01 | 2022

MAX PLANCK
Research

HUMAN HISTORY
An ancient bead network

DEVELOPMENTAL BIOLOGY
The gut is teeming with life

BRAIN SCIENCES
Music in your head

UNDER PRESSURE

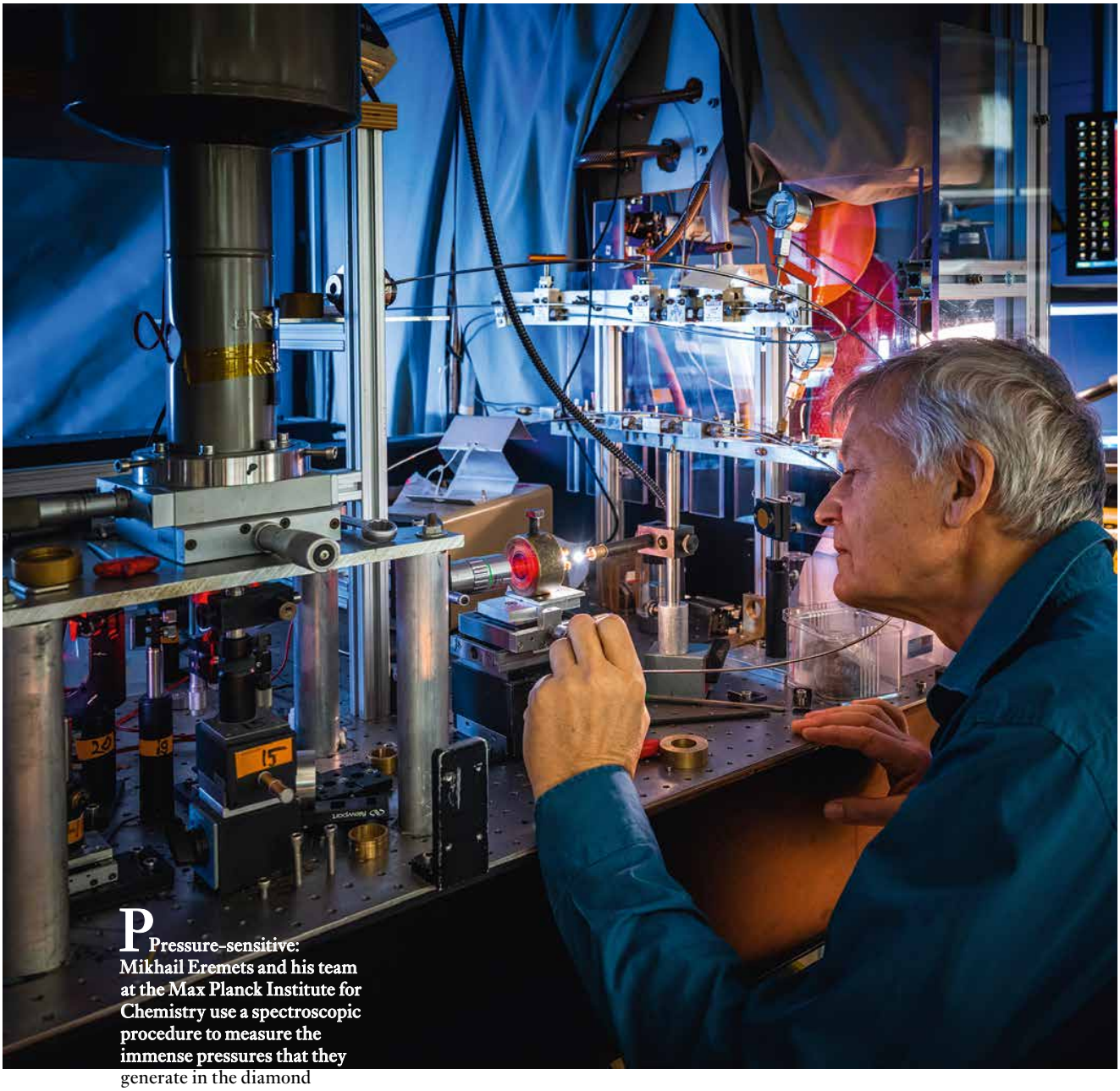

PHOTO: JAN HOSAN

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Pressure-sensitive: Mikhail Eremets and his team at the Max Planck Institute for Chemistry use a spectroscopic procedure to measure the immense pressures that they generate in the diamond anvil cell (cover image). In their experiments, they bring hydrogen-rich materials to a supraconductive state at relatively moderate temperatures.

EDITORIAL

Dear reader,

"Pressure" is a word with many meanings. The first thing that comes to most people's minds would probably be the stress we encounter in our day-to-day lives. But it's not only individuals that can be affected; societies too can experience substantial pressure – economically, ecologically, socially or politically, and in the worst case even existentially, as is currently happening in Ukraine. In all these cases, "pressure", as the term used in physics to describe the physical force exerted on an object, serves as a metaphor for burdens that can sometimes seem unbearable.

One example is psychosocial pressure, which we experience as stress. It not only makes our lives miserable, but also negatively impacts our health. Research teams from the Max Planck Institute of Psychiatry and the Max Planck Institute of Human Cognitive and Brain Sciences are investigating the genetic factors that influence human stress responses and the consequences stress can have on the body even before birth.

We rarely perceive this type of pressure as beneficial, however. Physical pressure is quite different: it is a vital part of many processes, also biological ones. Pressure controls the constant remodeling of bones, for example. The way in which this happens, and the feats that organisms perform in the process, are the subject of close study by researchers at the Max Planck Institute of Colloids and Interfaces, with often surprising findings.

Equally astonishing are the breakthroughs being made by a group at the Max Planck Institute for Chemistry that is studying pressure. The researchers discovered that pressure of the kind found in the Earth's interior is helping to break down the electrical resistance of materials – the first time that this has taken place at temperatures that are almost feasible. This is giving rise to new ideas for research into superconductors, which have been the focus of many still unfulfilled hopes since the early 20th century.

We have assembled articles on some of the many aspects of pressure and sent them to press. We hope you will find this issue of our magazine insightful – read and enjoy it at your leisure – and with no pressure!

Your editorial team

PHOTOS: DAVID AUSSERHOFER (ABOVE LEFT), ANNA ZIEGLER (ABOVE RIGHT), FELIX BERNOULLY (BELOW LEFT) SCIENCE PHOTO LIBRARY (BELOW RIGHT)

38 | *DYNAMIC*

Our skeleton supports the body and is constantly being rebuilt.

46 | *LOGICAL*

Christoph Weidenbach solves complex mathematical problems.

60 | *MUSICAL*

We learn to enjoy and create harmonies from the cradle.

66 | *GENETIC*

Sticklebacks have colonized new freshwater habitats from the sea multiple times.

CONTENT

A SENSE OF RHYTHM

At this kindergarten in a community center in Bamako, the capital of Mali, children usually romp and play. But today, the focus is all about a sense of rhythm, informal learning and also cultural stereotypes.

Rainer Polak and Nori Jacoby from the Max Planck Institute for Empirical Aesthetics have rented the premises to research traditional dance and music in West Africa. They've engaged several groups of local professional artists. A drum ensemble with three musicians, two singers and several dancers are involved. All elements of this live session are recorded via multimedia. Video cameras capture the performance from several perspectives, and the membranes of all the drums have been fitted with sensors to directly pick up their mechanical vibrations. One of the dancers wears a motion-capture suit incorporating seventeen sensors, each of which is simultaneously recording her movements' acceleration, rotation and magnetic field data. This allows the movement of the dancer in the room to be precisely calculated and, for instance, correlated with the rhythms played by the instrumentalists.

The researchers from the Institute in Frankfurt regularly collect such and other data in Mali and Bolivia – and for comparison, also in Germany, Bulgaria, the U.S., Great Britain and Uruguay. They've discovered that people from different cultures perceive identical rhythms differently. Do Africans have more "rhythm in their blood" than Europeans? Probably not. The decisive factor is the person's cultural familiarity with the rhythm in question – in other words, whether they've unconsciously become familiarized with it in their customary social environment.

PHOTO: RAINER POLAK / MPI FOR EMPIRICAL AESTHETICS

ON LOCATION

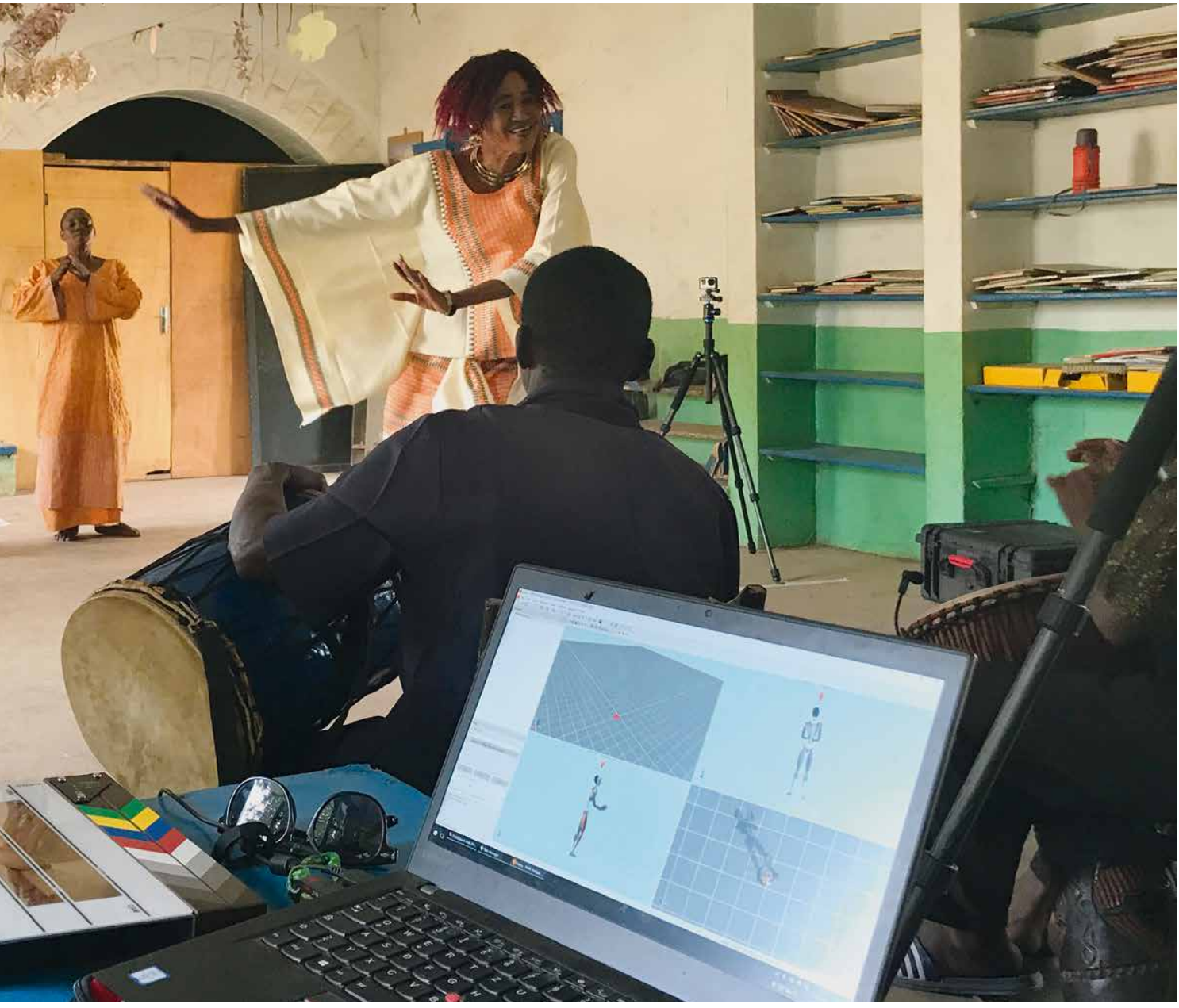


PHOTO: MQV / CHRISTOPH HOHMANN

Getting started: Max Planck President Martin Stratmann (front) and representatives of the other partners at the formal founding of the Munich Quantum Valley research hub, which took place at the Bavarian Academy of Sciences and Humanities.

QUANTUM NETWORK FOR BAVARIA

A quantum computer that runs circles around conventional computers, tap-proof communication methods, and fundamental elements of quantum technology are among the goals that scientists will pursue in Munich Quantum Valley. This new research hub was formally founded in January 2022 at the official signing of the founding document in the presence of Bavaria's Minister-President Markus Söder. The founding partners are both of Munich's universities, the Friedrich-Alexander University of Erlangen-Nuremberg and the Bavarian Academy of Sciences and Humanities, the German Aerospace Center, the Fraunhofer-Gesellschaft, and the Max Planck Society. The aim of the Munich Quantum Valley research hub is to set up a Center for Quantum Computing and Quantum Technologies over the next five years. This center will provide access to the three most promising quantum computing technologies currently available, i.e. computers based on superconducting, ionic, and atomic qubits. In addition to the EUR 300 million provided by Bavaria's Hightech Agenda, the initiative has already secured more than EUR 80 million in government funding for its projects.

www.mpg.de/18184418

FIRST CENTER IN AUSTRALIA

The Max Planck Institute of Colloids and Interfaces, the Max Planck Institute for Intelligent Systems, and Queensland University of Technology have established a new joint venture: the Max Planck Queensland Center for the Materials Science of Extracellular Matrices (MPQC). The first Max Planck Center on the Australian continent has set itself the goal of researching extracellular matrices. These biological materials are considered to be the pillars of life: although they are not animate, they provide cells with support, respond to changing environmental conditions, and store information that stimulates or inhibits cell growth. A more precise knowledge of how the composition and structure of extracellular matrices (ECM) influence their functions is relevant not only for biomedical applications and a better understanding of biological systems, but also for technical applications – for example, in robotics or architecture. The MPQC is also committed to the education and training of junior scientists. The Center will be training the future experts who are to become world leaders in the field of bioengineering.

www.mpg.de/18189505

AWARD-WINNING ★

PHOTO: SEBASTIAN ROST/MPI OF COLLOIDS AND INTERFACES

FERENC KRAUSZ

Ferenc Krausz has been awarded this year's Wolf Prize in Physics for his pioneering contributions to ultrafast laser science and attosecond physics. The Hungarian-Austrian physicist is the Director of the Max Planck Institute of Quantum Optics and holds the Chair for Experimental Physics at the Ludwig Maximilian University of Munich. Attosecond light flashes make it possible to record the ultrafast movements of electrons in molecules and atoms. Ferenc Krausz shares the prize with his colleagues Paul Corkum from the University of Ottawa and Anne L'Huillier from the University of Lund. The Wolf Prize is one of the most prestigious awards in the field of physics.

IN BRIEF

> ALL NATIONS MUST COME TO THE DECISION TO RENOUNCE FORCE AS A FINAL RESORT OF POLICY. IF THEY ARE NOT PREPARED TO DO THIS, THEY WILL CEASE TO EXIST.
>
> MAINAU DECLARATION
> 1955

CALL FOR PEACE

Nobel Prize laureates in various disciplines are calling for peace following the Russian invasion of Ukraine. They have signed a declaration initiated by the Max Planck Society, which is also supported by the Lindau Nobel Laureate Meetings. The declaration follows on from the Mainau Declaration of 1955, in which Nobel Prize winners attending the Lindau Nobel Laureate Meeting issued a warning against nuclear war and called for all nations to renounce force as a final resort of policy. One of the initiators of that declaration was Otto Hahn, the first President of the Max Planck Society. The approximately 150 signatories of the current declaration are calling on governments and business leaders to use scientific discoveries and technologies responsibly and in full awareness of their long-term consequences. Russian President Vladimir Putin is urged to honor the agreements concluded under international law, withdraw his armed forces, commence negotiations, and establish peace.

www.mpg.de/peace-declaration-nobel-prize-laureates

CANCER DRUG TO ENTER CLINICAL TRIALS

The U.S. Food and Drug Administration (FDA) has given the green light for clinical trials of a novel cancer drug. Up to seventy patients with advanced solid tumors are to receive an active substance known as Q901 as part of a phase 1/2 study taking place in the U.S. The initial goal will be to determine the dosage more precisely. Data from pre-clinical studies have shown that Q901, which targets cyclin-dependent kinase 7 (CDK7), can specifically target and kill cancer cells with aberrant cell division cycles or transcriptional regulation. The underlying research was performed as part of a joint project involving the University of Muenster, the Max Planck Institute of Immunobiology and Epigenetics in Freiburg, and the Lead Discovery Center established by the Max Planck Society. The South Korean biotech company Qurient licensed the results from the technology transfer organization Max-Planck-Innovation, optimized the program still further, and completed the studies required for the investigational new drug (IND) application. If the clinical trials are successful, the drug could be used to treat various malignancies including ovarian, breast, prostate, colorectal, lung, and pancreatic cancer.

www.mpg.de/18270598 (in German)

Regional discrepancies in the effects of the plague: samples of cereal pollen from wetlands and sediments show where cereal cultivation declined, presumably due to a significant decrease in the population (red), and where agriculture continued to prosper (green), implying that there was sufficient labor.

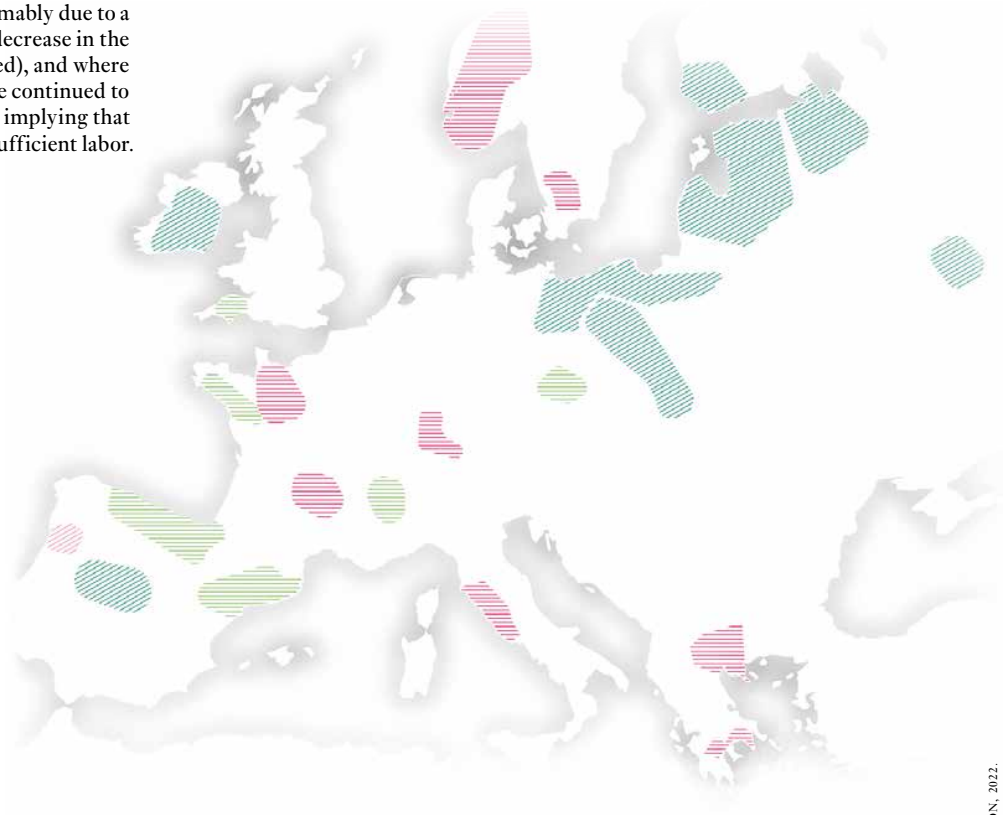


IMAGE: GCO ACCORDING TO HANS SELL, MICHELLE O'REILLY, ADAM IZDEBSKI, IZDEBSKI ET AL., NATURE ECOLOGY & EVOLUTION, 2022.

LIGHT NEUTRINO

The most common elementary particle in the universe is also far and away the lightest. The Karlsruhe Tritium Neutrino Experiment (KATRIN) at Karlsruhe Institute of Technology has now revealed that neutrinos have a mass of less than 0.8 electron volt, i.e. approximately 10^{-33} grams (10^{-33} means one zero in front of the decimal point, 32 zeros after it, and then a one). KATRIN uses the beta decay of tritium, an unstable hydrogen isotope, to determine the mass of the neutrino from the energy distribution of electrons released during the decay process. This requires immense technical effort: the 70-meter-long experimental facility houses the world's most intense tritium source and a giant spectrometer that can measure the energies of decay electrons with unprecedented precision. KATRIN's measurements, which also involved a team from the Max Planck Institute for Physics, have thus achieved a precision of less than one electron volt for the very first time. The upper limit for the mass of a neutrino is therefore less than 1 electron volt (1 eV). This means that the neutrino has no more than one millionth of the mass of an electron, which itself is not exactly heavy. The precision of KATRIN is to be increased still further in order to determine how heavy neutrinos really are. Because these elementary particles are so common, the knowledge of a neutrino's actual mass could help improve models depicting the development of the universe, e.g. the formation of galaxies.

www.mpg.de/18230856

LESS DEADLY THAN ORIGINALLY THOUGHT

Also known as the Black Death, the plague that ravaged Europe between 1347 and 1352 is one of the most infamous pandemics in history. Historians estimate that the plague took the lives of almost half the European population. A study has now demonstrated that the plague's high mortality rate was less extensive than assumed. An international team led by researchers from the Max Planck Institute for the Science of Human History analyzed pollen from 261 sites in 19 European countries to find out which plants grew there in which quantities, thus providing clues as to whether agricultural activities continued or ceased in the respective regions. The results indicate that agricultural activity declined particularly sharply in Scandinavia, France, southwestern Germany, Greece, and central Italy, a finding which correlates with the information available from medieval sources. In contrast, central and eastern Europe and parts of western Europe – including Ireland and the Iberian Peninsula – show signs of continuity and lasting growth. One reason for these surprising results may be that many of the written sources originated in cities, where people lived in particularly close proximity and hygiene was poor. However, at that time, more than three quarters of Europe's population lived in rural areas, where the plague was not as widespread. ***www.mpg.de/18236353***

PHOTO: MPI FOR BIOLOGY, TUEBINGEN

Important model organism: thale cress, *Arabidopsis thaliana*.

IMPORTANT GENES MUTATE LESS OFTEN

Changes to DNA, known as mutations, occur regardless of their consequences for the organism – for many decades, this was a basic hypothesis in evolutionary biology. A team from the Max Planck Institute for Biology in Tuebingen has now refuted this dogma. Their study shows that non-genetic segments in thale cress *(Arabidopsis thaliana)* DNA mutate twice as often as genetic segments. On the other hand, less important genes mutate almost 50 percent more often than those that are essential for the plant's survival. This asymmetrical distribution is the result of chemical changes within the DNA and its associated proteins. These modifications regulate the cell's natural repair mechanisms in such a way that any damage to particularly crucial segments of the DNA is repaired more frequently than damage to the rest of the genome. This finding explains why it is quite difficult to alter certain plant genes. The researchers assume that all organisms, not just thale cress, can preserve key areas of their genome from mutation.

www.mpg.de/18132001

JET FUSION PLANT SETS A NEW WORLD ENERGY RECORD

The highest output ever achieved by a fusion plant: the Joint European Torus (JET for short) in Culham, near Oxford, UK, has succeeded in releasing 59 megajoules from a stable plasma, a very hot ionized gas, in just five seconds – equivalent to an average output of 11 megawatts. As with stars, nuclear fusion could generate practically inexhaustible supplies of climate-friendly energy in the future by fusing hydrogen isotopes. However, the JET facility is too small to produce more energy than is required to heat the plasma used. The fusion experiment was set up by an international team consisting of several hundred scientists, who included researchers from the Max Planck Institute for Plasma Physics. The experiment is seen as preparation for firing up the international fusion plant ITER, since JET used the same mixture of the heavy hydrogen isotopes deuterium and tritium that will burn in ITER. ITER, which is currently under construction in Cadarache, in southern France, is expected to be the first fusion device able to generate more energy than is required to heat its fuel.

www.mpg.de/18250857

PHOTO: EUROFUSION CONSORTIUM

Burst of energy: this fusion plasma in JET released 59 megajoules.

