

MAX PLANCK

Research

PROCESS ENGINEERING
Circular Chemistry

SOCIAL PSYCHOLOGY
Democracy in the Playoffs

CLIMATE RESEARCH
CO₂ That Comes from the Cold



**AI SPARKS
LIFE SCIENCES**



Artificial neural networks, which form the basis of machine learning algorithms, mimic the brain's workings in a simplified way. The picture shows an electron microscope image of a neuron from the brain of a rat.

IMAGE: COVER & IFC: MPI FOR BIOLOGY, JURGEN BERGER & BERNHARD GOTZE; ISTOCK

EDITORIAL

Dear Reader,

Today, the most common form of artificial intelligence (AI) is based on artificial neural networks.

These networks are comprised of countless processing units—known as artificial neurons—that are interconnected and arranged in layers.

Despite some similarities, the way artificial networks operate differs greatly from that of the human brain. The language model ChatGPT, which itself is based on a neural network, says: “Artificial neural networks are biologically inspired abstractions, not replicas. (...) They adopt the idea of networked learning, but the differences in complexity, dynamics, and flexibility are enormous.”

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Researchers at the Ernst Strüngmann Institute (ESI) for Neuroscience are working to equip artificial neural networks with another brain-like property: rhythmic activity. These oscillations make the networks significantly more powerful and energy efficient. The researchers are convinced that this is the path to AI becoming truly “intelligent” one day.

Biomedical research is increasingly relying on AI. This issue looks at two examples in detail. In the first, researchers are able to use AI to analyze findings from infrared blood measurements. One day, a simple blood sample could be enough to detect diabetes, cancer, and many other diseases at an early stage.

The second example concerns the description of biological processes, which requires AI that takes physical laws into account from the outset. Only in this way can physically impossible findings (and thus unnecessary calculations) be avoided. In Dresden, researchers are therefore seeking to combine AI, physics, and biology as a way of better understanding organisms.

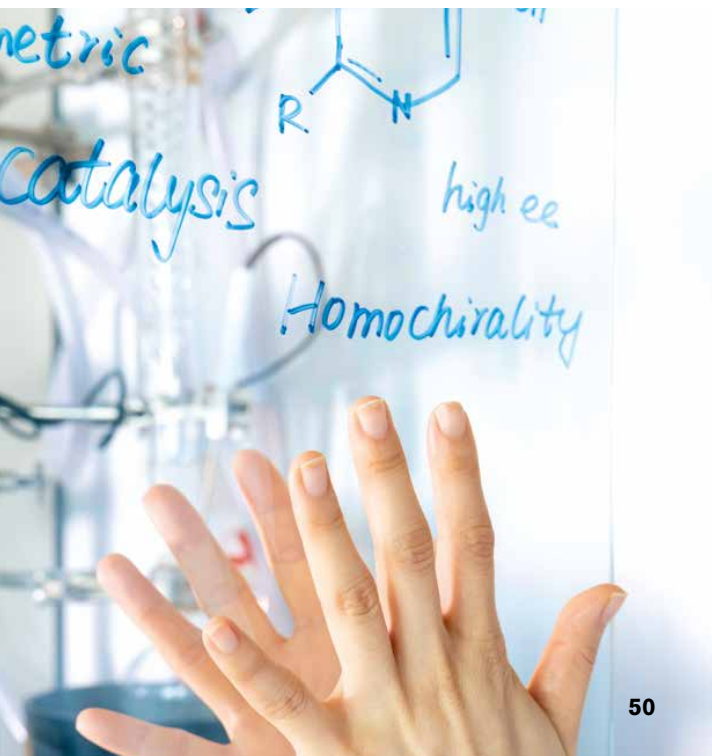
We at the Max Planck Editorial Team wish you an inspiring read.



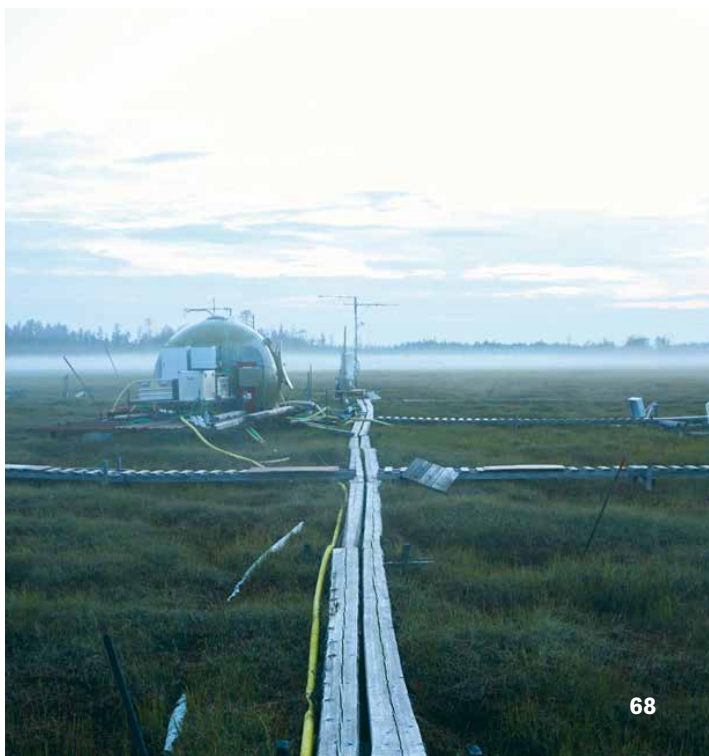
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Catalysts that come in two laterally inverted variants, like hands, are more efficient at splitting water.

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Various measurements, such as this one, enable researchers to determine the greenhouse-gas balance of the Arctic Boreal Zone.

IMAGES: THORSTEN NAESER / MPQ (TOP LEFT), KATRIN BINNER / MPG (TOP RIGHT), SVEN DORING / MPG (BOTTOM LEFT), MATTHIAS PEICHL / MPG (BOTTOM RIGHT)

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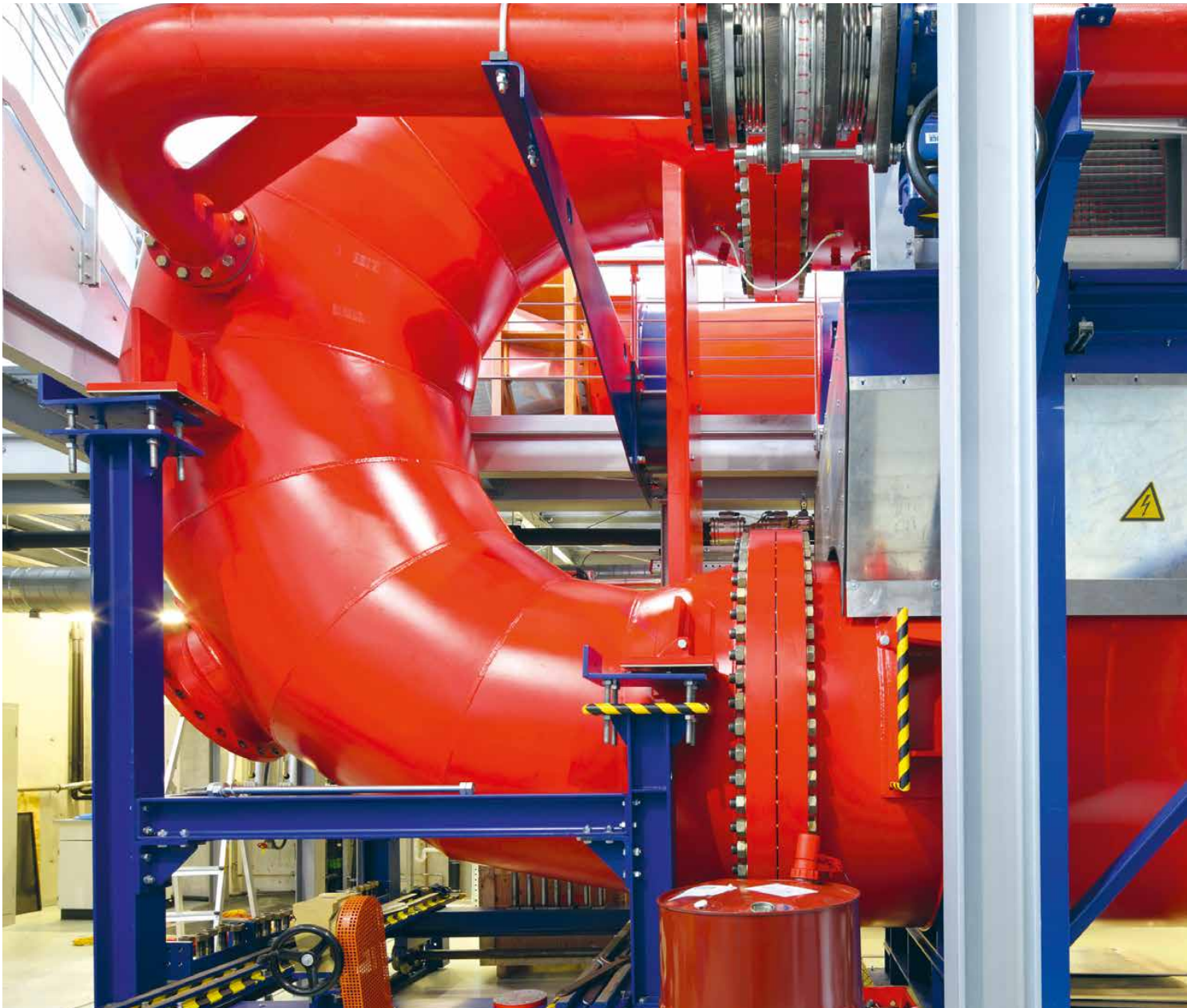
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A VORTEX IN THE RED TUBE

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ON LOCATION



IMAGE: ANDREAS MUHLS, MPI FOR DYNAMICS AND SELF-ORGANIZATION

This giant, firetruck-red tube is the wind tunnel at the Max Planck Institute for Dynamics and Self-Organization in Göttingen. It runs for an impressive 18 meters. Inside its sealed loop, the flow is turbulent—because researchers are using its space to recreate complex atmospheric currents. With these experiments, they aim to subject the chaos of turbulence to scientific control; from a mathematical perspective, vortices are nearly impossible to predict. Turbulence is a ubiquitous physical phenomenon; it arises in many contexts, such as when an obstacle intrudes into a stream of air or liquid, or when the wind sweeps across the Earth's surface.

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Atmospheric currents are especially complex because their smallest eddies are only a few millimeters in size, while the largest can span many kilometers. The Göttingen wind tunnel allows researchers to investigate these vastly different turbulence phenomena, as their behavior can be scaled down by a factor of 130. This is accomplished by filling the channel with the heavy gas sulfur hexafluoride (SF₆), which is then pressurized and set into motion. This ingenious method renders the flow inside the wind tunnel 130 times heavier and denser than air.

Using a grid that sits in the channel like a large filter, researchers can precisely control both the vortices and the flow within the channel. This active grid comprises over 100 flaps that open and close. To make the resulting turbulence visible, tiny particles are introduced into the flow and illuminated. This allows them to be filmed from multiple angles with high-speed cameras. The insights from these experiments could help improve the efficiency of wind farms in the future. After all, wind farms should be built such that turbulence can't impair power generation. Detailed knowledge of turbulence also benefits climate research.

