Lars Jaeger

THE SECOND QUANTUM REVOLUTION

From Entanglement to Quantum Computing and Other Super-Technologies

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To my friends Wolfgang and Alexander

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Part V Entanglement—Getting to the Crux of the Matter

Prologue: The White Rabbit

In Douglas Adam's parody of intergalactic life *The Hitchhiker's Guide to the Galaxy*, one reads at the beginning of the second book:

> *There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable. There is another theory which states that this has already happened.*

The physics of the twentieth century can hardly be described more fittingly. Around 1900, physical concepts such as fields and waves, the invisible force of gravity, and entropy were already quite bizarre and difficult to grasp for a broad audience. Not all these phenomena could be seen or touched, but they were calculable and predictable and reflected what people were experiencing in their everyday lives. Despite their abstractness, they were still quite real in comparison with the mental constructs physicists had to develop to understand the nature of the atomic world (as well as the vastness of the universe).

The triumph of the totally bizarre began with the observation that at the level of atoms certain quantities cannot take just any value. For example, the radiated energy of certain bodies only assumes fixed, and in fact discrete values. It is so to speak packaged in what physicists were to call quanta (from the Latin word *quantum*—that much). If the rules of the microworld were also valid in "our" world, one would only be able set the temperature in one's living room at 10, 20, or 30 °C, while all values in between would simply not exist. A short time later, physicists realized that light has a dual nature: sometimes it is a wave, while another time it may be a particle. The same holds for the electron, as was observed shortly afterward. But how can a spatially localized particle simultaneously be a spatially extended (de-localized) wave? In the world of classical science, where white is always white and black is exactly black, this "wave-particle duality" seemed like an outrageous provocation.

By the end of the nineteenth century, physicists were just becoming accustomed to the idea that their theories would soon provide a complete understanding of everything in the world. What felt like a moment later, they were suddenly forced to say goodbye to 250-year-old physical truths and more than 2500-year-old philosophical certainties. They had to deal with more and more seemingly impossible circumstances. Quantum entities can be in several states at the same time, for example, they can be in several places at once. And then quantum entities do not even possess objectively defined properties: their properties can only be specified with probabilities, the results of measurements depend on the observer, and their quantum states (wave functions) simply decay outside any window of time. And finally there is the strangest of all quantum phenomena: the entanglement of spatially separated particles. Even when they are far apart, two particles can be coupled together as if by magic. The bottom line is that the nature and properties of quantum entities are highly abstract and can no longer be reconciled with the way we perceive and think about things in our everyday lives.

However, despite all these imponderables, today's quantum theories predict the outcome of experiments and natural phenomena with an accuracy unsurpassed by any other theory in science. Here is another counter-intuitive manifestation that contradicts any everyday experience: something that is indefinite and elusive is nevertheless a process that can be calculated 100% accurately.

> Quantum physics seems completely crackbrained. We do not understand what exactly happens, nor why, but we can calculate it precisely.

Because we can calculate ever more exactly what is going on at the atomic level, we are able to gain more and more control over the microcosm. Applications of quantum physics have long since become a concrete part of our lives. Electronics, digital technologies, lasers, mobile phones, satellites, televisions, radio, nuclear technology, modern chemistry, medical diagnostics—all these technologies are based on it. We rely on quantum technologies, even though the theory underpinning them describes a world which—in our common understanding—possesses uncertain and unsustainable features and seemingly paradoxical properties.

Only in recent years have physicists begun to realize that quantum physics can ensure a significant supply of as yet unexploited technological capabilities. The renowned quantum physicist Rainer Blatt predicts another "century of quantum technology" for the twenty-first century, enough to fundamentally change both our economy and society. We are just at the beginning of our understanding of the possibilities arising from this revolution, Blatt believes.[1]

Much of what is applied technologically has not long been fully understood theoretically, and some is still not fully understood even today. Today's quantum physicists are like magicians on a stage who pull white rabbits out of hats every evening with the utmost ease. But they have as little understanding as the audience as to how these got into the hat in the first place.

