search engines to identify the key factors in the data, the next question is how to adjust them to maximize certain factors, such as profit. At the very least, large corporations, universities, and government agencies will use quantum computers to minimize their expenses and maximize their efficiency and profit. For example, a company's net proceeds depends on hundreds of factors, such as salaries, sales, expenses, and so forth, which all change rapidly with time. It might overwhelm a traditional digital computer to find the right combination of these myriad factors to maximize their profit margin. Meanwhile, a financial firm may want to use quantum computers to predict the future of certain financial markets that handle billions of dollars in transactions daily. This is where quantum computers can help by providing the computational muscle to optimize their bottom line.

3. Simulation

Quantum computers might also solve complex equations that are beyond the ability of digital computers. For example, engineering firms may use quantum computers to calculate the aerodynamics of jets, airplanes, and cars, to find the ideal shape that reduces friction, minimizes cost, and maximizes efficiency. Or governments may use quantum computers to predict the weather, from determining the path of a monster hurricane to calculating how global warming will affect the economy and our way of life decades into the future. Or scientists may use quantum computers to find the optimal configuration of magnets in giant nuclear fusion machines in order to harness the power of hydrogen fusion and "put the sun in a bottle."

But perhaps the greatest benefit is to use quantum computers to simulate hundreds of vital chemical processes. The dream would be to predict the outcome of any chemical reaction at the atomic level without using chemicals at all, only quantum computers. This new branch of science, computational chemistry, determines chemical properties not by experiment, but by simulating them in a quantum computer, which may one day eliminate expensive and time-consuming testing. All of biology, medicine, and chemistry would be reduced to quantum mechanics. This means creating a "virtual laboratory" in which we can rapidly try out new drugs, therapies, and cures in the memory of a quantum computer, bypassing decades of trial and error and slow, tedious laboratory experiments. Instead of performing thousands of complex, expensive, and time-consuming chemical experiments, one might simply push the button on a quantum computer.

4. Merger of AI and Quantum Computers

Artificial intelligence (AI) excels at being able to learn from mistakes, so that it can perform increasingly difficult tasks. It has already proven its worth in industry and medicine. However, one limitation of AI is that the vast amount of data that it must process can easily overwhelm a conventional digital computer. But the ability to sift through mountains of data is one of the strong points of quantum computers. So the cross-fertilization of AI and quantum computers can significantly increase their power to solve problems of all kinds.

Further Applications of Quantum Computers

Quantum computers have the power to change entire industries. For example, quantum computers may finally usher in the long-awaited Solar Age. For decades, futurists and visionaries have predicted that renewable energy would phase out fossil fuels and solve the greenhouse effect that is warming our planet. Armies of these thinkers and dreamers have extolled the virtues of renewable energy.

But the Solar Age got sidetracked.

While costs have dropped for wind turbines and solar panels, they still only represent a small fraction of the world's energy production. The question is: What happened?

Every new technology has to confront the bottom line: costs. After decades of singing the praises of solar and wind power, boosters have to face the fact that it is still a bit more expensive than fossil fuels on average. The reason is clear. When the sun does not shine and the winds don't blow, renewable energy technology sits there unused, gathering dust.

The key bottleneck for the Solar Age is often overlooked; it is the battery. We have been spoiled by the fact that computer power grows exponentially fast, and we unconsciously assume that the same pace of improvement applies for all electronic technology.

Computer power has exploded in part because we can use shorter wavelengths of ultraviolet radiation to etch tiny transistors on a silicon chip. But batteries are different; they are messy, using a collection of exotic chemicals in complex interplay. Battery power grows slowly and tediously, by trial and error, not by systematically etching with shorter wavelengths of UV light. Furthermore, the energy stored in a battery is a tiny fraction of the energy stored in gasoline.

Quantum computers could change that. They may be able to model thousands of possible chemical reactions without having to perform them in the laboratory in order to find the most efficient process for a super battery, thereby ushering in the Solar Age.

Already, utilities and car companies are using first-generation quantum computers from IBM to attack the battery problem. They are trying to increase the capacity and recharging speed for the next generation of lithium-sulfur batteries. But this is just one way climate will be affected. In addition, ExxonMobil is using IBM's quantum computers to create new chemicals for low-energy processing and carbon capture. In particular, they want quantum computers to be able to simulate materials and determine their chemical nature, such as heat capacity.