VISION-BASED SENSE OF TOUCH FOR ROBOTS

Robots may be able to function with greater sensitivity in the future. A team at the Max Planck Institute for Intelligent Systems in Stuttgart has developed a sensor that can register even gentle physical contact using vision-based technology and artificial intelligence. Named Insight, this sensor is similar to a thumb with a flexible "skin" that is four millimeters thick; inside, it is equipped with a ring of colored light-emitting diodes and a camera. The diodes generate a pattern of colored light inside the sensor that changes in response to touch and is recorded by the camera. Using machine-based learning techniques, the researchers trained the sensor to identify which forces are acting on it from which direction, based on the changes in color pattern. Unlike previous haptic sensors, Insight can detect touch over a wider range and also senses forces acting parallel to its surface. It is also more robust and easier to manufacture. It could therefore help robots handle objects more carefully and interact with humans without putting them at risk.

www.mpg.de/0120221en

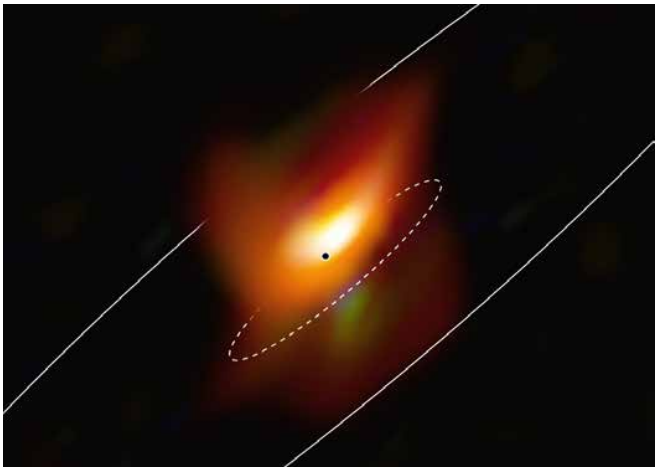
Sensitive thumb: the sensor Insight detects how firmly it is being touched and from which direction, using color patterns that are generated by light-emitting diodes and recorded by a camera in its interior.

IMAGE: SUN, H., KUCHENBECKER, K.J. & MARTIUS, G. A SOFT, THUMB-SIZED, VISION-BASED SENSOR WITH ACCURATE ALL-ROUND FORCE PERCEPTION. NAT MACH INTELL 4, 135–145 (2022)

BLACK HOLE IN A RING OF DUST

A gigantic black hole is lurking behind a cosmic dust cloud at the heart of the Messier 77 galaxy (NGC 1068). A team has now exposed this supermassive gravity trap using the Very Large Telescope at the European Southern Observatory (ESO). The researchers, who include scientists from the Max Planck Institutes for Astronomy and Radio Astronomy, detected a thick ring of cosmic dust and gas that shrouded a black hole at its center. This massive monster is fed by material that spirals towards it, following the irresistible force of gravity. Enormous amounts of energy are released in the process, literally outshining the light emitted by all the stars in the galaxy. It appears that black holes are found in all active galactic nuclei, although they shine with varying degrees of brightness. According to a 30-year-old theory, their brightness depends on the angle from which we observe the black hole and its thick dust ring from the Earth – in other words, how much the ring obscures or even completely conceals the black hole from our view. The latest observations show this dust very clearly and thus support this theory.

www.mpg.de/18287037



Dust at the center: the image shows the inner region of the active galaxy Messier 77. The black dot shows the most probable position of the black hole, while the inner ellipse (dotted line) shows the extent of the thick inner dust ring, and the outer ellipse indicates the extent of the large dust disk.

IMAGE: ESO/JAFFE, GÁMEZ-ROSAS ET AL.

Rich ecosystem: communities consisting of dozens of sponges with diameters ranging from one centimeter to half a meter cover the peaks of the submarine mountain range in the Arctic Ocean.

PHOTO: PS101 AWI OFOS SYSTEM

WEIGHTY DATA LEAKS

Whistleblowers not only help uncover immoral or criminal acts, they can also deter offenders. Niels Johannesen from the University of Copenhagen and Tim Stolper, a former research associate at the Max Planck Institute for Tax Law and Public Finance, have found clear evidence of this. Their study showed that following the public disclosure of the first data leak at the LGT Bank in Liechtenstein, Swiss banks that engaged in cross-border tax evasion, suffered sharp declines in their share prices. Banks that helped conceal money from the financial authorities saw their profit expectations drop significantly as a result of the data leak from the LGT Bank. Since the Liechtenstein tax affair was the first data leak to become public knowledge, the researchers presume that tax evaders and their accomplices had hitherto paid insufficient attention to the risks associated with data leaks. The initial realization of the existence of such a risk had a correspondingly chilling effect on the supply and demand for tax-haven transactions, thus reducing the banks' expected profits and thereby their share prices.

www.mpg.de/18313408

DEEP SEA SPONGE GARDENS

Hardly any food reaches the deeper layers of the Arctic Ocean, because parts of it are constantly covered by ice that lets little light through to support the growth of algae. Nonetheless, these areas are teeming with life. Scientists from Bremen, Bremerhaven and Kiel have discovered a densely populated ecosystem with countless sponges growing on the extinct volcanic peaks of a submarine mountain range at the North Pole. But how can these sponges get the nutrients they need in such a nutrient-poor environment? After all, the algae in the upper layers of water that die and sink into the deep account for less than one percent of the carbon that the sponges need to consume. Using tissue samples, researchers from the Max Planck Institute for Marine Microbiology discovered that the sponges live in symbiosis with microorganisms that enable them to make use of old organic matter. Thousands of years ago, substances seeped from the Earth's crust and supplied a rich ecosystem inhabited by numerous creatures. The remnants of these now-extinct inhabitants – which include worm tubes composed of proteins and chitin, fossilized remains from deep-sea vents and seeps, and other trapped organic detritus – now form the basis of these sponge gardens.

www.mpg.de/18207355

RADIO FLASHES AT AN UNUSUAL LOCATION

They are among the great mysteries of the universe: bursts of radiation that last about a thousandth of a second and only appear in radio telescopes. A team including researchers from the Max Planck Institute for Radio Astronomy using its 100-meter antenna in Effelsberg has now found one of these fast radio bursts (FRB) closer to the Earth than ever before, in the spiral galaxy Messier 81 some 12 million light years away. Moreover, the source appears to be located in a globular cluster in this galaxy – the last place where one would expect to find an FRB, since these clusters only contain old stars. In theory, however, the flashes could be coming from magnetars. These neutron stars – which are about 20 kilometers in size, rotate rapidly, and have extremely strong magnetic fields – are said to be the relatively young remnants of exploded suns. However, it appears that there is another process that leads to the birth of a magnetar. The researchers postulate that an object of this type could also form when a white dwarf – an old, burnt-out star – accumulates so much mass from a stellar partner that it collapses under its own weight and turns into a magnetar. Large numbers of white dwarfs are believed to exist in globular clusters.

www.mpg.de/18354177

12,000,000

light years from Earth – this is the distance of the closest fast radio burst (FRB) yet observed.

SHOSHONE ROCK ART PRECISELY DATED

The rocks in America's Great Basin are decorated with human-like beings, fantastic animal shapes, and geometric patterns. Tracey and Meinrat O. Andreae, both researchers at the Max Planck Institute for Chemistry, have now reliably dated the petroglyphs left by the ancestors of the Shoshone people. The results indicate that the pictures are around 12,000 years old. The researchers made this discovery by using a portable x-ray fluorescence spectrometer to analyze the proportion of manganese in the natural rock varnish, most commonly known as desert varnish. This mixture of manganese and iron oxides forms in layers on rocks in desert environments. The age of the petroglyphs can be determined from the quantity of manganese deposited on them. The results of the analyses, for which no samples had to be taken, are more accurate than the dating previously obtained using other methods. According to the new measurements, the petroglyphs give insights into the conceptual world of the Shoshone people at a particularly interesting time, i.e. during the transition from the Pleistocene epoch to the Holocene.

www.mpg.de/18213975

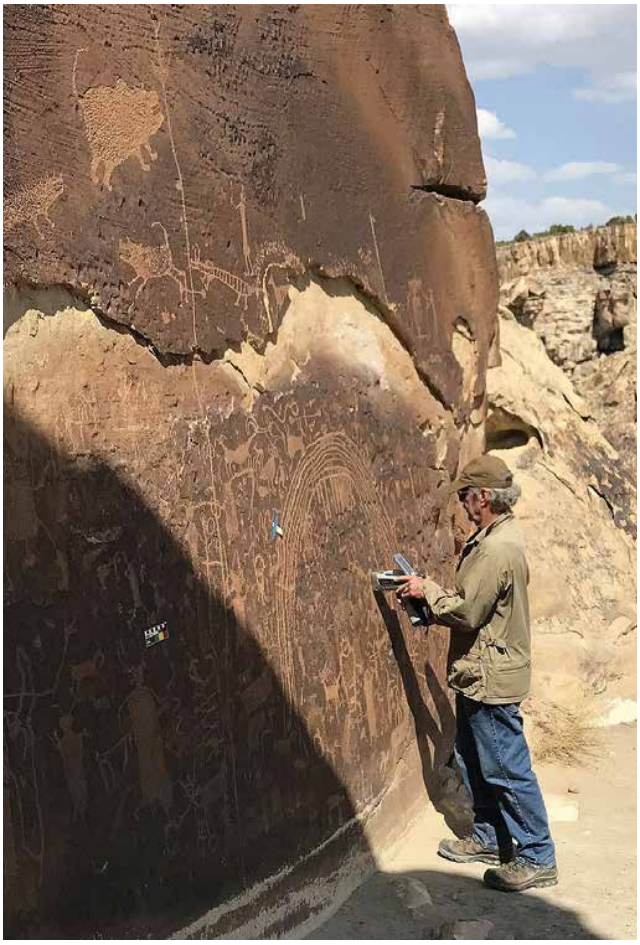


PHOTO: TRACEY ANDREAE, MPI FOR CHEMISTRY

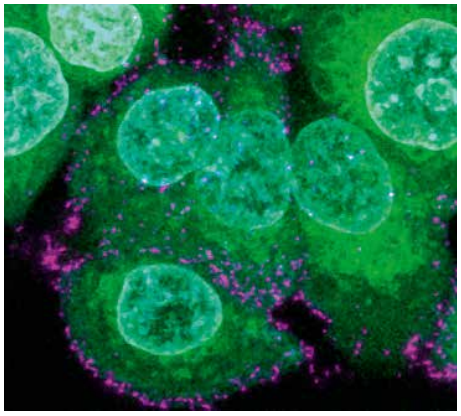
Mobile dating: Meinrat O. Andreae measures the rock varnish using a portable x-ray fluorescence spectrometer.

VIRAL ARTIFICE

A new approach developed by the Max Planck Institute for Medical Research, involving the production of artificial virus-like particles, is now making it easier to study SARS-CoV-2. Known as virions, these particles have a similar structure to natural viruses but contain no genetic information and are therefore unable to reproduce. The artificially created chemical environment of the virions can be used to investigate questions relating not only to SARS-CoV-2, but also to other viruses. One way in which the researchers have been using the synthetic particles is to analyze the effects of the fatty acids that are released when inflammation occurs in the body; these fatty acids are responsible for controlling the body's immune response. The team discovered that the coronavirus spike protein changes its shape when it binds with a fatty acid. On the one hand, the virus uses this spike protein to bind to the host cells' ACE2 receptors and infect them; on the other, antibodies produced by the host bind to the spike protein and mark the virus as a target for the immune system. The shape change means that the spike protein can no longer bind with the ACE2 receptor. This may be one way in which the virus inhibits the host's immune response and infects the host more efficiently. ***www.mpg.de/18300636***

Under the microscope: human epithelial cells (green with nuclei) and synthetic SARS-CoV-2 virions (magenta).

IMAGE: OSKAR STAUFER/MPI FOR MEDICAL RESEARCH

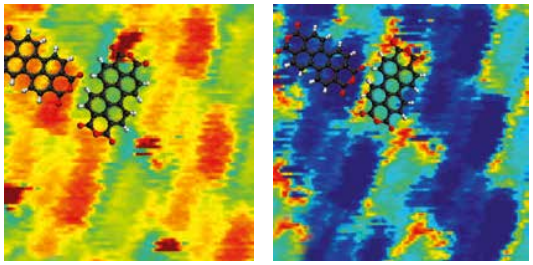


ROLL CAMERA!

It is often used as a metaphor for great – or at least tangible – progress, but in reality, a quantum leap is minute, quick as a flash, and almost impossible to record. Nevertheless, a team from the Max Planck Institute for Solid State Research has now managed to capture a quantum leap on film for the very first time. The researchers achieved this by combining scanning tunneling microscopy and attosecond laser spectroscopy. Scanning tunneling microscopy allows high spatial resolution, while spectroscopy with attosecond pulses achieves exceptional temporal resolution. This is because these pulses last only one billionth of one billionth of a second, i.e. one billionth of a nanosecond. The team was thus able to capture the leaps between various quantum states of a molecule. A better understanding of such processes could one day help control chemical reactions with greater precision.

www.mpg.de/18173993

IMAGES: MANISH GARG/MPI FOR SOLID STATE RESEARCH



In the quantum world: two images from a sequence in which researchers recorded the leap between a lower-energy (left) and a higher-energy state (right).

A LEGACY FROM THE NEANDERTHALS

Whether or not a person falls seriously ill with COVID-19 depends on a number of factors, including specific gene variants in their DNA. Some time ago, researchers from the Max Planck Institute for Evolutionary Anthropology discovered that the most important genetic risk factor for falling seriously ill with COVID-19 is a gene variant passed on by Neanderthals to their modern descendants when the two hominins interbred tens of thousands of years ago. Further analyses have shown that the prevalence of this variant has increased among modern humans since the end of the last ice age. Back then, it must have given its carriers an advantage in the fight for survival. The variant is located in a region on chromosome 3 that includes several immune system receptor genes. New studies have now shown that people who carry this COVID-19 risk variant have fewer CCR5 receptors, which are used as a gateway by another pathogen: the HIV virus. In fact, it has been found that carriers of the COVID-19 risk variant are almost 30 percent less likely to contract HIV. However, since HIV did not emerge until the 20th century, the COVID-19 risk variant's protective effect against this infectious disease cannot explain why it was already so prevalent among humans ten thousand years ago. It may have been the protection it gave from another disease that caused this gene variant to become so widespread. ***www.mpg.de/18289931***

AN UNEXPECTED FUTURE FOR OIL AND GAS

The crisis in Ukraine has driven up energy prices, obscuring a dilemma that we're likely to face in the near future: if many countries are increasingly able to generate energy without using oil and natural gas, the price of these commodities will fall. This means that the use of fossil fuels will become more attractive again for countries that cannot afford or do not want to make the transition to renewable energies. Against this backdrop, our author advocates speeding up the search for alternative uses, starting now.

Around the world, there are huge gas and oil reserves that – if burned – will produce large quantities of greenhouse gases. If global warming is to be kept within manageable limits, the energy industry must wean itself off fossil fuels. Recent studies indicate that in order to achieve the climate targets that have been set, 60 percent of oil and gas reserves should not be burned – not to mention coal deposits. But how can this be accomplished?

When it comes to decarbonization, current national and international climate policy relies on suppressing demand for fossil fuels – for example, by means of internationally tradable carbon emission certificates, taxes on CO_2 emissions, an announced ban on oil heating systems, or the phasing out of combustion engines. At the same time, subsidies for climate-neutral forms of energy are intended to kick-start the substitution processes to move away from oil and gas. The problem is that demand for fossil fuels must be suppressed at the global level, and this objective cannot be achieved by non-binding agreements or by trusting all countries to do the right thing. Rather, we would need an agreement with binding commit-

→

VIEW POINT

KAI A. KONRAD

ILLUSTRATION: SOPHIE KETTERER FOR MPG

Prior to his current position as Director at the Max Planck Institute for Tax Law and Public Finance, Kai A. Konrad was a professor at the Free University of Berlin while also serving as Director of the Research Unit Market Processes and Governance at the Wissenschaftszentrum Berlin für Sozialforschung (WZB). In his work, he studies the interaction between economic actions and institutional framework conditions. Konrad is a member of the Leopoldina German National Academy of Sciences as well as several other scientific academies and, as a member and former Chairman of the Scientific Advisory Board to the German Federal Ministry of Finance, plays an active role as an economic policy advisor.

ments between sovereign states that not only defines the total reduction in emissions but also regulates how this is divided up. An agreement like this is not only grueling to negotiate, but also very difficult to enforce and monitor. There have been some constructive approaches – as well as more than 25 annual UN Climate Change Conferences that have provided a forum for negotiations. However, the progress made so far gives little cause for optimism.

Moreover, even if these collective efforts were to succeed in reducing global demand for oil and gas, a second problem would arise. The world's oil and natural gas reserves will not simply disappear when demand for them collapses. For example, the deposits under the desert sands of Saudi Arabia still hold billions of barrels of fossil fuels – with a value of billions upon billions of euros at today's market prices. But what would it mean for Saudi Arabia if global demand for oil and gas were to dry up within a few decades? The remaining reserves would become largely worthless, and so it's better for Saudi Arabia – and any other country with large oil and gas deposits – to pump its own reserves out of the ground quickly and sell them before they lose their value. From an economic perspective, these considerations can be understood via intertemporal equilibrium models for exhaustible natural resources, and are consistent with fundamental scientific insights in the field of resource economics. Market logic dictates that falling demand in the future will lead to a rapidly increasing supply of oil and gas in the present and hence to a fall in prices. As prices fall, the use of oil and gas will increase, and so will CO_2 emissions in countries that are not party to a climate agreement – and elsewhere – until the demand restrictions imposed by such an agreement take effect. The drop in prices will also make it difficult for alternative energy sources to assert themselves in a market flooded with cheap oil and gas. Moreover, there will be a decrease in the natural incentives for innovation in green technologies.

DEMAND RESTRICTIONS ON CARBON BASED ENERGY ARE SUPPOSED TO TRIGGER A HARMFUL RUSH TO BURN

The impact of war and sanctions has meant that gas and oil prices have not followed this pattern in recent weeks. Although it will take a while to compensate for disruptions in the supply coming from Russia, these disruptions do not affect the total quantity of oil and gas available for extraction over time. In this respect, this price volatility does not contradict the supply decisions outlined here – and these decisions are likely to be taken in the coming years and decades should a binding and effective global climate agreement be adopted.

Scientists refer to this problem commonly as "rush to burn" or "green paradox." Though it may sound paradoxical, the increasing severity of political measures seeking to restrict the future use of fossil hydrocarbons in energy production actually counteracts the desired policy impacts of a

climate agreement in the present day. These risks have been highlighted in extensive theoretical literature relating to the green paradox. The literature has also provided empirical evidence of market responses in line with the theory predictions. In 2009, the economist Hans-Werner Sinn received the "Dinosaur of the Year" award for delivering this bad news. Since then, word of the compelling logic of this correlation has gotten around – at least among climate economists.

A few years ago, in light of these problems, it was suggested that countries with oil and gas reserves should be paid not to extract them and instead to leave these resources in the ground forever. This approach does not offer a compelling solution however, for it would quickly require unimaginably large annual compensation payments to the resource owning countries. Moreover, international negotiations regarding financing by the international community would be just as challenging as the ongoing climate negotiations aimed at securing measures to address demand.

It would be better to extract oil and gas and put them to good use, albeit not in a way that is harmful to the climate but rather for climate-neutral or climate-friendly products. This would usher in a radical transformation of the market. Oil and gas – as raw materials for products – would be more valuable than they are today, putting an end to the rush to burn. Resource-rich countries would not need to extract their stocks as quickly as possible or sell them at dumping prices. Rather, they could take their time to extract and commercialize the reserves over decades. As a result, oil and gas would already be in shorter supply today, and prices would be higher. Higher prices would stimulate the energy transition by making alternative, climate-friendly energy concepts more competitive on the market and their innovation economically more attractive. Ideally, oil and gas would become too valuable and expensive to burn – and there would be no need for an international climate agreement, carbon taxes or prohibitions on the use of oil and gas for combustion.

Although some of these economically attractive climate-neutral products made from oil and gas may not be ready for the market for years or decades to come, equilibrium-theory considerations show that they would have an immediate effect on the market. This is because of a special feature of markets for exhaustible natural resources: since oil and gas reserves are known and finite quantities, those who squander their reserves today will have nothing to sell tomorrow. Just as the impending worthlessness of oil and gas spurs on faster extraction, the prospect of a more economically attractive future application leads resource owners to withhold supply today. It makes sense for them to preserve their stocks and sell them at a later stage. This intuitive conclusion is also backed up by the results of economic-theoretical models.

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These considerations would be purely academic wishful thinking in the absence of clear, climate-friendly alternative uses of oil and gas. But what might these climate-neutral applications actually be? Perhaps one of the most interesting ideas is to produce hydrogen from methane, which is the main constituent of natural gas and accounts for approximately 75 to 99 percent of the mixture. This is also the subject of research at some institutes inside the Max Planck Society. So far, insights relate primarily to the production of "grey" or "blue hydrogen," in which methane is broken down and at least some CO_2 results as a byproduct. More elegant solutions lie in processes such as catalytic pyrolysis, which avoids the release of CO_2 and produces not only hydrogen but also carbon, that can take the form of valuable nanomaterials. Lively publication activity stands as a testament to advances in the production of this "turquoise hydrogen." Although catalytic decomposition requires an input of energy, it only needs about an eighth of that used to produce the "green hydrogen" that everyone is talking about nowadays.

WE MUST INNOVATE AND PROMOTE ENVIRONMENTALLY FRIENDLY PRODUCTS FROM OIL AND GAS

As a climate-friendly and carbon-neutral energy carrier, hydrogen will be a key energy input to the economy following the energy transition. And the carbon nanomaterials – e.g., carbon nanotubes (CNTs) – produced during pyrolysis might actually be even more important than the hydrogen. Products made from carbon nanomaterials have potential applications in areas like construction, the automotive industry and aerospace engineering, where they could replace traditional materials such as steel, aluminum or concrete. As the production of these materials usually carries a considerable carbon footprint, replacing them could also lead to major reductions in CO_2 emissions.

It may be some time before we see the large-scale application of CO_2 emission-free catalytic pyrolysis, but the theoretical analysis of intertemporal relationships in markets for exhaustible natural resources shows that an effective reversal of the rush to burn does not depend on the immediate availability of climate-friendly uses of oil and gas. Rather, the mere promise of these potential future applications is sufficient to prevent the resources from being sold off.

Climate-friendly uses of hydrocarbons needn't be limited to the decomposition of methane. Indeed, such uses already exist for oil today. Examples include synthetic fibers, insulating materials for the construction industry, and products made of plastic. In quantitative terms, these applications still play something of a subordinate role, although that may change. For many people, mentioning plastic will immediately raise concerns about the pollution of our oceans by plastic waste, the biological impact of microplastic particles in fish, animals and humans, and the fact that the plastic

that doesn't drift into the oceans via rivers all too often ends up in thermal power plants, where it's burned in a manner that's harmful to the climate. However, that is not an argument against using oil to produce useful plastics per se. Rather, the problem is the way that plastics are handled in our current economy and society. After all, it's not a law of nature that products made of plastic have to end up in oceans or have to be burned. For example, if plastic is buried deep in the soil at the end of its useful life – in other words, if it ends up where the raw material for plastic originally comes from – the use of plastics doesn't have a negative impact on the environment or the climate. Plastics would then become an application that made crude oil valuable, that withdrew it from carbon-intensive use in energy production, and that could bind fossil hydrocarbons in a climate-neutral manner for long periods of time.

Turquoise hydrogen, carbon fibers, plastics and other oil products would be a good first step toward combating the rush to burn. Perhaps even more important than the oil and gas products named here, however, are the products that don't yet exist but might be invented over the coming years. The right government policies can help set these processes in motion by setting a clear course forward and creating stable, long-term framework conditions.

The key thing when it comes to reversing the rush to burn will be to make natural gas and oil a scarce and valuable resource for climate-neutral uses. With this in mind, it is not very helpful to promote new substitute products derived from sustainable resources like wood or renewable plants. Such substitutes can reduce the demand for climate-neutral applications of fossil fuels. Paradoxically, these products and their promotion are actually more likely to encourage the rush to burn.

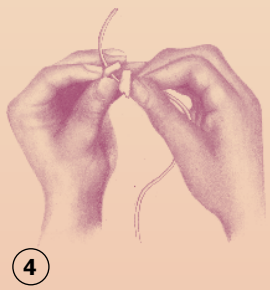
SUCH PRODUCTS CAN UNLEASH MARKET FORCES FOR THE TECHNOLOGY SHIFT TOWARDS A CLIMATE-FRIENDLY ENERGY SUPPLY

Instead, it would be more expedient to adopt policies that encourage innovation in climate-friendly products made from oil and gas. Instead of relying on building materials from the Middle Ages, the construction industry should accelerate the replacement of steel, aluminum and concrete with carbon-based building materials. In the automotive or aviation sectors, carbon-based construction materials produced in a climate-neutral manner could probably replace building materials from carbon-intensive production processes – potentially even having a positive effect on the limits of technical feasibility. And if this approach succeeds in making gas and oil sufficiently attractive and therefore expensive, it can also pave the way for a successful energy transition that is in accordance with a free market economy and actually relies on market mechanisms rather than on large subsidies for a successful energy transition that is in accordance with a free market economy and actually relies on market mechanisms rather than on large subsidies.

