03 | 2024

MAX PLANCK
Research

MICROBIOLOGY
Diversity in the Sand

CHEMISTRY
From Pollutant to Raw Material

PHYSICS
Artificial Inspiration

ON LIFE AND SURVIVAL

PHOTO: ADOBESTOCK

For better or for worse: plants need water to survive, while humans need water and plants. What might appear self-evident is in fact becoming less and less evident as a reality. In this issue, we look at how humanity can safeguard life's basic necessities in the face of worsening climate extremes.

EDITORIAL

Dear Reader,

Freedom has many dimensions. In the first two issues of this year, we illuminated some of the political and societal dimensions of freedom and the legal framework that underpins it. This issue focuses on another aspect of freedom: the fulfillment of our existential needs. Hardly anything restricts freedom as much as a threat to the basic necessities of life, for example, a lack of food, clean water, or a safe place to live. These necessities can be threatened by wars or by catastrophes such as crop failure, floods, or fires. We investigate how increasing climate extremes are endangering the basic necessities of life and how we can safeguard them.

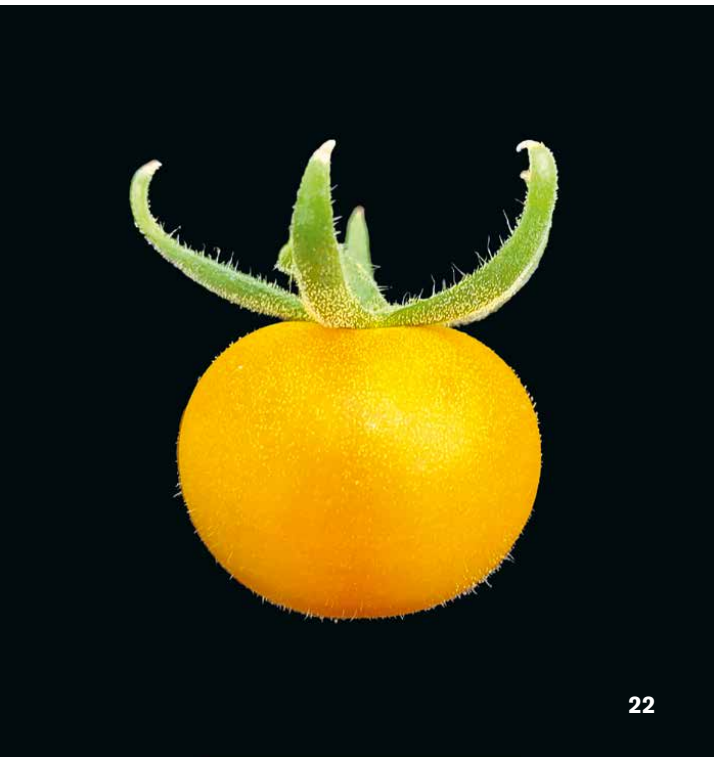
In many parts of the world, drought and heavy rainfall are making food production difficult or even impossible. Plant breeders are looking for varieties that can be used to feed the population, even in regions that are particularly affected by climate change. Hybrid plants can produce a higher yield and be more resistant to harmful environmental influences. However, these properties are lost in the next generation. A team at the Max Planck Institute for Plant Breeding Research is searching for a way to permanently preserve these properties in the seeds of hybrid plants.

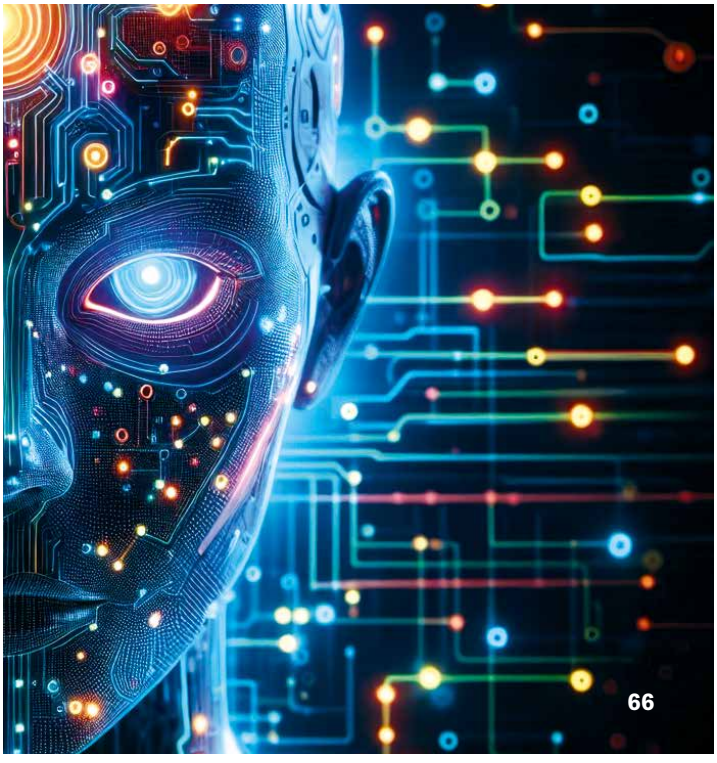
Increasing dryness not only threatens agriculture, but also increases the risk of wildfires, which can wipe out vegetation in one fell swoop. The prevention of and effective fight against such wildfires is the mission of the Global Fire Monitoring Center, which the United Nations has now elevated to become the Global Fire Monitoring Hub. One of the GFMC's key findings is that it is often more effective to work with fire than against it. Meteorological teams across the world are researching why wildfires are occurring with increased frequency and intensity. Altered precipitation patterns are one of the main causes here and one of the gravest aspects of climate change. We describe how the water cycle will continue to change and the measures we can take in response.

Alongside all the necessary efforts to adapt to already palpable and future changes in the climate, there is one thing in particular that will secure the basic necessities of life for future generations: decisive action to halt global warming. Science and research are creating the basis for this action.

In this spirit, we wish you a stimulating read!

Your Editorial Team





IMAGES: YAZHONG WANG / MPI FOR PLANT BREEDING RESEARCH (TOP LEFT), CHRISTOPH SEELBACH FOR MPG (TOP RIGHT), FANNI ASPETSBERGER / MPI FOR METEOROLOGY (BOTTOM LEFT), ADOBESTOCK (BOTTOM RIGHT)

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Hybrid varieties such as tomatoes should retain their characteristics for generations.

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Katharina Höfer's team has given her a superwoman double.

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Researchers are taking samples from the MS Farm off the coast of Spitsbergen.

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Algorithms from artificial intelligence are helping with physical research.

CONTENT

FEVER IN THE ARCTIC CIRCLE

The Abisko National Park in northern Sweden is a remote natural paradise popular with tourists and hiking enthusiasts. The two people in the picture, however, are not on vacation; they are researchers from the Max Planck Institute for Biogeochemistry in Jena. Not far from the national park, they are investigating changes in the permafrost soil, most of which remains frozen even in summer.

The research team has been conducting fieldwork in this region during various seasons over the past two years. A key piece of equipment they carry with them is a portable system consisting of several chambers. This is used on site to measure greenhouse gases released by the thawing soil, such as methane, carbon dioxide, and nitrous oxide. In addition, the team collects data on weather conditions and other environmental factors. The portable system enables the researchers to thoroughly examine the landscapes typical of Arctic permafrost regions, such as wet depressions and dry plateaus, and their extremely varied characteristics.

In its frozen state, the permafrost soil of the northern hemisphere stores vast quantities of carbon in an organic form. When it thaws, microorganisms are then able to decompose the organic substances in the soil which leads to the formation and release of greenhouse gases. This can also lead to the release of methane deposits lying deeper underground. If these greenhouse gases make it into the atmosphere, they accelerate global warming. The results of the field research can be used to refine physical models of the climate system, which serve as a basis for predicting future climate developments.

ON LOCATION

PHOTO: FABIO CIAN

EUR 1.3 MILLION FOR LUCID GENOMICS

The Berlin start-up Lucid Genomics, a spin-off of the Max Planck Institute for Molecular Genetics and the Institute of Medical Genetics and Human Genetics at Charité – Universitätsmedizin Berlin, has raised 1.3 million euros. The funds are being used to further develop AI-based technology that extracts all genomic information from genetic material and, in doing so, improves medical diagnostics and makes it easier to develop medication. At this time, sequencing of human genetic material takes into account only two percent of the genome and ignores the "dark genome" – the parts of the DNA that do not code any genes. To enable use of the entire genome, the team at Lucid Genomics is building upon years of experience in DNA sequencing and the development of machine learning methods that can be utilized to substantially improve recognition of genetic variants.

www.mpg.de/23160085

OUTSTANDING! ✶

PHOTO: KÖRBER-STIFTUNG

ERIN SCHUMAN

The Director at the Max Planck Institute for Brain Research in Frankfurt has been awarded the Körber European Science Prize, which is presented alongside 1 million euros in prize money. Schuman has demonstrated that proteins which play a decisive role in communication among nerve cells, memory formation, and the overall development of the brain are formed locally at the synapses, the switching points between nerve cells. This discovery disproves the hypothesis that proteins are created only in the cell bodies of nerve cells, which was assumed to be the case for quite some time.

A VISIT TO PRESIDENT LULA

MaxPlanckResearch made a visit to a prominent reader: Luiz Inácio Lula da Silva. During a literary journey through his native Brazil, Bruno Rodrigues de Lima, a researcher at the Max Planck Institute for Legal History and Legal Theory, also met the country's president and showed him an article in *MaxPlanckResearch 2/2024*: an article about Lima and his dissertation on the lawyer and human rights activist Luiz Gama (1830–1882). Gama, the son of a Brazilian bon vivant and a former slave, was sold into slavery by his own father. He was able to free himself from bondage and became a successful lawyer, who championed the rights of enslaved people and helped hundreds gain their freedom. Lima's dissertation paved the way for a biography, which he was presenting in Brazil.

www.mpg.de/22505145

PHOTO: RICARDO STUCKERT

The Brazilian lawyer Bruno Rodrigues de Lima meets President Luiz Inácio Lula da Silva.

PHOTO: HENKEL

LORRAINE DASTON

The retired Director of the Max Planck Institute for the History of Science has been awarded the Balzan Prize. The jury honored Daston for the scope, originality, and diversity of her work, which examines mental notions and associations that underlie research activity. The science historian laid the foundation for demonstrating the variability of key scientific concepts like objectivity, reason, and rationality throughout history – from the Early Modern Age to the present.

IN BRIEF

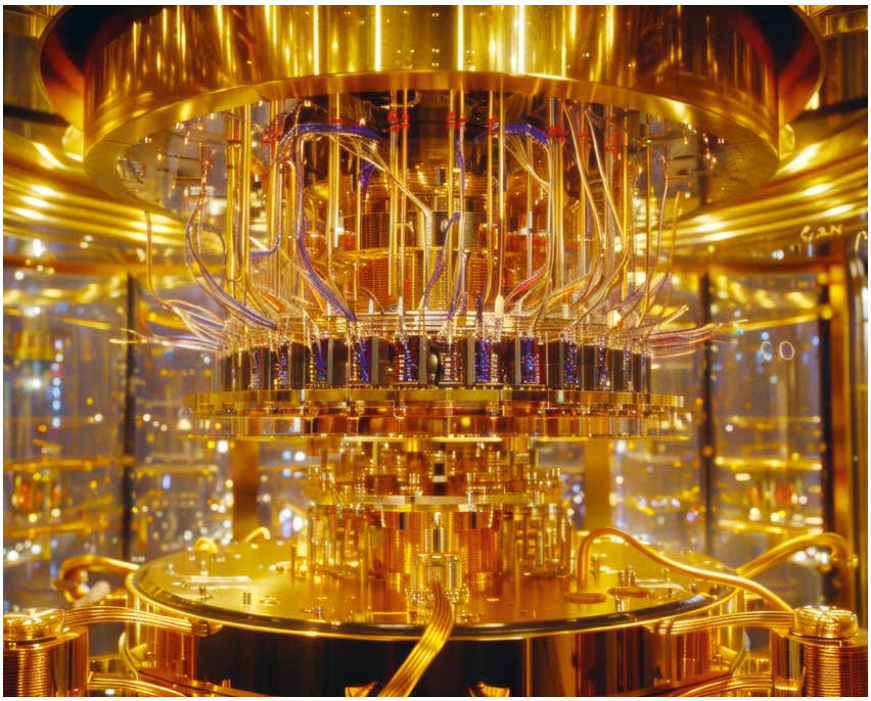

IMAGE: ADOBESTOCK

Quantum computers will be able to solve mathematical problems that form the basis of many current ciphering methods much more efficiently. That is why new cryptography methods are needed.

NEW ENCRYPTION STANDARDS

Once quantum computers have reached their full computing power, they could crack present-day encryptions used to protect emails, online transactions, or bank transactions. That is why experts from around the world have been developing cryptography methods that will still be secure in the post-quantum era. The National Institute for Standards and Technology in the United States has now published standards for three ciphering methods. Peter Schwabe, Director at the Max Planck Institute for Security and Privacy in Bochum played an essential role in their development. The U.S. authority selected the three methods Sphincs+, CRYSTALS-Dilithium, and CRYSTALS-Kyber from among 82 proposals. It will probably establish standards for a fourth method named Falcon later. These standards make it easier for online service providers to use the new ciphering methods

www.mpi-sp.org/68024

MOURNING SOCIETIES

Every year, hundreds of thousands of people fall victim to armed conflicts, either by losing their own lives or through the loss of relatives. Researchers have now examined how many people in Ukraine, Afghanistan, and other regions have lost a close relative. They evaluated data concerning deaths in regions impacted by war for this purpose. Their calculations show that several loved ones suffer trauma as a result of each casualty. In Syria, for instance, every casualty leaves behind an average of four mourning relatives, and in Ukraine the average is above two. By the end of 2023, an estimated 1 in 20 people in Syria had lost a loved one owing to the conflict over the course of their lives, and in Ukraine it was 1 in 200. Studies show that mourning lasts for decades, prevents reconciliation, and can sow the seeds of future violence. That is why fast solutions to the conflicts and support for the bereaved are necessary.

www.mpg.de/22328125

Artistic depiction of a cold gas giant revolving around a red dwarf.

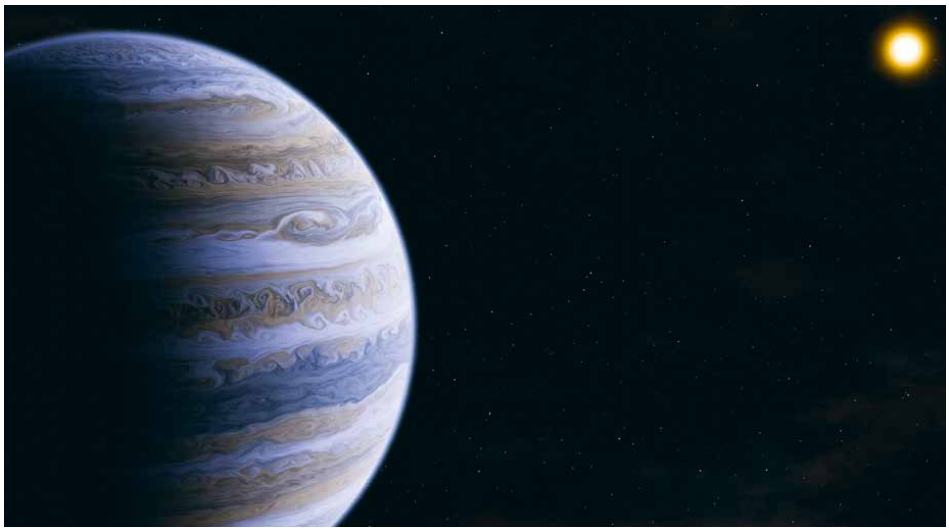

IMAGE: T. MÜLLER (MPIA/HDA)

SUPER-JUPITER PHOTOGRAPH

In a rare cosmic snapshot, the James Webb Space Telescope has directly imaged the exoplanet Epsilon Indi B in the triple star system Epsilon Indi. With six times the mass of Jupiter, the exoplanet belongs to the super-Jupiter class. It is the oldest known gas giant and also the coldest, with a surface temperature of approximately 0 °C. It revolves around its home star at a distance similar to the one between Neptune and the Sun. Primarily indirect methods of proof have been able to detect around 6000 exoplanets, but to date it has only been possible to photograph an exoplanet beside its star in about two dozen cases because the star usually outshines the much darker planet. Due to the type of observation concerned, the planets that have been photographed to date are almost exclusively young, hot gas giants that emit infrared light because of their temperature. However, the mature exoplanet Epsilon Indi B, which a team from the Max Planck Institute for Astronomy has now photographed, and its main star, a red dwarf, are about as old as the solar system. The researchers were even able to gain information about the planet's atmosphere from the image. This allows them to learn more about how gas giants form. Additionally, a comparison with our solar system helps clarify whether other systems form similarly to ours or whether our solar system is exceptional in this regard. ***www.mpg.de/22154949***

ALZHEIMER'S DISEASE AND DEPOSITS

Harmful clumps of protein form in the nerve cells of the brain in people with Parkinson's and Alzheimer's disease. Until now, it was believed that immune cells, known as microglia cells, could not absorb these proteins until they had been released from dead nerve cells. However, researchers from the Max Planck Institute for Biology of Ageing have now discovered that microglia can remove harmful proteins directly from the nerve cells. To do so, they use tubular extensions to connect to the nerve cells. Using these tubules, the microglia can not only transport toxic substances, but also supply damaged neurons with new mitochondria and thus support their energy metabolism. Genetic mutations that impair the tubules' ability to function also increase a person's risk of becoming ill with Parkinson's or Alzheimer's disease. Problems in tubule formation can, as a result, contribute to the development of neurodegenerative diseases. Researchers at the Max Planck Institute for Multidisciplinary Sciences have also discovered that, in addition to the nerve cells, oligodendrocytes produce beta amyloid proteins, whose deposits play a key role in Alzheimer's disease. Oligodendrocytes wrap around the nerve fibers and, in doing so, increase the nerve cells' transmission speed. The researchers found 30 percent fewer deposits in the brains of mice whose oligodendrocytes were not able to form beta amyloid.

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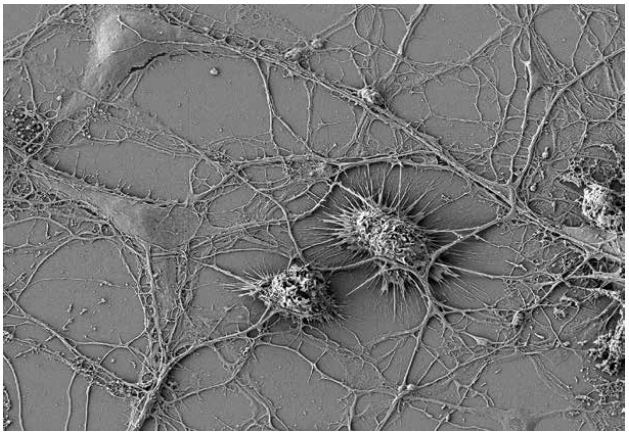

IMAGE: SCHEIBLICH / HENEKA

Two immune cells (microglia, in the middle) in the brain are connected to nerve cells (left) via nanotubes.

ROBOTIC LEG JUMPS TO NEW HEIGHTS

Researchers at the Max Planck Institute for Intelligent Systems and ETH Zurich have developed a robotic leg driven by electrohydraulic artificial muscles. This system is more energy efficient than traditional electric motors and enables high jumps and fast movements across various surfaces – without complex sensors. The artificial muscles resemble plastic bags that are used to create ice cubes, and they stretch and compress when subjected to electricity. This allows the robotic leg to lift its weight with lightning speed and demonstrate enough elasticity to adjust itself flexibly to different terrains. This technology constitutes considerable progress in soft robotics and opens up new possibilities for adaptive robots in various applications, for example, humanoid robots with an especially efficient and adaptable gait are now conceivable.

www.mpg.de/23443589

The common noctule primarily lives in the forest and inhabits wide stretches of Europe.

RAPID HEARTBEAT

Flying is strenuous. That is why bats in particular need to mind their energy consumption. Scholars at the Max Planck Institute of Animal Behavior in Konstanz have now measured the energy requirements of the common noctule in the spring and summer. They attached small heart rate transmitters weighing only 0.8 grams to the bats. Heartbeats can be used to draw conclusions about energy consumption. Since the receivers can register the transmitters' signals within a range of only a few hundred meters, the researchers needed to follow the animals in planes while they flew. The measurements revealed that male noctule bats consume over 40 percent more energy in the summer than they do in the spring. This is primarily due to the fact that the bats enter into a form of brief hibernation during the day in the spring, which enables them to reduce their heart rate from 900 to 6 beats per minute. In the summer, on the other hand, the males are awake day and night and invest a great deal of energy in sperm production in order to be well-prepared for mating season in the fall. They acquire the energy needed for this purpose by hunting for twice as long in the summer as they do in the spring. They can consume over 30 maybugs and 2500 mosquitoes in a single night during the summer. However, since insect populations are declining, it is becoming increasingly difficult for bats to fulfill their high energy requirements in the summer.

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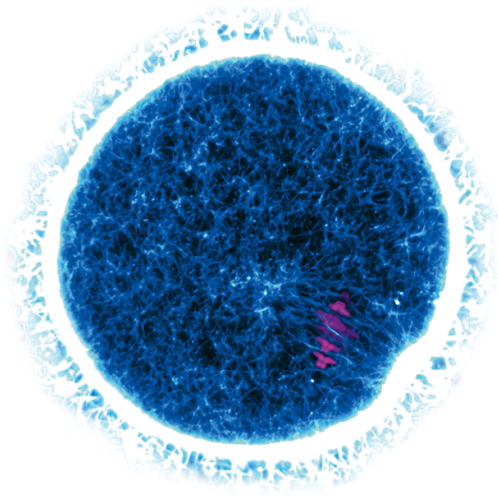

IMAGE: MPI FOR MULTIDISCIPLINARY SCIENCES / MELINA SCHUH

Egg cell from a mouse with chromosomes (magenta) and the cell skeleton protein actin (blue-white).

