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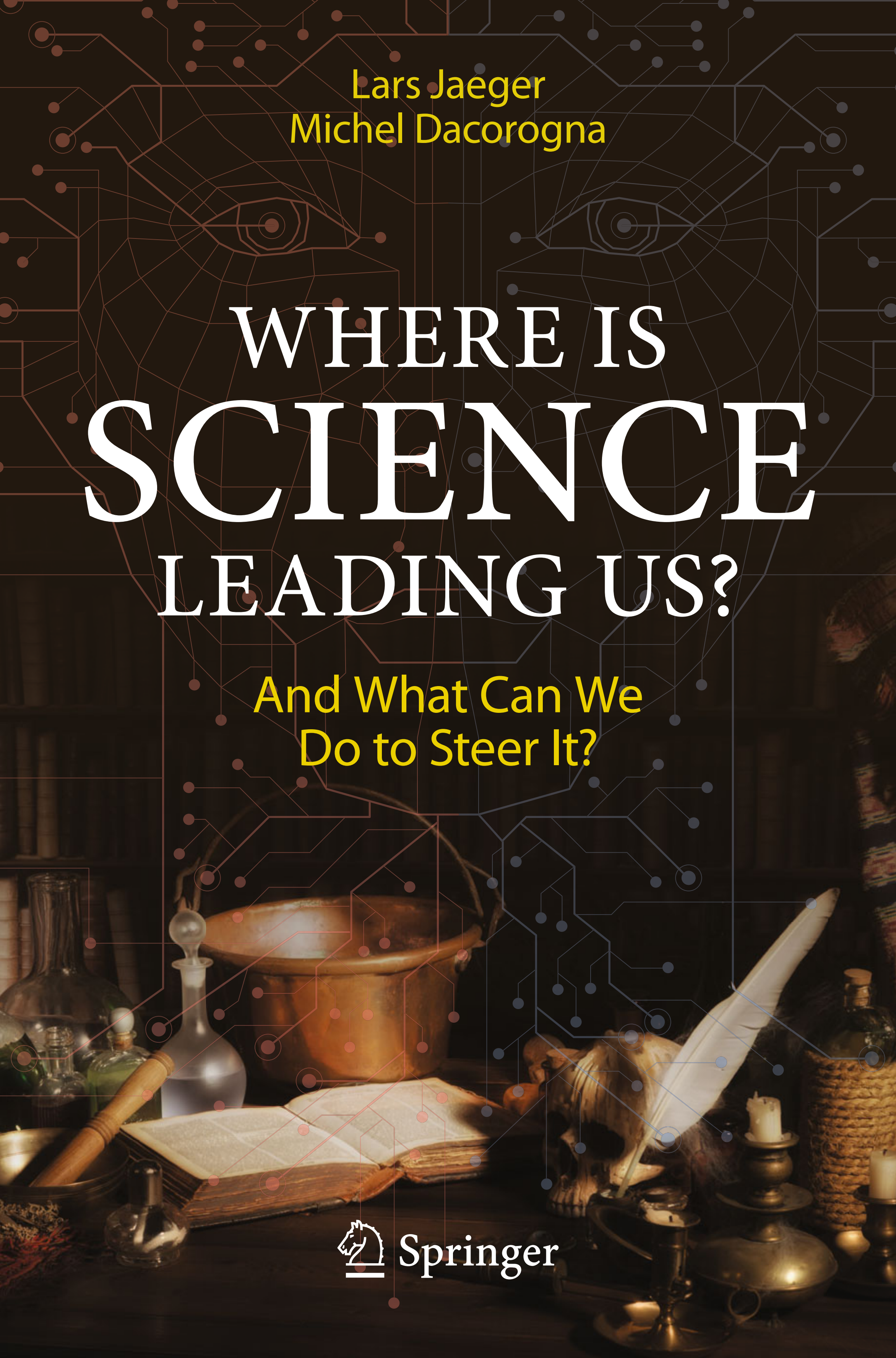
# WHERE IS SCIENCE LEADING US?

## And What Can We Do to Steer It?



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Cover illustration: The cover images illustrate the fact that sometime modern science is playing the alchemist

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# 1

# Introduction

In around eighty years, from the end of the nineteenth to the middle of the twentieth century, science made advances that led to the greatest revolution in human thoughts of all time. These upheavals were more drastic than the revolutions of the Renaissance and the Enlightenment and happened roughly during the lifetime of an individual person. Moreover, these advances occurred after a period during which all sciences, including mathematics, had faced the greatest crises in their respective histories, crises that frustrated scientists like never before (and even led to a suicide of one scientific leader). The work of a whole series of scientific geniuses of breath-taking creativity then led all sciences out of their crises in ways that were as exciting as they were bizarre. In this process of completely restructuring of all its disciplines, science itself not infrequently reached the limits of reason and coherence, as these developments also called into question principles established over 2000 years ago in Western philosophy.[1]

Furthermore, during this process science experienced a significant change of its very foundation which is of equally important philosophical significance. The scientists were forced to drastically change a paradigm which their believes had been fundamentally based on until then: They had to abandon the idea that their job consists of seeking *eternal truths*, a scientific belief

[1] For more details about the scientific revolutions between 1870 and 1950, see: Lars Jaeger, *The Stumbling Progress of 20th Century Science - How Crises and Great Minds Have Shaped Our Modern World*, Springer (2023).