I want to take you into the completely crazy, fabulous, and incredible world of the quantum. On this journey, we will first take a look at the world of the quantum technologies that are already shaping our world today. We will then realize that we are at the beginning of another breathtaking development. In Parts II and III of the book, we take a closer look at the strange discoveries in the quantum world, which, as will be explained in Part IV, also strongly shaped the philosophical, spiritual, and religious thinking of the twentieth century. Part V then takes us to the very core of the quantum world, which at the same time represents the basis of several exciting future quantum technologies, and on which physicists have only in the last few years been able to get any kind of hold: *the phenomenon of entanglement*. Here, as we shall see, we find solutions to some of the most challenging contradictions that the founding fathers of quantum physics were struggling to resolve. However, we will encounter new questions and apparent contradictions. In the last chapter, we shall venture some suggestions as to how new quantum technologies could shape our future.

*****

Many people have read this text and made valuable suggestions for improvement. First and foremost, I would like to thank Bettina Burchardt, without whom the book would not have been possible in its original German form. For many hours, she has dedicated herself to the text and its contents and has brought this book into the form it now has. Furthermore,

[1] Sixty-sixth Lindau Nobel Laureate Meetings, 26 June–1 July 2016.

Michael ten Brink has made a considerable contribution to the final form of this book. I greatly appreciated his input on technical issues. Then, I would like to thank my partner Yuka Nakamura for her emotional support over the many weeks of writing and then translating. I would also like to thank Frank Wigger for his excellent project management and support during the completion of this book. Equal thanks go to my agent Beate Riess and her colleague German Neundorfer, for all their support and encouragement, not only for this book.

Despite all this help, some mistakes and many omissions seem to be inevitable. I apologize to the reader and of course take full responsibility for this.

But now, curtains up!

Baar, Switzerland
June 2018

Part I

Quantum 2.0—The Second Technological Revolution Arising from the Quantum World

1

Mighty Power: How a Theory of the Microcosm Changed Our World

It all started with three problems:

1. In 1900 Max Planck found himself unable to explain that so-called black bodies emit energy not in arbitrary quantities, but rather in "energy packets" of a certain size.
2. In 1905 Albert Einstein was forced to conclude that light is both wave and particle.
3. In 1912 Ernest Rutherford discovered in a startling experiment that the atom consists of a nucleus of protons with electrons orbiting around it; however, according to the laws of classical physics this should not be possible.

With these three phenomena in their backpacks, physicists embarked on one of the most exciting intellectual journeys in human history. In the first 30 years of the 20th century they set out from the safe shores of classical physics to cross an uncharted ocean, like the sailors of the fifteenth and sixteenth centuries, keen to find out what was on the other side.

> At the beginning of the 20th century, physicists discovered that the laws of classical physics do not always apply.

Their experiments showed them more and more clearly that some fundamental properties of the atomic world cannot be reconciled either with our everyday perceptions or with the conceptual systems of Western philosophy:

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- Superposition:
  Quantum entities can concurrently be in a mixture of different states that would be mutually exclusive in the classical world. For example, they can move simultaneously along different paths, i.e., they can be at different places at the same time.
- Randomness in behavior:
  The measurable properties of a quantum system and their temporal development can no longer be absolutely determined. With its ability to be both here and there at the same time, its observable properties can only be specified probabilistically.
- Dependence of a quantum state on measurement:
  In the micro world, measurements have a direct influence on the measured object. Even stranger is the fact that only observation assigns a definite state to a quantum particle. In essence, this means that quantum particles have no independent and objective properties. Any properties they have are obtained by an external observer.
- Entanglement:
  Quantum particles may be non-locally interconnected. Even if they are spatially far apart, they can still belong to a common physical entity (physicists say a single "wave function"). They are thus coupled together as if by some magic force.

Each of these features of the micro world violates one of four key traditional philosophical principles:

1. the *principle of uniqueness*, according to which things are in definite states (the chair stands in front of the window and not next to the door);
2. the *principle of causality*, according to which every effect must have a cause (if the chair falls over, a force must have acted on it);
3. the *principle of objectivity* (related to the *principle of reality*) according to which things have an objective existence independently of our subjective perception of them (when we leave the room, the chair remains exactly where it stands and is still there even when we no longer look at it)[1]; and

[1]Here, however, there had already existed important philosophical movements of thought that questioned the independence of things from our perception of them, such as the Kantian philosophy, which doubts that we can have knowledge of "things in themselves."