COLLABORATION FOR GREENER BATTERIES

Sodium-sulfur batteries could be the solution to one of the problems facing the transition to green energy. They have the potential to store electricity from wind and solar power in a cost-effective and environmentally friendly way. This is important because wind and sunlight are not always available when energy is needed most. Markus Antonietti, Director at the Max Planck Institute of Colloids and Interfaces, led a team that developed a cathode material made of sulfur and carbon. This material significantly extends the

service life of sodium-sulfur batteries and makes them more efficient. The Institute has now signed a cooperation agreement with the Australian-British battery manufacturer Gelion to further develop sulfur-carbon materials for widespread use in stationary energy storage systems. Gelion will provide EUR 600,000 in funding for relevant research at Max Planck over three years. In return, Gelion will have the exclusive right to license any resulting patents.

www.mpg.de/250202en

OUTSTANDING! ★



DENNIS GAITSGORY

The Director at the Max Planck Institute for Mathematics received the 2025 Breakthrough Prize in Mathematics, which is awarded alongside a grant of USD 3 million. He was awarded the prize for his fundamental work and numerous groundbreaking contributions to the geometric Langlands program and its quantum version.

IMAGE: MAX PLANCK INSTITUTE FOR MATHEMATICS

CHANCES FOR HEALTHIER EGG CELLS

The chances of successful artificial insemination and the birth of a healthy child should increase in the future, especially for women over 35. Ovo Labs, a spin-off from the Max Planck Institute for Multidisciplinary Sciences, is developing therapeutics for reducing genetic defects in aging egg cells. The company has raised GBP 4 million (around EUR 4.7 million) in seed capital from various investors to further develop the active ingredients for clinical trials.

www.mpg.de/24636024



CLAUDIA FELSER

received the L'Oréal-UNESCO For Women in Science International Award for her contributions to condensed matter physics. Her work bridges the gap between basic science and applications in data storage and green energy technologies. The prize is awarded annually to five female scientists from five continents in alternating disciplines alongside a grant of EUR 100,000 for each scientist.

IMAGE: SVEN DÖRING / MPG

20 YEARS OF THE JOINT INITIATIVE FOR RESEARCH AND INNOVATION

The German federal government and the federal states first concluded the Joint Initiative for Research and Innovation in 2005 and have extended it several times since. The Joint Initiative guarantees non-university research an annual increase in funding of three percent. This benefits the German

Research Foundation, the Fraunhofer-Gesellschaft, the Helmholtz Association, the Leibniz Association, and the Max Planck Society. At the 20th anniversary event, Dorothee Bär, the new Federal Minister of Research, Technology, and Space, emphasized that the Joint Initiative safeguards the qual-

ity, dynamism, and independence of German research: "In these times especially, we need strong science systems—resilient, networked, and as open as possible."

www.mpg.de/24729344 (in German)

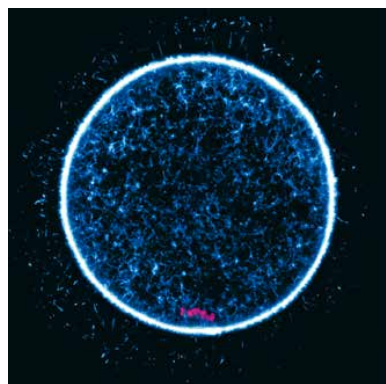




IMAGE: ESO/CHEFOX

The delegation included Frank-Walter Steinmeier (center) and his wife, Elke Bündenbender (third from left). With Eso Director General Xavier Barcons (third from right) and Max Planck Director Reinhard Genzel (far right).

SETTING SAIL WITH NEW ENERGY

The MS Wissenschaft is once again traveling on German waterways and stopping off in many cities with an exhibition on future energy. Research Minister Dorothee Bär and Simone Schwanitz, Secretary General of the Max Planck Society, opened the exhibition in Berlin on May 14. The exhibition features exhibits from three Max Planck Institutes, including one on nuclear fusion, which generates energy in the same way as the sun, and one on CO₂ as a source of raw materials for the chemical industry.

ms-wissenschaft.de/en/visit/tour-2025/

VISITING ENDANGERED TELESCOPES

German President Frank-Walter Steinmeier visited the Paranal Observatory of the European Southern Observatory (Eso) in Chile. The trip was attended by Eso Director General Xavier Barcons and Reinhard Genzel, a Nobel Prize winner and Director at the Max Planck Institute for Extraterrestrial Physics. It also took Steinmeier to the construction site of the Extremely Large Telescope, which will

be the largest telescope in the world. However, shortly before the telescope's completion, it became unclear whether its scientific goals, such as searching for traces of life on distant planets, were at risk. According to a study, an industrial plant planned nearby on the Chilean coast would cause air and light pollution, interfering with the telescopes' observations.

www.mpg.de/24318815

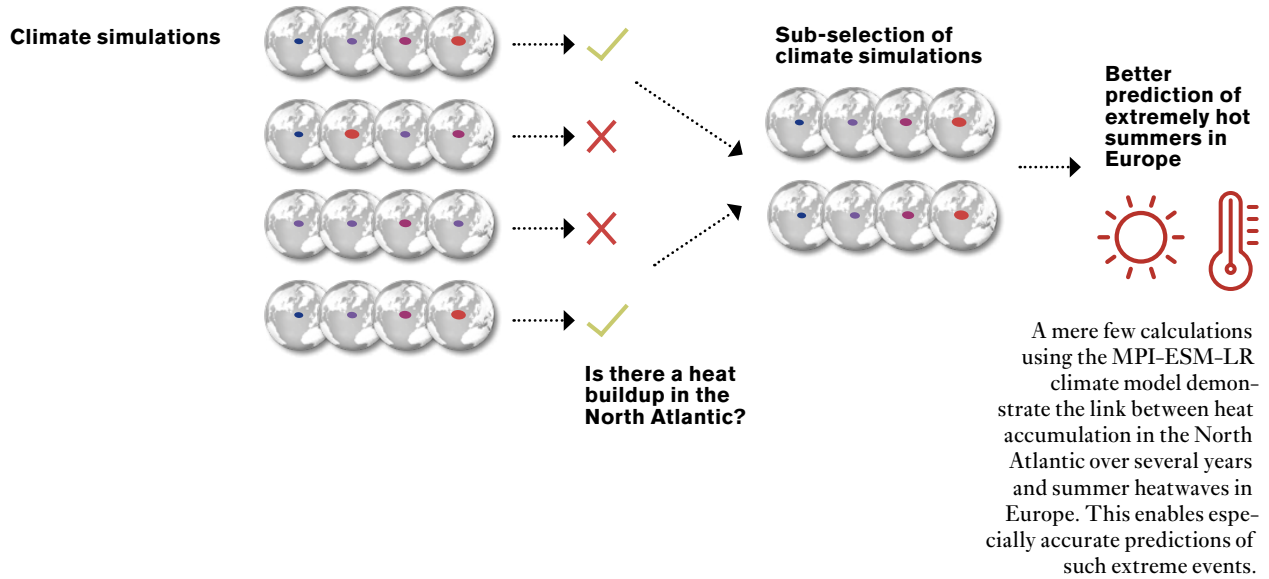
HEAT WARNINGS YEARS IN ADVANCE

In the future, it may be possible to predict summer heatwaves in Europe up to three years in advance. An international team led by the Max Planck Institute for Meteorology has shown that extremely hot European summers can be predicted more accurately based on heat content in the North Atlantic. Previously, Max Planck researchers discovered that heat

accumulation in the North Atlantic often builds up over three years before summer heatwaves in Europe. A new study shows that model calculations taking this mechanism into account depicted heatwave summers over the past six decades more reliably than simulations neglecting that connection. As a byproduct of the study, the model calculations predict

a heatwave in Europe for 2025. This aligns with forecasts from the European Centre for Medium-Range Weather Forecasts. The Max Planck team is now working on calculating heat extremes with regional accuracy and making these forecasts available to the agricultural sector.

www.mpg.de/24671106



GRAPHIC: GCO, BASED ON LARA WALLBERG

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GREEN NICKEL FOR THE ENERGY TRANSITION

Nickel is a key component in stainless steel and many other alloys used in special applications. It is also essential for producing high-performance lithium-ion batteries. It's no wonder that the demand for nickel is expected to double by 2040. However, around 20 metric tons of CO₂ are currently emitted for every metric ton of nickel produced. A team from the Max Planck Institute for Sustainable Materials has developed a climate-friendly, energy-efficient process for extracting nickel. This new process also allows for the use of previously overlooked low-grade ores. Nickel is extracted from these ores in a single step using hydrogen plasma. Considering the CO₂ released during nickel ore mining and transportation, the new process reduces CO₂ emissions by 84 percent. Additionally, the new process eliminates the need for the repeated heating and cooling required in the conventional pro-

cess. This lowers the energy required for nickel production by up to 18 percent. The process is easy to implement in industry as the necessary equipment is already widely available for other purposes. It can be used to extract other metals as well, such as cobalt, which plays a key role in electric vehicles and energy storage.

www.mpg.de/24637660

Conventional nickel production, like the kind used here in Sorowako, Indonesia, generates 20 metric tons of CO₂ per metric ton of nickel.



IMAGE: SOPA IMAGES / SIPA USA / PICTURE ALLIANCE

LIARS LIE AGAIN

People who have lied once are likely to lie again in similar situations. This is demonstrated by a recent study by the Max Planck Institute for the Study of Crime, Security and Law. Previous studies had indicated that the likelihood of a person lying depends largely on the specific situation. However, these earlier studies investigated lying behavior under very different conditions. In a new study, the Max Planck team investigated lying in situations that are structurally very similar. The researchers observed how people behave when they repeatedly find themselves in situations in which they can earn a small amount of money by lying—without fear of being punished for their dishonesty. The finding: repeated lying is not a matter of opportunity, but of personality. www.mpg.de/24406277

SHY AND INNOVATIVE

The assumption that exploratory and risk-taking personalities are better problem solvers is widespread, both in behavioral research and among the public. However, one study suggests that this is not the case—at least not in mice. Researchers from the Max Planck Institute for Evolutionary Biology tested over 100 wild house mice in natural enclosures and laboratory conditions to see how well they could solve tasks. Shy mice, who tend to avoid risky situations, returned to the tasks more often than courageous mice, thus increasing their chances of success. This means that innovative

mice are first and foremost persistent, and not necessarily courageous. The test environment also had a significant impact on innovation. In the quiet laboratory environment, 60 percent of the mice succeeded in solving at least one task. In the turbulent environment of the natural enclosures, only around 20 percent succeeded. The same animal often behaved very differently in the two environments. Therefore, laboratory tests tend to provide information about what animals could do, not necessarily what they actually do in the wild. www.mpg.de/24460941



IMAGE: MPI FOR EVOLUTIONARY BIOLOGY / ALEXANDROS VEZIRAKIS

A house mouse tries to reach a mealworm in a hiding place that it needs to push open to access.

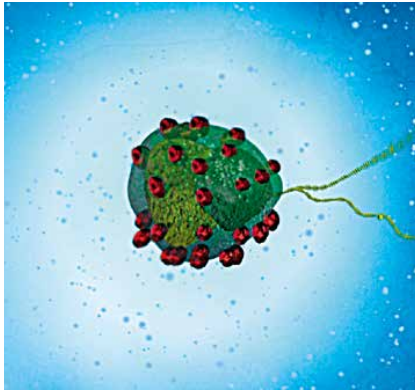
FOIE GRAS WITHOUT FORCE-FEEDING

Foie gras is made from goose liver, and it is considered a delicacy. However, it has long been the subject of criticism because the production process requires the brutal force-feeding of geese. Researchers at the Max Planck Institute for Polymer Research in Mainz, together with colleagues from the University of Southern Denmark, have now developed an alternative that has a sim-

ilar texture and taste. First, the team examined the fat content and proportion of collagen fibers, which make up a large part of the food's mouthfeel. Based on these analyses, the researchers designed a recipe for foie gras that's more friendly to animal welfare. They produced a gel from collagen-rich tissue, such as goose skin, and mixed it with liver and fat to create a pâté. The

fat was previously treated with goose lipases, which are enzymes that help digest fat. The pâté produced in this way closely mimics the mouthfeel and melting texture of foie gras. The researchers have applied for a patent on the recipe and hope to collaborate with companies that can produce it as an alternative product. www.mpg.de/24396968

IMAGE: MPI-IS



This illustration shows an alga of the species *Chlamydomonas reinhardtii* that is equipped with magnetic nanoparticles and can therefore be controlled by magnetic fields.