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that had been strongly rooted in Western philosophy (and often even in religions). Science today has to be content with *relative truths*, i.e. truths that can change, once there exists enough empirical evidences for a better truth, without losing its ability to change our reality, quite the contrary.

As of 1960 all these developments strongly shaped human societies. As exciting and influential for the character of our societies the revolutions from 1870 to around 1950 were, the developments of sciences and – especially – of technological applications based on them profoundly changed the human society itself in the years after 1950 to today. Responsible for this were the following three developments:

- The *number of scientists* worldwide increased exponentially, and has grown by more than twenty times since then. Today, it stands at around nine million people.
- The *number of scientific articles* grew also extremely fast. In the same period, it has doubled every 9 years, i.e. a growth factor of about 250 times from 1950 to today.[2] There is a joke among physicists that says one thing can eventually grow faster than the speed of light and thus break Einstein's law: the list of research articles published by all these scientists, as the number published has become the sole measure of scientific success (the ironic answer of other physicists to this is that this event will not break Einstein's laws as no information is passed along any longer).
- Also, the pure spectrum of scientific areas (i.e. universities, public and private research institutes, etc.) grew equally exponentially to host all those scientists.

A consequence of this "explosion" of scientific research, the pure number of individuals working in this field since 1950, and their respective scientific articles published is that, compared to the 80-year phase before, not any individual scientist today is as well-known as Albert Einstein, Max Planck, Charles Darwin, Louis Pasteur or Robert Koch in the revolutionary period between 1870 and 1950. As of the 1960s even the greatest scientists became more and more experts in specific fields due to the equally immense growth of special scientific areas. The time of universal scientific geniuses is now over. This explains why today the names of Nobel Prize winners rarely ever remain known in the broader public's memory a few days past the award announcement. This makes the writing of an entertaining book about this period to

[2] For more details, see: Lutz Bornmann, Ruediger Mutz, *Growth rates of modern science: A bibliometric analysis based on the number of publications and cited references*, Journal of the Association for Information Science and Technology, 65, 11 (2015).

non-scientists more difficult than covering the period before. Furthermore, the different sciences today are much more connected than they were before, so they can barely be discussed separately. Accordingly, we refer with respective remarks to other chapters and sometimes even discuss the same topic from two different perspectives.

Nevertheless, it was the processes in (natural) sciences and the technologies they made possible that created our modern human life today beyond what society experienced with the first industrial revolution. Besides scientists getting deeper and deeper into areas such as particle (quantum) physics, functions of individual genes, or understanding more deeply the human brain, the *real shaping* entities that have formed our modern society and are continuing to do so - ever more dramatically and rapidly than ever before - are the technological application thereof. In this process, as we will see in this book, the usual distinction between science and technology blurs and it becomes difficult to separate them.

This book aims to provide an overview of the scientific progress since 1960. However, it will also discuss how technologies can in the next 30 years shape the *future life of humans and human societies* more than it has ever done in the past. We thereby assess some of the main problems today as well as in the near future (like the climate change, probable loss of personal data protection, potential genetic change of us, virtual reality) and opportunities (like addressing the climate change[3]). For this we also introduce and assess a philosophical context which is almost deserted by modern science. This combination of the historical context after the scientific revolution of the first half of the 20th until today, a discussion of the possible implications for our societies in the next 30 years, and providing a philosophical perspective on this is, as far as we know, the first assessment of this kind. The main question is hereby: What are the dramatic changes today and how should (and can) we address and deal with them from a social and society perspective?

In the last 250 years, women and men have already profoundly changed their environment and living conditions through science and new technologies from it (we refer to the development in the nineteenth century already as the "Industrial Revolution"). Yet the biological and psycho-spiritual foundation of mankind has so far remained largely untouched. But now, for the first time in history, the human being itself is becoming an object of technological developments. In the dynamics of scientific as well as technological progress, we are at a point where biotechnology, genetic engineering, quantum technology, neurotechnology and their interactions can transform the human

[3] For discussing climate change issues and possible paths towards addressing it: Lars Jaeger, *Ways Out of the Climate Catastrophe - Ingredients for a Sustainable Energy and Climate Policy*, Springer (2022).

being and human civilisation themselves in hitherto unimaginable ways, and this in only a fraction of a human life. What awaits us is not just another industrial revolution, of which there have already been a few, but we must prepare ourselves for the first *revolutionem humanam*, a revolution of being human in itself, an "inversion" of what makes us human in our innermost being and what we define ourselves as.

The technological developments could potentially be anything from just continuing in making us richer and richer and living better and better (unlikely) to changing or even reprograming humans themselves (much more likely). Developments will with highest probability be much more society shaping than what we have seen in the past. For this reason, it is not only the scientists and technologists who should shape the content of their doing. They rather should be joined - next to by economists - by politicians, social workers, and many other people co-deciding on sciences' technological effort - not on the fundamental research itself, but on the technologies grown out of it. For this, also the amount of public and private money that flows into scientific research requires that a - better than today - control of scientists' doing with respect to technological developments must be installed.