4. the *principle of independence*, according to which things behave individually and independently of one another (the chair is not influenced by the fact that there is another chair in the adjoining room).

For more than 2,500 years, philosophers have grappled with the existential questions of humanity. Democritus wondered whether matter could be split endlessly into smaller and smaller parts and had come to the conclusion that there must be minute particles that are indivisible, the atoms. Parmenides was in search of the ultimate and changeless substance. Aristotle and Plato were interested in how we as observers relate to the observed. There followed a hundred generations of philosophers who painstakingly sought clarity and coherent descriptions of the world. But then, at the beginning of the 20th century, it became apparent that many philosophical principles found through this tireless and thorough reflection apply only to part of the world.

Some properties of atoms and their constituents differ completely from our everyday world of experience. Where the laws of classical physics no longer work, even philosophical principles lose their validity.

Quantum Physicists—From Magicians to Engineers

While the phenomena and properties of the micro world seemed at first like magic to physicists, with the help of mathematical means and tricks, they learned over time to calculate more and more accurately and ultimately tame this magical world, despite the fact that they did not fully understand it. Their intellectual voyage led physicists to a theory that explained the observed phenomena in the micro world, though with entirely new principles and concepts: *quantum theory*. With this theoretical basis, physicists were no longer magicians, but went back to being scientists—and later engineers, as the new theory made possible many amazing and sometimes terrifying technologies. The first of these arose when physicists applied their quantum physical models to the atomic nucleus. They realized that within in it there lay a vast amount of hidden energy.

In the years in which the world around them toppled into the chaos of two world wars and entire cities fell victim to bombing by the warring parties, physicists had to cope with the collapse of their own traditional ways of thinking. And from the bizarre new theory emerged a technology that could destroy not just a few streets, but entire cities in one fell swoop. Even as physicists—far from the public eye—were still disputing the strange and sometimes grotesque features of the micro world, quantum physics made its first appearance on the world stage, and with a very real and loud bang.

> The very first technical application of quantum physics was the most terrible weapon ever deployed by the military: the atomic bomb.

How did this terrible weapon come into existence? Since Rutherford's experiment in 1912, it had been known that the atomic nucleus consists of elementary particles carrying a positive electric charge (protons). But as we learn at school, like-charged particles repel each other. How then can atomic nuclei be stable? The many protons in the atomic nucleus should fly apart! Another force had to act attractively at the very short distances inside the atomic nucleus, and strongly enough to balance the electric force. But physicists had no idea what that force could be. Here then was another quantum puzzle!

In 1938, the German researchers Otto Hahn and Lise Meitner conducted experiments with uranium nuclei to investigate the unknown force in the atomic nucleus in more detail. The uranium nucleus contains 92 protons, and either 143 or 146 neutrons, depending on the isotope. Uranium nuclei were bombarded with slowed down neutrons and two very different elements emerged from time to time: barium and krypton. Barium atoms, which were rapidly detected by means of radiochemical techniques, have an atomic number of 56 and are thus less than half the mass of uranium nuclei. How was that possible? Using theoretical quantum physical calculations, Meitner came to the conclusion that the uranium nuclei had been broken into parts by the neutron bombardment, and the fragments absorbed a great deal of energy, much more than was the case in any previously known atomic process. But where did this energy come from? Another puzzle. Meitner also calculated that the two nuclei that emerged from the fission (along with three neutrons that were also emitted) weighed slightly less than the original uranium nucleus plus the neutron that triggered the fission. What had happened to the missing mass?

At this point, Einstein's famous formula $E=mc^2$, discovered more than 30 years earlier, entered the stage: for the difference between the total mass before and after the fission corresponded exactly to the energy that the fragments had acquired. This was the first known process in which the equivalence of energy and mass formulated by Einstein was directly revealed. At the same time, it became clear that unimaginable energies lay dormant inside these atoms!