Jeremy O'Brien, founder of PsiQuantum, emphasizes that this revolution is not about building faster computers. Instead, it's about tackling problems, like complex chemical and biological reactions, that no conventional computer could solve no matter how much time we gave it.

He says, "We're not talking about doing things faster or better . . . we're talking about being able to do these things at all. . . . These problems are forever beyond the reach of any conventional computer that we could ever build . . . even if we took every silicon atom on the planet and turned it into a supercomputer, we still could not solve these . . . hard problems."

Feeding the Planet

Another crucial application of quantum computers might be to feed the world's growing population. Certain bacteria can effortlessly take nitrogen from the air and convert it into ammonia, which is then turned into chemicals that become fertilizer. This nitrogen-fixing process is the reason why life flourishes on earth, allowing for the growth of lush vegetation that feeds humans and animals. The Green Revolution was unleashed when chemists duplicated this feat with the Haber-Bosch process. However, this process requires a vast amount of energy. In fact, an astounding 2 percent of the entire energy production of the world goes into this process.

So that is the irony. *Bacteria can do something for free that consumes a huge fraction of the world's energy.*

The question is: Can quantum computers solve this problem of efficient fertilizer production, creating a second Green Revolution? Without another revolution in food production, some futurists have predicted an ecological catastrophe as an ever-expanding world population becomes more and more difficult to feed, which could lead to mass starvation and food riots around the globe.

Already, scientists at Microsoft have made some of the first attempts to use quantum computers to increase the yields from fertilizers and unlock the secret of nitrogen fixing. In the end, quantum computers may help save human civilization from itself. Yet another miracle of nature is photosynthesis, in which sunlight and carbon dioxide are turned into oxygen and glucose, which then forms the foundation of nearly all animal life. Without photosynthesis, the food chain collapses and life on this planet would quickly wither away.

Scientists have spent decades trying to tease apart all the steps behind this process, molecule for molecule. But the problem of converting light into sugar is a quantum mechanical process. After years of effort, scientists have isolated where quantum effects dominate this process, and all are beyond the reach of digital computers. Therefore, to create a synthetic photosynthesis that could potentially be more efficient than the natural one still eludes our finest chemists.

Quantum computers may be able to help create a more efficient synthetic photosynthesis or perhaps entirely new ways of capturing the power of sunlight. The future of our food supply may depend on this.

Birth of Quantum Medicine

So quantum computers have the power to rejuvenate the environment and plant life. But they can also heal the sick and dying. Not only can quantum computers simultaneously analyze the efficacy of millions of potential drugs faster than any conventional computer, they can also unravel the nature of disease itself.

Quantum computers may answer questions like: What causes healthy cells to suddenly become cancerous, and how can they be stopped? What causes Alzheimer's disease? Why are Parkinson's and

ALS incurable? More recently, the coronavirus has been known to mutate, but how dangerous are each of these mutant viruses and how will they respond to treatment?

Two of the greatest discoveries in all of medicine are antibiotics and vaccines. But new antibiotics are found largely by trial and error, without understanding precisely how they work at the molecular level, and vaccines only stimulate the human body to produce chemicals to attack an invading virus. In both cases, the precise molecular mechanisms are still a mystery, and quantum computers may offer insight into how we might develop better vaccines and antibiotics.

When it comes to understanding the body, the first giant step was the Human Genome Project, which listed all of the 3 billion base pairs and 20,000 genes that form a blueprint for the human body. But this is just the beginning. The problem is that digital computers are used mainly to search through vast databases of known genetic codes, but they are helpless when it comes to explaining precisely how DNA and proteins perform their miracles inside the body. Proteins are complex objects, often consisting of thousands of atoms, which fold up into a small ball in specific and unexplainable ways when they do their molecular magic. At its most fundamental level, all life is quantum mechanical, and so beyond the reach of digital computers.

But quantum computers will lead the way into the next stage, when we decipher the mechanisms at the molecular level that tell us how they work, allowing scientists to create new genetic pathways, new therapies, new cures to conquer previously incurable diseases.

For example, pharmaceutical corporations, including firms like ProteinQure, Digital Health 150, Merck, and Biogen, are already setting up research centers to analyze how quantum computers will affect drug analysis.

Scientists are amazed that Mother Nature has been able to create a vast arsenal of molecular mechanisms that make the miracle of life possible. But these mechanisms are a by-product of chance and random natural selection operating over billions of years. That is why we still suffer from certain incurable diseases and the aging process. Once we understand how these molecular mechanisms work, then we will be able to use quantum computers to improve on them or create new versions of them.

