# the world after the revolution: physics in the second half of the twentieth century

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## The great revolutions of the twentieth century

During the first half of the twentieth century—actually, the first quarter—there were two major scientific revolutions. Those cognitive cataclysms took place in physics, and are known as the relativist and quantum revolutions. They are respectively related to the special and general theories of relativity (Einstein 1905a, 1915), and quantum mechanics (Heisenberg 1925, Schrödinger 1926).

### Relativity

Much has been written, and will be written in the future, about the importance of those theories and their effect on physics as a whole, even before the middle of the century. Created to resolve the increasingly evident "lack of understanding" between Newtonian mechanics and the electrodynamics of James Clerk Maxwell (1831-1879), the special theory of relativity imposed radical modifications of ideas and definitions that had been in force ever since Isaac Newton (1642-1727) included them in the majestic structure contained in his *Philosophiae Naturalis Principia Mathematica* (1687)—concepts as basic from a physical, ontological and epistemological viewpoint as space, time and matter (mass). The result, in which measurements of space and time depend on the state of movement of the observer, and mass, *m*, is equivalent to energy, *E* (the famous expression $E=m\cdot c^2$, where *c* represents the speed of light), opened new doors for understanding the physical world. For example, this theory helped explain how it was possible that radioactive elements (uranium, polonium, radium, thorium) that had been studied for the first time by Henri Becquerel (1852-1908) and Marie (1867-1934) and Pierre Curie (1859-1906), emit radiation in a continuous manner with no apparent loss of mass.

And then there was the general theory of relativity, which explained gravity by converting space—actually, four-dimensional space-time—into something curved, and with variable geometry! It was immediately apparent that, compared to Newton's universal gravitation, Einstein's new theory made it much easier to understand perceptible phenomena in the solar system (it solved, for example, a century-old anomaly in the movement of Mercury's perihelion). As if that were not enough, Einstein himself (1917) had the intellectual daring to apply his general theory of relativity to the overall Universe, thus creating cosmology as an authentically scientific and predictive field. While it is true that the model Einstein proposed at that time, in which the Universe is static, did not survive in the end; what matters is that it opened the doors to a scientific approach to the Universe, which makes it an almost unprecedented event in the history of science.[1]

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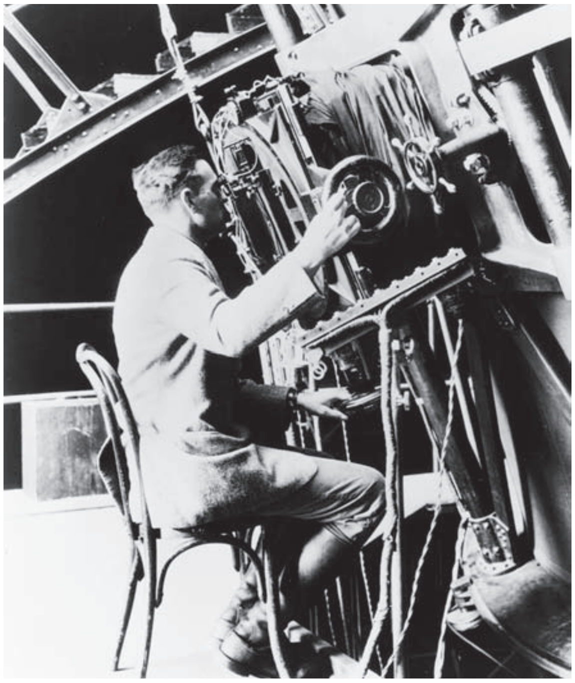
In order to construct a model of a static universe, Einstein had to modify the basic equations of general relativity, adding an additional term that included a "cosmological constant."

To find the exact solution to the equations of relativistic cosmology he was using, Einstein (1879-1955) employed physical considerations. Other mathematicians or physicists with special sensibilities and mathematical skills followed a different path, quickly finding new exact solutions—which implicitly represented other models of the universe—based exclusively on mathematical techniques, which they used to address the complexities of the equations of relativistic cosmology (a system of ten non-linear equations in partial derivatives). Alexander Friedmann (1888-1925), Howard Robertson (1903-1961) and Arthur Walker (b. 1909) found solutions implying that the Universe was expanding. In fact, another scientist obtained similar results: the Belgian Catholic priest, Georges Lemaître (1894-1966). This, however, should be mentioned separately because, as Einstein had done with his static model, Lemaître (1927) used physical considerations to defend his idea of a possible, real expansion of the Universe.

All of these models arose from solutions of cosmological equations; that is, they addressed theoretical possibilities. The question of how the Universe really is—static? expanding?—had yet to be elucidated, and for that, the only acceptable proof had to come from observation.

The lasting glory of having found experimental evidence indicating that the Universe is expanding belongs to the United States astrophysicist Edwin Hubble (1889-1953), who took advantage of the magnificent 2.5 meter-diameter reflector telescope at the Mount Wilson (California) observatory where he worked, along with excellent indicators of distance. Those indicators were cepheids, stars of variable luminosity in which it is possible to verify a linear relation between their intrinsic luminosity and the period of how that luminosity varies (Hubble 1929; Hubble and Humason 1931). And if, as Hubble maintained, the Universe is expanding, that would mean that there must have been a moment in the past (initially estimated as around ten thousand million years ago, later, fifteen thousand million, and now around thirteen thousand seven hundred million years) when all matter would have been concentrated in a small area: Lemaître's "primitive atom" or, the Big Bang, which turned out to be a very successful name.



Edwin Hubble taking photographs with the 2.5 meter Mount Wilson telescope (1924).

This was the birth of a conception of the Universe that is now a part of our most basic culture. But that has not always been the case. In fact, in 1948, as the first half of the twentieth century neared its end, three physicists and cosmologists working in Cambridge —Fred Hoyle (1915-2001), on one hand, and Hermann Bondi (1919-2005) and Thomas Gold (1920-2004) on the other (all three had discussed these ideas before publishing their respective articles)—published a different model of an expanding Universe: the steady-state cosmology, which held that the Universe has always had, and will always have, the same form, including the density of matter. This last aspect forced them to introduce the idea of the creation of matter, so that a "volume" of the universe would always have the same contents, even though it was expanding. According to them, the Universe had no beginning and would never end.[2]

Despite what we may think of it today —we are now fully imbued with the Big Bang paradigm—, steady-state cosmology was highly influential during the nineteen fifties. As we will see, it was not until the second half of the century that it was finally rejected (except in the minds of a few true believers, led by Hoyle himself).

**Quantum Physics**

The second major revolution mentioned above is quantum physics. While not rigorously exact, there are more than enough arguments to consider that this revolution's starting point was in 1900. While studying the distribution of energy in black-body radiation, the German physicist, Max Planck (1858-1947), introduced the equation, $E=h\cdot\upsilon$, where $E$ is, as in the relativistic equation, energy, $h$ is a universal constant (later called "Planck's constant") and $\upsilon$ is the frequency of the radiation involved (Planck 1900). Initially, he resisted this result's implication that electromagnetic radiation

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Hoyle (1948), Bondi and Gold (1948).

Werner Heisenberg in Goettingen (around 1924).

(that is, light, which was still considered a *continuous* wave at that time) could somehow also consist of "corpuscles" (later called "photons") of energy $h{\cdot}\upsilon$. But that implication of a "wave-corpuscle duality" eventually held sway, and Einstein (1905b) was decisive in its acceptance.

For a quarter century, physicists struggled to bring sense to those quantum phenomena, which eventually included radioactivity, spectroscopy and atomic physics as well. Here, it is impossible to offer so much as a list of the number of scientists involved, the ideas they handled and the concepts they introduced, let alone their observations and experiments. I can only say that a decisive moment in the history of quantum physics arrived in 1925, when a young German physicist named Werner Heisenberg (1901-1976) developed the first coherent formulation of quantum mechanics: *matrix quantum mechanics.* Soon thereafter, the Austrian Erwin Schrödinger (1887-1961) discovered a new version (they soon proved identical): *wave quantum mechanics.*

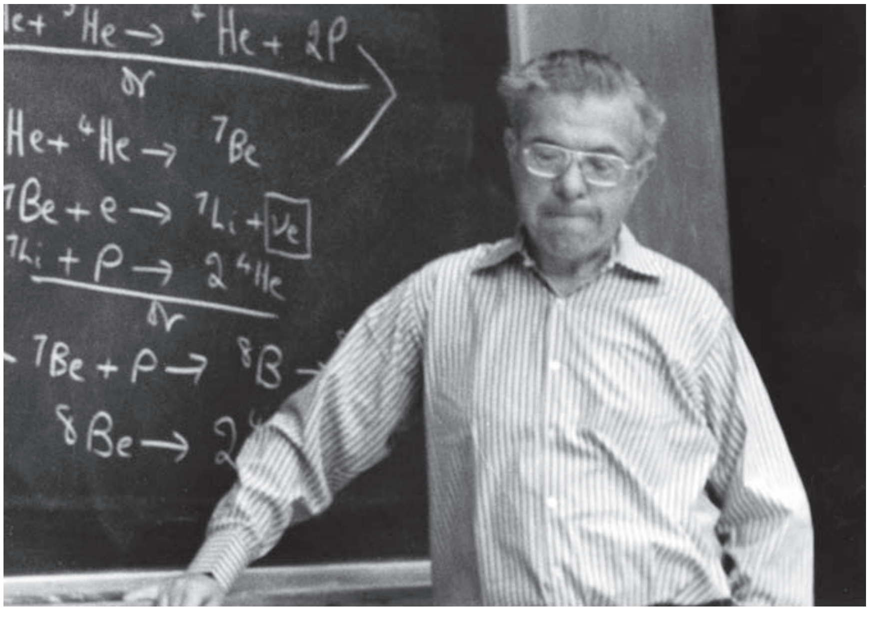
The stipulation by one of the two axioms of the special theory of relativity that the speed of light had to be constant, the dependence of space and time measurements on the movement of the observer, and the dynamical curvature of space-time, were already innovative and surprising findings, contradictory to "common sense." But the contents or deductions of quantum mechanics were even more shocking, including two that must be mentioned here: 1) Max Born's (1882-1970) interpretation of the wave function set out in Schrödinger's equation, according to which that function—the basic element used by quantum physics to describe the phenomenon under consideration—represents the probability of a concrete result (Born 1926); and 2) the principle of uncertainty (Heisenberg 1927), which maintains that canonically conjugated magnitudes (such as position and velocity, or energy and time) can only be determined simultaneously with a characteristic indeterminacy (Planck's constant): $\Delta x{\cdot}\Delta p \geq h$, where $x$ represents position and $p$ the linear momentum (the product of mass multiplied by velocity). At the end of his article, Heisenberg drew a conclusion from his results that has had lasting philosophical implications: "In the strong formulation of the causal law *'If we know the present with exactitude, we can predict the future,'* it is not the conclusion, but rather the premise that is false. *We cannot know,* as a matter of principle, the present in all its details." And he added: "In view of the intimate relation between the statistical character of quantum theory and the imprecision of all perception, it is possible to suggest that behind the statistical universe of perception there is a hidden "real" world ruled by causality. Such speculations seem to us—and we must emphasize this point—useless and meaningless. For physics must limit itself to the formal description of relations among perceptions."

Heisenberg and Schrödinger's quantum physics opened up a new world, both scientifically and technologically, but that was only the first step. There were still many challenges to be met, including making it compatible with the requirements of the special theory of relativity, and building an electromagnetic theory, an electrodynamics that would include quantum requirements. Einstein had shown, and later quantum physics agreed, that light, an electromagnetic wave, was quantized, that is, that it was simultaneously a wave and a "current" of photons. But the electrodynamics constructed by Maxwell in the nineteenth century described light exclusively as a wave, with no relation to Planck's constant. So, it was clear that something was wrong: the electromagnetic field also had to be quantized.

It was not necessary, though, to wait until the second half of the twentieth century for quantum electrodynamics. That theory, which describes the interaction of charged particles though their interaction with photons, took shape in the nineteen forties. It was independently developed and proposed by Japanese physicist Sin-itiro Tomonaga (1906-1979), and the Americans Julian Schwinger (1918-1984) and Richard Feynman (1918-1988).[3]

Quantum electrodynamics was a considerable theoretical advance, but it was nowhere near the culmination of quantum physics. At most, it was one more step up a ladder whose end was still far away. First of all, by the time the Tomonaga-Schwinger-Feynman theory came out, it was already clear that, besides the traditional forces of electromagnetism and gravity, there were two more: weak force, responsible for the existence of radioactivity; and strong force, which holds together the components (protons and neutrons) of atomic nuclei.[4] Therefore, it was not enough to have a quantum theory of electromagnetic interaction; quantum theories for the other three forces also had to be constructed.

Intimately linked to this problem was the proliferation of "elemental" particles. In 1897, Joseph John Thomson (1856-1940) discovered the electron as a universal component of matter. The proton (which coincides with the nucleus of hydrogen) was definitively identified thanks to experiments carried out by Wilhelm Wien (1864-1928) in 1898 and Thomson in 1910. And the neutron (a particle without a charge) was discovered in 1932 by the English physicist James Chadwick (1891-1974). In December of that same year, the United States physicist Carl Anderson (1905-1991) discovered the positron (identical to the electron, but with the opposite charge, that is, positive). That latter particle had already been predicted in theory by the relativistic equation for the electron, introduced in 1928 by one of the pioneers in the determination of the basic structure of quantum mechanics, the English physicist Paul Dirac (1902-1984).




Fred Hoyle at a seminar on nucleosynthesis at Rice University (United States, March 1975).

Electrons, protons, neutrons, photons and positrons were only the first members of an extended family (actually, families) that has not stopped growing since then, especially with the advent of machines called "particle accelerators." This branch of physics is the most characteristic of what has come to be known as *Big Science*, that is, science requiring enormous economic resources and very numerous teams of scientists and technicians. Its most distinguished founder was Ernest O. Lawrence (1901-1958), who began developing one type of accelerator at the University of Berkeley in California in the 1930s. Called "cyclotron," this type of accelerator causes "elemental" particles to move faster and faster, gaining energy with every revolution until they are forced to collide with each other. Such collisions are photographed in order to study the products, among which new "elemental" particles appear. I will further discuss this field—called "high-energy physics"—later on, when I cover the second half of the twentieth century. For the time being, it is enough to say that its origin lies in the first half of the century.