TRAVELING THROUGH THE BODY VIA ALGAE

Is a remote-controlled journey through the body's blood vessels and veins mere science fiction, or is it reality? Shrinking down a submarine will probably remain in the realms of fiction. Yet, as an alternative, researchers are focusing on unicellular microalgae because they are excellent swimmers. These cells propel themselves forward in liquids with the help of two flagella, much like breaststroke swimmers. Two researchers from the Max Planck In-

stitute for Intelligent Systems have coated the ten-micrometer-sized cells with magnetic nanoparticles. Using external magnetic fields, the researchers were able to steer the microswimmers precisely through a pool of water and through a 3D-printed tunnel system with narrow spaces and channels, similar to those in the human body. In the future, these microswimmers could be used to deliver medication to specific disease sites. www.mpg.de/24701449

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Conducting research in Minecraft: a player searches for food in the green blocks.



IMAGE: CHARLEY WU

SUCCESSFUL LEARNING

Those who can skillfully combine their own knowledge and the experience of others tend to be particularly successful in competitive situations. An international team of researchers, including those from the Max Planck Institute for Human Development, investigated how people combine individual and social learning in the video game Minecraft. The task was to find hidden vegetables in a de-

finied area, either alone or as part of a team. Team players could observe other teams searching and draw conclusions about other hiding places based on where they saw those teams find what they were looking for. The most successful participants were those who adapted their approach flexibly to the environment. Using a specially developed method to measure gaze data, the team developed a

model that integrates where people look, how they move, and the decisions they make when searching for food. This model combines individual and social learning. The new approach makes it possible to link artificial intelligence learning algorithms with flexible social mechanisms based on the successful behavior of others.

www.mpg.de/24616885

COLORFUL BIRDS

Increasing urbanization around the world is considered one of the main causes of the ongoing decline in biodiversity. Studies show that city life poses major challenges for animals and impacts their behavior. Birds, for example, give birth to fewer and smaller offspring in urban environments than they do in rural areas, and traffic noise impairs their development. Researchers at the Max Planck Institute for Biological Intelligence have now discovered another unexpected effect. They investigated whether bird species that are successful in urban environments differ in color from non-urban species. They found that urban birds are less likely to have brown plumage. Additionally, there are more bird species with eye-catching plumage living in urban environments. City life, therefore, appears to be favorable for more colorful species. This could be because there are fewer predators, so “being seen” poses less of a risk than in more

rural areas. Additionally, birds in cities do not need to use dark feathers to protect themselves against the cold because it is usually warmer there than in the surrounding countryside.

www.mpg.de/24483331



IMAGE: MPI FOR BIOLOGICAL INTELLIGENCE / KASPAR DELHEY

The blue-faced honeyeater *Entomyzon cyanotis*, with its striking coloration, has successfully colonized cities in Australia.

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MINI-INJURIES TO THE BRAIN

Cerebral small vessel disease is an important risk factor for stroke and dementia. It damages the small blood vessels that supply nerve fibers and areas inside the brain. Because the disease progresses gradually, it often goes undetected for a long time. Researchers at the Max Planck Institute for Human Cognitive and Brain Sciences investigated which factors play a role in the development of damage in different locations in the brain. Their

findings show that people with high blood pressure and obesity are often affected by the disease. Amyloid, a protein associated with Alzheimer’s disease, also appears to play a role in vascular damage in deep areas of the brain. The researchers now aim to identify the genetic factors underlying such damage, which could enable the development of targeted therapies in the future.

www.mpg.de/24518139

In cerebral small vessel disease, damage (orange and yellow) occurs at characteristic sites.

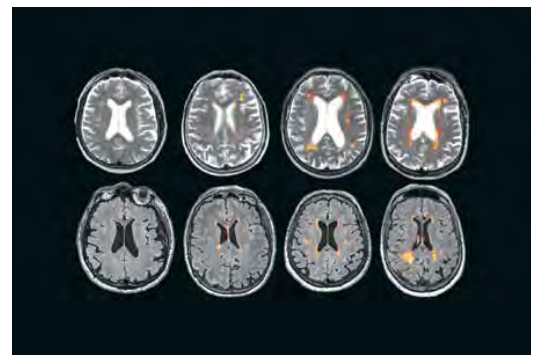


IMAGE: MPI CBS



A chimpanzee mother and her young in Tai National Park in Côte d'Ivoire.

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HUMAN-LIKE

Social relationships in childhood significantly influence a person's emotional and social development. A secure attachment to a caregiver fosters self-confidence and resilience. Children with insecure-avoidant attachments are more independent and do not seek their caregivers' support as much. Another type found in people is referred to as disorganized attachment. This occurs when a caregiver acts aggressively toward the child, triggering fear and trauma. Consequently, the child may behave inconsistently, seeking affection while also being afraid of the caregiver. This type of attachment can make it difficult to process emotions and may lead to lifelong psychological issues. Researchers at the Max Planck Institute for Evolutionary Anthropology discovered that young chimpanzees also develop different types of attachment. Some feel secure and rely on their mother in times of need. They confidently explore their environment because they know their mother is there for them. Others have an insecure-avoidant attachment. Disorganized attachments do not appear to

exist in chimpanzees living in the wild. However, over 60 percent of chimpanzee orphans living in human care do indeed exhibit this type of attachment. Chimpanzees are also more similar to humans in their communication abilities than previously thought. Researchers have discovered that these animals can combine individual calls to give them new meaning. In one study, they examined the meanings of various individual calls and calls made up of two individual calls. The chimpanzees use combinations that add meaning (e.g., A = eating, B = resting, and AB = eating plus resting) and combinations that specify meaning (e.g. A = eating or locomotion, B = aggression, and AB = locomotion). Additionally, they use combinations that create new meanings (e.g. A = resting, B = belonging, and AB = nest building). These findings show that the ability of chimpanzees to communicate has been greatly underestimated, as, perhaps, has the ability of other animal species.

www.mpg.de/24675832
www.mpg.de/24666339

DIFFICULT ACCESS

Applicants for the police force are in high demand, but many fail due to barriers related to their origin. In a comprehensive study, Sabrina Ellebrecht from the Max Planck Institute for the Study of Crime, Security and Law compared the success rates and test results of applicants with and without a migration background. She also analyzed the assessment processes of personnel decision-makers. The findings showed that discrimination risks were evident even during the pre-selection and cognitive per-

formance tests, during which applicants remain anonymous to the organization. Despite having a similar education, applicants with a migration background had poorer chances due to language-heavy test elements. Many also failed questions asking how they would behave as police officers in typical or critical situations, such as delivering news of someone's death. Such tasks are culturally sensitive, so people who have experienced different cultural socialization may be at risk of discrimination.

www.mpg.de/24461010



The Esa's Euclid space telescope has photographed a circular, luminous Einstein ring surrounding the center of the galaxy NGC 6505.

ONE RING TO FIND THEM

Shortly after the start of its scientific mission, the Euclid space telescope observed a rare phenomenon: an Einstein ring formed around the center of the galaxy NGC 6505. This ring of light originates from a previously unknown galaxy lying far behind NGC 6505. Rings such as these are formed when a massive galaxy or cluster of galaxies bends the light of distant objects and amplifies it like a magnifying glass. This phenomenon is based on the general theory of relativity, which states that large masses distort space-time. Light no longer

moves in straight lines. Using model calculations, researchers at the Max Planck Institute for Astrophysics deduced the mass that bends the light and how this mass must be spatially distributed across the shape and size of the ring. The luminous mass of NGC 6505 is known. However, according to the model calculations, the mass forming the Einstein ring around the galaxy is larger, which means that approximately 11 percent of the curvature of the light is due to dark matter.

www.mpg.de/24225918

MULTIPLE SCLEROSIS AND INTESTINAL FLORA

In people suffering from multiple sclerosis (MS), immune cells attack and damage the insulating layer of nerve fibers in the brain. Several factors must align for the disease to manifest. One of these factors could be intestinal bacteria. Researchers, including those from the Max Planck Institute for Biological Intelligence, have examined identical twins, one of whom has MS. The siblings exhibited minor genetic differences and had lived together until early adulthood, so they had been exposed to similar environmental conditions. The scientists examined stool samples, as well as samples taken endoscopically from the small intestine, the place where microbes can affect the body's im-

mune cells. They then gave samples from the small intestines of either a healthy or an ill twin to genetically modified mice. In a germ-free environment, these mice remain healthy for the duration of their lives; however, after colonization with intestinal bacteria, they can develop an MS-like disease. In the study, the mice that showed symptoms were mainly those whose intestines had been colonized with microbes from MS patients. The researchers identified two types of bacteria in the stool of the diseased animals that are potentially disease-causing. The next step is to investigate whether other microbes could be involved in the development of MS.

www.mpg.de/24685137

HEREDITARY LOVE OF MUSIC

Melodies can touch us, make us dance, cry, or dream, but not everyone responds the same way. The extent to which people enjoy music is largely determined by genetics. This is demonstrated by a study of over 9000 twins from Sweden. A research team led by the Max Planck Institutes for Psycholinguistics and Empirical Aesthetics compared the musical preferences of identical and fraternal twins. Since identical twins are more similar in this regard than fraternal twins, genetics presumably plays a role. Indeed, the Swedish sample showed that 54 percent of differences in music perception are genetic. The researchers also found evidence that different genes influence different aspects of music enjoyment, such as dancing to the beat or making music with others.

www.mpg.de/250201en



IMAGE: MPI FOR BIOLOGICAL INTELLIGENCE / JULIA KUHL

A study on twins shows which intestinal bacteria may play a role in the development of multiple sclerosis.

NATURE CONSERVATION IN THE ANTHROPOCENE

We are living in an age of unprecedented upheaval—climate change, biodiversity loss, and technological marvels. Amid this disruption, Carla Avolio and Martin Wikelski envision a new kind of conservation, one where technology helps us to protect nature and even return its agency.

It's hard to say when the idea of nature conservation was born—the moment when we grasped that our exploitation of nature was threatening the ecosystems that sustain us. But in the part of the world that we often call “the West” there is a moment in history that, while not necessarily the first, is certainly considered a defining chapter in the story. This moment came in 1804 when, amidst the unbearable humidity of a summer day in Washington D.C., Alexander von Humboldt stepped into the private study of the third President of the United States. The 34-year-old Humboldt was on his way home from his remarkable expedition across Latin America. Then President, Thomas Jefferson, was eager to hear of the naturalist's discoveries. The pair met that day, and several times after, spending hours discussing politics and nature, and how the former can wreak irrevocable damage to the latter.

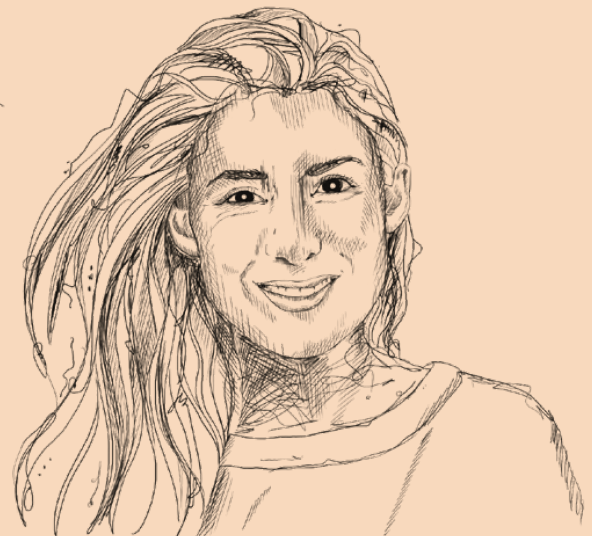
Humboldt's travels through the Spanish-controlled territories of the Americas had exposed him to the devastating effects of colonial exploitation on the environment: valleys in Mexico left barren by drainage; Cuba stripped of forests for sugar plantations; and mines everywhere plundering the soil of its raw materials. During Humboldt's stop in Washington, he and President Jefferson discussed how politics, economics, and the environ- →

VIEW POINT

MARTIN WIKELSKI & CARLA AVOLIO



Martin Wikelski heads the Department of Animal Migration at the Max Planck Institute of Animal Behavior in Konstanz. He has played a leading role in developing Icarus, a satellite-based system for continuous wildlife monitoring. The system makes it possible for researchers worldwide to gain valuable insights into animal behavior. Beyond that, Icarus also ushers in a new era of conservation. Acting as sensors for the health of the Earth, animals form a planet-wide network—an “Internet of Animals.”