For example, with DNA genomics, we can use computers to identify genes like BRCA1 and BRCA2 that can likely result in breast cancer. But digital computers are useless to determine precisely how these defective genes cause cancer. And they are also powerless to stop cancer once it spreads throughout the body. But quantum computers, by deciphering the molecular intricacies of our immune system, may be able to create new drugs and therapies to combat these diseases.

Another example is Alzheimer's disease, which some believe will be the "disease of the century" as the world population ages. With digital computers, one can show that mutations in certain genes, like the ApoE4 gene, are associated with Alzheimer's. But digital computers are useless in explaining why this is so.

One leading theory is that Alzheimer's is caused by prions, a certain amyloid protein that is incorrectly folded in the brain. When the renegade molecule bumps into another protein molecule, it causes that molecule to fold up the wrong way as well. Thus, the disease can spread by contact, even though bacteria and viruses are not involved. It is suspected that renegade prions might be the culprit behind Alzheimer's, Parkinson's, ALS, and a host of other incurable diseases that target the elderly.

So the protein folding problem is one of the greatest, uncharted areas in biology. In fact it may hold the secret of life itself. But precisely how a protein molecule folds up is beyond the capability of any conventional computer. Quantum computers, however, can provide new pathways by which to neutralize renegade proteins and provide new therapies.

In addition, the aforementioned merger of AI and quantum computers may turn out to be the future of medicine. Already, AI programs like AlphaFold have been able to map the detailed atomic structure of an astounding 350,000 different types of proteins, including the complete set of proteins that make up the human body. The next step is to use the unique methods of quantum computers to find out how these proteins do their magic, and to use them to create the next generation of drugs and therapies.

Quantum computers are already being connected to neural networks, to create the next generation of learning machines that can literally reinvent themselves. The laptop sitting on your desk, by contrast, never learns. It is no more powerful today than it was last year. Only recently, with new advances in deep learning, are computers taking the first steps to recognizing mistakes and learning. Quantum computers could exponentially accelerate this process and have singular impacts on medicine and biology.

Google CEO Sundar Pichai compares the arrival of quantum computers to the Wright brothers' historic 1903 flight. The original test was not so amazing by itself, because the flight lasted only a modest twelve seconds. But this short flight was the trigger that initiated modern aviation, which in turn has changed the course of human civilization.

What is at stake is nothing less than our future. It's up for grabs for whoever is able to build and use a quantum computer. But to truly understand the impact this revolution might have on our daily lives, it is useful to retrace some of the valiant attempts made in the past to fulfill our dream of using computers to simulate and understand the world around us.

And it all began with a mysterious, 2,000-year-old relic found at the bottom of the Mediterranean.

CHAPTER 2

END OF THE DIGITAL AGE

From the bottom of the Aegean Sea came one of the most intriguing, captivating puzzles of the ancient world. In 1901, divers were able to salvage a strange curiosity near the island of Antikythera. Among the scattered pieces of broken pottery, coins, jewelry, and statues in a shipwreck, divers found one object that was oddly different. At first, it looked like a worthless piece of coral-encrusted rock.

But when layers of debris were cleaned off, archaeologists began to realize that they were staring at an exceedingly rare, one-of-a-kind treasure. It was full of gears, wheels, and strange inscriptions, a machine of intricate and exquisite design.

Dating the artifacts found within the shipwreck, it was estimated that it was crafted sometime between 150 and 100 BCE. Some historians believe it was being taken from Rhodes to Rome, to be given as a gift to Julius Caesar for a triumphal parade.

In 2008, scientists using X-ray tomography and high-resolution surface scanning were able to penetrate the interior of this intriguing object. They were shocked when they realized that they were staring at an ancient mechanical device that was unbelievably advanced.

Nowhere in the ancient record was there any mention of a mechanism this sophisticated. It dawned on them that this magnificent machine must have been the pinnacle of scientific knowledge of the ancient world. It was a supernova of brilliance staring at them from millennia past. This was the *world's oldest computer,* a device that would not be duplicated for another two thousand years.