AN ANCIENT BEAD NETWORK

Beads made from ostrich eggshells are considered the world's oldest handmade jewelry. Jennifer M. Miller and Yiming Wang of the Max Planck Institute for the Science of Human History in Jena, Germany, have compared 1,500 beads discovered in East and South Africa dating from various early historical phases and made a surprising discovery: about 50,000 to 33,000 years ago, the people in those regions were using nearly identical beads – even though they were living about 3,000 km apart. The similarities are so extensive and unique that they can only be explained by a cultural exchange between the two distant populations.

The oldest bead finds from southern Africa are more than 43,000 years old (above). Younger specimens from the region tend to be much smaller like these 1,100 to 11,000-year-old beads (center). On the other hand, the size distribution of beads from the East did not differ over the millennia – here are finds from Tanzania (below) that are about 10,000 years old.

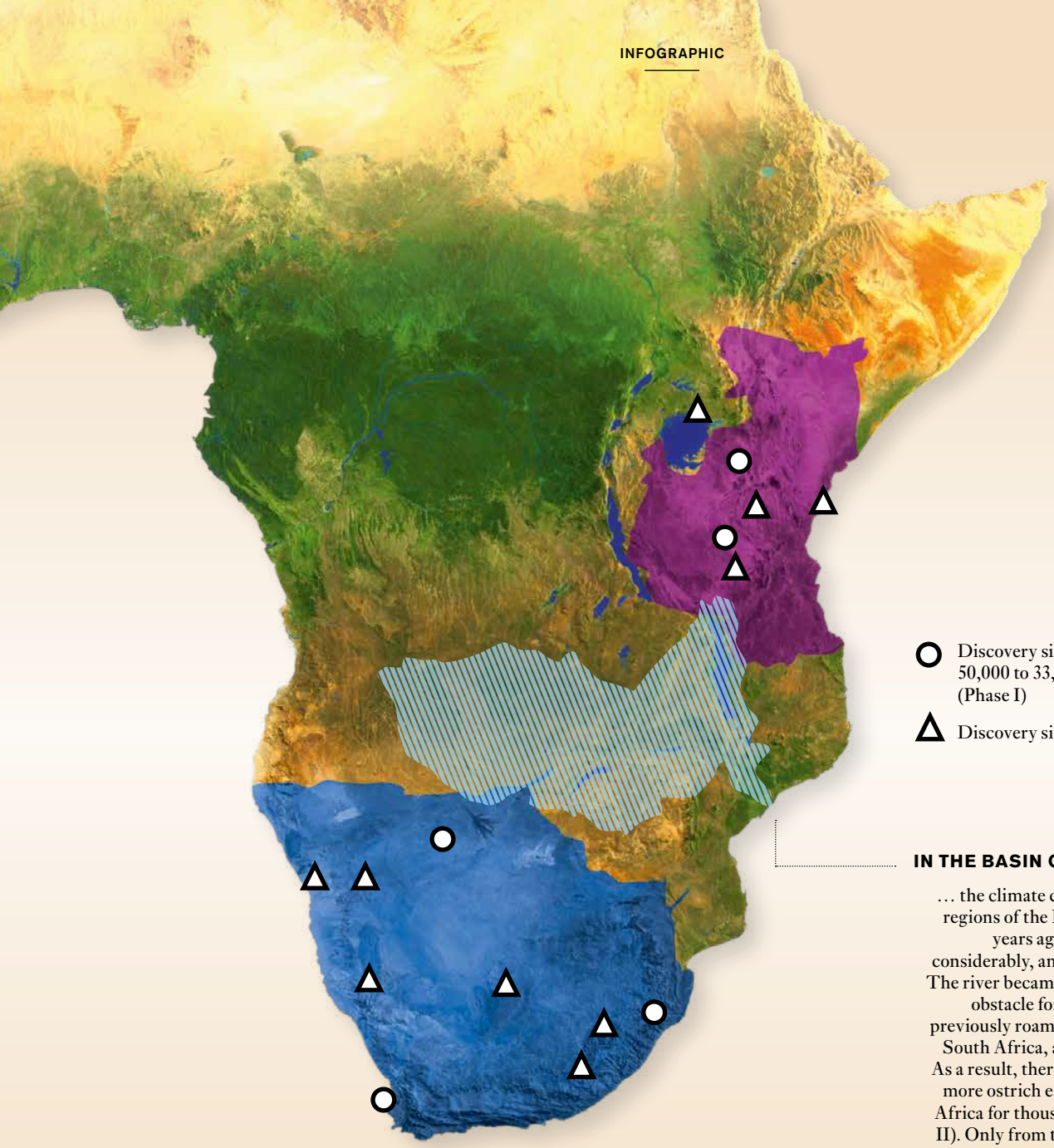


PRODUCTION

Even today, beads are handcrafted from ostrich eggs in Africa:

1. Ostrich eggshells are broken into small pieces.
2. A hole is drilled in each piece from the inside.
3. The blanks are still quite unevenly shaped.
4. For further processing, the beads are threaded onto a string.
5. Each bead is rounded individually using tools such as an animal horn.
6. The edges of the threaded beads are polished smooth using a specially shaped stone.

IMAGE: GCO, VALERIA DUMLER, ACCORDING TO MILLER, J.M., WANG, Y.V. OSTRICH EGGSHELL BEADS REVEAL 50,000-YEAR-OLD SOCIAL NETWORKS IN AFRICA. NATURE 601, 234–239 (2022).



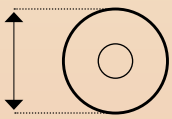
Discovery sites from the period 50,000 to 33,000 years ago (Phase I)

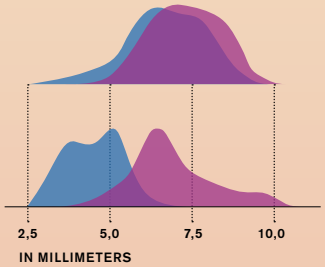
Discovery sites from later phases

IN THE BASIN OF THE SAMBESI

… the climate changed – as in many regions of the Earth – about 33,000 years ago. Rainfall increased considerably, and flooding occurred. The river became an insurmountable obstacle for the people who had previously roamed between East and South Africa, and exchange ceased. As a result, there were apparently no more ostrich egg beads in southern Africa for thousands of years (Phase II). Only from the period beginning 19,000 years ago have bead finds been documented again (Phase III).

SIZE DISTRIBUTION OF BEAD DIAMETERS





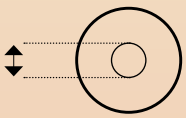
Eastern Africa

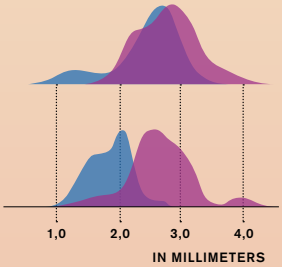
Southern Africa

Phase I (50,000 to 33,000 years ago)

Phase III (19,000 to 11,600 years ago)

SIZE DISTRIBUTION OF HOLE DIAMETERS





FOCUS

UNDER PRESSURE

PHOTO: JAN HOSAN

A gemstone press: the Mainz research team uses two cone-shaped synthetic diamonds to place materials under high pressure. The researchers press the micrometer-sized tips of the stones together with the sample between them in an anvil cell, only part of which is visible here.

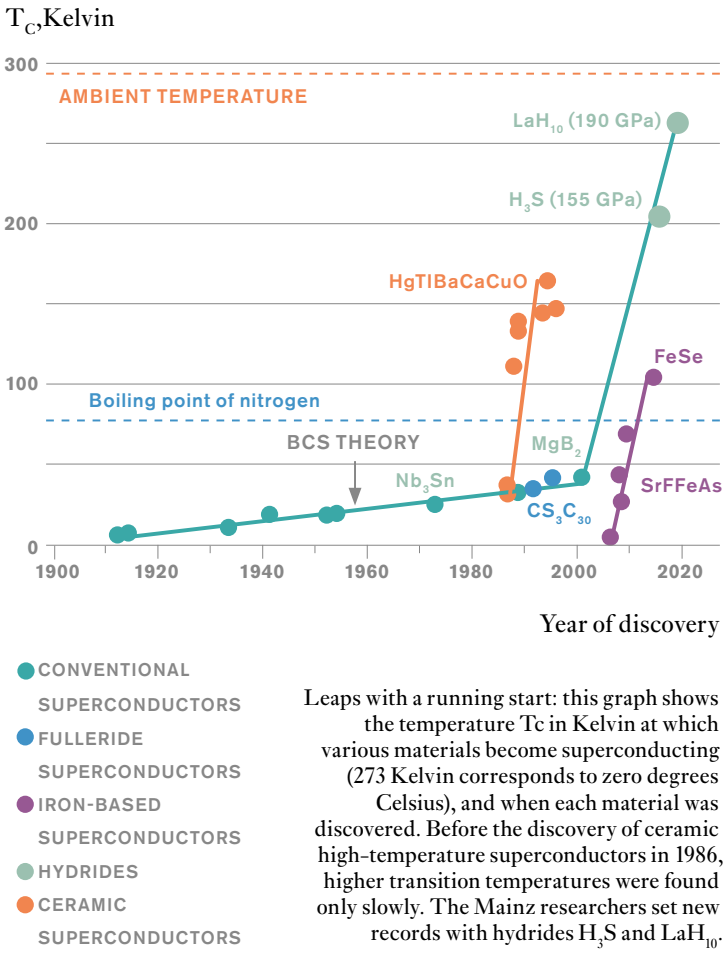
CONDUCTIVE HYDROGEN

TEXT: CHRISTIAN J. MEIER

Materials that can conduct electricity without any losses would improve energy efficiency in many areas. However, superconductivity would have to occur at more practical temperature levels. By taking a new approach, Mikhail Eremets and his team at the Max Planck Institute for Chemistry have come significantly closer to this goal – in particular by placing their materials under truly astronomical pressure.

Gazing around Mikhail Eremets's office, a visitor hardly knows where to look first: physics books share their shelves with metal workpieces, there's a monitor and keyboard on one table and two microscopes stacked on another. There are dumbbells on the floor, and a pull-up bar is mounted above the door. The physicist evidently lives here, in room B 2.75 of the Max Planck Institute for Chemistry in Mainz, and he lives for his research – with success. With his research, Eremets has achieved what few other scientists attain: he has brought an entirely new perspective to a field of research that had long failed to yield the anticipated breakthroughs.

His field of research is the phenomenon of superconductivity – it was discovered over a hundred years ago, was explained 65 years ago, and has the potential to profoundly impact our lives every single day: superconductors conduct electrical current with no resistance. They would enable many new applications: aircraft with light but powerful electric motors, lighter generators for wind turbines, magnetic levitation ("maglev") trains, or an MRI machine in every doctor's office. Superconductors could also pave the way for entirely new technologies: nuclear fusion power plants and ultra-fast quantum computers.



Leaps with a running start: this graph shows the temperature Tc in Kelvin at which various materials become superconducting (273 Kelvin corresponds to zero degrees Celsius), and when each material was discovered. Before the discovery of ceramic high-temperature superconductors in 1986, higher transition temperatures were found only slowly. The Mainz researchers set new records with hydrides H_3S and LaH_{10}.

GRAPHIC: GCO BASED ON A PRESENTATION BY MIKHAIL EREMETS

Slow progress at first

Mikhail Eremets recounts the story of superconductivity as one of the greatest achievements in the field of physics. But it ends on a frustrating note. For now, anyway. The story begins over one hundred years ago with Dutch physicist Heike Kamerlingh Onnes, who was the first to liquefy the noble gas helium – at only four degrees above the temperature of absolute zero. In 1911, he used liquid helium to cool mercury and discovered something: at about minus 269 degrees Celsius, the metal suddenly loses its electrical resistance. Onnes had discovered superconductivity. But a superconductor requiring such extreme cooling was completely unusable for practical applications. And that was how things remained for those materials for a long time. "Progress after that was very slow," Eremets says. Nor did the situation change in 1957, when John Bardeen, Leon Neil Cooper and John Robert Schrieffer used their eponymous "BCS" theory to explain why certain metals conduct electricity without resistance once they are below a specific temperature, known as the critical temperature.

At higher temperatures, electrical resistance occurs because electrons passing through the crystal lattice of a metal continually interact with individual atoms and are deflected from their path. The situation is different in a superconducting material. Here, an electron passing through the lattice draws the positively charged atomic cores in the lattice towards it. Because it takes a finite time for the atoms to spring back into place, a track temporarily forms in which the atoms are closer together than in the rest of the crystal, resulting in a concentration of positive charge. The track thus attracts a second electron, which follows the first at an appropriate distance – because the electrons themselves repel each other. The two electrons now form a Cooper pair, named after one of the fathers of the BCS theory. Many Cooper pairs form in the superconductor.

What happens next can only be understood in the context of quantum mechanics. According to quantum mechanics and the BCS theory, particles can behave like waves. As temperature decreases, the material wave of a particle expands. For the matter waves of Cooper pairs, this means: they are superimposed. Because it is no longer possible to distinguish between individual pairs, they merge to a common state that extends throughout the entire conductor. There are no longer any individual electrons losing energy by rubbing against the atomic lattice. Instead, Cooper pairs form a macroscopic quantum state that is unaffected by occasional obstacles like atomic nuclei. Electrical resistance simply vanishes. "One would think that an explanation of superconductivity would have provided a path for experiments leading to higher critical temperatures,"

says Eremets. But this hope was initially in vain. One of the most dedicated researchers in this field, the German-American Bernd Matthias, drew a sobering conclusion in 1971: room-temperature superconductivity will forever remain a pipe dream.

Still, physicists have discovered thousands of superconducting materials in the interim. They have even found a second class of superconductors: ceramics with significantly higher critical temperatures of up to minus 135 degrees Celsius, known as high-temperature superconductors. However, this type of superconductivity cannot be explained by the interaction between electrons and the vibrations of the crystal lattice. In contrast, the BCS theory enables more fundamental research into superconductors, and that is what Eremets is working on. In so doing, he is also dispelling a false assumption: the prevailing opinion regarding superconductors was that the critical temperature would always have an upper limit that was still so low that no workable superconductors could ever be found.

So is all hope lost? Mikhail Eremets leans back in his office chair. "Let's take a step back here," he says. He points to a picture showing the planets in the solar system. Jupiter and Saturn dominate with their size. These giant planets are made up mostly of hydrogen. Inside the planets, the molecules are subjected to tremendous pressure due to gravity. The hydrogen becomes more and more compacted as the depth increases. The molecules break up and the hydrogen atoms move very close together. Finally, they form an atomic lattice. Physicists have long suspected that hydrogen becomes electrically conductive in this state and is hence metallic. "Our work mainly involves metallic hydrogen," says Eremets. However, producing it requires a pressure similar to that in the Earth's outer core – roughly three million times atmospheric pressure at ground level. So how do the Mainz researchers plan to generate such high pressure?

Between his thumb and forefinger, Eremets holds a metal cylinder that looks like a pipe fitting. This is a diamond anvil cell that produces tremendous pressures. Pressure works like bicycle gears: it's a question of gear ratios. It's not just how much force is applied that counts: when you concentrate a given force over half the surface area, the pressure that is generated doubles. The anvil cell presses the tips of two diamonds together on

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Fine tuning: Panpan Kong, a scientist in the Mainz team, uses a focused ion beam to process a diamond, visible on the left screen.

PHOTO: JAN HOSAN

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an area smaller than the cross-section of a hair. So simply tightening the hex socket screws on the cell is sufficient to generate pressures between the diamonds amounting to millions of bars, i.e. megabars, a unit of pressure equal to one million bars. Using this method in 2011, Eremets and his colleague Ivan Troyan succeeded in bringing hydrogen to an electrically conductive state, achieving it at 2.7 million bars of pressure. The pressure at the Earth's surface is roughly 1 bar. The Mainz team and other scientists have since gathered further proof that hydrogen becomes metallic at high pressure.

But what does this have to do with the dream of a room-temperature superconductor? More than 50 years ago, British physicist Neil Ashcroft wrote an article, titled: *Metallic hydrogen: a high-temperature superconductor.* The BCS theory suggests it, argued Ashcroft. "He expressed himself very cautiously," Eremets observes. "At the time, it was simply hard to imagine." However, years later, Ashcroft made another prediction: that chemical compounds that are rich in hydrogen could also have high transition temperatures. According to Ashcroft, the other chemical elements in the compound already exert pressure on the hydrogen, so it takes less additional pressure to make it metallic. At the time, the hope grew that a room-temperature superconductor would now be easier to achieve.

"Then something fascinating happened," says Eremets. Physicists had since learned how to simulate crystals with computers. This was possible due to the rapid growth in the computing power of semiconductor chips. "At the same time, the calculation methods were also being optimized," adds Reinhold Kleiner, who performs research in superconductivity at the University of Tuebingen. "Researchers well know which approximations they can make and which ones they can't." These advancements also made it possible to roughly predict the transition temperature for a superconductor. Physicists made just this calculation for hundreds of hydrogen compounds, including for trihydrogen sulfide (H_3S) – a good choice. Not long after, in 2015, Eremets's team, which included Alexander Drozdov (the first author), caused a sensation: they set a new transition temperature record. Under high pressure, the molecules compressed to form an H_3S crystal. This became superconducting at a balmy minus 70 degrees Celsius. This temperature can be achieved using liquid nitrogen, which is technically much easier to produce than liquid helium. However, the team still had to apply a pressure of roughly one megabar – about a third of that needed to produce metallic hydrogen.

Eremets believes that this success is based on a paradigm shift. Previously, relatively high critical temperatures had been discovered mostly by accident. "Now, theoreticians and experimenters are working together systematically," explains the physicist. For example, his own group has everything they need to conduct experimental studies – from preparation of the samples to their comprehensive investigation. The five-member team in Mainz can thus machine diamonds to a precision of a thousandth of a millimeter. "But our diamonds are useless as jewelry," jokes Eremets: they measure only about two millimeters in size and weigh a mere 0.1 carat. At the tip of these diamonds, the researchers use a complicated focused ion-beam man-sized machine to attach the miniature electrical leads used to study the conductivity of the sample. The contacts come within a few thousandths of a millimeter of each other, but must not touch. The metallic casing of the anvil cell is manufactured by the Max Planck Institute for Chemistry's in-house metal shop.

One of the labs is darkened. That is where the Mainz team uses lasers to heat the sample and to study it spectroscopically. They use what is known as Raman spectroscopy to obtain clues about how the high pressure changes the sample's material properties. The lab also contains a barrel-shaped measuring device known as a SQUID magnometer. This is used to detect a characteristic that only superconductors have: they completely expel magnetic fields from their interior – a phenomenon physicists call the Meissner-Ochsenfeld effect. Superconductors thereby establish a field around themselves that exactly opposes the external magnetic field, enabling a magnet to float above a superconductor. "To perform the measurement within the SQUID magnetometer, we need an especially small anvil cell that can fit inside the instrument," Eremets explains. Before his team obtained the SQUID device, the physicist built a small anvil cell just to indulge his curiosity. He wanted to give it a try to see if it would work. So when the scientific journal Nature required proof of the Meissner-Ochsenfeld effect before publication, Eremets already had the expertise he needed to do just that.

With their instruments, Eremets's team can also address one of the most interesting questions: how can the high transition temperature of H_3S and other hydrogen compounds be explained? Pioneer Neil Ashcroft had already provided the theory for this. According to Ashcroft, hydrogen should be especially well-suited as a superconductor, because it has the lightest atomic nucleus: a single proton. This is especially easily attracted by passing electrons. According to BCS theory, it leaves be-

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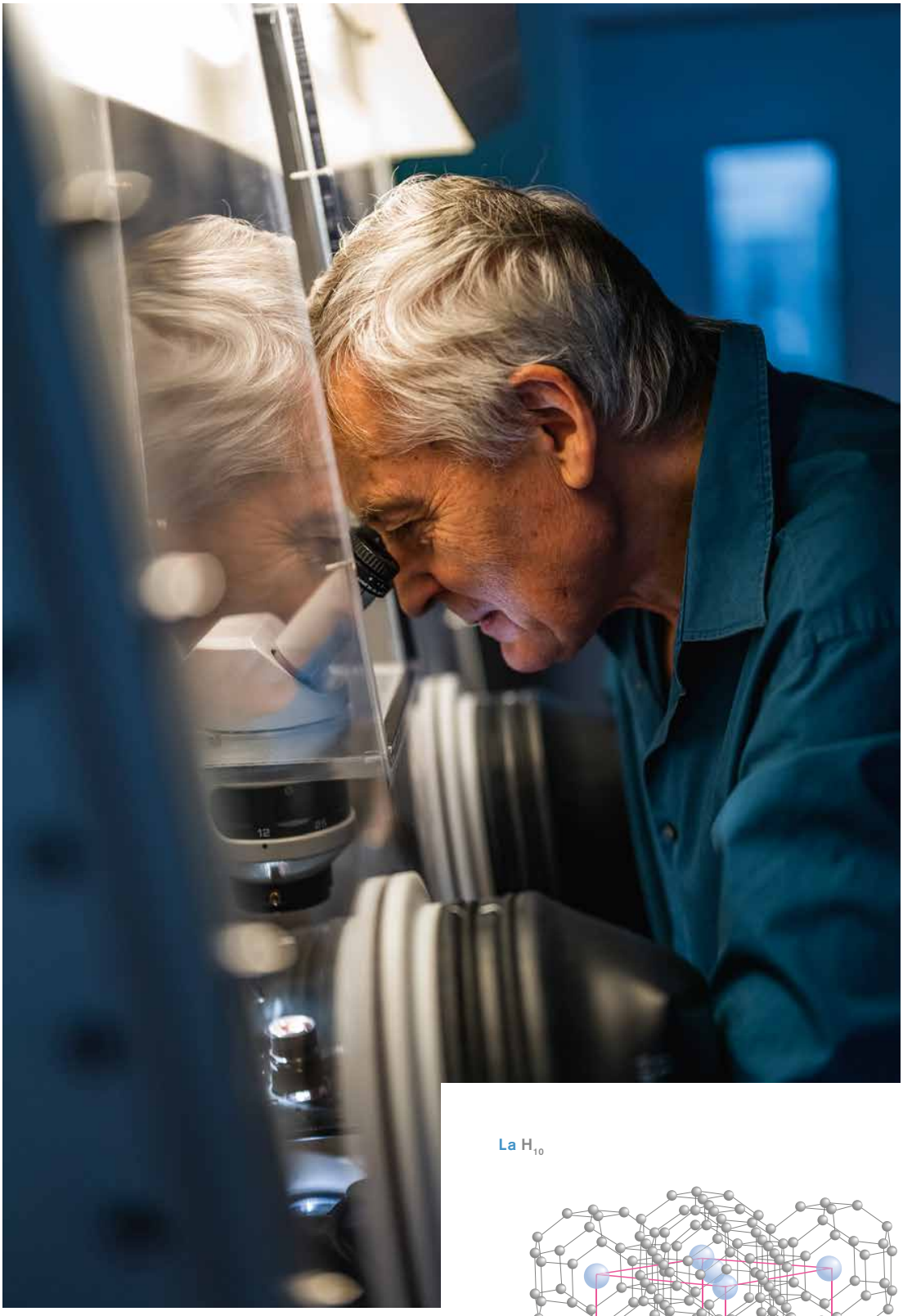
SUMMARY

Superconductivity has long been observed only at temperatures far below zero degrees Celsius. A Max Planck team in Mainz has since achieved superconductivity at only minus 23 degrees Celsius.

