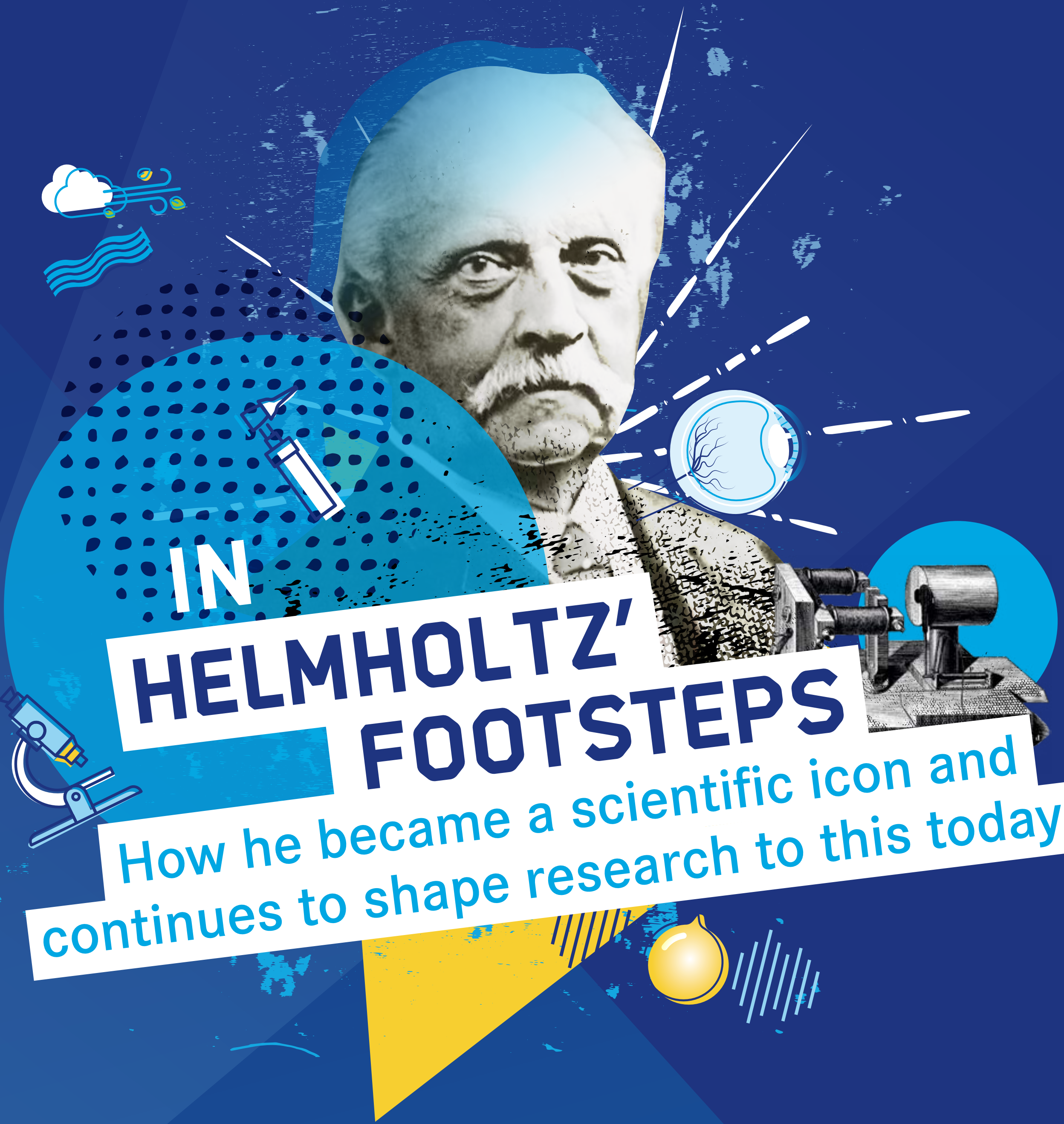
HELMHOLTZ
PERSPEKTIVEN
THE RESEARCH MAGAZINE OF THE HELMHOLTZ ASSOCIATION

01
2021

ANNIVERSARY ISSUE



IN HELMHOLTZ' FOOTSTEPS

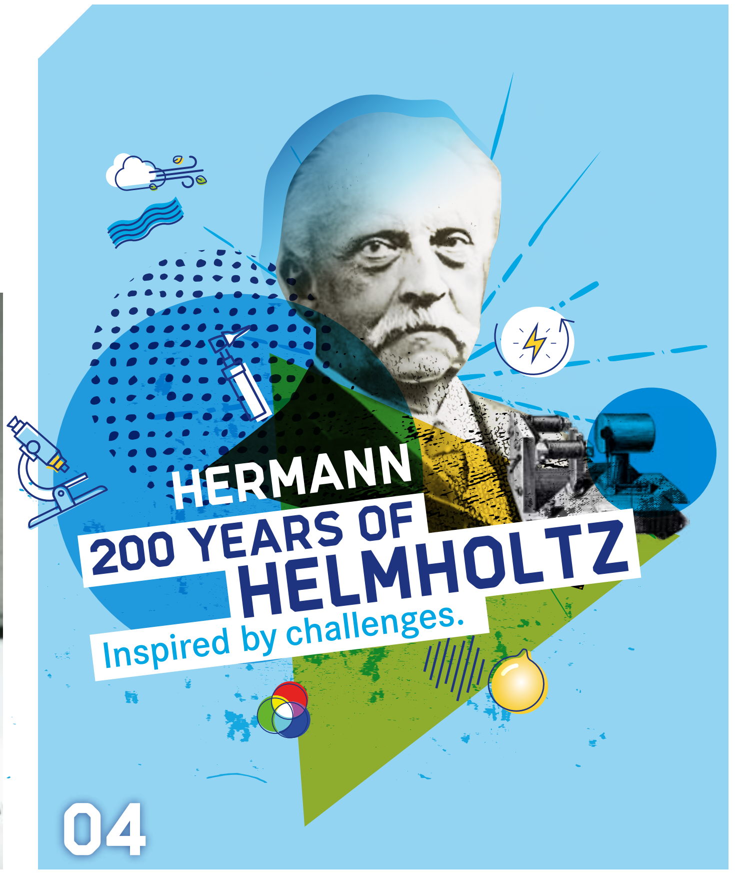
How he became a scientific icon and continues to shape research to this today

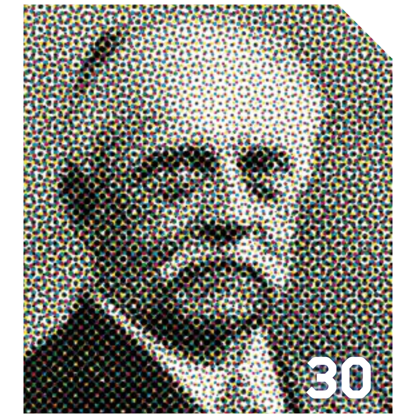
HELMHOLTZ, THE MAN
Interview with his great-great-great grandson Björn von Siemens

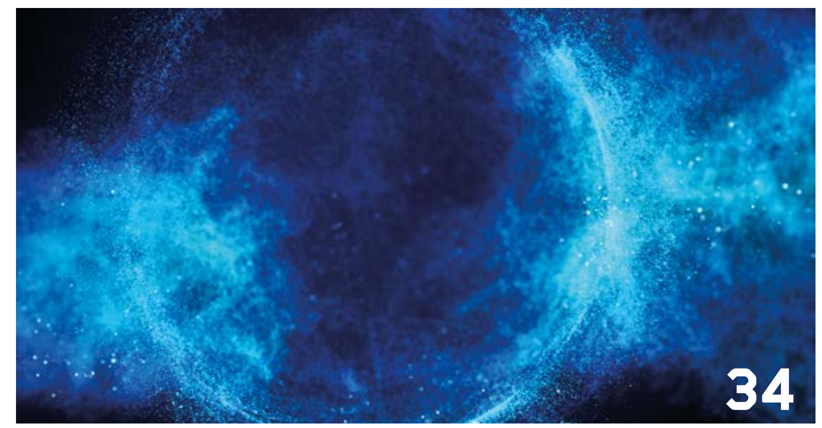
HELMHOLTZ TODAY
From the Helmholtz machine to AI

HELMHOLTZ AND THE ARTS
How science and the arts can inspire each other

200 YEARS HELMHOLTZ







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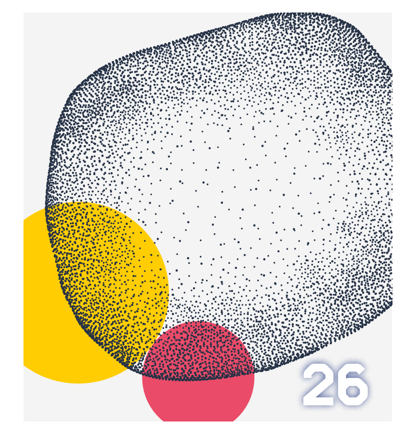


DEAR READERS,

Helmholtz conducts top-level research of the highest caliber and has grown in recent decades to become one of the most powerful research organizations in Europe. But who really was the man who gave it its name? What influence did Hermann von Helmholtz have on the research community in his day, and to what extent is his scientific prowess still relevant in our present times? In this anniversary issue of Helmholtz Perspektiven, we mark his 200th birthday by exploring these questions and more.

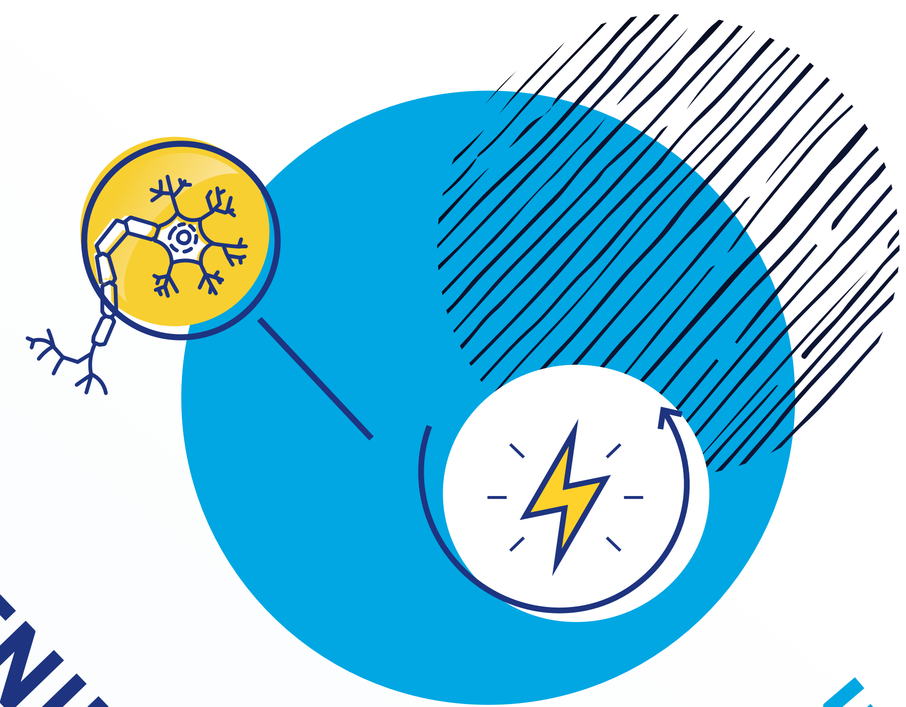
We trace Helmholtz' footsteps in Berlin in our title feature (starting on page 4) and discover unknown sides of the universal scholar and family man in a conversation with his great-great-great grandson (starting on page 12). Helmholtz expert David Cahan describes his ascent to the status of scientific icon in an article titled "A life in science" (starting on page 18).

In "The researcher, the pianist," (starting on page 40), you can also learn more about Helmholtz' love of music and how it informed his scientific work—and why Helmholtz coined a term that is even used in the field of artificial intelligence (starting on page 30).

Our anniversary issue shows that Hermann von Helmholtz continues to inspire the day-to-day work of researchers in a vast array of disciplines, even today. But why not read on and find out for yourself. I hope you enjoy this issue of Helmholtz Perspektiven!

Professor Otmar D. Wiestler,
President of the Helmholtz Association

Diagram: Julia Blenn



THE GENIUS FROM THE SPREE

The story of how the doctor Hermann von Helmholtz revolutionized physics is one of the greatest pioneer tales of the 19th century. We took a walk in his footsteps—and discovered how he continues to inspire researchers today.

Construction work is underway again, but Dieter Hoffmann doesn't let it bother him. "Mrs. von Helmholtz wasn't happy when she had to move here from the center of Berlin, at the end of the 19th century," he says, "out here to the 'sandy steppe' and the 'desolate suburbs', as she called it." A digger rumbles past Hoffmann, a scientific historian from the Max Planck Institute for the History of Science; new cables are being laid under the street. But even without the construction work, nothing of the "steppe" that Anna von Helmholtz complained about remains to be seen today. The area here in the Berlin district of Charlottenburg has long since become densely populated, and the expansive premises of the Physikalisch-Technische Bundesanstalt (PTB) are surrounded by six-story apartment blocks. "Over there," says Hoffmann, pointing across a site fence to a shell of a building at the edge of the plot, "is where the presidential villa used to be."

Hermann von Helmholtz lived through his crowning achievements there, in what was once an impressive villa. With the title "Imperial Chancellor of the Sciences," he mixed with the highest ranks of the nobility and members of the imperial dynasty—and the salons that drew Berlin's high society to his home were legendary. The scholar had reached the pinnacle of his creative career; the work he did at that time continues to shape science to this day. "This right here was the first large-scale research institution of the modern age," says Hoffmann as he walks across the premises of the Bundesanstalt, which was still known then as the German Imperial Physical-Technical Institute (PTR) back then. Hoffmann is a professor emeritus, a recognized Helmholtz expert—and it is clear that he has become deeply involved in the subject of his research.

Helmholtz expert
Physicist Dieter Hoffmann is a scientific adviser at Germany's national metrology institute, the Physikalisch-Technische Bundesanstalt.
Image: Helmholtz/Christian Kielmann

"This was the first large-scale research institute of the modern era, and Hermann von Helmholtz was its first president."

Dieter Hoffmann, Historian

Image: Heidelberg University Archives

"During the first seven years of my life I was a sickly boy who was long bound to his room, and often enough to the bed, but I had a lively drive to talk and be active."

Hermann von Helmholtz

He is a physicist himself, a scientific adviser to the PTB, and also worked at the German Physical Society (DPG), which Hermann von Helmholtz played a role in shaping. And last but not least, Hoffmann was also born in the region, as evidenced by his strong Berlin accent.

The area where Helmholtz lived and worked was limited to a small circle around this location on the premises of the former PTR. This circle extends to Potsdam, where Helmholtz was born in 1821 as the son of a secondary school teacher, and in particular to what is now the district of Berlin-Mitte, where he studied at the Friedrich-Wilhelms Institute of Medicine and Surgery. While Hermann von Helmholtz did take up posts in what was then known as Königsberg, in Bonn and in Heidelberg, the most productive years of his life were spent here in Berlin, in this small geographic circle around the PTR.