PROTEINS FOR A LIFETIME

Of the approximately 1 to 2 million egg cells that a woman is born with, only about 400 mature before menopause. Some of these cells thus become several decades old. Extremely long-lived proteins could play an important role in preserving fertility as long as possible. Researchers at the Max Planck Institute for Multidisciplinary Sciences in Göttingen made this discovery during experiments with mice. While most cell types renew the majority of their proteins within a few days, the researchers say that many proteins in egg cells and other types of cells in the ovaries of female mice remain intact until the end of their lives. Above all, these include proteins that repair DNA or protect cells from clumping molecules. Since mitochondria, the power plant of the cell, originate from the egg cell, they should remain functional at least until an embryo is capable of producing its own. Accordingly, mitochondria also contain especially long-lived proteins. Over time, the quantity of these proteins in the egg cells and ovaries declines. Their gradual disappearance could explain why fertility diminishes over time.

www.mpg.de/22190551

ONE TEST FOR MANY DISEASES

PHOTO: THORSTEN NAESER

One sample, many diagnoses: The vial hardly contains more than a drop of blood plasma. An infrared measurement can be used to diagnose various metabolic disorders, among other conditions.

In the future, it might be possible to diagnose some common illnesses more easily and quickly than in the past. In a representative study, a team at the Max Planck Institute of Quantum Optics, LMU Munich, and Helmholtz Munich has demonstrated that machine learning and infrared light measurements of blood plasma can be used to detect various metabolic disorders, such as type 2 diabetes, and high blood pressure. The method can also be used to diagnose prediabetes, which other procedures often overlook. In the past, individual tests have been required to detect each of numerous different diseases. That is one reason why the diseases remain undetected for a long time in many cases. According to the Robert Koch Institute, as a result around 1.3 million people suffer from undetected type 2 diabetes, and approximately 5 million people have high blood pressure without knowing it. Since now only one measurement is needed to diagnose various common illnesses – a measurement which only requires a drop of blood and a few minutes – this method makes it possible to perform comprehensive health screening for an entire population. That could help detect the diseases early on and thus reduce the risks associated with them.

www.mpg.de/22471897

STARS REVEAL A BLACK HOLE

When stars revolve around an invisible center, like planets around a star, this indicates the presence of a black hole with considerable mass. Under the leadership of the Max Planck Institute for Astronomy, astronomers have discovered such a black hole with 8200 solar masses in the star cluster Omega Centauri. This star cluster is located in the Milky Way and is 17,000 light years away from Earth. At one time, the star cluster was its own galaxy, but it was incorporated by the Milky Way billions of years ago. However, its galactic nucleus remained largely unchanged. The black hole in Omega Centauri is more massive than the black holes that remain after the explosion of a heavy star and lighter than the other known extreme: supermassive gravity traps of millions to billions of solar masses in the centers of full-fledged galaxies. Since such especially massive specimens can form when smaller black holes converge, scientists had long suspected that there must also be black holes with medium-sized masses. However, they had been unable to reliably prove the existence of such black holes until now.

www.mpg.de/22157737

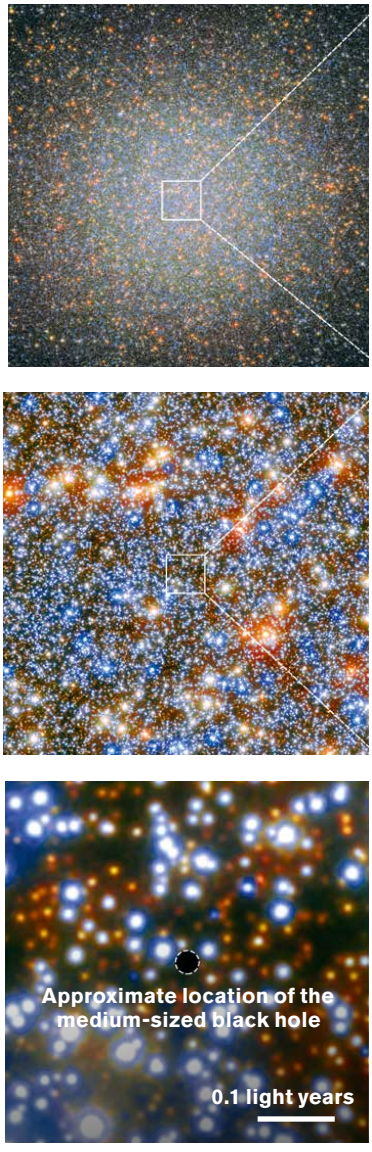

IMAGE: ESA/HUBBLE & NASA, M. HÄBERLE (MPIA)

Zooming in on individual stars at the center of the globular cluster Omega Centauri at three levels. The stars are revolving around a black hole in the center (bottom) at up to 400,000 km/h.

PHOTO: GABRIEL BARATHIEU

The fragrance ambroxide, which is contained in many perfumes, was obtained from sperm whales for a long time. A team from Mülheim has now found a simpler alternative to the common present-day synthetic method.

SWELL SMELLS!

People have been using ambroxide as a fragrance since antiquity. Back then, they derived it from ambergris, a waxy substance obtained from the digestive tracts of sperm whales. Today more than 30 metric tons of it are created every year from a substance in muscatel sage, which grows from the Mediterranean to Central Asia. However, this process of manufacturing ambroxide requires several reaction steps. What is more, the availability of muscatel sage fluctuates. Now a team at the Max-Planck-Institut für Kohlenforschung in Mülheim has cooperated with the chemical company BASF and managed to synthesize the substance from nerolidol in one step. Nerolidol is present in many plants, such as ginger and jasmine. The combination of catalyst and solvent is decisive for the simple synthesis. Both of these substances can be recovered after the reaction, which is an important advantage in industrial applications. ***www.kofo.mpg.de/988988***

Modern technology makes it possible to determine information about place of residence and nutrition across centuries.

PHOTO: PATXI PÉREZ RAMALLO

ARCHAEOLOGICAL RIDDLE SOLVED

Rumor has it that Bishop Teodomiro from Iria Flavia in northeastern Spain discovered the grave of the apostle Jacob on a hill in Galicia in the ninth century. He reported his discovery to King Alfonso of Asturias, who had a chapel built on top of the site and founded one of the most important places of pilgrimage for Christians: Santiago de Compostela. Whether the bishop lies buried in the cathedral was a matter of dispute for some time, even though an inscription on a gravestone in the church indicates this is the case. In the 1950s, researchers found remains that were attributed first to a man, then to a woman. Now an international team headed by Patxi Pérez Ramallo, who previously worked at the Max Planck Institute of Geoanthropology, has investigated the human remains again using bone, isotope, radiocarbon, and DNA analyses. The analyses of the bones revealed that they were the remains of a man who was probably over 45 years old. Owing to the age and diet of the deceased revealed by the isotope analysis and their genetic profile, the researchers assume that the remains most likely belong to Bishop Teodomiro. If that is the case, he would be the oldest identified historic figure in Spain and one of the oldest in Europe.

www.mpg.de/22500491

WHO OWNS BIODIVERSITY AND CULTURAL HERITAGE?

Vaccines, medicines, food, fashion: different industries are keen to make use of genetic resources and the cultural heritage of Indigenous peoples. But who owns such assets, who can make use of them, and at what price? Despite the agreements in place and a UN conference in Cali, all this remains unclear. Giving an overview of the regulatory landscape legal expert Pedro Henrique D. Batista knows which approaches are needed today.

In 2024, the industrialized nations negotiated new international agreements on this issue with countries that are rich in biodiversity. Despite the advances precise and effective international regulation is still needed to guarantee legal certainty and efficient access for entitled users, as well as fair benefit-sharing to protect biodiversity, the sovereignty of the countries of origin, and the fundamental rights of Indigenous peoples.

High-selling products are ever more frequently rooted in the cultural heritage of Indigenous peoples, genetic resources, and the information obtained from them. Genetic material from organisms – often taken from Indigenous land – is used to develop vaccines, medicines, and food products, for example. Fashion, meanwhile, in part incorporates designs based on the art of Indigenous peoples.

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VIEW POINT

PEDRO HENRIQUE D. BATISTA

Pedro Henrique D. Batista is a senior research fellow at the Max Planck Institute for Innovation and Competition in the field of intellectual property rights. The focal areas of his research include patent law, trademark law, copyright law, biotechnology, and ethics. Among others, he has examined how effective protection of genetic resources and Indigenous knowledge can be achieved in practice. He is a participant in the World Intellectual Property Organization (Wipo) Intergovernmental Committee on Genetic Resources, Traditional Knowledge and Folklore, the Working Group on Benefit-Sharing from the Use of Digital Sequence Information of the United Nations Environment Programme (Convention on Biological Diversity – CBD), and a permanent member of the German Association for Intellectual Property Law's (GRUR) Special Committee for the Protection of Plant Breeding.

ILLUSTRATION: SOPHIE KETTERER FOR MPG

Whether in fashion, accessories, or biotechnology, such uses are still plagued by an age-old question: to what extent can they take place without the consent of the countries of origin or the Indigenous peoples to whom these resources and cultural artifacts belong?

The last few decades have seen much talk about cases of "biopiracy", "cultural appropriation", and "theft of cultural heritage." These cases reflect the demands of countries that are home to Indigenous peoples and have abundant biodiversity for a fair share in the benefits that come from the use of their biodiversity and culture. These demands are rooted in the rights of Indigenous peoples as well as sovereign rights of countries to their genetic resources and in the protection of their biodiversity.

COUNTRIES THAT HAVE GREAT BIODIVERSITY AND ARE HOME TO INDIGENOUS PEOPLES HAVE DEMANDS FOR A SHARE OF BENEFITS

Accordingly, many of these countries – particularly in Latin America, Africa, and Asia – have introduced legal protection for genetic resources (such as genes and their sequences) and cultural heritage. Yet this protection at a purely national level is often not sufficient to ensure the desired fair distribution of benefits, since the use of biodiversity and cultural heritage usually takes place in countries with a strong industrial base – such as the USA, Japan, and those of the European Union – and these countries are generally not particularly interested in strong legal protection for the genetic resources and cultural heritage. In particular, they do not want the bureaucratic requirements of the system to create legal uncertainty or barriers to innovation and creative freedom.

In recent decades, several important treaties have been adopted in an attempt to reconcile these conflicting interests. The 1992 *Convention on Biological Diversity* (CBD) and its *Nagoya Protocol* from 2010, for example, require users – such as businesses or research institutions – not only to obtain consent from countries of origin or Indigenous peoples to gain access to their genetic resources and the traditional knowledge associated with them, but also to provide appropriate compensation for the benefits that arise from their use. This might take the form of financial benefits (such as access fees, a share in the profits from production, or research resources) or of non-financial benefits (such as scientific collaboration, technology transfer, or shared ownership of patents).

This bilateral relationship between users and countries of origin (or Indigenous peoples) can nevertheless be particularly costly and time-consuming in some instances. To ensure that innovation is not hampered in areas of particular significance for humanity, the Food and Agriculture Organization's *International Treaty on Plant Genetic Resources for Food and Agriculture* and the World Health Organization's *Pandemic Influenza Pre-*

paredness Framework provide for a multilateral benefit-sharing mechanism for the use of certain crops (such as apples, bananas, potatoes, carrots, corn, or sunflowers) as well as influenza viruses. In these instances, the benefits flow into a special fund that distributes them to countries and projects according to predetermined criteria.

Finally, the *Agreement on Marine Biodiversity in Areas beyond National Jurisdiction* (BBJN) was signed in 2023 as part of the United Nations Convention on the Law of the Sea. Among other things, this agreement governs the sharing of benefits in the event that genetic resources are used from waters over which no country has jurisdiction.

Despite these advances, gaps in protection and the imprecise formulations of these treaties mean that only a small proportion of commercial benefits are shared with the countries of origin or Indigenous peoples. Moreover, important elements of cultural heritage remain unprotected. Yet there are complaints from industry, too, about substantial legal uncertainty in relation to their obligations, since access rules are often unclear and vary considerably across different countries. Consequently, there is still a need for further international regulation.

IMPORTANT ELEMENTS OF BIODIVERSITY AND CULTURAL HERITAGE STILL REMAIN UNPROTECTED

Against this background, the year 2024 could be considered the year of biodiversity and cultural heritage, as no fewer than four important international agreements were simultaneously negotiated in these areas.

The most successful thus far is the *Treaty on Intellectual Property, Genetic Resources and Associated Traditional Knowledge* of the World Intellectual Property Organization (Wipo), which was adopted last May. It aims to bolster legal certainty and create transparency to ensure compliance with national access and benefit-sharing rules. The treaty includes an obligation for patent applicants to indicate the country of origin, or at least the source of the genetic resources or traditional knowledge, in patent applications. Where this obligation is not met, national sanctions are generally applied outside of patent law, which may include fines, market bans, or exclusion from public tendering procedures. The patent can also be declared invalid if the patent applicant fraudulently fails to state the origin or states it incorrectly.

It remains to be seen how far this agreement will ensure effective legal protection of genetic resources and cultural heritage. The patent applicant is still permitted not to state the country of origin where this is unknown, and there is still a lack of clarity regarding the implementation of control mea-

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sures and sanctions on a national level. In parallel, two further treaties have been negotiated at the Wipo, one to protect other traditional knowledge and one to protect traditional cultural expressions (such as dances, clothing, jewelry, and designs by Indigenous groups). In these instances, it is expected that use of such cultural assets will require consent from the corresponding Indigenous peoples. However, the countries have not yet been able to agree on key aspects of the protection system, such as the definition of protected cultural assets, ownership of rights, exceptions, and term of protection, so it is unlikely that the negotiations will make rapid progress.

Ultimately, digitalization is also an important factor in this area. Digital sequence information (DSI) – such as the nucleotide sequence of a gene – has been increasingly used for development of biotechnology products and services, for example, in the areas of pharmaceuticals, food, cosmetics, and biofuels. Given the particular challenge of identifying the country of origin and bilateral negotiations on access to and use of a great volume of information, the parties to the Convention on Biological Diversity agreed at their 16th Conference (Cop 16 in Cali, Colombia) in early November to set up a multilateral mechanism to share the benefits resulting from the use of this information.

THE UNAUTHORIZED USE OF A RESOURCE MAY BE PERMITTED IN ONE COUNTRY BUT PROHIBITED IN ANOTHER

In short, DSI users – particularly companies operating in the areas of pharmaceuticals, nutraceuticals, cosmetics, biotechnology, laboratory equipment for sequencing, and use of DSI and related services – will now have to share the financial and non-financial benefits resulting from such use multilaterally. Based on the profit or revenues from DSI-related products and services, the shared financial benefits will be transferred to an independent international fund that will specifically support biodiversity conservation, Indigenous peoples, and capacity building.

Nevertheless, the mechanism is not legally binding and does not apply in relation to sequence information whose access and use is governed by an agreement between the user and the country of origin. It remains to be seen how the mechanism will be implemented in practice by the Contracting Parties and how far it will influence DSI regulation in other international organizations (for example, within the framework of the above-mentioned agreements of the Food and Agriculture Organization and the World Health Organization).

So, who owns biodiversity and cultural heritage? The regulatory complexity means there is no straightforward answer. It varies depending on the protected assets, the applicable agreement, and the valid exceptions.

This regulatory variety reflects the differences in the nature of the protected goods, which can be tangible (e.g., genetic resources) or intangible (e.g., traditional knowledge, DSI) and have different rightholders (e.g., countries of origin, Indigenous people) – or simply have no rightholder.

NOTHING PREVENTS COUNTRIES FROM ADOPTING FURTHER MEASURES AT A REGIONAL OR MULTILATERAL LEVEL

Moreover, international regulation enables a variety of interpretations regarding how the rules should be implemented at the national level. The precise material and temporal scope of protection, compliance measures, and sanctions, for instance, may deeply vary from country to country. This can lead to situations where the unauthorized use of a specific resource or knowledge is permitted in one country but prohibited in another. Additionally, international law does not ensure that procedures related to the access to genetic resources and traditional knowledge are efficient, which is disadvantageous for users.

In light of this, it is important for companies and researchers in the biotechnology sector to be aware of this regulatory conundrum in the course of their activities. This does not preclude international law from being improved. An important foundation would be laid if international lawmakers were able to set out clear, precise, effective and more comprehensive regulatory mechanisms in order not only to promote a better harmonization of national laws, but also to ensure legal certainty and efficient access for entitled users and also a fair benefit-sharing. A legally binding dispute resolution mechanism between countries to determine the proper implementation of international law could ensure regulatory unity.

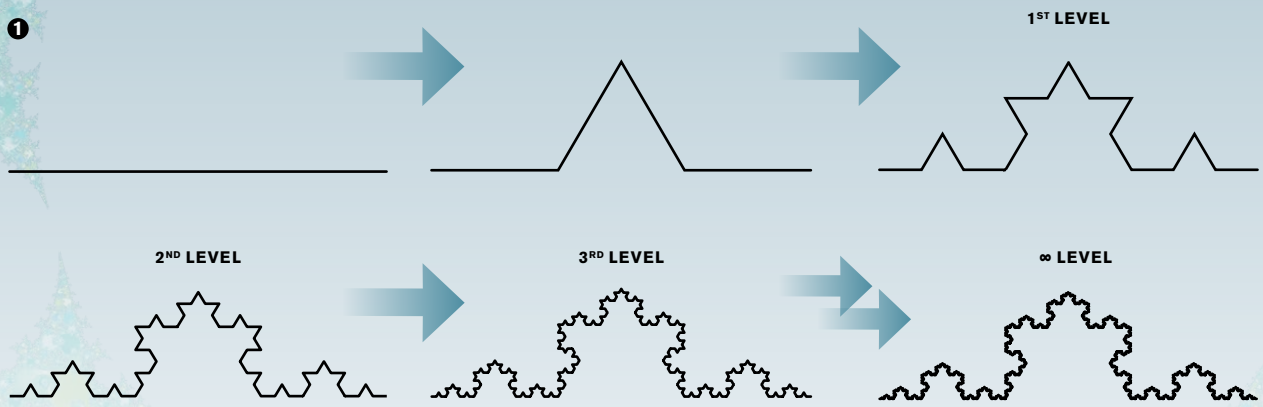
Divergence of interests between countries may hinder advances in international law. However, nothing prevents countries interested in achieving efficient and effective legal protection for genetic resources and traditional knowledge from adopting such measures at a regional or multilateral level. If similar rules on efficiency, scope of protection, compliance and sanctions are adopted by a group of countries, companies and researchers operating in the global biotechnology market would be incentivized to comply to them in order to avoid multiple sanctions. This would prevent countries from competing to offer more favorable access conditions, which would lead to a ‘race to the bottom’ regarding the amount of benefit-sharing required.

In summary, effective and efficient regulation at the international level—or, alternatively, at the regional level—can facilitate the work of researchers and companies while ensuring fair and equitable benefit-sharing.

BIG AND SMALL ALIKE

Geometric figures that are composed of scaled-down versions of themselves are known as fractals. That means that if you enlarge a section of a fractal to any extent, its geometry remains unchanged (self-similarity). The Mandelbrot set, named after mathematician Benoit Mandelbrot, is a well-known fractal that appears here as a translucent background. However, fractals aren't simply a mathematical construct – in our environment, too, there are objects with fractal structures. Researchers from the Max Planck Institute for Terrestrial Microbiology in Marburg have now discovered that even proteins can have fractal structures.

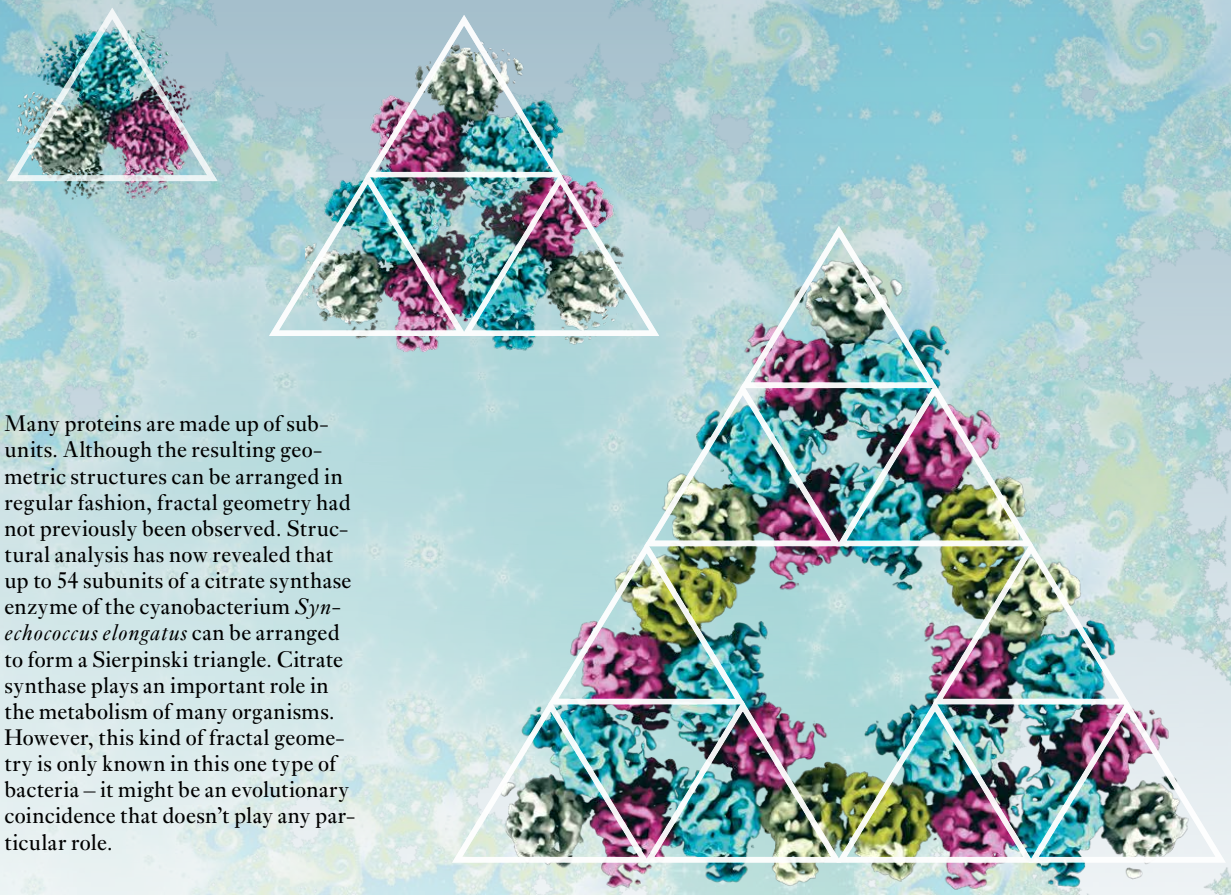
❶



❷

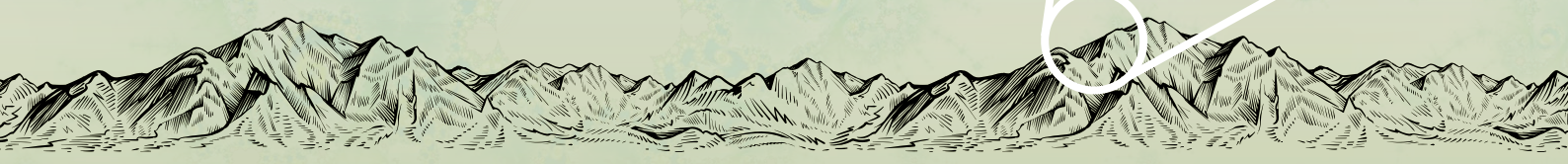
GRAPHIC: GCO BASED ON SENDKER ET AL., 2024 ISTOCK

The Koch curve ❶ is based on a simple rule: the sides of an equilateral triangle are inserted into the middle third of a line. If this process is repeated again and again, you get a fractal that looks like a snowflake. The Sierpinski triangle ❷ is also a fractal. It is created when you connect the central points of the sides of a triangle with lines. The result is four smaller triangles, of which the central smaller triangle is then removed. This process can be applied as many times as you like to the remaining triangles as they get smaller and smaller.