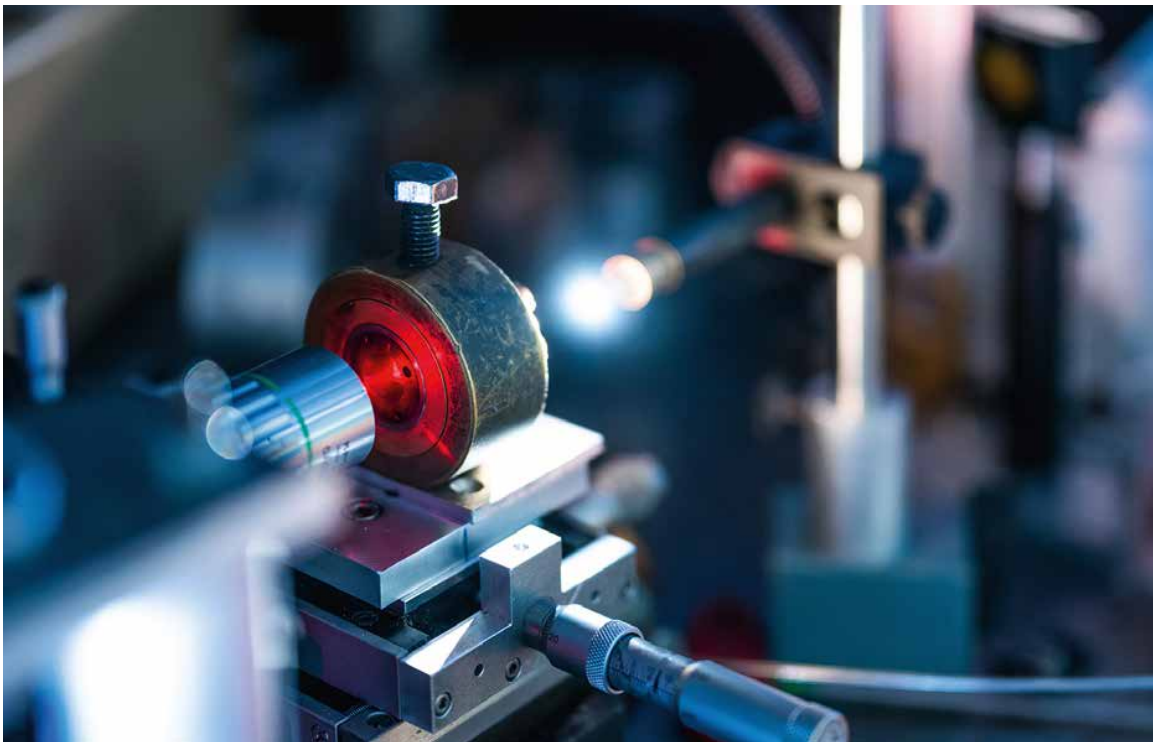
Advances in critical temperature have been made possible because the researchers have been investigating hydrogen-rich materials. However, to date they have had to place these materials under a pressure of more than one million bar.

Hydrogenous compounds that can build up this pressure to a certain degree by virtue of their structure could come closer to superconductivity at practical temperatures and pressures. Another approach is offered by materials whose atoms vibrate at a high frequency, e.g. in metallic hydrogen.

PHOTO: JAN HOSAN; GRAPHIC: MIKHAIL EREMETS



Special atmosphere: Mikhail Eremets uses a glovebox to load a sample into an anvil cell in the absence of air. His team observed a record-high transition temperature of minus 23 degrees in lanthanum hydride (LaH_{10}, bottom right), which consists of many hydrogen atoms (gray) interspersed with lanthanum atoms (blue).



Optical pressure gauge: the researchers in Mainz determine the pressure in a diamond anvil cell by using a laser to measure how the Raman spectrum of the diamonds changes when they are pressed together.

hind a particularly distinct, positively-charged track that can be easily followed by the second electron in the Cooper pair. To test whether this mechanism works in H_3S, the Mainz team repeated the experiment with a heavier hydrogen variant: deuterium. Its atomic nucleus contains one proton and one neutron. Because the mass of the nucleus is now about doubled, it should be more difficult to achieve superconductivity – and the critical temperature should therefore be significantly lower. And that is exactly what the researchers observed: D3S does not become superconducting until minus 120 degrees Celsius.

A new track

This led the Mainz researchers to their next step: if hydrogen is the key, compounds containing an especially high fraction of this element should have the highest critical temperatures. The team selected lanthanum hydride. This substance contains a remarkable ten hydrogen atoms for every atom of lanthanum, a rare earth metal. "It's essentially metallic hydrogen with some lanthanum atoms embedded in it," says Eremets. In 2019, his team set a new record for critical temperature using this compound: it was only 23 degrees below the freezing point of water, a temperature nearly reached on some very cold winter days here in Germany. However, a high pressure of 1.7 megabar was still necessary to achieve it. The journal Nature ranked his work among its ten most important publications of 2019. The following year, researchers at the University of Rochester in New York state presented a critical temperature of 15 degrees Celsius, nearly room temperature, using a compound of hydrogen, sulfur and carbon, upon which they exerted a comparatively high pressure of 2.7 megabar. But Eremets takes a skeptical view of his U.S. colleagues' work: "It's now two years later, and this result still has not been replicated by any other group."

Nonetheless, the research in Rochester points in the right direction: the combination of three elements brings with it the prospect of superconductivity at room temperature or even higher. A team headed by Simone Di Cataldo at the University of Graz has shown this in a model calculation for a compound of boron, lanthanum and hydrogen. In this model, boron and lanthanum form a crystal lattice by themselves, within which metallic hydrogen is interwoven as a second atomic lattice. The first lattice stabilizes the second one, the researchers explain. The model calculation shows the material already losing electrical resistance at 0.5 megabar, although this occurs at a fairly low temperature of about minus 147 degrees Celsius. On the other hand, other model calculations yield an extremely high transition temperature of nearly plus 100 degrees Celsius for a compound of lithium, magnesium and hydrogen, although this occurs at a pressure of 2.5 megabar. However, a combination that yields a low pressure and a high transition temperature has yet to be found. And such a combination probably won't be found any time soon: "It would be misleading to think that this could be achieved through chemical pressure," says Mikhail Eremets. His team therefore wants to understand how superconductivity develops in hydrogen compounds.

PHOTO: JAN HOSAN

GLOSSARY

BCS THEORY
The explanation for the mechanism of superconductivity in metals, named after John Bardeen, Leon Neil Cooper and John Robert Schrieffer. According to this theory, lattice vibrations promote the formation of Cooper pairs, which form a common quantum state at low temperatures and therefore no longer interact with the atomic lattice.

CRITICAL TEMPERATURE
The temperature below which a material becomes superconducting.

SUPERCONDUCTIVITY
The state in which a material conducts electricity with no electrical resistance.

This could then yield insights for further studies. "We already know that high vibrational frequencies in the crystal lattice are important," says Eremets. And this knowledge could be applied in the search for an ideal substance. The researcher also has a possible approach at the ready: diamond contains very rigid chemical bonds between its carbon atoms that vibrate at a similar rate as those in metallic hydrogen. "The problem is that diamond is an electrical insulator," Eremets explains. In order to function as a superconductor, it would first have to be made to be conductive. "Perhaps we could add small quantities of dopant (or impurity) atoms, to alter its original electrical properties," suggests Eremets.

Researchers therefore still have a long way to go before they can attain a room-temperature superconductor at normal pressure. Still, Reinhold Kleiner from the University of Tuebingen is cautiously optimistic. "If theoreticians and experimenters can continue working together this effectively, we'll find superconductivity in other systems as well," the physicist declares. However, he is skeptical that this will work at normal pressure, and adds: "At this point, I'm just happy with the systematic search that is happening and the results it has yielded."

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Under pressure to perform: taking an exam is a source of stress for most people. But stress can also have a positive effect. You become more awake and focused, and your attention and reactivity levels increase.

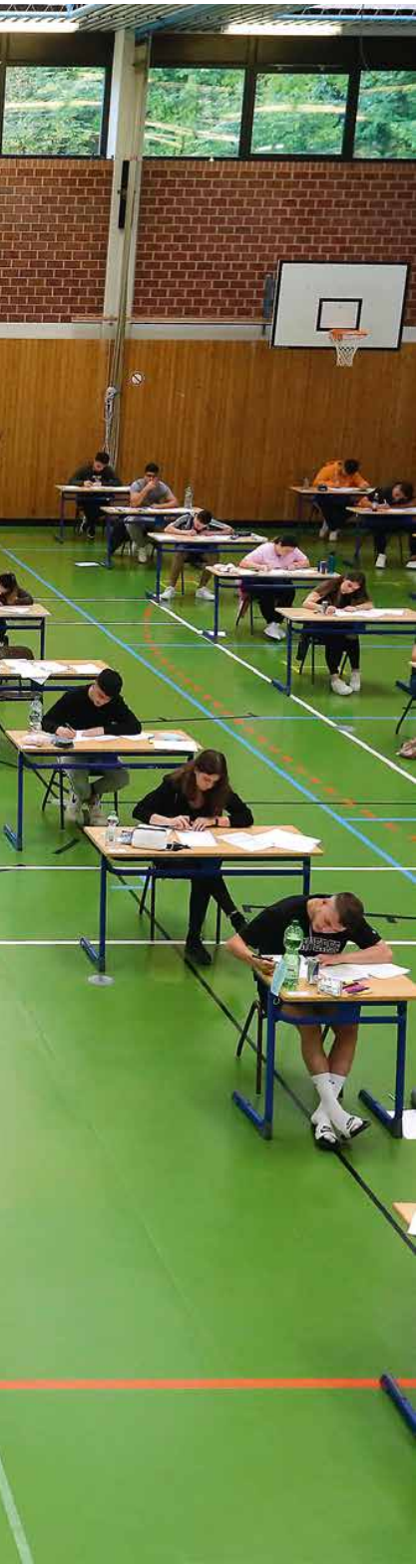

PHOTO: PICTURE ALLIANCE / SZ PHOTO | MARCO EINFELDT

DON'T STRESS YOURSELF

TEXT: JAN SCHWENKENBECHER

When the human body is exposed to stress, it goes into the very same emergency mode that it used in the Stone Age. However, that reaction is not nearly as well suited to our way of life today. Scientists at the Max Planck Institute of Psychiatry and the Max Planck Institute for Human Cognitive and Brain Sciences are studying what happens in the body during stress, who is particularly susceptible to stress, as well as when it is an especially bad time to have to deal with a large amount of stress.

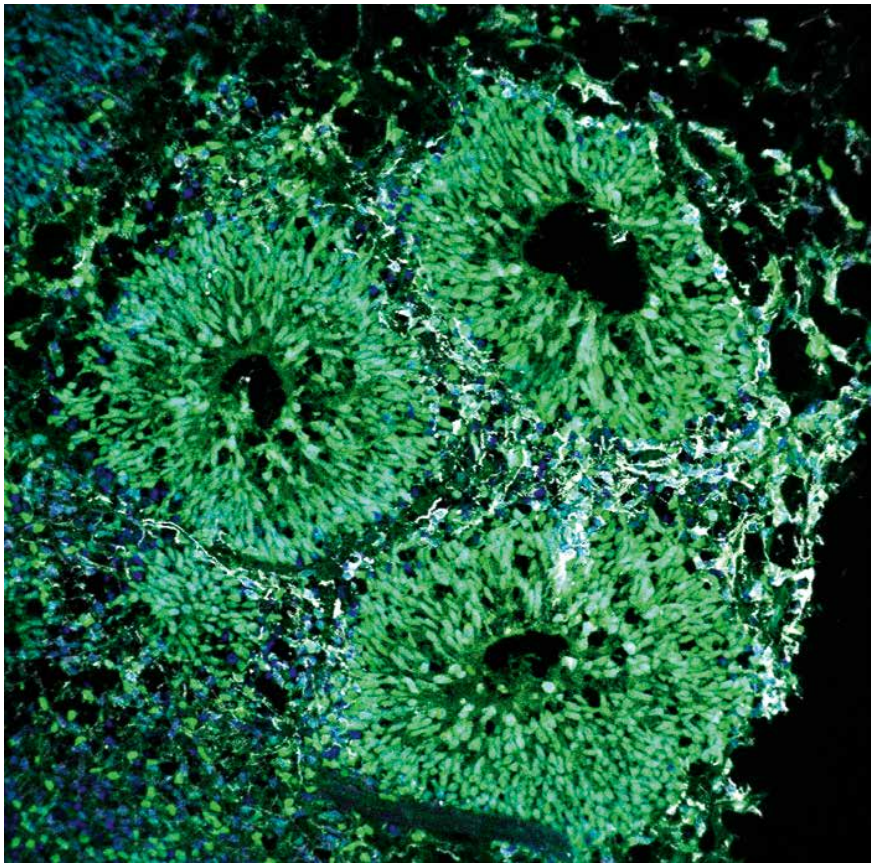

PHOTO: ANTHI KRONTIRA/MPI FOR PSYCHIATRY

Stress in the cell culture: researchers are using brain organoids to study the impact of stress hormones on brain development. These organoids consist of neuronal precursor cells (green) and newly created neurons (gray).

Just imagine: you have just ten minutes to prepare. And then you need to give a five-minute presentation about why you're the best candidate for a job. Without notes. And to make things worse, you have to do this in front of two psychologists in white coats, who are both experts in non-verbal behavior, who will sit motionless and impassive, just watching you. Audio and video recordings of your presentation will also be made and analyzed. And then there will be five minutes left in which you have to solve mathematical problems of medium-level difficulty. Holy moly! This doesn't exactly sound like a leisurely walk in the park – more like maximum stress!

In fact, that's the whole idea. The situation described is part of the script for the Trier Social Stress Test, or TSST. The test is designed with just one aim in mind: to trigger stress. It is particularly effective at doing just that, since the test situation combines three central components of psychosocial stress: unfamiliarity with a new situation, lack of control and a threat to the ego – in other words, something happens that has a negative impact on your own self-image or sense of self-worth. Psychologists and stress researchers use the TSST to simulate stress in scientific studies. One of these researchers is Veronika Engert from the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig. Engert is a psychologist and a professor of social neurosciences at the University Hospital in Jena. At the Max Planck Institute, she is the leader of the Social Stress and Family Health Research Group. Together with her team, she is studying when people experience stress in social contexts, how this occurs, and what they can do to protect themselves.

The human stress system originally evolved as a kind of emergency response system that floods the body with energy within a matter of seconds, making us better able to overcome a potentially life-threatening situation. Our senses become more alert, our muscles get stronger, and our regenerative capacity increases. At one time, our physical stress response often saved lives. Today, however, the World Health Organization has declared stress to be one of the greatest health risks of the 21st century.

"Life-threatening stressors have become relatively rare in our modern, western society," says Veronika Engert. "The things that stress us are mainly of a psychological nature." These things can range from a meeting with your boss, to the growing stack of unpaid bills on your desk, to having a phone conversation about work while you're picking up the kids from daycare, to getting stuck in traffic. "There are countless small incidents that occur in everyday life that make us feel stressed. The interesting thing is that our bodies respond in the very same way as if we were being threatened by a bear," she explains. The body releases a vast amount of hormones, ratchets up our blood pressure and accelerates our breathing. "But we often don't need that added energy – for example, when we're only sitting in the car stuck in a traffic jam. It just makes us even more agitated." Another problem is that people today feel stress

"But we generally don't need that added energy at all."

VERONIKA ENGERT

far more frequently than they used to. "The way we live our lives means that most of us are exposed to low-threshold stress too often," Engert says. In other words, it might be just minor incidents that bother us, but there are far too many of them, in too quick succession. "The next stressor usually rears its head before our body can recover from the last. As a result, we're constantly in a state of increased stress and stewing in toxic stress hormones."

Being in a state of stress is first and foremost bad for the health of the person who is experiencing it. However, that's not all. Together with her group, Veronika Engert has demonstrated multiple times that we not only feel stressed when we are personally exposed to time pressure, arguments, traffic jams or aggravation. We also experience it when we see that other people are feeling stressed. A few years ago, Engert and her colleagues published the results of a study of 211 couples who were either life partners or two people who didn't know each other. In the laboratory, one person in each dyad underwent the TSST and became increasingly stressed, while the other half of the dyad watched, either via video recording or through a panel that appeared as a mirror on the other side. Engert and her team took saliva samples from both participants before and after the TSST and examined them for cortisol levels. Created by the body in the adrenal cortex, this hormone is primarily released when we are under stress, and acts as a biological marker for researchers studying the stress that a person has recently experienced. As Engert and her team discovered, the levels of cortisol among the observers increased to the same extent as those of their actively stressed partners. Simply knowing how stressful the situation must be for the other person was sufficient to cause the observers to experience stress themselves. After their visit to the laboratory, the test subjects who were partners in real life were asked to collect six saliva samples each over the course of two more days, and to send them to the team. It emerged that in everyday life, too, if one partner was stressed, the other person felt stressed in response.

"The stress felt by others activates my own stress axis," Engert explains. This phenomenon is known among researchers as 'empathic stress'. "This effect even occurs when the person who is stressed is someone I don't know," Engert says. "However, the closer my relationship is to the stressed person, the more strongly I experience the stress myself." The question is: what's the point in encumbering myself with the stress felt by others on top of the stress I'm feeling myself? "Empathic stress does indeed have a useful function," Engert explains. "For example, as a mother, if I can see that my child is experiencing stress right now, that gives me the energy to help." Or conversely: if a mother and child are crossing the road and a car approaches at high speed, the child might not yet be able to assess the situation correctly. However, because the child feels the mother's stress, he or she gains the energy and insight needed to quickly jump to one side.

"Empathic stress therefore has an important, positive function," says Engert. However, as is so often the case with stress, there is also another side to the coin. "When I think of a child living in a home with chronically stressed parents, who is constantly exposed to their stress, then it's easy to imagine that this situation isn't exactly healthy for that child." Just how bad stress is for our health, and who is particularly affected by it, is demonstrated by the research being conducted by Mathias Schmidt at the Max Planck Institute of Psychiatry in Munich. "There is a whole range of diseases that are either caused or exacerbated by stress," Schmidt explains. "Anxiety disorders and depression are just two examples."

Schmidt is the leader of the Neurobiology of Stress Resilience Research Group. Together with his team, he is studying the influence of acute and chronic stress on the human body during different stages of development. One of his key questions is: when and why does one person tend to be resistant to stress; and when and why is someone else particularly susceptible to it?

Biomarkers are an indication of susceptibility

As Schmidt already knows: "On the one hand, our genes play an important role. We have observed in mice that they react differently to stress, depending on their genetic predisposition." However, genes are not the only triggers for that response. "We also know that environmental factors play a very important role," Schmidt says. "It's not necessarily the case that someone with a certain genetic background will inevitably be sensitive to stress. Genes are a risk factor, but there are several other factors that also play a role." It's never about one single stress gene. When stress researchers like Schmidt talk about "genetic influence", they mean a large number of different genes, each of which increases the likelihood that someone responds more sensitively to stress, at least to a small degree.

To find answers to his questions, Mathias Schmidt conducts experiments on mice. For him, this has several advantages. For one thing, pregnancy in mice lasts for just three weeks, and mice are already teenagers just a few weeks after birth. As a result, the researchers are often able to study the longer-term consequences of stress without having to wait years to do so. "In this

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way, we want to find out which genes and which circuits in the brain cause mouse one to be more vulnerable during stress exposure, but do not have that effect in mouse two," Schmidt explains. "To do that, we look for biomarkers – physical signs that can predict what will happen without us having to put the mouse under stress." There are various things that can be used as biomarkers: brain structures or entire circuits, as well as individual genes or certain combinations of several genes. "Meanwhile we've found several indicators for such biomarkers, which let us know that by manipulating them, we can increase or reduce the sensitivity to stress," says Schmidt. One example is the protein FKBP51. It performs several tasks in the body, but one of them is of particular interest to researchers: it influences the sensitivity of stress hormone receptors. In so doing, it also has an effect on the processes in the cell that are triggered when the stress hormones bond with them after the body has released them as a response to stress. "Here, FKBP51 appears to play a very important role," Schmidt says. "And we now also know from studies on humans that changes in the genetic structure of the FKBP gene, known as polymorphisms, influence how sensitive someone is to stress, and even affect the risk of their susceptibility to depression."

Children in their mother's womb are also at risk

Schmidt's research is directly linked to the field of psychiatry. It is application-oriented, preventive research. "We do the same for other diseases," he explains. "When a doctor ascertains that I have an increased blood sugar level, I know that I need to be careful and to adapt my way of life. Because if I continue my behaviors, I might develop diabetes in two years' time." A very similar approach could be taken in psychiatry in the future: if there is an awareness of a susceptibility to stress in a person's individual risk profile, those who are more at risk could be advised to reduce the level of stress in their everyday lives. This could prevent certain psychological disorders from developing.

Once again: stress isn't a bad thing in itself. The body's stress response helps us become more capable of taking effective action within seconds. However, what matters is the amount of stress, and the point in time at which it occurs. Constantly living with time pressure, daily agitation and upsets among work colleagues, or exposure to incessant city noise, means that stress becomes a permanent situation that can lead to problems in the long term. The same is true if stress occurs at the wrong time. Cristiana Cruceanu knows all about that. She is a postdoc who also works at the Max Planck Institute of Psychiatry in Munich, in the Translational Research in Psychiatry Department. According to a study published by Cruceanu in the fall of last year, one of these cases of bad timing occurs even before a baby is born. Cruceanu uses brain organoids to conduct her research. These are three-dimensional models which, starting from stem cells, create a model of human brain growth in a petri dish. "Of course, it's not a real brain," explains Cruceanu. "But it does have many features of a brain, and we can monitor its development over a period of time that corresponds to the development of a baby in the womb during pregnancy." Naturally, it's not possible, she says, to exactly compare the petri-dish brain with a real-life brain. However, if you know which questions it's worth asking and which are not, brain organoids can be of huge benefit.

Cruceanu and her colleagues asked the following question in their study: what happens when a developing brain is confronted with an increased level of the stress hormone cortisol? "We know that this hormone plays an important role in development," Cruceanu says. "We also know that the increased level of cortisol in mothers who are suffering from extreme stress – perhaps because they are suffering from a psychological disorder, are experiencing war or forms of abuse in their daily lives – is in part transferred to the unborn child. We wanted to find out whether this increase in cortisol has an impact on the baby's development, and if so, how." The researchers found the brain does indeed develop differently: it develops a significantly higher number of nerve cells. What does that mean? "It could be beneficial that leads to a higher tolerance for stress in later life," Cruceanu explains. "However, there are also indications that it is a disadvantage." Here, the limits of the brain model have been reached; the question will need to be answered in other studies, using other methods. But some studies have already been conducted that shed light on this topic, Cruceanu says. "We know from earlier research that in households in which the mothers were exposed to stress, the children more frequently suffer from depression, autism spectrum disorders or other neurological development dis-

"Mice respond differently to stress depending on their genetic disposition."

MATHIAS SCHMIDT

PHOTO: VERONIKA ENGERT/MPI FOR HUMAN COGNITIVE AND BRAIN SCIENCES

Stress test: for the Trier Social Stress Test, a test subject is made to face a grueling job application situation. Using this simulation, researchers aim to obtain new insights into how social stress is created and what its consequences are.

SUMMARY

Researchers are looking for physical signs that provide early indicators of whether stress can lead to psychiatric disorders.

Stress in expectant mothers influences the brain development of the embryo.

The phenomenon of "empathic stress" causes individuals who are exposed to people who are stressed to experience stress themselves.

If someone feels compassion for a stressed person instead of empathy, they may be less likely to take on that person's stress.

orders." Therefore, too much stress harms more than the stressed individuals themselves. Expectant mothers who are constantly or severely stressed during pregnancy are probably increasing the risk of their child becoming more susceptible to stress later on.

And Veronika Engert's research on empathic stress shows that parents transmit their stress to their children, even after they're born. But, thanks to the latest research by Engert and her team, help may be on the way, particularly with regard to the transmission of stress. Engert's team is currently studying the extent to which it makes a difference if an individual who witnesses someone close to them feeling stress responds with empathy or compassion. "In science, we differentiate between empathy and compassion," Engert says. "Empathy is purely sharing the other person's distress: 'I feel your suffering.' Compassion goes beyond this to: 'I want to relieve your suffering.' A person who feels compassion always wants the other person to be in a good situation, to experience mercy, in spite of their suffering." Engert and her team are now investigating whether children are protected against that stress reaction if they tend to feel more compassion than empathy.

"We have a few interim results which indicate that children who feel a particularly high level of empathy experience the stress reaction of their mother more profoundly," Engert says. "In contrast, children who primarily show compassion and who wish to help their mother don't experience the stress themselves to nearly the same degree." If these results are confirmed, this would be an approach that could help define methods of stress prevention. After all, feeling compassion instead of empathy is something that we can learn. This kind of training is already available, particularly for people who work in the care sector, such as doctors, therapists and caregivers. Perhaps similar programs could also be developed for families.

In any case, Veronika Engert's research on empathic stress comes to the same conclusion as Mathias Schmidt's and Cristina Cruceanu's findings: the stress response helps humans react to unusual situations in an unusual way. For this reason, it's important that these situations remain unusual, and that they by no means become the rule. The best way to tackle stress is not to let yourself be influenced by it in the first place.