This, then, is the general context. Let us now address the second half of the century, which is the true subject of the present article. I will begin with the most general setting: the Universe, in which gravitational interaction plays a central role, though not, as we will see, an exclusive one—especially in the first moments of its existence.

## The world of gravitation

### Evidence of the Universe's expansion: cosmic microwave radiation

I mentioned above that not all physicists, astrophysicists and cosmologists understood the expansion discovered by Hubble as evidence that the Universe had a beginning, a Big Bang. Hoyle, Bondi and Gold's steady-state cosmology offered a theoretical framework in which the universe had always been the same, and that idea was widely accepted. Nevertheless, in the decade following its formulation, the nineteen fifties, it began to have problems. This was not due to theoretical considerations, but to the new observational possibilities offered by technological development. This matter merits emphasis: what we call science is the product of a delicate combination of theory and observation. There can be no science without the construction of systems (theories) that describe groups of phenomena, but it is equally inconceivable without observations of what really happens in nature (we are simply unable to imagine how nature behaves). That observation requires instruments, and the more powerful they are—that is, the more they are able to improve the

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Fukuda, Miyamoto and Tomonaga (1949), Schwinger (1949) and Feynman (1949). For their work, the three sahred the Nobel Prize for Physics in 1965.

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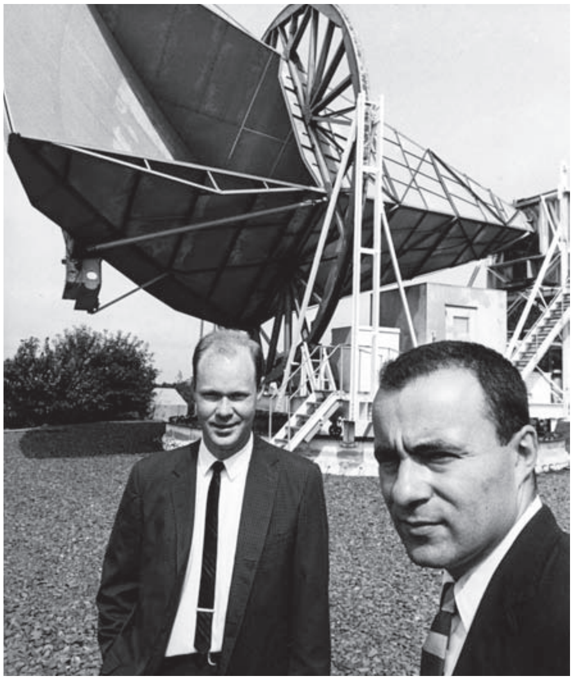
Until then, it had been thought that atomic nuclei were made up of protons (positively charged) and electrons (negatively charged). This was considered the only possible explanation of the emission of electrons (beta radiation) that takes place in radioactive processes. Beta disintegration was finally explained using one of the most striking properties of quantum physics: the creation and annihilation of particles: electrons are not in the nucleus, they are *created* by beta disintegration.



Robert Wilson and Arno Penzias in front of the antenna with which they discovered the cosmic microwave background.

potential of our own senses— the better. This, then, is a matter of technological development, and the second half of the twentieth century was a period in which technology underwent gigantic development—much greater than any previous period—that very positively affected scientific advancement in general, and astrophysics and cosmology in particular. In that sense, the problems affecting steady-state cosmology, mentioned above, were revealed by the development of radio-astronomy, a field that began in the nineteen thirties, thanks to the work of Karl Jansky (1905-1950), an electrical engineer working for Bell Laboratories (strictly speaking: Bell Telephone Laboratories), the "department" of the American Telephone and Telegraph Corporation in charge of research and development. In 1932, while looking for possible sources of noise in radio transmissions, Jansky detected electrical emissions coming from the center of our galaxy. Despite the importance we assign to his observations in hindsight, Jansky did not continue exploring the possibilities they offered. After all, pure research was not his field.

Not immediately, but soon thereafter, primitive antennae evolved into refined radiotelescopes —usually dishes of ever-greater diameter—that pick up electromagnetic radiation from outer space. The importance of those instruments for the study of the Universe is obvious: the optical telescopes on which astronomy and astrophysics had been based until then could only study a very narrow range of the electromagnetic spectrum. They were, so to speak, almost "blind."

One of the first places that radio-astronomy flourished was Cambridge (England). It was there where Martin Ryle (1918-1984) decidedly to follow the path opened by Jansky. In doing so, he drew on knowledge he had obtained during World War II when he worked at the government's Telecommunications Research Establishment (later called the Royal Radar Establishment). He was also aided by improvements in electronic instruments brought about by the war. In 1950, using radio-telescopes that included components he designed himself, Ryle identified fifty radio-sources. That number grew radically, reaching two thousand in just five years. One of his discoveries was a radio-source in the Cygnus constellation, 500 light-years from the Milky Way. As he looked deeper into space, he was also looking farther back in time (the signals he was receiving had been emitted long ago—but it took them that long to reach the Earth). His observations were thus a look into the past history of the Universe. Hubble had taken the first great step *en route* to observational cosmology, and Ryle—who was awarded the Nobel Prize for Physics in 1974—took the second one.

Thanks to his observation of radio-sources, Ryle reached conclusions opposed to steady-state cosmology, thus favoring the Big Bang theory. In analyzing the curves that related the number of radio-stars per unit of solid angle with the intensity of their emissions, Ryle (1955) concluded that he saw no "way in which those observations could be explained in terms of steady-state theory."

A far more conclusive argument in favor of the existence of a major explosion in the past was provided by one of the most famous and important discoveries in the history of astrophysics and cosmology: microwave background radiation.

In 1961, E. A. Ohm, a physicist at one of the Bell Laboratory installations in Crawford Hill, New Jersey, built a radiometer to receive microwaves from NASA's Echo balloon (a reflector of electromagnetic signals launched in 1960). This was no coincidence: Bell Laboratories wanted to begin work in the field of communications satellites. In observations carried out on the 11-cm. wavelength, Ohm encountered a temperature excess of 3.3° (degrees, Kelvin) in his antenna, but that result was hardly noticed.[5]

Another instrument being developed at Crawford Hills at that time was an antenna whose horn shape was supposed to reduce interferences. The original idea was to use this antenna to communicate, via the Echo balloon, with the company's Telstar satellite. The antenna had to be very precise because the balloon's shape caused signals bouncing off it to be very diffused. A postdoctoral fellow at the California Technological

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The relation between temperatures and wavelengths can be obtained using laws such as those by Boltzmann, Wien or Planck. The relation between Celsius and Kelvin degrees is defined by the following relations: 0°C equals 273.15°K and 100°C equals 373.15°K.

Institute (Caltech), Robert Wilson (b. 1936), knew about this antenna and left his post for a job at Bell Laboratories. A Columbia University graduate, Arno Penzias (b. 1933), was three years older than Wilson and had already been at Bell for two years. Fortunately, that same year, the small but highly sensitive antenna became available for radio-astronomy use, as the company had decided to abandon the business of satellite communications. While making measurements on a wavelength of 7.4 centimeters, Penzias and Wilson found a temperature of 7.5ºK that should only have been 3.3ºK. Moreover, this extra radiation (or temperature), which they believed to be the effect of some sort of background noise, turned out to be constant, no matter which direction the antenna was pointing. The data indicated that the origin of what they were measuring was not in the atmosphere, or the sun, or even our galaxy. It was a mystery.

Having verified that the noise did not come from the antenna itself, the only possible conclusion they could draw was that it had something to do with the cosmos, although they did not know what its cause might be. The answer to that question came from their colleagues at nearby Princeton University, some of whom, like James Peebles (b. 1935), had already considered the idea that if there had been a Big Bang, there should be some background noise remaining from the primitive Universe. Such noise, in the form of radiation, would correspond to a much lower temperature—due to cooling associated with the Universe's expansion—than the enormously high one that must have coincided with the initial explosion. Peebles' ideas led his colleague at Princeton, Robert Dicke (1916-1995), to begin experiments intended to find that cosmic background radiation. Unwittingly, Penzias and Wilson stumbled upon it first. It was, however, the Princeton group that supplied the interpretation of Penzias and Wilson's observations (1965), which had been published by the them with no mention of their possible cosmological implications. According to current estimates, the temperature corresponding to that radiation in the microwave realm is around 2.7ºK (in their 1965 article, Penzias and Wilson put it at 3.5K).

It is significant that Penzias and Wilson detected the microwave background at a center dedicated to industrial research, where new instruments were developed and available. It is a perfect example of what we mentioned above: the necessity for more precise instruments and new technology in order to advance our knowledge of the Universe. As such technology became available, the image of the cosmos grew, and this led to more discoveries, two of which I will discuss below: pulsars and quasars.

**Pulsars and quasars**

In 1963, Cyril Hazard, an English radio-astronomer working in Australia, precisely established the position of a powerful radio-source, called 3C273. With that data, Maarten Schmidt (b. 1929), a Dutch astronomer working at the Mount Palomar Observatory in California, optically located the corresponding emitter, discovering that the spectral lines of 3C273 were shifted towards the red side of the spectrum to such a degree that it was clearly moving away from the Earth at an enormous speed: sixteen percent of the speed of light. Hubble's law, which states that the distance between galaxies is directly proportional to their speed of recession, indicated that 3C273 was very far away. This, in turn, implied that it was an extremely luminous object—more than one hundred times as bright as a typical galaxy. Objects of this type are called *quasi-stellar sources,* or *quasars* for short, and are thought to be galaxies with very active nuclei.

Since 3C273 was discovered, several million more quasars have been found. They constitute ten percent of all light-emitting galaxies and many astrophysicists believe that many of the most brilliant galaxies pass briefly through a quasar phase. Most quasars are very far from our galaxy, which means that the light that reaches us must have been emitted when the Universe was much younger. That makes them magnificent instruments for the study of the Universe's history.

In 1967, Jocelyn S. Bell (b. 1943), Anthony Hewish (b. 1924) and the latter's collaborators at Cambridge built a detector to observe quasars at radio frequencies. While using it, Bell observed a signal that appeared and disappeared with great rapidity and regularity. Its cycle was so constant that it seemed to have an artificial origin (could it possibly be a sign of intelligent extraterrestrial life?). Following a careful search, however, Bell and Hewish concluded that those "pulsars," as they were finally denominated, had an astronomical origin (Hewish, Bell, Pilkington, Scott and Collins 1968).[6] But what were those highly regular radio sources? A theoretical interpretation was not long in coming, and was provided by Thomas Gold, one of the "fathers" of steady-state cosmology, who had now accepted the Big Bang. Gold (1968) realized that such short cycles (around one to three seconds in the first detected pulsars), could only come from a very small source. White dwarfs were too large to rotate or vibrate at such a frequency, but neutron stars could.[7] But did the origin of the signals being received lie in the vibration or rotation of such stars? Certainly not their vibrations, because neutron stars vibrate much too fast (around a thousand times a second) to explain the cycles of most pulsars. So pulsars had to be rotating neutron stars.

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In 1974, Hewish shared the Nobel Prize for Physics with Ryle. Jocelyn Bell, who had first observed pulsars, was left out.

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The possible existence of neutron stars—a sort of giant nucleus made entirely of neutrons linked by the force of gravity—was first proposed in 1934 (that is, just two years after Chadwick discovered the neutron) by the California-based (Caltech) Swiss physicist and astrophysicist, Fritz Zwicky (1898-1974). According to general relativity, the minimum mass that would allow a neutron star to exist is 0.1 solar masses, while the maximum seems to be around 6 solar masses. In the case of a neutron star of one solar mass, its radius would be about 13 kilometers and its density $2 \cdot 10^{17}$ kilos per cubic meter, which is about $2 \cdot 10^{14}$ times as dense as water.

Since then, scientists have discovered pulsars that emit X-rays or gamma rays (and some even emit light in the visible spectrum), so nowadays, scientists also accept the possibility of other mechanisms for the production of their radiation emissions, including the accretion of matter in double systems.

Besides their astrophysical interest, pulsars serve other functions. They have been used to test general relativity's prediction that accelerated masses emit gravitational radiation (a phenomenon analogous to that produced by electrical charges: electromagnetic radiation).

Confirmation that gravitational radiation does, in fact, exist came in 1974, with the discovery of the first system consisting of two pulsars interacting with each other (called PSR1913+16), for which Russell Hulse (b. 1950) and Joseph Taylor (b. 1941) received the 1993 Nobel Prize for Physics. In 1978, after various years of continuous observation of that binary system, they were able to conclude that the orbits of those pulsars vary and are growing closer together. That result was thought to indicate that the system is losing energy due to the emission of gravitational waves (Taylor, Fowler and McCulloch 1979). Since then, other binary pulsar systems have been discovered, but it is still not possible to detect gravitational radiation with instruments built and installed on Earth. This is extremely difficult, due to the extreme faintness of the affects involved. The gravitational waves that would arrive at the Earth from some part of the Universe where an extremely violent event had taken place would produce distortion in the detectors no greater than one part out of $10^{21}$. That would be a tiny fraction the size of an atom. However, there are already devices designed to achieve this: the four-kilometer system of detectors in the United States known as LIGO (Laser Interferometric Gravitational wave Observatories).

Quasars are also very useful for studying the Universe in conjunction with general relativity. About one of every five-hundred quasars is involved in a very interesting relativist phenomenon: the diversion of the light it emits due to the gravitational effect of other galaxies situated between that quasar and the Earth, from which that effect is being observed. This effect is called "gravitational lensing",[8] and can be so powerful that multiple images of a single quasar are observable.

Actually, gravitational lenses are not produced exclusively by quasars, they are also produced by large accumulations of masses (such as cumuli of galaxies) which divert light from, for example, galaxies behind them (with respect to us) so that, instead of a more-or-less clear image, we see a halo of light, a "double image." They were first observed in 1979, when Walsh, Carswell and Weyman (1979) discovered a multiple image of a quasar in 0957+561. Since then, the Hubble space telescope has photographed a cumulus of galaxies about a thousand million light-years away in which, besides the light of the cumulus of galaxies itself, it is possible —though difficult because of their lesser luminescence— to detect numerous arcs (segments of rings). Those arcs are actually images of galaxies much farther away from us that the cumulus, but seen through the effect of the gravitational lens (the cumulous acts as a lens, distorting the light coming from those galaxies). Beside offering new evidence supporting general relativity, these observations have the added value that the magnitude of diversion and distortion visible in those luminous arcs is far greater than could be expected if the cumulus only contained the galaxies we see in it. In fact, evidence indicates that those cumuli contain between five and ten times more matter than we can see. Could this be the dark matter we will discuss further on?