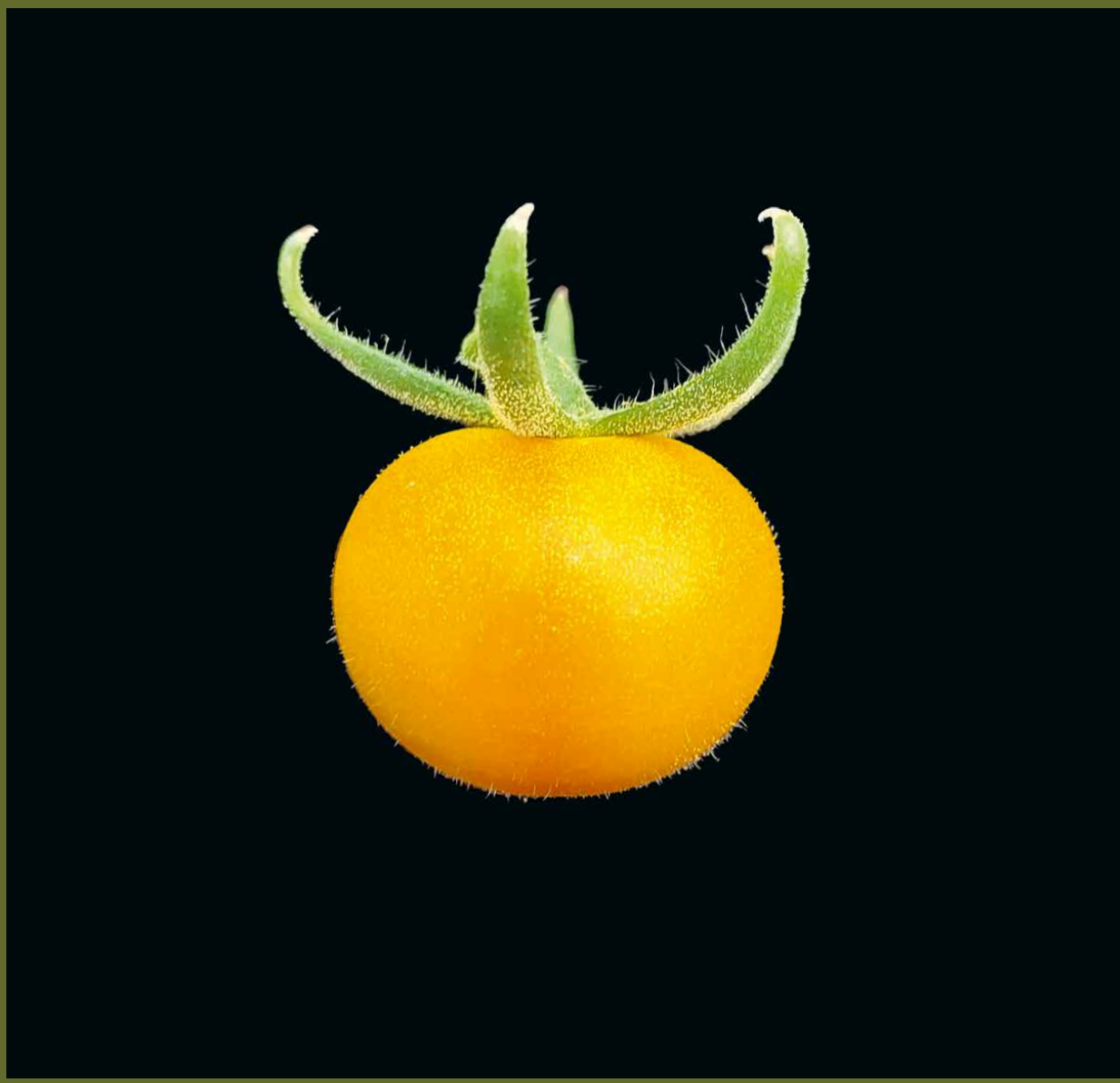
Many proteins are made up of subunits. Although the resulting geometric structures can be arranged in regular fashion, fractal geometry had not previously been observed. Structural analysis has now revealed that up to 54 subunits of a citrate synthase enzyme of the cyanobacterium *Synechococcus elongatus* can be arranged to form a Sierpinski triangle. Citrate synthase plays an important role in the metabolism of many organisms. However, this kind of fractal geometry is only known in this one type of bacteria – it might be an evolutionary coincidence that doesn't play any particular role.

Other self-similar objects in nature include fern leaves and mountains, for example. In architecture, too, there may be fractal structures. Unlike mathematical fractals, however, natural fractals do not have an infinite number of self-similar levels.



FOCUS

ON LIFE AND SURVIVAL



Tomato with a quadruple set of chromosomes. Of these, three come from the standard vine *tomato Solanum lycopersicum* and one is from the wild tomato *Solanum pennellii*. It was bred using a new method in which genetically identical seeds are produced from hybrid plants.

PHOTO: YAZHONG WANG / MPI FOR PLANT BREEDING RESEARCH

TURBO-CHARGED SEEDS

TEXT: ANDREAS LORENZ-MEYER

When different varieties of one plant species are crossed with each other, their hybrid offspring are often more robust and grow more quickly than their parents. However, in the next generation this effect disappears. New methods make it possible to preserve the advantageous qualities of these kinds of hybrid plants for the long term and to deliberately design plants with four sets of chromosomes rather than two. The techniques should make it easier to breed particularly high-yielding and resistant crops that could feed a growing global population even in times of climate crisis.

As far back as 1759, over a hundred years before the Austrian Augustinian monk Gregor Johann Mendel published his work on inheritance in peas, scientists were already pondering the question of how plants pass on their traits to their offspring. It was during that year in St. Petersburg that a competition was held by the Russian Academy of Sciences. The task set was to prove that plants also possess sexuality. The winner was Joseph Gottlieb Kölreuter, the son of a pharmacist from Sulz am Neckar. Kölreuter, who later became a professor of natural history in Karlsruhe, had crossed two inbred tobacco plants and, in doing so, noticed that traits specific to each parent were present in the next generation after crossing. He concluded that they were passed on from the parent plants in equal proportions. In addition, the first-generation plants from the cross looked the same – a finding that Mendel also formulated in his principle of uniformity. But the botanist noticed something else too: the offspring thrived better than their parents.

Thus, more than 250 years ago, Kölreuter discovered the "heterosis effect", otherwise known as hybrid vigor. This occurs when first generation hybrids – that stem from a deliberate crossing of two inbred varieties of the same or closely related species – are superior to their parents in terms of vitality and growth. How this phenomenon comes about has not yet been conclusively clarified. Still, modern agriculture has this effect to thank for the cultivation of high-performing hybrid varieties of maize, rapeseed, rice, rye, and many other crops.

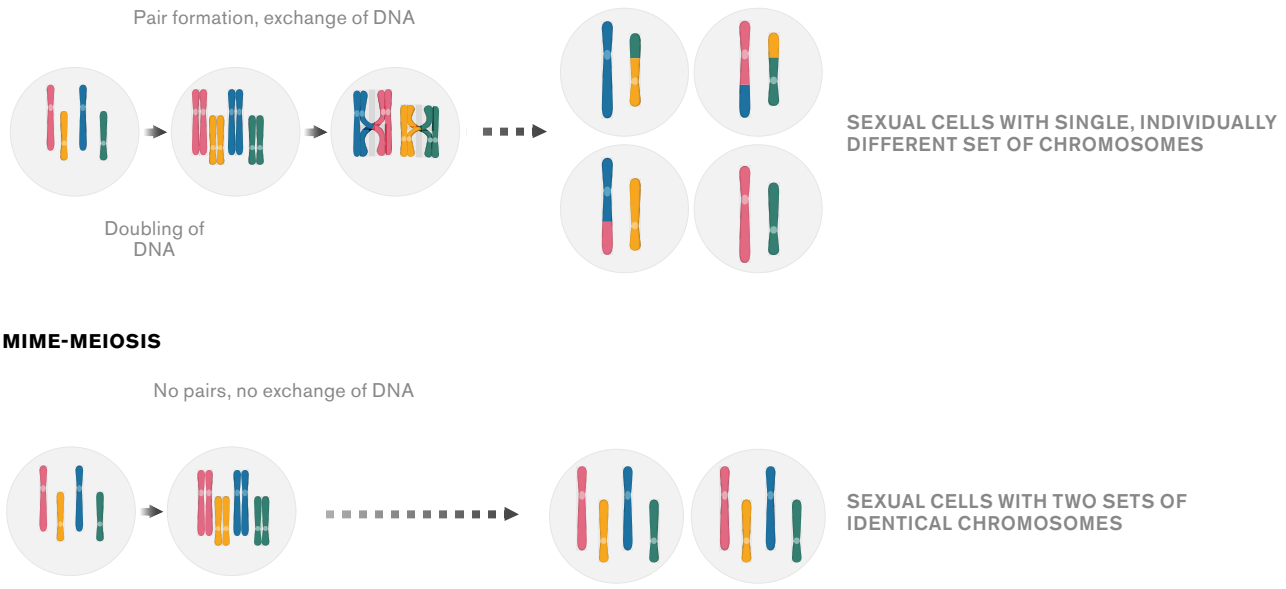
Short-lived effect

Outwardly, hybrid crop varieties grow quicker and are more robust to abiotic and biotic stresses than their inbred relatives. Hybrid maize, for example, produces 30 percent greater yields. But there's a problem: the heterosis effect doesn't last. The yield increase achieved by the cross in the first generation of offspring is lost by the second. The plants also lose their outward uniformity. The reason for this is the processes involved in sexual reproduction: during the meiotic cell division necessary for the formation of germ cells – i.e., egg cells and pollen – the genetic material of the germ cells is mixed up – or recombined – so in the next generation none of the plants are exactly like their parents. In this way, meiosis enhances genetic diversity in plants and animals. If, however, the hybrids could be propagated asexually, i.e., cloned, through seeds they could pass on their complete genetic material and thus their advantageous traits to the next generation. This would massively reduce the costs associated with hybrid seed production and could lead to the development of many more hybrid varieties than are currently available.

Raphaël Mercier, Head of the Department of Chromosome Biology at the Max Planck Institute for Plant Breeding Research, and Charles Underwood, Research Group Leader in Mercier's department, are aiming to make that possible. The two scientists present their progress in the production of hybrid seeds in the Institute's greenhouses, in which, in addition to the thale cress – an inconspicuous wild herb on which the scientists have gained fundamental insights – barley, potatoes, and tomatoes grow. To do so, they must ensure two preconditions are met: first, the entire genetic material of the mother plant must be preserved in the female gamete, which is only possible if the meiotic cell division, during which the genes are mixed up, does not take place as usual and a clonal egg cell is produced. Next, the new plant must develop from the clonal egg cell without fertilization by a male gamete, because, without meiosis, the number of chromosomes is not halved. So, if a pollen cell were to fertilize this kind of egg cell, it would then have too many chromosomes. "We need to overcome two obstacles: meiosis and fertilization. Only in this way can we produce seeds that are

Shoot of a tomato plant in a culture medium. Thanks to the growth factors it contains, just a small piece of tissue can develop into a complete plant several meters high.

PHOTO: FRANK VINKEN FOR MPG



GRAPHIC: GCO BASED ON DATA FROM CHARLES UNDERWOOD / BIORENDER.COM

Formation of gametes in plants: in the meiotic cell, pairs of chromosomes of the same type form and exchange DNA segments with each other. The pairs then arrange themselves in one plane, and the previously duplicated genetic material separates in an orthogonal direction. This results in four cells with a single, individually different set of chromosomes. In the MiMe process, sexual cells are formed without meiosis, and there is no exchange of DNA segments between chromosomes. This produces two cells that each have two sets of chromosomes identical to that of the initial meiotic cell.

genetically identical to one another and to the mother plant. With this kind of clonal hybrid seed, the hybrid state can thus be extended almost indefinitely," explains Mercier.

Mercier began his investigations in 2009 at the INRA Jean-Pierre Bourgin Institute Versailles-Saclay in France. "It is still my goal to find out which genes are involved in the meiotic cell division and development of egg and pollen cells. On a fundamental level, I want to know how these processes work." In the thale cress, he identified three genes that control important processes for meiosis and differentiate meiosis from mitosis, a process in which a cell divides into two identical daughter cells. When Mercier deactivated these three genes simultaneously, meiosis reverted to mitosis, and the plants formed clonal germ cells. The genetic material of the egg cells and the number of chromosomes were therefore identical to those of the mother plant. Through this experimentation, Mercier discovered a process that bypassed meiosis.

Rice from cloned seeds

In 2016, Mercier and Emmanuel Guiderdoni from the French Agricultural Research Centre for International Development (Cirad) applied the process, dubbed MiMe (mitosis instead of meiosis), to rice and thus for the first time to a crop. Alongside maize and wheat, rice is one of the most important cereal crops worldwide and is a staple food for 90 percent of the world's population. The three genes have been conserved during evolution and control meiosis in both thale cress and rice. It emerged that, without these genes, in the rice too an egg cell formed that was genetically identical to the mother plant.

In 2019 Mercier and Venkatesan Sundaresan from the University of California Davis, tackled the second obstacle: through activation of the BBM1 gene in the egg cell, which is otherwise only active in pollen and the embryo, the development of the embryo could be triggered without fertilization. BBM1 is a transcription factor that triggers embryogenesis. It becomes active in the cell as a result of the fertilization of the egg cell by a pollen cell. The feasibility of clonal reproduction for a crop plant through seeds was thus proven. But the process is not yet ready to be put into practice. "Compared to sexually reproducing rice, these plants still produce 30 percent fewer seeds. This is a problem, of course, because that means a 30 percent lower yield for crops from which we harvest the seeds. However, I am confident that this problem can be solved in the near future."

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Another crop with which the researchers have now tried out the MiMe technique is the tomato, the world's number one vegetable crop. Among other varieties, the scientists used date and vine tomatoes in their research – hybrid varieties that are also available in the supermarket. Charles Underwood and his team have not only developed a MiMe technique for this, but also utilized it in a different way. First, they established MiMe in different hybrid tomato plants to generate clonal sex cells. The fertilization of a clonal egg from one plant by a clonal sperm from another led to plants containing the complete genetic information of both parents. This approach – termed "polyploid genome design" – allowed Underwood and his team to design plants with a four-fold set of chromosomes instead of a two-fold one. The polyploidy observed in these tomato plants is similar to that observed in many other cultivated crops like wheat, rapeseed, bananas, and potatoes. The difference here is the polyploidy was induced by the MiMe process. "The result is a kind of super-hybrid," says Underwood.

The scientist is standing in front of an LED-lit greenhouse filled with tomato plants and points to the plant at the front to the right, which boasts particularly large fruit. "This plant has a quadruple set of chromosomes, so it carries the complete genetic material of both parent plants. As far as we are aware, this was the first time clonal sex cells from two different parents have fused – in any plant or animal – ensuring complete inheritance from both parents." Next to the "super-hybrid" is a plant that admittedly bears considerably smaller fruit, but is nonetheless very robust. "This is the result of crossing a MiMe tomato hybrid with a wild relative of tomato, *Solanum pennellii*. This wild accession comes from a barren location in South America and is particularly resistant to heat, drought, and salty soils. The genes for this stress tolerance are now also present in this hybrid plant," says Underwood. This also explains why the fruit are smaller: large fruit actually don't occur in nature at all, but are the result of thousands of years of artificial selection by humans. The hybrid tomatoes are part of an effort by Underwood and his colleagues to harness MiMe in developing new breeding systems that can fully make use of the stress tolerance of crop wild relatives.

Another candidate for the MiMe method is the potato. Potatoes and tomatoes may look very different, but the plants themselves are closely related. They both belong to the nightshade family and indeed to the same genus. "Many of today's varieties are already quite old – the 'Russet Burbank' variety, for example, has been cultivated in the US for over a century. There is an urgent need to speed up the development of disease-resistant potato varieties that can tolerate the increasingly variable summer climates, because potatoes are still one of our most important crops," explains Underwood.

SUMMARY

Crossing two varieties can produce hybrid daughter plants with particularly advantageous traits, but these traits are then lost in the following generation.

With the MiMe technique, hybrid plants can form clonal sex cells without meiosis. Clonal egg cells can be used to develop clonal plants without fertilization. The genetic material of these new plants is identical to that of the mother plant, preserving the high performance of hybrid plants for the long term.

The MiMe technique can also be applied in polyploid genome design. This offers a route to increase the genetic diversity within a single plant by, for example, engineering plants with four sets of chromosomes rather than two.

One problem that arises in the cultivation of potatoes is disease. The pathogen that causes potato blight, for example, damages both the above-ground parts of the plant and the tubers that lay underground. If the pathogen attacks the potato plants during the growth phase, this results in high losses in yields. In Ireland in the mid-19th century, the fungal disease led to a devastating famine. As with the wild tomato, genetic material from wild potato species could make its domestic relatives more resistant. "MiMe could enable breeding varieties that are more resistant to potato blight, but otherwise have the usual characteristics of potatoes. This could help to reduce the need to spray the plants with pesticides." For Raphaël Mercier too, MiMe hybrid po-

"The process could enable us to breed varieties that are more resistant to potato blight."

RAPHAËL MERCIER

PHOTO: FRANK VINKEN FOR MPG

Yazhong Wang, Charles Underwood, and Raphaël Mercier (left to right) examine a super-hybrid tomato plant that contains the complete genetic information of both parent plants.

tato varieties have huge potential, partly because it is not the seeds or fruits that are harvested, but rather the tubers lying under the ground. "The fact that MiMe hybrid potatoes don't form as many seeds is therefore not as relevant as for rice, since this doesn't have a negative impact on the yield."

There's a barrier to the application of this technique, however – namely the strict EU regulations concerning genetically modified crops. These regulations restrict techniques like MiMe that are based on genome editing, i.e., the targeted alteration or deactivation of genes. "The EU should follow the example of the US and UK and make it easier to cultivate genome-edited plants. Ultimately, we need to make future food production more efficient so that we can feed a growing global population in times of more frequent extreme climatic events. Hybrids that can produce higher yields and be made more robust with genetic scissors can make a contribution here," says Mercier.

Other researchers are therefore also calling for modernized genetic technology legislation in the EU that takes into consideration new techniques and findings, since the existing legislation is now more than 20 years old. A legislative proposal by the European Commission that would facilitate the approval of genome-edited plants was approved by the European Parliament at the beginning of the year. Now the EU member states have to agree on a final draft of the text for the legislation.

It is politicians who will therefore decide whether these kinds of plants will one day grow in the fields of Europe. Ultimately though, it depends on whether consumers would like to see genome-edited produce on their plates. Perhaps that decision might be influenced by the fact that the MiMe technique is not as unnatural as it might seem at first glance. The dandelion, and other plants such as various blackberries and grasses, reproduce in nature entirely without female meiosis or fertilization of the egg cell. Clearly, the yellow carpets of dandelions that appear on our meadows every spring are evidence of just how well this mode of reproduction works.

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

The charred ruins of a forest: the fire that raged in the Saxon and Bohemian Switzerland National Parks in 2022, consuming 1100 hectares of forest, reached the striking sandstone cliffs.

PHOTO: PICTURE ALLIANCE / DPA | ROBERT MICHAEL

WORKING WITH FIRE

TEXT: TOBIAS BEUCHERT AND PETER HERGERSBERG

Incidences of forest fires are increasing worldwide, including around the Mediterranean and in Germany. The main driver here can be attributed to the ongoing drought stress to which forests are exposed as a result of climate change. The Global Fire Monitoring Center, led by fire ecologist Johann Georg Goldammer, is pursuing new approaches to fire management.

In July 2022, wildfires burned large areas of the Saxon Switzerland and Bohemian Switzerland National Parks, which adjoin at the border between Germany and the Czech Republic. Arson struck a forest that was completely dried out and infested with bark beetles. More than a thousand firefighters battled a conflagration that broke out on the Czech side and eventually engulfed 1100 hectares of forest. Fabian Hälschke, the local fire chief of the Großschönau Fire Department, and his team drove their fire truck to Mezní Louka, 30 kilometers across the Czech border as soon as the alarm went off. When the firefighters could no longer get through the forest with their vehicle, they fought the flames on foot. "The fire had tremendous power. We were right in the middle of the vortex, which was sucking in oxygen, and we ended up having to run for our lives," recalls Hälschke. "When it became clear that we couldn't stop the fire in the forest, we wanted to at least save the village." They pumped as much water as they could into Mezní Louka. "It was like a battle," says Hälschke. As the experienced fire chief knows, even though the inferno in the Saxon-Bohemian border region in 2022 was exceptional, the number and intensity of forest fires have generally increased in recent years.