"That's exactly why I started studying Helmholtz," says Hoffmann. "I've actually been interested in the history of the Imperial Physical-Technical Institute since the beginning of my academic career, and he was its first president, after all." With this as his starting point, Hoffmann delved ever deeper into the universal scholar's life over many years, closely scrutinizing the minutiae of his life and work. So what was he like, the great researcher?

Part of the answer can be found exactly six kilometers away from Helmholtz' presidential villa, where he passed away in 1894. Hermann von Helmholtz still stands on the attractive courtyard in front of Humboldt University of Berlin on the broad Unter den Linden boulevard, larger than life. The stone statue's gaze is firm and serious; he wears a long coat and his left hand rests on a stack of books. "All of the representations from that time are very iconographic," says Hoffmann, "and the photographs were static and contrived for purely technical reasons." But that's not what we see here—it is no coincidence that the stone likenesses of the two Humboldt brothers, along with Max Planck, are directly adjacent to the Helmholtz statue. "There's a clear sequence here, a connection as regards their work," explains Hoffmann. "Biographically speaking, Humboldt came first of the three; he looked at nature in its entirety. Then came Helmholtz, who considered physics as a whole rather than as various branches of the field. And then there was Planck, whose focus was somewhat narrower, but he nonetheless kept an eye on the big picture." Arranged in this sequence, Hoffmann says, their statues symbolize the development of the sciences and the distinctions that were drawn between disciplines in the 19th and early 20th centuries. Germany's scientific system took a gigantic leap forward within the lifetimes of these three men, Hoffmann continues.

One of Hermann von Helmholtz' most famous inventions—the ophthalmoscope—demonstrates how he succeeded in continually pushing the limits of technology, acquiring ever-deeper →

Imposing Larger than life, a statue of Hermann von Helmholtz still stands in front of Humboldt University in Berlin today. Image: Christian Wolf, www.c-w-design.de (CC BY-SA 3.0)

insights into the laws of nature. “The replica we have here at the museum is very similar to Helmholtz’ original,” says Thomas Schnalke. The professor of medical history, who heads up the Berlin Museum of the History of Medicine at the Charité hospital, points to an unassuming object less than a foot long. A brass mounting, which the doctor holds up to the patient’s eye, is affixed to an ebony handle. An attached, semi-permeable mirror allows the doctor to look through the patient’s pupil into the ocular fundus, or interior surface of the eye. This was impossible until Helmholtz invented his ophthalmoscope, because the doctor carrying out the examination always had to stand with his own head blocking the light from penetrating the pupil. “It’s a brilliant device based on a brilliantly simple functional principle,” says Schnalke.

But the technology wasn’t the only factor at play here. “It was the first time in human history that doctors could look inside the living human body,” Schnalke exclaims with evident enthusiasm. He still remembers how he and his fellow students took turns examining each other with the ophthalmoscope during his own medical training. “The picture it provided of the ocular fundus was stupendous, and it was one of the experiences during my training that continues to stand out,” he still enthuses today. “The way the vascular tree branches out, the different widths of the veins, the entry point of the optic nerve, it was all there right in front of you!” Helmholtz’ invention, says Schnalke, is one of the few medical developments that—like anesthesia—quickly made its way around the entire world. And what is more, he notes, the invention was one of the factors that resulted in ophthalmology being recognized as a distinct medical discipline. Schnalke shakes his head at how improbable Helmholtz’ ingenuity seems to him. “He spend just around three months of his life taking a closer look at optics and ended up building the ophthalmoscope!”

With this invention, Hermann von Helmholtz showed he was a man who had his finger on the pulse. A group of young academics were working to underpin the field of medicine with scientific principles at that time, and Berlin served as a hub for vital momentum in these efforts. Helmholtz committed to serve in the military for several years in return for a state-funded place at university to study medicine; they were years during which the young doctor worked systematically to expand his knowledge. He was among those studying under Professor Gustav Magnus, who founded Germany’s first physical institute at his home on Kupfergraben Street near the Pergamonmuseum. It was in Professor Magnus’ living room that a collective of progressive scientists also came together to discuss, learn, experiment, and delve ever deeper into the mysteries of the sciences. Hermann von Helmholtz himself declared it a “stroke of good fortune” that he “as a man equipped with a certain amount of geometrical understanding and knowledge of physics found myself thrown in among the doctors, where I happened upon virgin soil of great fertility in the field of physiology, and that, moreover, my knowledge of living phenomena led me to questions and considerations that were typically foreign to those who dedicated their studies entirely to mathematics and physics.”

These were the very principles that later aided his invention of the ophthalmoscope. “Later” specifically refers to the year 1851, →

“Physics was still considered an unprofitable art at the time. My parents had no choice but to be very frugal; my father therefore said he would not be able to further support my study of physics unless I accepted that I would also have to take up medicine.”

Hermann von Helmholtz

A sense for the practical The ophthalmoscope is Helmholtz’ most famous invention. Image: Christoph Weber, Berlin

Time-honored tradition Tobias Schäffter's office is located in the oldest building on the PTB campus, the observatory—just as Helmholtz' once was.
Image: Physikalisch-Technische Bundesanstalt

when Hermann von Helmholtz was 30 years old and had just accepted his first post at the university in what was then the city of Königsberg. "It was a professorship in physiology, so a position in the field of medicine, and this was followed by posts in Bonn and Heidelberg—likewise as a medical doctor," says Helmholtz expert Dieter Hoffmann. As with the ophthalmoscope, Hermann von Helmholtz continuously expanded his range of interests. He conducted experiments on nerve conduction velocity, formulated the energy conservation principle, and tirelessly researched any phenomenon that presented him with a riddle. Hoffmann describes it as "basic medical research using physical methods," and in retrospect it is clear that this precise approach was what paved the way for Helmholtz' return to Berlin. "When the professorship of one of his academic lecturers opened up, namely Gustav Magnus, he was among the circle of those who could lay intellectual claim to it." Helmholtz was appointed to the position, not least thanks to the influence of his friend and colleague Emil du Bois-Reymond, who at that time was rector of Berlin University; Hoffmann says that this move from Heidelberg back to Berlin represents the point at which Hermann von Helmholtz finally made the switch from medical doctor to full-fledged physicist.

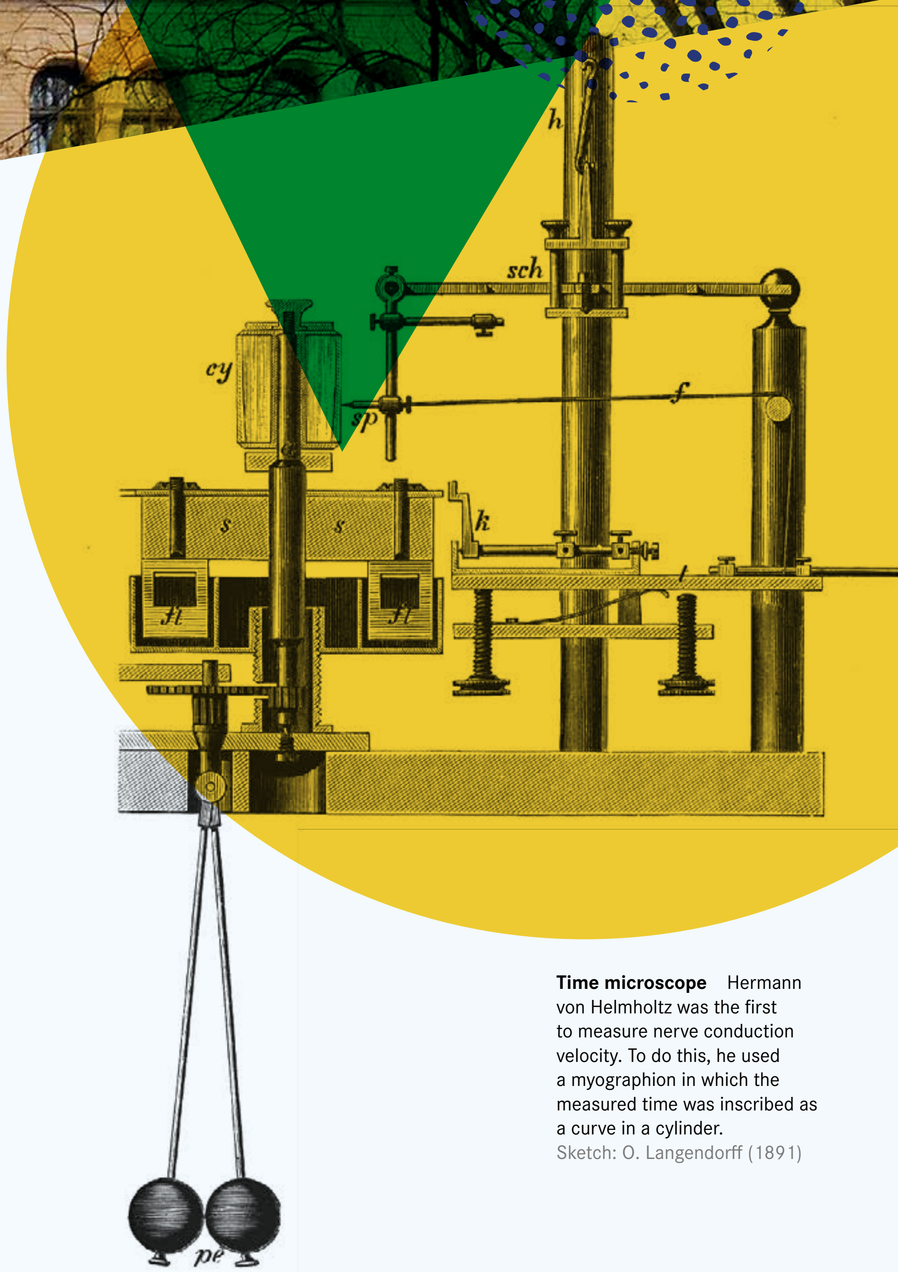
What followed was an unparalleled ascent, both to the highest circles of society and the pinnacle of science. Helmholtz' reputation as a gifted researcher spread rapidly; he was a sought-after celebrated speaker whenever he made appearances at conventions or meetings. He was granted the status of nobility and was henceforth entitled to use "von" in front of his name, as was typical for the nobility in Germany. Helmholtz was also known as the "Imperial Chancellor of the Sciences," in analogy to Chancellor Bismarck. The crowning achievement of his life's work came in 1887 at the age of 66, when the PTR was founded.

"Some people say that this table is from his original office," says Tobias Schäffter, rapping on the polished wood surface of the large, oval meeting table. Schäffter is a professor who heads up the Berlin Institute at the PTB and, as Helmholtz once did, has his office in the observatory on the institute's expansive campus. The parallels are immediately obvious when you listen to Schäffter describe Helmholtz' legacy and what he himself is researching with his department for medical physics today. He talks about how Hermann von Helmholtz used simple means to measure the conduction velocity of nerves in his day, and how he and his team are still coming up against the limits of what can be measured even now.

"Let's think in strategic terms and imagine: What would someone like Helmholtz actually do today?" asks Schäffter. "Would it still be physics, with its capacity for innovation? Would it be biotechnology? Or networked thinking and digitalization?" We will never know. But there is yet another link connecting Hermann von Helmholtz to the present: When Schäffter looks out the window of his office, he sees the construction site. There, where the presidential villa—which was destroyed in the war—once stood, work is progressing on the construction of a new seminar center dedicated to networking science and industry. Even in his day, the villa was a place where Helmholtz brought everyone together: the old guard of scientists with up-and-coming talent such as the then-unknown physicist Max Planck; industrialists like his friend Werner von Siemens with musicians and politicians. "Creating the impetus for these fascinating conversations, getting everyone talking with each other—that's what we should be working to emulate again today," enthuses Schäffter. And when he says it here at the old meeting table from Helmholtz' former office, it sounds like a firm resolution.

Even today, 200 years after he was born in Potsdam, Hermann von Helmholtz has contributions to share with science. ◆

Kilian Kirchgeßner



Time microscope Hermann von Helmholtz was the first to measure nerve conduction velocity. To do this, he used a myographion in which the measured time was inscribed as a curve in a cylinder.
Sketch: O. Langendorff (1891)

"HE HAD A SPIRITUAL SIDE, TOO"

Björn von Siemens is Hermann von Helmholtz' great-great-great grandson. We spoke with him about the lesser-known sides of the universal scholar's character—and how his family preserves his memory to this day.

Images: Phil Dera

Mr. von Siemens, your great-great-great grandfather Werner von Siemens is still a very strong presence in your family, just by virtue of the name. What is your family's take on your other great-great-great grandfather?

Hermann von Helmholtz continues to live on for us as well, that goes without saying! One way is the many memories and stories I've heard throughout my life from my parents and grandparents, and from my aunts and uncles. Second, there are the many artifacts—writings, books, and pictures—that we've grown up with in our family for many generations now. And then there's the third area: Our family has been very happy to see Hermann von Helmholtz' memory experience a renaissance, not least through the Helmholtz Association.

As a child, when did you first become aware of who Hermann von Helmholtz actually was and that much of what you were learning in your physics classes was directly or indirectly connected to him?

My parents and grandparents always pointed out the areas where you'll still come across phenomena that he focused on in his research. This concept of him being a universal scholar, a universal genius, always impressed me.

The famous statue in front of Humboldt University depicts Hermann von Helmholtz as a stern, unapproachable character. What image do you have of him in your family?

I remember being asked to play something on the piano for the family as a child. I am somewhat shy and introverted, and felt horribly nervous. Then my grandmother took me aside and told me that one of my forefathers named Hermann von Helmholtz had also been very introverted. But she said he had still been a very capable pianist and, what's more, a universal genius. This was the first time that I really remember hearing about him, and I've imagined him as a calm and rather reserved person since then.

And what was he like apart from that?

I'm fascinated by the way he dedicated his life to science. Our family likes to tell the story of how he once traveled to the Mediterranean with his wife and children—and then spent days on end sitting on the beach analyzing the waves. His family probably would have preferred to do something else, but he just sat there making sketches of the waves. But there's also a side to Hermann von Helmholtz that very few people know about ...

... and what side is that?

He was also very much a family man and put his family before many other things. When his first wife got sick, he didn't meet the requirements of his post in Königsberg to the extent he could have. Another nice story is the way he spoke with his children and grandchildren about the areas he was working in, about sound waves and light waves. Then they looked at the stars together, and he told them about how far away they were but that they weren't so far away that we couldn't experience a part of them. And then he said that stars weren't the only things that emit these types of waves; humans, too, have relationships that manifest themselves in waves. He said it was also possible to communicate with people who might not be there anymore. And that's why his children and grandchildren looked up at the moon after Hermann von Helmholtz' death and in some sense communicated with him.

In other words, he showed that he had a spiritual side.

That's right; you wouldn't necessarily expect it from a scientist like him, but philosophy and the arts were actually very important to him as well. He always had a lot of contact with philosophers—for example, he derived his concept of the indestructibility of energy from philosophy. And that is exactly what I still find impressive about him today—the breadth and depth of the topics he addressed. And I'm impressed by the range he covered between what we today would divide into basic research and application.

What kind of relationship did your two great-great-great grandfathers Werner von Siemens and Hermann von Helmholtz have?