Carla Avolio leads the press team at the Max Planck Institute of Animal Behavior. As a freelance writer, the biologist has published feature stories on wildlife for journals and magazines.

ILLUSTRATION: SOPHIE KETTERER, MPG

ment were forces that were intricately intertwined. Humboldt's key insight—that the world was a single, interconnected organism—influenced leading thinkers of the American republic, shaping a national identity linked to nature. Today, US national parks generate USD 30 billion each year, and about two-thirds of voters favor protecting and strengthening the national park system. Almost 70 years after that historic meeting in Washington, the United States passed the 1872 act that created the world's first national park—Yellowstone.

It may be surprising that the world's 195 countries have only been setting aside parts of nature as state-run reserves for about 150 years. Yet today, several thousands national parks around the globe stand as monuments to that vision. This rapid shift in mindset is a reminder that human attitudes towards nature can change—and fast. As we grapple with a sixth extinction event, that change is more urgent than ever.

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IS IT STILL
POSSIBLE
TO STOP
SPECIES GOING
EXTINCT?

The planet's ecosystems still provide trillions of dollars in services every year—an overwhelming reminder of nature's productivity and our dependence on it. Yet we enjoy this bounty in the shadow of a crisis. Wild animal populations are plummeting. Some species are already extinct, while others are teetering on the brink. In Europe, there are 600 million fewer birds today than in 1980—a loss of nearly 20 percent. In North America, bird numbers have fallen by 30 percent since 1970. Insect diversity is declining as well. You've probably witnessed this "disappearing" of life firsthand. How many songbirds have you heard in the woods recently? When did you last clean your windshield of insects?

There's no mystery what lies at the heart of this biodiversity crisis. In the last few centuries, our human population has ballooned. Today, with nearly 8 billion of us on the planet, the human species leaves its mark everywhere: destroying habitats, polluting landscapes, overhunting wildlife. With all these threats, is it even possible to halt the mass extinction of species? The answer is not just "yes"—it's an urgent "yes." The tools to safeguard our planet's biodiversity are within reach, but they demand new research, technological innovation, and a reimagined global conservation mindset.

The Galápagos Islands offer a striking example of what conservation can look like. In the 1950s, a young Max Planck researcher traveled to the Galápagos hoping to study the islands' unique ecosystems in their pristine

THE KEY IS TO LINK PROTECTED AREAS

form. Over several visits, the work of Irenäus Eibl-Eibesfeldt paved the way for Ecuador and the United Nations to place the Galápagos Archipelago under strict protection. But it soon became clear that this traditional approach—setting aside a space for nature to thrive—was not enough to fend off humanity’s inexorable creep in the Galápagos.

Invasive species such as goats, rats, and pigs had ravaged the islands’ native plants and wildlife. So, Felipe Cruz, a local conservationist and external collaborator at the Max Planck Institute for Behavioral Physiology in Seewiesen, proposed a radical fix: instead of merely protecting what remained, the ecosystem should be restored by removing the invaders. It was a bold idea that ran counter to prevailing conservation norms and drew strong opposition. But it worked: the iconic giant tortoises, once pushed to the brink of starvation by goats, now roam the islands in large numbers again. On Floreana Island, where they had been extinct until recently, they are now being reintroduced and monitored across their whole lives with a technique that we developed. This success shows that we can safeguard nature on our planet by fostering its capacity to adapt and evolve. This is what can provide safe passage for animals, old enough to have seen Darwin stepping off the Beagle, to walk with their descendants into green pastures.

Conservationists are therefore calling for an expansion of the “Galápagos paradigm,” essentially the “rewilding” of nature. The Half-Earth Project, popularized by American biologist E. O. Wilson, proposes setting aside half the planet’s surface as protected spaces for nature. These natural areas would form a contiguous network, similar to the plan that former Director at the Max Planck Institute for Ornithology Peter Berthold proposed for Germany. Connectivity is the key. The reserves would not be isolated islands, but interconnected ecosystems where animals can move as freely as possible. Granted, it is a bold vision. But it conveys an uncomfortable truth: we can only preserve both nature and its economic value if we restore the evolutionary potential of large landscapes.

Thankfully, we have more than vision—we have the means to realize it too. One of the most exciting advances in conservation today is the use of wearable technology to monitor animal behavior in real time. These devices are revolutionizing the way we understand and protect wildlife. They allow us to track migration patterns, monitor health, and even predict when an animal is in danger. This data is not only valuable for researchers—it is transformative for conservationists on the ground, enabling rapid



responses to threats and a more proactive approach to protecting endangered species.

Take, for example, the case of the white stork. Using GPS trackers, scientists discovered that electrocution from overhead power lines was a major cause of stork mortality. A simple intervention—replacing insulators—has sharply reduced the number of fatalities. Thanks to this and other improvements, stork populations are rebounding across Europe. In a similar way, we have tracked the movements of wild dogs in South Africa’s Kruger National Park. Now we can alert park rangers immediately whenever an

animal is caught in a wire snare set by poachers. Over the past two years, our Max Planck partner Louis van Schalkwyk has freed 45 wild dogs from snares—about ten percent of the entire Kruger population.

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WITH THEIR EYES,
NOSES, AND EARS
ON THE GROUND,
ANIMALS ACT AS AN
EARLY-WARNING
SYSTEM

With the gift of foresight, we could even prevent animals from innocently stepping into the countless traps we set for them, whether those traps are intentional or not. Technology is making an increasing contribution here: in southern Africa, where poachers kill hundreds of rhinos every year, we are equipping impala, zebra, giraffe, and elephants with the tools to protect rhinos and each other. Animals are fitted with tiny wearable ear tags that send data on their movement to rangers. Operating as a collective of eyes, noses, and ears on the ground, the animals are an

early warning system for the presence of poachers: when poachers are on the move and the surrounding wildlife is behaving unusually, rangers can rush to the rhinos’ aid.

Beyond wildlife wearables, an arsenal of remote sensing technology is helping to bring large-scale events—too big and complex for us to fathom alone—into view. These are being deployed off the coast of California, where whales feed in the same waters used by international shipping vessels. The Whale Safe tool gathers live data from acoustic monitoring, oceanographic models, and human whale sightings to warn vessels of potential collisions. Similarly, BirdCast draws on multiple data streams, including radar stations across the United States, to predict when cities should dim building lights to ensure migrating flocks are less likely to strike them.

Artificial intelligence is boosting our predictive power further. Our Institute is trialing a smart cat collar that we hope can halt the staggering decline

ANIMALS ARE GAINING A PLACE IN A NATION'S ECONOMY

of songbirds. According to the Nature and Biodiversity Conservation Union (NABU), domestic cats kill up to 200 million songbirds in Germany every year. Powered by AI, our cat collar recognizes hunting movements and plays a blackbird alarm call that scares birds away.

As we develop these technologies, we are moving toward a paradigm shift: one where animals have a voice in their conservation. A groundbreaking project already under way in Rwanda is giving animals a place in the nation's economy. The country's gorilla population is valued at more than USD 1 billion, and the Rwandan government is testing a system that lets the animals hold their own bank account. As a first step, a family of mountain gorillas in Volcanoes National Park has been handed control of a few million US dollars. Each gorilla—that is, its digital avatar—can now authorize daily micro-payments to the people who best safeguard its well-being, for example, by protecting the forest or warding off poachers. The system combines AI with the knowledge of local rangers to identify the gorillas' needs and to make the payments. In this way, people are motivated to protect the animals rather than exploit them. The gorillas are therefore pioneers of a new model of collaboration between animals and humans.

Despite the fact that wearables for wildlife were only conceived as research tools some two decades ago, they may become vital to conservation in many areas. That's because these wearables are part of a tech revolution that has the power to reconnect humanity with wild animals and the natural world. We argue that this change in mindset—reconnecting us to life on our planet—is needed if global conservation is to be successful in the future.

That same insight came to Alexander von Humboldt on a June day in 1802, as he stood at the precipice of an inactive volcano in present-day Ecuador. Humboldt and his team had made a grueling ascent toward the summit of Chimborazo, enduring icy winds, treacherous ridges, and dizzying sickness. When they could go no further, Humboldt paused to take a reading from the barometer: 19,413 feet. No one had ever come this high. As the naturalist looked down Chimborazo's slopes and over the vast landscape, he was struck by an epiphany: the world was interwoven into a single web of life. Everything, he realized, was connected.

The time has now come for us to act on that insight.



FEAR OF THE COLD-HEARTED CHATBOTS

Would you accept a court verdict delivered by an artificial intelligence (AI)? Or confide in a religious leader whose spirituality is AI-generated? Questions like these are at the heart of a current study involving the Max Planck Institute for Human Development. Drawing on several professions as examples, the researchers assessed how strongly people in different countries fear that AI might replace human labor.



Judge

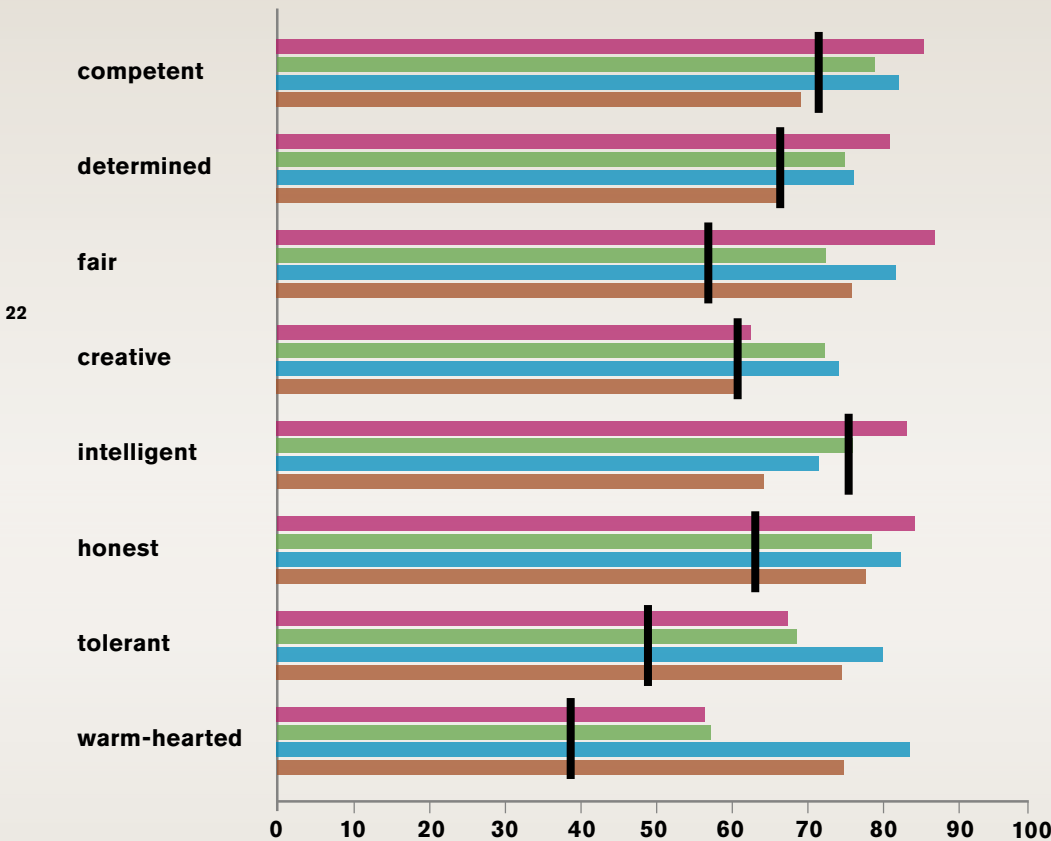


DIAGRAM: GCO, FROM DONG ET AL., AMERICAN PSYCHOLOGIST, 2024

HOW WELL CAN AI MIMIC HUMAN CHARACTERISTICS?