Vegetation fires on the rise

In 2022, more than 3000 hectares of forest burned in Germany, which is equivalent to the area of Borkum, the largest of the East Frisian islands. In 2018 and 2019, the figure was 2000 hectares. Even that is more than double the average for the years 1991 to 2017. And globally, the wildfire situation has worsened even more, according to a study published in Nature Ecology and Evolution in 2024. The study analyzed nearly 90 million satellite images of fires not only in forests, but also in shrublands and grasslands. According to this research, extreme vegetation fires are about twice as frequent and severe today as they were 20 years ago, with the last six to seven years being the most extreme. With climate change leading to more intense and prolonged droughts, more vegetation around the world is at risk of burning. Regions around the Mediterranean are particularly affected, as evidenced by the almost annual reports of devastating fires in Greece. Even Canada's vast coniferous forests are burning like never before. In 2023, for example, 17 million hectares of forest succumbed to fire in Canada. To put this in perspective, Germany's total forest area is just under 11 million hectares.

Johann Georg Goldammer, who heads the Global Fire Monitoring Center (GFMC) and the Fire Ecology Research Group in Freiburg, a branch of the Max Planck Institute for Chemistry in Mainz, is investigating how to combat fires in forests and agricultural areas. This vegetation fire expert has his office on the top floor of a former air control tower in Freiburg. This is the headquarters of the organization, which is active in nine locations worldwide. Behind Goldammer's desk, a map of the world takes up almost the entire wall. Contrary to its name, the Global Fire Monitoring Center's main task is not to monitor fires around the world. Rather, the GFMC pools knowledge on fire ecology and regional experience in dealing with vegetation fires. Goldammer and his team make this knowledge available primarily to decision-makers in public administration and politics – but also to those who deal directly with fire, such as firefighters, foresters, and farmers. At the invitation of governments in a number of countries, the GFMC has convened and moderated roundtable discussions for representatives of administrative bodies and civil society to develop national strategies for dealing with vegetation fires. In Greece, for example, Goldammer chairs the National Committee "Perspectives for the Future Management of Landscape Fires." The GFMC is also active in Ukraine. There, however, the Russian war of aggression interrupted the development of a national strategy. Ten years before the war, Goldammer had brought Ukraine and Russia together in Krasnoyarsk, Siberia, because fires often cross the border between the two countries. "All the coordination that was achieved between these countries is now going up in flames," Goldammer notes. His team in Ukraine is now recording war-related fires in forests and protected areas on a daily basis. Such missions in crisis areas are a hallmark of the GFMC. The center has also been working with the United Nations for years. The UN is now elevating the GFMC to the status of Global Fire Management Hub, making it a central international point of contact for all aspects of fire management.

SUMMARY

As a result of climate change, vegetation fires in natural and cultural landscapes are becoming more frequent and more severe all over the world – including in Germany.

The Global Fire Monitoring Center conducts research on fire ecology and integrates its findings into the practice of nature conservation and forest fire protection in Germany and worldwide.

Internationally, the GFMC works at the interface between science and policy. It supports multilateral organizations such as the United Nations.

"The fire had tremendous power. In the end, we had to run for our lives."

FABIAN HÄLSCHKE

PHOTO: DMYTRO GILITUKHA

Seeing through the thick smoke: Johann Georg Goldammer (front) trains firefighters in Ukraine on how to combat wildfires.

Johann Georg Goldammer has been researching how humans, the environment, and fire interact, mainly at the Max Planck Institute for Chemistry, since his Ph.D. thesis at the University of Freiburg in 1975 – entitled Feuerökologie (Fire Ecology). His work also involves investigating how people use fire in many cultures around the world. One such culture is in Ghana, where the GFMC has a regional center. "Here, fire is an important part of the ecosystem and agriculture," says Lucy Amissah, who runs the center. In the savanna that characterizes parts of Ghana, fire is part of the natural cycle of vegetation. "But farmers also prepare their land for planting by intentionally setting fires," says Amissah. "Some plants even need fire for their seeds to germinate." In Germany, too, Johann Georg Goldammer has introduced fire into nature conservation and landscape management – for example, to preserve dwarf shrub heaths. Controlled fires are used in place of mowing and grazing.

But fire can also be a means of fighting fire. To show how this works, Goldammer opens a massive iron door on the first floor of the Freiburg tower, emblazoned with stickers from fire departments in various countries, including South Africa. In the workshop behind it, bright yellow firefighting gear hangs on a clothes rack – alongside a bright red helmet that Goldammer wears on his missions around the world. The simple equipment needed to "manage" a fire is laid out on a workbench: Goldammer shows off a small metal bottle filled with a mixture of gasoline and diesel. With it, firefighters can ignite a backfire in front of a head fire, in order to take away fuel from the approaching flames. If the fire jumps, they extinguish it with a handy backpack pump that holds up to 20 liters of water. Finally, Goldammer shows a combination tool that resembles a garden hoe and can be used as a rake, a hoe, and an axe. It can be used to remove flammable vegetation from a firebreak. Such techniques are now included in guidelines for policy and practice in Germany. The fire ecologist and his team are also training German firefighters in hands-on firefighting techniques. For example, the insight that a narrow firebreak is more effective than large equipment and using up precious water is now widely known: "Over the past 20 years, fire departments have purchased a lot of large firefighting equipment," says Matthias Ott, head of the Department for Fire Services and Disaster Control Operations at the Bavarian State Ministry of the Interior. "The goal now is to use knowledge from other parts of the world about how to fight wildfires rather than blindly relying on technology."

The GMFC is not only there to fight fires, however; its main objective is prevention. Fire can also play a role in this, but more on that later. In Germany, preventing forest fires means restructuring forests. German forests have limited means to combat climate change and fire. A look at history shows why this is the case: since the late Middle Ages, many trees have fallen victim to slash-and-burn agriculture and logging, and after World War II, reparations were paid in the form of timber. "Considering the circumstances at the time, reforesting with fast-growing spruce was justifiable," says Goldammer. Today, spruce trees stand in rows in many places. They currently make up a quarter of the forest. But it's getting too warm and dry for spruces, and bark beetles often finish them off. What's more, other trees are also finding it increasingly difficult to cope with the drought. According to the annual national Forest Condition Survey, drought is already tearing holes in the canopy of about 80 percent of the forest. In turn, more sunlight falls on the forest floor, which dries out even more. This becomes a vicious cycle. Dead and dried-out trees are particularly vulnerable to fire.

Spreading the risk through forest conversion

There is a social consensus that forests should be preserved. They are part of the cultural landscape shaped by humans. Not only do they provide timber, but they can also promote biodiversity; protect settlements from floods, landslides, and avalanches; provide recreation; and sequester CO_2 – although nowhere near as much as humans release by burning fossil fuels. To ensure that forests can continue to perform their functions in the future, foresters are increasingly focusing on mixed forests. These forests are designed to contain at least 30 percent more drought-tolerant deciduous and coniferous trees, such as oak, beech, Douglas fir, and pine. The idea is to spread the risk: even if it gets too hot for one species, another may survive. "But even foresters have to be careful here," says Goldammer. There is no single answer to the question of what forests will look like in the future.

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PHOTO: GFMC

Landscape Fire Task Force: under the direction of Johann Georg Goldammer (front left), the Freiburg fire department practices setting a backfire on a harvested field.

To make matters worse, forests are a place in which a number of conflicting interests converge. For example, in Bavaria, the most densely forested state in Germany, more than half of forests are privately owned. Some of them are interested in high timber yields, while others seek to cultivate the largest possible game populations for hunting. Others, though, are more concerned with the forest's ability to perform all of its functions in a sustainable manner. This also happens to be the goal of the forestry services, which are responsible for the 30 percent of forests owned by the state. Fire departments, on the other hand, want to reduce the amount of highly flammable material, and some want a better-developed road network for their fire trucks. With all of these mixed interests, it is difficult to pursue a consistent strategy for forest conversion. While some see dead wood as a biodiversity hotspot, others see it as additional fuel. How to renew forests to reduce the risk of fire was the topic of a conference on vegetation fires held in the townhall of the spa town of Bad Kötzting, near Regensburg, last December. More than 130 representatives from the Bavarian forestry services, private owner associations, local authorities, state governments, and fire departments attended. "For the first time, we brought everyone together to talk about solutions," says Matthias Ott from the Bavarian Ministry of the Interior, who helped organize the conference. As the irony of climate change would have it, the meeting took place amid the chaotic snowstorms that paralyzed much of southern Germany in December 2023. Snow piled up several meters high overnight, bringing all local and long-distance transportation to a standstill. "In summer, not a drop of precipitation falls for weeks, and in winter it all comes down at once," said District Administrator Franz Löffler at the opening of the symposium.

Clear-cut firebreaks

Johann Georg Goldammer was invited as a keynote speaker. The respect that the other participants had for him as a forest fire expert was palpable. But he had come not only to share his knowledge, but also to listen – especially to the firefighters, who were easy to identify among the group. The invitation had stated: "For those with uniforms, the event will be held in uniform." Goldammer is fluent in the jargon of various interest groups, which makes it easy for him to talk to people in the field and get his message across to his audience. In his talk, he presented statistics on the forest fire situation and pictures of forests that are easy prey for the flames. Take the Harz Mountains, for example: hanging branches, more brown than green; spruce trunks

lying crisscrossed like matchsticks. The audience nodded. But what Goldammer really wanted was to offer a way out of the misery. He showed the audience a photo of a cross-section cut from the ground-level part of a pine trunk in the Siberian taiga. It was roughly the shape of a crescent moon and as long as a person's forearm. Fires had apparently repeatedly eaten into one side of the pine. Dents showed where the tree had tried to grow over the fire scars. The message: although the pine has been attacked by flames many times over the centuries, it had survived.

"Getting soot on our noses one day and standing in front of the United Nations the next day with a collar and tie"

JOHANN GEORG GOLDAMMER

Pines, along with larches and Douglas firs, could make Germany's forests more resistant to fire too. They have roots that reach water in deep soil layers and suffer less from drought than the shallow-rooted spruce. Goldammer also advocates the creation of clear-cut strips a few hundred meters wide at regular intervals in forests. The trees in these strips should be about ten meters apart – this does not stop forest fires, but it does prevent their uncontrolled spread. Siberian sparse forests can serve as a model. There, lightning repeatedly ignites fires to which the forest has adapted. Larches and pines are spaced far apart. This means that fires run out of steam quickly before reaching other trunks, and the trees end up not depleting each other's increasingly scarce water. However, sparse forest corridors must be intensively maintained and the undergrowth kept to a minimum. One option is to graze the firebreaks or mulch the grass regularly and process the undergrowth into pellets or wood chips as a renewable energy source. Alternatively, the low vegetation could be burned out as a preventive measure.

During his talk, Goldammer held up the red metal bottle that is usually kept in his materials warehouse in Freiburg. "This is almost everything you need," he said. It may sound surprising to intentionally utilize fire – an approach known as a "prescribed" or "controlled fire" – but fire management has a long tradition in Germany, for example, in the reclamation of agricultural land through slash-and-burn. In today's densely populated cultural landscape, however, greater caution is required when dealing with fire. After all, 99 percent of wildfires in Germany are caused by people, whether accidentally or on purpose. Sometimes all it takes is a spark from a combine harvester hitting a stone for a field of grain to catch fire. This not only threatens the harvest, but also spreads quickly to towns, villages, and forests. However, Germany does not record statistics on fires on agricultural land, with the result that they do not receive as much media attention as forest fires. This is a problem. "We have been observing for years that agricultural fires repeatedly occur on a massive scale," says fire chief Fabian Hälschke. And they cause a lot of damage.

Farmers as an auxiliary fire department

In the future, farmers may be able to help themselves if their fields catch fire. Participants at the Bad Kötzting conference were able to see how this might work in front of the town hall. There, a massive yellow steel cage had been set up, holding a tank with up to 1600 liters of water. Goldammer developed the concept with Welte, a company that manufactures forestry and other specialty vehicles. The idea is simple: the tank is quickly strapped onto a tractor, which takes it to the source of the fire. The fire can then be efficiently put out with an extinguishing lance that looks like the gun on a pressure washer. "Tractors are faster in the field than firefighters. Farmers can help us in such situations, and we can ensure their safety," said Sebastian Muth, District Fire Inspector from Kitzingen. Practical solutions for firefighting and prevention are just as much a part of Goldammer's team's work as appearing at conferences or talking to politicians: "Getting soot on our noses one day and standing in front of the United Nations the next day with a collar and tie – that's been our exciting routine for decades."

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

From the Siberian taiga: cross-section of a pine tree that has survived many fires. The numbers mark the years of big fires. In these places, the tree has grown over the fire scars.

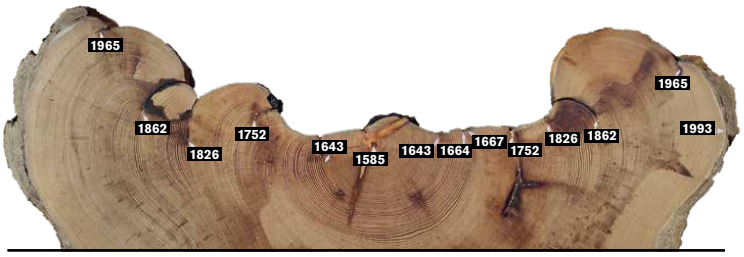


PHOTO: TOBIAS BELCHERT

Sometimes too little, sometimes too much: climate change brings both longer dry spells and more heavy rainfall. Water cannot seep away from parched or sealed surfaces, increasing the risk of flooding.

PHOTO: ADOBESTOCK

WATER ON A WAYWARD PATH

TEXT: JAN BERNDORFF

Drought and heavy rainfall – climate change is altering the planet's water cycles. That has considerable consequences for ecosystems and thus for our food supply. Max Planck researchers are refining climate models to better understand interrelationships, predict regional impacts, and enable adaptation to changing water availability.

In a good orchestra, all the parts – strings, wind, and percussion – harmonize to create a melodious experience. Research is no different, even if the result is more important than the experience. That is why nearly 50 research institutions from 11 countries have chosen this analogy for their major measurement campaign: Orcestra. The acronym stands for Organized Convection and Earthcare Studies over the Tropical Atlantic. In August and September, about 200 researchers and technicians collected data across the Atlantic Ocean between Cabo Verde off the coast of West Africa to Barbados just north of South America to find out how the climate and towering rain-bearing tropical clouds interact. It was an immense effort, spread over eight individual projects – the parts of the orchestra, so to speak – with acronyms named after musical instruments: Cello, Clarinet, Strings, and Percussion. The researchers use specially equipped research aircraft to make measurements above, in and around clouds; ships and ground stations to take measurements under them; and last but not least, the new Earthcare satellites to get a good overview from space. They make use of cameras, radar, lasers, autonomous probes, and everything else that technology has to offer.

SUMMARY

Climate change is altering the global water cycle. In particular, precipitation is being distributed differently: the Mediterranean region, for example, is experiencing longer and more intense droughts, as well as more and heavier downpours that cannot be absorbed by the soil.

Higher-resolution models make it possible to represent rain-forming processes much more physically and thereby simulate regional and local weather extremes missing from existing models. Measurement campaigns such as Orcestra are organized to help provide the data needed to fine tune these models.

The measurements and model predictions will enable societies to adapt to changes in water availability and prepare for extreme events.

A poorly understood climate driver

In addition to Max Planck Institutes, Helmholtz Centers, German University partners funded by the DFG, and Leibniz Institutes, the European Space Agency (Esa), the CNRS (France), and universities from various European countries and the US, as well as the Instituto Nacional de Meteorologia et Geofísica of Cabo Verde and the Caribbean Institute for Meteorology and Hydrology were all involved. "We are putting together a big orchestra to unravel the secrets of rain-bearing clouds," says Ulrike Kirchner, Research Operations Coordinator at the Max Planck Institute for Meteorology in Hamburg, which co-initiated the campaign. The goal is to gain a clearer picture of how and where rain forms and develops in the Intertropical Convergence Zone (ITCZ); how it and the clouds that accompany it influence the regional, but also the global water cycle and ultimately the climate; and how climate change is altering these processes.

The ITCZ is the zone near the equator where the trade winds from the north and south meet. They are part of a cycle that is important for the entire global climate: where the sun is highest, the air heats up the most and rises. As it rises, it cools to form towering clouds that gather and tower above the ocean in ferocious bands of rain. Above, the cooled, now dry air flows toward the edges of the tropical zone. There it sinks again, forming an area of high pressure, which usually means dry, hot weather: this is why there are so many deserts along the Tropics of Cancer and Capricorn. At ground level, the air flows back toward the equator as a trade wind.

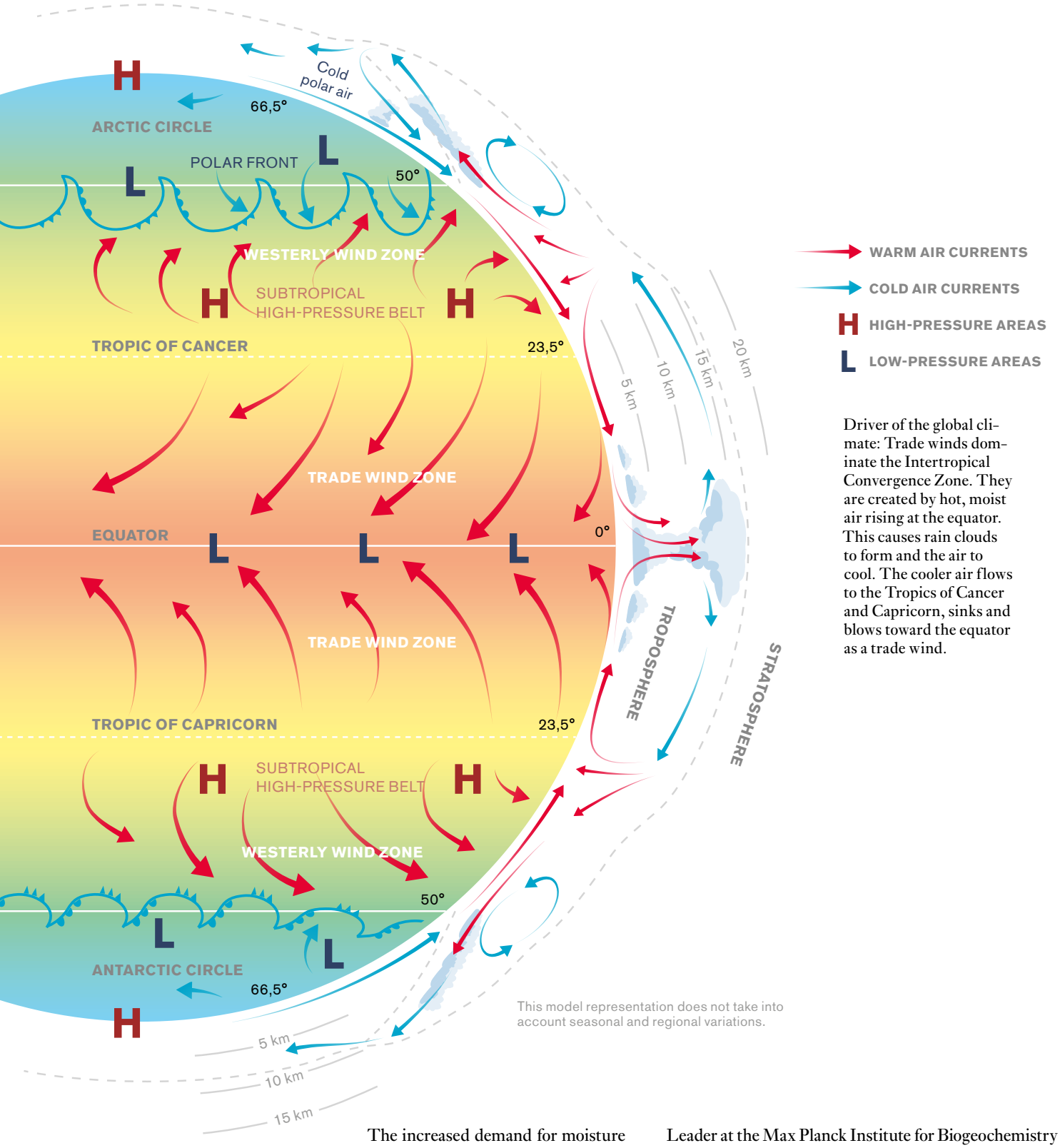
This pattern is known as the Hadley cell. It influences other cycles of air and water in the atmosphere that occur closer to the poles and determine weather around the globe. The driver of this process is in the ITCZ. "It's startling," says Bjorn Stevens, Director at the Max Planck Institute for Meteorology, "how little we understand this circulation system." The Orcestra campaign aims to change that and contribute to a better understanding of how the global climate changes.

These predictions are already alarming, as the reports of the Intergovernmental Panel on Climate Change (IPCC) make clear: by the end of this century, the global climate will have warmed by an average of 1.6 to 4.7 °C compared to pre-industrial times, depending on the amount of greenhouse gases humans continue to emit. These estimates seem conservative, as the world is already on track to be over 1.5 °C warmer in the present year. Warming intensifies the hydrological cycle as anyone who has experienced the difference between a tropical deluge and a northern European rain shower can attest. This will bring with it intensified heat waves, drought, and fire, but on other hand, storms, and floods too. Overall precipitation will increase, but it will be distributed differently.

"Soils will tend to become drier, even though there is no reduction in rainfall."

RENÉ ORTH

GRAPHIC: *GEO* BASED ON WESTERMANN



This model representation does not take into account seasonal and regional variations.

Driver of the global climate: Trade winds dominate the Intertropical Convergence Zone. They are created by hot, moist air rising at the equator. This causes rain clouds to form and the air to cool. The cooler air flows to the Tropics of Cancer and Capricorn, sinks and blows toward the equator as a trade wind.

The increased demand for moisture as a result of a warmer atmosphere means soil moisture is likely to decrease in many regions of the world, including Europe, especially in the Mediterranean region. This effect may be compounded by soils that have been dried out by prolonged hot spells and are unable to absorb the heavy rainfall, leading to more runoff and less replenishment. "Soils will tend to become drier, even though there is no reduction in rainfall," says climate researcher René Orth, former Research Group Leader at the Max Planck Institute for Biogeochemistry and now a professor at the University of Freiburg.