They maintained very close contact with each other and later shared a very good friendship as well—as they also did with Johann Georg Halske by the way, with whom Werner von Siemens laid the foundation for the company now known as Siemens AG. The three of them worked together to take ideas from theory to experiment to application. Hermann von Helmholtz was primarily a man who was →

"I imagine him as a calm and rather reserved person."

dedicated to research and teaching, and frequently spent hours working, publishing, and experimenting on his own. Of the three of them, Johann Georg Halske was the engineer with a bent for action, and Werner von Siemens was extremely capable when it came to translating his inventions and technology into real life. This way of building bridges from basic research to concrete applications is something we can still learn a lot from today.

What would you like to see modern science take away from Hermann von Helmholtz as a paragon of science?
Today, we're in a mode where we primarily focus on making incremental improvements—the targets we're given are three percent more output or motors that are three percent cleaner, and that makes us risk averse. We lack the courage to make a bold move. It's something I think about a lot, because we are looking back on a generation of inventors and scientists who achieved absolutely monumental things and had to show great courage to do this. Their willingness to take risks is something we can learn from today.

Could you put that in more specific terms for us though? What kind of innovative landscape would you like to see in Germany?
The paradox is that Germany actually has everything that is needed. There are fantastic research institutions, an incredible number of very smart, hardworking researchers, and great companies. But it's still clear that many of the things that have shaped the world in recent years haven't come from here. Or, and this is at least as bad, they have their roots here but became a success somewhere else. I'd like to see us make our way back to a culture of entrepreneurship where entrepreneurial mistakes are also accepted and don't automatically mean the end of a career anymore.

The goal of your own company is to make having an operation as safe as taking a flight—it's the slogan you advertise with. What does this involve?
Our goal is to make surgery safer and more efficient—these two aspects are closely interlinked. We are using a very empirical method to do this. We gather data from several million surgical interventions every year and evaluate the data with the hospitals or other partners. Our objective in doing this is to make improvements in the procedures and minimize the risk of errors.

"This way of building bridges from basic research to concrete applications is something we can still learn a lot from today."

Hermann von Helmholtz was a doctor, your mother is a doctor, and you are an entrepreneur in the healthcare sector—it's almost become a family tradition, hasn't it?
I actually wanted to become an intensive care doctor like my mother, and I still see that as the most motivating job you could do. But I was also fascinated by this one idea that Hermann von Helmholtz truly lived—the idea of looking beyond your own horizons. As an entrepreneur, you have the opportunity to tap into various industries and scientific disciplines, the arts, and philosophy to pave the way for progress. His wife Anna really inspired me as well. She was the grande dame on Berlin's salon scene and created a fantastic network. She hosted the big names of the time, from Cosima Wagner to Max Liebermann to Rudolf Virchow. Whenever this international network gathered, they came up with new ideas. And I see us as a source of new ideas in this same sense. We bring momentum from a wide range of areas together—from aviation, team sports, medical technology, and so on—with the goal of making medical advances.

Your company combines the worlds of both of your famous ancestors—the entrepreneurial side from Werner von Siemens, and the scientific side from Hermann von Helmholtz. Which of these worlds do you personally identify with more?
Who could compare themselves with these two great men or achieve things at the same level they did? But I do hope that what we are doing here can set things in motion in the entrepreneurial sphere, based on the latest scientific findings. I myself am definitely closer to the business side of things than the scientific—I certainly see it that way, and I sometimes regret that I didn't end up studying something in the sciences.

"But I was also fascinated by this idea that Hermann von Helmholtz truly lived—the idea of looking beyond your own horizons."

The high-tech medicine that your company stands for now is miles away from the type of medicine that Hermann von Helmholtz learned about back when he was studying medicine. Do you think you would have anything to say to each other if he were to walk around your offices with you here today?
Hermann von Helmholtz' research progressed from muscle power to machine power and generally derived many aspects from human physiology for the field of physics. It's the other way around for us today. We look at the field of industrial applications in the area of automation and at systems with artificial intelligence that can be used to make predictions, and then apply them in the field of medicine. I'm certain that he would be very interested in our work and that he would also understand it quickly. What we're doing isn't actually anything other than collecting and analyzing data at scale—and he used these methods in his observations as well; the only difference is that now we are doing this at the magnitude of big data. I'm certain that we would have a great conversation. ◆

Interview: **Kilian Kirchgeßner**

ONLINE

The **full interview** is available as an audio version and brief audio report (both in German) at:
→ www.helmholtz.de/interview-siemens

HELMHOLTZ IN OUR LIVES

Many scientific disciplines build on Helmholtz' achievements. But very ordinary, everyday items like loudspeakers or medical apparatuses also got their start in the great scientist's findings or inventions.

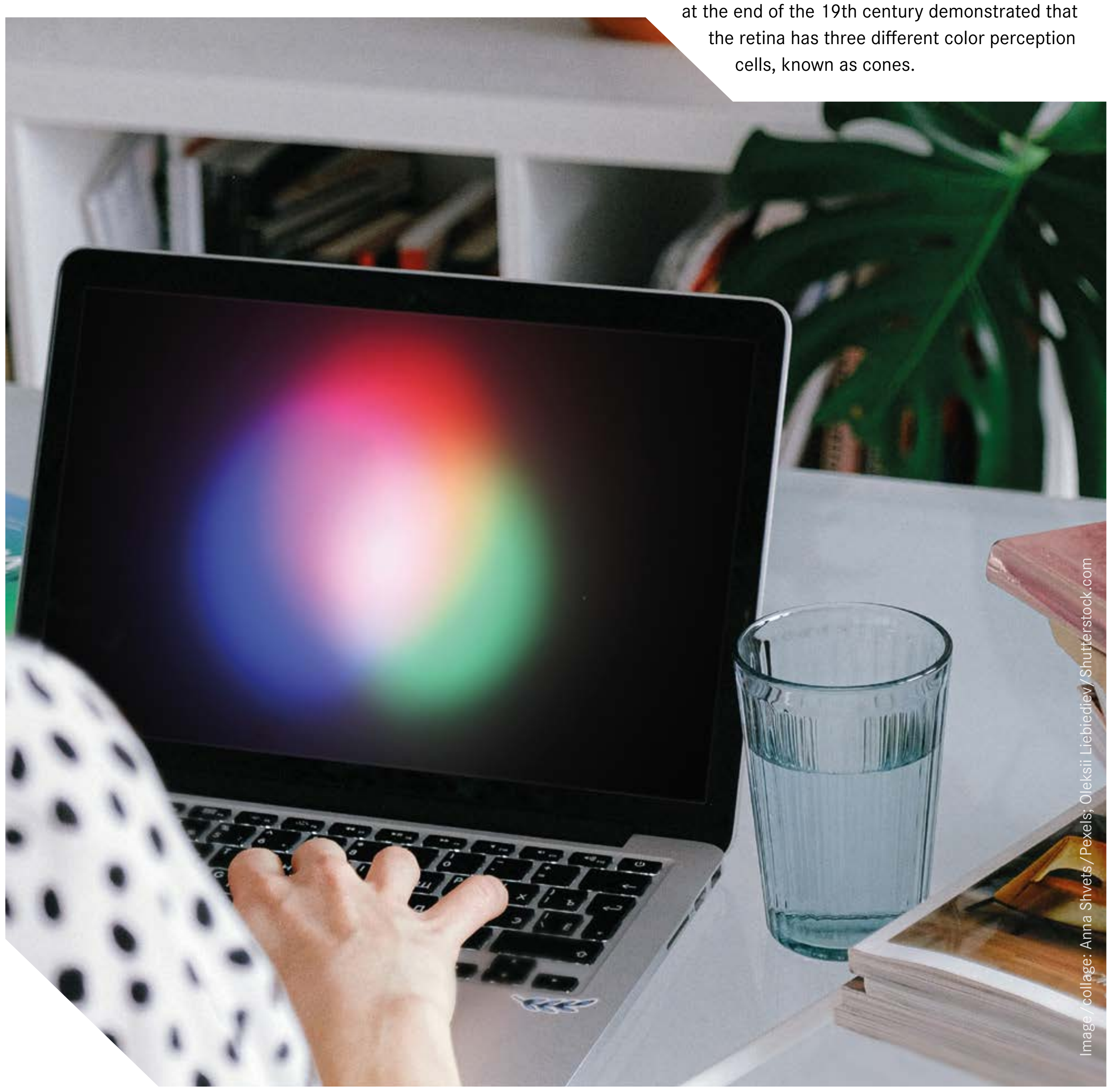
Image: wavebreakmedia/Shutterstock.com

01 LOOKING DEEP INSIDE THE EYE

Hermann von Helmholtz invented the ophthalmoscope in 1850. The principle he used was a simple one: When a doctor holds the device up to a patient's eye, a tilted mirror enables him or her to look through the pupil and observe the ocular fundus without obscuring the source of light with their body. Prior to the invention of the ophthalmoscope, doctors were only able to describe disorders that could be identified by examining the eye from the outside. Hermann von Helmholtz became very famous thanks to the ophthalmoscope. And while there are more complex devices that can be used to examine the eye today, the ophthalmoscope is still used around the world—with a few small, modern modifications.

02 HOW WE SEE COLORS

The colored images on monitors and televisions are made up of numerous individual red, green, and blue dots. The principle behind these dots is the trichromatic theory that Hermann von Helmholtz developed in 1850 on the basis of one of Thomas Young's theories. Hermann von Helmholtz observed that the light from the three colors red, green, and blue (RGB) could be mixed to create any other color. He hypothesized that there are three types of receptors in the eye which react differently to light of different wavelengths, and that this is what enables people to see colors. He was right: Researchers at the end of the 19th century demonstrated that the retina has three different color perception cells, known as cones.



Image/collage: Anna Shvets/Pexels; Oleksii Liebiediev/Shutterstock.com

A LIFE IN SCIENCE

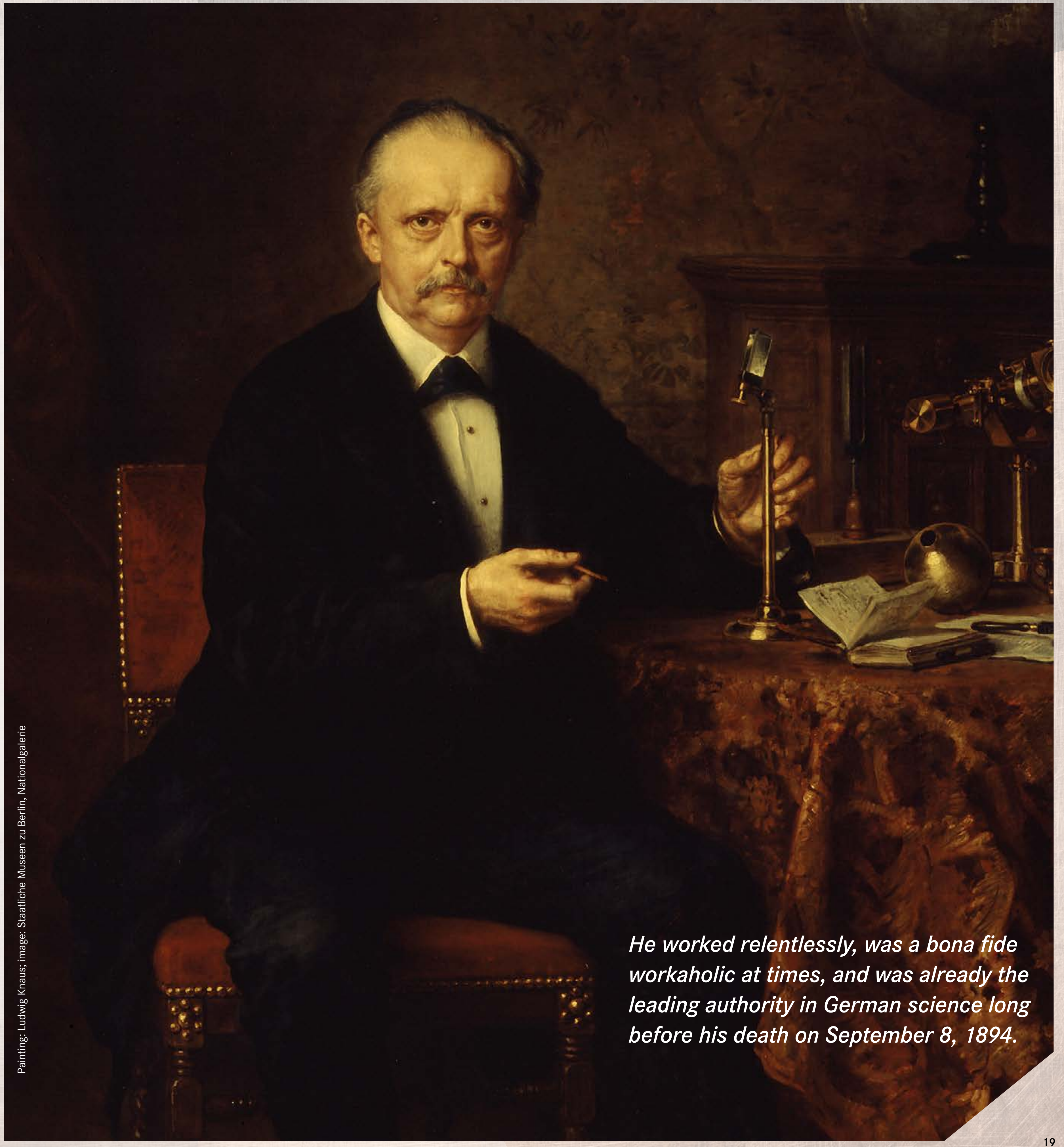
Science historians list Hermann von Helmholtz among famous names such as Alexander von Humboldt, Max Planck, Charles Darwin, and Louis Pasteur. But what can Helmholtz' status as a scientific icon be attributed to?

August 31, 2021, marks the 200th anniversary of the birth of scientist and natural philosopher Hermann Ludwig Ferdinand Helmholtz. He was born in Potsdam into a humble family, without privileges and without the prefix "von," which he would later be granted as a member of the nobility. Neither his father, an ordinary secondary school teacher, nor his mother, a modest and reserved housewife, had wealth or social position when they married. While the family wasn't poor, they struggled to make do on his father's limited salary. For this reason, Hermann—the oldest of six children, two of whom died at a relatively young age—did not have the opportunity to attend university, deciding instead to study at the Friedrich-Wilhelms Institute of Medicine and Surgery, thereby committing to a period of military service in return thereafter.

When the title of nobility was ultimately conferred on Hermann von Helmholtz in January 1883, he was the first for many generations to be honored in this way by the State of Prussia for his scientific (rather than military or political) achievements. He was very proud of the high social standing he had attained and considered it one of his greatest successes. Moreover, he was proud to be a bearer of culture (and also considered himself as such). In addition to a great deal of hard work, talent, and luck, Helmholtz had his extensive education to thank for his ascent in German society. And, in particular, it was his numerous outstanding achievements in various scientific disciplines and his ability to convey to others the crucial insights, methods, and objectives of science—the basic principles of which he had learned from his father, at school in Potsdam, and through his education at the medical institute. Helmholtz' scientific achievements and his philosophical reflections on science are so extensive that they fill seven thick books. The three volumes titled "Scientific Papers" (1882–95) contain around 175 original scientific articles (primarily on the subjects of physiology and physics, but also on meteorology, chemistry, and other sciences): In addition to its primary subject, the three-part "Treatise on Physiological Optics" (1856–67) also influenced the related fields of ophthalmology (medicine) and psychology. Helmholtz' "On the Sensations of Tone as a Physiological Basis for the Theory of Music" (1863) served to realign and further research into the scientific foundations of music. And the two volumes of "Popular Lectures on Scientific Subjects" (1884), a collection of informative scientific and philosophical essays, shed light on the nature, methods, and most important recent findings and laws of science for an educated audience. In addition, his seven-part "Lectures on Theoretical Physics" (1897–1907) were published posthumously in six volumes. He was incredibly productive and addressed a broad spectrum of topics with a degree of originality that was virtually unsurpassed among his contemporaries.