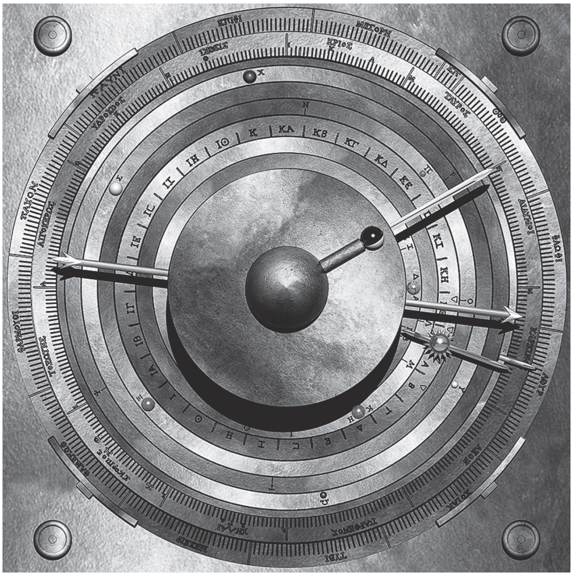

Figure 1: The Antikythera mechanism
Two thousand years ago, the Greeks created the Antikythera, the very first in the long evolutionary line of computers, depicted here as a model based on the original device. While the Antikythera represents the beginning of computer technology, the quantum computer may represent the highest stage in its evolution.

Scientists began to construct mechanical reproductions of this remarkable device. By turning a crank, a series of complex wheels and cogs were set into motion for the first time in thousands of years. It had at least thirty-seven bronze gears. In one set of gears, the motion of the moon and sun were calculated. Another set of gears could predict the coming of the next eclipse of the sun. It was so sensitive it could even calculate small irregularities in the orbit of the moon. Translations of the inscriptions on the device chronicle the motion of Mercury, Venus, Mars, Saturn, and Jupiter, the planets known to the ancients, but it is believed that yet another portion of the device, which is missing, could actually plot out the planets as they move in the heavens.

Since then, scientists have created elaborate models of the interior of the device, which have given historians unprecedented insight into the knowledge and mind of the ancients. The device heralded the birth of an entirely new branch of science, which uses mechanical tools to simulate the universe. This was the world's oldest analog computer—a device that could calculate using continuous mechanical motions.

So the purpose of the world's first computer was to simulate heavenly bodies, to reproduce the mysteries of the cosmos in a device you could hold in your hands. Instead of just staring in awe at the night sky, these ancient scientists wanted to understand its detailed workings, allowing them unprecedented insight into the motion of celestial bodies in the heavens.

Quantum Computers: The Ultimate Simulation

Archaeologists found that the Antikythera represented the pinnacle of our ancient attempts to simulate the cosmos. In fact, this same age-old urge to simulate the world around us is one of the driving forces behind the quantum computer, which represents the ultimate effort in the 2,000-year journey to simulate everything from the cosmos down to the atom itself.

Simulation is one of our deepest human desires. Children use simulation with toy figures to understand human behavior. When children play cops and robbers, teacher and student, or doctor and patient, they are simulating a piece of adult society in order to understand complex human relations.

Sadly, it would take many centuries before scientists could build machines of sufficient complexity to simulate our world as well as the Antikythera could.

Babbage and the Difference Machine

With the fall of the Roman Empire, scientific progress in many areas, including simulating the universe, came to a standstill.

It wasn't until the 1800s that interest was gradually revived. By then, there were urgent, practical questions that could only be answered by mechanical analog computers.

For example, navigators depended on detailed maps and charts to plot the courses of their ships. They needed devices to help make these maps as accurate as possible.

Machines of increasing complexity were also needed to keep track of trade and commerce as people began to accumulate wealth in greater and greater quantities. Accountants were required to compile large mathematical tables of interest and mortgage rates by hand.

But humans, however, would often make costly and crucial errors. So there was acute interest in devising mechanical adding machines that wouldn't make these mistakes. As adding machines became more complex, an informal competition arose among enterprising inventors to see who could build the most advanced one.

Perhaps the most ambitious of these projects was led by the eccentric English inventor and visionary Charles Babbage, who is often called the Father of the Computer. He dabbled in a number of disparate fields, including art and even politics, but was always fascinated by numbers. Fortunately, he was born into a wealthy family, so his banker father could help him pursue many of his diverse interests.

His dream was to create the most advanced computing machine of his time, which could be used by bankers, engineers, sailors, and the military to unerringly perform tedious but essential calculations. He had two goals. As a founding member of the Royal Astronomical Society, he had an interest in creating a machine that could track the motion of the planets and astronomical bodies (essentially following in the same pioneering path taken by those who built the