Various weather-related disasters in recent years have shown what this can mean. Although individual events cannot be clearly attributed to climate change, some researchers are attempting to quantify how much more likely a particular heat wave or heavy rainfall has become as a result of global warming. The crux of the matter is that to be prepared, people naturally want to know ex-

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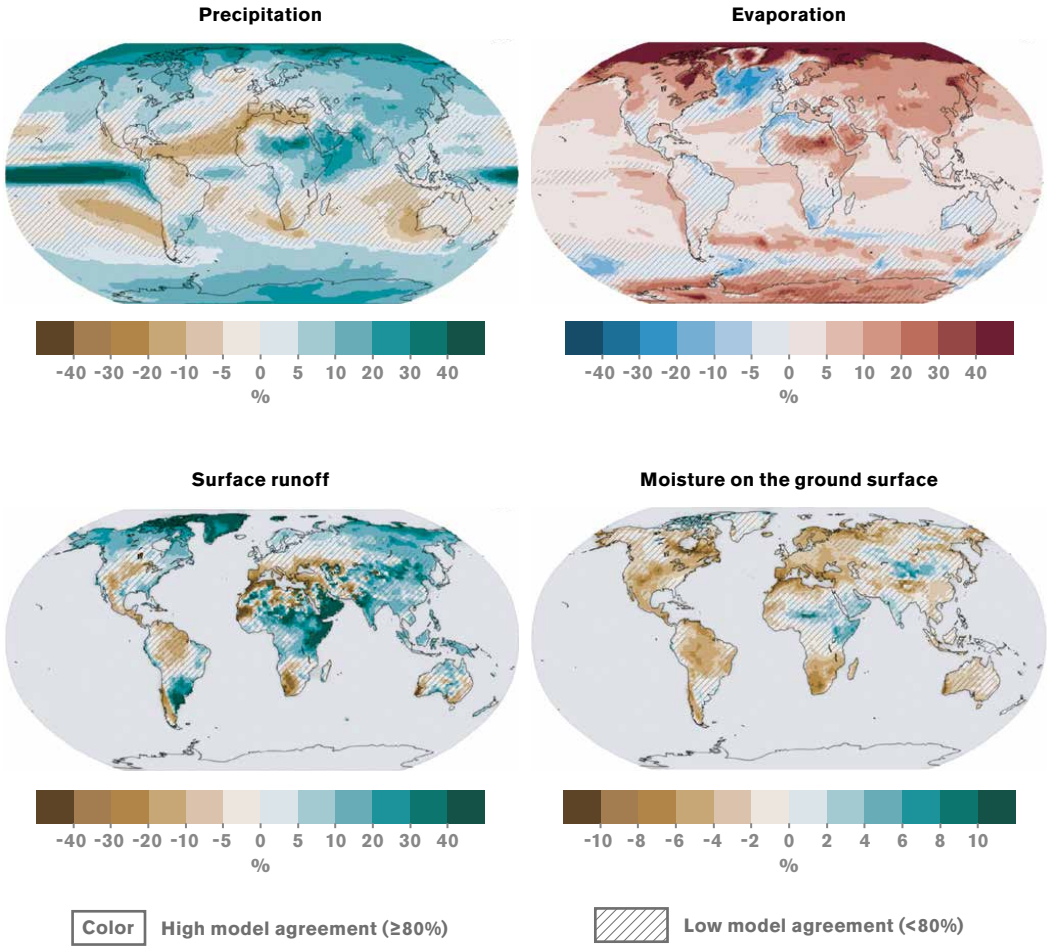

Climate change: by the end of the century, the global water cycle will have changed, in some cases drastically, compared to the average of the years 1995 to 2014, according to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. This will affect amounts of precipitation, evaporation, surface runoff, and soil moisture (scenarios of global warming 3 °C above pre-industrial levels).

GRAPHIC: GCO BASED ON BOX TS.6, FIGURE 1 IN IPCC, 2021: TECHNICAL

actly where and when such natural disasters are likely to occur and how much water will be available. And not just when a storm or drought is approaching. But that's not something attribution science, or today's climate models can deliver.

The specific consequences of these climate impacts vary greatly from place to place. Global climate models typically have a resolution of only 100 to 150 kilometers. And this means that many essential processes in climate models must be calculated empirically, rather than through the use of basic physical principles. Much finer computations are possible, allowing a more physical representation of the climate system, but climate researchers have not had the dedicated access to the most powerful computers needed to perform much finer computations. But things are changing thanks to new supercomputers and artificial intelligence: global models with a resolution of a few kilometers are beginning to be developed and used – by many of the same people participating in Orcestra. What they are missing is the data needed for their evaluation and fine-tuning – this is where Orcestra comes in.

Eurec4a, a similarly complex measurement campaign that took place in Barbados in 2020 and which demonstrated new measurement approaches on which Orcestra is based, has already delivered a surprise (see MaxPlanckResearch 1/2024): until now, models showed that global warming should lead to a decrease in trade wind clouds – the typical low, fleecy clouds that populate the trade winds. Because these clouds reflect much of the Sun's energy back into space, their decline would heat the Earth even more. But Eurec4a has shown that there has not been a reduction in cloud formation.

Thunderstorms in climate models

Orcestra will now study the high, dark thunderclouds of the ITCZ. How and where do they cluster? This process, which is crucial for understanding how they influence rain formation and attract winds, is not only central to understanding the climate in the tropics, but worldwide. Nonetheless it's a process entirely ne-

glected by the types of climate models on which international assessment are made. It's quite an amazing fact considering that 30 percent of all the rain on Earth falls from these clouds, and that they form the seeds tropical cyclones (hurricanes and typhoons), which cause enormous damage in temperate zones as well.

Atmospheric scientist Cathy Hohenegger's research group at the Max Planck Institute for Meteorology specializes in thunderstorms. She notes that it is still unclear how they will change in our latitudes as a result of global warming. Current models predict that they will become more frequent and severe. "But we don't have a clear idea because we can't simulate thunderstorms in a global context with existing models. The resolution of these models isn't high enough. So far, the models can only guess where thunderstorms will occur based on rules of thumb." However, the researchers have now developed a new model that can simulate the climate globally with a resolution of five kilometers or even finer: "This finally makes it possible to study individual thunderstorms and their interaction with large-scale circulation." With these more detailed models, the team hopes to answer questions such as whether thunderstorms get their moisture primarily from evaporation from soil, water, and plants or from larger-scale atmospheric circulation. Previous models suggest the former, but the new model suggests the latter. "This has implications for the importance of land use," says Hohenegger. "It would mean that changes in surface conditions, such as deforestation, do not affect the frequency and intensity of thunderstorms as much as previously thought." Conversely, of course, changes in the frequency and intensity of thunderstorms have direct consequences for our land use – especially in the world's arid regions. "The dry seasons there are already getting longer and the rainfall more intense," says Hohenegger. This is disastrous for agriculture, on which many people in these regions depend. The soil dries out more, and when it rains heavily, the masses of water wash everything away.

"We need to take action if we don't want to destroy our livelihoods."

SUSAN TRUMBORE

A correlation between land use and rainfall distribution can be seen in the Amazon rainforest in Brazil. Experts from the Max Planck Institute for Biogeochemistry in Jena are measuring the water and carbon cycles both in the middle of the remaining, still intact rainforest and in a region where slash-and-burn agriculture and deforestation have already destroyed large parts of the rainforest. The latter is now home, at best, to secondary forests, but mostly to soybean farms and other plantations or livestock farms (see MaxPlanckResearch 4/2019). This is the case of the Tanguro Ranch in the state of Mato Grosso, where we can clearly see the impact of human intervention. "Tanguro is the place where we first tested the prediction that the rainforest will gradually turn into savanna as a result of global warming and overexploitation," says Susan Trumbore, Director at the Max Planck Institute for Biogeochemistry in Jena. Mato Grosso is a heavily agricultural state, and much of the forest has been cleared to make way for cattle pastures and plantations. But because crops and grasses allow less rain to evaporate from their surfaces and do not draw water from deeper underground, they produce much less evaporative cooling than trees. This causes the temperature to rise in addition to general global warming. "In fact, this thermal effect of land use in the region is as strong as the global greenhouse effect," says Trumbore.

More fires in the Amazon

Less evaporation on cultivated land also reduces rainfall, with consequences for the remaining forest and for agriculture itself, which is exposed to higher risks and faces economic losses. In addition, more water runs off the surface and heats up because there are no trees to provide shade. The warmer water affects fish and other animals in the rivers. "We originally identified the impact of agricultural fertilizers in bodies of water, but it turns out that the warming and increased risk of flooding are much more serious," says Trumbore.

At the edges of the remaining forests, the added heat and lower humidity are leading to greater drought stress. "The least drought-tolerant tree species will die out and be replaced by generalists," says Trumbore. However, some functions of the former forest, such as cooling, remain largely intact even in a damaged forest. "That means that a damaged forest is better than no forest at all," she says. However, drier conditions increase the likelihood that fires will break out and destroy sensitive forests. For example, especially devastating fires raged in the Amazon rainforest in 2023 and 2024 and will continue to do so as the increasing drought caused by climate change is exacerbated by the El Niño phenomenon. "The big question is what will happen to the damaged forests," says Trumbore. "Under what conditions can they recover, and how long will it take? And if their condition continues to deteriorate, what does that mean for agriculture and the climate in the region?"

The interplay between vegetation and the water cycle is the subject of another project involving the Max Planck Institute for Biogeochemistry, this one focusing on the effects of climate change in Germany. At the edge of the

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Hainich beech forest in Thuringia, researchers led by the University of Jena are investigating the extent to which water, soluble solids, and gases such as CO_2 are exchanged between vegetation, differently managed soils, and groundwater. For example, plant compounds predominate in the water at the top of the soil, while microbial compounds dominate in the groundwater. "This shows the breakdown of substances by the many microorganisms as they seep downward," explains Susan Trumbore. However, the difference between near-surface and deep water has become significantly smaller over the 12 years that measurements have been taken at this site. "This shows that the filtering effect is diminishing," says Trumbore. The researchers attribute this in part to more frequent heavy rains: large amounts of water seep through more quickly, and the microbes do not have enough time to do their work. As a result, not only do more plant substances get into the groundwater, but pollutants such as pesticides and nitrates from agriculture too. Due to increased evaporation rates and changes in the distribution of precipitation, groundwater levels do not simply sink, as can be seen in many parts of Germany and elsewhere in the world, water purity also suffers. And with it, the quality of our drinking water, some 70 percent of which in Germany comes from groundwater.

Hainich also shows that forests depend on groundwater – especially in dry periods. Even then, deep-rooted trees can still draw water from intact groundwater reservoirs. The researchers are investigating how deep the root system can reach. They can then estimate how far the water table can drop before the forest canopy is affected. In other words, the planet's vegetation, and thus the cultivation of crops, can adapt to some extent to the changes brought about by climate change. But the balance is becoming increasingly fragile. This has been confirmed by studies conducted by René Orth during his time at the Max Planck Institute for Biogeochemistry: with his group, he used 40 years of satellite data to investigate the extent to which vegetation activity – expressed as leaf area – is related to near-surface soil moisture, which can also be measured by satellite. In other words, he looked at how tolerant plants are to changes in water availability. "The result was that plants are becoming increasingly sensitive," says Orth. Although many species are extremely adaptable, certain species are simply replaced by others. But the climate is apparently changing so much, or so fast, that at some point it will exceed their tolerance – with implications for our drinking water and food supplies.

More accurate predictions of extreme events

A group led by Markus Reichstein, another Director at the Max Planck Institute for Biogeochemistry, is also working on better predicting the consequences of climate change, especially extreme events such as droughts and heavy rainfall (see MaxPlanckResearch

An eye for clouds: the Earthcare satellite, launched by the European and Japanese space agencies in late May 2024, monitors the extent to which clouds and aerosols reflect sunlight back into space or contribute to the greenhouse effect.

IMAGE: ESA / P. CARRIL, 2013

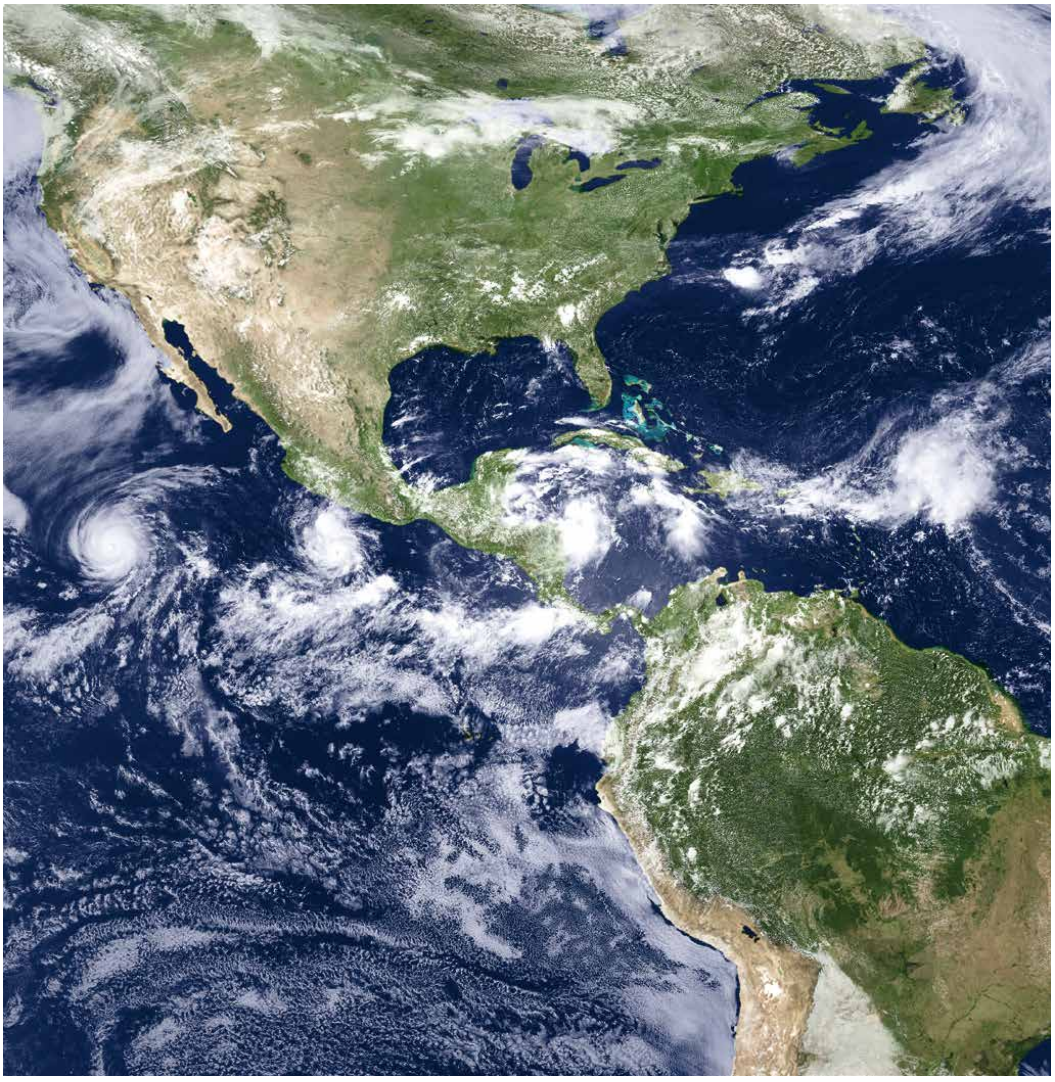

PHOTO: NOAA

A hotbed of hurricanes: this image from the EWS-G1 satellite shows two hurricanes west of Central America and a disturbance in the Caribbean that could develop into a tropical storm.

GLOSSARY

INTERTROPICAL CONVERGENCE ZONE (ITCZ) is the name of a zone near the equator where trade winds from the north and south meet and influence the global climate. The trade winds are part of a cycle called the Hadley cell: at the equator, air heats up, rises, cools, and forms rain clouds. Up above, the cooled, dry air flows to the northern and southern edges of the tropics. There it sinks again and flows back to the equator as a trade wind.

ORCESTRA is a measurement campaign involving nearly 50 research institutions from 11 countries. They use methods including ships, aircraft, and remote sensing to investigate how thunderclouds form in the ITCZ, from which about 30 percent of the world's rain falls, and how climate change affects their formation.

1/2021). "With data such as that from the ESA's Sentinel satellites, which provide measurements of the atmosphere and the Earth's surface with an accuracy of 10 to 20 meters, increasingly precise forecasts will be possible – for individual cities, forest areas, agricultural fields, and even your own yard," the geoecologist promises. His department is also researching the interplay between climate extremes and societies, combining high-resolution models and AI. One objective is to allow organizations such as the Red Cross to prepare international relief missions based on forecasts of storms, droughts, and floods even before the disasters show up on weather radar. "In regions that the models identify as particularly vulnerable, they can send a team in advance to set up relief infrastructure," says Reichstein. Based on past experience, this approach also produces false alarms, but ultimately saves a lot of damage costs. The goal now is to make the models more reliable and accurate. "We are currently training our AI with landscape data and climate conditions from the past to develop scenarios of the problems that certain regions can expect with warming of one or two degrees."

Ideally, humanity will not let it get that far and will curb both global warming and the active destruction of forests. While the links between climate change, water cycles, ecosystems, and society are not yet fully understood, says Trumbore, it is clear that evolution has not prepared our ecosystems for changes like these. "Our research is a clear indication that we need to take action if we don't want to destroy our livelihoods. If you are heading toward a precipice, you should at least slow down."

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

If you want to carry out research in Marburg, you literally have to climb mountains. It is not for nothing that the site on which the university and various research facilities are located is called "Campus Lahnberge." And so, if you want to cycle to the Max Planck Institute for Terrestrial Microbiology, you might get a little out of breath. But not Katharina Höfer – for her, it's routine.

TEXT: CATARINA PIETSCHMANN

Every morning, Katharina Höfer zips down the steep alleys of Marburg's Oberstadt on her gravel bike and then rides six kilometers through the forest, up and down hills, to the Max Planck Institute for Terrestrial Microbiology. "I have to climb 200 meters on my route. That keeps me in shape, much more than the distance itself," says the microbiologist. She also gets her best ideas while riding. As soon as she arrives at the Institute, she parks her bike in front of her desk and jumps in the shower. Clothes and up to six pairs of shoes – from comfortable to chic – are then on hand to start the day.

Höfer has been conducting research with her working group at the Max Planck Institute in Marburg since 2020. She is also associated with the Center for Synthetic Microbiology, a unique joint venture between Philipps University Marburg and the Max Planck Institute for Terrestrial Microbiology, and was recently appointed as Loewe Top Professor at Philipps University.

Höfer comes from a town of 200 near Nordhausen in northern Thuringia. She was born three years before German reunification. At the age of 18, she graduated from high school and packed her bags to study molecular biology, microbiology, and organic chemistry in Hanover. She first took up residence in a dormitory – in a small room measuring 11 square meters, with more than 20 roommates per corridor. Privacy and quiet time for studying were the exception. Six months later, she moved into a shared apartment with a fellow student. The degree program was time-consuming and demanding. Her student loan, child benefit, and some money from a part-time job gave her just enough to live on.

After graduating, she was initially unsure whether she should stay in academic research or go into industry. And so, she completed an internship at the biomedical company Miltenyi Biotec in Bergisch Gladbach. She isolated and cloned proteins there and had bacteria produce them. The proteins were then attached to magnetic particles so that certain cell types that bind to the proteins could be fished out of a solution — just like using a fishing rod. Today, the Miltenyi system is used in many immunology laboratories. "I really enjoyed putting all the theoretical knowledge from my studies into practice." After a further internship at the German Primate Center in Göttingen, she took on a master's degree in molecular biotechnology in Andres Jäschke's laboratory at the University of Hei-

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VISIT TO

KATHARINA HÖFER

PHOTO: CHRISTOPH SEELBACH FOR MPG

Katharina Höfer with a gift from her team: her cardboard superwoman doppelganger.

delberg. She was so fascinated by the research there that she followed up her master's degree with a doctorate, booking the "lifetime ticket," as she refers to it. The idea for the first project of her doctoral thesis, visualizing RNA formation in real time, came to her in the shower – back when she didn't have to cycle up any hills to her Institute. For her project, she used spinach RNA – an artificial RNA molecule that can make small molecules glow. The intensity of the fluorescence can be measured and used to calculate the amount of RNA formed. This method already works in living cells. Höfer was able to demonstrate that the technique also works in the test tube, outside of cells. Her research on RNA brought her into contact with BioNTech employees. BioNTech – then a small and unknown start-up, later to become one of the first developers of a coronavirus vaccine – was interested in her method and still uses it today. "This still makes me proud."

From then on, Höfer never let go of RNA. She wanted to develop a method with which she could isolate RNA molecules from cells that have the building block NAD (nicotinamide adenine dinucleotide). Together with her colleagues in Jäschke's team, she searched for such NAD-RNA molecules. In 2015, the researchers published a study in the renowned journal Nature, demonstrating that NAD in bacteria can act like a protective cap, shielding molecules from degradation. She also succeeded in finding the

PHOTO: CHRISTOPH SEELBACH FOR MPG

enzymes that cleave NAD. After completing her dissertation, she received postdoctoral scholarships from the Carl Zeiss Foundation and the Baden-Württemberg Foundation. She investigated whether the NAD molecule can link RNA with proteins. She and her research group later succeeded in proving and discovering the mechanisms for this at the Max Planck Institute in Marburg. This process is known today as RNAylation. It is an enzymatic reaction occurring in bacteria that are infected with viruses, known as bacteriophages. In the process, RNA molecules are firmly linked with proteins, creating entirely new biomolecules. Höfer and her group in Marburg are now researching what functions these have. What's particularly striking here is that the protein factories of bacterial cells, the ribosomes, are being connected with RNA. It is possible that bacteriophages can regulate the production of their own proteins during an infection.

But back to Höfer's scientific career: after her postdoc, she wanted to climb to the next level in academia and set up her own research group. She weighed several offers before choosing the Max Planck Free-Floater Research Group Program: this presented the opportunity for her and her team to move to a Max Planck Institute of her choice after the start-up phase. She opted for Marburg and has since concentrated on researching bacteriophages. Having received little attention for many years, these viruses have once again become the focus of research in recent years because they are effective killers. Some can kill a bacterial cell within 30 minutes – an ability that makes them increasingly interesting for medicine in times of rampant antibiotic resistance. At the Max Planck Institute, Höfer wants to find out how gene transcription and protein production change after a phage infection. "Phages have fascinating properties," she says. "These could help us in the fight against bacterial infections. But there is still a long way to go before they can be used for medical purposes."

Katharina Höfer prefers to get around by bike – whether on vacation or on her way to work. On her gravel bike, she can also tackle bumpy forest paths in the Marburg area.

"Cycling tours give me a real sense of freedom."