Given the ongoing war, the presence of such a lot of energy in such a small space quickly aroused the interest of the military. In the greatest secrecy (not even the Vice President was informed), the American government put together a team of senior scientists and technicians. The goal of the *Manhattan Project*, the most complex and difficult engineering project ever undertaken until then, was the construction of an atomic bomb. The scientists were successful. On July 16, 1945, on a test site in the desert of New Mexico, the first ever atomic bomb exploded. Its force exceeded even the most optimistic expectations of the physicists. But when the immense nuclear mushroom cloud appeared on the horizon, they felt a sense of deep discomfort. As the head of the Manhattan project, Robert Oppenheimer, later reported, he quoted a phrase from the "Bhagavad Gita" of Indian mythology: "Now I am become Death, the destroyer of worlds." One of his colleagues, the director of the test, Kenneth Bainbridge, expressed it even more vividly: "Now we are all sons of bitches". Their sense of disillusionment was well justified. Only three weeks later, the second atomic mushroom emerged, this time over the skies of Japan, to be followed only two days later by the third. Just under seven years had passed from the scientific discovery of nuclear fission to the atomic mushroom clouds over Hiroshima and Nagasaki.

With the atomic bomb, quantum physics lost its innocence right from the start. Physicists had to realize that their thirst for knowledge could destroy not only the prevailing world view, but also the world itself.

Ever More Abstract Theory, Ever More Technology—The Laser

But atomic energy also has peaceful applications, such as in nuclear power plants. And quantum physics has shaped a variety of other very useful technologies, one of which is known to all: the laser.

According to quantum theory as expounded in Bohr's atomic model, in their movements around the atomic nucleus, electrons can spontaneously jump from one orbit to another. These are the proverbial "quantum leaps". In fact, all the most important mechanisms known in nature to produce light, including chemical processes like burning, are based on such quantum leaps (radiation emitted by accelerated charged particles, such as bremsstrahlung which generates X-rays, are a relatively insignificant source of light). But how exactly do these jumps take place? In order to jump to an energetically higher state, the electron must absorb the energy of an incoming light particle (photon); when jumping back to a lower level, the electron then releases a photon. So far so good. But where exactly do light particles come from and where do they go? And yet another question arises: single quantum leaps are not causal processes that can be precisely predicted. They are instead instantaneous processes, which happen, so to speak, outside of time. What does that mean? A light switch, when activated, lights up the light, from one moment to the next. In other words, it takes a split second before the effect occurs. But when an electron jumps, no time passes, not even a fraction of a fraction of a fraction of a second.

> When an electron spontaneously jumps back to its ground level, there is no direct cause for it, and nor can we assign any definite moment or time interval at which or during which that process occurs.

In 1917, these quantum puzzles motivated Einstein to investigate the question of light absorption and emission in atoms in more detail. Planck's radiation formula describes the quantized emission of photons from black bodies. From purely theoretical considerations, Einstein succeeded in finding another, as he wrote himself, "amazingly simple derivation" of the law of spontaneous light emission. In addition, he also identified a completely new process, which he referred to as "induced light emission". This is the emission of photons from appropriately prepared ("excited") atoms, which does not occur spontaneously, but is triggered by another incoming photon. The energy thereby discharged is released into the electromagnetic field generating another photon. The triggering photon continues to exist. Thus, in an environment in which many atoms are in an excited state, i.e., many electrons are at a higher energy level, there can occur a chain reaction of electrons jumping to lower levels—and this implies a concurrent emission of light.

The interesting feature here is that each of the newly emitted photons has exactly the same characteristics: all oscillate with identical phase, propagate in the same direction, and have the same frequency and polarization (direction of oscillation). Thus, out of a few photons that initiate the chain reaction, there comes a very strong light with properties identical to those of its constituent photons. Physicists also speak of a “coherent light wave”.