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DEFINITELY NOT BONE IDLE

TEXT: CATARINA PIETSCHMANN

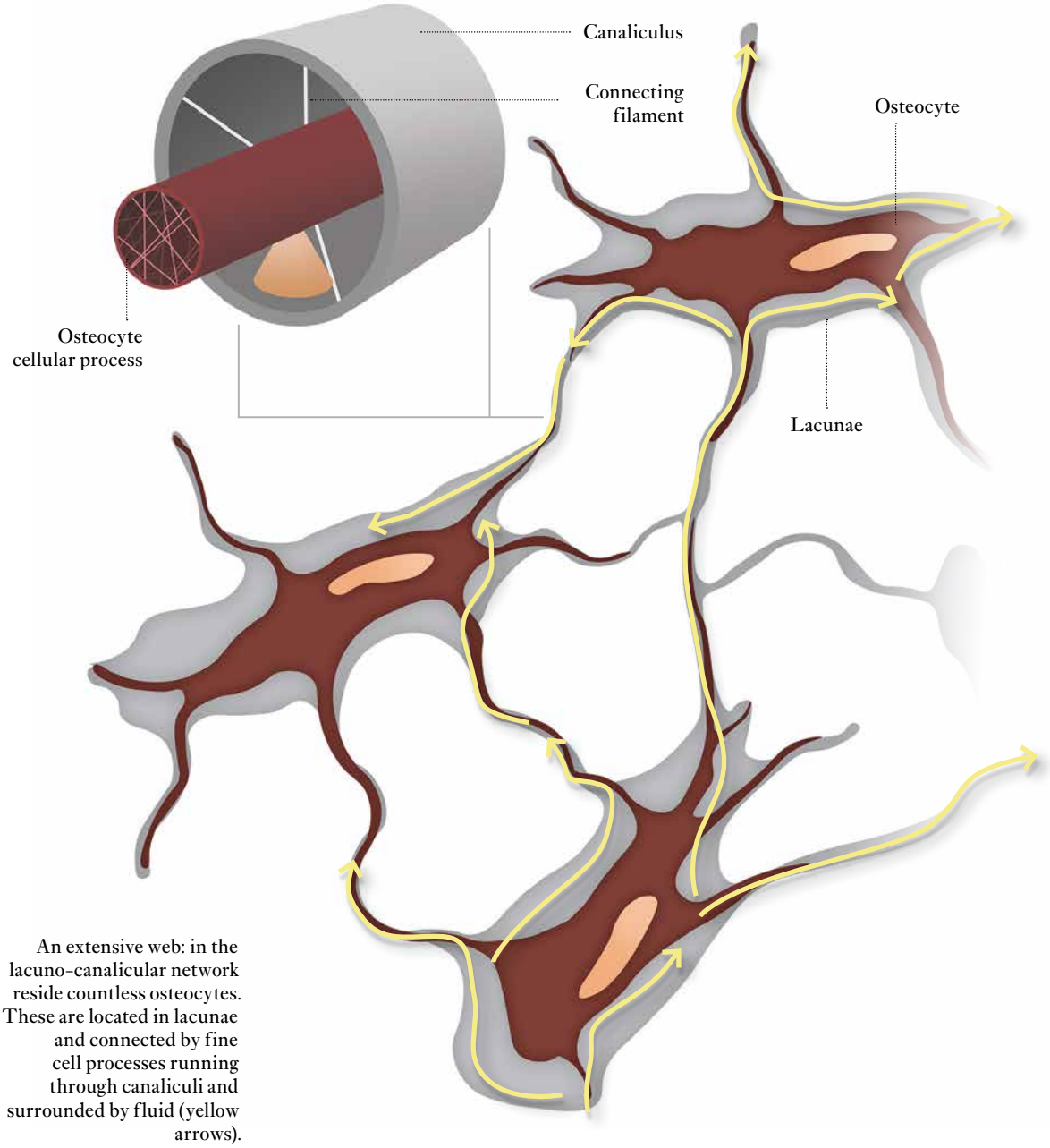
PHOTO: DAVID AUSSERHOFER

Your skeleton provides support for your body. But this framework is anything but static; mechanical stress causes your bones to constantly renew and remodel themselves. Richard Weinkamer and Wolfgang Wagermaier at the Max Planck Institute of Colloids and Interfaces are investigating precisely how this happens and what structure makes bones stiff and strong. Their findings could also prove relevant for medicine and materials science.

Transilluminated: the Potsdam team uses a variety of methods to study the structure of bone tissue – for example, using a micro-computed tomography scanner. The researchers place bone samples into the tubes of these scanners. Here, a thin section has been stained with rhodamine for further examination.

Fractures, crooked spines, worn hip joints – as a surgeon at the Charité, Julius Wolff had seen a lot. X-rays had not yet been discovered when he formulated his law of transformation of bones (otherwise known as "Wolff's law") in 1892. When he held them up to the light, thin slices of bone cut with an ivory saw revealed that the fine, sponge-like matrix of the bones' interiors could remodel themselves in response to mechanical stress. Form follows function, as we now say. And when it comes to the architecture of bone, that design concept can be taken literally. To dissipate tension and achieve maximum stability, bone reacts actively and permanently to mechanical stimuli. This means that material is added in areas that bear heavier loads and removed in areas under less load. But the precise factors triggering and governing this process are still a mystery to scientists 130 years later.

At the Department of Biomaterials of the Max Planck Institute of Colloids and Interfaces in Potsdam, two Austrian scientists have been using state-of-the-art techniques to delve deep into this question – and are



An extensive web: in the lacuno-canalicular network reside countless osteocytes. These are located in lacunae and connected by fine cell processes running through canaliculi and surrounded by fluid (yellow arrows).

ILLUSTRATION: GCO BASED ON AN MPG DESIGN.

SUMMARY

Bones are constantly being renewed and remodeled. Osteocytes and the lacuno-canalicular network play a key role in this process.

Studies conducted by Max Planck researchers corroborate the fluid flow hypothesis. According to the hypothesis, osteocytes can sense changes in the external pressure based on changes to the velocity of fluid flow through the lacuno-canalicular network. There is increasing evidence that osteocytes and the lacuno-canalicular network are also involved in recycling bone material.

Improving our knowledge of how bone renewal is controlled could enhance our understanding of diseases such as osteoporosis.

Detailed knowledge of bone structure is inspiring the development of particularly strong and rigid materials.

steadily getting closer to the answer. One of them, Richard Weinkamer, a mathematician and physicist, is chiefly interested in the mechanobiology of bone. The other, Wolfgang Wagermaier, with his background as a materials scientist, is fascinated by bone, which is a natural hybrid material. Their research focuses on fundamental insights that on the one hand will help us to better understand bone diseases, and, on the other, will also lead to the discovery of synthetic materials with interesting new properties.

Bones are composed of an inherently soft collagen matrix, in which extremely fine platelets of calcium phosphate are embedded. This construction lends the material not only strength and rigidity, but also a degree of elasticity. "Hybrid materials composed of proteins and minerals such as calcium phosphate, calcium carbonate, silicon oxide or iron oxide are widespread in nature. Mother-of-pearl, diatoms and teeth are obvious examples. As well as, of course, bone," says Wagermaier. "We wouldn't get far if our bones were merely soft masses of tissue. Not only that, bones also act as reservoirs of calcium in the body." In this way, they maintain a very sustainable and practicable materials management system. It needs to be practicable, because the more than 200 bones, which constitute about ten percent of an adult's body weight, are constantly being remodeled. It wouldn't be feasible to continually consume the amounts of new minerals needed for that job through our diet alone.

Thirty million cells per cubic centimeter

The material that makes up a compact bone like the tibia is entirely remodeled within ten years. In the case of spongy bones like the vertebrae, this occurs even faster – within five years. This task of demolition and reconstruction is performed by specialized cells: osteoblasts build up bone material, while osteoclasts break it down again. However, 95 percent of all bone cells are osteocytes. As if they were straight out of an Edgar Allan Poe novel, they live for years, sometimes even decades, walled up alive in small cavities in the bone – some 30 million cells per cubic centimeter! Because they are not directly involved in the restructuring processes and are difficult to access in their cavities, cells of this type were overlooked by researchers for a long time. That makes them all the more interesting to Richard Weinkamer and Wolfgang Wagermaier. Osteocytes perform important tasks, so the researchers in Potsdam are investigating these in a combination of diverse methods: optical techniques, characterization methods from material science, mathematical computations and simulations. Osteocytes, for example, are not only involved in maintaining mineral balance; they even secrete hormones and, as the researchers have recently discovered, serve as pressure sensors.

Osteocytes need to be enclosed in their bony prisons to perform some of their functions. And they get imprisoned by their own actions. "At some time in the past, osteoclasts have eaten small tunnels into the bone at these sites. Then osteoblasts have come along and filled the tunnels back up again, layer by layer, thereby enclosing themselves and differentiating into mature bone cells – into osteocytes," explains Richard Weinkamer.

The osteocyte network

To investigate the confined osteocytes, the researchers first saw off a sample of bone, embed it in plastics, and viewed it under an electron microscope. The first things that stand out are the large dark spots. They are channels that traverse the bone, through which blood vessels run. They are surrounded by "osteons": concentric structures similar to annual tree rings and only a shade darker than the lighter part of the bone sample. "Here, surrounding the blood channel, the bone is even younger and less mineralized," explains Wolfgang Wagermaier. "The small, dark spots in the middle are the lacunae. And in these oval cavities, some 15 micrometers in diameter, reside the osteocytes."

If you look very closely, you'll immediately see a fine structure that extends away from the blood vessels toward the exterior: a labyrinth of channels. The researchers immerse the bone sample in a solution containing the fluorescent stain rhodamine and view it under a confocal laser scanning microscope, revealing a bright, filigree structure on a black background, like an extremely fine crochet pattern: the "lacuno-canalicular network." Even though the cell bodies of the osteocytes are locked inside the lacunae, they are connected to their neighboring cells via up to 80 finger-like cellular protrusions running through this network of channels. It resembles the network of neurons in the brain. "The stain allows us to reveal areas that would otherwise be inaccessible. It covers the entire inner surface of the cavity system, and the laser light causes it to become excited and fluorescent," explains Wagermaier. Bone isn't

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transparent, but it is possible to look through thin layers with a light microscope. Confocal microscopy, in which a focused laser beam scans the sample, can be used to capture images of different layers of the bone, which are then combined into a 3D image. Doing so allows the researchers to gather detailed information on the density and connectivity of the lacuno-canalicular network, down to a depth of 40 micrometers. Drawing on his mathematical background, Weinkamer used a computer to virtually extract it from the bone material and calculate the extent of the network. "If you could string together lengthwise all the channels from just one cubic centimeter of bone, they would extend for about 74 kilometers! It's truly spectacular."

Wolff's law states that bone is reinforced exactly where it is mechanically needed. But where is the sensor that controls the process? We know that cells are sensitive to mechanical stimuli, like pressure. However, the pressure exerted from the outside on the relatively stiff bone barely deforms it and isn't sufficient to activate osteoblasts and osteoclasts. Osteocytes may play an important role in this, as was suggested back in the early 1990s in the "fluid flow hypothesis." The idea is that the entire network of channels and cavities containing osteocytes is filled with fluid. "It's essentially like a wet sponge. When the sponge is squeezed, the pressure forces the liquid away, toward other areas where it can escape. If the bone is subjected to mechanical stress, the fluid within this network is forced into the wide channels around blood vessels," explains Weinkamer. The osteocytes feel the forces of the fluid as it flows over their surface. As a simplification, one could say: the greater the load on the bone, the faster the fluid flows. "And it's this information that the osteocytes pass on through the network to the bone surface. That's where the osteoblasts and osteoclasts reside, which then take over."

Bone training for mice

Being able to image the canal network in the bone meant this hypothesis could now be tested by the Potsdam researchers. Together with his colleague Bettina Willie from McGill University in Quebec, Canada, Weinkamer studied three genetically identical mice. The rodents were anesthetized, one of their hind legs was placed in a leg press similar to one in a gym, and a small amount of mechanical force was applied along its longitudinal axis. The untrained second leg served as a control. The mice were then placed in the computed tomography scanner to scan their bones and awakened again. The mice went through this entire procedure several times. Analyzing all the data gave an accurate picture of where new bone was being formed after fitness training and where it was not.

The Potsdam team then examined in detail the lacuno-canalicular networks containing several million small channels in the bones of the three mice. Using the data gathered about the networks, the researchers then calculated the flow of fluids through them. This allowed them to simulate where in the cross-section of the mouse leg they would expect bone to be formed and where it would be resorbed. The simulation did indeed precisely predict where this bone remodeling took place. Based on the evidence from the bone training in the three Canadian mice, the researchers verified that the mechanical sensor in the bone really does functions as predicted by the fluid flow hypothesis. During the training, the bones of the three mice all responded to the training – but to different degrees. Richard Weinkamer discovered why when he compared the channel networks in great detail using samples from the crucial bone areas. His flow velocity calculations established that the architecture of mouse two's network (which gained less bone during training) only allowed fluid to flow slowly.

Bone formation from an embryo to an adult vertebrate follows a sophisticated program. Constant rebuilding is a part of this from the very beginning. "It all starts with a cartilage condensation. As soon as a small amount of bone is present, some of it is removed from the inside and added to the outside," explains Richard Weinkamer. "This is how, little by little, the radius of a bone in-

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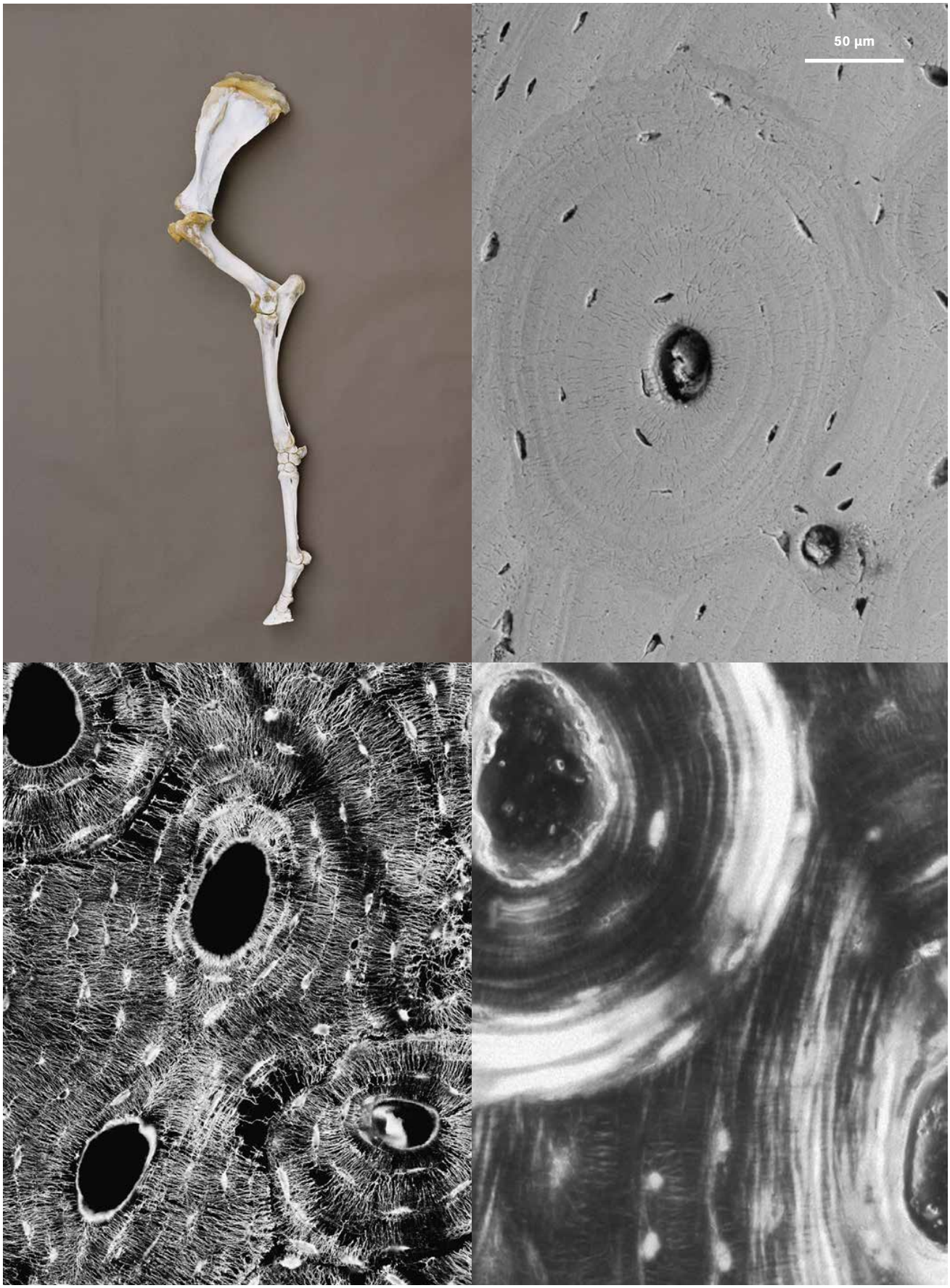
Close-ups of bones from a horse (top left). An image obtained by scanning electron microscopy reveals the larger, circular openings for blood vessels and the smaller cavities of the lacunae in a section through the femur (top right). Under a confocal laser scanning microscope, rhodamine staining highlights the channels of the lacuno-canalicular network (lower left). Polarized light microscopy reveals that the collagen fibers are arranged in a ring around the blood vessels (bottom right).

"If you could string together lengthwise all the channels from just one cubic centimeter of bone, they would extend for about 74 kilometers."

RICHARD WEINKAMER



PHOTOS: SCIENCE PHOTO LIBRARY, MPI FOR COLLOID AND INTERFACE RESEARCH (2), KERSCHNITZKI, WAGERMAIER ET AL., J STRUC BIOL 2011, CELLS TISSUES ORGANS 2011 (CLOCKWISE FROM TOP LEFT)

PHOTO: DAVID AUSSERHOFER

"Tennis players possess more bone volume in their dominant, racket arm."

WOLFGANG WAGERMAIER

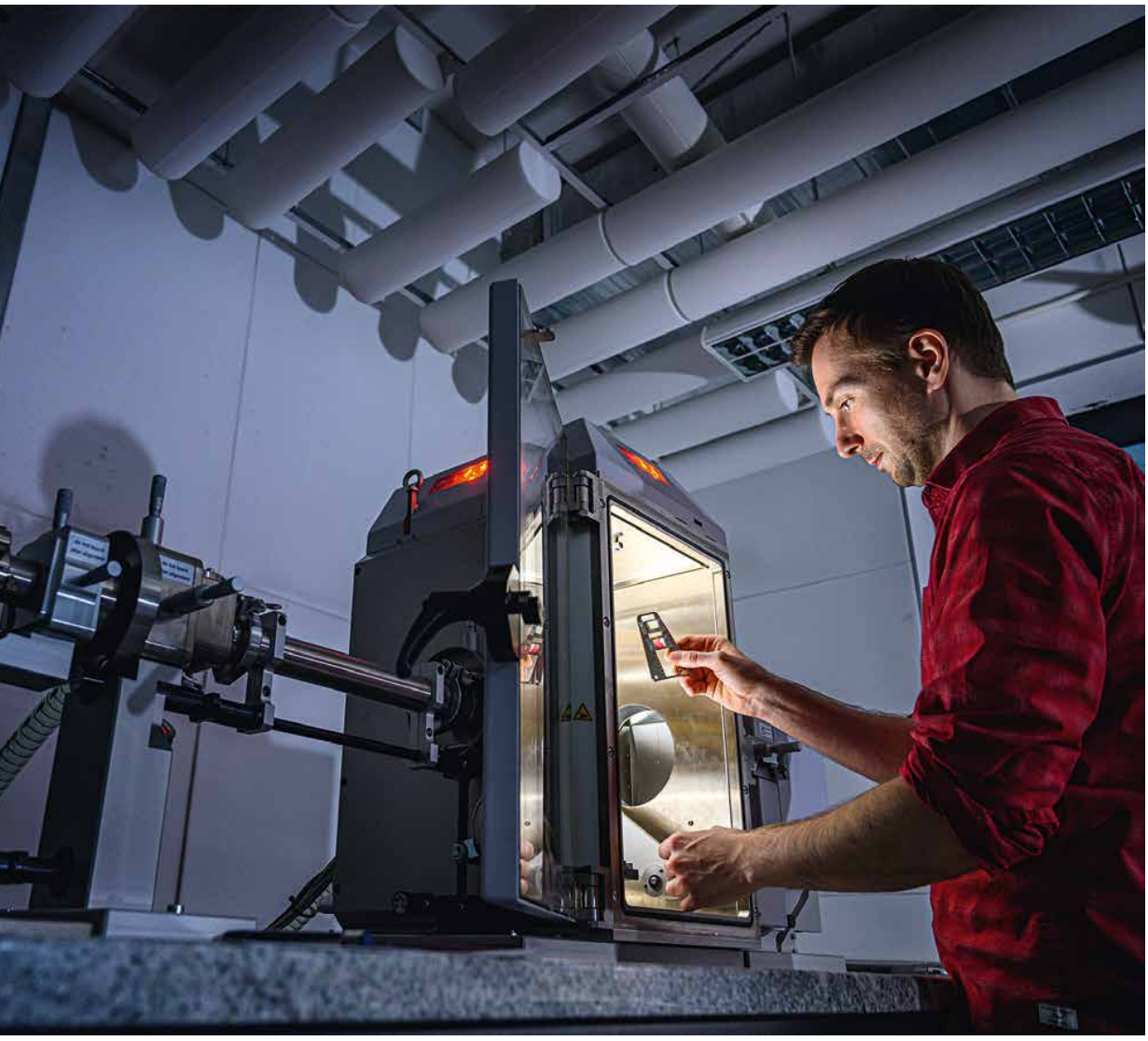
creases. Longitudinal growth is a little more complicated." In this case, the calcium phosphate is broken down in a two-step process. First, the osteoclasts secrete acid to dissolve the mineral component. They do this by developing "fingers" – tiny cell protrusions that they literally push into the material. In the second step, they use enzymes to degrade the collagen matrix. But how do the osteoblasts recover the building material? This transport route for calcium phosphate is currently being studied by Wagermaier and Weinkamer. "Obviously, some kind of recycling is taking place. Some of the mineral is packed into vesicles. We're using the electron microscope to search for these vesicles and calculating how many would have to pass through to mineralize the bone," Weinkamer explains. There is now increasing evidence, including that from the Potsdam team's research, that osteocytes are likewise involved in regulating mineral balance. There's no doubt that the breakdown and incorporation of calcium phosphate, a process known as mineral homeostasis, is also a very laborious process. "The lacuno-canalicular network may also serve to ensure that the mineral is extracted without completely destroying the collagen matrix," says Wolfgang Wagermaier.

Dysfunctions in bone mineralization and demineralization are the cause of many bone diseases. Osteoporosis and brittle bone disease (osteogenesis imperfecta) are two examples. Using animal models like mice that carry specific genetic defects with a pattern of disorders similar to human bone diseases, researchers around the world are attempting to learn about these diseases – and to identify potential therapeutic approaches.

While Richard Weinkamer is concentrating on the lacunae and the web of channels, materials scientist Wolfgang Wagermaier is primarily interested in the areas that appear black under the confocal laser scanning microscope: the compact bone material surrounding the canal network, like the rock of a mountain surrounding a cave system. To visualize it, Wagermaier's team is bombarding samples with short-wavelength X-rays at the electron storage ring BESSY II in Berlin-Adlershof. This procedure yields diffraction images, which they can use to determine the sizes of the mineral particles in the collagen matrix. Wagermaier is searching for inspiration from biology to create new materials, in this case the relationships between the material parameters – the orientations, for instance, of collagen fibers or the sizes of mineral particles – and the architecture of the lacuno-canalicular network. Polarized light reveals the ring-shaped structure of the collagen matrix. Small-angle X-ray scattering reveals deeper structures, including collagen fibrils. Wide-angle X-ray scattering provides even more detail. "Each fibril contains numerous collagen molecules that are arranged in a surprisingly regular fashion," Wagermaier says. "Each individual collagen molecule is twisted into a triple helix about 300 nanometers long. The collagen helices are separated by gaps of about 40 nanometers." In these gaps, the mineral platelets begin to grow, attaining a thickness of two to seven nanometers, depending on the type of bone.