She has been researching RNA since 2009. "A really long relationship," she says with a smile. Her first doctoral researchers have already been awarded their doctorates. The biggest challenge will be to find out what the almost 200 known RNA modifications actually do in a cell. This will probably keep a whole generation of scientists busy. "We won't know for at least ten years whether they can trigger diseases, for example. If so, we'll found a start-up for sure!" Then she would no longer be torn between academic and applied research: she would simply do both!

As a group leader, she is constantly on the go attending lectures and conferences and is busy providing 15 employees with new ideas and supporting them with her experience. She also has to keep an eye on the specialist literature so as not to miss any devel-

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IMAGE: SCIENCE PHOTO LIBRARY / BIOZENTRUM / UNIVERSITY OF BASEL

Electron micrograph of a T4 bacteriophage (orange). Bacteriophages are viruses that infect bacteria. T4 exclusively infects Escherichia coli (blue). Its angular head part consists of proteins and contains a DNA molecule; other proteins form the tail part. The virus attaches itself to the bacterial cell with stilt-shaped proteins and injects its DNA. This no longer produces only its own proteins, but also viral proteins. After 30 minutes, countless new viruses are released, and the bacterium dies.

opments in this rapidly evolving field of research. To make her happy, one shouldn't give her a book, but rather invite her on a hike or bike ride, or to a barbecue. "When I hear the word barbecue, my Thuringian heart immediately beats faster. Of course, I get the sausages sent to me from home."

She has also always been an "outdoor child." Walking through the forest with her grandpa and sister, sorting potatoes by size – that was more her thing than poring over books. "I was at home in mud! I already needed a change of clothes before breakfast had even begun." In summer, she got up at 6:00 AM and let the chickens out of the coop. Being close to nature is still important to her today. She has crossed the Alps on foot several times. This summer, she completed the 300 kilometers and 3000 vertical meters of the Salzkammergut cycle route. "I really enjoy tours like this, they give me a real sense of freedom. And the steep alleyways of Marburg's old town are the best training for this!"

"In ten years' time, we will know whether changes in RNA can trigger diseases."

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IMAGE: FROM: AMERICA DE BRY, ED. GEREON SIEVERNICH, BERLIN/NEW YORK 1990 P. 176

DOUBLE TAKE

BIBLIOTHECA HERTZIANA, MAX PLANCK INSTITUTE FOR ART HISTORY

Precious jewelry, vessels, and other art objects were collected by the Spanish conquistadors in the Americas during the 16th century. Theodor de Bry's copperplate engraving from 1594 (left) shows an Inca prince in what is now Panama in front of General de Balboa. The conquistadors had many of these works of art melted down and shipped off, some in the form of flat discs about 12 cm in diameter (right), marked with royal Spanish tax and coinage stamps. The "XIX" stamp with the three dots shows that the disc is 19 ¾ carats. Art historians in Rome are investigating how art objects were moved, modified, and reclassified as a result of the conflicts in the early modern period. They are also discovering the treasures that were thus irrevocably lost in the melting pot.

IMAGE: THE THOMSON COLLECTION AT THE ART GALLERY OF ONTARIO

DIVERSITY IN THE SAND

TEXT: NORA LESSING

Marine microorganisms play an instrumental role in Earth's elemental cycles: among other things, they help to maintain the ocean's role as a climate buffer. Katrin Knittel and her team at the Max Planck Institute for Marine Microbiology in Bremen study bacterial communities on the ocean floor in one of the planet's most inhospitable regions: the Arctic.

An icy wind howls along the coast of Spitsbergen. Snow covers the shore, the valleys, and the mountains. In the distance, the ghostly silhouette of a polar bear moves along the coastline, barely visible under the ship's spotlight. It's Christmastime on Isfjorden near Longyearbyen, and the Arctic darkness reigns 24 hours a day. The researchers are aboard a small ship, 5 meters wide and 15 meters long, as waves splash against the bow. Equipped with headlamps, they lower a custom-built sediment grab into the water. They call it the "Ellrott Grab," named after its inventor, Andreas Ellrott, an engineer at the Max Planck Institute in Bremen. With this device, the researchers can collect sediment samples without disturbing them or losing the porewater – that is, the water in the spaces between sediment grains. The grab is small and light, perfectly suited for the compact research vessel. With the help of a camera the researchers ensure that the device touches down gently on the ocean floor. In one smooth motion, the grab collects the sample: sand from the ocean floor, covered by a thin layer of water. A lid seals the sample before the researchers pull it back aboard.

To the naked eye, the sediment sample does not look like anything out of the ordinary – algae, grains of sand in various sizes and colors, and gray-brown silt. But under a microscope, it reveals astonishing biodiversity. "Between 100 million and several billion microorganisms belonging to thousands of different species live in a single gram of sediment," explains Katrin Knittel, Project Leader in the Department of Molecular Ecology at the Max Planck Institute for Marine Microbiology in Bremen. No matter

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PHOTO: FANNI ASPETSBERGER/MPI FOR MARINE MICROBIOLOGY

KNOWLEDGE FROM

BIOLOGY & MEDICINE

Over 100 kilometers in length, Isfjorden on the west coast of Spitsbergen is one of the largest fjords on the island. Researchers at the Max Planck Institute for Marine Microbiology have chartered the 15-meter-long MS Farm on a regular basis in the past three decades to collect water and sediment samples for study in the lab.

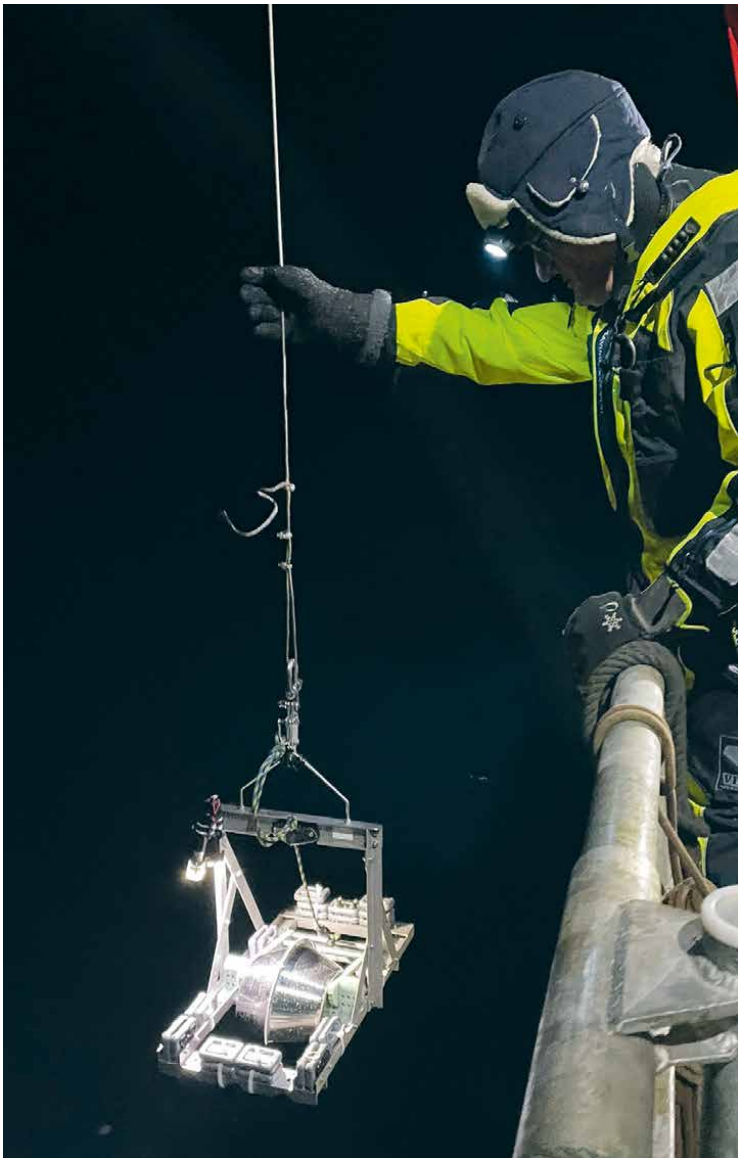

PHOTO: KATRIN KNITTEL/MPI FOR MARINE MICROBIOLOGY

During the polar night in Isfjorden, Dirk de Beer uses a small crane to lower the Ellrott grab into the water. The device is a sediment sampler designed by the researchers. It is equipped with a flashlight and a camera to illuminate and view the seabed and the surrounding area, and to ensure that the device touches down on the sediment gently. Weights stabilize the device during sampling.

where she and her team cast the grab; the sediment is always bursting with a diverse array of microorganisms, each playing a distinct role in a delicately balanced ecosystem.

Bacteria are tiny compared to a grain of sand; most are only 0.001 millimeters in size. To a bacterium, a grain of sand is like a little planet, with valleys, hills, chasms, and cracks. Many bacteria settle there gladly because the terrain offers protection from currents, abrasion, and predators. A single grain of sand can host up to 100,000 bacteria from 3000 to 6000 species. Sometimes bacteria settle side by side, while in other cases they leave vast, uninhabited regions. The reason behind this remains a mystery. Another surprising discovery: unlike in other habitats, bacteria rarely form monospecific colonies on grains of sand. On the contrary, different species often thrive side by side in close proximity.

Contrasting lifestyles

Chyrene Moncada's doctoral thesis examines which microorganisms live where in the sediment and under what conditions. She counts the cells, identifies the different species, and analyzes their metabolisms. Moncada has developed a method to divide the bacteria into three groups based on their lifestyle in the sand: firmly attached bacteria, loosely attached bacteria, and porewater bacteria. The first are firmly attached to grains of sand and can only be separated by means of ultrasonication. They make up around 85 percent of all the microbes in the sediment, but are often less active than the other groups of bacteria, and usually reproduce slowly. The loosely attached bacteria also sit on grains of sand, but can be shaken off. These bacteria appear to be very active. They consume oxygen and process food more quickly than their firmly attached neighbors. The third group lives in the water between grains of sand, known as porewater. This group is among the most active in Moncada's experiments. "The bacteria in the porewater have first access to fresh nutrients from the environment," explains the microbiologist. "The loosely and firmly attached bacteria then process what the porewater bacteria leave behind."

The porewater bacteria therefore have a locational advantage: food that sinks down from the water column above is immediately available to them. It would be reasonable then to expect these bacteria to be especially numerous. However, this is not the case. "There are far fewer bacteria in the porewater than on the grains of sand," says Moncada. "We speculate that they are eaten by grazing and filter-feeding animals or flushed out by currents." Any bacteria feasting on the plentiful food in the porewater clearly

do so at their own constant peril. The firmly attached bacteria that hunker down in the grain's cracks and fissures have opted for a safer neighborhood. However, less food arrives there. "They are safer and won't get washed away. But the competition with neighbors may be fiercer," adds Moncada.

In the bacterial communities that form on and around the grains of sand, cooperation plays a key role, perhaps even more so than competition. Sebastián Silva-Solar's doctoral thesis examines how these habitats are populated by different species and how the species deal with competition. His experiments involve mixing seawater with sterilized grains of sand and observing how different species of bacteria gradually colonize the surface or the cracks in a grain of sand. The first to arrive might possibly determine who settles there next. "I imagine this to be like the reseeding of an area covered in ashes after a volcanic eruption: at first there's nothing there. Over time, grass and bushes take root, creating the preconditions for other species to move in."

One striking example of cooperation is how bacteria break down sugar. On the one hand, there is a "selfish" uptake method. The microorganisms use surface enzymes to grab sugar molecules, partially split them into smaller molecules, and transport them through their outer cell membrane. In the space between the outer and inner cell membrane, the sugar is further broken down and then taken into the cell. "Few or no degradation products are released into the environment, thus the food is protected from competitors," explains Katrin Knittel. On the other hand, some bacteria break down the sugar entirely outside the cell. The resulting degradation products can then also be used by other microorganisms. "The 'selfish' degradation pathway is rare in the sediment. The microorganisms here maintain a good neighborly relationship — they share," says Knittel. "The bacteria cohabiting in a confined space produce a cocktail of enzymes that breaks down sugar molecules and makes them available to the community." However, the details on which species indulge in this "communist behavior" remain unclear. "The majority of the species that we find in seawater have not yet been cultivated in a lab," explains Knittel. Nevertheless, it is possible to study these bacteria and their role in the ecosystem. "We have developed a range of research methods that don't require us to keep the species in the lab. Genetic analysis of the sediment communities reveals, for example, the individual capabilities of organisms to break down sugars." Furthermore, it is often the case that the decisive factor is the community as a whole rather than the individual species.

Summers like winters

Another research focus of Knittel and her team is how the complex bacterial community on the ocean floor reacts to changing environmental conditions. This ocean floor community has been shown to be surprisingly stable. The researchers went to sea and took samples during different seasons – in summer and winter, under the midnight sun and in the polar night. At first glance, the bacterial community composition hardly changed, despite the significant changes in the type and amount of sinking organic material (e.g., because algae, needing sunlight to grow, are hardly found during the dark season). While the bacterial community in the open water changes and adjusts with the changing seasons, the community composition in the sediments seems hardly affected by the change of spring, summer, fall, and winter. "The diversity of species and the number of individuals per species remains very stable throughout the year," explains Knittel. But are the sand bacteria really indifferent to the seasons, the midnight sun, and the polar night? A closer look revealed that some species were more active at certain times, even if the number of residents on the sand grains hardly changed. This raises the question: could seasonal changes in enzyme activity be linked

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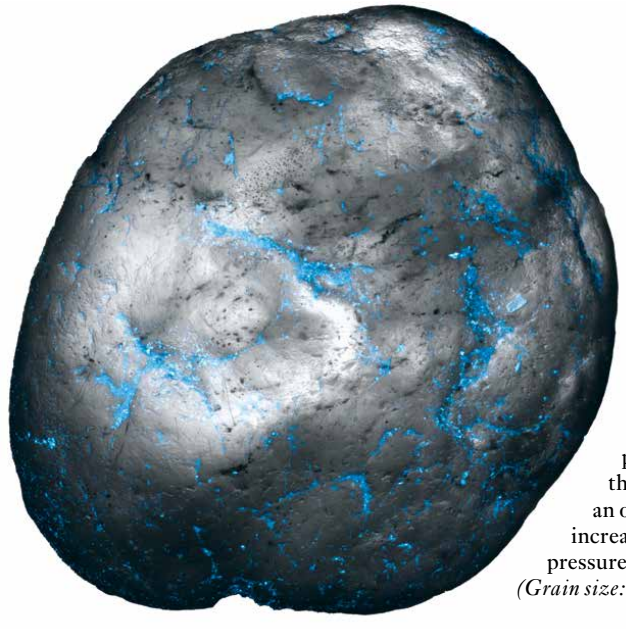

PHOTO: SEBASTIÁN SILVA-SOLAR/MPI FOR MARINE MICROBIOLOGY

Microorganisms (blue) attached to grains of sand prefer to settle in cracks and hollows in the grains, where they are protected from environmental influences and predators. However, they have to cope with an oxygen shortage and increased competitive pressure from other species. *(Grain size: 0.5 millimeters)*

SUMMARY

The coastal ocean floor harbors an incredibly diverse range of microorganisms. Up to 100,000 bacteria belonging to thousands of species can live on a single grain of sand.

The bacterial community in the seabed near the coast remains remarkably stable regardless of seasonal changes in food supply. The more diverse the community, the better its protection against disruptions. However, it remains unclear how these communities will cope with rising water temperatures and the acidification and pollution of the oceans in the long term.

PHOTO: FANNI ASPETSBERGER/MPI FOR MARINE MICROBIOLOGY

After taking a sample in Isfjorden, Chyrene Moncada hauls the Ellrott grab back on board and checks whether the sample collection was successful.

to the varying types of food available on the ocean floor?

Genes for breaking down sugar

To answer this question, the researchers from Bremen examined which genes the bacteria possess for breaking down algal sugars and to what extent they use these genes. Sure enough, they found clearer differences here compared to the composition of the bacterial community. Especially in spring and summer, when fresh material sinks down from the water, the sediment bacteria quickly take advantage of it. In addition, they possess the enzymes needed to consume the material that is present year-round or produced on the ocean floor, such as animal mucus and chitin. This, the bacteria nibble on all year long and it is especially important in winter, when other food sources are lacking. The long-term availability of these substances on the ocean floor stabilizes the local bacterial community as a whole. "The enzymes reflect which algal sugars are available to the bacteria at different times of year," explains Knittel. "It's not so different from when we go to the farmers' market. In summer, there are lots of different local fresh fruits and vegetables for sale, but at some point in winter there's nothing left but potatoes from the cellar." The researchers suspect that the fluctuating availability of food affects mainly the porewater bacteria and loosely attached bacteria, but not so much their firmly attached neighbors.

It remains to be seen how this apparently robust ecosystem will respond to climate change. In polar regions such as Spitsbergen, this change is particularly dramatic. Researchers still know too little about how rising temperatures and changes in marine chemistry will affect life on the ocean floor. But the insights gained by Knittel and her team are a beacon of hope. The findings reveal a highly diverse bacterial community, and ecosystems with higher biodiversity are more resilient to environmental pressures. A healthy ecosystem can serve as a buffer for environmental fluctuations, even when several factors fall out of balance in the short term. Bacteria in the ocean could counteract climate change by, for example, decomposing environmentally damaging methane gas, which bubbles up from the seabed in various places. Nevertheless, Knittel stresses: "Like any ecosystem, this one has its limits. If its delicate balance is disrupted long enough, it will eventually reach its capacity."

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Fuel for the energy revolution: plants such as this one belonging to Evonik in the town of Marl in North Rhine-Westphalia can generate hydrogen using surplus electricity from wind and solar plants. When combined with CO_2, hydrogen can generate synthetic fuels and raw materials such as methane for the chemical industry.

PHOTO: PICTURE ALLIANCE/SVENSIMON | MALTE OSSOWSKI

FROM POLLUTANT TO RAW MATERIAL

TEXT: KARL HÜBNER

Recycling efforts have focused primarily on paper, glass, and plastic. But CO_2 can be recycled, for example, into methane, the main ingredient in natural gas. A team at the Max Planck Institute for Dynamics of Complex Technical Systems in Magdeburg has developed a process which enables the methanation of CO_2 on an industrial scale. The process could help decrease the use of fossil raw materials.

It is one of the truly massive tasks connected with the energy revolution: the more progress we make in developing renewable energies, the more surplus green energy there will be at times when there is no immediate need to use it. Storing these surpluses is therefore crucial. Battery installations are one possible solution. Another possible approach, however, is to use the excess energy to synthesize chemical substances, which can then be used as energy sources or raw materials – a concept known as Power-to-X. Candidates include hydrogen, methanol, and ammonia.

Another useful reservoir for green energy would be methane. As the main ingredient in natural gas, it could replace its fossil counterpart. A team led by Sundmacher the "methanation" of carbon dioxide (CO_2), in which hydrogen and CO_2 react with each other. The requisite hydrogen could be extracted by using the excess green electricity to electrolyze water. For CO_2, we could use industrial waste gas from cement, steel, and power plants, as well as from biogas plants. This would allow us to recycle greenhouse gas and limit further increases in CO_2 emissions. Methane created in this way could be used as an interim solution in gas power plants until they can be powered directly with hydrogen. "From our point of view, it would be especially useful to employ the methane as a raw material in the chemical industry, which could use it to make many products," says Kai Sundmacher, Director of the Process Engineering Department at the Max Planck Institute for Dynamics of Complex Technical Systems. "Unlike the energy industry, the chemical industry can't be completely decarbonized, because carbon is a crucial ingredient in most plastics, dyes, and medicinal substances, for example.

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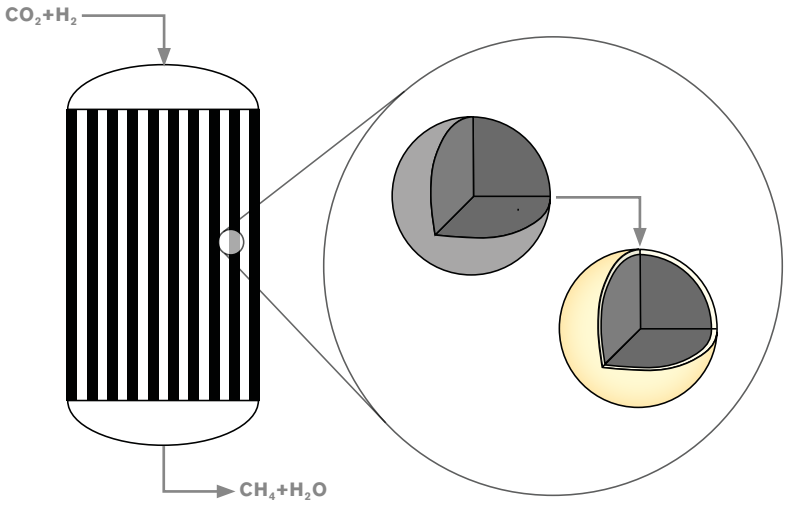
But like other industries, the chemical industry must defossilize its production processes by replacing them with climate-friendly alternatives."

A team led by Sundmacher has developed a process for CO_2 methanation that could be implemented on an industrial scale. After all, there are not yet any industrial plants for methanation that store renewable energy. This is partly due to technical challenges involving the chemical process. When CO_2 and hydrogen react, a lot of heat is released, which raises the temperature in the reactor. This temperature cannot be allowed to exceed 550 °C, however, because that would deactivate the nickel catalyst and quickly bring the reaction to a standstill.

As a result, there is a need for a design that keeps the reactor from getting too hot. Admittedly, there is a whole range of technical approaches, but many of them are expensive and therefore impractical. A process has yet to make it past the scale of a pilot plant. The team in Magdeburg has developed a concept that will yield economically viable quantities of methane, while preventing the temperature from getting too high. In the process, the researchers have taken the idea of core-shell catalyst pellets a step further. "This catalyst design, with a catalytically active core and an inactive shell, makes it possible to limit the reactor temperature, thus paving the way for industrial-scale methanation of carbon dioxide," Sundmacher explains.



GRAPHIC: GCO BASED ON WILEY-VCH PUBLISHER 2020

Protection from overheating: catalyst pellets consisting of an active core (gray) and an inactive shell (yellow) make it possible to control the reaction rate and hence the heat buildup. This is done by modifying the shell thickness and other properties. Consisting of bundles of pipes a few centimeters in diameter, the reactor is likewise designed in a way that prevents a sharp increase in temperature that could harm the catalyst.