Only in the 1950s and 1960s did physicists succeed in and experimental proof and technological realization of this stimulated emission of photons, which Einstein had described in 1917 on purely theoretical grounds. It became the basis of the laser, another key quantum technology of the 20th century. A laser is produced in two steps: first, electrons in a medium are stimulated by light radiation, an electric current, or other processes to jump to higher energy states (physicists speak of “pumping”). Then, light particles with the same energy (frequency) as the excitation energy of the electrons are sent into the medium, causing the electrons to jump back to their ground state. They thus send out photons, which are exact copies of the incoming photons. This process gives the laser its name: *Light Amplification by Stimulated Emission of Radiation*.

Even with the laser, physicists remained in the dark for some time regarding the exact nature of the processes involved. Only an even more complex and even less comprehensible quantum theory would eventually be able to describe the atomic quantum leaps of electrons and the associated spontaneous formation and destruction of light quanta: the quantum theory of the electromagnetic field, or quantum electrodynamics. For this description, even more abstract mathematics was needed than for the original quantum mechanics.

The laser again reveals this key feature of quantum physics: extremely abstract and non-descriptive theories can produce very real technological applications.

Quantum Physics and Electronics—From the Transistor to the Integrated Circuit

The properties of solid state of matter, such as thermal conductivity, elasticity, and chemical reactivity, are largely determined by the properties and states of the electrons in the matter. Here, too, quantum effects play a decisive role.

Among other things, quantum physics gives a precise explanation for the electrical conductivity of substances, including those of the so-called semiconductors. Their conductivity lies between those of electrical conductors (such as copper) and non-conductors (such as porcelain), but can be strongly influenced by various means. For example, changing the temperature of certain semiconductors changes their conductivity, and this in quite a different way to what happens in metals: it increases rather than decreases with rising temperature. Introducing foreign atoms into their crystal structure (a process known as "doping") can also significantly influence their conductivity. Thus, micro transistors are nothing but a combination of differently doped semiconductor elements, and their mode of operation is largely determined by the flow of electrons inside them. Once again, all this follows from the laws of quantum physics.

Semiconductor components are the building blocks of all electronics, and indeed the entire computer and information technologies that shape our lives so profoundly today. In "integrated circuits", they are packaged in the billions on small chips so that highly complex electronic circuits can be interconnected on elements as small as a few square millimeters (e.g., in microprocessors and memory chips). Today the individual elements of these integrated circuits consist of only a few dozen atomic layers (about 10 nm thick)—whatever takes place in them obeys the laws of quantum physics.

> Without making use of quantum physics, today's chips for computers, cell phones, and other electronic devices could not be produced.

An example of a quantum effect which is enormously important in microscopic transistors and diodes is the *tunnel effect*: With a certain probability, quantum particles can overcome a barrier, even if they don't strictly have enough energy for that according to the laws of classical physics. The particle simply tunnels through the energy barrier. Transferred to our macro world, that would mean that if we fired a thousand rubber arrows at a lead wall, some would appear on the other side, and what's more, we could calculate very precisely how many arrows that would be. Quantum tunneling is a bizarre feature that has very real and important consequences in today's technological world. This is due to the fact that, if the distances between the conductive regions of circuits shrink to 10 nm and less, complications arise: the electrons will tunnel uncontrollably and cause interference. To prevent this, engineers have to come up with all sorts of tricks. For example, they combine different materials so that the electrons are trapped, i.e., less likely to tunnel. In the meantime, physicists are even able to calculate the tunnel effect so well that they can construct "tunnel-effect transistors" (TFETs) whose functioning is based explicitly on the tunnel effect. Because even the "tunnel current" can be controlled.

The tunnel effect of quantum physics plays a major role in modern microelectronics—on the one hand, as an obstacle to the ever-increasing miniaturization, on the other, as the basis of a new transistor technology.

In addition to the electrical conductivity of solids, everyday properties such as color, translucency, freezing point, magnetism, viscosity, deformability, and chemical characteristics, etc., can only be understood using the laws of quantum physics. The field of solid state physics would no longer be conceivable without knowledge of quantum effects. Again and again, physicists come across surprising effects and properties and observe astonishing new macroscopic quantum effects that open the way to further possible applications.