Participants were asked to rate on a scale from 0 to 100 which human traits they expect from each profession and how capable they believe AI is of fulfilling those traits (black line). The chart shows the results for 500 respondents from Germany.



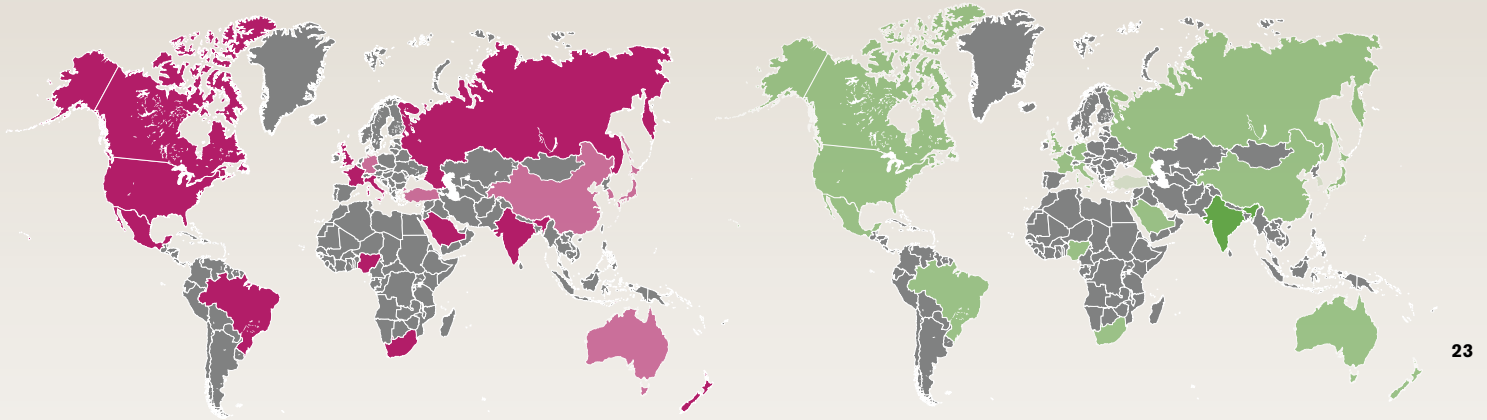
Journalist



Carer



Religious leader



Little fear

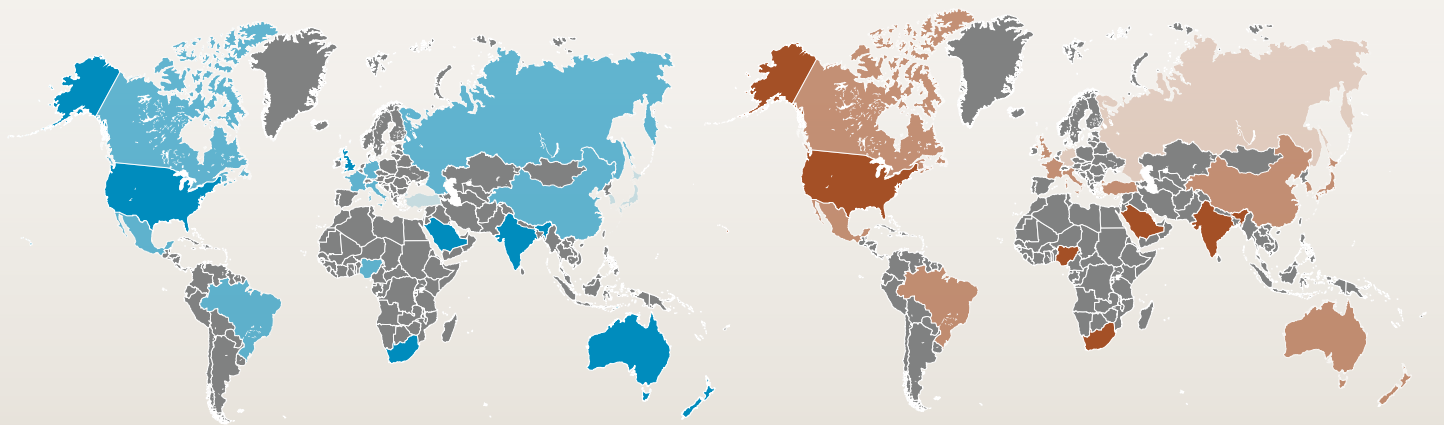


Moderate fear



Significant fear

23



CULTURAL DIFFERENCES IN THE PERCEPTION OF AI

In a global survey of 10,000 people across 20 countries, researchers assessed how strongly respondents fear that AI could take over these professions. They found clear differences between countries: the highest average fear levels were recorded in India, Saudi Arabia, and the US, and the lowest in Turkey, Japan, and China. In Germany, concerns are at a moderate level. Overall, the level of fear depends on the gap between the human traits people expect and the capabilities they attribute to AI (see the chart on the left). Uneven experiences with technology, different media portrayals, and AI policies may explain these country-specific differences.

FOCUS

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Phase diagram of the activity of a node in a harmonically oscillating network. The line shows how the activity of the node changes when there is a wave-shaped input signal. The color indicates the phase of the input signal the system is currently experiencing, from blue (early phase) to red (late phase).

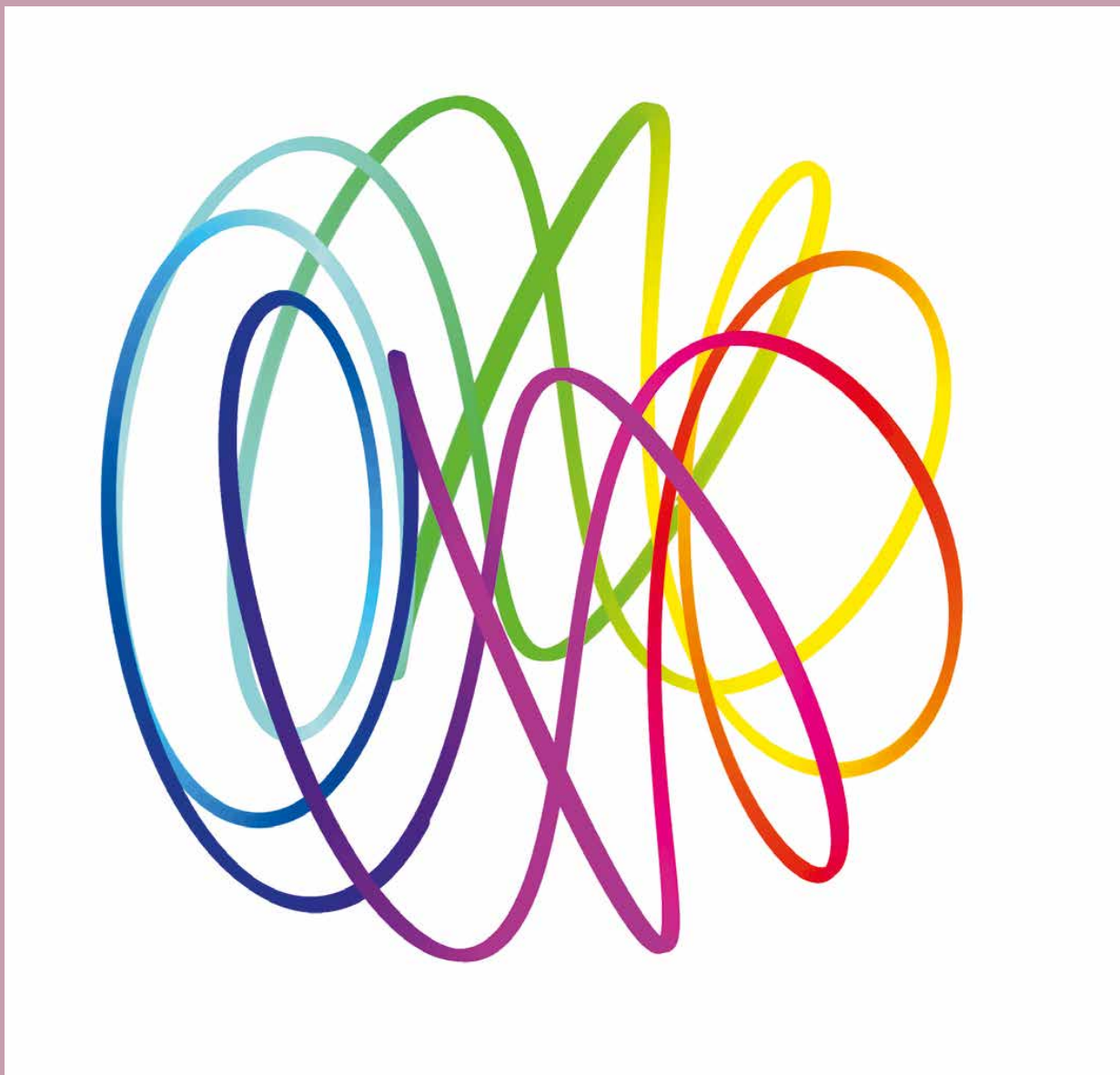


IMAGE: EFFENBERGER, F., CARVALHO, P., DUBININ, I. AND SINGER, W., 2025. "THE FUNCTIONAL ROLE OF OSCILLATORY DYNAMICS IN NEOCORTICAL CIRCUITS: A COMPUTATIONAL PERSPECTIVE." PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES, 122(4), P.E2412830122

AI GATHERS MOMENTUM

TEXT: TIM SCHRÖDER

Natural brains work much more efficiently than present-day AI systems. Felix Effenberger is researching the role of rhythmic activity in information processing as part of Wolf Singer's group at the Ernst Strüngmann Institute (ESI) for Neuroscience in Frankfurt. Based on the results of the research, it may be possible to develop novel computer chips for AI that function similarly to neural networks in the brain, fulfill functions that are challenging for digital computers, and require considerably less energy than today's digital chips.

Both the training and ongoing operation of current AI large language models (LLMs) like ChatGPT consume a significant amount of energy. They present a quickly growing, global demand for energy that will continue to increase as AI applications become more widespread. Training just a single current LLM consumes an enormous amount of energy, and the ongoing operation of ChatGPT likely requires more than 500 megawatt-hours every day. The elementary computing operations of these models are not particularly complex; however, they need to be performed extremely often and using huge volumes of data. The thirst for energy of today's AI systems is a result of their sheer size. In contrast, the human brain consumes approximately 30 watts of energy, equivalent to less than a kilowatt-hour per day, while accomplishing tasks that artificial systems have yet to imitate. Additionally, the brain needs only a small fraction of the data required to train modern AI systems.

- 26 What makes the brain so efficient, and what can it teach us about the ongoing development of AI? Alongside his colleagues in Wolf Singer's working group at the ESI, Felix Effenberger is researching how information is processed in the brain. The legally independent institute was founded by the brothers Andreas and Thomas Strüngmann in 2008 and is affiliated with the Max Planck Society. Effenberger's findings are not only relevant for neuroscience; they could also form the basis of a new type of AI model that functions similarly to its natural precursors, solves certain problems more elegantly than current AI models, and consumes much less energy.