The key: porosity and shell thickness

The key to the core-shell approach is the chemically inert, porous shell. Molecules intended to react with each other must first penetrate this shell to reach the catalytically active nickel sites on the core. It is only there that methane is formed. "The diffusion of the reactants through pores in the shells is what slows down the reaction rate, which in turn prevents the temperature from getting too high," explains Ronny Tobias Zimmermann, a chemical engineer on Sundmacher's team. What's more, by modifying the properties of the shell, such as its diameter or porosity, it is possible to determine how hot the reactor can get. "The thicker the shell, the lower the maximum possible temperature," explains Zimmermann. That's simply because a thicker shell increases the distance individual molecules have to travel on their way to the catalyst, thus slowing the reaction.

The Magdeburg team ran simulations and conducted subsequent experiments to determine the optimal properties and dimensions of both the core-shell catalyst pellets and the reactor. The resulting approach is to construct a reactor from a bundle of pipes three meters long and several centimeters thick, which are then filled with spherical core-shell catalyst pellets. Each pellet is around three millimeters in size, while the shell is only 0.1 millimeter thick,

SUMMARY

Carbon dioxide reacts with hydrogen to form methane, which could be used as a raw material for the chemical industry. Current process concepts cannot efficiently handle the heat generated by the reaction, which makes it difficult to implement CO_2 methanation on an industrial scale.

A team in Magdeburg has developed a new process based on core-shell catalyst pellets that enables precise control of the reactor temperature.

The Magdeburg process is load flexible, meaning that the supply of raw material can fluctuate. This is relevant from an industrial standpoint, because green hydrogen is not always available in the same quantity due to fluctuations in the supply of electricity from renewable sources.

roughly twice the thickness of a human hair. The methanation process involves running a mixture of hydrogen and carbon dioxide through pipes heated to around 300 °C. The resulting methane gas is collected at the other end of the pipes. Once purified, it can be fed into tanks or the natural gas network.

"Everything is designed to ensure that the reactor never gets hotter than 480 °C, regardless of how much starting material we put in," explains Zimmermann. The nickel cannot be deactivated, even when varying quantities of hydrogen and CO_2 are used. This flexibility and robustness are especially important when using renewable energies, whose electrical output fluctuates. The amount of hydrogen that is generated and that can react with the CO_2 fluctuates with the electricity supply. These fluctuations in reactant quantity are generally a major challenge for process engineering. Solutions that are good at handling fluctuations are called "load flexible."

"Of course, it's possible to avoid the problem by storing the hydrogen temporarily and constantly retrieving it," says Sundmacher. "But that kind of storage is quite expensive." Consequently, there is a lot of interest in a load-flexible solution like the one just developed. As for where the reactors for methane extraction could be deployed, the Magdeburg team is focused mainly on places where surpluses in renewable energy can provide the necessary hydrogen, that is, wind farms and large solar plants.

Contact with chemical companies

In the meantime, the Magdeburg researchers have tested the core-shell concept for CO_2 methanation at the Institute's own pilot plant hall, which allows them to test processes under circumstances approximating industrial conditions. "We are now trying to introduce the process for industrial use, and are already in contact with chemical companies," says Sundmacher. But core-shell catalysts can be used for more than just synthesizing methane from carbon dioxide. They can also extract other substances of interest to the chemical industry, such as methanol, from the greenhouse gas. Generally speaking, the concept of tailor-made core-shell catalyst pellets can be applied to all gas phase reactions that generate a lot of heat, Sundmacher explains. That includes the production of ammonia from hydrogen and nitrogen. At present, the Institute in Magdeburg is also involved in a number of H2Mare projects, whose overall purpose is to use surplus electricity from offshore wind plants to generate hydrogen directly. Reactors with core-shell catalyst pellets for generating methane and ammonia are being tested as a way of possibly reusing the resulting hydrogen. Sundmacher and his team also see enormous potential in storing renewable electricity as chemicals and energy sources. He adds that the main limitation right now is the amount of renewable energy. But that should change in the future.

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Pellets on trial: Ronny Tobias Zimmermann conducts experiments in which the different core-shell catalyst pellets are tested.

PHOTO: NILS THOMAS/MPI FOR DYNAMICS OF COMPLEX TECHNICAL SYSTEMS

GLOSSARY

CO_2-METHANATION
is the conversion of carbon dioxide and hydrogen into methane.

DEFOSSILIZATION
refers to the movement away from fossil raw materials such as petroleum and natural gas towards renewable carbon-based raw materials such as biomass or CO_2.

DECARBONIZATION
means the abandonment of carbon-based energy sources, which release the greenhouse gas CO_2 when burned.

CORE-SHELL CATALYST PELLETS
is a chemical reaction accelerator consisting of an active core and a porous, inactive shell. The heat buildup in the reactor can be controlled by varying the thickness and porosity of the shell.

BAD FOR THE ENVIRONMENT, GOOD FOR THE CLIMATE

TEXT: PETER HERGERSBERG

Excessive amounts of nitrogen fertilizer and nitrogen compounds from fossil fuels pollute the soil, air, and water in different ways. But how do these substances affect our climate? An international team led by researchers at the Max Planck Institute for Biogeochemistry in Jena has taken stock of the various climate effects of nitrogen compounds.

When it comes to the environment, nitrogen is an essential element for life and a fertilizer, but too much of it makes it a pollutant: nitrogen compounds increase the concentration of particulate matter in the air and the nitrate content of drinking water, lead to eutrophication, reduce biodiversity, and damage the stratospheric ozone layer. When it comes to the climate, however, the situation is more complicated. Nitrogen compounds affect our climate in many different ways. Although elemental nitrogen, which makes up about 80 percent of our air, is climate neutral, all compounds of the element – known scientifically as reactive nitrogen – have a direct or indirect effect on the average global temperature, sometimes warming it and sometimes cooling it. For example, nitrous oxide, also known as dinitrogen monoxide, which escapes from fertilized soil, is almost 300 times more potent a greenhouse gas than CO_2. In contrast, aerosols, fine particles suspended in the atmosphere, are made up of other short-lived nitrogen oxides, mainly from the burning of fossil fuels. They block sunlight, which cools the climate. In addition, nitrogen inputs generally cause plants to grow more abundantly. They absorb CO_2 from the atmosphere, which also has a cooling effect. Nitric oxides also play a role in the destruction of methane, which cools the atmosphere, but at the same time, they lead to the formation of tropospheric ozone, which is a greenhouse gas and has a warming effect.

The international team led by Sönke Zaehle and Cheng Gong from the Max Planck Institute for Biogeochemistry has taken stock of the various effects. The bottom line: nitrogen that enters the Earth system as a result of human activities cools the climate. In climate research this is called "negative radiative forcing." In 2019, this cooling amounted to 0.34 watts per square meter. To put this in perspective, in the case of human-driven global warming, the atmosphere is heated by an additional 2.7 watts per square meter, mainly from greenhouse gases generated by the consumption of fossil fuels – according to the average for the years 2011 to 2020 given by the Intergovernmental Panel on Climate Change in its latest status report. This means that nitrogen emissions have reduced human-caused global warming by about one-eighth during this period.

During this period, the Earth was on average 1.1 °C warmer than in pre-industrial times. "The negative radiative forcing due to nitrogen input cannot simply be translated into a change in global average temperature, because there are local effects and the climate system reacts in a complex way to such changes in radiative forcing," says Sönke Zaehle, Director at the Max Planck Institute for Biogeochemistry. Without the extra nitrogen, however, the climate would have continued to warm. "This may sound like good news, but you have to keep in mind that nitrogen emissions have many harmful effects, for example, on health, biodiversity, and the strato-

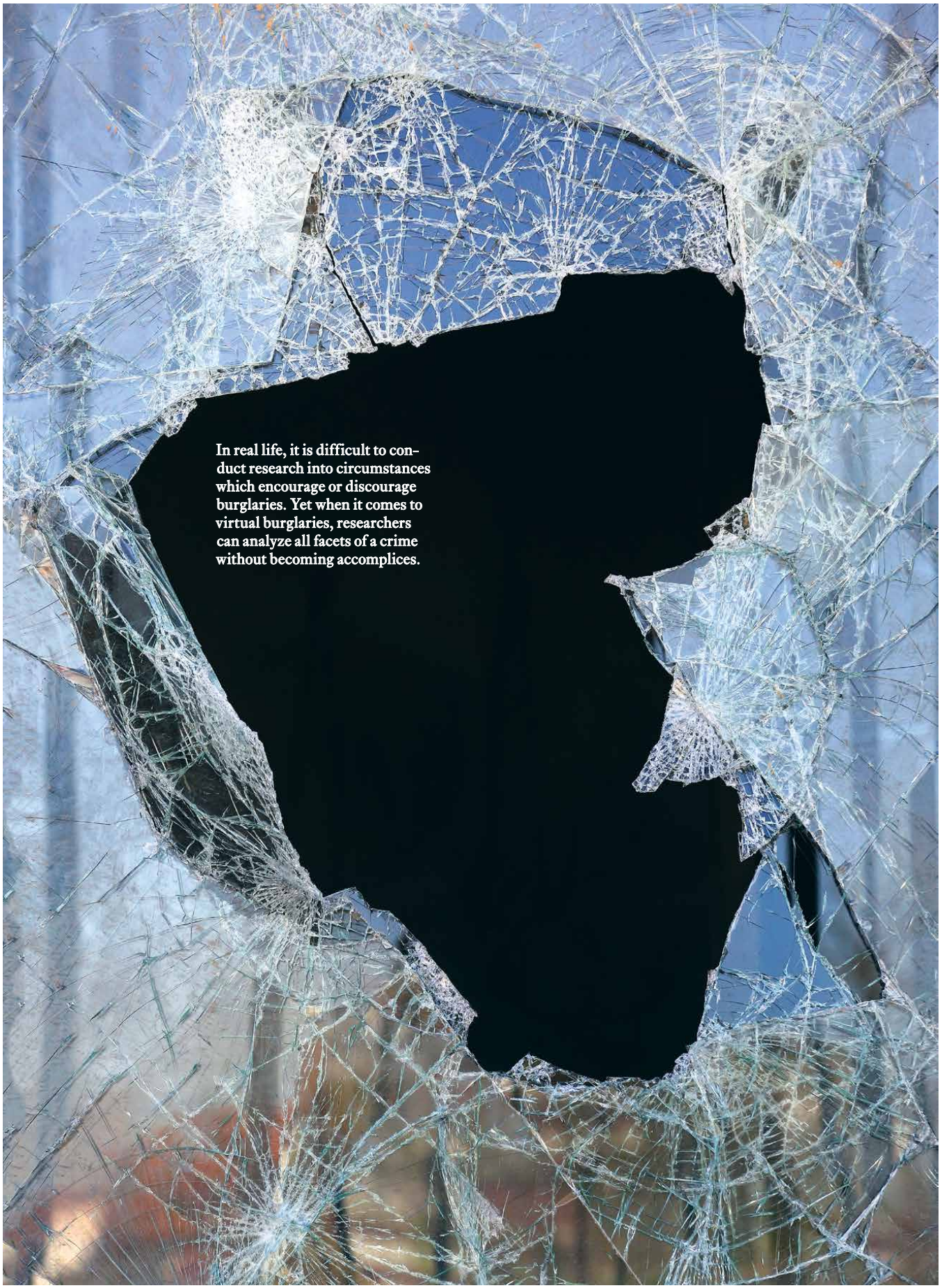
Fossil fuel and agriculture are responsible for most emissions of nitrogen compounds, including nitric oxides, nitrous oxide, and ammonia. Nitrogen input has many harmful effects on the environment – but it also cools the climate.

PHOTO: PICTURE ALLIANCE / JOCHEN TACK

spheric ozone layer," says Zaehle. "The current finding therefore only improves the environmental balance of nitrogen inputs in one respect and is no reason to gloss over it, let alone see additional nitrogen inputs as a means to combat global warming."

The goal: less nitrogen and less CO_2

The researchers found the total impact of nitrogen from human sources by first determining the amounts of various nitrogen compounds that end up in the soil, water, and air. They fed this data into models that depict the global terrestrial nitrogen cycle and its effect on the carbon cycle, in other words, the stimulation of plant growth and ultimately the change in CO_2 and methane levels in the atmosphere. From the results of these model simulations, they used another atmospheric chemistry model to calculate the effect of anthropogenic nitrogen emissions on radiative forcing, or the amount of radiant energy that hits a square meter of the Earth's surface per unit of time. "Previous estimates based on literature studies have tended to be fragmentary, ignoring the fact that the processes of the global nitrogen cycle are spatially diverse, tightly coupled, and non-linear. Our calculations take these features into account," says Gong, postdoc at the Max Planck Institute for Biogeochemistry and first author of the study. "Nitrogen emissions should be reduced," says Zaehle. For example, by improving agricultural practices, it might be possible to use nitrogen more efficiently as a fertilizer. "This could, for example, reduce emissions of nitrous oxide, which contributes to global warming and damages the stratospheric ozone layer," Zaehle continues. "However, it is important to recognize that while reducing human nitrogen emissions benefits our health and ecosystems, it also has an impact on the climate. Consequently, greenhouse gas emissions, especially CO_2 and methane from fossil fuels, must also be reduced to a greater extent. Only then can we better protect our human health and nature and also mitigate climate change."



In real life, it is difficult to conduct research into circumstances which encourage or discourage burglaries. Yet when it comes to virtual burglaries, researchers can analyze all facets of a crime without becoming accomplices.

PHOTO: ADOBESTOCK

STUDYING CRIME IN REAL TIME

TEXT: BENNO STIEBER

Researchers in Freiburg are creating virtual spaces to observe burglars in action. This helps to make residential areas safer and also solves a long-standing problem in criminology.

The residential area is dark, and the hedges around the parking space next to the house could offer protection from prying eyes. Yet the professional burglar considers it more promising to enter the yard using a path behind the houses that is tucked away and difficult to see. This narrow path with high walls could give him unobserved access to the house. To someone just walking past, this town house development may seem like any other residential area, but to an experienced burglar like him, it is a topography of opportunities and more or less hidden risks. And once inside, it will take him an average of seven minutes to search all the rooms likely to hold any interesting valuables.

While this house and the entire neighborhood exist only on a computer, and the burglary takes place in the virtual world, the men who wear virtual reality headsets and use game controls to navigate these artificially created spaces are real-life convicted burglars. Researchers from an international team sought them out in prisons across Europe and the US and asked them to participate in a unique project. The man behind it all is Jean-Louis van Gelder, Director of the Department of Criminology at the Max Planck Institute for the Study of Crime, Security and Law in Freiburg. This is where the data converges, making a long-held dream of criminologists come true: to go beyond inspecting crime scenes and asking perpetrators after the fact why they chose a victim, how they planned their actions, which risks they took and which they avoided. Like a biologist, who is able to observe cells dividing under a microscope, criminologists have long wanted to follow criminal acts in real time. Yet there are many practical and, above all, ethical objections to this. After all, researchers must not become accomplices.

As a result, science has been forced to remain imprecise when it comes to crucial issues in settings in which most of what is to be investigated is done in secret and away from the public eye. Traditionally, criminologists have therefore relied on indirect methods, such as registration data or interviewing offenders. "But them describing their actions is just not the same as me observing them as they go along," says Professor van Gelder, who holds a doctorate in law and psychology. The indirect approach lacks emotion and the ability to capture thoughts straight away.

Burglary in a virtual world

Using VR headsets and artificial spaces, researchers seem to at least be getting closer to solving this problem. In initial studies at the University of Portsmouth involving convicted criminals, researcher Claire Nee was able to demonstrate that a virtual burglary is in fact comparable to a real one as early as 2015. She showed that burglars in the virtual world often enter through unmonitored back doors, search the home from top to bottom, and prefer stealing light, valuable

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items, just like in real life. This has also been confirmed by research conducted by the Max Planck Institute. The researchers took laptops, VR headsets, and controllers into prisons in the UK, the Netherlands, the US, and Germany and recruited convicted burglars for their research. Many inmates were happy to take part in the project and found the virtual burglary a welcome change from the monotony of prison life. "It was important for them to see that we were not acting on behalf of the police or the justice system," Jean-Louis van Gelder emphasizes.

And so, observed by the team of criminologists, these professional burglars went on the prowl. "Some of the test subjects found the virtual spaces so real that they felt an adrenaline rush, as if they were 'on tour' again," says van Gelder. Sometimes, working with VR headsets acted as an icebreaker that allowed them to bond with these men and have more in-depth conversations. One of the studies which produced new findings took place in the US, in which postdoc Patrick McClanahan observed 160 convicted burglars commit virtual crimes. Eye movements and actions were recorded in real time. The researchers repeatedly changed details in the virtual scenarios to see how offenders reacted. What we can learn from this and other studies conducted by the Institute is that – contrary to expectations – elaborate lighting and sound interventions designed to make burglars feel like they are not alone have little deterrent effect. By contrast, the mere presence of a person in the area is much more likely to deter burglars, regardless of how passive this person is. Signs depicting sets of eyes, "watching eyes," were also surprisingly successful – conveying that a street is under surveillance. However, signs warning of firearms do not deter professional burglars in the US. In fact, they may make them suspect that more valuable items are to be had. In the test burglaries, the subjects were even prepared to use firearms themselves, showing that this threat was in vain.

Children's toys in the garden and around the house might be more effective. This is the case because they indicate to potential burglars that the house is lived-in, and that parents are vigilant and keeping an eye on their children. "It's clear that the more people there are in a place, the lower the likelihood of a burglary," van Gelder says. "The actual behavior of the people present doesn't seem to have any additional effect: for example, whether they are actively monitoring a place or starting a verbal argument with the burglar." The researchers also found that burglars tend to look for money and documents in desk drawers, almost never in children's rooms or bathrooms.

The extensive data collected by van Gelder's team now needs to be analyzed. The Institute will gradually provide the justice system, but also lo-

SUMMARY

Virtual scenarios provide insights into the behavior of criminals, as well as the effectiveness of preventive measures.

Studies involving experienced burglars using virtual crime sites show that the mere presence of people in a house or neighborhood is the strongest deterrent.

The findings of the Max Planck team in Freiburg aim to help prevent crime – the state of Baden-Württemberg and the city of Freiburg have already voiced interest.

IMAGE: MARCO OTTE

Virtual reality allows researchers to observe how burglars behave in different residential neighborhoods and homes. The technology records what the offenders look at, what targets they choose, what entry points they use, and how they proceed during a burglary. This enables the research team to study how street lighting, alarm systems, warning signs, and the presence of people affect burglars' behavior.

PHOTO: SKUB

Max Planck Director Jean-Louis van Gelder and a member of his team use modern technology to study property crime. VR headsets and various sensors transport test subjects into virtual worlds.

cal authorities and insurance companies with actionable results. In this way, homes and entire neighborhoods can be made safer. "I believe this is our social responsibility," says van Gelder.

New research lab in Freiburg

Burglary is a clearly defined offence with a definite beginning and end, making it ideal for testing the new technology and collecting usable data. Working with burglars, however, is just the first step for researchers studying crime in virtual worlds. Peter Wozniak, Director of MAXLab Freiburg, gives a tour of his team's premises in the middle of Freiburg's city center. They are building a studio that will allow multiple people to move around in a virtual world. "It takes a lot of technical expertise and funding to create the virtual environment for this research," says Wozniak. The computer scientist is happy to be able to do something useful for society. A pioneer in virtual crime research, the Freiburg team is now planning to make their infrastructure accessible to researchers from all over the world using an open-source model. After all, virtual worlds can be used in a variety of ways to investigate many types of crime. For example, MAXLab Freiburg is currently investigating stimulus-response patterns in connection with violence and sexual assault in a virtual nightclub. While the test subjects cannot actually move around the room, they are confronted with real-life scenarios, their physical and psychological responses being recorded. To make the bar scenes appear realistic, the criminologists worked with a film production company and professional actors. According to van Gelder, it is also conceivable to use this technology to train people's reactions to violence in public spaces. "We can easily imagine virtual reality being used for anti-aggression training in the future," he says. In their next virtual criminology study, the researchers plan to use virtual twins of real public places and streets that are accurate down to the last detail to study residents' reactions, for example to preventive measures, in more depth. One possible application would be to test interventions, such as additional street lighting, in the neighborhoods being studied. Van Gelder is hopeful: "This will give us a clear picture of how measures directly affect people's sense of safety and how we can increase safety in public spaces." The State Criminal Police Office of Baden-Württemberg – and the city of Freiburg itself – have already voiced interest in the project. Indeed, a crime hotspot right on the MAXLab team's doorstep could also serve as a case study for virtual studies on public safety: Freiburg's nightlife district in the old town is a constant source of negative headlines. Locals call it the "Bermuda Triangle." Jean-Louis van Gelder thinks this could be a good name for a research project.

Vision and reality: artificial intelligence still has a long way to go before it truly understands complex relationships in physics. But today's algorithms are already capable of inspiring researchers and suggesting surprising designs for experiments.

IMAGE: ADOBESTOCK

ARTIFICIAL INSPIRATION

TEXT: ROLAND WENGENMAYR

Whether making a medical diagnosis, searching for materials for the energy revolution, or predicting protein structures, artificial intelligence algorithms are an effective tool in many scientific fields today. But are they useful in physics, where the goal is to understand the fundamental processes of nature? Mario Krenn and Florian Marquardt are already assisted by AI at the Max Planck Institute for the Science of Light, where they are getting a feel for what the algorithms can and cannot (yet) do.

Artificial intelligence, or AI for short, is booming. Many people use ChatGPT, for instance. The most famous example of an AI based on a large language model, ChatGPT helps people conduct research or write texts. AI can also be used to generate images or videos from text prompts and has long served as a tool in the art world. But what is its role in the sciences?

AI is already well established in the life sciences and chemistry. The AlphaFold program from DeepMind gained prominence in biology due to its ability to calculate protein structures. You may recall that DeepMind caused a furor with its program AlphaGo in 2016, when it beat the world's strongest Go player, Lee Sedol. It was a sensation, because there are so many possible next moves in Go that no computer can calculate them all. For that reason, AlphaGo had to learn by training like a human, developing a feeling for patterns in the combinations of stones played on the board – and hence a kind of understanding of what constitutes a smart move. In the process, it definitely benefited from brute-force calculating power. It was able to train against itself, so to speak, by playing millions of games, whereas professional Go players only ever play a few thousand.