One example is superconductivity, the complete disappearance of electrical resistance in certain metals when reduced to temperatures close to absolute zero. This effect was first observed in 1911 and can be explained by a specific many-particle quantum theory called "BCS theory", named after John Bardeen, Leon Neil Cooper, and John Robert Schrieffer who invented it in 1957. (John Bardeen thus became the only person to date to receive a second Nobel Prize in physics, in addition to the one for his discovery of the transistor effect.) However, in 1986 physicists discovered that in some materials the temperature at which they start conducting the electric current without resistance is much higher than in all previously known superconducting metals (and this was rewarded by another Nobel Prize only one year later). As is often the case in quantum physics, this phenomenon is not yet entirely understood (BCS theory does not explain it), but it has tremendous technological potential. The dream of quantum engineers is to identify substances that are superconducting at room temperature. This would allow electricity to be transported across entire countries and continents without any energy loss—about 5% of the energy in today's electricity networks actually gets lost.

New Connections—Quantum Chemistry and Quantum Biology

With quantum theory scientists also recognized a whole new connection between physics and chemistry. How atoms combine to form molecules and other compounds is determined by the quantum properties of the electron shells in those atoms. That implies that chemistry is nothing more than applied quantum physics. Only with knowledge of quantum physics can the structures of chemical bonds be understood. Some readers may recall the cloud-like structures that form around the atomic nucleus. These clouds, which are called orbitals, are nothing but approximate solutions of the fundamental equation of quantum mechanics, the Schrödinger equation. They determine the probabilities of finding the electrons at different positions (but note that these solutions only consider the interactions between the electrons and the atomic nucleus, not those between the electrons).

"Quantum chemistry" consists in calculating the electronic structures of molecules using the theoretical and mathematical methods of quantum physics and thereby analyzing properties such as their reactive behavior, the nature and strength of their chemical bonds, and resonances or hybridizations. The ever increasing power of computers makes it possible to determine chemical processes and compounds more and more precisely, and this has gained great significance not only in the chemical industry and in materials research, but also in disciplines such as drug development and agro-chemistry.

Last but not least, quantum physics helps us to better understand the biochemistry of life. A few years ago bio-scientists started talking about "quantum biology". For example, the details of photosynthesis in plants can only be understood by explicitly considering quantum effects. And among other things, the genetic code is not completely stable, as protons in DNA are vulnerable to the tunnel effect, and it is this effect that is partly responsible for the emergence of spontaneous mutations (Chap. 22 will elaborate on this further).

Yet as always, when something is labelled with the word "quantum", there is some fuzziness in the package. Theoretically, the structures of atoms and molecules and the dynamics of chemical reactions can be determined by solving the Schrödinger equation (or other quantum equations) for all atomic nuclei and electrons involved in a reaction. However, these calculations are so complicated that, using the means available today, an *exact* solution is possible only for the special case of hydrogen, i.e., for a system with a single proton and a single electron. In more complex systems, i.e., in practically all real applications in chemistry, the Schrödinger equation can only be solved using approximations. And this requires the most powerful computers available today.

Theoretically, the equations of quantum theory can be used to calculate any process in the world.[2] However, even for simple molecules the calculations are so complex that they require the fastest computers available today, and physicists must nevertheless satisfy themselves with only approximate results.

[2] This statement is most likely not true on a cosmic scale. Here the general theory of relativity applies, and this theory has so far proved to be incompatible with any quantum theory (see Chap. 14).

Quantum Physics Everywhere—And Much More to Come

From modern chemistry to solid state physics, from signal processing to medical imaging systems—today we encounter quantum physics everywhere. We trust its laws when we get into a car (and rely on on-board electronics), power up our computer (which consists of integrated circuits, i.e., electronics based on quantum phenomena), listen to music (CDs are read by lasers, a pure quantum phenomenon), undergo X-ray or MRI scans of our bodies,[3] let ourselves be guided by GPS, or communicate via mobile phone. According to various estimates, between one-quarter and one-half of the gross national product of industrialized nations today is directly or indirectly based on inventions that have their foundation in quantum theory.