For many scientists—at least until the problem of dark matter and dark energy took the fore—the background radiation, pulsars and quasars discussed in this section were the three most important discoveries in astrophysics during the second half of the twentieth century. What those discoveries tell us, especially pulsars and quasars, is that the Universe is made up of much more surprising and substantially different objects than were thought to exist in the first half of the twentieth century. Of course, when we speak of *surprising* or *exotic* stellar objects, we inevitably have to mention black holes, another "child" of the general theory of relativity.

**Black holes**

For decades after Einstein's theory was formulated in 1915 and its predictions about gravity with relation to the Solar System were exploited (the anomalous, with regards Newton's theory, movement of Mercury's perihelion, the curvature of light rays and the gravitational shift of spectral lines), general relativity was mostly in the hand of mathematicians—men like Hermann Weyl (1885-1955), Tullio Levi-Civita (1873-1941), Jan Arnouldus Schouten (1883-1971), Cornelius Lanczos (1892-1974) or André Lichnerowicz (1915-1998). This was partially due to the theory's mathematical difficulty and partially to the lack of almost any real situation in which to apply it. That theory mainly addressed the Universe, and exploring it would require technological means that did not even exist at the time, not to mention significant financial support. This problem began fading at the end of the nineteen sixties, and it can now be said that general relativity is fully integrated into experimental physics, including areas that are not even that close, such as the Global Positioning System (GPS). It is not only a

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As on other occasions, Einstein (1936) had already predicted the existence of this phenomenon.

part of experimental physics related to astrophysics and cosmology; as we will see further on; it is also a part of high-energy physics.

And here we must mention one of the most surprising and attractive stellar objects linked to general relativity discovered in the last few decades: black holes, whose existence has even reached beyond purely scientific circles and entered the social realm.

As I said, these object belong to the theoretical tenets of general relativity, although their Newtonian equivalents had already been proposed—and forgotten—much earlier by the British astronomer John Michell (c. 1724-1793) in 1783, and later by Pierre Simon Laplace (1749-1827) in 1795. Their exoticism derives from the fact that they involve such radical notions as the destruction of space-time at points called "singularities."[9]

Studies leading to black holes began in the nineteen thirties, when the Hindu physicist Subrahamanyan Chandrasekhar (1910-1995) and the Russian Lev Landau (1908-1968) demonstrated that in the Newtonian theory of gravitation, a cold body with a mass superior to 1.5 times that of the Sun could not support the pressure produced by gravity (Chandrasekhar 1931; Landau 1932). That result led scientists to ask what general relativity predicted for the same situation. In 1932, Robert Oppenheimer (1904-1967) and two of his collaborators, George M. Volkoff and Hartland Snyder (1913-1962) demonstrated that a star with that mass would collapse until it was reduced to a singularity; that is, to a point with a volume of zero and an infinite density (Oppenheimer and Volkoff 1939, Oppenheimer and Snyder 1939).

Stephen Hawking.

Oppenheimer and his collaborators' work received little attention or credence and it was ignored until interest in strong gravitational fields was spurred by the discovery of quasars and pulsars. In 1963, Soviet physicists, Evgenii M. Lifshitz (1915-1985) and Isaak M. Khalatnikov (b. 1919) took the first step and began studying the singularities of relativist space-time. Following the work of his Soviet colleges, the British mathematician and physicist Roger Penrose (b. 1931) and the physicist Stephen Hawking (b. 1942) applied powerful mathematic techniques to this question in the mid-nineteen sixties. They demonstrated that such singularities were inevitable when a star collapsed, providing certain conditions were met.[10]

A couple of years after Penrose and Hawking published their first articles, the physics of space-time singularities became that of "black holes," a felicitous term that has attracted considerable popular attention to this physical entity. The man responsible for this apparently insignificant terminological revolution was the United States physicist John A. Wheeler (1911-2008). He, himself, explained the genesis of that term in the following manner (Wheeler and Ford 1998, 296-297):

> In the fall of 1967, Vittorio Canuto, administrative director of NASA's Goddard Institute for Space Studies at 2880 Broadway in New York, invited me to give a lecture on possible interpretations of the new and stimulating evidence arriving from England about pulsars. What were those pulsars? Vibrating white dwarfs? Rotating neutron stars? What? In my lecture, I argued that we should consider the possibility that, at the center of a pulsar, we might find a completely collapsed gravitational object. I pointed out that we could not continue to say, over and over again, "completely collapsed gravitational object." We needed a much shorter descriptive term. "How about black hole" asked someone in the audience. I had been looking for the right term for months, ruminating in bed, in the bathtub, in my car, whenever I had a free moment. Suddenly, that name seemed totally correct to me. A few months later, on 29 December 1967, when I gave the more formal Sigma Xi-Phi Kappa lecture at the New York Hilton's West Ballroom, I used that term, and I later included it in the written version of the lecture published in spring 1968.

The name was catchy, and it stuck, but the explanation was mistaken (as I pointed out above, a pulsar is driven by a neutron star).

While the history of black holes began with the physics work of Oppenheimer and his collaborators,

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We must remember that from the standpoint of the general theory of relativity, space-time and gravity represent the same physical concept, as the curvature of the former is what describes the latter.

**10**
See, for example, Penrose (1965), Hawking (1965, 1966a, 1966b) and Hawking and Penrose (1969). I will not go into more depth here, but I do want to point out that other scientists also took part in this project, including G. F. R. Ellis.

mentioned above, for some years, the field was dominated by purely mathematical studies like the previously mentioned ones by Penrose and Hawking. The underlying physical idea was that they must be very different than any other type of star, even though their origins were linked to them. They would occur when, after exhausting its nuclear fuel, a very massive star began to contract irreversibly, due to gravitational force. A moment would thus arrive when it would form a region (called "horizon") in which matter and radiation could only enter, without anything being able to get out, not even light (from whence the denomination, "black"). The larger such an object was, the more it would "eat", and the more it ate, the bigger it would get. The center of a black hole is its point of *collapse.* According to general relativity, there, the matter that once made up the star is compressed and expulsed, apparently "out of existence."

Clearly, "out of existence" is not an acceptable idea. However, there is a possible way out of such a paradoxical situation: the general theory of relativity is not compatible with quantum requirements, but clearly, when matter is compressed into a very reduced area, its behaviour will follow quantum rules. Thus, a true understanding of the physics of black holes calls for a quantum theory of gravitation (either by quantizing general relativity, or by constructing a new theory of gravitational interaction that can be quantized). At the present time, this has yet to be done, although some steps have been made in that direction, including one by Hawking himself, the grand guru of black holes. What is called "Hawking's radiation" (Hawking 1975), predicts that, due to quantum processes, black holes are not as black as we though, and are able to emit radiation.[11]

As a result, we do not really know what those mysterious and attractive objects are. Do they, in fact, exist at all? The answer is yes. There are ever-greater indications that they do. On 12 December 1970, the United States launched a satellite from Kenya to celebrate its independence. Called Uhuru—the Swahili word for "freedom"—this satellite carried instruments capable of determining the position of the most powerful sources of X rays. Among the 339 identified sources is Cygnus X-1, one of the most brilliant in the Milky Way, located in the region of the Swan. This source was later linked to a visible super-giant blue star with a mass 30 times that of the Sun and an invisible companion. The movement of the blue star indicated that its companion had a mass 7 times that of the Sun, a magnitude too great to be a white dwarf or a neutron star. It must be, therefore, a black hole. However, some argue that its mass is 3 solar masses, in which case it could be a neutron star. Anyhow, at least other 10 binary systems have been found in which one of its members seems to be a black hole: for example, V404 Cygni, formed by a star with 2/3 the mass of the Sun, and a black hole of 12 solar masses.

It is now generally accepted that there are super-massive black holes at the center of those galaxies whose nucleus is more luminous that all the rest of the galaxy (about 1% of all galaxies in the Universe are that way). In over two hundred cases, it has been possible to indirectly determine the masses of those super black holes, but a direct determination has only been possible in a few cases. One of the latter is in our own Milky Way.

**Inflation and "wrinkles in time"**

The study of the Universe is enormously puzzling. Obviously, measuring such basic data as distances, masses and velocities is extremely complex there. We cannot do so directly, nor can we "see" everything with precision. With the data then available, there was a time when the model that offered the Robertson-Walker-Friedmann solution to general relativity was sufficient. It represents a Universe that expands with an acceleration that depends on its mass-energy content. But there were increasingly clear problems with the cosmology of the Big Bang.

One of these was the question of whether mass-energy is such that the Universe will continue to expand forever, or if it is large enough that gravitational attraction will eventually overcome the force of the initial explosion, reaching the point where it begins to contract and finally arrives at a *Big Crunch.* Another problem lay in the considerable uniformity with which mass appears to be distributed throughout the Universe. This is observable using units of measurement of some 300 million light-years or more (of course, on a small scale, the Universe, with its stars, galaxies, cumuli of galaxies and enormous interstellar voids, is not homogeneous). Background microwave radiation is good proof of this macro-homogeneity. Now then, using the standard Big Bang theory, it is difficult to explain this homogeneity in terms of known physical phenomena: moreover, considering that information about what happens cannot be transmitted between different points in space-time any faster that the speed of light, it turns out that during the first moments of the Universe's existence it would not have been possible for different regions to "reach a consensus," so to speak, about what the mean density of matter and radiation should be.[12]

To resolve this problem the idea of an inflationary Universe was proposed. It hypothesizes that, during the Universe's first instants of existence, there was a gigantic, exponential increase in the speed of its

**11**
Such an emission would lead to a slow decrease in the mass of a black hole. If that decrease were continuous, the black hole could eventually disappear. For normal black holes (those of just a few solar masses), however, that would not happen. For example, a black hole of just one solar mass would have a lower temperature than that of the radiation coming from the microwave background, which means that black holes of such mass would absorb radiation faster than they could emit it, so they would continue to increase in mass. If, however, there were very small black holes (made, for example, during the first instants of the Universe by fluctuations in density that must have happened at that time), then they would have a much higher temperature, emitting more radiation than they could absorb. They would lose mass, which would make them even hotter, and would finally blow up in a large explosion of energy. Their life would be such that we might be able to observe such explosions how. None has yet been detected, however.

**12**
This difficulty is called the "horizon problem."

expansion. In other words, the mini-universe must have experienced a growth so rapid that there was not enough time to develop physical processes that would have led to non-homogeneous distributions. Once that inflationary stage ended, the Universe must have continued evolving according to the classic Big Bang model.

Among the scientists responsible for this inflationary theory, we should mention the American, Alan Guth (b. 1947) and the Soviet, Andrei Linde (b. 1948).[13] But, more than specific names, what I want to point out is that it is impossible to understand this theory without recourse to high-energy physics—what used to be called elementary-particle physics, which I will discuss further on—especially the Grand Unified Theories (GUT), which predict that there would have to be a phase shift at temperatures around $10^{27}$ degrees Kelvin.[14] Here, we have an example of one of the most important phenomena to take place in the field of physics during the second half of the twentieth century: the encounter between cosmology (the science of "the big") and high-energy/elemental-particle physics (the science of "the small"). Naturally, their meeting place is the first instants of the Universe's existence, when the energies involved were gigantic.

So, inflation lies at the origin of a uniform Universe. But then, what caused the miniscule primordial non-homogeneities that, with the passage of time and the effect of gravitational force, gave birth to cosmic structures such as galaxies?

One possible answer is that inflation may have enormously amplified the ultramicroscopic quantum fluctuations that occurred as a result of the uncertainty principle applied to energies and time ($\Delta E \cdot \Delta t \geq h$). If that were the case, what better place to look for non-homogeneities than the microwave radiation background?

The answer to this question appeared in the work of a team of US scientists led by John C. Mather (b. 1946) and George Smoot (b. 1945). In 1982, NASA approved funding for the construction of a satellite—the Cosmic Background Explorer (COBE), which was put into orbit 900 kilometers above the Earth in the fall of 1989—to study the cosmic microwave background. The entire project was coordinated by Mather, including the experiment (in which he used a spectrophotometer cooled to 1.5ºK) that showed that the shape of the microwave radiation background corresponds to that of the radiation of a black body at a temperature of 2.735ºK. Meanwhile, Smoot measured the miniscule irregularities predicted by inflation theory. Ten years later, following the work of over a thousand people and a cost of 160 million dollars, it was announced (Mather et al. 1990; Smoot et al. 1992) that COBE had detected what Smoot called "wrinkles" in space-time, the seeds that led to the complex structures—such as galaxies—we now see in the Universe.[15]

Just how thrilled those researchers were when they confirmed their results is clear in a book for lay readers published by Smoot soon thereafter. *Wrinkles in Time* (Smoot and Davidson, 1994, 336):

> I was looking at the primordial form of the wrinkles, I could feel it in my bones. Some of the structures were so huge that they could only have been generated when the Universe was born, no later. What was before my eyes was the mark of creation, the seeds of the present Universe.

Consequently, "the Big Bang theory was correct and the notion of inflation worked; the wrinkles model fit in with the formation of structures from cold dark matter; and the magnitude of the distribution would have produced the larger structures of the current universe under the influence of gravitational collapse over the course of 15,000 million years."

COBE was a magnificent instrument, but it was by no means the only one. There are many examples of astrophysics and technology working hand in hand, not only with Earth-based instruments, but also spacecraft. At this point, scientists have been exploring our Solar System for quite some time using satellites with refined instruments that send us all sorts of data and images: space probes such as Mariner 10, which observed Venus from a distance of 10,000 kilometers in 1973; Pioneer 10 and Voyager 1 and 2, which approached Jupiter, Saturn, Uranus and Pluto between 1972 and 1977, and Galileo, aimed at Jupiter and its moons.

A very special type of vehicle is the Hubble space telescope, which NASA put into orbit following a long process in the spring of 1990.[16] A telescope in an artificial satellite has the advantage of being outside the Earth's atmosphere, which is the greatest barrier to the reception of radiation. Since it was launched, and especially since its defects were corrected, Hubble has sent, and continues to send, spectacular images of the Universe. Thanks to it, we have the first photos of regions (such as the Orion nebulous) where it appears that stars are being born. It would not be a complete exaggeration to say that Hubble has revolutionized our knowledge of the Universe.