Most of today's AI systems are based on a principle of information processing that was proposed for machine-based pattern recognition in the middle of the 20th century known as the "perceptron." The model for this principle was the contemporary understanding of the organization of neural networks as they occur in animals and humans. In this model, data flows through different processing layers from an input layer to an output layer. "The problem with current AI systems is that their performance is achieved mainly by scaling this principle. That means increasingly large models must be used to achieve better performance. And this scaling paradigm continuously increases the computa-

tional effort, and the energy required," explains Effenberger.

SUMMARY

The information processing strategies in artificial and natural systems are fundamentally different. The former are based on serially processing digital signals and are typically not dynamic. The latter exploit the dynamics of recurrent networks with oscillating nodes and the distributed processing of analog signals.

The researchers have recreated some characteristic properties of natural systems in artificial networks. They employ a computing principle that has been scarcely researched to date, utilizing oscillations, waves, and interference patterns to process information. That makes the resulting models especially powerful.

AI research is likely on the brink of a paradigm shift. The current strategy of improving the performance of traditional AI systems through sheer scaling will be replaced by the development of analog and hybrid analog-digital systems inspired by nature.

Despite the success achieved by the strategy of continuously enlarging classic model structures to date, it is now reaching its limits, as further scaling becomes both technically challenging and prohibitively expensive. One limitation of the current models is that such systems are not dynamic; that is, the model's state doesn't change over time. Instead, all processing steps occur sequentially. In natural neural networks, however, all neurons interact with each other simultaneously, creating a complex dynamic that can be harnessed for parallel information processing. That's why natural systems can compare an enormous number of variables with each other at the same time, allowing them to work with smaller systems. Artificial systems, lacking the dynamic properties of natural systems, are forced to explicitly simulate temporal relationships, and these calculations are expensive. Most current artificial systems thus do not have the dimension "time" at their disposal for the purposes of computation. Additionally, computing processes and storage are strictly segregated on present-day computers. This is a typical characteristic of modern digital computers, ranging from pocket calculators to supercomputers, which are all based on the architecture designed by the mathematician John von Neumann in the mid-20th century. However, the transfer of information between the processor and memory, which is necessary at every computing step, is inefficient and energy intensive. The brain functions in a fundamentally different way: it is a dynamic system whose processing units—individual neurons or small circuits composed of neurons—continually exchange information amongst each other using reciprocal connections. "That's why we talk about recurrent networks with feedback," Singer explains. Unlike serially coupled networks, which do not allow for temporal dynamics, brains can effortlessly calculate spatial and temporal relationships between variables, processing them simultaneously. This allows nature to work with smaller and more efficient networks.

An additional characteristic property of natural networks is that they can oscillate, with these oscillations covering a wide range of frequencies. The responses of pop-

“If oscillations, waves, and interference patterns are used to process information, AI will start to become truly intelligent.”

FELIX EFFENBERGER

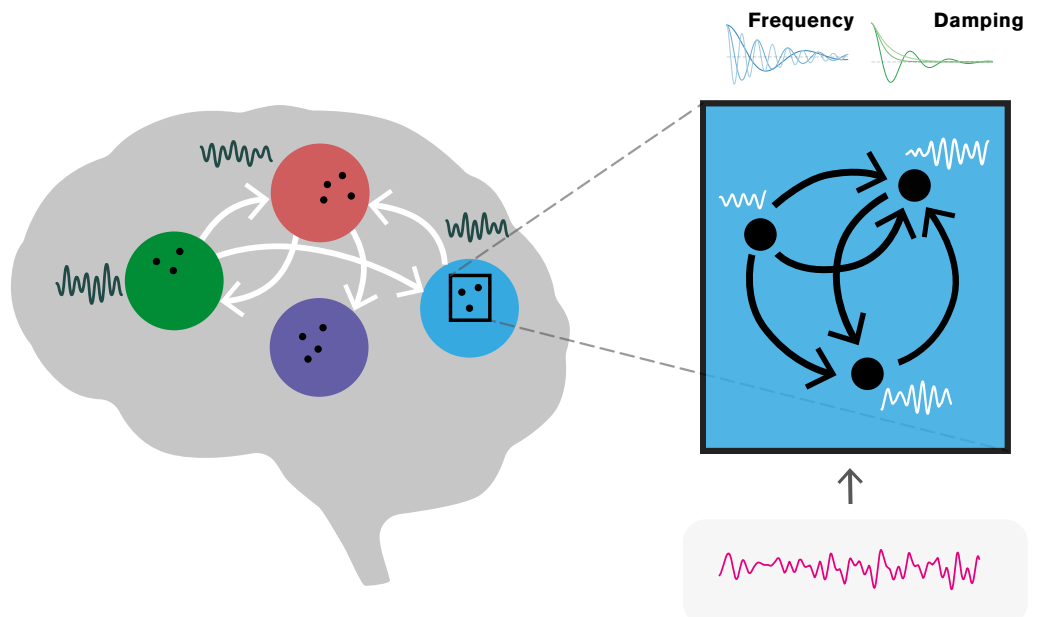
ulations of neurons tend to be rhythmic, exhibiting a temporal structure that can be used to encode temporal relationships. This furthermore enables the coding of information by means of synchronized activity among a population of neurons and allows resonance to be utilized in order to process information. “Whether these oscillations fulfill a certain function is the subject of controversial discussions to this day. They may simply be a by-product of neuronal interactions. However, they may also facilitate coordination and clocking in computing operations, or even form the basis of a computing principle,” says Singer. To determine the function of oscillations in the brain, Effenberger and Singer have developed a model inspired by networks of the mammalian cerebral cortex. What is special about this approach is that the researchers designed the nodes of the network, which were simulated in a computer experiment, so that their ability to oscillate, or rhythmically respond, could be controlled. The dynamic properties of the network

nodes could be precisely adjusted by controlling their individual excitability, natural frequency, and damping. The researchers named their oscillating networks “HORNs”, which stands for “harmonically oscillating recurrent networks.” To their surprise, it turned out that these networks are superior to non-oscillating neural networks in many regards: they learn faster, tolerate noise better, and require considerably fewer parameters than non-oscillating networks while delivering comparable performance. Effenberger: “We were able to considerably increase the performance of neural networks by allowing them to oscillate in a controlled way. We found that this enables them to exploit a newly uncovered computational principle based on waves and their interference.” The oscillating networks convert any input signals into oscillating activity patterns. These spread throughout the entire network as waves, becoming superimposed, interfering, and thus generating complex patterns that can be used for information processing. “Processing does not take place serially or in isolation. Instead, it is distributed and holistic, comparable to the superimposition patterns of waves on the surface of water,” Singer explains. Over time, the interference patterns develop, exploit resonance phenomena, and form dynamic patterns. In HORNs, input signals interact with experience-based knowledge that is stored in the architecture of the synaptic weights. The substrate for computation and memory is identical, a property known as “in-memory computing.”

The wave patterns formed in oscillating recurrent networks enable a new form of information processing. These dynamic patterns can encode, store, and transport information through the phase position, fre- →

IMAGE: EFFENBERGER, F., CARVALHO, P., DUBININ, I. AND SINGER, W., 2025. “THE FUNCTIONAL ROLE OF OSCILLATORY DYNAMICS IN NEOCORTICAL CIRCUITS: A COMPUTATIONAL PERSPECTIVE.” PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES, 122(9), P. E242830122

A harmonically oscillating network as the counterpart to neural networks in the brain. Regions in the brain influence each other through their wave-shaped activity (left). The blue network consists of three recurrently coupled nodes (right). A stimulus that changes over time (red curve) is fed into the network and processed. The frequency (blue curve) and damping (green curve) of the oscillating nodes can be deliberately adjusted to reproduce some aspects of even more complex dynamics of the brain.



quency, and amplitude of the waves. Since they replicate a wealth of experimentally confirmed properties of the cerebral cortex, the researchers in Frankfurt suspect that the computing principle realized in the oscillating networks is also utilized in natural networks such as the cerebral cortex. To compare the performance of the oscillating networks and traditional systems, the researchers in Frankfurt have trained their networks to recognize handwritten numbers and spoken words. In this process, it became evident that even small networks learn surprisingly quickly and manage noisy data better than non-oscillating networks.

Effenberg and his team are thus combining the basics of machine learning and neuroscience, an approach referred to as NeuroAI. The insights obtained from sim-

ulating oscillating networks helped resolve longstanding questions in brain research, as the simulations made it possible to uncover mechanisms that are difficult to prove through experimentation. One example is the binding problem researched by Singer. It addresses the challenge of identifying which of multiple overlapping contours, colors, and textures belong to a specific object or background when observing a complex scene. The same problem arises when characteristics such as shape, smell, and noise need to be associated with a certain object, even though these properties are processed in different regions of the brain that are anatomically separate. The theory posits that the synchronization of nerve cell assemblies can be used to uniquely identify which groups of neurons (called ensembles) are involved in representing a specific object. The hy-

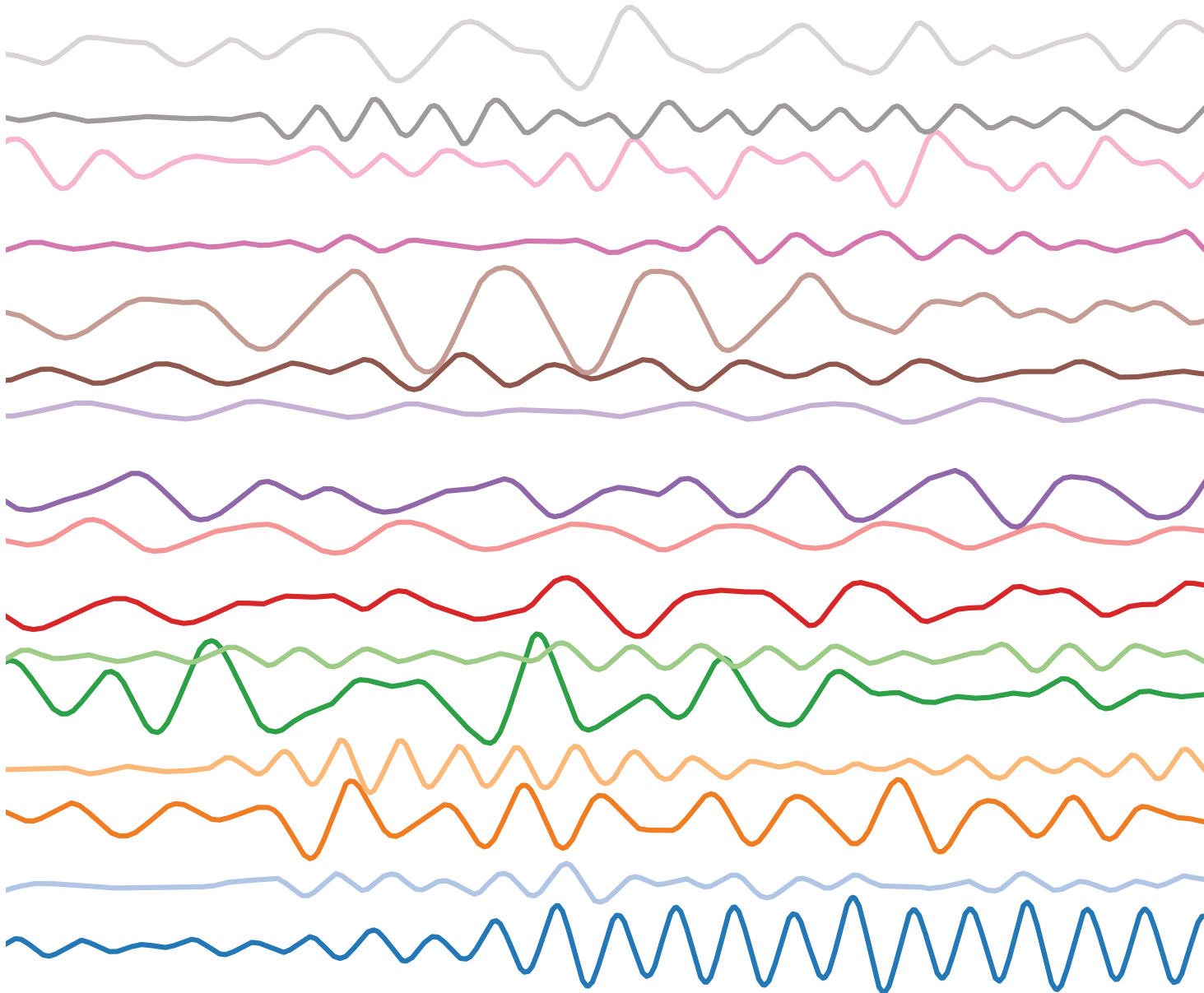
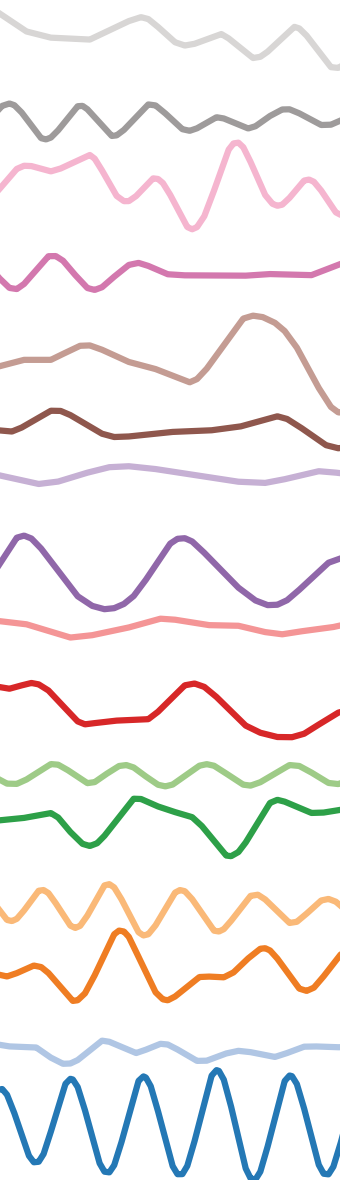