This percentage will increase rapidly in coming years. In the wake of nuclear technology, medical applications, lasers, semiconductor technology, and modern physical chemistry, all developed between 1940 and 1990, a second generation of quantum technologies has started to emerge over the past 25 years, and this is likely to shape our lives even more dramatically than the first generation. This has also been recognized by a country that was long regarded as a developing country when it came to scientific research, but has meanwhile been catching up with huge strides: the People's Republic of China. In its 13th Five-Year Plan, it has specified the new quantum technologies as a strategic area of scientific research. Meanwhile, Europe has also recognized the signs of the times and has begun investing massively in quantum technologies. These will be the subject of the next three chapters.

> More than 100 years ago the first quantum revolution began to take shape. We are now experiencing the beginning of the second quantum revolution.

[3] There are two types of X-ray radiation: *Bremsstrahlung* and characteristic radiation. For the explanation and application of the former, classical physics is sufficient. It was discovered by Konrad Röntgen, who received the very first Nobel Prize in Physics in 1901. The second requires quantum physics and was discovered by Charles Glover Barkla, who received the 1917 Nobel Prize in Physics.

2

There's Plenty of Room at the Bottom: A New Generation of Quantum Technologies

In 1959, the quantum physicist and later Nobel laureate Richard Feynman gave a much-cited lecture which outlined how future technologies could operate on a micro- and nanoscopic scale (scales of one thousandth or one millionth of a millimetre, respectively). The talk was entitled "*There's Plenty of Room at the Bottom*". Feynman's vision was very concrete: he predicted that man would soon be able to manipulate matter down to the level of individual atoms. Feynman's lecture is considered to be the big bang of nanotechnology, one of the most exciting technologies being developed today. Its goal is the control and manipulation of individual quantum states.

In fact, many of Feynman's ideas have already long since become a reality. Examples are:

- The electron microscope, in which the object to be observed is scanned point by point using an electron beam with wavelength up to 10,000 times shorter than the wavelength of visible light. This allows resolutions up to 50 pm (50×10^{-12} m) and magnifications up to 10,000,000, while light microscopes cannot achieve resolutions of more than 200 nm (200×10^{-9} m) and magnifications of 2,000.
- Microscopic data storage units based on semiconductor technology, which allow 500 gigabytes to be stored on a thumbnail-sized surface.
- Integrated circuits with elements involving only 10 to 100 atoms each, which enable the ultrafast processing of information in modern computers, thanks to the vast numbers of them that can be integrated into a single microchip.

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- Nanomachines in medicine, which can be introduced into the human body, e.g., to search autonomously for cancer cells.

> Many of Feynman's visions from 1959 are already part of our everyday technological lives today.

Feynman's most ground-breaking vision in 1959, however, concerned the possibility of constructing ultra-small machines that can manipulate matter at the atomic level. These machines would be able to put together any kind of material from a kit of atoms of various elements, rather like playing Lego using a manual given by humans, the only prerequisite being that the synthetically produced composites must be energetically stable.

First versions of such basic building blocks exist already: nano wheels that can actually roll long, nano gearwheels that spin along a jagged edge of atoms, nano propellers, hinges, grapples, switches, and more. They are all about ten thousandths of a millimetre in size, and obey the laws of quantum physics rather than classical Newtonian mechanics, which makes nanotechnology essentially a quantum technology.

In his science fiction novel "The Lord of All Things" (in German. "Herr der kleinen Dinge", 2011), the science fiction author Andreas Eschbach describes how nanomachines can put together individual atoms and molecules in almost any desired way. Eventually, they start replicating themselves in a way which leads to an exponential expansion in their numbers. Thanks to their abilities, these nanomachines are able to produce things almost out of nothing. The main protagonist of the novel learns to control them and has them spontaneously build things he needs at any particular moment (cars, planes, even a spaceship). Ultimately, he manages to control these processes solely through his own thoughts, by having them directly measure his brain signals.

Are such nanomachines actually possible or is this pure science fiction? Feynman claims that there is no law of nature that speaks *against* their construction. In fact, today's nano-researchers are getting closer and closer to his vision. The 2016 Nobel Prize for Chemistry, awarded to Jean-Pierre Sauvage, Fraser Stoddart, and Bernard Feringa for their work on molecular nanomachines, shows how important the research community considers this particular work.