**Extrasolar planets**

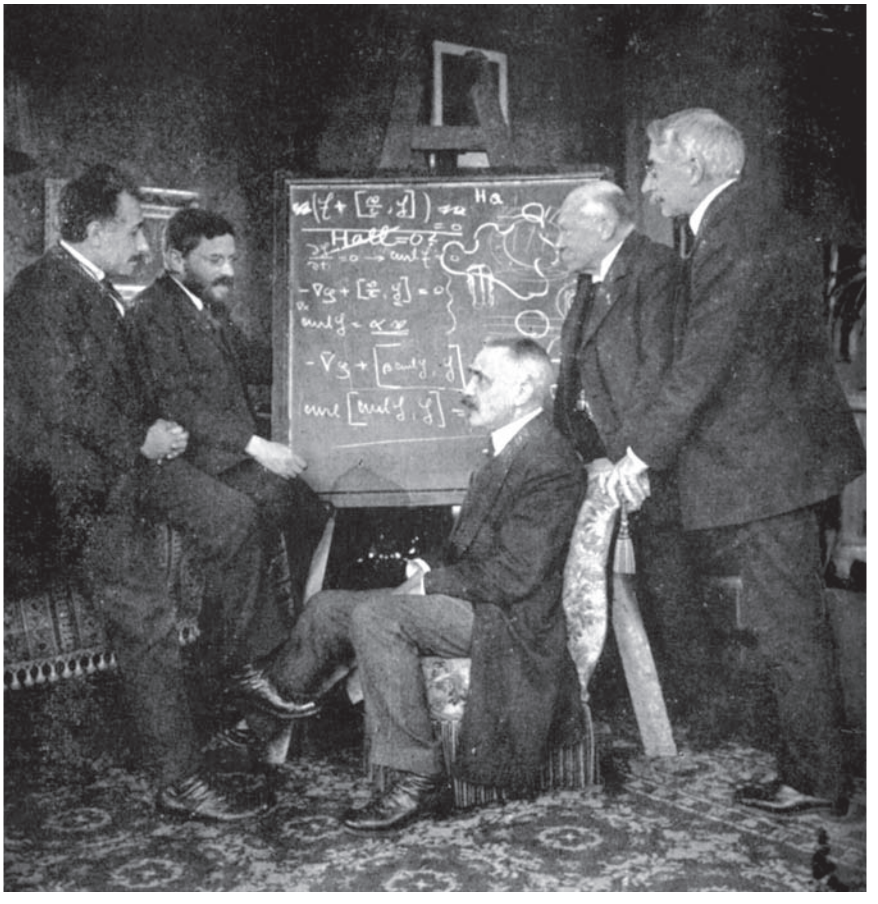
Thanks to technological advances, scientists are starting to be able to see new aspects and objects in the cosmos, such as planetary systems associated with stars other than the Sun. The first discovery of this sort took place in 1992, when Alex Wolszczan and Dale Frail found that at least two Earthlike planets were orbiting around a pulsar (Wolszczan and Frail 1992). Three years later, Michel Mayor and Didier Queloz announced their

13
Guth (1981), Linde (1982).

14
In a phase shift, there is a sudden change in the state of the system in question. On example is when water (liquid) turns into ice (solid).

15
For their work, both received the Nobel Prize for Physics in 2006.

16
Until the early nineteen nineties, the largest mirrors on optical telescopes installed on Earth were between five and six meters in diameter. The largest telescope at that time, with a primary (or collector) mirror six meters in diameter, was in the Russian Caucasus. It was followed by the telescope at the Mount Palomar Observatory, inaugurated soon after World War II, with a diameter of 5 meters, and then a long list of telescopes with mirrors around 4 meters in diameter. Now a series of large telescopes have been completed or are being built whose characteristics and employment of the most modern technology is making an important quantitative leap—and in many senses, a qualitative one, as well—in astrophysical research. These are telescopes of up to ten meters, such as the one already in use at Mauna Kea, Hawaii, which belongs to the California Institute of Technology and the University of California. Another of similar characteristics is being built at the same location. With the one already in use, which is the largest in the world, it has been possible to observe a brown dwarf (PPL15) in the Pleiades cumulus. This kind of star is so small that it does not shine like others, so none had ever been seen before, although they could sometimes be detected because of their gravitational effects. Another instrument of this size is the Grand Telescope at the Canary Islands Astrophysics Institute. Installed at Roque de los Muchachos, it has seen its "first light" recently.



Albert Einstein with Paul Ehrenfest, Paul Langein, Heike Kamerlingh Onnes and Pierre Weiss at Erenfest's house (Leiden, 1920).

discovery of a planet of the same size and type as Jupiter (a gaseous giant) orbiting around the star 51 Peasi (Mayor and Queloz 1995). Since then, the number of known extrasolar planets has grown considerably. And if such planets exist, life may have developed on some of them as well. Now, while the biology that addresses the problem of the origin of life supports the possibility that in sufficiently favorable environments combinations of chemicals could produce life through synergic processes, most probably such life would be of a different type than human life. Evolutionist biology, supported by geological data, has shown that the human species is the product of evolutionary chance. If, for example, an asteroid or comet approximately ten kilometers in diameter had not collided with the Earth some 65 million years ago—it hit the Earth at a speed of about thirty kilometers a second, producing energy equivalent to the explosion of one hundred million hydrogen bombs—then an enormous number of plant and animal species might never have disappeared (or certainly not then). These included the dinosaurs that impeded the rise of those small mammals that later evolved into *homo sapiens* and other species.

It is that element of chance that makes it impossible to be certain there is intelligent life on other planets —in our galaxy or others—or that such a life form might be trying, or have tried, to understand nature, build scientific systems, and attempt to communicate with other living beings that may exist in the Universe. Still, for quite some time, research programs have been scanning the Universe in search of signs of intelligent life—programs such as the Search of Extra-Terrestrial Intelligence (SETI), which has used 250-million-channel receivers that carry out around twenty thousand million operations per second.

### Dark matter and dark energy

The existence of extrasolar planets certainly thrills and moves us, but it is not something "fundamental." It does not shake the foundations of science. But other discoveries relative to the contents of the Universe are a very different matter. For example, we have good reasons to believe that the cosmos contains a large amount of invisible matter that exercises gravitational force. The most immediate evidence comes from rotating disk-shaped galaxies (such as our own Milky Way). When we look at the outer part of such galaxies, we see that their gas moves at a surprising speed —much faster than it should, given the gravitational attraction produced by the stars and gasses we can detect inside it. Other evidence comes from the internal movement of galaxy cumuli. This "dark" matter is thought to constitute thirty percent of all the matter in the Universe, but what is its nature? That is one of the problems. It could consist of barely luminescent stars (such as brown dwarfs), or exotic elemental particles, or black holes. We cannot really understand what galaxies are, or how they came into being, until we know what this dark matter is. Nor will we be able to know what the ultimate destiny of the Universe is.

Along with dark matter, another similar question came to the fore in the last decade of the twentieth century: dark energy. While studying a type of supernova —stars that have exploded, leaving a nucleus—a group led by Saul Perlmutter (at the Lawrence Berkeley National Laboratory in California) and another by Brian Schmidt (at the Mount Stromlo and Siding Spring observatories in Australia) arrived at the conclusion that, contrary to previous suppositions, the Universe's expansion is accelerating (Perlmutter et al. 1998; Schmidt et al. 1998). The problem was that the Universe's mass could not explain such an acceleration; it was necessary to assume that gravity was behaving in a surprising new way: pushing masses away from each other rather than attracting them to each other. It had been assumed that the Big Bang must have been driven by a repulsive energy during the creation of the universe, but no one had imagined that such energy could continue to exist in the now-mature Universe.

Thus, a new energy came into play, a "dark" energy residing in empty space. And since energy is equivalent to mass, that dark energy signified a new contribution to the total mass of the Universe, thought not the same as dark matter. It is now thought that around 3% of the Universe consists of ordinary mass, 30%, of dark mass, and the other 67%, of dark energy. In other words: we thought we knew what the Universe is, and it turns out to be practically unknown to us, because we know the nature and make up of neither dark matter nor dark energy. One possible explanation of the latter could be found in the term introduced by Einstein in 1916 in his field equations for general relativity. As we saw, when applying his theory of gravitational interaction to the entire Universe, Einstein sought a model that would represent a static Universe. That obliged him to introduce a new term into his equations, the previously mentioned cosmological constant, which actually represents a field of repulsive forces that compensate for the attractive effects of gravitation. When relativistic cosmology found solutions that represent an expanding Universe, and that expansion was demonstrated by observation (Hubble), Einstein thought that it was no longer necessary to maintain that constant, although it could be included without any difficulty in theoretical expansive models. Now, it seems necessary to resurrect this term, but it will not be enough to include it in relativist cosmology again; it has to find its place and meaning in quantum theories that attempt to make gravity a part of quantum system. After all, dark energy is the energy of the void, and from a quantum viewpoint, vacuum has a structure. And given that quantum physics has again entered the picture here, let us discuss how the quantum revolution developed and solidified during the second half of the twentieth century.

## A quantum world

### High-energy physics: from protons, neutrons and electrons to quarks

When discussing the quantum revolution that emerged during the first half of the twentieth century, I mentioned the search for the basic components of matter, the so-called "elemental particles." There, we saw that moving beyond protons, electrons and neutrons, the most basic of those particles, required more elevated energy than could be supplied by the "projectiles"—alpha particles, for example—coming from the emissions of radioactive elements (especially, radium). We also saw that it was Ernest Lawrence who found a new way forward, developing instruments called particle accelerators (in his case, cyclotrons), which functioned by accelerating particles to high energy levels and then making them collide with each other (or with some predetermined target). The idea was to examine what was produced by such collisions, that is, what new and smaller components make up such particles if, in fact, there are any.[17]

The physics of elemental particles, also called high-energy physics, as I indicated above, became one of the main protagonists of the second half of the twentieth century. This is very expensive science (it is the epitome of *Big Science,* which requires large teams of scientists and technicians and large investments), and is becoming ever more expensive, as the size of accelerators grows, making it possible to reach higher energy levels.

After World War II, especially in the United States, high-energy physics drew on the prestige of nuclear physics, which had supplied the powerful atomic bombs. Here, I will mention only the most important accelerators. In 1952, the Cosmotron entered service in Brookhaven, New York. It was for protons and reached 2.8 GeV;[18] It was followed, among others, by the Bevatron (Berkeley, protons; 1954), with 3.5 GeV; Dubna (USSR, protons; 1957), 4.5 GeV; the Proton-Synchroton (CERN, Geneva, protons; 1959), 7 GeV; SLAC (Stanford, California; 1966), 20 GeV; PETRA (Hamburg, electrons and positrons; 1978), 38 GeV; Collider (CERN, protons and antiprotons; 1981), 40 GeV; Tevatron (Fermilab, Chicago, protons and antiprotons), 2,000 GeV, and SLC (Stanford, electrons and positrons), 100 GeV, both in 1986; LEP (CERN, electrons and positrons; 1987), 100 GeV, and HERA (Hamburg, electrons and protons; 1992), 310 GeV.

The initials, CERN, correspond to the *Centre Européen de Recherches Nucleaires* (European Nuclear Research Center), an institution created by twelve European nations in Geneva in 1954 to compete with the United States. CERN now includes more countries (including Spain) and with its accelerators it has played an outstanding role in the development of high-energy physics. In fact, in difficult times for this field, like the present, CERN has just completed (2008) construction of a new one in which protons will collide with an energy of 14,000 GeV: the Large Hadron Collider (LHC). Thus, old Europe carries the torch and "keeps the fire" for this costly branch of physics.

So why do I speak of "difficult times for this field?" Because due to its high cost, this branch of physics has been having difficulties in recent years. In fact, it was recently dealt a serious blow by what had been, until then, its strongest supporter: the United States. I am referring to the Superconducting Super Collider (SSC). This gigantic accelerator, which U.S. high-energy physicists considered indispensable for continuing

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Strictly speaking, it was not Lawrence who opened the door to elemental-particle physics using non-radioactive sources, although it is true that he did find the most adequate technical procedure. At Cambridge in 1932, John D. Cockcroft (1897-1967) and Ernst T. S. Walton (1903-1995) used a voltaic multiplier to obtain the 500 kV (1 kV = 1000 volts) that allowed them to become the first to observe the artificial disintegration of lithium atoms into two particles. And there were more precedents, such as the generators developed by Robert J. van de Graaff (1901-1967).

18
1 GeV = 1000 million electron-volts. 1 electron-volt is the motion energy a single electron would gain when subjected to the potential difference of one volt.

to develop the structure of the so-called standard model, was going to consist of an 84 kilometer tunnel to be dug near a small town of 18,000 inhabitants about thirty kilometers southeast of Dallas, in Waxahachie. Inside that tunnel, thousands of magnetic superconductor spools would guide two proton beams. After millions of laps, they would reach levels twenty times higher than could be attained with existing accelerators. At various points along the ring, protons from the two beams would collide and enormous detectors would track the results of those collisions. The project would take ten years, and its cost was initially estimated at 6,000 million dollars.

Things got off to a rocky start, but the tunnel excavation was completed. However, on 19 October 1993, following prolonged, difficult and changing discussions in both houses of Congress, the House of Representatives finally cancelled the project. Other scientific programs—especially in the field of biomedicine—were more attractive to American congressmen, senators and—why deny it?—society, which was more interested in health-related matters.

However, let us abandon the subject of accelerators, and discuss their products, those particles that appear to be "elemental." Thanks to those accelerators, their number grew so great that it wound up drastically undermining the idea that most of them could really be elemental in the fundamental sense. Among the "particles" discovered, we can recall pions and muons of various sorts, or those called $\Lambda$, W or Z, not to mention their corresponding antiparticles.[19] The number—hundreds—of such particles grew so great that scientists began speaking of a "particle zoo," a zoo with too many occupants.

One of its inhabitants was particularly striking: quarks. Their existence had been theorized in 1964 by U.S. physicists, Murray Gell-Mann (b. 1929) and George Zweig (b. 1937). Until quarks appeared in the complex and varied world of elemental particles, it was thought that protons and neutrons were indivisible atomic structures, truly basic, and that their electrical charge was an indivisible unit. But quarks did not obey this rule, and they were assigned fractional charges. According to Gell-Mann (1964) and Zweig (1964), hadrons—particles subject to strong interaction—are made up of two or three types of quarks and antiquarks called *u* (*up*), *d* (*down*) and *s* (*strange*), that respectively have electrical charges of 2/3, -1/3 and -1/3 of that of an electron.[20] Thus, a proton is made up of two *u* quarks and one *d*, while a neutron consists of two *d* quarks and one *u*. Therefore, they are composite structures. Later, other physicists proposed the existence of three other quarks: *charm* (*c;* 1974), *bottom* (*b;* 1977) and *top* (*t;* 1995). To characterize these quarks, scientists say they have six *flavors*. Moreover, each of the six types comes in three varieties, or *colors:* red, yellow (or green) and blue. And for each quark there is, of course, an antiquark.