In fact, even if they have been quite distant from science over the past 85 years, in the future, philosophers in particular should be asked to critically assess the development of science and technologies given where science and especially technologies have developed towards. However, a philosophical discussion of science is not new: In the history of modern science since its early beginnings with Galilei, Kepler and Newton philosophy has always played a key role. Yet, it was mostly concentrated on what philosophers call *epistemology*, i.e. in what sense scientific results are influenced by our own given capability to observe and judge on natural processes. *Today*, a more significant philosophical field which needs to be applied to technologies is *ethics*, i.e. the questions what we can do without breaking given values. But what are the appropriate ethical values? How to perform scientific research ethically is exactly a sort of question that is philosophical and not scientific. Possibly the use of nuclear bombs by the US against Japan in late WW II can be seen as the first outcome of science having become ethically critical (with an outcome not so highly ethical).

In all this discussion, we need to make a highly important distinction between two types of science: the leading core scientific models on the one side and current scientific research on the other. The first is a body of knowledge upon which (almost) all scientists agree and there is currently no serious doubt about it. Classic examples of this are the facts that the Earth is round, that all life has gone through an evolution or that physics in the magnitudes of atoms is structurally different than in the range of our experiences. The second aims at answering a body of currently open questions raised within science or from new societal problems like climate change or pandemics. Regarding those, there is a lot of doubts, critics and controversies among scientists. Taking the second for the first is unfortunately a widespread confusion in non-scientific circles. Thus, people often challenge accepted knowledge like that humans are genetically quite close to monkeys or that quantum physics matches experiments very, very well, as they do not match with our daily perceptions. They therefore argue that science is relative. To state it very clearly: While our daily research is relative and questionable among the various scientists, the body of collected scientific knowledge is not. These two areas must be clearly separated and treated differently! (as we will discuss in more detail starting in Chap. 14).

An important fact of today's technological progress is: While in the past, there were at given times *single* technologies that evolved over periods of several generations, today, in contrast, there exists *an entire list of key technologies that develop at the same time* that will each have a similarly massive impact on our lives as the technological revolutions in the past (most likely even higher ones). Their list is as long and fascinating as it is frightening: Conversions occur from more than a dozen different directions with each one providing a fundamental change for humanity itself. And any of them develops at a speed that will create massive impacts on human lives within only a fraction of a generation. All of them together they create a depth of changing the very human life at today still unimaginable, uncontrollable, and by most humans likely unwanted steps. It is thus necessary that a *broad public* understands these dramatic changes. This is what we are aiming to achieve in this book.

We want to mention a last aspect of modern science before getting started. It concerns the appearance of new types of risks created by it that, other than single populations such as the South Americans after the European invaded their countries, can potentially lead to mankind dying out *as a whole*. An example of this is the power unleashed by nuclear bombs, but today also bioengineered pandemics (the frankenvirus[4]), genetical modifications, superintelligences and others. Thus, *risk management* is a new tool that must also be applied to science, including the assessment of such extreme risks. The key question is here: How do we evaluate scientific projects, with their highly complex questions and insights, in what their new knowledges and life benefits are, but also the risky and dangerous consequences of their technologies?

[4] Frankenviruses are so called from "Frankenstein" the famous hero of Mary Shelley and are viruses developed in laboratories by piecing together various parts of different viruses.

It is why, besides describing the history of science and technologies of the last 60 years, we cannot get by the important question to where we want to go with it, a question that is of philosophical nature and more important than ever in history.

On the structure of the book: The second and third chapters deal with the general development of the natural sciences from about 1960 onwards. After their centre had shifted from Europe to the USA after the Second World War (second chapter), the differentiation of the natural sciences increased strongly and - parallel to this - the financial dependence on third-party funding (third chapter). The fourth chapter then illustrates the detachment of the American-influenced sciences from philosophy, and how it needs to get back to science, this time also and especially for the ethics. The fifth chapter then presents the most significant future technologies, each of which will probably bring about a similarly profound social upheaval as the individual technological revolutions in the past (from mechanics and thermodynamics in the first, electrodynamics for the second, and quantum physics and information technology for the third industrial revolution). From the sixth chapter onwards, the focus is then on the individual scientific fields - physics (including the most recent astrophysics), chemistry (implied by physics on the one hand and providing the basis for biology on the other), biology (mainly the new genetics) and mathematics, and two core technologies that have emerged from them - in more detail:

- Chapters 6 and 7: Physics;
- 8th chapter: Genetics and Biology;
- 9th chapter: Brain Research;
- 10th chapter: Artificial Intelligence;
- 11th chapter: Mathematics;
- 12th chapter: Astrophysics.

In Chap. 13, we will outline scenarios of what potentially unimaginable social upheavals the sciences and technologies could bring in the (near) future, before the final two chapters, the 14th and 15th, that will deal with the social shaping of the future sciences and, in particular, the applications that emerge from them in order to manage the technological changes for the benefit of all humans, the development of their freedom rather than serving to their enslavement in whatever form.

So let us now dive into the for the future most fascinating and influential area that determines our future lives more than anything else. It is thus most mesmerizing and scary at the same time: We are on the one side in times of great opportunities and on the other side of great risks. It is only through reason and knowledge that we can shape an enriching future for mankind.

Lars Jaeger and Michel Dacorogna, Zug/Zürich in June 2023.