Synthetic materials with mineral nanoparticles

The combination of flexible fibers and hard particles can also be harnessed to optimize synthetic materials. A study conducted together with Hans Börner of the Humboldt University in Berlin, for example, has shown that when mineral nanoparticles are embedded in a polymer matrix using a kind of adhesive at the interfaces, synthetic materials become significantly stronger and stiffer. The work performed by osteoblasts in building the bone structure, which provides a model for materials science, is extremely elaborate. However, its effects are often visible on a macroscopic scale. "People who play tennis frequently possess more bone volume in their dominant, racket arm," Wagermaier states. And in testing greyhounds who repeatedly race in one direction around a circular track, it was found that the bones of the outer legs are often slightly denser than those of the inner legs. In general, bones obey the following principle: absence of a mechanical stimulus causes them to lose mass. This is not just a problem that occurs due to lack of exercise in old age; it also affects astronauts during extended space missions. In a study conducted by NASA, subjects



Sample for the "nanostar": technician Daniel Werner prepares to analyze a sample of bone using small-angle X-ray scattering (SAXS) to determine the size of its mineral particles.

who were not permitted to leave their beds for four weeks lost both muscle and bone mass. The extent of this varied from person to person. Weinkamer and Wagermaier suspect that, similar to the mice, differences in the network structure of the bones play a role.

Bones can remodel and renew themselves throughout life. Nevertheless, bone density starts to decrease at around the age of 35. "We don't know why. Does the sensitivity of the bones' mechanosensing system decrease with age? Just like our other sensory organs – our eyes, and ears – it becomes less sensitive," muses Wagermaier. In his view, using drugs as a prophylactic measure would be ill-advised. It would be better to take countermeasures, like exercise and gentle strength training. This would maintain the pressure on bones to prevent their restoration from decreasing, even into advanced old age.

www.mpg.de/podcasts/druck (in German)

GLOSSARY

LACUNO-CANALICULAR NETWORK
The micrometer-fine channel system that runs through bone. It connects the lacunae in which osteocytes reside and is filled with fluid.

OSTEOBLASTS
Cells that secrete collagen and calcium phosphate and thus build bone material.

OSTEOCLASTS
Cells that break down bone material and make this material available for rebuilding.

OSTEOCYTES
Cells that are derived from osteoblasts and are located in the lacunae of the lacuno-canalicular network.

Logical processes help computers crack complex mathematical problems, thus making them smarter and faster. Logic can even take human-machine communications to a whole new level. Christoph Weidenbach from the Max Planck Institute for Informatics has been developing such promising logical algorithms for thirty years, and is even testing them on his own race car.

TEXT: TIM SCHRÖDER

Christoph Weidenbach is a fan of fast cars. He owns an Opel Speedster, a roadster that weighs in at just 900 kilograms. He opens the garage door to reveal the immaculately clean room that houses his Speedster, gleaming except for a few splattered insects on the front grill. The vehicle is painted yellow and black. "Like Maya the Bee," he says with a smile. Weidenbach lives south of Mainz, in a small village that is known for its wines. Whenever he really wants to put his Speedster through its paces, he wends his way through the vineyards to the nearest highway, then heads up past Koblenz to the Nuerburgring in the Eifel region about an hour and a half away.

The so-called Nordschleife (North Loop) of the Nuerburgring, which snakes its way through 20 kilometers of hilly and forested terrain, is considered the most challenging racetrack in the world. All automobile manufacturers test their sports cars there and private citizens are also allowed to blast their own cars around the track. "The Nordschleife is like a roller coaster," says Weidenbach. "The only difference is that you have to steer it yourself. This year, I'll be taking my four-year-old daughter there for the first time." A few years ago, Weidenbach and his brother fine-tuned the Speedster, disassembling and rebuilding the entire car, including the engine. He added a supercharger that forces compressed air into the combustion chamber. The car used to be too slow for him, but it now produces nearly 300 hp – twice as much as the production model. His father owned an Opel dealership, so it is no wonder that he could already drive a car by the age of twelve.

Although he never became a car mechanic, his research over the years has always had some connection with cars. Weidenbach works at the Max Planck Institute for Informatics in Saarbruecken, where he heads up the independent "Automation of Logic" research group. Their key objective is to formulate logical descriptions of complex situations, so that they can be automated to enable computers to solve the associated problems independently. This is somewhat reminiscent of chess-playing computers, although Weidenbach's approach is much more complicated.

Generally speaking, the problems for which he and his team develop computer algorithms are generally "provably unsolvable," in that they are arbitrarily difficult and beyond the capacities of any computer. This is precisely why it is important to test the novel algorithms on real applications that are known to be solvable in principle. Weidenbach used pure logic to model his Speedster's engine control unit, so his research results accompany him every time he takes the car out for a spin. The engine control unit regulates the amount of air entering the engine, as well as the amount of gasoline that is injected. Conventional control units simply do what they are programmed to do. But thanks to logic, Weidenbach's version can monitor its own actions and evaluate in a fraction of a second whether they make good sense or not. Moreover,

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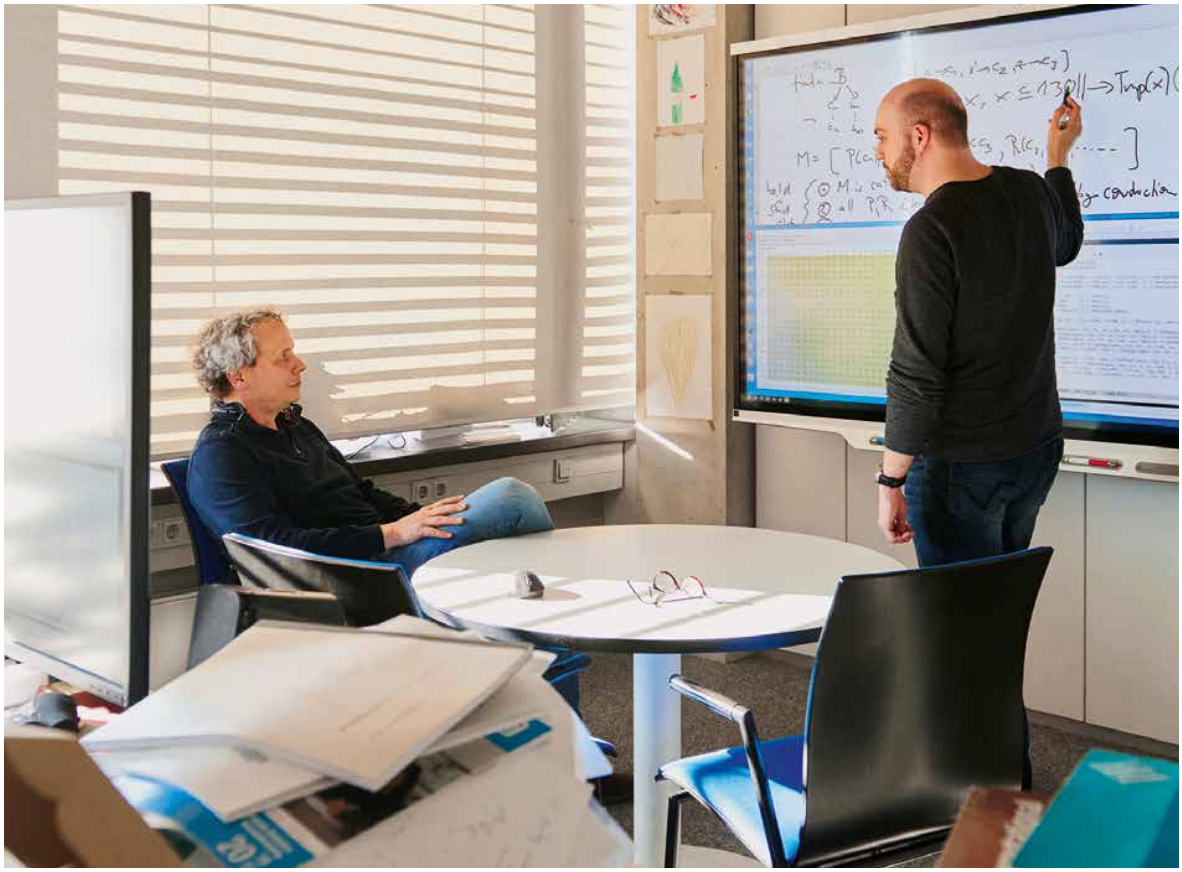
VISIT TO

CHRISTOPH WEIDENBACH

PHOTO: ANNA ZIEGLER

Focused in the cockpit: Christoph Weidenbach and his team are developing algorithms for programs in logic that control complex technical systems in safer, more efficient, and self-explanatory ways – like the engine of an Opel Speedster.



PHOTOS: ANNA ZIEGLER

Think tank: Weidenbach and his colleague Martin Bromberger are modeling an engine control unit to come up with ways to expand their methods. Weidenbach uses a laptop to read out the data from this device, which he installed in his car.

his engine control unit can even explain its actions if necessary. As we know, computers are basically dumb: all they do is switch their transistors on and off to mindlessly perform a series of calculations, enabling them to add or subtract, for example. Drawing logical conclusions presents more of a challenge, as can be seen even in a simple syllogism such as: "All human beings are mortal, Socrates is a human being, therefore Socrates is mortal". All software programs and anything that a computer can calculate are based on these types of logical, If-Then relationships, i.e., rules.

The airbag is a good example: its control system continuously monitors whether it needs to be deployed or not, by analyzing such parameters as deceleration and it has to decide in an instant whether an accident has actually occurred. If it were to deploy and suddenly hit the driver in the face at the wrong moment, it could easily cause an accident. That is why systematic testing is carried out during the development of airbag control programs, to ensure that the software will always function correctly when installed in a car. Weidenbach's approach can be used to prove the correctness of the control program. The challenge for programs in logic simply consists of having to process enormous amounts of data in fractions of a second and their ability to do so is still extremely limited. But Weidenbach is already well ahead of the game. The algorithms he uses in his Speedster are still very new and are not yet being used in the industrial sector.

After completing his habilitation degree in the early 2000s, Weidenbach spent some time working for the General Motors Company (GMC). But back then, his job had little to do with logic. One of his managerial tasks was to assist with the introduction of the SAP resource planning system in Europe. "However," he says, "at that time, I had negotiated a contract that allowed me to continue my work at the Max Planck Institute for fourteen days a year. That's actually a pretty unique arrangement." That kept Weidenbach connected to the world of research over the years, and in 2005 he finally returned to work at the Institute full time, because he had been missing the clearcut, rational methodology. As a result, he is very familiar with both sides – the logical discipline of computer science and the needs of industry.

Another area in which the algorithms developed by Weidenbach are applicable is in the product kits used by automobile manufacturers. These kits consist of complex lists of all the components installed in the various car models, encompassing everything from the screws to the windshield. The ideal situation for a manufacturer is to be able to reuse existing components in new models, but it is not always easy to determine whether this is possible or not. For example, it is difficult to know whether a new model can be built to have certain, specific characteristics – for example, a top speed of 200 kmh, while using only 4 liters of fuel per 100 km (3.785 liters = 1 gallon). In this case, giving the computer a plan like, "Engine Z will be used in the new Model X," is not enough. The computer needs rules, such as "Engine Z will fit in any car that has an engine compartment volume of 1.10 meters wide and 0.6 meters deep."

"The great thing about the logical approach is that the devices in question can also explain why they do something."

The leading automobile manufacturers are already using these modeling techniques, but the problems still exist, due to the enormous number of variants. A specific car could be a coupe or a convertible and could be fitted with any one of ten different engines, five different transmission systems, and various wheel types. Some vehicles come with a trailer hitch, others with a high-end hi-fi system. The number of potential variations is in the billions, so simply listing all the possible variants is usually not an option. Modern logic algorithms solve the problem by deriving new insights from

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the known rules. One such insight might be that no engine can achieve 100 km to the gallon in combination with the weight of the heavy-duty hi-fi system, which is a useful thing to know.

Another problem is that the number of these insights is still excessively large, because of the vast number of possible combinations. This means that the system could come up with quite a few useless statements, such as, "The trailer hitch cannot be combined with a bike rack," which has precious little to do with the initial problem. So, current programs that employ this operating principle of learning by generating new insights are rendered ineffective by the sheer number of potential combinations and insights.

"The current solution," Weidenbach explains, "is to delete unnecessary insights." For example, if no connection can be made between the insight "the trailer hitch cannot be combined with a bike rack" and the original requirement "100 km to the gallon" via a few logical steps, then it is deleted. But as Weidenbach explains, "Even this approach will eliminate only about a third of the insights." So, his goal is to use a combination of mathematics and logic to produce a set of rules that can be applied in practice and come up with a solution within a reasonable span of time – for modeling a new car while taking all available kit components and technical correlations into account, but also for solving a whole host of other problems.

Christoph Weidenbach and his team have developed the "Superlog" system, a software framework that uses so-called model assumptions to compute the required solutions. The program derives certain assumed facts from the given rules and calculates new information only for those areas where the existing logical model doesn't yet work, which is akin to assuming at the outset that Socrates is a human being. This approach significantly reduces the computational effort required, so that huge amounts of data can be transferred efficiently into the basic rules. One practical application of this technology already exists. The software for the engine control unit in Weidenbach's Speedster records a series of engine parameters in just a few milliseconds and uses them to calculate what to tell the engine to do in real time. The speed of this logical analysis is unparalleled. "The great thing about the logical approach," Weidenbach explains, "is that the devices in question can also explain why they have made a particular decision." This differs from conventional control systems, which simply issue commands based on specific parameters.

Systems like this could make human-computer communications much easier and more secure. One example that Weidenbach likes to quote is the plane crash on June 1st, 2009, when an Air France plane suddenly fell out of the sky on a flight from Brazil to Paris. The crash occurred because the impact pressure sensors were iced over and sent conflicting information to the autopilot, which caused it to shut down halfway across the Atlantic. The conversation captured by the flight recorder shows that the pilots were confused by the behavior of the flight control system, which caused the on-duty pilot to pull the nose of the airplane up at too steep an angle without the other two pilots noticing. Eventually, the plane stalled due to the lack of speed and crashed into the sea. Had the plane's control unit been modeled on the rules of logic, it could have simply explained that the joystick of the pilot pulling the plane's nose upward had priority over that of the co-pilot who was trying to gain speed by forcing the plane downwards.

"I thought his approach was wrong and Ganzinger thought my doctoral topic was nonsense. He told me that to my face."

The fact that Weidenbach ended up modeling non-trivial technical issues is basically due to a coincidence. While he was working on his doctorate in 1991, his supervisor relocated to Saarbruecken to join Harald Ganzinger, then Director of the Institute and head of the Logic of Programming working group. Ganzinger was interested in the concept of limiting and simplifying computational logic using so-called orders. "I thought his approach was wrong and

Ganzinger thought my doctoral topic was nonsense," says Weidenbach. "He told me that to my face. But we finally examined each other's theories in more detail and published some really good papers together."

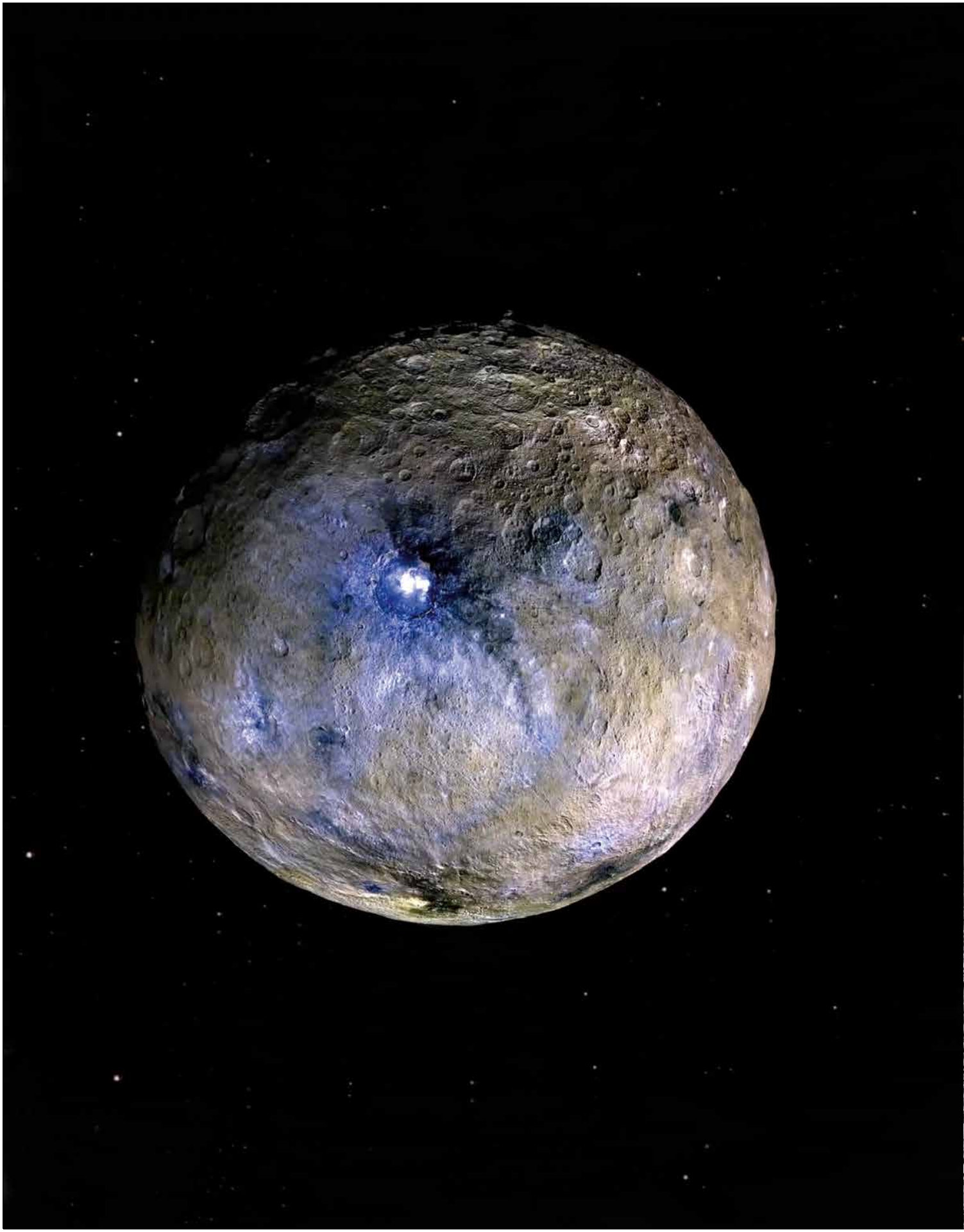
During his teens, Weidenbach was an excellent saxophonist. He was only fifteen when he played in the state youth big band of Rhineland-Palatinate, which was a kind of talent incubator. "At that time, I was thinking of a career in jazz," Weidenbach says. On weekends, he and one of his musician friends used to earn money – to save up for a motorbike – by playing gigs in nearby villages and on club dance nights. "But, at some point I came to realize that you can't earn a long term living from that – and certainly not as a jazz musician." So, he decided to study computer science. The then Central Office for the Allocation of Places in Higher Education sent him to the Technical University of Kaiserslautern. He isn't exactly sure why he chose this particular field, but thinks the multiplication tables his father taught him might have had something to do with it. His cousin, who had studied mathematics in Bonn and had inspired his young mind with the logic of mathematical proofs, also had a major influence on his decision. To some extent, Christoph Weidenbach's career has been shaped by coincidence.

PHOTO: ANNA ZIEGLER

Innovative approach: computer science, as practiced by car buff Christoph Weidenbach, is by no means limited to theoretical studies; he also puts the results of his research into practice and tests them out in his 300 hp roadster, which he occasionally takes out for a spin on the Nuerburgring.

He currently helps young people to choose a career path and to achieve their goals more easily. He also heads the advisory board of the German National Computer Science Competition (Bundeswettbewerb Informatik – BwInf), which promotes young talent. Following two rounds of competition each year, thirty candidates are shortlisted from over a thousand high school students, who are then interviewed separately and given group tasks to solve. The best of them receive a scholarship from the German National Academic Foundation. In Weidenbach's view, it is particularly important to mentor young people: "We know where they teach computer sciences well and have interesting content and we ensure that the upcoming generation will be in the best hands – and it sometimes helps if we can give them a good letter of recommendation."

Weidenbach wants to ensure that their talent doesn't go to waste. "Kids simply get lost in the shuffle at huge universities. A work-study program doesn't do justice to the really good students. We ensure that our candidates don't lose their way when it comes to their studies," says Weidenbach, who adds that he was lucky to have landed with Ganzinger, who threw the door open in terms of his professional development. "Now I'm the one trying to point young people in the right direction."



PHOTOS: NASA/JPL-CALTECH/UCLA/MPS/DLR/IDA/WWU

DOUBLE TAKE

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

The bizarre landscape seen in the photo is literally not of this world. Rather, the image shows the central area of the Occator crater on Ceres – a dwarf planet with a diameter of around 950 kilometers. Seen in full view on the left, Ceres was and may still be the scene of cryovolcanic activity in which saline solution rose from the interior and the water evaporated to leave behind bright deposits. Within Occator, the images from the unmanned Nasa space probe Dawn additionally revealed a 340-meter-high dome that is also covered in salt deposits. This "snow-covered" region looks particularly realistic in the 3D reconstruction. Models like this help to shed light on the geology and developmental history of the crater, which measures some 92 kilometers across. One essential element was Dawn's on-board scientific camera system, which was supplied by the Max Planck Institute for Solar System Research in Goettingen. Although the mission officially ended in 2018, the researchers are still analyzing the data today. They even recently detected organic compounds in another crater, known as Urvara.

THE GUT IS TEEMING WITH LIFE

TEXT: TIM SCHRÖDER

Bacteria are almost everywhere. We encounter them as pathogens or causative agents of infections. But they are our indispensable helpers. For example, without intestinal bacteria we would not be able to digest our food so effectively. A diverse microbial community – known as the microbiome – has co-existed with humans for hundreds of thousands of years. Ruth Ley and her team at the Max Planck Institute for Biology, Tuebingen are researching how microbes have influenced human evolution.

Our body is a veritable biotope – not for plants or animals but rather for bacteria: billions of microbes settle on – and in – our bodies. It may sound a bit unsettling, but it is essential for our survival. These commensal organisms fend off harmful pathogens, help us with digestion, and provide us with vital trace elements. Some bacterial species have co-existed with humans since we left Africa and colonized almost all of the Earth's continents tens of thousands of years ago. So it's not dogs – but rather bacteria – that are humans' best friends and most faithful companions!

Helicobacter pylori, the bacterium that causes stomach cancer, is one microbe that has been with humans from very early on. But Helicobacter is not the only bacterium that has co-evolved with humans. "Our findings suggest that a whole range of other intestinal bacteria tracked with our ancestors out of Africa," says Ruth Ley, research scientist at the Max Planck Institute for Biology, Tuebingen. Many of them are quite beneficial for humans. For example, the intestinal bacterium *Prevotella copri*, or Eubacterium *hallii*, both common inhabitants of the gut.

As humans encountered and adapted to new environments as we colonized the globe (adapting to new climatic conditions, novel pathogens, or agriculture and animal husbandry), our genetic make-up changed. Our microbes have undergone genetic changes as well. When mutations occurred in the human genome, changes often occurred in the genomes of bacteria as well. Ruth Ley and her team at the Max Planck Institute in Tuebingen are looking for evidence that the evolution of gut bacteria and archaea has tracked with the evolution of their hosts. "We're seeing a fascinating interplay between bacteria and humans," says Ley.