Needless to say, terms like these—*color*, *flavor*, *up*, *down*, and so on—do not represent the reality we normally associate with such concepts, although in some cases there can be a certain logic to them, as happens with *color.* This is what Gell-Mann (1995, 199) had to say about that term:

> While the term "color" is mostly a funny name, it is also a metaphor. There are three colors, called red, green and blue, like the three basic colors in a simple theory of human color vision (in the case of painting, the three primary colors are usually red, yellow and blue, but when mixing light instead of pigment, yellow is replaced by green). The recipe for a neutron or a proton calls for a quark of each color, that is, one red, one green and one blue, so that the sum of the colors cancels out. As in vision, where white can be considered a mixture of red, green and blue, we can metaphorically state that neutrons and protons are white.

In short, quarks have *color* but hadrons do not: they are white. The idea is that only *white* particles are directly observable in nature, while quarks are not; they are "confined," that is, grouped to form hadrons. We will never be able to observe a free quark. Now in order for quarks to remain confined, there have to be forces among them that are very different than electromagnetic or other kinds of forces. "Just as electromagnetic force between electrons is mediated by the virtual exchange of photons," as Gell-Mann put it (1995, 200), "quarks are linked together by a force that arises from the exchange of other quanta: gluons, whose name comes from the fact that they make quarks stick together to form observable white objects such as protons and neutrons."[21]

About ten years after quarks appeared, a theory, quantum chromodynamics, was formulated to explain why quarks are so strongly confined that they can never escape from the hadron structures they form. Of course the name *chromodynamic*—from the Greek term *chromos* (color)—alluded to the *color* of quarks (and the adjective "quantum" to the fact that this theory is compatible with quantum requirements). Inasmuch as quantum chromodynamics is a theory of colored elemental particles, and given that color is associated with quarks, which are, in turn, associated with hadrons—"particles" subject to strong interaction—we can say that this theory describes that interaction.

With quantum electrodynamics —which, as I already stated, emerged in the first half of the twentieth century—and quantum chromodynamics, we have quantum theories for both electromagnetic and strong interactions. But what about the weak interaction, responsible for radioactive phenomena? In 1932, Enrico

**19**
Each particle has its antiparticle (although they sometimes coincide): when they meet each other, they disappear—annihilating each other—producing energy.

**20**
There are two types of hadrons: baryons (protons, neutrons and hyperons) and mesons (particles whose mass have values between those of an electron and a proton).

**21**
It is also interesting to quote what Gell-Mann (1995, 198) wrote about the name "quark": "In 1963, when I gave the name "quark" to the elemental parts of nucleons, I based my choice on a sound that was not written that way, sort of like "cuorc." Then, in one of my occasional readings of James Joyce's *Finnegans wake,* I discovered the word "quark" in the sentence "Three quarks for Muster Mark." Given that "quark" (which is used mostly to describe the cry of a seagull) was there to rhyme with "Mark," I had to find some excuse to pronounce it like "cuorc." But the book narrates the dreams of an inn-keeper named Humphry Chipden Earkwicker. The words in the text often come from various sources at the same time, like the "hybrid words" in Lewis Carroll's *Through the Looking Glass.* Sometimes, sentences partially determined by bar slang appear. I thus reasoned that one of the sources of the expression "Three quarks for Muster Mark," might be "Three quarts for Mister Mark," in which case the pronunciation, "cuorc," would not be totally unjustified. At any rate, the number three fits perfectly with the number of quarks present in nature."

Fermi (1901-1954), one of the greatest physicists of his century, developed a theory for weak interaction, which he applied primarily to what was called "beta disintegration," a radioactive process in which a neutron disintegrates, leaving a proton, an electron and an antineutrino. Fermi's theory was improved in 1959 by Robert Marshak (1916-1992), E. C. George Sudarshan (b. 1931), Richard Feynman and Murray Gell-Mann, but the most satisfactory version of a quantum theory of weak interaction was put forth in 1967 by the US scientist, Steven Weinberg (b. 1933) and a year later by the English-based Pakistani, Abdus Salam (1929-1996). They independently proposed a theory that unified electromagnetic and weak interactions. Their model included ideas proposed by Sheldon Glashow (b. 1932) in 1960.[22] For their work, Weinberg, Salam and Glashow shared the Nobel Prize for Physics in 1979. This happened after one of the predictions of their theory—the existence of what they called "weak neutral currents"—was experimentally corroborated at CERN in 1973.

The electroweak theory unified the description of electromagnetic and weak interactions. But could it be possible to take a farther step on the path to unification, formulating a theory that would also include the strong interaction described by quantum chromodynamics? The affirmative answer to this question was provided by Howard Georgi (b. 1947) and Glashow (Georgi and Glashow 1974), who presented the first ideas of what came to be called, as we mentioned earlier, Grand Unified Theories (GUT).

This family of theories had the most impact on cosmology, especially on the description of the Universe's first instants. From the perspective of GUTs, in the beginning there was only one force, which contained electromagnetic, weak and strong forces. However, as the Universe cooled, they began to separate.

Such theoretical tools make it possible to explain questions such as the existence (at least in appearance, and fortunately for us) of more matter than antimatter in the Universe. This is due to something the different GUTs have in common: they do not conserve a magnitude called the "baryonic number," meaning that processes are possible in which the number of baryons—remember, these include protons and neutrons—produced is not equal to the number of anti-baryons. The Japanese physicist, Motohiko Yoshimura (1978) used this property to demonstrate that an initial state in which there was an equal amount of matter and antimatter could evolve into one with more protons or neutrons than their respective antiparticles, thus producing a Universe like ours, in which there is more matter than antimatter.

Thanks to the group of theories mentioned above, we have an extraordinary theoretical framework in which to understand what nature is made of. Its predictive capacity is incredible. These theories accept that all matter in the universe is made up of aggregates of three types of elemental particles: electrons and their relatives (those called muon and tau), neutrinos (electronic, muonic and tauonic neutrinos) and quarks, as well as the quanta associated with the fields of the four forces we recognize in nature:[23] photons, for electromagnetic interaction, Z and W particles (gauge bosons) for weak interaction, gluons for strong interaction; and even though gravitation has yet to be included in this framework, the as-yet-unobserved gravitons, for gravitational interaction. The subset formed by quantum chromodynamics and electroweak theory (that is, the theoretical system that includes relativistic and quantum theories of strong, electromagnetic and weak interactions) proves especially powerful in its balance of predictions and experimental confirmation. It is called the *Standard model* and, according to the distinguished physicist and science historian, Silvan Schweber (1997, 645), "the formulation of the Standard Model is one of the great achievements of the human intellect—one that rivals the genesis of quantum mechanics. It will be remembered—together with general relativity, quantum mechanics, and the unravelling of the genetic code—as one of the most outstanding intellectual advances of the twentieth century. But much more so than general relativity and quantum mechanics, it is the product of a communal effort." Allow me to emphasize that last expression, "communal effort." The attentive reader will have easily noticed in these pages that I have only mentioned a few physicists, no more than the tip of the iceberg. That is inevitable: the history of high-energy physics calls not for an entire book, but for several.

Of course, notwithstanding its success, the Standard model is obviously not the "final theory." On one hand because it leaves out gravitational interaction, on the other, because it includes too many parameters that have to be determined experimentally. Those are the always uncomfortable yet fundamental "why" questions. "Why do the fundamental particles we have detected exist? Why do those particles have the masses they have? Why, for example, does the tau weigh around 3,520 times as much as an electron? Why are there four fundamental interactions, instead of three, five, or just one? And why do those interactions have the properties they do (such as intensity or range of action)?"

### A world of ultra-tiny strings?

Let us now consider gravitation, the other basic interaction. Can it be unified with the other three? A central problem is the lack of a quantum theory of gravitation that has been subjected to experimental

**22**
Glashow (1960), Weinberg (1967), Salam (1968).

**23**
To understand the idea of the quantum of an interaction it is enough to consider the case of electromagnetic radiation mentioned above. According to classic theory, it propagates in fields (waves), while quantum physics expresses that propagation in terms of corpuscles (photons), which are *quanta* of $h\cdot$ energy as proposed by Einstein in 1905.

testing. There are, however, candidates for this splendid unifying dream: complex mathematical structures called string theories.

According to string theory, basic particles existing in nature are actually one-dimensional filaments (extremely thin strings) in spaces with many more dimensions than the three spatial and single temporal one we are aware of. Although, rather than saying that they "are" or "consist of" such strings, we would have to say that they "are manifestations" of the vibrations of those strings. In other words, if our instruments were powerful enough, what we would see are not "points" with certain characteristics—what we call electrons, quarks, photons or neutrinos, for example—but tiny vibrating strings, with open or closed ends. The image this new view of matter calls to mind is thus more "musical" than "physical." In his best-seller, *The Elegant Universe* (2001, 166-168), Brian Greene, a physicist and outstanding member of the "string community" explains: "Just as the different vibratory patterns of a violin string generate different musical notes, *the different vibratory models of a fundamental string generate different masses and force charges…* The Universe—which is made up of an enormous number of these vibrating strings—is something similar to a cosmic symphony."

It is easy to understand how attractive these ideas can be: "Strings are truly fundamental; they are 'atoms,' that is, *indivisible components,* in the most authentic sense of that Greek word, just as it was used by the ancient Greeks. As absolutely minimum components of anything, they represent the end of the line—the last and smallest of the Russian 'matrioshka' nesting dolls—in the numerous layers of substructures within the microscopic world." (Greene 2001, 163). So what kind of materiality do these one-dimensional theoretical constructs have? Can we consider them a sort of "elemental matter" in a way similar to our customary concept of matter, including particles that are as elemental (though maybe only in appearance) as an electron, a muon or a quark?

I said before that string theories are complex mathematical structures, and that is certainly true. In fact, the mathematics of string theory are so complicated that, up to the present, no one even knows the equations of this theory's exact formulas—only approximations to those equations. And even those approximate equations are so complicated that, to date, they have only partially been solved. So it is no surprise that one of the great leaders in this field was a physicist with a special gift for mathematics. I am referring to the American, Edward Witten (b. 1951). The reader will get an idea of his stature as a mathematician when I mention that, in 1990, he received one of the four Fields medals (alongside Pierre-Louis Lions, Jean-Christophe Yoccoz and Shigefumi Mori) that are awarded every four years and are the mathematical equivalent of the Nobel Prize. In 1995, Witten launched "the second string revolution" when he argued that string (or super-string) theory could only become all-encompassing—a Theory of Everything—if it had ten spatial dimensions plus a temporal one. This eleven-dimensional theory, which Witten called M Theory, has yet to be completely developed.[24]

Faced with these string theories, it is reasonable to wonder whether we have reached a point in our exploration of the structure of matter in which "materiality"—that is, matter—disappears, becoming another thing altogether. But what is that other thing? If we are speaking about particles that appear as string vibrations, wouldn't that "other thing" actually be a mathematical structure? After all, a vibration is the oscillation of some sort of matter, but as a permanent structure, it is probably more of a mathematical than a material entity. If that were the case, we could say that one of Pythagoras' dreams had come true. Physicists would have been working very hard for centuries, or even millennia, only to discover that matter has finally slipped between their fingers, like a net, turning into mathematics, that is, mathematical structures. In sum, string theory unearths age-old problems, and maybe even ghosts: problems such as the relation between physics (and the world) and mathematics.

Independently of those essentially philosophical aspects of nature, there are others that must be mentioned here. Up to now, string theory has demonstrated very little, especially in light of the fact that science is not only theoretical explanation, but also experiments in which theory is subjected to the ultimate arbiter: experimental testing. String theories are admired by some, discussed by many, and criticized by quite a few, who insist that its nature is excessively speculative. Thus, the distinguished theoretical physician, Lee Smolin (2007, 17-18), pointed out in a book about these theories:

> In the last twenty years, a great deal of effort has gone into string theory, but we still do not know if it is certain or not. Even after all the work that has been done, the theory offers no prediction that can be tested through current experiments, or at least, experiments conceivable at the present time. The few clean predictions they propose have already been formulated by other accepted theories.
>
> Part of the reason why string theory makes no new predictions is that there seem to be an infinite number of versions. Even if we limit ourselves to theories that coincide with some of the basic facts observed in our universe, such as its vast size or the existence of dark energy, there continue to be something like $10^{500}$ different string theories; that is a one with five hundred zeros behind it, which is more than all the known atoms in the universe. Such a quantity

**24**
There is no consensus about why the letter "M" was chosen. Some think it signifies Mother Theory, others, Mystery Theory, other Membrane Theory, and still others, Matrix Theory.

of theories offers little hope of identifying the result of any experiment that would not fit any of them. Thus, no matter what experiments show, it is not possible to demonstrate that string theory is false, although the opposite is equally true: no experiment can demonstrate that it is true.

In that sense, we should remember that one of the most influential methodologies in science continues to be the one put forth by Karl Popper (1902-1994), an Austrian philosopher who wound up at the London School of Economics. Popper always insisted that a theory that cannot be refuted by any imaginable experiment is not scientific. In other words, if it is not possible to imagine any experiment whose results contradict the predictions of a theory, then that theory is not truly scientific. In my opinion, that criterion is too strict to be invariably true, but it is certainly a good guide. At any rate, the future will have the final say about string theory.

**Stellar Nucleosynthesis**

Above, I dealt with the basic aspects of the structure of matter, but science is not limited to a search for the most fundamental, the smallest structure. It also seeks to understand what is closest to us and most familiar. In that sense, we must mention another of the great achievements of twentieth-century physics: the theoretical reconstruction of the processes —nucleosynthesis—that led to the formation of the atoms we find in nature, those of which we, ourselves, are made. These are questions addressed by nuclear physics, a field naturally related to high-energy physics —though the latter is more "fundamental," as it studies structures more basic than atomic nuclei.