# 2

# The Takeover of Scientific Leadership

## How the Centre of Science Shifted from Europe to the USA in Just a Few Years - And How This Changed the Nature of Science Itself

As we saw in the introduction: The eighty years from 1870 to 1950, a blink of an eye in the history of mankind, was the period of the greatest revolution in thinking of all times. The drivers of these revolutions were processes in science, and the most dramatic of the scientific upheavals was what occurred in physics. However, fundamental revolutions also occurred in all other sciences, among them biology, organic chemistry, genetics, brain research, artificial intelligence, even in mathematics.

The period around 1960 to today then meant even more and more scientific revolutions, this time including and often lead by technologies that shaped up mankind itself like in an unprecedented manner and which constitute not only our modern society but will likely shape its future even more dramatically. Soon we might face a time when humanity in its biological foundation itself is changed.

In this chapter we will describe some of the key feature of science and technological development in the period from the 1960s onwards. However, in order to grasp this more deeply, it is necessary to first take a brief look back at the development of the period before, in particular the years from roughly 1900 to 1950.[1] There will be a somewhat natural focus on physics. However, we will also assess dramatic changes in other areas, like in Chaps. 8–11.

[1] For more details of this revolutionary developments, see: Lars Jaeger, *The Stumbling Progress of 20th Century Science - How Crises and Great Minds Have Shaped Our Modern World*, Springer (2022).


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## Geniuses Create a New World

Geniuses are generally characterised by more than just a particularly high talent or intelligence. As creators of something completely new out of very brilliant ideas they are particularly creative in the very meaning of the word. On top of this, they come with highest levels of perceptions and endurances in dealing with particularly difficult problems over a longer period of time, with the power to turn a domain fundamentally upside down. They thus enter realms that are not only beyond what has already been explored and accomplished, but that their contemporaries did not even imagine they existed. In this way, geniuses expand the boundaries of our knowledge and enlarge the playing field available to humanity.

In the history of science, progress has mostly been driven by solitary geniuses; Kepler, Galileo, Newton and Leibniz, or Gauß were such figures in their time (regarding Newton, see next chapter), as were James Clerk Maxwell, Ludwig Boltzmann, Georg Cantor, or Sofia Kowalewskaja in the second half of the nineteenth century. But from the first half of the twentieth century onwards, a surprisingly large number of exceptional minds worked together in all scientific disciplines and engaged in lively exchange with each other eventually (and after several crises) creating the most significant revolutions in science's history. In physics and mathematics, chemistry and biology, but also in philosophy or anthropology, and psychology or history, the genius scientists opened up possibilities for their disciplines to deal with fundamental contradictions that had come up. In some cases, they even succeeded in eliminating inconsistencies that had been known already by ancient thinkers. Their courage and achievements can thus not be overestimated.

Physicists such as Max Planck, Albert Einstein or Niels Bohr made a start when they left classical physics of the seventeenth to nineteenth century behind with relativity (combining time and location into a four-dimensional space) and first steps into quantum theory (behaviour of smallest particles), and even moved outside Western philosophy that had not been questioned for 2500 years. In fact, all sciences were until then actually founded on thoughts that had been shaped by ancient philosophers, especially by Plato and Aristotle, as well as the Catholic church, i.e. a strong belief in God, or in transcendence as far as Greek philosophers are concerned.[2]

Also in mathematics, geniuses such as Cantor, Hilbert, Poincaré, Lebesgue, Borel, Emmy Noether, von Neumann, Kolmogorov and Gödel left the safe

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[2] See Lars Jaeger, *Sternstunden der Wissenschaften* (only in German), Südverlag (2020).

and familiar shores of the classical - rather concrete - version of their discipline and ventured out into new, much deeper waters. The first acts of genius were to mathematically tackle the (for many prior mathematicians) scary features of uncountable infinities as well as to search for ways to deal with probabilistic chances. They had to leave behind the clarity and classical logic that had given mathematicians a foothold and framework until the late nineteenth century and thus developed, respectively conquered areas of mathematics whose seeming absurdity and high degree of abstraction defy any everyday experience and conceptuality - but that did often (sometimes many years later) end up being very important for science, in particular physics. They even succeeded in "controlling chance" by transforming many uncertainties into measurable risks thus laying the ground for quantitative risk management.

In addition, from the early twentieth century onwards, the science of life also received decisive stimuli. It was not the least due to numerous physicists, such as Max Delbrück and even Erwin Schrödinger in his late life, whose focus had shifted to biology. With their mathematical and physical skills they solved riddles left behind by nineteenth century researchers Darwin and Mendel in biology and advanced the decoding of heredity by discovering the genetic code. The decisive breakthrough of the molecular gen structures came in 1953 with the deciphering of the DNA code by the physicist Francis Crick and the biologist James Watson - as well as by the chemist and X-ray crystallographer Rosalind Franklin who also played crucial roles in deciphering the helical structure of the DNA molecule but was not given the deserved credit for that. The resulting possibilities of applications in genetic engineering are affecting us today more than ever.