Scientists are able to read and reconstruct the migration history of humans based on their genetic make-up. "Geneticists have created a map of human genetic adaptions to new envi-

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PHOTO: MPI FOR BIOLOGY, TUEBINGEN

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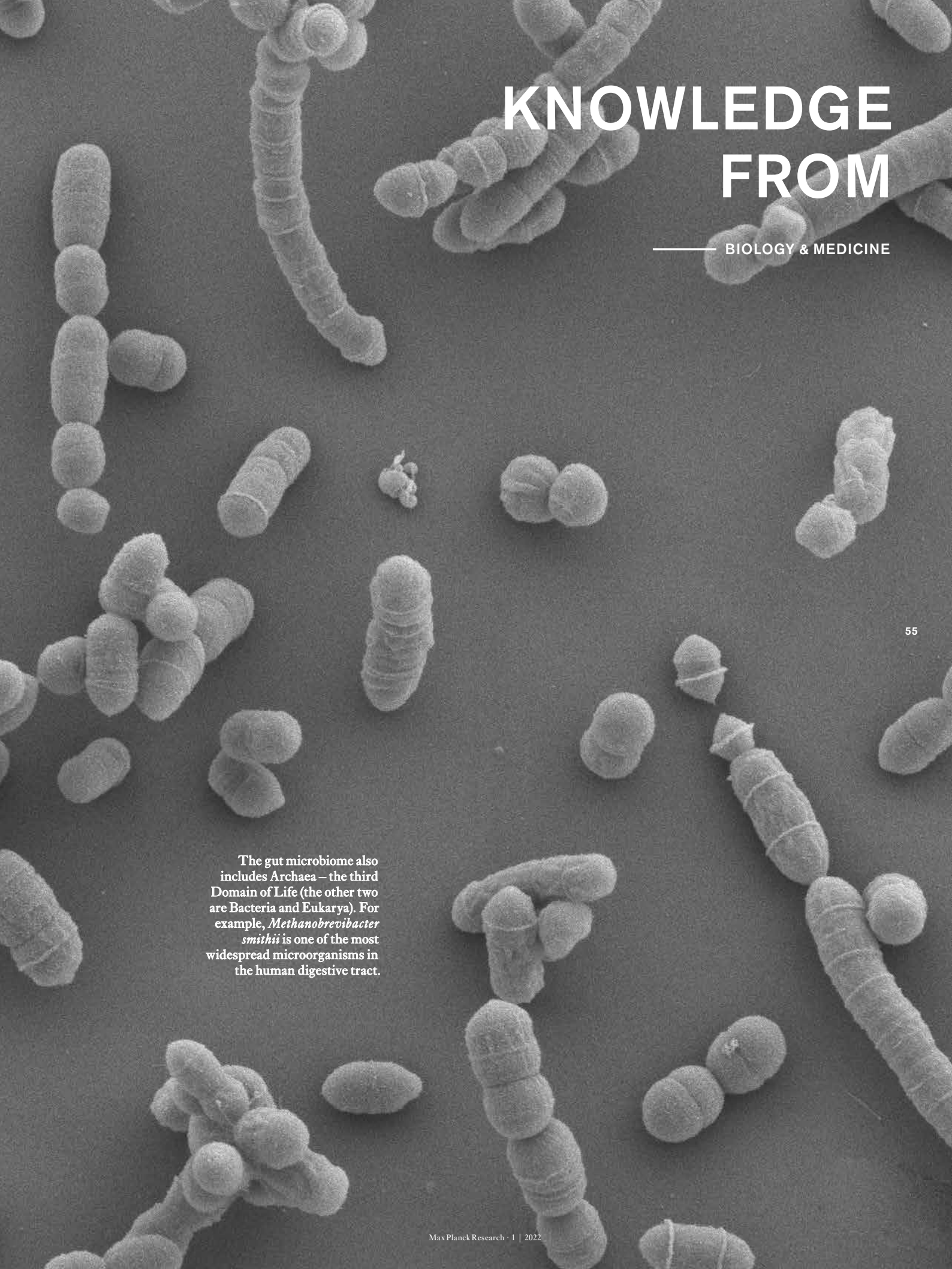

The gut microbiome also includes Archaea – the third Domain of Life (the other two are Bacteria and Eukarya). For example, *Methanobrevibacter smithii* is one of the most widespread microorganisms in the human digestive tract.

ronments, and we are using that map to guide us in looking for corresponding genetic changes to the microorganisms living on and inside us: our microbiome," Ley explains.

A prime example of the interaction between humans and microbes is the digestion of lactose. Lactose is broken down in the small intestine by the enzyme lactase and provides energy for newborns during the nursing period. For almost all of human history, the milk content of our diet decreased considerably after the nursing period – and so did lactase production, as lactase was no longer needed in the digestion of the adult diet. This changed with the domestication of wild cattle, goats, and sheep some 2,500 to 10,000 years ago. "People were then able to use the milk from these animals as a source of food, i.e., energy into adulthood and throughout their lives," explains Ley. "In some populations, such as in Northern Europe, people who produced lactase into adulthood thus had a considerable evolutionary advantage." In fact, this so-called lactase persistence has become very common in regions with high milk consumption such as Europe, where gene variants that maintain lactase production throughout a person's lifetime are common.

Digestion of lactose

But the lactase enzyme is only one of the ways in which lactose can be broken down. Lactose can also be broken down by gut bacteria. One example are the bifidobacteria, bacteria common in mammals. While lactase breaks down lactose in the small intestine, bifidobacteria and other micro-organisms can also metabolize it. They either take it up whole, or they may for instance first break down lactose with the enzyme beta-galactosidase (also known as β-galactosidase) and then ferment the resulting fragments of glucose and galactose. However, bacterial breakdown provides less energy to the host than the breakdown of lactose by lactase and the direct absorption of glucose and galactose by the body. For people who consume milk, it is thus worthwhile – from an energetic standpoint – for the body to maintain its own lactase enzyme production beyond infancy, in order to perpetuate direct utilization of lactose.

People who produce lactase throughout their lives and not only during the nursing period essentially compete with bifidobacteria for the lactose. All others should consider themselves lucky that there are bifidobacteria that digest lactose for them. Without the microbes, the valuable sugar would pass through the intestine unused and be lost. People who produce little or no lactase as adults therefore also have higher concentrations of bifidobacteria than those who are lactase persistent (i.e., produce lactase throughout their lives).

When people who are lactase non-persistent experience diarrhea or abdominal pain after ingesting lactose from dairy products, this is called lactose intolerance. The cause is osmotic imbalances and/or gases produced during lactose fermentation by the microbiome. But this is not always the case: Ley's analyses show that in Vietnam and Gabon, 20 percent of people without sustained lactase production do not produce gases during lactose digestion. These people have more bifidobacterial, or other microbiota that digest the lactose without producing large amounts of gas. This observation suggests a treatment for lactose intolerance: one option would be to increase the population of specific bacteria in the form of probiotics. "However, you have to test the efficacy of such treatments and find out which species or strains work in which concentration," Ley explains.

Ley's findings suggest that bifidobacteria were likely essential as metabolizers of lactose when humans began domesticating cattle, sheep, and goats. At that time, the microbe helped us to extract energy from the animals' milk. Then, over time, human gene variants emerged that allowed life-long lactase production, thereby making the work of the microbes redundant. "Unlike the co-evolution of cells and their organelles, this is not a classic co-evolution of two organisms that merge and become completely interdependent," Ley emphasizes. One example of such a particularly close form of co-evolution is mitochondria – organelles that supply cells with energy. It has been postulated that millions of years ago, one cell engulfed another – possibly an archaea – and permanently incorporated it. Since then, a lively exchange of genes has taken place between the cells of higher organisms and the mitochondria.

Mutual evolution?

"Although the genomes of humans and bacteria do indeed influence each other, we cannot rule out the possibility that they evolve separately. So far there is no evidence that humans and their gut microbes have co-evolved in the classic sense," explains Ley. In order to decipher the nature of such relationships, Ley compares the changes in the genomes of humans

SUMMARY

The human body is colonized by countless microorganisms. Without this so-called microbiome, we wouldn't be able to survive. For instance, the bacteria found in the intestine are indispensable for digestion and other key functions.

The evolution of humans is closely linked to the development of their intestinal bacteria. Researchers can reconstruct human migration patterns from similarities in their genetic histories.

PHOTO: JEAN-CLAUDE WINKLER PHOTOGRAPHY

At the Max Planck Institute for Biology in Tuebingen, Ruth Ley and her team are investigating how humans and the microorganisms in their gut mutually influence each other in their evolution.

with those of microbes. By doing this, she obtains information about the evolutionary relationships of the human hosts to their symbiotic partners in their intestines. Microbes that have evolved with humans have very similar branching patterns in their phylogenetic trees, i.e., evolutionary histories. "Sequencing DNA and decoding genetic information is only part of the work. The real challenge is compiling the data," says Ley.

For this, the researchers need human DNA and stool samples. From these stool samples, they can extract the genetic material of the intestinal bacteria (the microbiome's metagenome). "A great deal of research has been conducted exclusively in Western Europe. With our comparisons of the microbial genome comparisons in relation to human genomes, we are conducting pioneering research." It took Ley and her team three years to collect the genome data of close to a thousand people and their respective intestinal flora. Working with Peter Gottfried Kremsner, Professor of Tropical Medicine at the Tuebingen University Hospital, and his associates, Ley's team collected samples from more than 700 adults and 300 children in Vietnam, Gabon, and Germany. Working with collaborators, Ley has also assembled data in Britain, Cameroon and South Korea, in addition to data compiled from public sources. Comparing parents and children is important because intestinal bacteria are passed down over many generations.

The researchers have found that there are bacteria that are particularly loyal to human families and communities. Others quickly colonize new populations. Over time, a population's intestinal bacteria may become adapted to their foods, or other local environmental factors. "We are pursuing the idea that this has led to different populations of people having bacterial species that are precisely tailored to them – both to their genomes and to their diet," says Ley.

Utilization of starch

Ley is convinced that bacteria have played a far greater role in human evolution than previously thought – and not only as pathogens. For one thing, Ley's work has shown that bacteria enable us to use starch effectively. The seeds of important agricultural crops (e.g., cereals, rice, and corn, and also tubers) contain large amounts of starch. However, the forms vary in digestibility depending on the plant. After humans started to cultivate these plants, they suddenly had a first-class energy supplier at their dis-

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posal. But only if they were also able to digest it. This requires sufficient quantities of the enzyme amylase. The digestion of the more easily digestible starch begins in the mouth by the amylase contained in the saliva. Starches that are more difficult to digest are broken down and fermented by bacteria in the digestive tract.

How the host and microbe divide up the breakdown of starch depends largely on a person's genetic make-up. If the gene for the production of salivary amylase is present several times in the genome, more starch can be broken down in the mouth. Humans with a history of living as hunter-gatherers have on average fewer copies of the amylase gene compared to humans with an agrarian background. But at that time, starchy foods likely made up a smaller proportion of their daily diet. With the cultivation of cereals, rice, and corn, it became more important to be able to efficiently digest starch. Duplication of the amylase gene resulting in a greater copy number may have given humans a fitness advantage because digestion via amylase in the mouth increased energy output compared with microbial fermentation.

Some people produce a lot of salivary amylase, while others produce only a little. Ley's work has shown that their microbiomes differ considerably. People with multiple copies of the amylase gene and produce more amylase in the mouth have high numbers of bacteria of the genus *Ruminococcus* – a bacterium that specializes in "resistant" starch that is difficult for the human alone to digest. Because these individuals break down simple starch almost completely in the mouth, only the resistant form remains for the microbiome. To make maximum use of this form of starch, a greater proportion of *Ruminococcus* are needed.

Ruth Ley and her team assume that *Ruminococcus* has given people with many copies of the amylase genes an evolutionary advantage because they can better utilize resistant starch: by digesting the simple starch with the help of salivary amylase and then fermenting the more complex starch with the help of intestinal bacteria. "Bacteria can likely influence the evolution of humans," Ley declares.

Such a parallel evolution of bacteria and their hosts is also likely in other mammals. Many pass on their bacteria from generation to generation through body contact or specific behaviors. In reptiles and birds, however, bacteria and hosts appear to evolve separately. Whether bacteria can also switch from one species to another is still an open question. For example, there are many strains of bifidobacteria, some of which live in the intestines of pigs. As Ruth Ley explains, "The question is, whether strains have been passed from one family to another and how faithful these bacteria actually are to humans – or whether some strains may have passed from one mammalian species to others."

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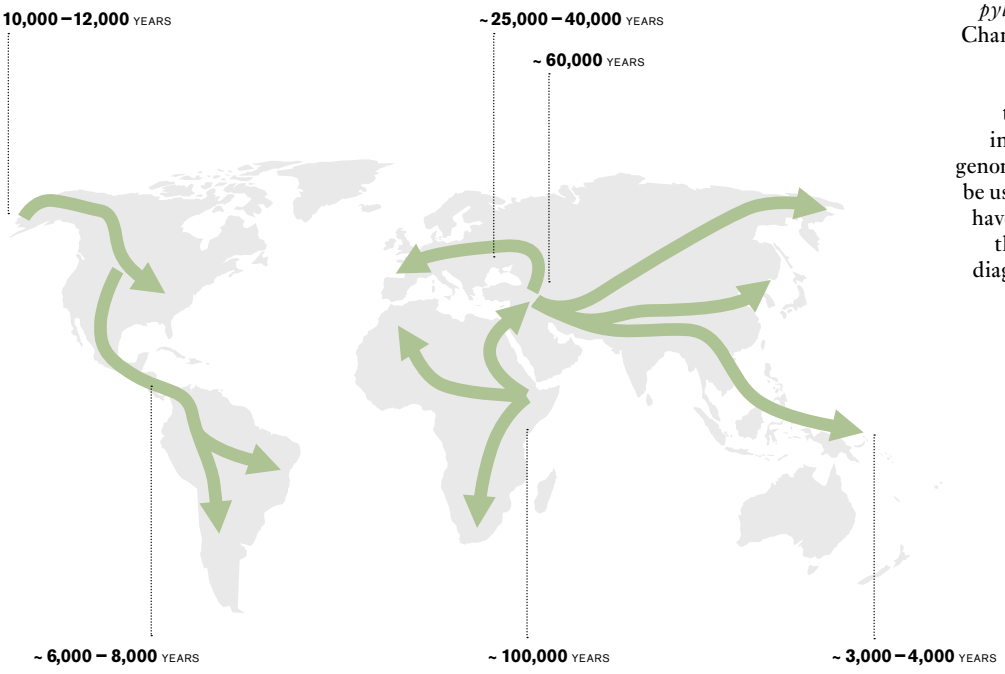

When humans left their original home in Africa, they took microorganisms such as the bacterium *Helicobacter pylori* with them in their intestines. Changes in the human genome made it possible to adapt to new living conditions. Correspondingly, the genes of the microorganisms in the intestine also changed. The genome of the microbes can therefore be used to trace which paths humans have taken as they dispersed all over the Earth. The annual data in the diagram refer to global migration in the period before today.

GRAPHIC: GCO BASED ON AN MPG DESIGN

Sunrise reloaded

In the summer of 2022, Sami Solanki's balloon carried SUNRISE observatory will again take a closer look at the sun's magnetic fields.

The Foundation is proud to support the Max Planck Institute for Solar System Research and the 3rd flight of the largest and most powerful solar telescope that has ever left the ground. This unique view will enable an even better and more effective research on how the sun influences.

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Under the hood: EEG measurements are used to monitor changes in brain activity when playing the piano, such as when the player is presented with musical challenges.

PHOTO: FELIX BERNOULLY/MPI FOR EMPIRICAL AESTHETICS

MUSIC IN YOUR HEAD

TEXT: STEFANIE REINBERGER

Music is an innate human ability. It is genetically programmed into our brains and, like language, it is a universal feature that we all share. The human mind is designed to both enjoy and create music. Together with her team at the Max Planck Institute for Empirical Aesthetics, Daniela Sammler is researching what exactly happens in our heads when we make music.

Humans have been making music for thousands of years. While exploring caves in the Swabian Alb mountains, archaeologists discovered bone flutes that were carved and played by Stone Age man around 35,000 years ago. These flutes are considered to be the oldest musical instruments ever found. However, we can assume that music already played a role in human evolution long before they were made. At the same time, it is highly likely that music is not simply an evolutionary by-product that developed from language, as researchers thought for many years. Instead, it appears to be a kind of sister to language, with these two means of communication originating from one shared early predecessor. This is reflected in the structure of the brain, which uses some of the same regions to process language and music.

Such similarities between language and music are a major topic of interest for Daniela Sammler and her Research Group at the Max Planck Institute for Empirical Aesthetics. Among other things, they also want to find out in which areas language and music are subject to similar mechanisms, and when the brain draws on different solutions in order to process these two forms of expression. Even before she began her research in Frankfurt, Sammler was exploring the way we listen to music, in collaboration with Stefan Koelsch and Angela Friederici at the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig. One of the key questions was how we perceive harmonies as well as disharmonies. In a similar way to grammar, music follows certain rules, which affect the way music is heard. We imbibe the musical rules of our cultural environment and intuitively apply them when we listen to music. For example, there are harmony sequences that appear to be "right" in our brains, and others that contradict this set of rules. In their experiments, the researchers did in fact succeed in demonstrating that the brain alters its activity in response to music that breaks the rules, such as "incorrect" final chords. "Interestingly, the brain's reaction to disharmonies is comparable to the way we observe grammatical errors in language," says Sammler.

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However, hearing music is just one side of the coin. Music is made when we play it, when people sing, drum or press the keys on a piano. "We therefore wanted to find out if these rules also influence people who produce music as an everyday activity," Sammler explains. Making music involves two components. First, there is a musical idea – in other words, the concept of how music should sound and which harmonies we consider appropriate; then, we put this idea into practice using movement – such as placing our fingers on a piano keyboard, covering certain holes on a flute, or moving our larynx and vocal cords when we sing.

Here, therefore, cognition and motor activity combine and mutually influence each other. This corresponds to the theory of "embodiment", which has attracted a great deal of interest, and which states that the body and mind work together. According to the theory, motor functions are not just the result of cognitive processes – instead, they themselves also support cognition. To take a simple example: children use their fingers when learning to count. According to the theory, the movement of a certain number of fingers supports the concept of counting in the brain. Pianists put a musical idea into practice by positioning their fingers on the keyboard and striking the keys. While they do so, the movement of their hands and fingers follows the grammatical rules of music. Conversely, the motor activity reinforces the musical idea – in other words, the notion of how the music should sound. Indeed, there is a great deal of evidence that indicates that among musicians, the auditory and motor systems are closely linked to each other.

However, playing the piano involves more than just hitting the right keys. In theory, a chord on the piano keyboard can be played using a wide range of different hand and finger movements. In practice, the choice of fingers used additionally depends on efficiency factors, such as how quickly a chord can be played with a particular fingering, and how the player can best move on from there to the next chord. A further aspect is the feeling that the player wishes to express. The player's thumb has more strength than their ring finger, for example, and this has an impact on the volume. When making music, pianists therefore coordinate at least two planning levels: which chord, i.e. what notes they need to play in order to implement the set of musical rules in their head, and what fingering they should use to create the chord.

SUMMARY

People absorb the musical rules of their culture and intuitively apply them, in a similar way to the grammar used in their native language.

Measurements of brain activity among pianists show that they respond to both non-observance of harmony rules and "incorrect" fingering. Both are processed separately in the brain.

When making music together, musicians' brainwaves synchronize. This is evidently done in order to coordinate their playing.

To find out what makes this possible, Sammler and her team used electroencephalogram (EEG) measurements to observe the brain activities of pianists while they were playing. All participants had received at least ten years of training in classical piano. Their task was now to play harmonic sequences that they had not practiced, in line with hand movements on a screen. "We consciously avoided allowing them to play from sheet music, since that would have set other processes in motion that would have made it very difficult for us to control the experiment. For example, not everyone is equally proficient at reading sheet music," Sammler explains. "As my choir leader used to say: you need to learn the notes by heart so that you can concentrate on the music and the way you sound together, and not on the score in front of you."

A final chord – with a stumbling block

The sequences given to the pianists to play in the experiment were all musically "correct". However, the final chord was sometimes fitting, and sometimes contained an error. This error either took the form of an "incorrect" harmony, in other words, a grammar error, or an unusual set of fingering which a practiced pianist would not use, since it is difficult to realize. How would the brains of the test subjects respond to the errors? Both types of error caused changes in the EEG, such as a delay in playing. However, it emerged that errors in the fingering always caused a delay. By contrast, errors in the harmony interfered particularly in cases when the musicians had understood the idea of the sequence – in other words, when after a few chords, they had developed a sense of how the music should continue. According to Sammler: "This demonstrates that in fact, our musical brain separates the two planning levels – 'what is being played?', and 'how should I play it?'."

However, she didn't want to stop there. "In the EEG, we can only identify that the brain activities change, but not where these processes occur. For that, we need MRI – Magnetic Resonance Imaging." Together with a group of colleagues and the Blüthner pianoforte factory in Leipzig, she designed an unusual experiment. She sent pianists into the MRI tube, together with their pianos. To make this possible, she ordered a kind of mini-piano to be made, which had just 27 keys, and which the test subjects were able to play lying on their back in the scanner. A two-way mirror enabled them to see their own hands on the key-

board, and at the same time, see the hands showing them how to play the chords on a monitor, as in the previous experiment. Once again, the task was to play short sequences, some of which contained either a harmonic error or an error in the fingering at the end.

This confirmed what the researchers had already concluded from previous experiments: the two planning stages – the what and the how – ran their course separately from each other. They activated different neuronal networks in the brain. In the main, regions in the brain responsible for motor activity were used to coordinate finger movement, while planning the musical idea mostly activated regions in the frontal and temporal lobes, which are thought by scientists to act as memory sites for learned sets of rules. "However, the most exciting thing was that Broca's area was active during both challenges. Many people only think of this region in the brain as being the speech center. However, it also plays a role when planning an activity, regardless of whether we're formulating a sentence, brewing a coffee or wanting to make music," Sammler explains.

Research on this area of the brain has brought to light new evidence of how the brain plans activities. It shows that the idea occurs first, such as "talk about something", "brew a cup of coffee", or "play a melody". The front portion of the brain region converts this idea into rules of behavior: what activity steps are needed to brew the coffee? The planning then becomes increasingly intricate inside Broca's area, running from front to back from an anatomical perspective. For example: how should I put the coffee into the machine to get the correct dose? "We can also observe this pattern when making music: the planning begins with the musical idea and becomes more and more intricate, right down to the specific movement of the fingers on the piano keyboard," Sammler explains. Planning movements when making music therefore works in exactly the same way as everyday activities. There is a translation from the "what" to the "how" – from the musical idea to the movement on the piano.

PHOTOS: MPI FOR HUMAN COGNITIVE AND BRAIN SCIENCES (2)

Custom built: a mini-piano built specially for the experiment enables researchers to study a pianist playing in an MRI scanner. This allows the researchers to understand which areas of the brain are particularly active when we make music.

As exciting as these findings are, they focus solely on solo performance, in other words, on what happens to an individual musician when they play their instrument. "Basically, this is a very reduced situation," Daniela Sammler explains. "After all, from an evolutionary biology perspective, music was very likely something that people made together in the group." Concerts in which individual musicians play for an audience are a relatively new invention, however. Music was originally designed to promote a sense of togetherness, such as the communication between a mother and her baby, or when looking for a partner, or to promote a feeling of belonging in a group. While studies of

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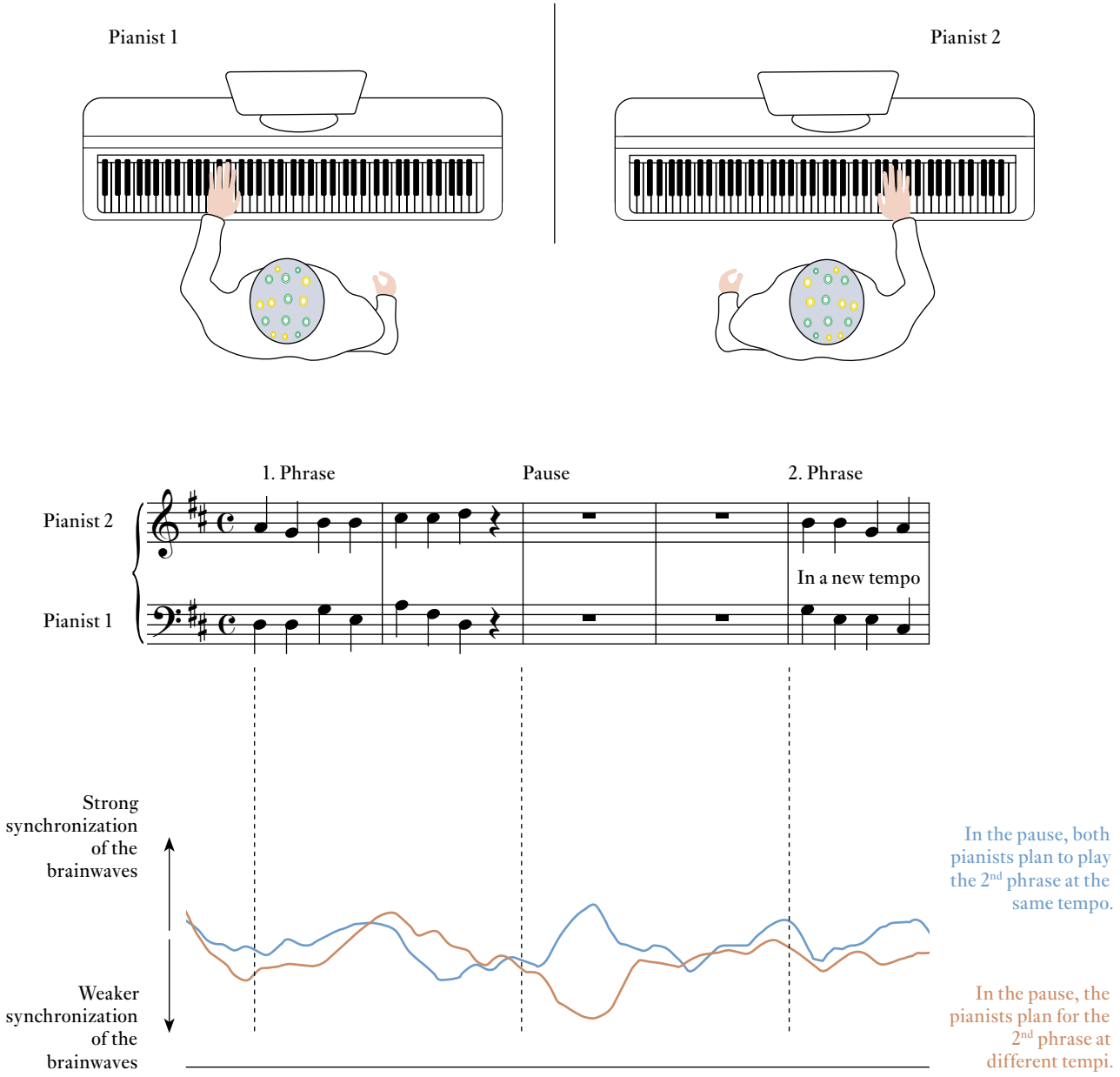

Synchronization test: two pianists play at the same time, initially at the same tempo. After a pause, they are told to change the tempo. The instructions given to each player are either the same or different. As a result, the synchronization of the brainwaves increases if the instructions given at the start of the pause are the same. By contrast, they deviate if the instructions differ. Scientists are still not exactly sure why the previous synchronization level is already achieved during the pause.