IMAGE: EFFENBERGER, F., CARVALHO, P., DUBININ, I. AND SINGER, W., 2025. "THE FUNCTIONAL ROLE OF OSCILLATORY DYNAMICS IN NEOCORTICAL CIRCUITS: A COMPUTATIONAL PERSPECTIVE." PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES, 122(4), P.E2412830122

hypothesis is based on experimental findings from Singer's laboratory: the responses from oscillating nerve cells are synchronized when they are stimulated by contours of the same object. The theory has not yet been proven beyond doubt in experiments, since oscillations cannot be manipulated in isolation without disrupting other processes. However, using the oscillating networks developed by the researchers in Frankfurt, the experimental observations can be reproduced, and the predictions in the hypothesis can be confirmed.

Additionally, the analyses demonstrated that the performance capability of the oscillating networks could be further enhanced if they were equipped with additional features inspired by nature. Networks whose nodes oscillate at different frequencies and damping levels, and



Activity of 16 oscillating nodes in a harmonically oscillating network processing a handwritten digit. The difference in both oscillation frequencies and damping creates an interference pattern that can be used to process and represent data. The wave patterns created resemble those of an EEG.

which are coupled with temporal delays, learn significantly faster than those in which every node is identical. These very properties also appear in natural systems, but their significance had not been clear until now. "All of these correlations convince us that our networks function according to the same principles as natural systems, and that the computational operations are much more complex than the ones present in non-oscillating networks," Effenberger says.

New Hardware for AI

Before oscillating recurrent networks can be incorporated into energy-efficient AI systems, however, a key obstacle must be overcome. Simulating these networks with existing digital chips is inefficient: for each time step, the network's state must be loaded from memory, processed, and written back again—a typical characteristic of von Neumann's digital architecture. The network's true strength is thus only evident when the actual dynamics of a physical system can be utilized for calculation. "That is why we want to construct new AI hardware that works with time-continuous, analog values—much like old record players or radios. In these chips, coupled electronic or optic oscillators are designed to take on the computing work, meaning continuous, analog information processing takes place instead of the serial processing of digital calculation steps," Effenberger explains. 29

These kinds of chips would not only be especially energy efficient, but also likely faster and potentially more adaptable than digital ones. What's more, they would be the first step toward artificial intelligence that functions more like its biological role model.

As the Frankfurt team's results demonstrated, oscillations are far from simple by-products of neuronal interactions. Instead, they form the basis of a fundamental computing principle. A new generation of AI systems that use efficient processing strategies instead of simply increasing computing power could benefit from these findings. "If oscillations, waves, and interference patterns are used to process information, AI will start to become truly intelligent," says Effenberger. The researchers from Frankfurt now aim to apply their findings in specific contexts as well. They plan to found a start-up with financial support from both private and public sectors and will develop computer chips based on computational strategies using oscillations. Perhaps the next paradigm shift in AI, therefore, does not lie in increasingly large models with more computing power, but rather in smaller, dynamic systems whose efficiency has been rigorously tested by evolution over millennia.

 www.mpg.de/podcasts/ki-und-biomedizin (in German)



A glimmer of light for diagnostics: Christina Hofer, who earned her doctorate at the Max Planck Institute of Quantum Optics, analyzes blood samples using an infrared laser. Machine learning methods can be used to detect various diseases in infrared spectra.



A DROP OF BLOOD IN LASER LIGHT

TEXT: THOMAS BRANDSTETTER

The biomolecules in our blood contain important information about the condition of our health. Researchers at the Max Planck Institute of Quantum Optics in Garching near Munich are using machine learning to simplify blood sample analysis. Their goal is to facilitate simple and inexpensive health checks that can detect diseases at an early stage.



IMAGE: THORSTEN NAESER / MPI OF QUANTUM OPTICS

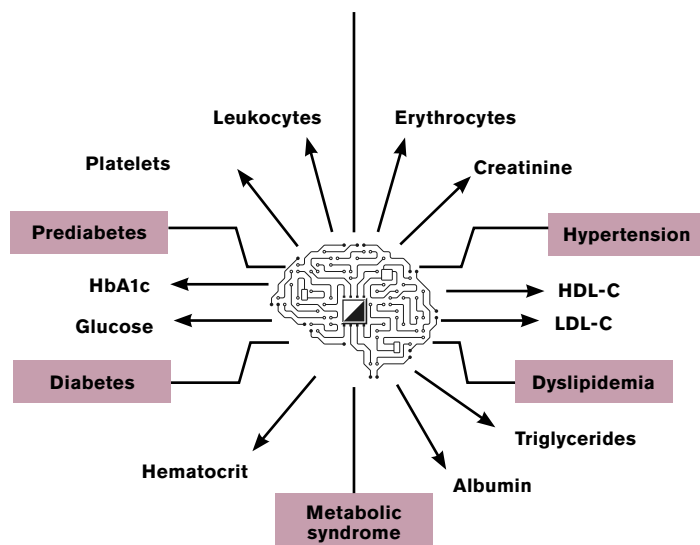
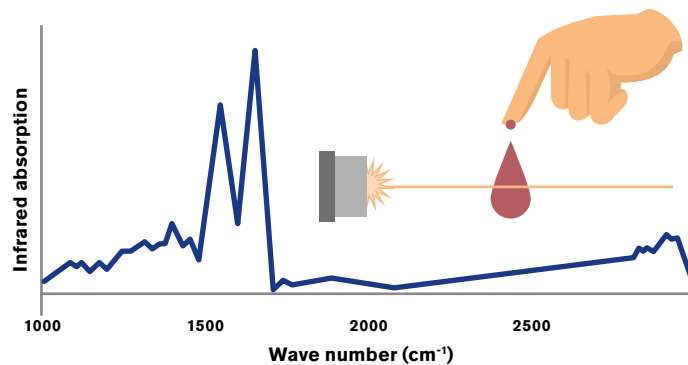
A quiet, yet powerful transition is spreading from medical laboratories to medical practices and hospitals: machine learning is rapidly conquering the world of health care. This is thanks to new, teachable algorithms that are highly effective when applied to tasks that require pattern detection. These algorithms help doctors evaluate X-rays, analyze tissue sections, and differentiate between benign birthmarks and melanomas. Increasingly often, their diagnoses are more accurate than those of human specialists. However, the lion's share of new methods that use artificial intelligence have yet to be approved for medical use. What we are currently experiencing is only the beginning of data-based medical progress.

At the Max Planck Institute of Quantum Optics, Kosmas Kepesidis is working on harnessing the power of machine learning for medical applications, specifically, the evaluation of measurements of human blood plasma. Together with his colleague Mihaela Zigman, the leader of the broadband infrared diagnostics research group, Kepesidis has developed a method that aims to make health screenings for the early detection of diseases like diabetes or lung cancer possible. The researchers' method requires just a single drop of blood that is subjected to a single measurement, which can be carried out in just a few minutes. The method is so fast and inexpensive that it has potential for mass implementation, which would enable comprehensive health screenings that can detect certain diseases at an early stage. This in turn would facilitate the development of better therapies. The potential benefit here is substantial—according to the Robert Koch Institute (RKI), around a million people in Germany suffer from undetected diabetes, and even more are unaware that they have high blood pressure.

Many diseases are reflected in the molecular composition of blood plasma. Modern laboratory technologies like mass spectrometry and nuclear magnetic resonance (NMR) spectroscopy have already shown potential for using measurements of individual biomarkers, like proteins or metabolic products, to detect diseases such as cancer or diabetes. However, these methods are elaborate and expensive. “They generally measure only a few molecules at once and often require complex sample preparation,” Kepesidis explains.

A Molecular Fingerprint

Suspicious changes in biomarkers can also be detected using infrared light, however. Humans perceive this part of the electromagnetic spectrum as thermal radiation. The light makes molecules vibrate. In this process, various substances respond to characteristic frequencies of the infra-



Comprehensive health check: combined with machine learning, infrared spectroscopy delivers a molecular fingerprint of blood plasma and makes it possible to detect widespread illnesses such as diabetes, high blood pressure, or a lipid metabolic disorder (which, together, constitute what is known as metabolic syndrome) with a single measurement.

red spectrum. It causes several hundred or thousands of atoms to wildly pulsate in complex biomolecules such as proteins. Kepesidis and Zigman use extremely short laser pulses with high bandwidths that stimulate all possible vibrations in the blood sample at the same time. If they shine light through a blood sample in this manner, the molecules contained in the sample absorb exactly the frequencies that are typical for them. The proteins, fats, and sugars in the blood plasma thus leave behind a kind of molecular fingerprint in the infrared spectrum. Even small changes in composition that are caused by diseases are reflected in the measurement.

“The new measuring method brought about a fundamental shift in how we evaluate the data,” says Kepesidis. Due to the countless molecular bonds in the sample, the measured spectrum is very complicated, and the molecular causes for a certain change cannot be easily detected. Thus, instead of analyzing why a certain peak in a spectrum is slightly higher or lower than normal, the machine learning models analyze the sample’s entire fingerprint at once. “That is the decisive advantage of our approach,” says Kepesidis. To do this, the researchers simply train their artificial neural network using the entire spectra. The “magic” in the depths of its neuron layers allows the AI to recognize patterns that indicate certain diseases.

To train the networks, Kepesidis and his team were able to use results from case-control studies (clinical studies). The goal of this was to find out whether certain factors, such as blood plasma composition, are connected to a certain disease. Typically, physicians initially form two groups for this purpose: people who already have the dis-

SUMMARY

Machine learning methods identify the signatures of different illnesses, such as diabetes, high blood pressure, metabolic syndrome, and diseases like lung cancer in infrared spectra.