Another example of an ongoing revolution in science today, with potentially equally influential consequences, is the understanding of the human brain structure and our thinking, which had its origin in the discovery of neurons and synapses in our brain more than 100 years ago. Recent research in this field might even lead us to grasping the fundamentals of our mind (see Chap. 9). In addition to the scientific motivation to understand what is arguably one of the most complex structures known in the universe today, the expansion of neuroscience has been driven by two main factors. One is a growing awareness of the social and economic burden of brain disease, but also the old disease of depression (major depressive disorder), which in most industrialized countries grows with the increase of populations age. The second one is a rising confidence of researchers that brain diseases are becoming a tractable problem. Conditions such as depression, schizophrenia, bipolar disorder, stroke and age-related cognitive decline, once considered inevitable features of the human condition, are now seen as specific diseases whose causes can be identified, prevented and ultimately cured. E.g. the specific progress for brain tumours (glioblastoma), until today not treatable, are currently more and more achieved.

With the spreading of science into many different fields the list of ongoing scientific revolutions has gotten correspondingly longer. And the speed at which they have been evolving has been rising constantly - and are still rising such that we experience an ongoing acceleration of the subsequent changes in our societies.

## The Shift of the Scientific Gravity Centre from Europe to the USA

In the late 1930s and early 1940s, especially driven by the Nazis kicking out key scientists from Germany and the outbreak of the Second World War in Europe, there occurred a significant geographical shift in the scientific gravity centre from Europe, particularly Germany, to the USA (which is presented in detail below). Here yet another group of geniuses brought itself onto the scene, such as Richard Feynman, who developed the first coherent quantum field theory, Robert Oppenheimer, (scientific) head of the Manhattan Project building the first atomic bomb, John Bardeen, who initiated the miniaturisation of computers with his semiconductor theory, for which he received the Physics Nobel Prize of 1956, and who later also explained superconductivity, for which he received a second Nobel Prize in Physics (1972), or, last but not least, Linus Pauling who also received two Nobel prices, one for Peace, the other in 1954 for chemistry for his work on chemical bonds.

With the US taking over the leading role in science something fundamental happened which we will elaborate on in this chapter: a major shift took place in the way science was understood and done. This change began first in physics but from there it spread into all other natural sciences, and it has transformed the face of scientific work to this day: Scientists left the field of philosophical reflection, which had played such a prominent role in European science from its very origin until then. The American scientific educational system gave much less importance to the general culture (in the spirit of Alexander von Humboldt). It placed much more emphasis on the hard sciences and their ability to solve practical problems than on philosophical questions. Thus, the researchers now devoted themselves much more to concrete application opportunities of the new scientific findings, while in Europe technological application had been advanced by engineers rather than scientist. Hence the triumphant advance of the technologies that followed scientific discoveries, which define our world to this day, had its core in the US (and has it there still today). The following list provides some important examples:

- Electronics together with the miniaturisation of processors (made possible by quantum physics) has led to the development of today's fast computers,
- Digital technologies,
- Lasers,
- Mobile phones,
- Satellites beyond the atmosphere,
- Television,
- Nuclear technology,
- Medical diagnostics and disease healing technologies,
- New materials with new functions that do not exist in nature (best example: plastic),
- Genetic engineering processes,
- Neuro-technologies,
- and last but not least, a whole new mathematics, the numerical methods of which have become so powerful (through ever and ever more powerful computers) that even world-wide hyper complex climate models have become realistic today.

The first and powerful manifestation of this development of US science and their applications was: the nuclear bomb (while the German scientists also working on it had still been in their thinking phase about it). It transformed the world in fundamental ways - changing forever the potential of global wars by making extinction of the entire mankind itself possible. Stalin, realizing after the war the importance of technological advances for the military, strongly increased the status of the academies of science in his country. Only four years after the US, his USSR had constructed the nuclear bomb themselves, with the help of Soviet spies in the US and the UK, in particular Klaus Fuchs (who emigrated from Germany to the UK and then, as of 1944, participated in the construction of the nuclear bomb in the US), sympathizing with Marxist ideology.

In the US as well as in the USSR, the new power of sciences was first directed towards technological developments mostly for military purposes. Other than in the US the scientific focus in the USSR remained largely in the military area, while in the West the triumphant advances of the technologies shaped the entire society. It improved everybody's daily life, and still does so today. To the broadening of wealth, another consequence of scientists leaving the field of philosophy and classical education was opening up the interest of and the access to sciences to all people, including those coming from less educated origin.[3] In a way, it brought a democratisation of the access to science, by introducing a way for gifted young people to climb up the social ladder.

The separation of science and philosophy had yet another consequence: Core philosophical questions remain unanswered by science. While still being influenced by its progress, questions such as the limits of reason, the implication of randomness in nature, the existence of reality outside the observer, and more fundamentally the very nature of life and consciousness were simply ignored. The human Ego remains largely a "terra incognita" today. This leads to strange contradictions, such as although we do not concretely understand what exactly and why something happens in the subatomic world, we can calculate it more exactly than anything else before, and accordingly also control it technologically. Let us thus make a quick excursion around the philosophical discussion in quantum physics.

## Philosophical Implications of Quantum Theory – The Concept of Reality Called into Question

Philosophy is still fundamentally important for physics (and vice versa). For more than three hundred years, until the early part of the twentieth century, classical physics and classical philosophy, the later going back to the Hellenistic tradition - supplemented by modern philosophies, for example Immanuel Kant's - were inextricably interwoven in the Western world. During this time, it was natural for physicists and other scientists to participate in philosophical discussions, particularly as they saw their laws as absolutely given and thus being a solid fundament of philosophical discourse as well. Conversely, many philosophers were able to discuss deep connections in the natural sciences, as well; Kant, for example, also taught Newton's physics at his university. It was not until the middle of the nineteenth century that mathematical calculations in physics became so complex that only a few philosophers were still able to assess the advances in physics. The physicists, on the other hand, continued to know and apply philosophy very well.