In fact, high-energy physics supplies the basis for nuclear physics, which studies stellar nucleosynthesis. And it was the high-energy physicists who addressed the question of how the particles that constitute atoms emerged from the undifferentiated "soup" of radiation and energy that followed the Big Bang.[25]

As the universe cooled, the constituent parts of this soup underwent a process of differentiation. At a temperature of around 30,000 million degrees Kelvin (which was reached in approximately 0.11 seconds), photons—in other words, light—became independent of matter and were uniformly distributed through space. It was only when the temperature of the universe reached 3,000 degrees Kelvin (almost 14 seconds after the original explosion), that protons and neutrons began joining to form some stable nuclei, basically hydrogen (one proton around which one electron orbits) and helium (a nucleus of two protons and two neutrons with two electrons as "satellites"). Along with photons and neutrinos, those two elements, the lightest ones existing in nature, were the main products of the Big Bang, and they represent approximately 73% (hydrogen) and 25% (helium) of the universe's makeup.[26]

Consequently, we believe that the *Big Bang* generously supplied the universe with hydrogen and helium. But what about the other elements? After all, we know there are many more elements in nature. One does not have to be an expert to know of the existence of oxygen, iron, nitrogen, carbon, lead, sodium, zinc, gold and many other elements. How were they formed?

Even before high-energy physicists began studying primordial nucleosynthesis, there were nuclear physicists in the first half of the twentieth century who addressed the problem of the formation of elements beyond hydrogen and helium. Among them, we must mention Carl Friedrich von Weizsäcker (1912-2007) in Germany, and Hans Bethe (1906-2005) in the United States (Weizsäcker 1938; Bethe and Critchfield 1938; Bethe 1939a, b).[27] Almost at the very beginning of the second half of the twentieth century, George Gamow (1904-1968) and his collaborators, Ralph Alpher (1921-2007) and Robert Herman (1914-1997), took another important step (Alpher, Herman and Gamow 1948). They were followed two decades later by Robert Wagoner (b. 1938), William Fowler (1911-1995) and Fred Hoyle, who used a much more complete set of data on nuclear reactions to explain that in the Universe lithium constitutes a small fraction ($10^{-8}$) of the mass corresponding to hydrogen and helium, while the total of the remaining elements represents a mere $10^{-11}$ (Wagoner, Fowler and Hoyle 1967).[28]

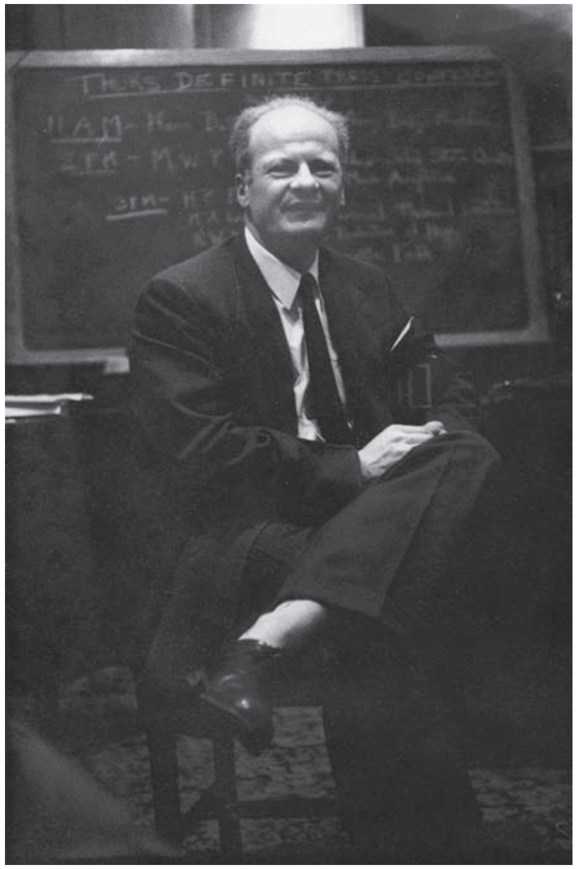
Thanks to their contributions—and those of many others—it has been possible to reconstruct the most important nuclear reactions in stellar nucleosynthesis. One of those reactions is the following: two helium nuclei collide and form an atom of beryllium, an element that occupies fourth place (atomic number) on the periodic table, following hydrogen, helium and lithium (its atomic weight is 9, compared to 1, for hydrogen, 4, for helium, and 6, for lithium). Actually, more than one type of beryllium was formed, and one of these was an isotope with an atomic weight of 8. It was very radioactive and lasted barely one ten-thousand-billionth of a second, after which it disintegrated, producing two helium nuclei again. But if, during that instant of life, the radioactive beryllium collided with a third helium nucleus, it could form a carbon nucleus (atomic number 6, atomic weight, 12), which is stable. And if the temperatures were high enough, then carbon nuclei would combine and disintegrate in very diverse ways, generating elements such as magnesium (atomic number 12), sodium (11), neon (10) and oxygen (8). In turn, two oxygen nuclei could join to generate sulphur and phosphorus. That is how increasingly heavy

25
A magnificent and pioneering exposition is that of Weinberg (1979).

26
I have not had occasion to mention that neutrinos, which were long thought to lack any mass (like photons), actually do have some. That is another of the important findings of physics from the second half of the twentieth century.

27
Bethe received the Nobel Prize for Physics for this work in 1967.

28
Fowler obtained the Nobel Prize for Physics for this work, which he shared with Chandrasekhar. Surprisingly, Hoyle, who initiated much of that work, was left out of the Swedish Academy's choice.



Hans Bethe (1957).

elements are made, up to, and including, iron (26).

Events like this raise another question: how did those elements reach the Earth, given that the place where they were made needed energy and temperatures unavailable on our planet? And if we suppose that there must not be too much difference between our planet and others —except for details such as their makeup and whether or not they have life— then, how did they arrive at any other planet? Some of the elements (up to iron) that were not produced during the universe's first instants were made primarily inside stars. They could then reach outer space in three different ways: through the lost of the mass in old stars in the so-called "giant" phase of stellar evolution; during the relatively frequent stellar explosions that astronomers call "novas;" and in the dramatic and spectacular explosions that take place in the final phase of a star's existence, called a "supernova" (one of these explosions was detected in 1987: the supernova SN1987A. It had actually occurred 170,000 years earlier, but it took the light that long to reach the Earth).

Supernova explosions are what most spread the heavy elements generated by stellar nucleosynthesis through space. It is not too clear why such explosions occur, but it is though that, besides expulsing elements that have accumulated inside them (except for a part that they retain, which turns into very peculiar objects, such as neutron stars); in the explosion itself, they synthesize elements even heavier than iron, such as copper, zinc, rubidium, silver, osmium, uranium, and so on, including the greater part of over a hundred elements that now make up the periodic table and are relatively abundant in star systems such as our Solar System.

It is precisely this abundance of heavy elements that makes it reasonable to assume that the Sun is a second-generation star, formed somewhat less than 5,000 million years ago by the condensation of residues of an earlier star that died in a supernova explosion. The material from such an explosion assembled in a disk of gas and dust with a proto-star in the center. The Sun "lit up" when the central nucleus was compressed so much that the hydrogen atoms melted into each other. The planets we now know as the Solar System—Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune and Pluto (though the latter has recently lost its planetary status) with their satellites, such as the Moon—formed around the Sun, along elliptical bands, following a similar but gravitationally less intense process.

From that perspective, the Earth (formed around 4,500 million years ago), like the other planets, is something similar to a small cosmic junk heap (or cemetery); an accumulation of star remains not important enough to give life to a new star, that is, agglomerates of elements in such small quantities that they were not able to trigger internal thermonuclear reactions like those occurring in stars. But just as life finds its place in garbage dumps, so too, it found its place on our Earth, 12.700 kilometers in diameter and about $6 \cdot 10^{21}$ (6 followed by 21 zeros) tons in weight. We are both witnesses and proof of that phenomenon.

About 7,500 million years from now, the central zone of the Sun, where hydrogen turns into helium, will increase in size as the hydrogen is used up. And when that helium nucleus grows large enough, the Sun will expand, turning into what is called a red giant. It will become so huge that its diameter will reach the Earth's orbit, destroying the planet. But before that happens, the Earth's surface will have become so hot that lead melts, the oceans boil and all traces of life disappear. Thus, the very nuclear processes that gave us life will take it away.

**Beyond the microscopic world**

The physics theories discussed in previous sections are certainly quantum theories, but the world of quantum physics is not limited to them, and it would be a grave error not to mention other advances in this world during the second half of the twentieth century. Given the difficulty of deciding which of them is most important, I have chosen two groups. The first includes developments that have strengthened quantum physics in the face of criticism formulated by Einstein, Podolsky and Rosen, among others. The second has to do with work that has revealed the existence of quantum phenomena at a *macroscopic* scale.

**A non-local theory: quantum entanglement**

The goal of science is to provide theoretical systems that permit the relation of as many natural phenomena as possible, and that have a predictive capacity. That is what we call "explaining nature." Now, "to explain" does not mean finding familiar answers that do not contradict our most common explicatory categories: why should nature conform to such patterns? Above, I mentioned that some of quantum physics' most successful theories quite forcefully show that reality can be profoundly different than our intuition would seem to indicate. If this was already clear when quantum mechanics began in 1925-1926, it is even more so today. Let us consider this, now.

In 1935, Albert Einstein, along with two of his collaborators, Boris Podolsky (1896-1966) and Nathan Rosen (1910-1995), published an article (Einstein, Podolsky and Rosen 1935) arguing that quantum mechanics could not be a complete theory, that new variables had to be added. It would take a long time to explain their arguments, which extend beyond pure physics and enter clearly philosophical areas (they offered a definition of what "physical reality" is). What I can say is that their analysis led John Stewart Bell (1928-1990)—a physicist from Belfast working in CERN's theory division—to demonstrate the existence of a series of relations (inequalities) that could be used in experiments to determine which type of theory was correct. The candidates were, on one hand, a "complete" theory (which would include some "hidden" variables for quantum formulation) that would obey the requirements proposed by Einstein, Podolsky and Rosen in 1935, and on the other, traditional quantum mechanics (Bell 1964, 1966). On the basis of Bell's analysis, John Clauser, Michael Horne, Abner Shimony and Richard Holt (1969) proposed a concrete experiment through which Bell's inequality test could be applied. This experiment was carried out at the Institute of Theoretical and Applied Optics of Orsay, on the outskirts of Paris, by a team led by Alain Aspect (b. 1947). The result (Aspect, Dalibard and Roger 1982) supported quantum mechanics. It might be rare, counterintuitive, have variables that cannot be determined simultaneously, and undermine our traditional idea of what reality is, but it is true. Bell's analysis and the experiment by Aspect's team also brought out a trait of quantum mechanics that, while known, had gone practically unnoticed: its nonlocality. All of the elements of a quantum system are connected, *entangled.* It does not matter that they might be so distant from each other that transmitting a signal to one element about what has happened to another is not even possible at the speed of light, which is the maximum allowed by special relativity. In other words, an element "finds out," and reacts instantly to, what has happened to another, no matter how much distance separates them. Nonlocality—which Einstein always rejected as contrary to common-sense physics—unquestionably poses a problem of compatibility with special relativity, but there is no reason to think that we will be unable, at some future date, to find a generalization of quantum mechanics that solves it. Still, it is certainly not going to be easy.

Moreover, nonlocality offers possibilities that would seem to belong to the realm of science fiction. Science writer Amir Aczel (2004, 20) put it this way: "Through entanglement, the state of a particle can also be 'teleported' a great distance, as happened whenever captain Kirk of the *Star Trek* TV series asked to be beamed up to the *Enterprise.* To be precise, no one has yet been able to teleport a person, but the state of a quantum system has been teleported in a laboratory. And this incredible phenomenon is beginning to be used in cryptography and (could be used) in future quantum computing."

Ideas, and to some degree realities, such as these show that science can even surpass science fiction. At any rate, these consequences of quantum physics are

John Bardeen.

more a matter for the twenty-first century than for the one that recently ended.

### Macroscopic quantum phenomena: The submicroscopic becomes macroscopic

We are accustomed to thinking that the domain of quantum physics is exclusively the ultramicroscopic, that of elemental particles, atoms and radiation. But such is not the case, even though historically those phenomena were responsible for the genesis of quantum theories. The two main manifestations of macroscopic quantum physics are Bose-Einstein condensation and superconductivity.

#### *Bose-Einstein condensates*

From a theoretical standpoint, Bose-Einstein condensates (or condensation) come from an article published by the Hindu physicist, Satyendranath Bose (1894-1974) in 1924. There, he introduced a new statistical method (a way of counting photons) to explain the law of black-body radiation that had led Max Planck to formulate the first notion of quantization in 1900. It was Einstein who recognized and helped publish Bose's work (1924), which he completed with two articles (Einstein 1924, 1925) in which he expanded Bose's conclusions. He pointed out, for example, that condensation could occur in photon gas: "One part 'condenses' and the rest continues to be a perfectly saturated gas" (Einstein 1925). With the term "condensation," Einstein meant that a group of photons acts like a unit, even though there do not appear to be any interactive forces among them. He also predicted that "if the temperature drops enough," the gas will experience "a brutal and accelerated drop in viscosity around a certain temperature." For liquid helium—where there were already indications of such superfluidity—he estimated this temperature to be around 2ºK.

The next advance in Einstein's prediction of the existence of superfluidity did not arrive until 8 January 1938, when the English magazine, *Nature,* published two brief articles—one by Piotr Kapitza (1894-1984) and the other by Jack Allen (1908-2001) and Don Misener (1911-1996). Kapitza had been a senior professor at the Cavendish Laboratory in Cambridge until 1934, when he returned to Russia on vacation. Stalin refused to let him leave, and he became director of the Physics Problems Institute in Moscow. Allen and Misener were two young Canadian physicists working in Cambridge at the Mond Laboratory sponsored by the Royal Society. Those articles (Kapitza 1938; Allen and Misener 1938) announced that, below 2.18ºK, liquid helium flowed with almost no viscosity-induced resistance. But the theoretical demonstration that this phenomenon constituted evidence of superfluidity came from Fritz London (1900-1954) and Laszlo Tisza (b. 1907).[29]

Of course, this was the old idea put forth by Einstein in 1924, which had drawn very little attention at the time. Now, it was more developed and had been applied to systems very different than the ideal gasses considered by the father of relativity.