It could be argued that only Charles Darwin and Louis Pasteur equaled his scientific renown and the status he enjoyed as a scientific icon in his day.

Hermann von Helmholtz also pursued a university career (and taught) in Königsberg, Bonn, Heidelberg, and Berlin. Moreover, he helped to establish three scientific institutes which he headed on his own (one for physiology in Heidelberg, one for physics in Berlin, and the Physikalisch-Technische Reichsanstalt für Physik und Metrologie in Charlottenburg). He worked relentlessly, was a bona fide workaholic at times, and was already the leading authority in German science long before his death on September 8, 1894. Helmholtz was →



Painting: Ludwig Knaus; image: Staatliche Museen zu Berlin, Nationalgalerie

He worked relentlessly, was a bona fide workaholic at times, and was already the leading authority in German science long before his death on September 8, 1894.

Famous predecessors, contemporaries, and successors
(left to right, top) Alexander von Humboldt, Max Planck, (bottom) Charles Darwin, Louis Pasteur
Images: Lukiyanova Natalia frenta/Shutterstock.com, Joseph Karl Stieler, picture alliance/ullstein bild, John Collier, picture alliance/United Archives/WHA

to the second half of the 19th century what Alexander von Humboldt had been to the first half—and Max Planck would be to the first half of the 20th century. It could be argued that only Charles Darwin and Louis Pasteur equaled his scientific renown and the status he enjoyed as a scientific icon in his day.

What is behind Hermann von Helmholtz' broadly diverse and profound accomplishments, and how can his status as a scientific icon be explained? Or, to put it another way: What are the guiding intellectual principles and driving forces that run through his creative, scientific, philosophical, and aesthetic life? There are three prominent themes: First, Hermann von Helmholtz possessed a passionate determination to unify the sciences, both within the individual disciplines as well as by joining them to form a unified, all-encompassing science. To this end, he sought to apply general, overarching laws and stringent concepts in the individual scientific disciplines in which he worked. He also revealed close relationships between physiology and physics—not least thanks to his vital contribution to a law of energy conservation—between physiology and his development of non-Euclidean geometry, between physics and geometry in general terms, between physics and chemical thermodynamics, and between physics and meteorology. Using a broad-based approach, he demonstrated the impacts of the scientific laws and various findings that he and other scientists discovered across the fields of medicine, experimental psychology, philosophy, music, and painting. He sought to comprehend human sight, sound, and warmth—primarily through an understanding of the physical and physiological laws governing them. In doing so, he demonstrated an astonishing ability to synthesize ideas, concepts, theories, and results from various scientific disciplines and people. But while he long hoped to develop an overarching framework of general, empirically supported principles incorporating every branch of science, this vision of the world proved difficult to attain.

Second, Hermann von Helmholtz directed a great deal of attention to epistemological questions; that is, the sources and methods of knowledge. He emphasized the immense importance of discovering and evaluating empirical knowledge by compiling and classifying facts. In light of these aspects in particular, he dedicated most of the first half of his career to studying the anatomy and physiology of the human eye and ear. He compiled the insights that he and others gleaned in the fields of anatomy, physiology, optics, and geometry and, among many other innovations, invented the first ophthalmoscope in 1850/51 to observe the retina of living human beings. (His prestige can be attributed primarily to this invention over any of his other scientific findings or theories.) In his theoretical analysis of the microscope, he also demonstrated that optical resolution is limited in its capacity. And, as a final example, he contributed significantly to efforts to assess the strengths and weaknesses of the German and English electromagnetic theories that were in contention in the middle of the century, brought James Clerk Maxwell's theory to the attention of scientists on the European continent, and was instrumental in helping this theory ultimately becoming generally accepted. As Hermann von Helmholtz himself explained it, a key factor behind his efforts was a psychological need to discover or establish laws within science. Starting in his childhood, he developed this drive to compensate for what he described as the inadequacies of his imperfect memory. This element later became the core aspect of his scientific philosophy. For Hermann von Helmholtz, laws made it possible to understand (and control) nature. In his view, general laws represented the very pinnacle of science, which, consequently, should direct its attention to such laws first and foremost. Two of Hermann von Helmholtz' favorite lines from Schiller's "The Walk" summarize what he saw as the crux of his prosaic work in science in powerful, poetic terms: "Seeks the familiar law in the awful wonders of hazard, / Seeks the immobile pole in the occurrence of flight." In other words, science looked for laws in the empirical wonders of nature.

Influential Helmholtz played an instrumental role in the general acceptance of James Clerk Maxwell's theory of electromagnetism.
Image: picture alliance/Bianchetti/leemage

> He was convinced that the problems addressed by the sciences could ultimately only be solved in a satisfactory manner by the scientific community as a whole.

Third and finally, Helmholtz possessed a fine instinct for the complementary and mutually rewarding roles played by art and science. The arts had been of central importanc e to him since his youth; he played the piano, read literary works, attended theater performances and concerts, and visited art museums to look at paintings and sculptures. As a scientist, he sought to understand the nature of sounds and colors, not least in their expression as music or paintings. He was also interested in how painters intimate spatial depth through the use of colors and by depicting objects at varying distances, and tried to understand how the human eye and ear perceive colors and sounds. He developed the fields of physiological acoustics and optics, using these in turn to arrive at a better understanding of auditory and visual perception. For Helmholtz, the arts represented inspiration and release while also serving, at least to a certain extent, as the object of scientific understanding—that is, a process of give and take. He was convinced that artists express laws in the same way that scientists do, even if these laws can never be articulated in the manner or to the extent that natural laws are.

Hermann von Helmholtz was very multifaceted as a person; but at the same time, he could never come close to solving all the scientific problems that he addressed in his work, just as he was unable to develop a uniform analysis of science as a whole or arrive at a completely satisfactory understanding (for himself or for others) of the complex epistemological principles underlying it. Like Newton before him, Darwin in his own time, or Einstein after him—and likely in the same way as all scientists at any time—Helmholtz was unable to resolve all the scientific problems that spurred him on. He was convinced that the problems addressed by the sciences could ultimately only be solved in a satisfactory manner by the scientific community as a whole. Science, he believed, represented a gain for civilization that would benefit humanity in its entirety. For him, science was a civilizing power. ◆

David Cahan

Text taken from David Cahan's book "Helmholtz: A Life in Science" (Chicago und London: University of Chicago Press, 2018). The German version "Helmholtz: Ein Leben für die Wissenschaft" is due to be released by the wbg publishing house in June 2021. David Cahan is the Charles Bessey Professor of History at the University of Nebraska-Lincoln and spent 25 years working on this biography of Helmholtz.

Image: Evgeny Hantonov/Shutterstock.com

03 THE STEINWAY GRAND

Helmholtz was an avid pianist himself and played for up to an hour every day. He went so far as to link his hobby with his research, for example, experimenting with the strike point while playing, the material of the hammers, the tension of the strings, and the resonance of sections of strings that were not producing sound. Based on this work, piano maker C. F. Theodore Steinway invented a system that resulted in a significantly brighter sound. His so-called duplex scale continues to be used to this day, and it is to this that the unique sound of the Steinway piano can be attributed. Steinway even visited Hermann von Helmholtz in Berlin in 1873 to make small adjustments that enhanced the sound of his piano. A Steinway concert grand that belonged to Hermann von Helmholtz is now on display at the Deutsches Museum in Munich.

04 THE HELMHOLTZ RESONATOR

In his work “On the Sensations of Tone,” Hermann von Helmholtz formulated important findings on modes of oscillation and resonance. His core insight was that there is a root note in every blend of tones. To better demonstrate this, he developed a resonator which amplified the respective root note thanks to an opening in the body of the resonator. The principle behind the Helmholtz resonator is still applied today—in musical instruments, loudspeakers, and apparatuses that dampen low-frequency sound waves in concert halls and conference rooms.

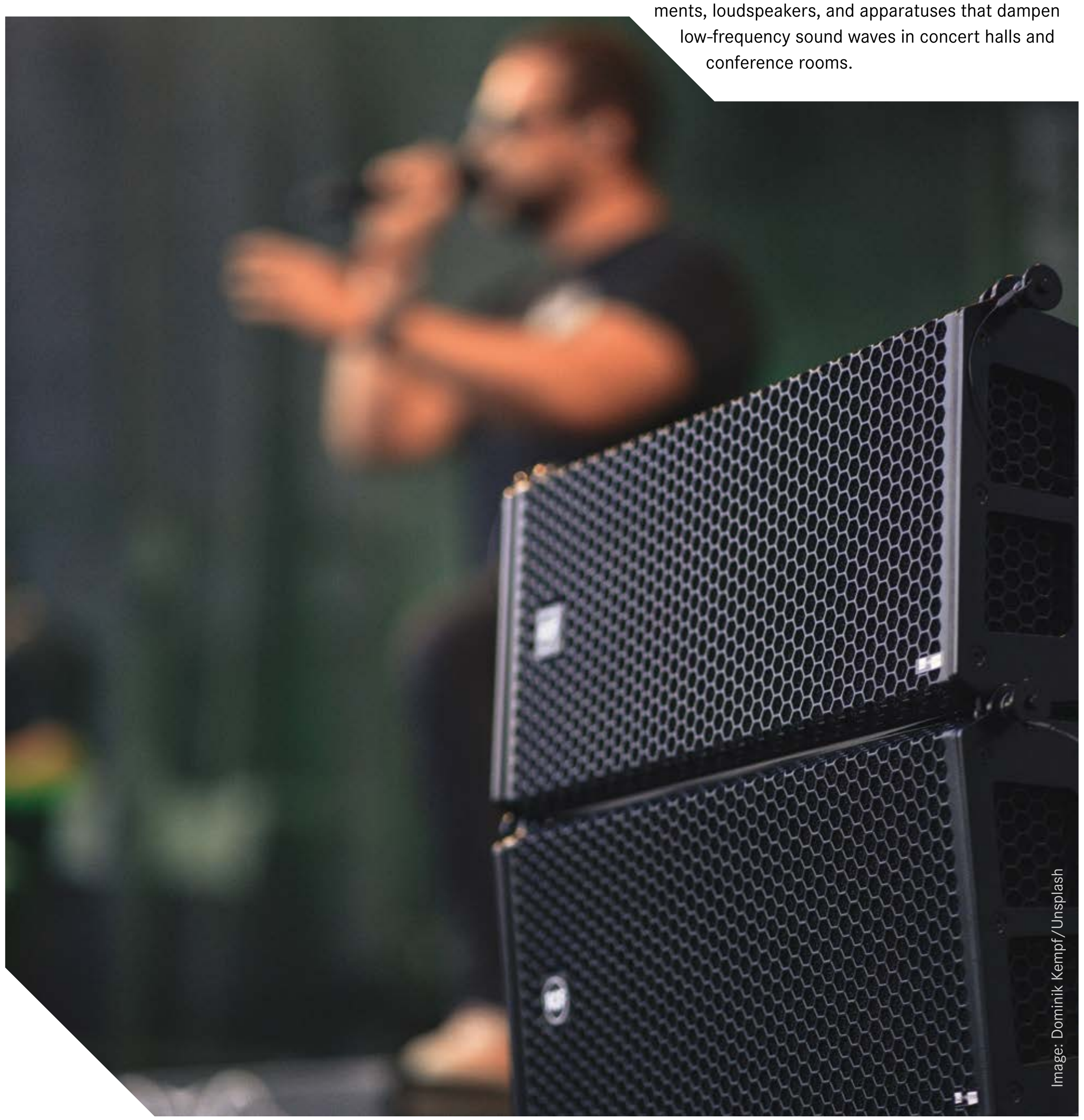


Image: Dominik Kempf/Unsplash

HELMHOLTZ AND HIS ERA

The 19th century was shaped by scientific, technical, and industrial progress, but also by crises. Our infographic outlines **Helmholtz'** milestones and those achieved by his contemporaries.

1804
Richard Trevithick
invents the steam locomotive

1820
Hans Christian Ørsted
discovers electromagnetism

8/31/1821
Hermann Helmholtz is born in Potsdam

1838
begins his training as a military doctor

1842
completes his doctoral thesis on nerve fibers

works as a surgeon at Charité hospital and serves as a military doctor in Potsdam and Berlin until **1848**

1845
Foundation of the Physical Society of Berlin
(known today as the German Physical Society, DPG)

1847
publishes "On the Conservation of Energy" (first law of thermodynamics)

1847
Werner Siemens und Johann Halske
found a telegraph office, marking the start of the Siemens company

1848/49
German Revolution

1849
takes up chair of physiology in Königsberg

marries **Olga von Velten**

1850
constructs the ophthalmoscope

is the first to measure nerve conduction velocity

1850/51
Rudolf Clausius und William Thomson
("Lord Kelvin") independently formulate the second law of thermodynamics

1852
develops the trichromatic theory

1855
takes up chair of physiology in Bonn

1856
publishes "Treatise on Physiological Optics"

1858
publishes findings on vortex motion in fluids

builds an apparatus to determine tones (= first synthesizer)

takes up chair of physiology in Heidelberg

1858
Rudolf Virchow
develops theory of cellular pathology

1859
Death of his wife Olga

1859
Charles Darwin
publishes theory of evolution ("On the Origin of Species")

1860
Louis Pasteur
proves that microorganisms are the cause of many diseases

1861
marries **Anna von Mohl**

1863
publishes "On the Sensations of Tone"

1864
Julius Lothar Meyer
develops the period system of the elements

1867
Karl Marx
publishes "Capital"

1867
Werner Siemens
discovers the dynamoelectric principle, thereby founding the modern field of power engineering

1870
publishes theory of electrodynamics

1870/71
Franco-Prussian War

1871
takes up chair of physics at Friedrich-Wilhelms-Universität Berlin (today: HU Berlin)

1872
Emil du Bois-Reymond
publishes "On the Limits of Natural Knowledge"

1874
determines the theoretical limit of the capacity of microscopes

1876
Robert Koch
publishes his findings on anthrax

1876
Alexander Graham Bell
invents the telephone

1877/78
becomes rector of Friedrich-Wilhelms-Universität zu Berlin

1879
Helmholtz' student **Wilhelm Wundt** founds Institute for Experimental Psychology at Leipzig

Thomas Alva Edison
invents the light bulb

1882/83
1883 conferred the title of nobility and is henceforth known as **Hermann von Helmholtz**

develops theory of the thermodynamics of chemical processes

1883
Imperial Chancellor Otto von Bismarck
initiates German social laws

1884
publishes findings on cyclones and thunderstorms

1886
Helmholtz' student **Heinrich Hertz** proves the existence of electromagnetic waves

Carl Benz und Gottlieb Daimler
invent the automobile

1887
becomes the first president of the newly founded Imperial Physical-Technical Institute (known today as the PTB)