[3] For the separation of science and philosophy, see: *The Origin of the Separation between Science and Philosophy*, Proceedings of the American Academy of Arts and Sciences, Vol. 80, No. 2 (May, 1952), pp. 115–139.

Heisenberg, for example, dealt intensively with Plato, Einstein with Spinoza, Leibniz and Berkeley[4] and Mach (he also had a long philosophical controversy with Bergson in 1922 about the concept of time), Langevin with Marx. One particular aspect of Western philosophical thought shaped by Plato and Aristotle was to cause physicists a lot of trouble in the first decades of the twentieth century: the dualism that separates the world in two parts, objective nature and human subjective experience and thinking. This dualism even became the basis of classical physics with two scientific principles:

- To find the material, unchanging building blocks of the world,
- To extract the substance of things from the confusion of subjective impressions in the form of eternally valid laws with the help of objective, repeatable experiments that provide us these laws of nature.

In the 1920s, however, it became known that strange conditions prevailed in the quantum world, in particular the simultaneous feature of electrons and other smallest particles as well as for electromagnetic waves of being *particles as well as waves* (however never at the same time) which in classical physics - as well as in our daily experiences - is impossible. It depends on the *subjective choice* to perform a particular experiment which one is obtained. What a strange thing this was, given the 2500 years tradition of decisively separating objects and subjects. However, the properties of quantum objects, electrons, photons, etc. are not only undetermined before the measurement, but they *do not exist* at all! To put it very clearly: a quantum object has no independent properties before the measurement! Only the measurement gives it such. They have no reality, but "only" a *potentiality*, as the physicists say. Consequently, the core of the description of a quantum object is the *wave function* (more about it below) that does not describe a "real" physical entity, but rather a mathematical, probabilistic one.

With quantum theory, central concepts of classical thinking disappeared from the map of physics (as well our everyday mental map)[5]:

1. Reality
2. Causality
3. Identity.

The last point, the indistinguishability of quantum particles, contradicts the classical philosophical principle that Gottfried Wilhelm Leibniz had

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[4] In his book *De Motu* Berkeley argued against Newton's doctrine of absolute space, time and motion.
[5] For more details see: Lars Jaeger, *The second Quantum Revolution*, Springer (2018).

formulated 250 years earlier, but which Aristotle already knew: the *principium identitatis indiscernibilium (pii)*. This "theorem of the identity of the indistinguishable" says that two separate things that are completely the same in *every* respect cannot exist. For Immanuel Kant it is above all the factor of "place" that is significant for each particle: Even if the properties of two parts are of the same material and are ruled by the same mechanism and thus appear to be very much the same, they must at least be in different places. The fact that pii does not apply in the micro-world is not a theoretical gimmick, but the very reason why in quantum theory fundamentally different laws apply than in classical physics.

## Highly Controversial Philosophical Discussions Among Physicists in the 1930s

But if very different laws apply to the micro- and the macroworld there needs to be an area in between them in which the laws transfer from one area to the other. This caused a subtle philosophical discussion between the physicists in the mid-1930s. Let us have a rather quick review of it.[6] Bohr had pragmatically stated that the laws of classical physics apply to "sufficiently large" systems and the laws of the quantum world apply to "sufficiently small systems". Where exactly, however, on the size scale the transition is located, he had to leave entirely open. However, he and his followers had to assume that the transition does not happen gradually, but that there must be a sharp split. The alternative would have been that there is a region in which two different types of laws apply simultaneously.

Schrödinger and Einstein recognised that Bohr's interpretation only concealed a central logical gap in his interpretation: Somewhere on the size scale the quantum world and the macroscopic world, in each of which completely different laws apply, must touch. Where exactly on the size scale is that transfer located?

In order to illustrate this issue Schrödinger described in his 1935 essay "The Present Situation in Quantum Mechanics"[7] his famous thought experiment with the cat. With it, he wanted to reveal the absurdity of the cut between quantum and macros laws. In a locked steel chamber, there is a cat

[6] For more details see: Lars Jaeger, *The Stumbling Progress of 20th Century Science - How Crises and Great Minds Have Shaped Our Modern World*, Springer (2022).

[7] Erwin Schrödinger, *Die gegenwärtige Situation in der Quantenmechanik* (The Present Situation in Quantum Mechanics), Naturwissenschaften. Volume 23 (1935), Pages 844–849 (English version originally translated in: Proceedings of the American Philosophical Society, 124 (1980), p. 332–338; available under http://hermes.ffn.ub.es/luisnavarro/nuevo_maletin/Schrodinger_1935_cat.pdf).

and a quantity of a radioactive substance calculated in such a way that statistically one of its atoms decays per hour. Since only an average is possible to steer, it may be that one, two, three or even no atom decay within an hour. Each decay of an atom is detected by a fine measuring device; if there is a decay, it shatters a container of deadly hydrogen cyanide. After an hour, an observer will not know whether one of the atoms has decayed and therefore whether the cat is alive or not. The genius of Schrödinger's thought experiment is that it causally couples the quantum and macro worlds directly with each other and thus makes the strict separation postulated by Bohr and Heisenberg permeable: Only one atomic nucleus, i.e. quantum particle has to decay for a macroscopic object, the cat, to be directly affected (here: killed).