IMAGE: GCO, ACCORDING TO A SUBMITTED ARTICLE FROM GCO CEREBRAL CORTEX, BHAB469

individual test subjects provide insights into the fundamental principles of how our brains work, this is ultimately just one small aspect of the overall picture, and possibly a very limited one. "This applies not only to music, but to all activities in which people interact in pairs or groups," says Sammler. "The Finnish neuroscientist Riitta Hari even went so far as to say that brains are designed primarily for interaction."

Interaction is therefore at the center of cognition. However, very little is understood yet about how it works at the neuronal level. What we do know is that brains begin to oscillate in the same rhythm when people interact with each other. This phenomenon appears on the EEG in the form of synchronized brainwaves, and is something that occurs during all activities, from taking a walk together, dancing, debating with each other or

making music. However, do the brainwaves synchronize because we move in the same rhythm, for example, or play the same melody? Is the effect a result of us doing similar things at the same time? Or is it a mechanism that supports interaction?

A key factor for making music together

To examine this issue in more detail, Daniela Sammler and her team again conducted experiments on pianists – but this time, the test subjects played a duet. Each time, two volunteers were asked to play a melody together while the researchers recorded their brainwaves on the EEG. During the experiment, one person played the part for the left hand and the other played the part for the right hand. The harmonic progression and tempo were predefined in advance and matched each other – until there was a pause in the piece. Then, the musicians were instructed to continue playing at a different tempo, while each were given contrary instructions. This in turn influenced the synchronicity of their brains. If both planned with the same instruction – to play faster or slower – the level of synchronicity was high. However, if different tempi were specified, the brainwaves deviated from each other. The degree to which this happened depended on how much the planned tempi differed from each other after the pause.

"Our interpretation of this result is that synchronization of the brainwaves is not simply a by-product of playing together, but that it's a mechanism that enables musicians to coordinate their interplay," Daniela Sammler explains. "This probably doesn't just apply to music, but also to other activities for which good interaction is necessary." In other words, general mechanisms of interpersonal cooperation. The research being conducted by Sammler in Frankfurt may currently only provide information about the key importance of synchronization when people play music together. As it stands, no-one can say where this synchronization originates in the brain. "To answer that question, we would need to put both pianists into different MRI scanners at the same time," Sammler says. She admits that this would present a big logistical challenge, of course. But she is very confident that they will manage it one day. "That experiment is yet to come!"

PHOTO: KATRIN BINNER

Carefully prepared: Research Group Leader Daniela Sammler prepares an EEG hood for an experiment with a pianist.

Stickleback males show splendid coloration at spawning time – with a red throat and breast and bright blue irises.

PHOTO: SCIENCE PHOTO LIBRARY

A FISH AT HOME IN ALL WATERS

TEXT: ELKE MAIER

Three-spined stickleback fish live in both salt and fresh water. When the glaciers melted at the end of the last ice age, new lakes were formed, and sticklebacks from the sea found new habitats in those freshwater environments. At the Friedrich Miescher Laboratory on the research campus of the Max Planck Society in Tuebingen, Germany, Felicity Jones and her team are studying how the genome of fish changes as they adapt. 12,000-year-old stickleback bones provide insight into the early phase of this transformation.

The story begins with a chance find. In spring 2018, a team of geologists from the Geological Survey of Norway (NGU) set out on a journey to the northernmost region of Norway. The goal of the expedition was to drill for cores in the sediment of lakes near the coast in order to gain further insight into the sea level fluctuations towards the end of the last ice age. When geologist Anders Romundset filtered his sediment samples through a fine sieve, he found not only algae and other plant residues but also the bony residues of fish that were only a few millimeters in size.

The tiny bones and spines were so well preserved that the scientist knew right away what he was dealing with: the three-spined stickleback *(Gasterosteus aculeatus)*. The four to six-centimeter fish are still found in the sea and lakes of Scandinavia. Using radiocarbon dating, the bones were determined to be around 12,000 years old. They thus date from a time when large parts of northern Europe were still covered by massive ice sheets.

When the glaciers melted towards the end of the Ice Age and the enormous weight of the ice also melted away, the compressed land mass gradually began to rise above sea level. In the process, bays and inlets were cut off from the sea and were subsequently filled with fresh water, thereby creating new lakes. One of those lakes was once home to the stickleback, the bones and spines of which were found by geologist Anders Romundset. During the intervening millennia, the bony relics remained embedded in the sediment at the bottom of the lake. The geologists turned their find over to Andrew Foote, evolutionary ecologist at the Norwegian University of Science and Technology in Trondheim. Foote, an expert in ancient DNA, seized the opportunity. In a special laboratory at the University of Copenhagen, he and his colleague Tom Gilbert began searching the bones for remnants of genetic material. One of the difficulties was that the samples contained not only stickleback DNA, but also fragments of DNA from other organisms (e.g., plants and bacteria) that were also living in that environment at the time. The fragments they were looking for ultimately made up only around 1% of this genetic hodgepodge. Nevertheless, with great effort, Foote managed to 'fish out' and sequence the stickleback DNA.

For Felicity Jones, research group leader at the Friedrich Miescher Laboratory in Tuebingen, Foote's success was a stroke of luck. Together with her team, Jones studies the fundamentals of evolution. The researchers hope to

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find out which molecular mechanisms ensure that organisms can adapt to new habitats or even form new species. Sticklebacks are the ideal model organisms for this purpose. Over the last 10,000 to 20,000 generations, marine sticklebacks have migrated to many different freshwaters (e.g., lakes, rivers, and marshes) and have adapted to the new conditions. These small fish are thus now widespread in the temperate climates of the northern hemisphere.

"The exciting thing for us is that sticklebacks have left the sea to colonize new freshwater habitats and in many cases did so independently," says Jones, who also conducted research in Scotland, New Zealand, and the U.S. before coming to Tuebingen. "This allows us to study the same questions in multiple parallel systems, thereby ruling out the possibility that the genetic adaptations we discover are merely isolated cases." As the fish adapted to their new environment, similar changes in their shape, behavior, and physiology occurred repeatedly at different sites – a process known as parallel evolution. Like in a giant field laboratory, the researchers can use sticklebacks to work out the basic molecular mechanisms that ensure that organisms can adapt to new habitats.

Over 160 years ago, Charles Darwin provided the first plausible explanation of how the diversity of life arose in his book, On the Origin of Species. According to Darwin, all present-day species are descended from common ancestors, the descendants of which have dispersed to different habitats and split into distinct lineages over millions of years. The driving force behind this development is natural selection. Of all the offspring of a living being, those that are best adapted to their environment have the greatest reproductive success. They therefore tend to pass on their hereditary traits to the next generation.

Famous examples of Darwin's theory are the finches of the Galapagos archipelago. Originating from one ancestral species, the birds living on the various islands of the archipelago have evolved quite different beak shapes depending on what types of food they consume. Evolutionary biologists refer to this as adaptive radiation. "Sticklebacks are another example – only much better," says Jones. Unlike the Galapagos finches, the evolutionary split occurred in several places at once. This allows the scientists to repeatedly observe the spectacle and thus verify their findings.

SUMMARY

Sticklebacks live in both salt and fresh water. They have colonized new freshwater habitats from the sea multiple times.

These small fish are ideal model organisms for studying how living organisms can adapt to changing environments and even form new species.

Max Planck researchers have analyzed DNA from 12,000-year-old stickleback bones found in ice-age lake sediment in Norway. The data provide insight into the evolutionary history of Scandinavian sticklebacks.

How the sticklebacks change in the course of adaptation is superbly demonstrated by the formation of bone plates on the sides of their bodies. Marine stickleback have armor plates covering the entire sides of their body, while freshwater sticklebacks have only a few plates towards the front of their body.

The reasons for this are still being investigated. Scientists hypothesize that the armor plates on individuals in the open sea protect them from predators that freshwater sticklebacks do not encounter.

An additional explanation is that limited amounts of calcium in freshwater habitats make growth of bony plates costly. Amazingly, when new freshwater habitats are colonized by high plated marine sticklebacks, the population rapidly evolves to a low-plated form within less than one hundred generations.

Evolutionary biology has made tremendous progress since Darwin. Thanks to modern analytical methods, researchers can now search the genome for the characteristic traces that evolution has left behind. "Most of our knowledge about how the genome works comes from model organisms specially bred in the laboratory. In contrast, we still know relatively little about how naturally occurring genetic differences influence the evolution of wild populations," says Jones.

A window into the past

The discovery of prehistoric bones opened up completely new possibilities for the Tuebingen team and their research partners. For the first time, they had an ancestor of the freshwater stickleback in front of them. This fish, which lived about 12,000 years ago, also revealed genetic information. "To our knowledge, these are the oldest fish bones from which genomic data have ever been obtained," says Jones. "They open a window into the past, allowing us to trace which genetic variation the fish brought with them as they adapted to their new habitats."

The bony relics were found in a sedimentary layer marking the transition from salt to fresh water. As individual coves and inlets gradually became cut off from the sea toward the end of the Ice Age, sticklebacks were left behind in the isolated waters. They adapted to the new conditions of brackish water and reproduced. Over time, numerous new types emerged in different waters; these sticklebacks are quite distinct from their marine relatives.

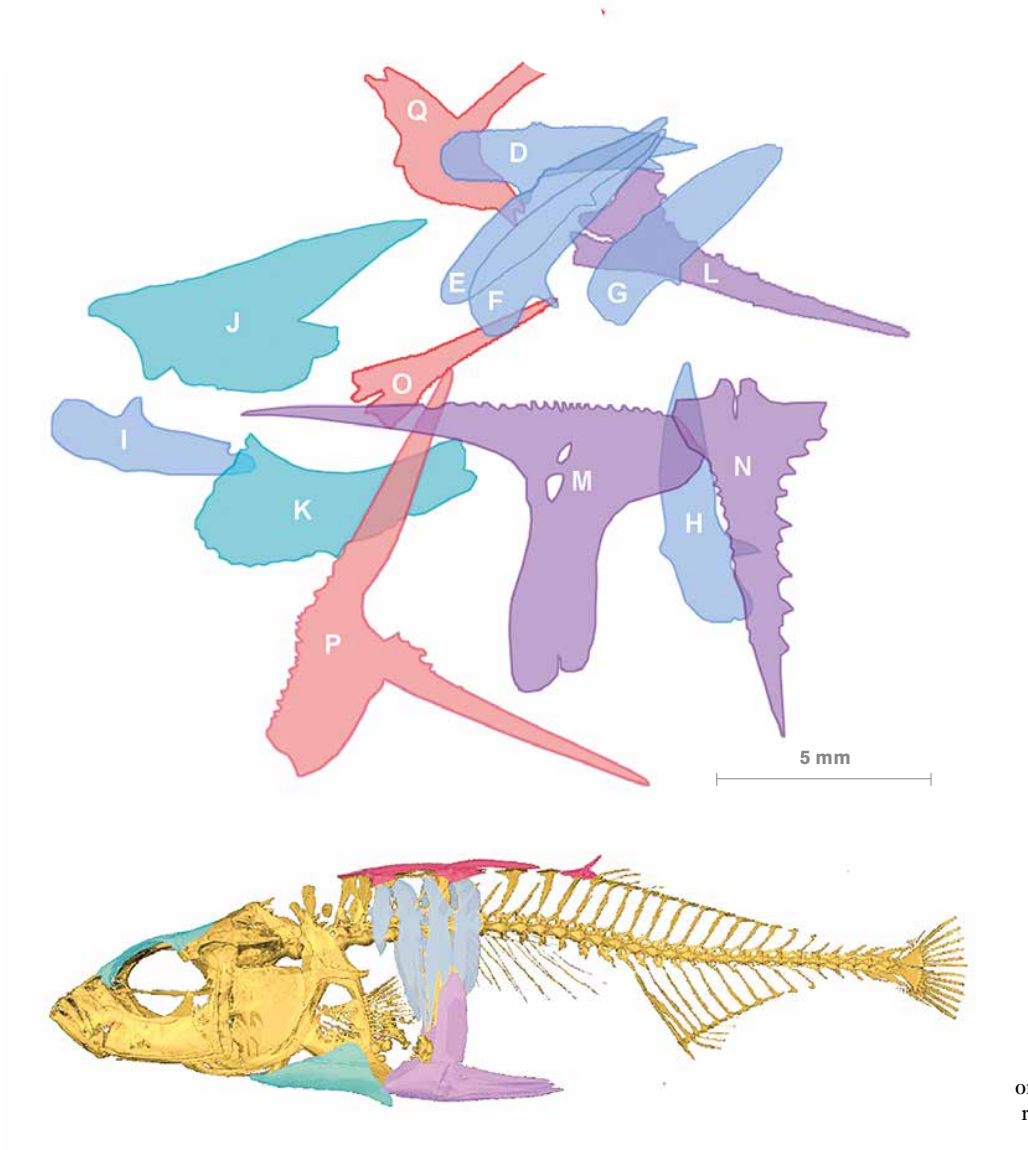

IMAGE: ANDY FOOTE, MELANIE KIRCH, ANDERS ROMUNDSET

Relics of the ice age: in order to identify them, the researchers compared the skeletal elements they found (top) with X-ray images of a present-day stickleback (below). This allowed them to match the ancient bones to a single individual.

The fish varied in body size and pigmentation, in the length of their dorsal spines, and in the size and number of their bony plates.

In order to get an idea of what had changed at the genetic level, the researchers compared the genetic makeup of the Ice Age stickleback with that of its descendants. To do so, they analyzed sticklebacks from two near-shore lakes south of the Norwegian city of Hammerfest. The bones that the geologists discovered and which contributed their prehistoric DNA also came from one of these lakes. The researchers also sequenced the genomes of marine sticklebacks from the same area.

The comparison of the genetic material revealed that the ice age fish was genetically quite similar to its present-day marine relatives. "The bones contained mostly those gene variants that are advantageous for living in salt water," explains Melanie Kirch, a doctoral student in Jones's research group, who analyzed much of the genomic data. There were also variants that showed an adaptation to freshwater.

Such gene variants are also found in isolated cases among today's marine sticklebacks. The researchers assume

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PHOTO: MPI FOR BIOLOGY TUEBINGEN/DERPHOTOGRAPH.DE

Fish in color: the researchers stained a stickleback skeleton to make individual bone fragments visible. Freshwater and saltwater sticklebacks differ in the length of their spines or the size and number of bone plates they grow on their bodies to protect themselves from predators.

that the latter occasionally mate with conspecifics from freshwater habitats (e.g., in the estuaries of rivers). As a result, freshwater genetic variants keep entering the marine population. For marine sticklebacks, these variants are useless or even disadvantageous and therefore do not spread. In contrast, they prove to be wild cards when colonizing new freshwater habitats. If evolution can access such ready-made building blocks, adaptation is possible in a relatively short time (in the case of the stickleback, within only a few decades). If, on the other hand, the appropriate gene variants first have to be created by chance through mutation, millions of years can sometimes pass.

The genome comparison provided even more insight into the evolution of freshwater sticklebacks. It revealed that the fish from the two lakes were genetically less diverse than their marine ancestors. This was partly because the isolated individuals that recolonized the lakes at that time brought with them only a small fraction of the gene variants that were present among marine sticklebacks. On the other hand, some variants within the newly established populations randomly disappeared from the gene pool over time – a process known as genetic drift. "That is how even those variants that would be beneficial for freshwater life have been lost – by chance alone," says Jones. Such severe genetic impoverishment – typical of small founder populations – is often referred to as a "genetic bottleneck".

For freshwater sticklebacks, this bottleneck was momentous. Genetic variation is the material from which evolution produces new adaptations. If many different gene variants are present, it can draw from the full range. In contrast, variation was greatly reduced in fish from the two lakes. "We suspect they are not as well adapted to their habitat as they could be," says Jones.

Jones and Foote are excited about the new possibilities that ice age DNA is offering. They would like to study the evolutionary history of Scandinavian sticklebacks in greater detail. One of their goals is to genetically evaluate even more prehistoric stickleback bones from younger sedimentary layers. "If we had bones not just from a single fish but rather from multiple individuals that lived hundreds of years apart, we could directly track how the genome changed over time after the sticklebacks arrived in their new habitat," says Jones.

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PHOTO: VICTOR RAULT, CAPTAIN DARWIN

Holding up the mirror: as Eduardo Sampaio observed during his dives off Cape Verde, octopuses respond to their own reflections, rapidly changing color and eventually attacking their "opponent."

Researchers from the Max Planck Society are currently collaborating with partners in over 120 countries. In this article, they write about their personal experiences and impressions. Researcher Eduardo Sampaio of the Max Planck Institute of Animal Behavior in Constance sailed around the Cape Verde coast aboard the *Captain Darwin,* almost 200 years after Charles Darwin visited the West African islands. In this article, he talks about a diverse but endangered underwater world, the mating behavior of octopuses, and how it is also possible to play a game of cat and mouse with fish.

An outbreak of cholera was the reason for Charles Darwin's visit to the Cape Verde Islands in January 1832, shortly after the young naturalist had embarked upon his circumnavigation of the globe aboard the *HMS Beagle*. When the ship was denied permission to dock in Tenerife as originally planned for fear that the crew would introduce that disease, Captain Robert FitzRoy sailed on to Cape Verde. Darwin found octopus living in the coastal tidal pools, which he observed with great interest and immortalized in his book *The Voyage of the Beagle*.

190 years later, I spent ten days as a guest aboard the *Captain Darwin*, a 12-meter sailboat that set sail in September 2021 on a four-year voyage following the original route taken by the *HMS Beagle*. The initiator of the project is the French filmmaker Victor Rault, who wants to find out how ecosystems around the world have changed since Darwin's time and, where possible, catch a glimpse of the future: where are we heading in the face of worsening climate change? Victor meets up with researchers at various stops along the way, who are there to study the same organisms as Darwin once did. He is documenting the entire voyage in a series of YouTube videos.

The octopuses were my ticket to this exclusive sailing trip. Besides our captain Victor, the other crew members were Martin, an experienced sailor, and Nico, an experienced diver. The sea was rough on the first day and my stomach caused me some problems, but by the second day I had already become used to the rocking of the waves. We cruised off the uninhabited Ilhas Desertas, an archipelago that lies in a marine reserve where I planned to study the hunting behavior of the common octopus (*Octopus vulgaris*). In other locations, I had previously observed the astonishing cooperation between an octopus and several fish that join forces to hunt: the fish locate the prey, after which the octopus uses its arms to extract these prey items from even the tightest nooks and crannies. However, the hunters don't always agree when it comes to sharing their communal meal and the octopus sometimes has to fend off the greedy fish with targeted blows from one of its long arms.

POST FROM

CAPE VERDE

We had diving tanks and a compressor on board and Nico and I did two to three dives a day. But as so often happens in field work, everything went differently than planned: we didn't get to see any hunting octopus, as they were in the mood to mate. I quickly changed my plans and set up some underwater cameras to film the previously under-researched reproductive behavior of the octopus. While we did so, we managed to make some exciting observations of fish as well. For example, we found that mullet respond to the rapid movements of a laser pointer, so it didn't take long for a wild game of underwater cat and mouse to ensue.

The mood aboard the *Captain Darwin* was laid back, and there was plenty of laughter. I was always thrilled to see the sun come up over the sea as I sat on the deck with a cup of coffee at six every morning. After finishing our work for the day, we would view the day's video footage or discuss world events over a beer out on the vast ocean. I spent my free time reading Darwin's book *On the Origin of Species*, in which he set out his findings from the voyage on the *Beagle*. Darwin would have been amazed had he had scuba diving gear back then because, whereas the islands are barren and desolate, the underwater world is vibrant and diverse. It appears intact at first glance, but it has changed profoundly since Darwin's time. Huge fishing fleets from Europe and China have decimated fish stocks off the West African coast to an alarming degree and global warming is also having an impact on marine life. What will it look like here in 200 years? That will all depend on whether we manage to regulate fishing and get greenhouse gas emissions under control.

PHOTO: PRIVATE

Eduardo Sampaio

33, studied biology at the University of Lisbon. During his studies there, he developed a soft spot for cephalopods. As a guest scientist at the Max Planck Institute of Animal Behavior in Constance, he conducts research into the decision-making and social behavior of these intelligent marine animals. After earning his doctorate, he intends to continue his studies as a postdoc at the Department of Collective Behaviour.

FIVE QUESTIONS

ABOUT NEW EU RULES FOR LARGE ONLINE COMPANIES

FOR HEIKO RICHTER

At the end of March, the bodies of the European Union reached a preliminary agreement on the Digital Markets Act (DMA). This aims to limit the market power of tech giants such as Google, Apple, Facebook/Meta, Amazon, or Microsoft in the future and to safeguard competition on the European market. Mr. Richter, why aren't the existing regulations sufficient?

HEIKO RICHTER So far, especially in antitrust law, we've only had ex post facto laws: these only take effect after an infringement has occurred or is suspected. As a result, it takes a very long time before the behavior is sanctioned. In some cases, the contested acts took place up to ten years ago and the legal proceedings have still not been concluded. The result is that antitrust law is too slow in this context.

What's going to change?

The basic concept of the DMA centers around ex ante – or "before-the-event" – regulation. It will impose conduct obligations on major online service providers. According to initial information, companies are to be considered "gatekeepers" if they generate an annual turnover in excess of EUR 7.5 billion in the EU or have a market value of more than EUR 75 billion. The service itself must have over 45 million end users per month, as well as 10,000 commercial users in the EU per year.

What obligations will gatekeepers have in the future?

In the list of obligations, particular importance is given to prohibitions on tying registration for one service to registration for another, for example, or on forbidding commercial users from offering their products and services at different prices and under different conditions on third-party platforms. In addition, operating systems such as Google's Android or Apple's iOS would have to allow app stores other than their own to be installed on smartphones. Self-preferencing is explicitly prohibited.

Can these new regulations make the digital markets more open and fairer?

The crucial point is how the rules will actually be applied and enforced in practice. It remains to be seen whether the agreed-upon procedure will be effective – including, for example, the envisaged dialog between the Commission and gatekeepers with regard to the regulatory measures. Other unresolved questions include how effectively national authorities and the EU Commission will work together and what role national courts will play in enforcing the rules. Furthermore, the plan is for the EU Commission to play a central role, with the power to order a wide variety of measures against gatekeepers while also monitoring compliance with the measures. To this end, the Commission will need to create numerous additional positions with specific expertise. Indeed, it will be taking on a completely new role as a regulatory authority, and it'll be interesting to see if it can ultimately stand up to the big tech companies on an equal footing.

Assuming everything goes according to plan, the new regulation will come into force in 2023. Can all of these innovative provisions be implemented immediately?

That remains to be seen. The problem is that many technical issues are not resolved and are instead simply being deferred. The fine-tuning of the DMA will take the form of so-called delegated acts that have yet to be issued by the Commission. In practice, this often takes years. For example, the German railway company Deutsche Bahn (DB) has so far not been obliged to provide other services, such as Google Maps, with real-time information about its trains. Although the EU Directive that regulates this issue has been in force since 2010, it was not until 2017 that the Commission clarified the details in a delegated act – and only in 2021 were the rules finally incorporated into the German Passenger Transportation Act. Nevertheless, it is still unclear whether Deutsche Bahn is required to provide this real-time information.

Interview: Michaela Hutterer

Dr. Heiko Richter is a Senior Research Fellow for Digitalization and Competition Law at the Max Planck Institute for Innovation and Competition.

ILLUSTRATION: SOPHIE KETTERER FOR MPG

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