1887
Emil Berliner
invents the record and the gramophone

1890
publishes findings on the movement of wind and water

1893
Otto Lilienthal
develops the glider

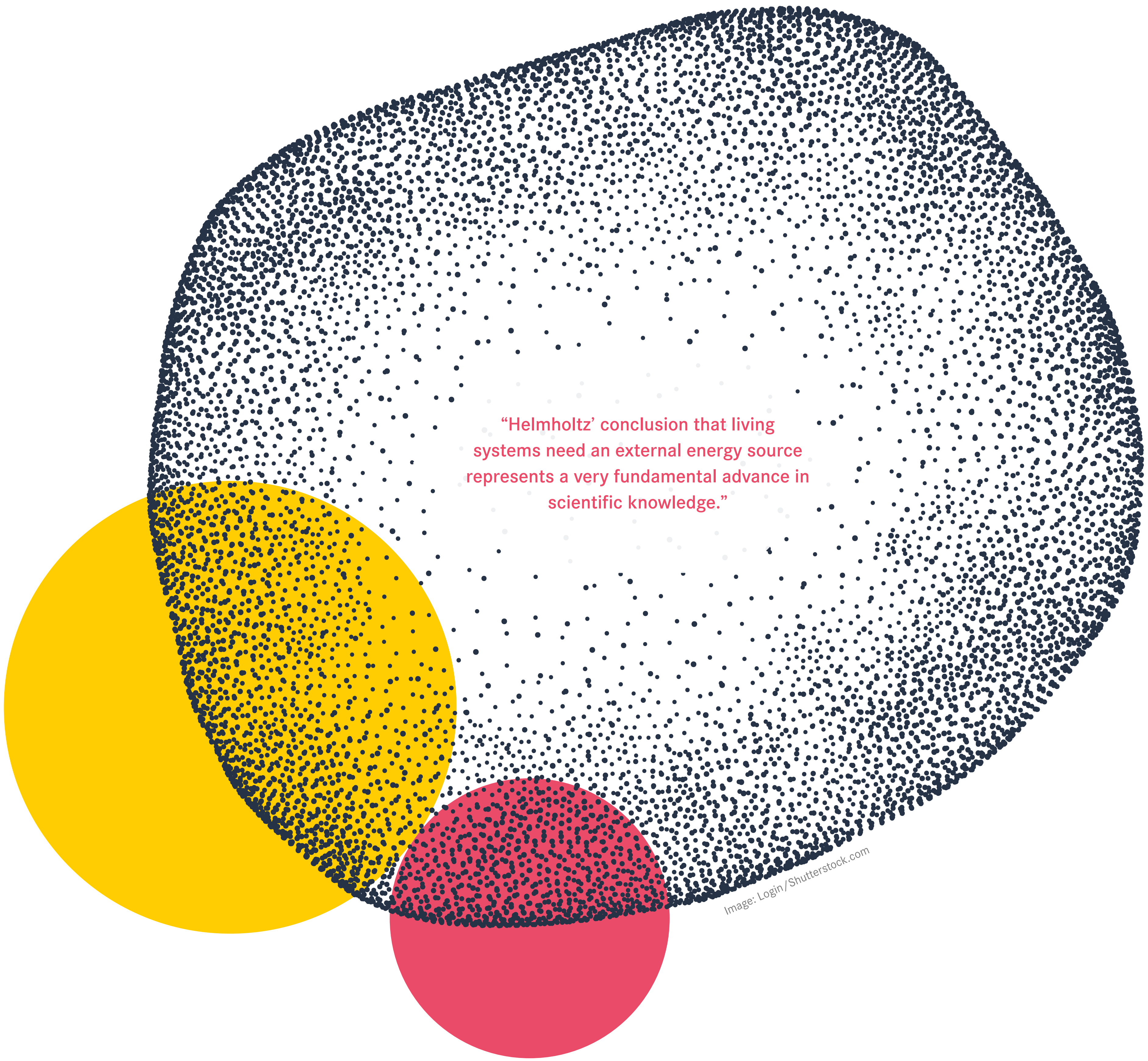
1894
09/08/1894
dies in the Charlottenburg district of Berlin

1895
Freud publishes the "Project for a Scientific Psychology" on the basis of scientific assumptions

Wilhelm Conrad Röntgen
discovers the X-ray

1896
Svante Arrhenius
is the first to predict that global warming will occur as a result of anthropogenic carbon dioxide emissions

Infographic: Julia Blenn; images: The British Railway Locomotive, H.M.S.O. (1804), Siemens AG (1847), Christoph Weber/Berlin (1850), Helmholtz (1858), DaimlerChrysler AG (1886), PTB (1887), Otto Lilienthal Museum Anklam (1893)



“Helmholtz’ conclusion that living systems need an external energy source represents a very fundamental advance in scientific knowledge.”

Image: Login/Shutterstock.com

MEASURING LIFE ITSELF

Hermann von Helmholtz’ research is ubiquitous in the modern field of biophysics. And the questions he studied in his day haven’t changed all that much, either—despite tremendous advances in scientific knowledge.

What is life, and where does it come from? Physiologist Emil Heinrich du Bois-Reymond, co-founder of the German Physical Society (DPG) and a close friend and supporter of Hermann von Helmholtz, saw this question as one of the “seven mysteries of the universe.” Hermann von Helmholtz also studied this question in depth. The majority of physiologists in his day considered the cause of life to be a “soul of life” that maintains a balance between the chemical and physical forces in an organism. But Hermann von Helmholtz wasn’t satisfied with this metaphysical explanation. A soul of life that generates energy out of nothing like a perpetuum mobile? This explanation was unacceptable to him. He demonstrated that energy can be neither created nor destroyed, but only converted into other forms—and the first law of thermodynamics at the universal level was thus born.

“Helmholtz was the first to document the law of energy conservation and conversion and also proved that external energy can be stored in an organism.”

“Helmholtz’ conclusion that living systems need an external energy source represents a very fundamental advance in scientific knowledge,” says biophysicist Petra Schwille of the Max Planck Institute of Biochemistry (MPIB) near Munich. Together with her working group, Schwille analyzes the fundamental characteristics of life at the molecular level. “Helmholtz was the first to document the law of energy conservation and conversion and also proved that external energy can be stored in an organism. Life is able to build up and maintain its own structures by absorbing energy from outside.” For Schwille, this is one of the enduring wonders of nature, because: “Nature actually seeks to achieve a mixed state, in other words, thermal equilibrium.” A cup of coffee is a good way to illustrate this. If you add some cold milk to a hot cup of coffee, the two liquids mix and exchange their thermal energy—until an equilibrium temperature has been achieved, and the milk has cooled the coffee.

“However, the basic building blocks of cells, or living matter, can segregate and establish a permanent order,” explains Schwille. According to the biophysicist, spontaneous mixing like coffee and milk, which is actually natural, can only be “staved off” because life is based on the formation of patterns and converts energy into order and complex structures—that is, an organized interplay between various proteins in a multilayered overall system. It’s a fundamental insight, and one for which Hermann von Helmholtz paved the way to a significant degree.

Christine Rose, a researcher at the Institute of Neurobiology at Heinrich Heine University Düsseldorf, also sees a number of parallels between her work in biophysics and Helmholtz’ own work. “We look at how brain cells work. Our analyses primarily focus on the way nerve cells communicate with what are known as glial cells. Hermann von Helmholtz was also driven by the basic question of how nerve cells work. How do they communicate with each other?” He already analyzed the anatomy of the nervous system in his doctoral thesis and demonstrated that invertebrates’ nerve fibers have their origin in what are called the ganglion cells. He later developed a measuring apparatus that enabled him to determine the conduction velocity of action potentials. These are electrical signals produced by nerve cells, which Rose and her team are still analyzing today—even →

though they now use high-tech methods that would have been inconceivable in Helmholtz' time. For example, she and her team research what happens when insufficient energy is provided to the human brain, for instance due to a stroke, and the brain cells thus lose their capacity to function. Together with her colleagues, Rose is also following in Hermann von Helmholtz' footsteps in another area. She is a professor at the International Helmholtz Research School of Biophysics and Soft Matter (IHRS BioSoft), the graduate school at Forschungszentrum Jülich, which is operated in cooperation with universities, the Helmholtz Association, and the Max Planck Society. If you look at the spectrum of topics addressed at IHRS, you'll find papers on "Self-organization processes in biophysical systems," "Thermodynamic non-equilibrium physics and protein dynamics," and "Biological signal processing"—in other words, the researchers continue to emulate their eponym's scope and interdisciplinary approach to this day.

Self-organization
Neurobiologist Christine Rose studies how nerve cells communicate with what are called glial cells.
Image: Jan Meyer

Andreas Stadler of Forschungszentrum Jülich is addressing the question of life from a different angle. He is a biophysicist and, together with his working group, primarily looks at the dynamics of biomolecules. "We are trying to understand the structure and dynamics of proteins and how they work." Stadler also sees Hermann von Helmholtz as playing a key role in the development of biophysics. "He was the first to apply physical methods in a consistent, systematic way to arrive at an understanding of biological and physiological circumstances." Stadler notes that Hermann von Helmholtz was instrumental in advancing the fields of thermodynamics and statistical physics at the time. He introduced fundamental concepts that are indispensable to understanding physical processes at the molecular level. "One especially noteworthy term is "entropy," which describes the state of disorder or mobility of a system," says Stadler. "And I see a direct correlation to Hermann von Helmholtz' work in this. He sought to understand the mobility of systems at the molecular level and how this dynamic influences the behavior of the system as a whole." In his day, he paid special attention to analyzing ideal gases—single-atom molecules that are not subject to interactions.

"Hermann von Helmholtz would certainly have been amazed at this, but also very pleased."

Today, Helmholtz' developments are transferred to highly complex biological systems such as biomolecules and macromolecules. "Hermann von Helmholtz would certainly have been amazed at this, but also very pleased," the Stadler says. But what is life, then? For Petra Schwille, the researcher at Max Planck in Munich, this question has yet to be answered. There are many different starting points, such as the ability to metabolize (the metabolism) and replicate (produce offspring) or the processing of information and movement, she says—"but we still don't have a fixed set of criteria that we can use to categorize life." Schwille thinks the really exciting question is what prompts life to form structures. "It's quite clear at the molecular level, that is, at the level of proteins and enzymes. But how we end up with the increasingly complex structures that continue to develop in living systems, from cells to tissues and organs up to a complex organism, is still completely unknown."

"How we end up with the increasingly complex structures that continue to develop in living systems, from cells to tissues and organs up to a complex organism, is still completely unknown."

So what are the principles by which living matter organizes and structures itself? Although the answer to this question is essential in order to ultimately answer the key question, "what is life?", Schwille says that progress in this area is moving at a very slow pace. "We still need a fundamentally new theoretical approach in order to grasp the phenomenon of 'life' and the corresponding 'physics in non-equilibrium' at a truly elementary level." For this reason, Schwille is convinced that a paradigm shift is still coming in the field of thermodynamics.

Hermann von Helmholtz would have seen this as only right. He was always open to new things and was aware that: "However, the realm that can be subjugated to the absolute dominion of science as a consummate whole is, unfortunately, very narrow, and even the organic world largely escapes its reach." But this couldn't prevent him from measuring life—and led him to fundamental insights that continue to occupy researchers to this day. ◆

Ilja Bohnet

What is life?
Biophysicist Petra Schwille seeks to establish the fundamental characteristics of life at the molecular level.
Image: Axel Griesch on behalf of MPG

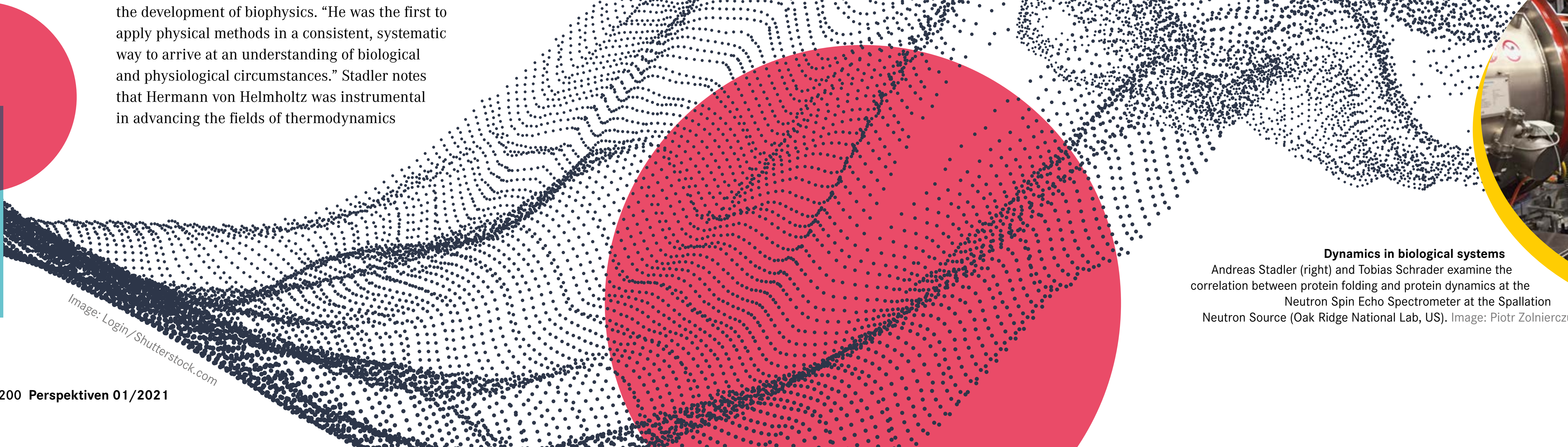


Image: Login/Shutterstock.com

Dynamics in biological systems
Andreas Stadler (right) and Tobias Schrader examine the correlation between protein folding and protein dynamics at the Neutron Spin Echo Spectrometer at the Spallation Neutron Source (Oak Ridge National Lab, US). Image: Piotr Zolnierczuk

FROM HELMHOLTZ' IDEA TO ARTIFICIAL INTELLIGENCE

Does what we see correspond to reality? Or do our eyes deceive us? How can we see and recognize things at all? Hermann von Helmholtz was very eager to get to the bottom of these questions. And his deliberations are highly topical once again, as computer scientists work with the concept of a "Helmholtz machine" to develop algorithms that detect patterns in data—with the goal of creating an artificial intelligence that actively learns.

Right at the start of his career, as a newly minted professor of physiology in Königsberg, Hermann von Helmholtz set up ingenious experiments with the aim of measuring the impulse conduction velocity in nerve cells. He invented the ophthalmoscope, with which he established his reputation. At the same time, he was considering a question that appears to be of a more philosophical nature: How do we progress from sensory impressions to perceptions, to a conscious image of the world?

> "Helmholtz was one of the first to note that seeing is not a passive process."

Hermann von Helmholtz was a keen observer, and he didn't fail to notice how easily our senses are deceived. What we perceive isn't identical to reality. Not only was Helmholtz familiar with optical illusions; he also knew a few magic tracks, as he enjoyed taking in magic shows with his friends. "Helmholtz was one of the first to note that seeing is not a passive process. When something catches our eye, an accurate copy of it is not produced in the brain," says Jenia Jitsev, a neuroinformatician at Forschungszentrum Jülich. Optical illusions are a good example of this. "Even if we know it's an optical illusion, we still see the effect. In order to stop the illusion, you have to cover part of the image. In other words, you have to block some of the sensory stimuli to recognize that the overall image is an illusion," explains Jitsev.