- As long as no measurement takes place on the atomic nucleus, it is in a state of superposition of "decayed" and "not decayed". This is quantum physically possible but does not exist in classical physics.
- In Schrödinger's experimental set-up, also the state of the cat in the steel chamber must consist of a superposition of "dead" and "alive": As long as the door to the box is not opened, the cat is objectively in both states at the same time! This is macrocosmically not possible.

This cat paradox was precisely Schrödinger's intention. Nobody doubted that the quantum laws were valid in the microworld. The question was: how far does their power extend into the macro world? Where in the chain *atomic nucleus - measuring device - prussic acid ampoule - cat - observer* must one place the transition from the quantum world to the macro world, in which we may trust our usual views and objects have clearly defined and independent properties?

Physicists had quite different answers to where to make the cut between macro- und microworld. And Schrödinger himself? Where did he make the cut? He found his own way of approaching this question: He looked at the measurement process, because it is precisely there that a device from the macro world comes into contact with a quantum object. While other physicists strictly separated the macroscopic world from the quantum world, Schrödinger consistently applied the principle of the common wave function to macroscopic measurements as well, i.e. to the moment when the macroscopic measurement system comes into contact with the quantum object to be measured. Somewhat casually, he remarked:

> It [*the $\Psi$-function of the measured object*] has, according to the inevitable law of the total $\Psi$-function, become entangled with that of the measuring instrument […]

Schrödinger thus gave his interpretation its own name, which to this day can hardly be surpassed in importance: "entanglement":

> This property [*entanglement*] is not one, but the property of quantum mechanics, the one in which the entire deviation from the classical way of thinking manifests itself.[8]

The most bitter opponent of the quantum uncertainty interpretation was, however, Albert Einstein. In 1935, he and his American assistants Boris Podolsky and Nathan Rosen published the article: "Can the quantum mechanical description of physical reality be considered complete?"[9] The thought experiment therein, later called the Einstein-Podolsky-Rosen paradox (EPR), was as ingenious as it was simple: Two quantum particles in superposition with each other are parts of a common wave function. Their momentum cannot be determined exactly, but it is known that the momentum of one particle is directly related to the momentum of the other particle. Now the two particles are separated from each other and brought to two different places. Then one of them is measured for his momentum so that the common wave function collapses so that the momentum of the partner particle is now also (instantly) defined. That cannot happen instantly though, as it breaks Einstein's law of the speed of light being fastest possible progress of information.

This was a rather clever move, which Bohr had little to oppose against. Nevertheless, the shot backfired, albeit only after Einstein's and Bohr's death: Precisely the falsified and seemingly impossible instantaneous action at a distance is the basis of many technological applications today, not least a possible future quantum computer. French physicist Alain Aspect's experiment from almost 50 years later, in 1982, validated the quantum entanglement and locality principles.[10] It also offered an experimental answer to Albert Einstein, Boris Podolsky and Nathan Rosen's paradox. Hereby, the laws of Einstein are not broken, as no information can be transferred in the described process.[11] For his experiment, Alain Aspect received the Nobel Prize in Physics another 40 years later, in 2022.

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[8] E. Schrödinger, Discussion of Probability Relations between separate systems. *Proceedings of the Cambridge Physical Society*, 31, (1935) S. 555.

[9] Albert Einstein, Boris Podolsky, Nathan Rosen, Can Quantum-Mechanical Description of Physical Reality be Considered Complete?, Physical Review. 47, 10 (1935) Pages 777–780.

[10] Alain Aspect, Philippe Grangier, Gérard Roger, *Experimental Realization of Einstein-Podolsky-Rosen-Bohm Gedankenexperiment: A New Violation of Bell's Inequalities*, Physical Review Letters, 49 (1982).

[11] In order to transfer information, one needs to know the initial state of either side. This can only obtained by a measurement. And these results have to be transferred by some kind of traditional transmission technology, not faster than the speed of light.

We see: Only when they had clarified these questions for themselves did the European developers of modern physics use mathematics to put their theory into suitable forms. Einstein and his colleagues understood their activity as part of a broader philosophical tradition in which they also saw their intellectual home.

## How Europe and Philosophy Both Lost Their Dominance in Science

In 1935, the dispute about the philosophical background of quantum physics climaxed. Einstein and other researchers such as John von Neumann, however, had already emigrated to the USA, and thus, the discussions took place over great distances. With that year, the philosophical discussion about quantum physics abruptly broke off entirely. Hardly anyone was further interested in the inner contradictions that had disturbed Einstein and Bohr so deeply. This had to do with a generational as well as the above already mentioned geographic change of the scientific centre after which the vast majority of physicists were no longer bothered by the fact that they could not explain *why* quantum mechanics worked, but simply applied it mathematically and in experiments. Only four of the greatest physicists of the twentieth century - Einstein and Schrödinger as critics of the given quantum mechanics, Bohr and Heisenberg as their advocates - continued the search for an explanation until their deaths. Despite all their efforts, they had to leave open the questions about spooky remote effects, entangled particles and half-dead cats until the end of their lives. For a long time, they were the last leading physicists for whom the philosophical background of their subject had any meaning. For the others, the successes of mathematics - and gradually technological applications - had become more important than unanswered philosophical questions. The same is true for British science and mathematics, despite Paul Dirac.