It should be pointed out, however, that despite the importance we now give to those 1938 discoveries as macroscopic examples of quantum behavior, that aspect was less evident at the time. In order to better understand the relation between Bose-Einstein condensation and macroscopic aspects of quantum physics, it was necessary to deal with atoms, producing "superatoms," that is, groups of atoms that behave like a unit and are perceptible macroscopically. That achievement arrived much later, in 1995, when Eric Cornell (b. 1961) and Carl Wieman (b. 1951), two physicists in Colorado, produced a superatom of rubidium. A few months later, Wolfgang Ketterle (b. 1957) did the same with sodium at MIT (all three shared the Nobel Prize for Physics in 2001). This is how the first two described their work (Cornell and Wieman 2003, 82):

> In June 1995, our research group at the Joint Institute for Laboratory Astrophysics (JILA) in Boulder created a tiny, but marvellous drop. By cooling 2000 rubidium atoms to a temperature less than a hundred thousand-millionths of a degree above absolute zero (100 thousand-millionths of a degree Kelvin), we got those atoms to lose their individual identities and behave like a single "superatom." The physical properties of each one, their movements, for example, became identical. The Bose-Einstein condensate, the first to be observed in a gas, is materially analogous to a laser, except that, in a condensate, it is atoms, not photons, that dance in unison.[30]

Further on, they add (Cornell and Wiemann 2003, 82-84):

> We rarely see the effects of quantum mechanics reflected in the behavior of a macroscopic amount of matter. The incoherent contributions of the immense number of particles in any portion of matter obscure the wavelike nature of quantum mechanics; we can only infer its effects. But in a Bose condensate, the wavelike nature of every atom is in phase with the rest in a precise manner. Quantum-mechanical waves run through the entire sample and are plainly visible. The submicroscopic becomes macroscopic.
>
> The creation of Bose-Einstein condensates has shed light on old paradoxes of quantum mechanics. For example, if two or more atoms are in a single quantum-mechanical state, which is what happens with a condensate, it will be impossible to tell them apart, no matter how they are measured. The two atoms will occupy the same volume of space, move at the same speed, disperse light of the same color, and so on.
>
> In our experience, based on the constant treatment of matter at normal temperatures, nothing can help us understand this paradox. For one reason: at the normal temperatures and scales of magnitude in which we generally work, it is possible to describe the position and movement of each and every one

**29**
London (1938), Tisza (1938).

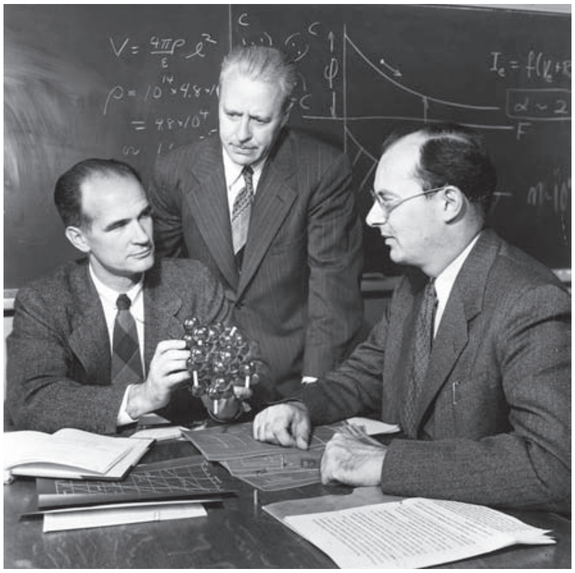
**30**
The temperature called absolute zero (0ºK) corresponds to -273.15ºC. At that temperature, molecules do not move.

of the objects in a group… At extremely low temperatures, or small scales of magnitude, classical mechanics no longer holds… We cannot know the exact position of each atom, and it is better to imagine them like imprecise stains. The stain is a package of waves, the region of space where one can expect that atom to be. As the group of atoms cools, the size of such wave packages increases. As long as each atom is spatially separate from the others, it will be possible, at least in principle, to tell them apart. But when the temperature gets low enough, the wave packages of neighbouring atoms overlap. Then, those atoms 'Bose-condense' in the lowest possible energy state and the wave packages merge to form a single macroscopic package. The atoms suffer a quantum identity crisis: we can no longer tell them apart.

### *Superconductivity*

Superconductivity is another of the physical phenomena in which quantization appears on a macroscopic scale. The phenomenon itself was discovered long ago, in 1911, by Heike Kamerlingh Onnes (1852-1926), a Dutch physicist and the world's leading expert on low temperatures. In his Leiden laboratory, he discovered that cooling mercury to 4°K entirely annulled its resistance to the passage of electric current (Kamerlingh Onnes 1911). Once the current began, it would continue indefinitely even if no power difference was applied. It was later discovered that other metals and compounds also became superconductors at temperatures near absolute zero. Of course experimental evidence is one thing and a theory capable of explaining it is quite another. It was not until 1957 that US scientists, John Bardeen (1908-1991), Leon Cooper (b. 1930) and John Robert Schrieffer (b. 1931) arrived at such a theory (known as the BCS theory, for the initials of their last names).[31]

Its explanation (Bardeen, Cooper and Schrieffer 1957) is that below a certain temperature the electrons that transport electric current in a superconductive element or compound form pairs that act as bosons; that is, particles like photons that are not subject to certain quantum requirements. Cooper (1956) had reached this supposition before, which is why they are now called "Cooper pairs." This grouping occurs at very low temperatures and is due to the interaction between electrons and the network of metal atoms in the superconductive compound. Once the pairs are formed, they march like a harmonious army of bosons, ignoring atomic impediments. That is how this quantum effect is manifested on a macroscopic scale.



The inventors of the transistor: W. Shockley, W. Brattain and J. Bardeen.

The BCS theory was a formidable success for quantum physics, but it is not totally satisfactory, as was revealed by its incapacity to predict the existence of superconductivity in ceramic materials at much higher temperatures than had previously been employed. It was in 1986, at the IBM laboratories in Zurich, that Georg Bednorz (b. 1950) and Alexander Müller (b. 1927) discovered that an oxide of lanthanum, barium and copper was superconductor at temperatures as high as 35°K (which is certainly not high by everyday human standards, of course).[32] The following year, Paul Chu (1987) raised the scale of superconductor temperatures when he discovered an oxide of yttrium, barium and copper that became superconductor at 93°K, a temperature that can be reached simply by bathing that oxide in liquid nitrogen—unlike helium, the latter is abundant and cheap. Since then, the number of such materials and the temperature at which they become superconductors has increased continually.

Bednorz and Müller's discovery (1986),[33] for which they received the Nobel Prize for Physics in 1987, offers new perspectives, not only for physics, but even more so, for technology. Materials that are superconductors at temperatures that can be achieved in everyday settings (that is, outside the laboratory) might revolutionize our lives some day.

### Quantum devices: transistors, chips, masers and lasers

Our previous observation about the relevance of quantum physics to technology extends far beyond superconductivity. Superconductors may someday change our lives, but there is not doubt at all that other materials—semiconductors—have already done so.[34] The first major use of semiconductors arrived after John Bardeen, William Shockley (1910-1989) and Walter Brattain (1902-1987) invented the transistor while working in Bell Laboratories' department of solid-state physics.[35] In 1956, the three were awarded the Nobel Prize for Physics—the first of two for Bardeen (as we saw above, he received the second for superconductivity).

**31**
The three shared the Nobel Prize for Physics in 1972.

**32**
Until then, an alloy of niobium and germanium had the highest known temperature for superconductivity (23°K).

**33**
See also, Müller and Bednorz (1987).

**34**
As its name indicates —although it is not an especially illustrative definition— a semiconductor is a material that conducts electricity to a degree that falls somewhere between the conductivity of a metal and that of an insulating material. The conductivity of semiconductors can normally be improved by adding small impurities, or through other factors. Silicon, for example, is a very poor conductor at low temperatures, but its conductivity increases with the application of heat, light or a difference of potential. That is why silicon is used in transistors, rectifiers and integrated circuits.

**35**
See Shockley (1947, 1948) and Bardeen and Brattain (1948, 1949).


Aleksandr Prokhorov and Nikolai Basov showing Charles Townes (in the middle) their laboratory in Moscow (1965).

A transistor is an electronic device made from a semiconductor material that can regulate a current passing through it. It can also act as an amplifier or as a photoelectric cell. Compared to the vacuum tubes that preceded them, transistors need only tiny amounts of energy to function. They are also more stable and compact, work instantly, and last longer.

Transistors were followed by integrated circuits, tiny and very thin devices on which the digital world is based. Integrated circuits are made with a substrate (usually silicon), on which are deposited fine films of materials that alternately conduct or insulate electricity. Assembled according to patterns drawn up beforehand, these films act as transistors (each integrated circuit can hold millions of transistors) that function like switches, controlling the flow of electricity through the circuit, or *chip.*

As part of these chips, transistors carry out basic functions in the billions and billions of microprocessors installed to control car engines, cell phones, missiles, satellites, gas networks, microwave ovens, computers and compact disc players. They have literally changed the way we communicate with each other, relate to money, listen to music, watch television, drive cars, wash clothes and cook.

Until the advent of transistors and integrated circuits, calculating machines were gigantic masses of electronic components. During World War II, one of the first electronic calculators was built: the Electronic Numerical Integrator And Computer (ENIAC). It had 17,000 vacuum tubes linked by miles of cable. It weighted 30 tons and consumed 174 kilowatts of electricity. We can consider it the paradigm of the first generation of computers. The second generation arrived in the nineteen fifties, with the advent of transistors. The first computer to emerge from solid-state physics —a branch of quantum physics—was called TRADIC (*Transistor Digital Computer*). Bell Laboratories built it in 1954 for use by the United States Air Force. It used 700 transistors and was as fast as ENIAC. The third generation of computers arrived in the late nineteen sixties, with the advent of integrated circuits. It was followed by a fourth generation, which used microprocessors and refined programming languages. There is now talk of quantum computers. Rather than *bits,* which have defined values of 0 or 1, they will use *qubits,* that is, *quantum bits,* which can take values between 0 and 1, just as quantum states can be the superposition of photons with horizontal and vertical polarizations. But if quantum computers are ever successfully made, they will probably belong to the second half of the twenty-first century.

Thanks to all these advances, we are now immersed in a world full of computers that carry out all kinds of functions with extraordinary speed and dependability. Without them, our lives would be very different. And it is very important to emphasize that none of this would have happened without the results obtained in one branch of quantum physics: solid-state physics (also known as condensed-matter physics).

Another positive aspect of this branch of physics is the way in which it has generated closer relations between science and society. In 1955, for example, Shockley, one of the transistor's inventors, left Bell Laboratores to found his own company in the Bay Area of San Francisco. The Shockley Semiconductor Laboratory opened for business in February 1956 and recruited an excellent group of professionals. Though not especially successful, it was the seed that led to the development of numerous high-technology companies in a part of California that came to be called Silicon Valley.

Science and technology are allied in this techo-scientific world in such an intimate way—so to speak—that we cannot really say that fundamental innovation occurs only in scientific enclaves and business in technological ones. In that sense, let us recall that the fundamental techniques (the "planar" process) for manufacturing chips were conceived in 1957 by Jean Hoerni (1924-1997) at the Fairchild Semiconductors company. The first integrated circuit was built at the same place by Robert N. Noyce (927-1990) in 1958. Ten years later (1968), Noyce left Fairchild to found Intel along with Gordon Moore (b. 1929). There, he and Ted Hoff (b. 1937) directed the invention of the microprocessor, which launched a new revolution.

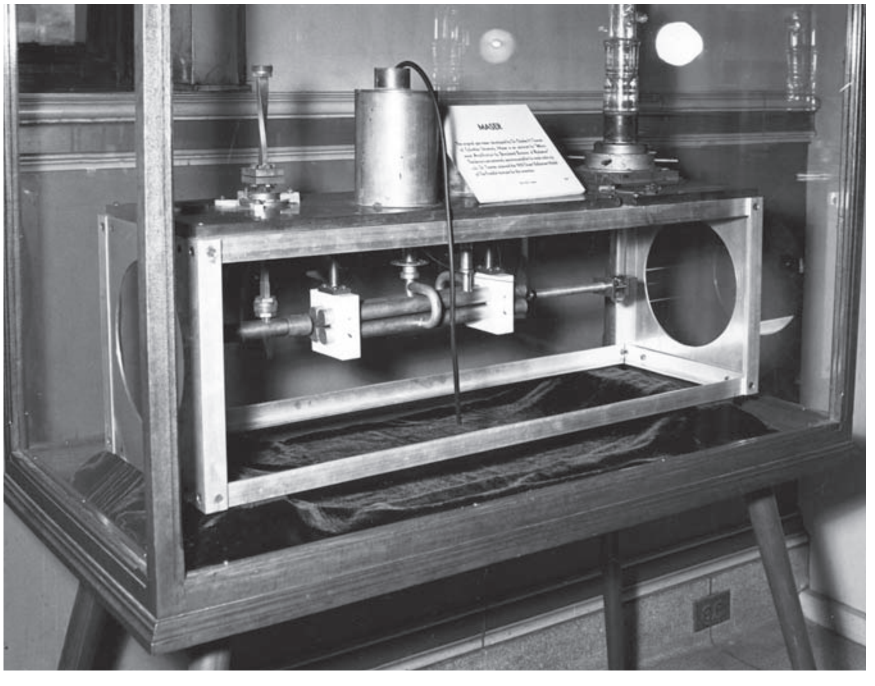
In that same sense, I should add that the development of electronic microprocessors has stimulated—and simultaneously benefited from—what is called "nanotechnology." The latter seeks to control and manipulate matter at a scale of between one and one-hundred nanometers (one nanometer equals $10^{-9}$ meters). Nanotechnology is more a technique (or group of techniques) than a science, but it can be expected to lead to developments (to a degree, it already is) that contribute not only to our material possibilities, but also to the most basic scientific knowledge.

### *Masers and lasers*

I have yet to mention the maser and the laser although chronologically they are earlier than some of the advances mentioned above. Those terms are acronyms for **m**icrowave **a**mplification by **s**timulated **e**mission of **r**adiation and **l**ight **a**mplification by **s**timulated **e**mission of **r**adiation, respectively.

From a theoretical standpoint, these instruments or procedures for amplifying waves of the same frequency (wavelength) are explained in two articles by Einstein (1916a, b). Their practical development, however, with all the new theoretical and experimental elements involved, did not arrive until the nineteen fifties. This achievement was carried out, independently, by physicists from the Lebedev Physics Institute in Moscow—Aleksandr M. Prokhorov (1916-2002) and Nicolai G. Basov (1922-2001)—and the United States scientist, Charles Townes (b. 1915), at Columbia University in New York (the three shared the Nobel Prize for Physics in 1964).