The idea that the image humans see of the world isn't objective was not a new concept. Plato had already discussed this in the "Allegory of the Cave." Immanuel Kant refined the idea, stating that in order to form a thought, it is necessary to lend structure to the chaos of our sensory impressions—based on existing notions of space, time, and causality. Helmholtz, who read Kant's works very closely, appended his own observations on learning. In a lecture on the facts of perception, he explained: "The less intellectually able animals are, the faster they learn that which they are capable of learning at all. The newborn human child is extremely unskilled at seeing; it requires several days for the child to learn to judge the direction of the visual image towards which it must turn its head so as to reach the mother's breast ."

Where instinct proves inadequate, Hermann von Helmholtz thus suggested, a living being must continually reassess impressions from the environment to determine how it should behave. It does this by deducing what could occur next on the basis of previous experiences. Then, it compares the sensory perceptions with this prediction. The comparison takes place unconsciously, Hermann von Helmholtz presumed, writing to his friend Emil Du Bois-Reymond: "A hopeless case, because it requires that one embark on psychological considerations to a significant degree."

> "The assumption is that every organism tries to avoid surprises."

Let's consider an example from everyday life: The child has fallen asleep, and its father now makes his way quietly out of the room. Presumably, he is aware that there are blocks of Lego on the carpet—he sees their brighter edges shining in the low light and steps over them.

But he only sees the bright piece of banana after he has stepped in it. He didn't expect it, and he therefore didn't perceive it either. This model →

Deceptive When you tilt your head, the image appears to move. But covering half of the picture causes this effect to disappear. Image: Andrey Korshenkov/Shutterstock.com

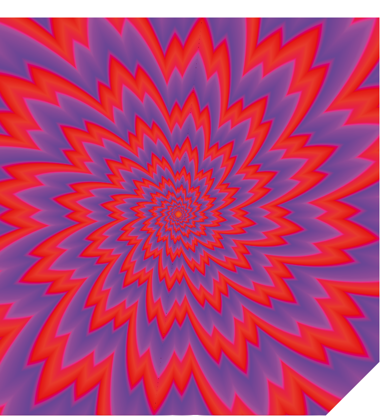
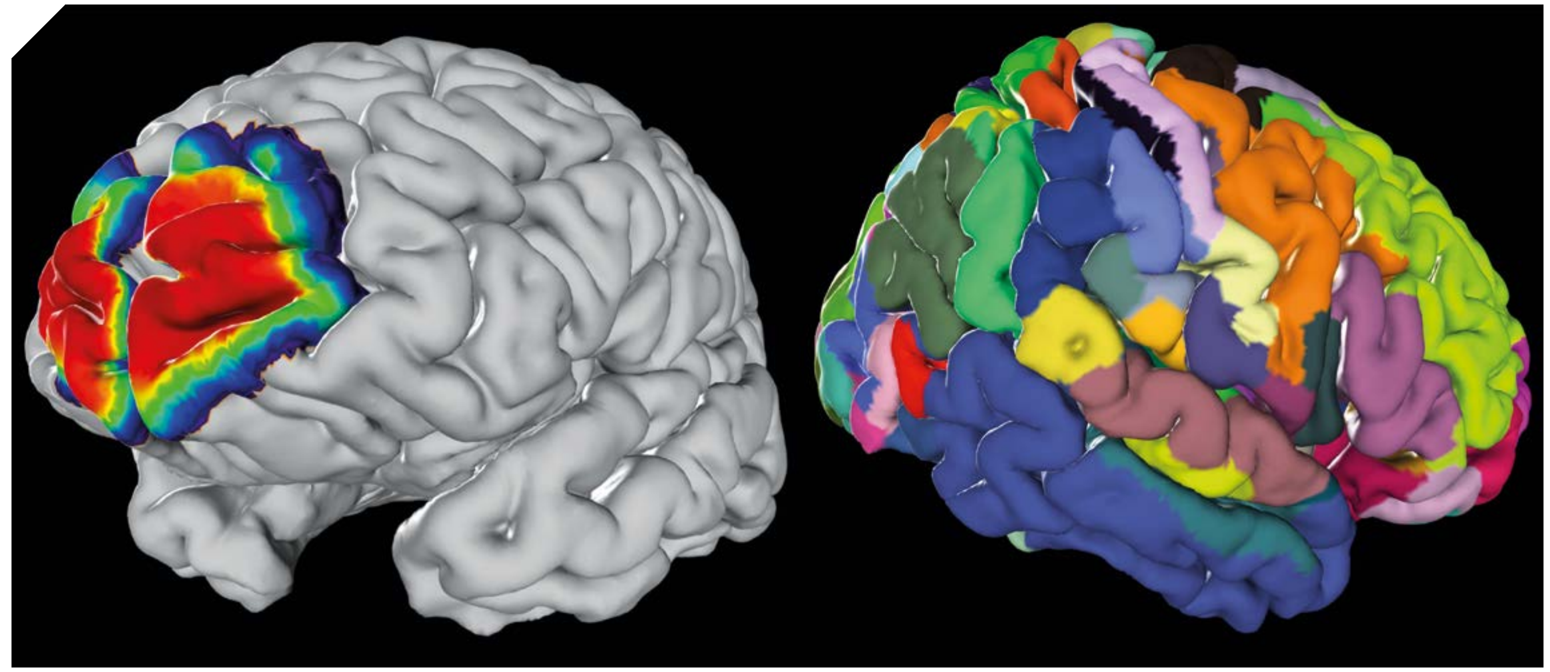


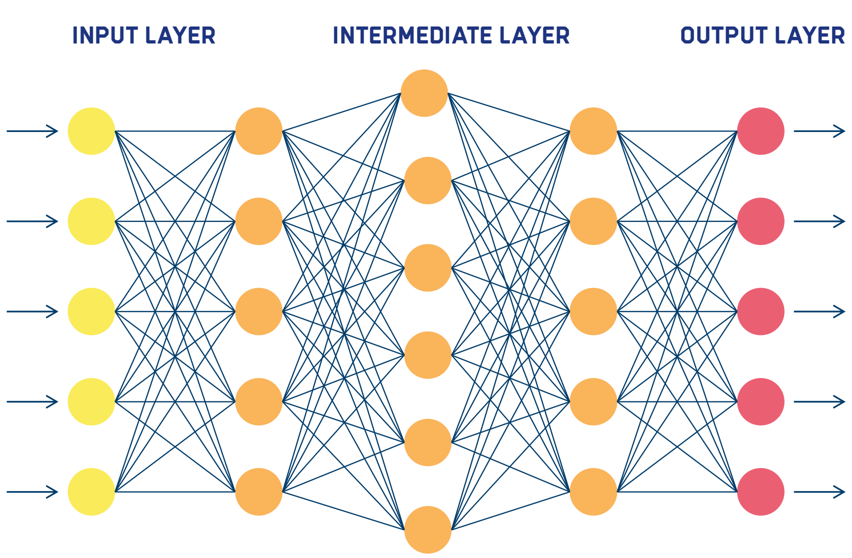
Image: Heidelberg University Archives / Collage: Helmholtz



Intelligent assistant
An AI can help researchers identify areas of the brain. Image: Forschungszentrum Jülich/Katrin Amunts

of perception is well established today in cognitive psychology and in the neurosciences. Neuroscientist Karl Friston formulated it in mathematical terms as an optimization problem a number of years ago, referring to the concept as a "Helmholtz machine." "Karl Friston's model builds on the ideas put forward by Hermann von Helmholtz. The assumption is that every organism tries to avoid surprises," says computer scientist Timo Dickscheid, who is working with his team at Forschungszentrum Jülich to develop a program for neuro-research based on artificial intelligence (AI). "But this is difficult, because the organism only ever knows a small section of its environment, and never the entire world. As a result, the organism sets out with an intrinsic model of the world, which it then improves with the help of sensory information so it can avoid surprises wherever possible."

To go back to the father in the dark in his child's bedroom: At first, his intrinsic model only includes Lego blocks. It is only when he steps on the banana that he obtains information that doesn't fit the model and requires that he modify it. In other words, the surprising perception of the banana has a much stronger influence on his learning than the Lego blocks he was expecting—and this is very efficient in terms of learning.



How neuronal networks learn Typical structure of a "deep" artificial neuronal network, which forms multiple layers of artificial neurons. The neurons in a given layer transmit stimuli to the next layer via the connections. Image: FZ Jülich/Tobias Schlößer

But there is an aspect that Hermann von Helmholtz never could have dreamed of in his time: Today, living beings aren't the only ones capable of learning; machines are too. They use algorithms or models that are partially inspired by the Helmholtz machine. "We still don't have a general model today that delivers very good predictions in every case," says Fabian Theis. The physicist from Helmholtz Zentrum München heads up the HAICU initiative, in which teams of researchers collaborate on the topics of AI and machine learning. "Either the model is simple and easy to understand, but then the predictions are somewhat poorer, or you have to do without good comprehensibility and optimize the results. That's the dilemma."

So far, AI programs have been trained extensively using examples, from which they then learn. This is supervised learning. Programs that evaluate and interpret medical images are already very successful. Theis and his working group have developed a learning program that analyzes images of the ocular fundus and is capable of detecting early signs of pathological changes. This is particularly helpful for patients with diabetes, who are at high risk of losing their sight. "The program works well, and we're also seeing the criteria it uses as the basis for classifying the level of risk. That is, it focuses specifically on regions with veins, which is where problems typically occur," Theis explains. However, this method of supervised learning requires millions of learning examples in order to train the task. Timo Dickscheid, the Jülich researcher, has to take a different approach in his project. "We have microscopic images of brains and want to use these to create an atlas of the entire human brain, a map of all the areas with a resolution at the level of individual neurons. It's not something we can do with human power. But because it would take such an incredible amount of effort to determine individual areas by hand, we are also unable to show the AI how it can recognize an area on the basis of millions of examples," Dickscheid says.

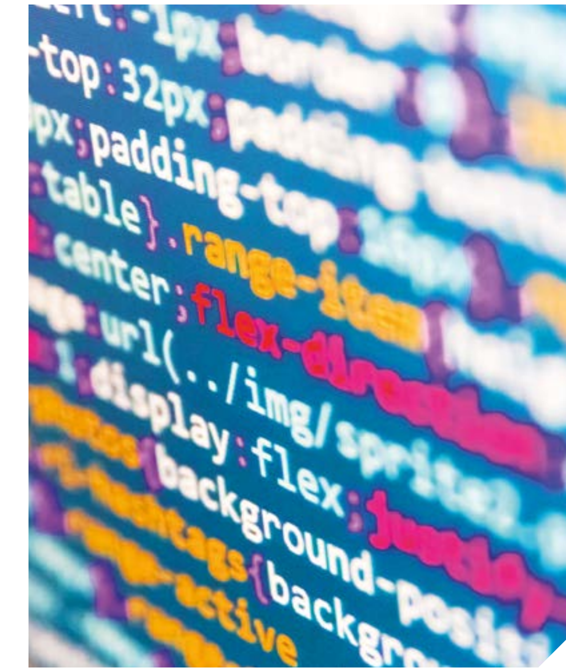
This is why he is deploying a new strategy: self-supervised learning. With this type of learning, the artificial intelligence generates its own learning examples by observing and analyzing high-resolution microscope images of brains. For example, it is able to detect differences between the part of the cerebral cortex that enables visual perception (visual cortex) and the part that coordinates movement (motor cortex).
"The system learns, for instance, that cells in the visual cortex have a different arrangement than in the motor cortex. It uses this approach to acquire experiential knowledge," the computer scientist explains.

> "While AI systems can continually improve their results at present, they do not observe their own learning process."

In science fiction films or books, an artificial intelligence is usually a being with its own will that leaves humanity far behind it. But that's only fiction for the moment, says Jenia Jitsev: "While AI systems can continually improve their results at present, they do not observe their own learning process." Only when an AI system is able to assess mistakes and independently inquire about missing input will algorithms also be able to take on creative tasks, such as writing texts. This already works quite well for factual texts, as demonstrated by the GPT3 text generator being developed in the Open AI community project. "It calculates which word is likely to come next and is already able to carry out some tasks using this method," says Jitsev. Describing his vision, he says: "I do think we'll have systems in the future that will be at least as capable as we are of learning from the world." Such systems could then be used for missions to Mars, for example, which humans wouldn't be able to survive in good health. But perhaps it could even be used for creative tasks or for making political decisions. In that case, humans would merely be consumers.

These considerations concern Timo Dickscheid: "Even today, AI is finding potential solutions that humans wouldn't have thought of for some tasks. That's a good thing, because this will hopefully put us in a better position to overcome fundamental problems." The flip side is that in that case, humans would have less and less of an insight into how an AI arrives at its results. "How can we make sure that we're still the ones controlling AI systems and that we can prevent malicious developments or ensure that powerful technology doesn't fall into the wrong hands?" It's a question that would certainly have preoccupied Hermann von Helmholtz as well, the universal researcher who was well-versed in philosophy, and whose credo was always that science should be used to the benefit of humanity. ◆

Antonia Rötger



Creative The GPT3 text generator calculates which word could come next and can create texts on specific topics on this basis. Image: BEST-BACKGROUNDS/Shutterstock.com

NOTHING IS LOST

Researchers once stumbled upon the idea that energy is never lost while trying to understand how steam engines work. Hermann von Helmholtz formulated the principle of the conservation of energy some 150 years ago in his work "On the Conservation of Energy." Today, the principle of energy conservation is fundamental in the field of physics—both in cosmology and in particle physics.

Crucial The Higgs field is of fundamental significance to our universe: It plays a key role in the fact that most elementary particles have a mass. Image: 2013 CERN

"That I may understand whatever / Binds the world's innermost core together [...]" This was the primary objective of Goethe's protagonist, a universal scholar, in Faust. To achieve it, Faust devoted his energies to magic. Particle physicists today are seeking an answer to the same question, though with very different means. At the most powerful particle accelerator in the world, the Large Hadron Collider (LHC), located underground in the foothills of the Jura mountain range on the border between France and Switzerland near Geneva, researchers explore this question by blasting protons or entire atomic nuclei into each other at virtually the speed of light. When the particles collide, they break apart, and vast quantities of new particles are created.

One of these particle physicists is Thomas Naumann from the German Electron Synchrotron DESY, where he analyzes the structure of protons. Naumann also coordinated communications for the LHC in Germany for many years. "The physics that we do there is very complex, and it's impossible to properly communicate what our work involves in a few minutes much less seconds, as many people expect today," he says from experience. "Sometimes, you need to explain a bit more."

Using detectors such as the ATLAS experiment at the LHC allows researchers to track down the elementary particles of matter and investigate the fundamental forces working between them. The question of which and how many elementary particles the researchers can generate in their experiments depends on the energies they apply when they fire the protons into each other. This is because the more energy-rich a collision is, the richer the end products are in mass. Once energy has been directed into a collision, it isn't lost—rather, it is converted into the masses and kinetic energies of these end products.