Despite the widespread application of AI since then, most programs function as a black box, meaning that a user gets a useful result without understanding how it was arrived at. That's often sufficient – for example, when the user is searching for a protein with a specific function. In this case, what matters is to understand why the structure discovered by the AI does what it should. But in physics, the most fundamental of all sciences, a black box undermines the goal of understanding a physical system. Researchers increasingly turn to AI in physics as well, but mostly for applications where the use of a black box doesn't inhibit understanding. However, experts are debating whether AI could become efficient enough to un-

→

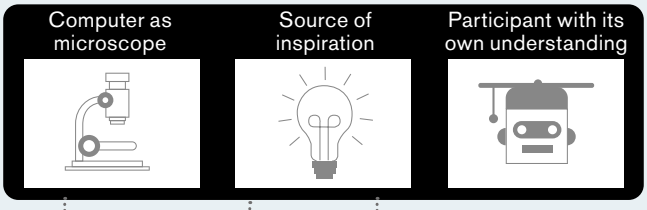
derstand complex physical systems even better than humans. If so, and if they were able to explain things to their human colleagues, would they gain an equal footing as artificial physicists? And could this inspire new ideas in physics?

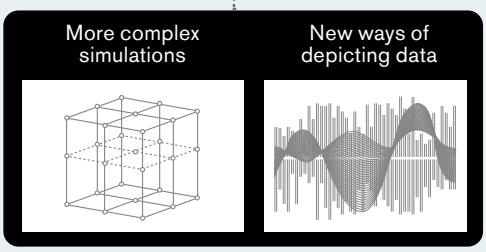
Eureka moment in machine learning

Mario Krenn and other physicists consider this type of AI an artificial muse. They wrote an article about it in the December 2022 issue of the trade journal Nature Reviews Physics. We are sitting in the cafeteria of the Max Planck Institute for the Science of Light in Erlangen. With us is the Director of the Theory Department, Florian Marquardt. Like Krenn, he has employed several methods for machine learning in the past few years and continues to refine them with his team. Krenn earned his Ph.D. in experimental quantum optics in Vienna under Anton Zeilinger, winner of the Nobel Prize for Physics in 2022. He changed course radically following a eureka moment involving machine learning. "I never set foot in a lab again," he says with a laugh. He is considered a pioneer in the use of AI in physics. Today he heads a research group at the Institute called the Artificial Scientist Lab; the name alone conveys a vision of an artificial physicist.

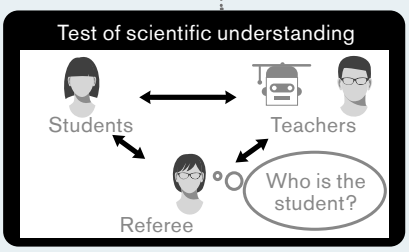
We'll say more about what motivated Krenn to change course in 2014, but first, it is necessary to explain the conditions under which an AI could be considered equal to a physicist. "To begin with, we have to understand how human researchers work," Krenn

AI can contribute to a scientific understanding of physics at several difficulty levels: as a kind of virtual microscope, as a source of inspiration, and as a participant with an understanding of its own.

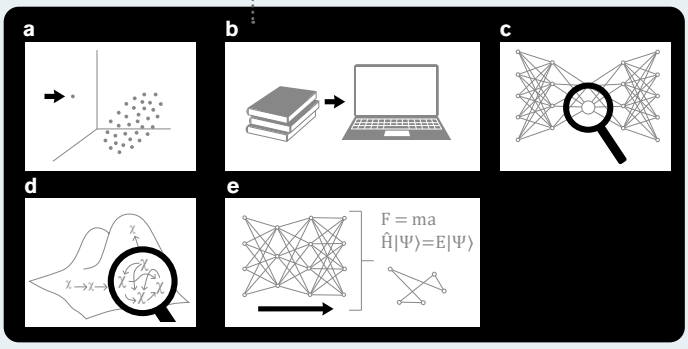




As a virtual microscope, AI can discover hidden relationships, allowing for increasingly complex simulations and the depiction of data in virtual environments involving 3D, sound, and touch, for example.



At the third and still unattained level, AI could achieve a physical understanding on its own. This could be proven with a test, in which an AI or a human explains a scientific theory to students. If a referee is no longer able to distinguish between the level of knowledge possessed by the teacher and the student, the theory has been understood and communicated by the teacher – whether AI or human.



It can draw inspiration from surprises in the datasets (a) or the scientific literature (b). Moreover, it can discover new and unexpected concepts by investigating scientific models (c), exploring a data space with programmed curiosity or creativity (d), or providing solutions in the form of, for example, mathematical formulas that researchers can interpret.

GRAPHIC: GCO BASED ON KRENN, M., POLLICE, R., GUO, S.Y. ET AL. ON SCIENTIFIC UNDERSTANDING WITH ARTIFICIAL INTELLIGENCE. NAT REV PHYS 4, 761–769 (2022).

emphasizes, "why they are creative, how they are creative, and what makes them curious." The question is therefore what motivates people to do their research. "Once we understand that, we have a better chance of doing truly autonomous, automated science," he says. Marquardt agrees, adding: "At the same time, we're learning something about what we humans are doing in science. It's far from clear that all of our priorities in research are really so objective!"

Consequently, we can establish as a starting point that an artificial physicist must be able to motivate itself to the same degree as a human. It sounds banal, but an example illustrates how challenging this vision is. "Take, for instance, a key question in solid-state physics," Marquardt suggests. "How can I manufacture a room-temperature superconductor?" Disregarding the fact that even a question this specific and unanswered is still too open and general for today's AI, an artificial physicist would have to arrive at this question by itself and rank it as important. The AI would therefore have to recognize on its own that lossless conduction of electrical power at room temperature is a desirable research objective. "But why do you want to transport electricity losslessly?" Krenn asks, inquiring into the next meta-level of knowledge. The AI would have to ask and answer this question itself without external prompting. In sum, it would have to know that electrical energy is crucially important to our society. But this goes into social issues that are far outside the purview of physics.

This example illustrates just how challenging the human traits of creativity and curiosity really are. AI is still a long way away. It might be closer to achieving a kind of understanding of physical theories, however. One question that arises here is what exactly it means to understand a physical relationship. The conversation with Krenn and Marquardt shed light on multiple aspects that play a key role in answering this question. To answer it, physicists need an intuitive, pictorial, or model-like representation, even if it's only an abstract mathematical description. In the case of AlphaGo, AI has already shown itself capable of this type of intuition – in the special case of the situation on a game board. However, to understand also means to be able to transfer insights and solutions from one area to another. "When an AI becomes familiar with a concept in one context, possibly by learning about it in the scientific literature like us, then maybe it can recognize that the concept can also be applied in another context," says Marquardt. Ultimately, an AI would have to be capable of explaining a relationship to humans as well, possibly with the help of a language model. Krenn and Marquardt believe an AI can manage it. But first, AI has a lot to learn.

In many specialized tasks, AI already leaves human physicists in the dust. And that's exactly what Krenn and Marquardt are counting on in their research. One method they rely on is artificial neural networks. The networks simulate interconnected nerve cells, which learn by strengthening or weakening certain neural connections through training. "Artificial neural networks are only one method, however. The spectrum of AI is much broader," Marquardt points out. "But all AI methods have in common the fact that they help deal with complexity." This includes being able to discover hidden patterns and solve mathematical optimization problems, says Marquardt. Through training with millions of images and other methods, AI learns to identify objects such as "cars" or "eagles" in a highly diverse range of perspectives and situations.

SUMMARY

Artificial intelligence is exceptionally good at detecting patterns in large quantities of data and reducing the complexity of relationships. This enables it to design experiments in the fields of, for example, quantum physics or gravitational wave physics.

In the future, AI might also be capable of understanding physical relationships when given a model of them, translating concepts from one field to another, and explaining a relationship to humans.

To be on a par with human scientists, AI would have to be capable of independently deriving questions based on the needs of society. That goal is still a long way off.

Solutions for quantum error correction

It is precisely this ability to recognize patterns that Marquardt leverages in his work. Several years ago, one of his teams trained an AI to find solutions for quantum error correction. The next generation of quantum computers will rely on this kind of correction, because their highly sensitive quantum bits are necessarily subject to disturbances from the environment. One of the peculiarities of the quantum world is that during a quantum calculation it isn't possible to take measurements to determine whether the qubits still contain the correct values. For that reason, quantum error correction has to cleverly avoid direct measurement. It's almost as if you were playing Go against an opponent whose white stones you couldn't see, and the only way to determine where they are is by placing your own stones carefully. As with other problems, quantum error correction therefore involves recognizing patterns. Furthermore, the Erlangen researchers' AI-based program has detected new sequences of quantum operations for certain correction algorithms.

With the help of AI, Florian Marquardt's group has also discovered other fault-tolerant programming methods for quantum computers, as well as designs for photonic integrated circuits – the optical counterparts of electronic integrated circuits. In addition, his group has developed approaches for neuromorphic computer architectures. Because of how it works, AI currently requires a lot of energy. →

Neuromorphic chips would be much more sustainable. They were inspired by our brains, which only use enough electricity to power a 20-Watt bulb.

Krenn's enlightening experience in 2014 was likewise guided by AI. At the time, his team led by Anton Zeilinger wanted to generate an especially complex form of entanglement between light quanta, photons. Entanglement is a central tool of quantum information technology. Roughly speaking, the quantum states of individual quantum objects, such as photons, are overlapped so that together they form a large quantum system. It's a bit like a rowing crew whose members are so highly synchronized that they row like a single super-athlete.

AI designs a quantum experiment

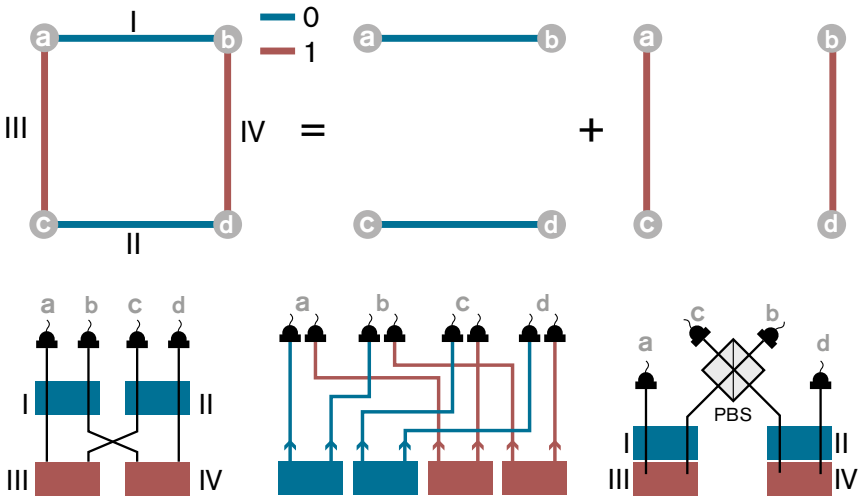
It was unclear which experimental setup would generate the special entanglement between photons most effectively. To determine this, Krenn developed a program called Melvin that simulated all the necessary optical components, including lasers, lenses, mirrors, and detectors. As such, it was able to test millions of combinations in a brief time until it found experiments that generated the desired entanglement. Because Melvin learned which combinations were useful, the program was able to create within hours something that four physicists – three experimenters and one theoretician – had labored in vain for three months to create; it provided a working design for the experiment.

PHOTO: STEFAN SPANGENBERG

Creators of an artificial colleague: the team led by Mario Krenn (center) develops artificial intelligence that puts forward surprising solutions for experiments and advances our understanding of physics.

After this "aha" moment, Krenn dedicated himself fully to developing AI that generates suggestions for physical experiments. There was one important insight that aided him in this task: "We noticed by accident that these quantum optics experiments can be abstracted to a large extent." In fact, they can be represented as a network of mathematical graphs made of lines, known as edges and nodes. Two nodes, for example, represent two photons, while a line between them represents their entanglement. "In this abstract space, it is much easier to search for, say, new quantum experiments," Krenn explains enthusiastically. Above all, it allows a user to find the optimum solution with a minimum of nodes and edges, which can then be implemented in reality in an especially economical design with the fewest possible components. However, Krenn doesn't use artificial neural networks in his AI programs. Such networks would have to be trained with existing experimental designs, which would hardly lead to fundamentally new ideas. "We employ what are known as exploration algorithms,"

GRAPHIC: GCO BASED ON MARIO KRENN/MPI FOR THE SCIENCE OF LIGHT



Radical simplification: a quantum experiment (below) can be depicted as a network of graphs (above). The experiment should entangle four photons, a through d (nodes in the network above). Colored lines I through IV depict pairings for the entanglement. The top left square represents the entanglement of all four photons. It results from the combination of the two adjacent graphs and can be realized in the three experiments depicted below them. The blue and red boxes represent light sources that generate individual photon pairs, while the black, hat-shaped icons symbolize detectors for incoming photons. PBS stands for an optical component that can split rays according to certain rules.

explains Krenn, "which explore the massive, abstract space of combinations for new solutions in a highly efficient way."

In the meantime, Krenn has made great strides with his research. In a work currently pre-published on the Arxiv server, an international team he was part of shows, for example, that AI can be used to develop new designs for gravitational wave detectors. Astonishingly, these designs were superior to the next generation of experiments planned for Ligo, a gravitational wave detector in the United States. Ligo became famous because it managed to discover gravitational waves whose existence had been postulated by Einstein 100 years earlier. The work was awarded the Nobel Prize in Physics in 2017. Today gravitational waves are an important new tool used by astrophysicists, for example, to detect black holes. A team led by Rana X. Adhikari is currently working on the design for the next generation, the Ligo Voyager. When the team found out Krenn had used AI to develop new quantum optics experiments, they asked him whether he would be willing to use his methods to search for new designs for the gravitational wave detectors. Collaboration resulted. As for the AI's detector designs, it will first be necessary to demonstrate in practice that unanticipated effects do not prevent them from realizing their theoretical advantages. When an experiment costs billions of dollars, however, people tend to be cautious with radical innovations.

A Nobel Prize for artificial intelligence?

With such good examples of artificial creativity, the question arises: are these harbingers of an artificial physicist? "We are now at the level where we can generate ideas," Krenn says with optimism. "On certain subjects, our AI systems can find totally new solutions that are already far more creative than human ideas in terms of novelty and utility!"

Marquardt is equally optimistic with regard to AI's applications, but far more reserved when it comes to the grand vision as a whole. For example, the question remains: when will an AI be in a position to formulate a real physical theory? Such a theory would have to be capable of being represented elegantly in clear mathematical formulas. It would have to link to existing physics and enable predictions for physical systems. It's a tall order, but Krenn is confident that within the next few years an AI will be able to provide the key idea in a discovery that wins a Nobel Prize. The Nobel Prize Committee might soon be confronted with the question of whether an AI or its creators can receive the highest prize in science. ←

GLOSSARY

ARTIFICIAL NEURAL NETWORKS
use standard computers to simulate nerve cells, which are interconnected and capable of learning by strengthening or weakening certain neural connections through training. This is only one AI method.

NEUROMORPHIC COMPUTERS
imitate the physical functioning of the human brain, which is far more energy efficient than the transistors in today's processors. Artificial neural networks can be simulated on neuromorphic computers using less energy, but are not equivalent to them.

Max Planck researchers collaborate with partners in more than 120 countries. Some of them have kindly agreed to write about their personal experiences and observations for our website. Dietmar Germerott from the Max Planck Institute for Solar System Research in Göttingen spent 11 weeks at the Esrange Space Center balloon and rocket base in northern Sweden, where he watched over the Sunrise III mission. Here, he recounts his experiences from the launch of the balloon-borne solar observatory.

PHOTO: MPS / D. GERMEROTT

The Sunrise III observatory shortly before launch on the Hercules crane vehicle. The huge balloon in the background to the right is already partially filled with helium. During flight, it carries a load of almost three metric tons.

"Oh, you're headed on another class trip?" asked my wife when I told her I was set to fly to Kiruna. By that stage, I'd been to the balloon and rocket launch base in northern Sweden so often that it was starting to feel like a class reunion: there's a huge number of researchers and technicians that pay frequent visits to the base, and I'm always bumping into old acquaintances. The Esrange Space Center is located in the forests of Lapland, surrounded by nature. It's far from unusual for a reindeer to suddenly appear in the middle of the launch area. The station has space for around 100 people. This time, however, there were so many teams on site that I initially had to move to accommodation around 25 kilometers out from the base. While there are rustic log cabins available there for summer use, every winter sees the construction of a new and exclusive "ice hotel."

I spent a total of 11 weeks in Kiruna. There was never a dull moment, and I never had to deal with the dreaded cabin fever. During the daytime, I generally worked on my computer. Then in the evening, I would head to Kiruna with colleagues for dinner. I even took a trip with a friend from Nasa to Narvik in Norway. But the thing that stood out for me was the fleet of vehicles that were available to us: my parents had a farm, so even as a child I'd had the chance to drive combine harvesters and tractors. There were no agricultural vehicles at Esrange Space Center, of course, but I was more than happy to make do with the wheel loaders and rollers – and Hercules, a huge crane and launch vehicle. In my spare time, I lent a hand to the people at Esrange by using a wheel loader and a roller to level the launch site after winter and prepare it for the spring. My efforts were rewarded with a snazzy jacket and a hat to match. And there was another surprise in store on my last day: they let me steer Hercules across the launch area!

Sunrise is the largest solar observatory ever to have left Earth's surface. The helium-filled balloon has a diameter of 130 meters and houses a gondola which, alongside its measuring instruments, rises to a height of 37 kilometers – where the conditions for observing the sun are every bit as good as in space. After two extraordinarily successful Sunrise missions in 2009 and 2013, Sunrise III was penciled in for 2022 and aimed to deliver new insights on the sun's atmosphere; however, due to technical problems, the

POST FROM

KIRUNA, SWEDEN

flight had to be aborted shortly after launch. So now it was time for a second try.

Sunrise's launch was timed around the midnight sun – a short time window during which the sun never sets on the Arctic Circle. It's only then that the solar telescope can collect data around the clock. But the weather was not on our side: June was a washout, and because the sensitive instruments have to be protected from rain, we were repeatedly forced to postpone the launch. Before we knew it, it was early July; the stratospheric winds were already starting to grow weaker. Soon they would be too weak to carry Sunrise westwards to Canada, where the landing was planned.

July 9 was the last possible launch day, and, as luck would have it, the weather forecast looked good. Winds die down at night, so we began our preparations around 9:00 PM. At 10:30 PM, Hercules went into action and maneuvered Sunrise from the main hall to the launch site. A tanker truck pumped helium into the balloon, which accommodates a full 500 kilograms of the noble gas. Inflation alone takes a good hour. Then a quality check to round things off: are all the connections good? Are the electronics working? The entire final check is recorded on video, to make sure any potential errors can be checked and reviewed afterward. Then – finally – the long-awaited command: "Ready for balloon liftoff!" The tether was released. At 6:24 AM, Sunrise took off into the sky and rose high above northern Sweden.

There was an incredible feeling of relief. It was still far too soon for euphoria, given the memories of the aborted mission of two years ago. Things can still go wrong, even after a successful start. Exhausted and full of mixed emotions, my next move was to head for breakfast. Then I went to grab some sleep. Once I'd woken up in the afternoon and had been able to reassure myself that everything was running smoothly, the last bit of tension fell away. Sunrise was in flight!

PHOTO: MPS / SIEBERT-RUST

Dietmar Germerott

60, is an engineer in Sami Solanki's working group. On the Sunrise mission, he is responsible for ensuring the smooth operation of data transmission. Sunrise III landed in the Canadian Northwest Territories after a six-day flight. Shortly afterward, the data storage devices were recovered undamaged.

FIVE QUESTIONS

ON INCENTIVES FOR BETTER CLIMATE PROTECTION

FOR AXEL OCKENFELS

Mr. Ockenfels, global CO_2 emissions continue to rise despite the efforts of some countries, such as Germany, to reduce them. Is reducing national CO_2 footprints a futile endeavor?

AXEL OCKENFELS: No, it isn't. But we have to make sure that we work together with other countries. The costs of national climate policies are borne domestically and the benefits are diffused globally; the incentives for ambitious national climate protection are too low. As a result, global emissions continue to rise – by more than Germany's total emissions last year. So, it's not enough to focus policy on our own climate footprint. We need to do better.

Do we need more ambitious climate targets?

Climate targets are not yet reducing global emissions. There is a huge gap between the Paris climate goals and national pledges. Even national climate targets are generally not being met. Moreover, unilateral efforts can actually reduce the incentives for others to cooperate, for example, if climate-damaging activities are relocated abroad or if fossil fuels saved in one country are diverted to other regions. In such cases, the efforts of climate altruists simply subsidize the CO_2 emissions of climate egoists. We need an incentive architecture that strengthens cooperation.

Is emissions trading a global panacea?

Emissions trading is one of the most effective climate policy instruments because it creates a CO_2 price that provides effective incentives to reduce emissions. But there is room for improvement. For instance, no more CO_2 can be saved in the European electricity sector than is allowed by the European emissions trading system with its cap. When emission rights are released as a result of ambitious national climate policies, the price of CO_2 emissions falls and the rights are sold to others who then save less CO_2. This improves the national climate footprint, but not the global one. If, on the other hand, a price floor were introduced for trading or if CO_2 were priced directly, these waterbed effects could be contained. But even such modifications to the emissions trading system would not yet solve the problem of international cooperation.

What could help?

Cooperation requires reciprocity. Reciprocity protects those willing to cooperate from those looking to exploit the system, while motivating those unwilling to cooperate to contribute to the common good. Virtually all cooperation is based on reciprocity, including international trade, arms agreements, and minimum tax treaties. Only climate diplomacy is based on nationally determined voluntary commitments.

What could this look like in practice?

There are different models. One is based on a common minimum price for CO_2 in a climate club, combined with climate tariffs on products imported from countries with less ambitious climate policies. The latter creates incentives to join the CO_2 pricing system. In addition, climate partnerships and climate funds can be used to support poorer countries if they themselves participate in internationally coordinated climate action. In the absence of international cooperation, we can also do a lot by developing and promoting green technologies. The cheaper green energy is compared to fossil fuels, the more it is in the interest of all countries and companies to leave fossil resources in the ground. This requires basic research and intelligent incentives. The market alone does not create enough incentives for innovation, and patents generally lead to high prices for a small number of users – the opposite of what we need.

Interview: Michaela Hutterer

Axel Ockenfels is Director at the Max Planck Institute for Research on Collective Goods. As an economist, he develops, tests, and implements market and incentive architectures based on game theory and behavioral research.

ILLUSTRATION: SOPHIE KETTERER FOR MPG

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