What caused the dramatic shift in particular? Until the mid-1930s, the development of physics (quantum mechanics and relativity theory) as well in all other sciences and mathematics was almost entirely driven by German-speaking scientists. Göttingen, Zurich and Berlin were the world's centres of theoretical physics and mathematics. The Dane Bohr himself spoke and loved this language like his mother tongue. Even the Englishman Paul Dirac spoke fluent German.

The elaboration of the mathematical foundations of the new physics was also shaped by German-speaking mathematicians: David Hilbert, Emmy

Noether and Hermann Weyl worked in Göttingen (Weyl was in Zurich for a long period but then took over Hilbert's chair in 1930). The best students and young scientists in physics and mathematics flocked to Germany from all over the world to learn and do research there. Plus, major progress in chemistry, biology and medicine originated in Germany. Paris, a leading place for mathematics and science for centuries, still had Borel, the leading mathematician of probability and statistics, Hadamard, who made major contributions in number theory, complex analysis, differential geometry and partial differential equations, and Louis de Broglie, the discoverer of wave properties of quantum particles, but overall had a much lower position in mathematics and science than one generation earlier at the turn of the century.

However, in 1933 the Nazis took over Germany and immediately applied a ban on Jewish scientists and mathematicians. Many scientists (even non-Jewish ones, when they had their own mindsets and were thus threatened by the Nazis) had to leave Germany. For most of them the US was the best place to move to. Among them were important names, but also highly talented young researchers.

- Albert Einstein was German (and of Jewish ancestry) but despised the conservative atmosphere in the country of his birth. As a young man he was stateless for a few years and in 1901 he took the Swiss citizenship, which he kept until the end of his life. Because he accepted a professorship in Berlin in 1914, he had to apply for a German passport again. In 1933, he gave up this citizenship for good and left Germany with the firm intention of never returning (which he fulfilled for the rest of his life).
- German Jewish statistician Emil Gumbel was one of the first to leave the University of Heidelberg in 1933 where he was a constant source of controversy with his pacifism and his leftist positions. After a short stay in France, he settled in New York where he taught at Columbia University. He ended up being one of the pioneers in statistics of Extreme Value Theory of which he wrote the first book dedicated entirely to this subject.
- Wolf Price recipient (in its inaugural year in 1978, together with Israel Gelfand), Carl Ludwig Siegel, considered then as the greatest living mathematician was an antimilitarist at the end of the First World War. Although he was not Jewish, he left Göttingen in 1940 and went to the US via Norway, where he joined the famous Institute of Advance Study in Princeton with Einstein and Gödel. He only came back to Germany in 1951.
- The Hungarian John von Neumann (born János Jajos Neumann) had already attended the German-language grammar school in Budapest and

lived in Berlin, Zurich and Göttingen as one of the most brilliant mathematicians in the 1920s and early 1930s. Like Einstein, he emigrated to the USA in 1933 (and - also like Einstein - despised Germany until his death), where he played a crucial role in the development of the nuclear bomb.

- The equally Hungarian Edward Teller also emigrated to America and later played a significant role in the development of the American hydrogen bomb.
- Hans Bethe worked on the properties of the electron in the 1920s and early 1930s, emigrated first to England in 1933 and later moved to the US.
- Emmy Noether, arguably the greatest female mathematician in history, was forced to leave Germany because of her Jewish background and went to the USA.[12]
- Max Delbrück, a theoretical physicist who shifted to biology, in 1935 (before he emigrated to the US), together with two others, published a work on gene mutations, in which they were the first to propose that genes can be understood as complex atomic assemblies. This was the beginning of modern genetics.
- An example from the Nazi's fascist partner: Enrico Fermi, the creator of the first nuclear reactor, the Chicago Pile-1, left fascist Italy in 1938 to escape the Italian racial laws that affected his Jewish wife, Laura Capon.

Many more names of great physicists and mathematician, but also biologists and medical researchers could be cited here. The brain drain was exorbitant and left behind a devastated scientific landscape in Germany. When the (already retired) mathematician David Hilbert attended a banquet in 1934, where he sat next to the Nazi Minister of Culture Bernhard Rust, the latter asked whether "the Mathematical Institute had really suffered so much because of the departure of the Jews". Hilbert's answer was: "Suffered? Mathematics has not suffered, Herr Minister. There is no such thing anymore!"

The centre of scientific activity shifted within not more than five years from the German-speaking countries to the English-speaking USA. And this was as we saw more than a mere change of location or language: Because in the USA a completely different intellectual climate prevailed, a new kind of theoretical and experimental physics (as well as of other sciences) developed. Here, people were simply not interested in the question of "what holds the world together at its core", but rather "what can we do to solve specific problems". Mathematics was to take over the explanation of the world, not the

[12] For more details on Emmy Noether, see Lars Jaeger, *Emmy Noether – Her rocky path to the world's top of mathematics* (only in German) Springer, 2022.