Initially, naturalists in a wide range of disciplines could only guess at certain assumptions that modern physics now builds on as a matter of course. In 1842, Julius Robert Mayer, a doctor in Heilbronn, Germany, was the first to state that the energy in a closed system remains constant. His work received very little recognition at first. Some years later, in 1847, Hermann von Helmholtz formulated the principle of energy conservation in greater detail in his paper "On the Conservation of Energy." He was also the one who associated electrical energy with chemical energy and thermal →

energy as well as describing energy conservation by means of physiological processes such as muscle strength. Energy is also maintained when it is converted from one form into another.

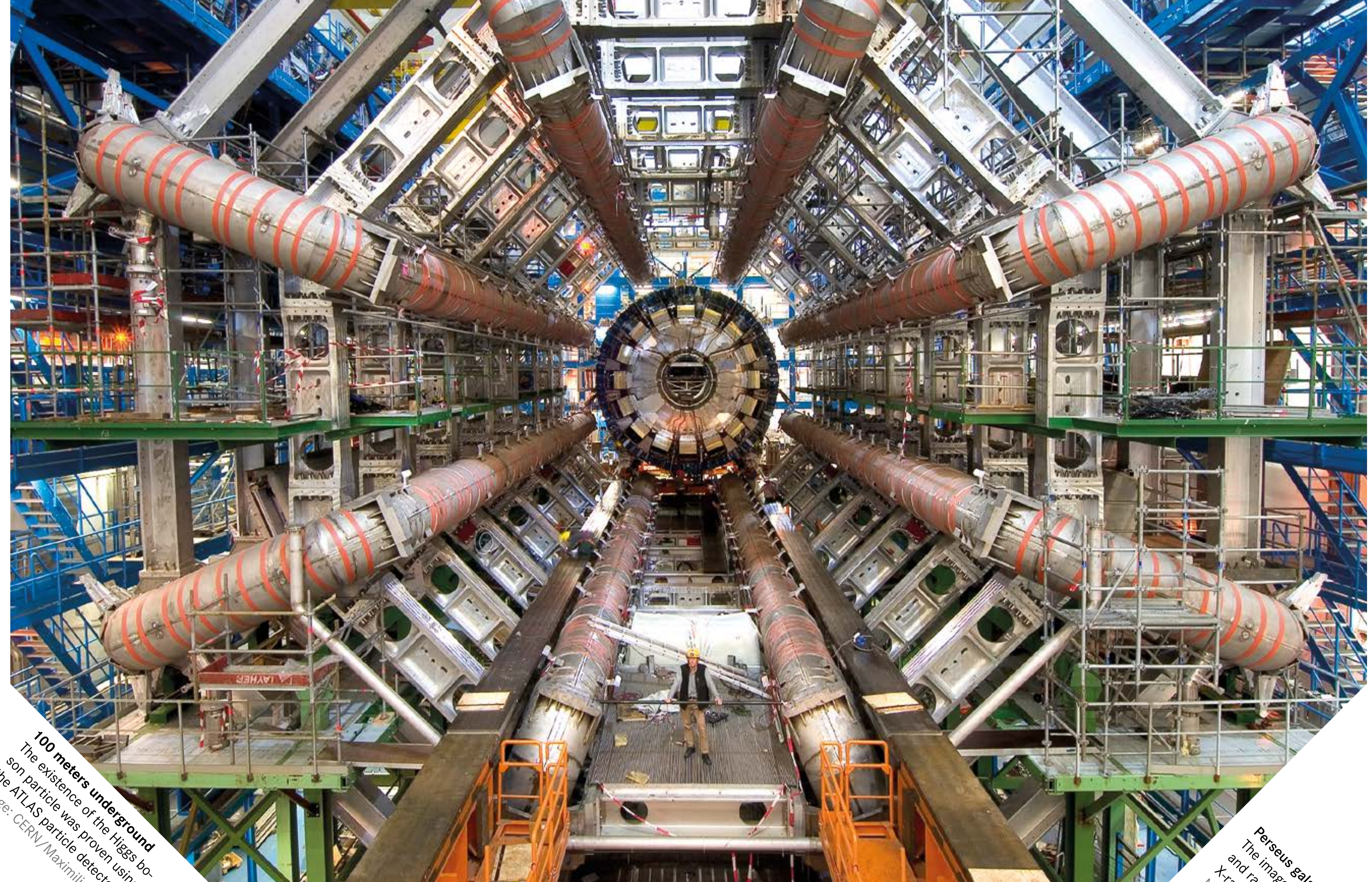
Today, the principle of energy conservation has long been established as the first law of thermodynamics and proves highly useful in the various areas of modern physics, both in particle physics and when it comes to considering the big picture as a whole in cosmology. "To start with, energy conservation was a purely empirical aspect that scientists came across partly in the context of the physics of steam engines," says Thomas Naumann. "But it's actually something quite fundamental."

> "Energy can be neither created nor destroyed. It can only be converted from one form into another."
> *Hermann von Helmholtz*

More than half a century after Helmholtz, German mathematician Emmy Noether set out the conditions for energy conservation as well as other physical conservation quantities in an ingenious fashion in the language of mathematics. "The Noether theorems always leave me awestruck," says physicist Naumann. "They back up the principle of the conservation of energy in a very elegant way in mathematical terms."

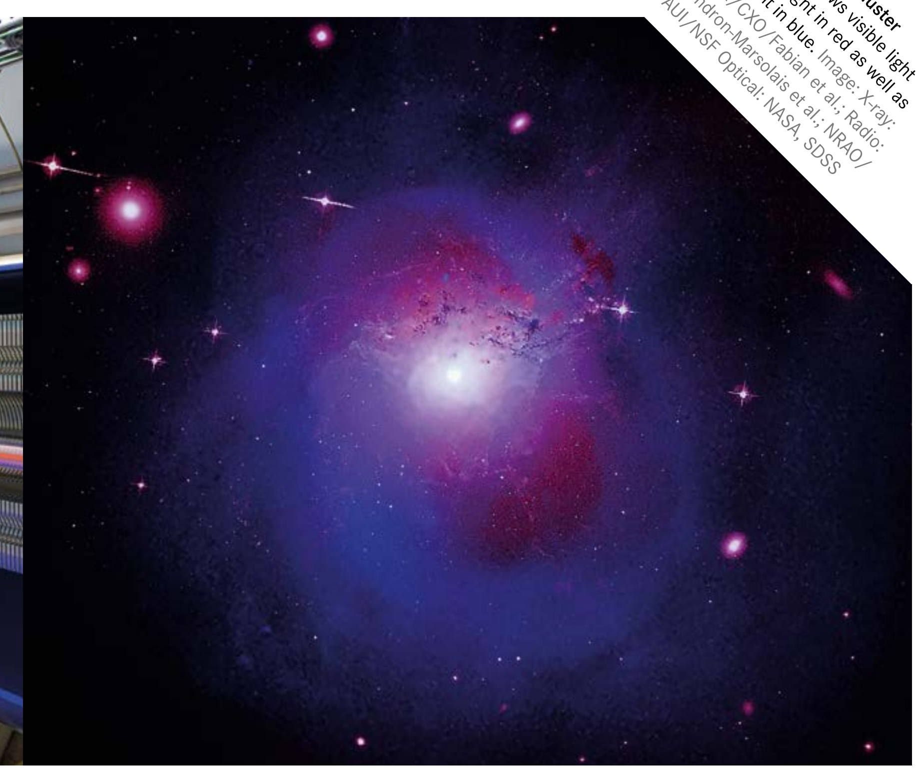
Noether's theorems serve as the starting point for a wide range of other conservation laws, including momentum and angular momentum as well as many other physical variables that determine the rules of particle physics at the elementary level. These laws also determine which particles are generated in the high-energy collisions in the LHC.

Even in the past, the energy conservation principle proved advantageous for particle physicists on a number of occasions. In the 1920s, some physicists thought that a type of radioactive nuclear decay, beta decay, contradicted the energy conservation principle. The electron emitted during the conversion of a neutron into a protein did not appear to carry sufficient energy. Austrian physicist Wolfgang Pauli believed the principle of energy conservation was correct and explained the phenomenon in 1930 by means of a particle that had not been observed thus far. He suggested



100 meters underground
The existence of the Higgs boson particle was proven using the ATLAS particle detector.
Image: CERN/Maximilien Brice

Accelerator rings
The tunnel tube of the LHC measures 27 kilometers in circumference.
Image: 2014 CERN



Perseus galaxy cluster
The image shows visible light and radio light in red as well as X-ray light in blue. Image: X-ray: NASA/CXO/Fabian et al.; Radio: Gendron-Marsolais et al.; NRAO/AUI/NSF Optical: NASA, SDSS

that this particle, the neutrino, was also emitted during beta decay and carried the missing energy along with it. The existence of this almost massless elementary particle was only proven in 1956.

Researchers today are once again on the hunt for as yet unknown particles. But the clues they pursue now come less from the particles themselves; rather, they lead into the depths of the cosmos. Astronomers have long observed that galaxies and clusters of galaxies here move in ways that can't be explained simply by the gravity of visible matter. Likewise, the deflection of light from quasars by clusters of galaxies is stronger than the mass of the visible matter in the clusters would allow on its own. Researchers believe that so-called dark matter accounts for the missing share of gravitationally effective mass.

> "As we look for particles of this mysterious dark matter, we use the energy conservation principle and check whether energy has disappeared from the detector without our seeing it."
> *Thomas Naumann*

According to their assumptions, this dark matter could consist of a new type of particle that adds gravity but does not impact other interactions. Because these elementary particles also do not interact with the electromagnetic force, they do not emit any light and are invisible. Physicists hope to track down these dark matter particles at the LHC or at an even more powerful accelerator in the future. And the principle of energy conservation is helpful in these efforts as well. "As we look for particles of this mysterious dark matter, we use the energy conservation principle and check whether energy has disappeared from the detector without our seeing it," explains Thomas Naumann. This is because, unlike the elementary particles of typical matter, their existence cannot be proven through known interactions. The search is set to continue for years to come. ◆

Felicitas Mokler

05

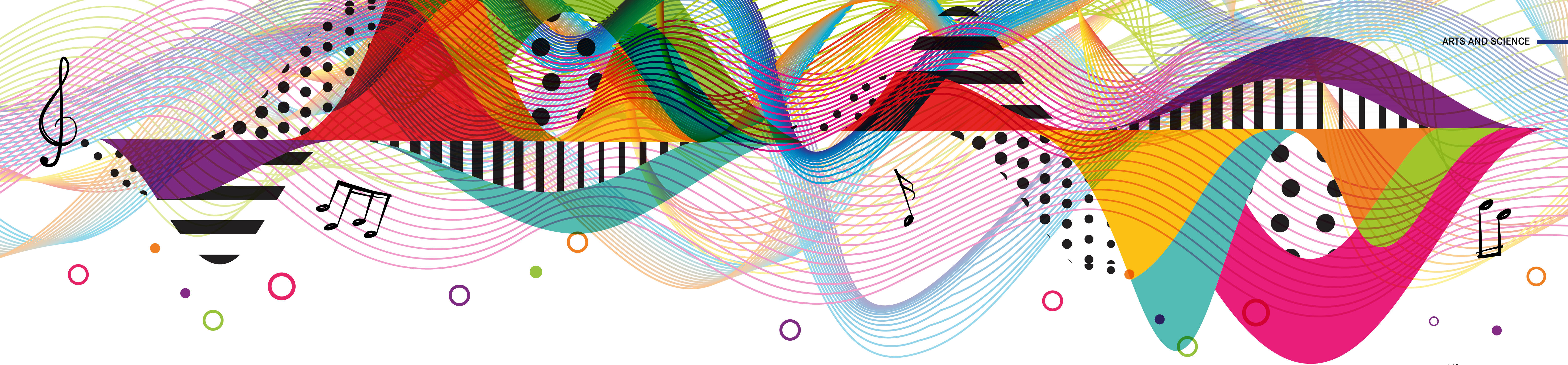
VORTEXES, WAVES, AND WEATHER

Hermann von Helmholtz sought to describe a wide range of natural phenomena in physical terms. Even on a vacation to the beach, he spent hours studying the movement of the waves. In his theory of vortexes, he described the movement and behavior of vortexes in liquids in precise mathematical terms, thereby providing key fundamental principles for hydrodynamics. He transferred his physical concepts to other natural phenomena and is considered one of the founding fathers of modern meteorology thanks to his studies on cyclones, thunderstorms, waves of air and water, and glaciers.

06

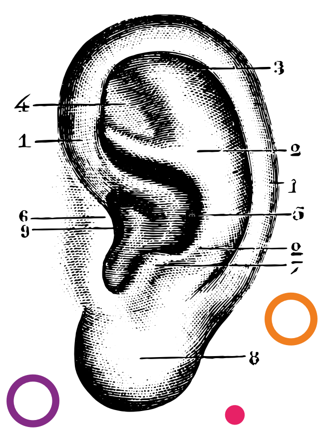
INCREDIBLY CHANGEABLE

Energy occurs in various forms, including radiation from the sun, as heat, as the energy of the wind's motion, and as chemical energy stored in carbohydrates. These forms of energy can be converted into one another. For example, heat is produced when the atmosphere absorbs solar radiation. The air that is heated in the process becomes lighter, rises, and is partially converted into the movement of the air. But the overall quantity of energy remains the same in any energy conversion that occurs. This principle is known as the first law of thermodynamics. Hermann von Helmholtz was the first to set out this law in a universal and mathematically formulated form.



THE RESEARCHER, THE PIANIST

Hermann von Helmholtz was an avid pianist and continually brought art and science together in his research. His writings on the subject were groundbreaking and are considered standard works to this day.



It was the summer of 1876, and Hermann von Helmholtz was attending the first Bayreuth Festival with his wife Anna. Anyone who was anyone was in town, "all of our good friends together, all the artists, Menzel, Meyerheim, Mackart, Lenbach," Anna enthused in a letter to her children. She later visited Richard Wagner in person at his home. "Liszt was there and many lovely, brilliant people," Anna continued in her letter. "Then Liszt played, and it was beautiful beyond words." Hermann von Helmholtz himself venerated Beethoven most of all and also enjoyed playing Mozart's works on the piano—but given how shy he was, he preferred to play alone rather than for an audience. He also enjoyed singing, even though it seems his singing wasn't great. "A person who loves and feels music but is unable to make it happily commends those who love, feel, and make it," he modestly said of his abilities.

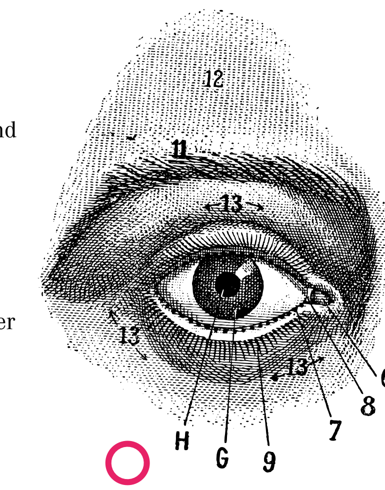
Music, painting, poetry, and theater not only served as a means of relaxation and contemplation for Hermann von Helmholtz—they carried a greater significance for him. In his pursuit of truth, he considered art to be an equal of science, even though he believed the arts sought knowledge by different means. Artistic expression, he said in a speech at the general assembly of the Goethe-Gesellschaft in Weimar in 1892, is even richer, more exquisite, and vivid than scientific representation. And in this same vein, he looked to the arts for inspiration in his scientific work. From early in his career, he sought to understand the nature of tones and colors and their physiological sensations.