In May 1952, at a conference on radio-spectroscopy at the USSR Academy of the Sciences, Basov and Prokhorov described the maser principle, although they did not publish anything until two years later (Basov and Prokhorov 1954). They not only described the principle; Basov even built one as part of his doctoral dissertation, just a few months after Townes had done so.

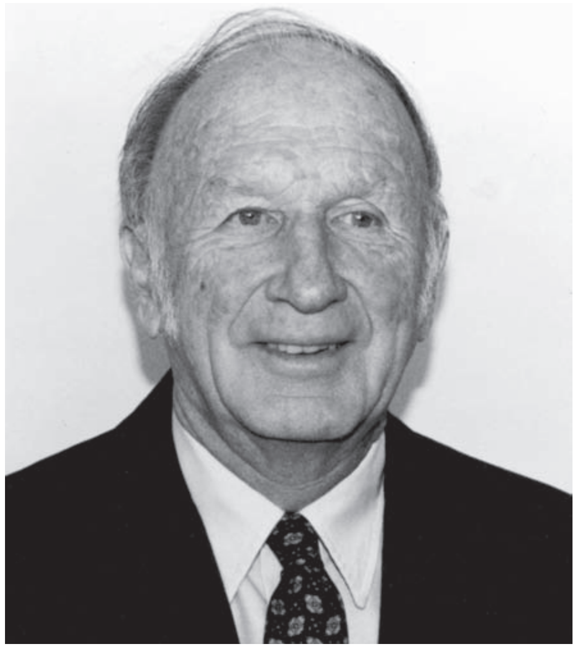


The first maser built by Townes and his collaborators, exhibited at the Franklin Institute (Philadelphia).

It is worth telling how Townes arrived independently at the same idea of a maser, as it shows how very diverse the elements making up a process of scientific discovery can actually be. After working at Bell Laboratories between 1939 and 1947, where he carried out research on radar, among other things, Townes moved to the Columbia University Radiation Laboratory, created during World War II to develop radars, instruments essential to the war effort. As with other institutions, this one continued to receive military funds after the war, and it dedicated 80% of its funding to the development of tubes able to generate microwaves. In the spring of 1950, Townes organized an advisory committee at Columbia to consider new ways of generating microwaves shorter than one centimeter for the Naval Research Office. After thinking about this question for a year, he was about to attend one of the committee sessions when he had an idea about a new way to approach it. That new idea was the maser. When, in 1954, Townes, a young doctor named Herbert J. Zeiger and a doctoral candidate named James P. Gordon managed to make the idea work, using a gas of ammonia molecules (Gordon, Zeiger and Townes 1954), it turned out that the oscillations produced by the maser were characterized not only by their high frequency and power, but also by their uniformity. In fact, the maser produced a coherent emission of microwaves; that is, highly concentrated microwaves with just one wavelength.

Even before the proliferation of masers, some physicists began attempting to apply that idea to other wavelengths. Among them were Townes himself (as well as Basov and Prokhorov), who began work in 1957 to move from microwaves to visible light. On this project, he collaborated with his brother-in-law, Arthur Schawlow (1921-1999), a physicist from Bell Laboratories. Together, they wrote a basic article explaining how a laser could be built, although they still called it an "optical maser" (Schawlow and Townes 1958). We might add that Bell Laboratories' lawyers thought that the idea of a laser was not sufficiently interesting to bother patenting it. They only did so at the insistence of the two scientists (Schawlow and Townes 1960).

From that moment, the race was on to build a laser. While later history has not always been sufficiently clear on this matter, the first successful one was built by Theodore Maiman (1927-2007) at Hughes Research Laboratories in Malibu, California. He managed to make a ruby laser function on 16 May 1960. Maiman sent a manuscript of his findings to the newly-established



Edward Lorenz.

magazine, *Physical Review Letters,* but its editor, Samuel Goudsmit, rejected it as "just another maser article." Maiman then turned to *Nature,* which published the results of his work on 6 August 1960 (Maiman 1960). Soon thereafter, Schawlow announced in *Physical Review Letters* that, along with five collaborators (Collins, Nelson, Schawlow, Bond, Garret and Kaiser 1960), he had gotten another laser to work. It was also a ruby laser, but considerably larger and more powerful than Maiman's. In light of all this, there is some question as to why it was Schawlow who received the Nobel Prize in 1981 (he shared it with Nicolaas Bloembergen and Kai Siegbahn), although, formally, it was for his and Bloembergen's contributions to laser spectroscopy.[36] Masers, and especially lasers (another "child" of quantum physics that makes quantum effects visible on a macroscopic scale), are instruments well known to the public, especially in certain applications (in detached retina operations, for example, which are carried out with lasers). But other uses of considerable scientific significance are not as well known. One of these is spectroscopy. The laser's high-energy monochromatic radiation makes it possible to precisely aim it at specific atomic levels; the results obtained offer considerable information on the properties of molecules, whose structure makes them much more difficult to study than atoms.

## A non-linear world

The discoveries and developments discussed above are probably the most outstanding from, let us say, a fundamental perspective. But they do not include a group of advances that are opening new and surprising windows in science's understanding of nature. We are referring to non-linear phenomena; that is, those governed by laws involving equations with quadratic terms.[37]

Looking back at the history of physics, we can see that, until well into the twentieth century, most of the most basic theories were either essentially linear (Newton's theory of universal gravitation or Maxwell's electrodynamics, for example), or they could be used by non-linear systems, as occurs with Newtonian mechanics, but have been applied mainly to linear systems, even when it is absolutely clear that this implies a mere approximation of reality. The most straightforward example in this sense is the simple flat pendulum. Any high-school student, not to mention physics students, knows that the differential equation used to describe the movement of this type of pendulum is:

$$d^2\theta(t)/dt^2 + (g/l)\theta(t) = 0$$

where $\theta$ represents the angular movement of the pendulum, $l$ his length, $g$ the acceleration of gravity and $t$, time. Now, when we deduce (it is not a difficult problem) the equation that the motion of a simple flat pendulum should meet, it turns out that it is not the one shown above, but instead:

$$d^2\theta(t)/dt^2 + (g/l)\sin\theta(t) = 0$$

which is obviously not linear, since $\sin(\theta_1+\theta_2) \neq \sin\theta_1+\sin\theta_2$. In order to avoid this circumstance, which enormously complicates the problem's resolution, it is generally limited to small oscillations, that is, small angles, which make it possible to use Taylor's serial development of the sine function:

$$\sin\theta \approx \theta - \theta^3/6 + \ldots$$

keeping only the first term in order to obtain the first (linear) of the two equations shown above.

This very straightforward example shows us that so-called "classical physics," is not free of non-linear systems, but it tries to avoid them because of the mathematical difficulty they entail. In fact, there are no general systematic mathematical methods for dealing with non-linear equations. Of course many problems associated with non-linear systems (laws) have long been known, especially those from the field of hydrodynamics, the physics of fluids. Thus, for example, when water flows slowly through a tube, its movement (called *laminar*), is regular and predictable, but when the speed involved is greater, then the water's movement becomes *turbulent,* making whirlpools that follow irregular and apparently erratic trajectories that are typical characteristics of non-linear behavior. Aerodynamics is, of course, another

**36**
Siegbahn received it for his contributions to the development of high-resolution electronic spectroscopy.

**37**
Symbolically, it could be said that the expression of linearity is the equation, A + A = 2A, while in the world of non-linearity, the universe in which the meeting of two beings generates, *creates,* new properties, A + A ≠ 2A. In a rigorous sense, that is, a mathematical one, the essential difference between a linear system and a non-linear one is that, while two solutions of a linear system can be added to create a new solution to the initial system ("the superposition principle") that is not true in the case of non-linear systems.

example of non-linear domains, as everyone involved in aircraft design knows so well.[38]

The wealth of non-linear systems is extraordinary; especially the wealth and novelties they offer with respect to linear ones. From a mathematical perspective (which frequently correlates with real domains), non-linear equations/systems can describe transitions from regular to apparently arbitrary behavior; localized pulses that produce rapidly decaying perturbations in linear systems maintain their individuality in non-linear ones. That is, they lead to localized and highly coherent structures. This has obvious implications in the apparition and maintenance of structures related to life (from cells and multicellular organisms right up to, strange as it may sound, mental thoughts). One of the first known examples of this sort of behavior are the famous "solitons," solutions to non-linear equations in partial derivates called Korteweg-de Vries (or KdV equations), developed in 1895 as an approximate description of water waves moving through a narrow, shallow canal. But it was not until 1965 that Norman Zabusky and Martin Kruskal found a solution to this equation that represents one of the purest forms of coherent structures in motion (Zabusky and Kruskal 1965): the soliton, a solitary wave that moves with constant velocity. Far from being mathematical entelechies, solitons actually appear in nature: for example, in surface waves (that move essentially in the same direction) observed in the Andaman sea that separates the isles of Andaman and Nicobar in the Malaysian peninsula.

### Chaos

An especially important case of non-linear systems is chaos systems. A system is characterized as chaotic when the solutions of equations that represent it are extremely sensitive to initial conditions. If those conditions change even slightly, the solution (the trajectory followed by the object described by the solution) will be radically modified, following a completely different path. This is the contrary of the non-chaotic systems that physics has offered us for centuries, in which small changes in the opening conditions do not substantially alter the solution. Extreme variability in the face of apparently insignificant changes in their starting points and conditions are what lead these systems to be called *chaotic*. But that does not mean that they are not subject to laws that can be expressed mathematically. We should emphasize that chaotic systems are described by laws codified as mathematical expressions, and these are actually similar to the ones that make up the universe of linear laws from Newton's dynamics.

Weather is one of the large-scale examples of chaotic systems; in fact, it was weather-research that revealed what chaos really is; small perturbations in the atmosphere can cause enormous climate changes. This was discovered by the United States theoretical meteorologist, Edward Norton Lorenz (1938-2008). In his weather research, he developed simple mathematical models and explored their properties with the help of computers. But, in 1960, he found that something strange occurred when he repeated previous calculations. Here is how he, himself, reconstructed the events and his reaction in the book, *The Essence of Chaos* (Lorenz 1995, 137-139), which he wrote years later:

> At one point, I decided to repeat some of the calculations in order to examine what was happening in greater detail. I stopped the computer, typed in a line of numbers that had come out of the printer a little earlier, and started it back up. I went to the lobby to have a cup of coffee and came back an hour later, during which time the computer had simulated about two months of weather. The numbers coming out of the printer had nothing to do with the previous ones. I immediately though one of the tubes had deteriorated, or that the computer had some other sort of breakdown, which was not infrequent, but before I called the technicians, I decided to find out where the problem was, knowing that that would speed up the repairs. Instead of a sudden interruption, I found that the new values repeated the previous ones at first, but soon began to differ by one or more units in the final decimal, then in the previous one, and then the one before that. In fact, the differences doubled in size more-or-less constantly every four days until any resemblance to the original figures disappeared at some point during the second month. That was enough for me to understand what was going on: the numbers I had typed into the computer were not exactly the original ones. They were rounded versions I had first given to the printer. The initial errors caused by rounding out the values were the cause: they constantly grew until they controlled the solution. Nowadays, we would call this chaos.

What Lorenz observed empirically with the help of his computer, is that there are systems that can exhibit unpredictable behavior (which does not mean "not subject to laws") in which small differences in a single variable have profound effects on the system's later history. Weather is such a chaotic system, which is why it is so hard to predict, so *unpredictable,* as we often put it. The article in which he presented his results (Lorenz 1963) is one of the great achievements of twentieth-century physics, although few non-meteorological scientists noticed it at the time. This was to change radically over the following decades. That change of attitude had much to do with a famous sentence that Lorenz included in a lecture he gave on December 1972 at a session of the annual meeting of the American Association for the advancement of Science: "a butterfly flapping its wings in Brazil can produce a tornado in Texas."[39]

It is becoming increasingly clear that chaotic phenomena are abundant in nature. We already see them at work in the fields of economics, aerodynamics, population biology (for example, in some "predator-prey"

**38**
Of all the great theories of classical physics, the most intrinsically non-linear is the general theory of relativity (the field equations of this theory of gravitational interaction are non-linear).

**39**
That lecture was not published in its time; it is included in Lorenz (1995, 185-188).

models), thermodynamics, chemistry and, of course, in the world of biomedicine (one example is certain heart problems). It seems that they can also show up in the apparently stable movements of the planets.

The consequences of the discovery of chaos—and, apparently, its ubiquity—for our view of the world are incalculable. The world is not how we thought it was, not only in the atomic domains described by quantum physics, but also in those ruled by the more "classic" Newtonian laws. They are Newtonian, of course, but unlike those used by the great Isaac Newton and all his followers, which were *linear*, these are *non-linear*. Nature is not linear, it is non-linear, but not all non-linear systems are chaotic, although the reverse is certainly true, for all chaotic systems are non-linear. Thus, the world is more complicated to explain and we cannot predict everything that is going to happen in the old Newtonian fashion. But why should nature be so "straightforward," anyway? What is marvelous is that we are able to discover such behavior and its underlying mathematical laws.

I could, and probably should have mentioned other developments that occurred or began in the second half of the twentieth century, including non-equilibrium thermodynamics, one of whose central elements are gradients or differences of magnitudes such as temperature or pressure. Their importance lies in the fact that those gradients are the true source of life, which has to struggle against nature's tendency to reduce gradients, that is, energy's tendency to dissipate according to the second law of thermodynamics (expressed by the much-used term, "entropy"). For living beings, thermodynamic equilibrium is equivalent to death, so understanding life necessarily requires understanding non-equilibrium thermodynamics, rather than just the equilibrium thermodynamics that predominated throughout most of the nineteenth and twentieth centuries. The complexity of life and other systems in nature is a natural result of the tendency to reduce gradients: wherever circumstances allow, cyclical organizations arise to dissipate entropy in the form of heat. It could even be argued—and this is a new, not especially Darwinian way of understanding evolution—that, inasmuch as access to gradients increases as perceptual capacities improve, then increasing intelligence is an evolutionary tendency that selectively favors prosperity by those who exploit dwindling resources without exhausting them. This branch of physics (and chemistry) experienced considerable growth during the second half of the twentieth century, making it a magnificent example of other advances in the field of physics that took place during that period, and possibly should have been addressed in the present text, even though they are "less fundamental" in some ways. But I have already written too much here, so it is time to stop.

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