> "Helmholtz saw very clearly that there doesn't need to be any resemblance between the signs and that to which the signs refer."

Art scholar Robert Kudielka came across Helmholtz' work in his research on Impressionism. Kudielka is a member of the Akademie der Künste, Berlin and is particularly interested in abstract painting and visual perception. "Helmholtz saw very clearly," says Kudielka, "that there doesn't need to be any resemblance between the signs and that to which the signs refer. It's a huge and very important insight, which has yet to sufficiently permeate the history of art to this day." He is particularly impressed by Helmholtz' insight that we by no means see a copy of the world but rather an interpretation of signs that our eyes sense physiologically and are constructed into a visual image without our being aware of it. In his lecture "On the Relation of Optics to Painting," Hermann von Helmholtz applies these insights to the art of painting. The painter's image is not a mere likeness of the object, "but a translation of his impression into another scale of sensitiveness, which belongs to a different degree of impressibility of the observing eye, in which the organ speaks a very different dialect in responding to the impressions of the outer world."

Kudielka waxes lyrical when discussing these sentences. They show, he says, that Hermann von Helmholtz understood the abstract nature of art—by which he is not referring to abstract art, but rather the intrinsic abstractness of creating images. "Specifically, the way signs in the visual arts actually work in relation to what they signify." Moreover, he continues, Helmholtz' statement carries significance for the cognitive sciences. "His words suggest that there is more to perception than just geometric optics—perception also represents a cognitive act of translation," says Kudielka.

Hermann von Helmholtz' writings are also fascinating to Günther Wess. A chemist and pharmacist, Wess was the scientific director of Helmholtz Zentrum München until 2018—and is a trained church musician. "Helmholtz was likely the first to do so when he recognized in the 19th century that that brain pieces together information from the various sensory systems and unconsciously draws conclusions on this basis," says Wess. He came across quotes by Hermann von Helmholtz while reading texts written by American composer Charles Ives, who continually referred to "On the Sensations of Tone" by Hermann von Helmholtz. Wess delved ever deeper into Helmholtz' research in this area and even wrote a book on the subject. "Helmholtz played the piano for at least an hour a day, was aware of major musical developments, compositions, and their composers, and was familiar with the theories of harmony and music. He therefore had a well-trained ear and an acute sensitivity for sounds." Helmholtz published "On the Sensations of Tone" in 1863, a comprehensive work covering 600 pages. Wess believes that no document has compared to it to this day. The work deals with the physical principles of tones and sounds, the physiology of the ear and the processes of hearing and perceiving, as well as philosophical questions pertaining to aesthetics and tonality. "With this work, he set in motion pioneering developments that continue to have an impact today," Wess says, pointing to composers in the new music movement, who used musical instruments in unusual ways to integrate new tones and sounds into their music and combined them to create complex tonal structures—from Ferruccio Busoni, Karlheinz Stockhausen, and John Cage to spectral musicians like Gérard Grisey. In spectral music, sound and its physical formation are paramount—melodies are almost irrelevant. Wess finds it impressive that Hermann von Helmholtz, who paved the way for these developments to a certain degree, was →



ONLINE

To read the full expert interviews (in German), visit:

→ www.helmholtz.de/kunst-wissenschaft

Original Günther Wess, himself a musician, plays Helmholtz' grand piano, which is now on display at the Deutsches Museum in Munich.
Image: Günther Wess

always receptive to change even though he personally embraced the aesthetic ideal of classical music and the principle of a classical tonality. "He always emphasized that music must not adhere to a set of musical rules. Hermann von Helmholtz was open to new developments and continually sought the new."

But what does Helmholtz' examination of art mean for the relationship between art and science—can the two disciplines find common ground? Art scholar Robert Kudielka from Berlin tends to be more cautious here. "Science looks for empirical certainties and is focused on moving forward. Art is the opposite. Not in the critical sense—rather, it produces something that is lacking in its time." Kudielka sees the subjective way humans perceive the world in contrast to the objectified way science perceives it as a major point of friction. "And it's extremely interesting to go back to Hermann von Helmholtz and think about his reflections on perception."

Sibylle Anderl also looks at the relationship between science and art. She studied philosophy, wrote her doctoral thesis in astrophysics, works as a journalist, and originally considered applying for a university place to study art. Her father is an artist, and Anderl has always enjoyed drawing. But she loves mathematics just as much, and this ultimately led her to the sciences. Six years ago, she started a special experiment that brought together four pairs of scientists and visual artists. These pairs looked at a shared topic from their own perspectives. Anderl called the project—in which the participants addressed the topics of sound, life, clouds, and human psychology—"WissensARTen" (KnowledgeARTs). She stresses that artists create freely and can express this diversity in very individual ways. "Scientists, on the other hand, categorize their observations in order to arrive at generalizations." But this is exactly why Anderl thinks there are good reasons to bring art and science together. "The arts can help science to develop a differentiated and enlightened viewpoint on its own methodologically restricted discipline," she says. And the same applies in reverse, of course: Artists can also draw inspiration from science.

In exchange Photographer Herlinde Koelbl speaks with psychiatrist Leonhard Schilbach as part of Sibylle Anderl's "WissensARTen" project.
Image: Sibylle Anderl

Anderl sees language as playing an important role in the mutual understanding between art and science. Misunderstandings frequently arise on both sides in the course of communication because terms can be used in different ways, have a different context, and provoke different associations.

> "Philosophy serves as common ground on which players from the arts and sciences can exchange their views."

This is why Anderl had each scientist/artist pair in her WissensARTen project meet without moderation or direction. Everyone on the project was worried at first that they would have nothing or very little to say to each other. "But after some initial struggles, things got going; the discussion really picked up intensively between everyone on the project, and it actually became quite difficult to separate the pairs in the end," the journalist says. Anderl finds it especially interesting that the conversations between the pairs very quickly shifted to the philosophical level. In other words, philosophy serves as common ground on which players from the arts and sciences can exchange their views in a situation like this one. It offers a way of communicating as equals—which is something that Hermann von Helmholtz also understood. The salons that his wife Anna organized brought artists and scientists together even in their day. After all, communicative exchange opens up a nuanced view of the world. ◆

Ilja Bohnet & Franziska Roeder

ANNA VON HELMHOLTZ (1834–1899) married Hermann von Helmholtz in 1861. She was his second wife and had three children with him: Robert, Ellen, and Friedrich Julius (Fritz).

Illustration: Sylvia Wolf

"I WAS NEVER A QUIET WIFE, I WANTED TO TAKE PART!"

Anna von Helmholtz was a personality: While she was best known for the person she was married to, her legendary salons were the prototype of upper-class sociability in her time. The following is a fictional interview with Anna after her husband's death at the end of the 1890s, reconstructed from her surviving letters, discussing her husband's role, her own ambitions, and the narrow constraints of her time.

Baroness von Helmholtz, may I address you as Mrs. von Helmholtz?
Anna von Helmholtz (AvH): Of course, cultivated intercourse shines in its simplicity.

Thank you! You are a fascinating woman—the wife and companion of one of the most famous researchers of the 19th century; you come from one of the best families but nonetheless remain in the background. Can you—as your husband did with his research into optics—shed some more light on this matter?
AvH: Gladly, if it would be of help to you.

When Hermann von Helmholtz was appointed to his position at the university in Heidelberg in 1858 and you met one another—how well prepared were you for the tremendous task of being his companion? After all, he was globally acclaimed and had audiences with heads of state, kings, and emperors.
AvH: My father, Robert von Mohl, was a statesmen, my uncles were scientists, my brother was in the diplomatic service. The conversations our family had around the table were my university. Women were not allowed to study, unfortunately, but education was still very important to us. My parents sent me to live with my aunt in Paris for almost two years, where I made the acquaintance of her salon and so many interesting people. I also spent time in England.

And would you have liked to have become a researcher yourself then?
AvH: I would have found it interesting, but it would have been most unusual. And I also did not wish to compete with my husband. At the same time, Hermann was ahead of his time, because he regarded women as equal in his research. His first wife worked as an assistant with him in the laboratory in Königsberg. I did not spend time with him in the laboratory. We married quite quickly, I had his first two children to care for, the house to keep, and then our own children Robert, Ellen, and Fritz were born. Nonetheless, we often spoke of scientific matters in our conversations as a married couple—and we shared this enthusiasm with our children. Intellectual work and intelligence were immensely important to Hermann and myself in our personal lives as well—this was our way of elevating our life together above the banality of the day-to-day.

You prepared scientific translations, which requires a profound understanding of the subject to hand.
AvH: Of course, I spoke with Hermann about his research quite often, and discussed more general questions—such as how little we know about light, that one cannot see ether, the interrelation of the body and soul, and how one can perceive the world. And I worked on the translations at Hermann's request and under his supervision; I did not always understand every aspect of the subject. On one occasion, I managed to translate a text by Tyndall, the British physicist, so well that he gave me a pearl brooch as a token of his appreciation. In other words, I was never the quiet wife at meetings with Hermann's colleagues; I wanted to take part. But women were often quiet at the table, as was the case when I hosted dinners that were attended by a great number of educated men and uneducated woman. Our company only became animated when we spoke of the fine arts.

So your husband considered you to be responsible for more than the fine arts?
AvH: In the many years we spent together, he considered me to be an earnest conversation partner. When he wasn't too tired, we spoke a great deal with each other. We both enjoyed it very much. I was his link to the outside world. His replete tranquility also meant great responsibility for me, as I had to manage our day-to-day life and shield him from bothersome visitors as well. After he came to Berlin, I scarcely saw him. He was exhausted when he came home at night; ate, slept, and had to attend meetings three or four times a week. He was truly hounded, and it wasn't what you could call a life. Fortunately, that changed when they finally built our Institute (the Physikalisch-Technische Reichsanstalt—author's note) and our home in the building. In the →

Salon society Hermann von Helmholtz (left) and Anna (second lady from the left) not only hosted evening gatherings themselves but also, as illustrated here, attended other salons like that hosted by Mrs. von Schleinitz (front left). Guests included scientists and artists as well as, for instance, Crown Princess Victoria (fourth lady from the left) and Crown Prince Friedrich Wilhelm (fourth gentleman from the right).
Drawing: Adolph Menzel

years when he became ill, I traveled with him as his health authority, as the doctors described it.

And you didn't find this role bothersome? You once wrote about "the ruinous absolutism of the stronger sex."
AvH: I have often observed the way that men decide everything. Nonetheless, I took it upon myself to be at Hermann's side, to support him—just as the role of a good wife demanded. In this way, I could even see my duty as wife and mother as a cheerful pursuit at times. At the same time, I was able to be a guest in Hermann's world of science, because I was the wife of the finest scholar of our century, as someone once referred to him.

Did you champion women's rights then?
AvH: While I never publicly expressed my support of the civil women's movement, I felt inwardly connected to it and therefore served on behalf of charitable institutions in a voluntary capacity. At first, I was the only lady in Berlin to do so.

The description of one sex as strong and the other as weak is of course a construct of this century. Can you accept this attribution?
AvH: After Hermann's death, the strength for which I was famed was naught. I only had strength as long as I was in secure ownership of the great foundation which gave my life value, and upon which it played out. But now, without Hermann—without a center, without the sun that gives life, light, and all good things—my existence is so worthless and indifferent that I am like an uprooted plant lying useless upon a path.

Nonetheless, you always had your salon throughout the years, even after your husband's death. What significance did the salon have for you?
AvH: I enjoyed hosting my salon as a means of inspiration for Hermann and as a place for intellectual discourse. Our guests included his scientific colleagues like Bunsen, Mommsen, Planck, Virchow, and their wives, our artist friends, diplomats, and educated people from the

"It is as if mere specialists are emerging today, and as if the link connecting all intellectual work has disappeared."

imperial court. Even Crown Princess Victoria came. That was my contribution to Berlin's intellectual life and my way of accompanying Hermann, for which, to my very great surprise, I received the Order of Louise.

You are considered the very ideal of the upper-class lady. Do you see yourself in the same way?
AvH: One could presumably see it that way. It could also be that I appeared aloof to some, and was not always popular. But as I have said many times before, I was not the type to be a meek professor's wife. Hermann's appointment to Berlin University opened up the city's circles to me, and I made expedient use of this opportunity. There were 25 big salons in Berlin, and my salon had a remarkably enlightened aspect to it, as we hosted a great many scientists. The fact that they played a significant role not only had something to do with their growing prestige but also with their growing number. Sometimes a mass of people came, but because they didn't eat anything, it didn't matter whether there were many or few people there. They were always interesting people.

You mentioned before that your strength failed you after Hermann's death. How is science coping?
AvH: When I see my husband's successors in his scientific work, with their proclivity for the personal and the mechanical, my heart feels very heavy. It is as if mere specialists are emerging today, and as if the link connecting all intellectual work had disappeared. ◆

Angela Bittner-Fesseler

IMPRINT

Helmholtz Perspektiven–Anniversary Issue
The Helmholtz research magazine
perspektiven@helmholtz.de
www.helmholtz.de/perspektiven

Publisher
Helmholtz-Gemeinschaft
Deutscher Forschungszentren e. V. (Helmholtz Association of German Research Centers)

Berlin Office, Communication & External Affairs
Responsible under the German Press Act Sara Arnsteiner
Anna-Louisa-Karsch-Str. 2 · 10178 Berlin
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Julia Krämer, Stephanie Lochmüller, Franziska Roeder

Image credits
Cover, p. 24–25, p. 45: Julia Blenn;
p. 3: David Ausserhofer; S. 40–43: mona redshinestudio/Morphart Creation/Yoko Design/Shutterstock.com

Printing/distribution
Druck- und Verlagshaus Zarbock GmbH & Co. KG, Frankfurt a. M.

Paper
Arctic Volume white

ISSN
2197-1579

FSC www.fsc.org MIX Papier aus verantwortungsvollen Quellen Paper from responsible sources FSC® C003425

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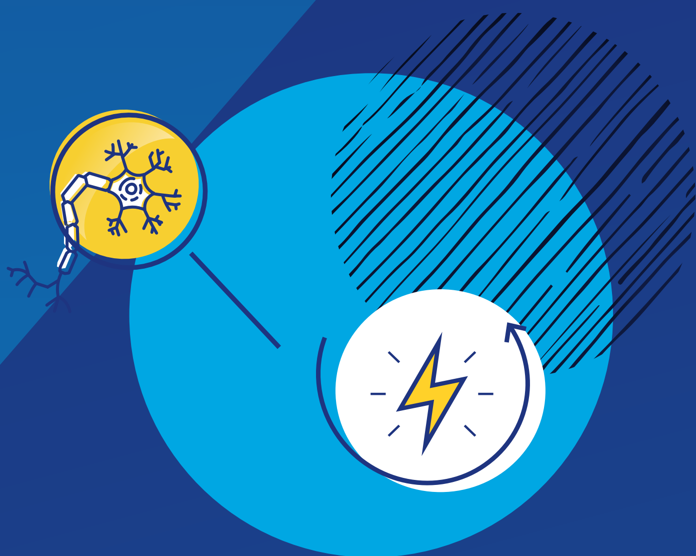

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