For this purpose, artificial intelligence is trained to analyze the entire spectra. It can also learn to reduce these spectra to the essential information required for diagnostics.

Since the infrared fingerprints detect changes in health at an early stage, they are suitable for use in preventive population-wide health screenings. Data security and protection must be guaranteed during both the handling of training data and the use of data-based methods.

ease (cases) and healthy people (controls). Next, they investigate whether the groups exhibit different characteristics, such as in their blood plasma. While a person can only correlate individual abnormalities in an infrared spectrum with a certain illness, artificial intelligence can also detect more complex relationships and patterns in the spectra. That is how Kepesidis and Zigman were able to detect a series of chronic illnesses using a single measurement of the molecular fingerprint, based on Fourier-transform infrared spectroscopy. Together with Tarek Eissa, the doctoral student working on this project, they published their initial results last year in the specialist journal *Cell Reports Medicine*, based on samples collected in the framework of the KORA study conducted by Helmholtz Munich.

For their study, together with colleagues at LMU Munich and the Technical University of Munich, they examined over 5000 blood samples using infrared spectroscopy and, in the process, detected a series of health abnormalities—from lipid metabolic disorders to high blood pressure and diabetes—with 95 percent accuracy. However, unlike traditional diagnostics, the system can simultaneously calculate the probabilities of different diseases that are independent of each other. “The result could be something to the effect that a patient has a 70 percent probability of suffering from high blood pressure and, at the same time, a 40 percent probability of having diabetes,” Kepesidis explains. “That information is important and could help doctors make their diagnoses.” Additionally, the researchers were able to predict whether someone would develop a metabolic syndrome in the future, and they could do so years before the disease becomes apparent.

Early Cancer Diagnosis

In another similar study, Kepesidis and Zigman were able to identify the molecular fingerprints of various cancers. To do so, they examined blood plasma from over 2500 people, including people with lung, prostate, breast, or bladder cancer, alongside a healthy control group. Here as well, the AI algorithms found special infrared patterns in the blood that indicated cancer in a very early stage. It worked especially well for lung cancer, demonstrating 88 percent accuracy. The accuracy for other types of cancer was between 60 and 70 percent. The new technology has thus already proven promising for reliably detecting cancer at an early stage as well. Kepesidis and his team are now



“The new measuring method brought about a fundamental shift in how we evaluate the data.”

KOSMAS KEPESIDIS

working on making the technology even more precise. For classification tasks, the artificial neural networks are also informed of the disease behind the data for each spectrum that they see during their training. In the above example, they therefore learn to connect suspicious patterns in the spectra to cancer. As an alternative approach, Kepesidis and his team are also looking into what are known as autoencoders. These are special neural networks that filter the noise out of spectra and isolate relevant information from them. “This is comparable to file compression,” Kepesidis explains. “You zip the files into a compact form, but you can also unzip them to restore all of the information.” Unlike classification tasks, however, the autoencoders receive no information about whether or which disease is in their spectrum during their training. They are trained only to reduce the spectra to a few latent variables that still contain enough information to reconstruct the original spectrum.

The deep neural network of an autoencoder is comparable to a funnel that absorbs a large amount of information at its entrance and channels it to the structure at its end. Only a few neurons are active in this narrow area, and they form the greatly reduced presentation of the original data. These latent variables contain the essence of the input data, while the autoencoder has removed irrelevant information. The neural network of the decoder, on the other hand, resembles an inverted funnel that takes in these latent variables at its narrow entrance and attempts to use them to restore the original data as accurately as possible. In this manner, the network learns how to compress data without losing important information in the process.

“That is how we identified latent variables that correlate with different diseases,” says Kepesidis. “These values have a diagnostic significance and could serve as biomarkers for certain diseases in the future.” As the recently published results demonstrate, the new method detects lung cancer with 2.6 percent better accuracy than simply interpreting the infrared spectra without autoencoding. “That is because the compressed spectra no longer contain any noise and redundant information; instead, they primarily concentrate on a few biologically relevant signals,” Kepesidis explains. Autoencoding thus has the advantage of creating more clarity during the interpretation of the spectra.

Combined Techniques

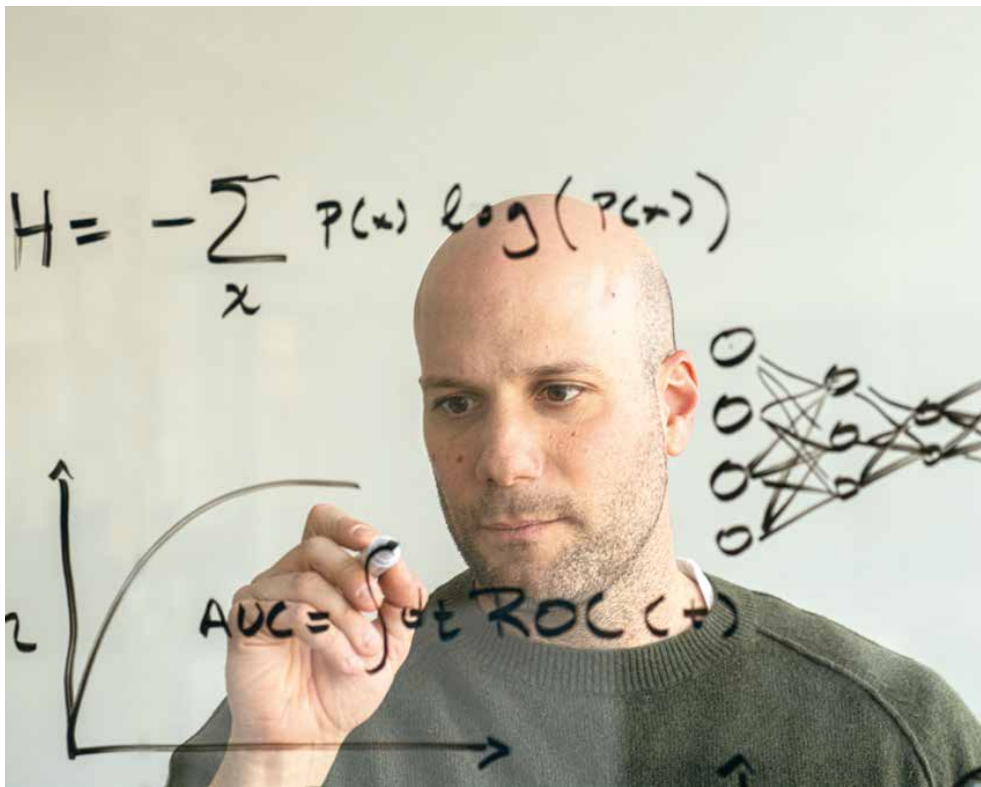
The autoencoders are also part of a current collaboration between Kepesidis and Ferenc Krausz, who leads the Department of Attosecond Physics as Director at the Max Planck Institute of Quantum Optics. Krausz won the Nobel Prize in Physics for generating extremely short laser pulses and the research he conducted with them in 2023. Unlike the case-control studies with Zigman, the project

with Krausz concerns longitudinal studies that track the development of participants over several years. “Our goal is to identify variables that signalize deviations from a healthy state and enable proactive health care,” explains Kepesidis. These studies have the greatest informative value when they use several complementary techniques. Mass spectrometry is especially well-suited for analyzing proteins, for example, while NMR spectroscopy is better for metabolites, the interim products in biochemical metabolic pathways. Both procedures use the same blood samples as infrared technology, but deliver different findings concerning the molecular composition of the samples. Unlike infrared spectroscopy, however, mass spectrometry and NMR spectroscopy are expensive. In order to gather the best information possible while minimizing costs, the researchers are initially using inexpensive methods here as well, such as infrared spectroscopy and machine learning. “If the infrared spectroscopy indicates initial signs of an illness, the AI will recommend specific follow-on tests, such as mass spectrometry,” Kepesidis explains.

Despite all their advantages, the new data-driven methods pose ethical questions. “One important aspect is handling patient data, for instance,” says Kepesidis. Eva Winkler agrees. The cancer researcher and Managing Director at the National Center for Tumor Diseases in Heidelberg is involved in the German Ethics Council’s discourse on innovations in the life sciences and ethically responsible health care. “AI training datasets are enormous and cannot be deleted after training,” she points out. “They are anonymized in most cases, but absolute anonymity does not exist.” What does exist is only a certain unlikelihood of traceability. Therefore, it is impossible to completely exclude the possibility that the data used to train the systems can be associated with the patients again and that they could experience disadvantages as a result, through discrimination due to higher risk of illness, for example. That could lead to insurance companies turning people away or discrimination due to psychiatric histories in the appointment process for becoming a tenured German civil servant, for instance. “Data security and data protec-

“Our goal ... is to enable proactive health care.”

KOSMAS KEPESIDIS



Kosmas Kepesidis and his group develop algorithms to improve and simplify medical diagnostics. Aspects concerning data ethics also play a role in the process.

tion are fundamental requirements for data-intensive medicine,” says Winkler. That is why the clinical studies at the Max Planck Institute of Quantum Optics are following a strict protocol approved by an ethics commission of the respective medical cooperation partner. Furthermore, the pattern recognition of AI systems is only as good as the data used to train them. “Here, we need to make sure that the people for whom such methods are used are also represented in the training samples used to develop these methods.” Accordingly, a test should not simply be able to detect diabetes or high blood pressure for a certain population group, but for all people. This is a problem of which Kepesidis is also aware. “A test trained on a patient in Munich may need to be adapted for other population groups,” the data scientist confirms.

There is another problem that concerns all AI applications, but is particularly challenging in a medical context: the lack of explainability of the results. When AI models evaluate spectroscopy data and thereby detect complex patterns that are hidden from the human eye, the infamous “black box” problem arises. “Physicians and medical laboratory specialists cannot check why the AI classifies a sample as abnormal,” Winkler explains. “Nevertheless, the physician is ultimately responsible if something goes wrong.” Winkler believes it would be better if there were a clear set of rules that

distributed responsibility among AI developers, the institutions using the technology, and the attending physicians, depending on the problem concerned.

Nonetheless, a central issue regarding the use of AI is that the systems may never make decisions on their own; a human physician must always be involved. “This is stipulated in European AI legislation,” Winkler says. There are studies in which AI outperforms specialists to some extent, but medical pictures must always be considered in the context of patient history. Most of the studies she knows of clearly show one thing, at any rate: the best results for patients are achieved through cooperation between humans and machines.



$$\begin{aligned}
 & \eta(2\partial_{yy}v_y + \partial_{xx}v_y + \partial_{xy}v_x + \partial_{yz}v_z + \partial_{zz}v_y) + \nu^2\gamma \left[\frac{1}{(p_x^2 + p_y^2 + p_z^2)^2} \left[-2p_xp_y(p_x\partial_xp_x + p_y\partial_xp_y + p_z\partial_xp_z)(p_x^2\partial_xv_x \right. \right. \\
 & + p_y^2\partial_yv_y + p_xp_z(\partial_xv_z + \partial_zv_x) + p_y p_z(\partial_yv_z + \partial_zv_y) + p_z^2\partial_zv_z) - 2p_y p_z(p_x\partial_zp_x + p_y\partial_zp_y + p_z\partial_zp_z)(p_x^2\partial_xv_x \\
 & + p_y^2\partial_yv_y + p_xp_z(\partial_xv_z + \partial_zv_x) + p_y p_z(\partial_yv_z + \partial_zv_y) + p_z^2\partial_zv_z) + \frac{1}{3}(2(p_x\partial_y p_x + p_y\partial_y p_y + p_z\partial_y p_z)(p_x^2 - 2p_y^2 \\
 & + \partial_yv_x) + p_y^2\partial_yv_y + p_xp_z(\partial_xv_z + \partial_zv_x) + p_y p_z(\partial_yv_z + \partial_zv_y) + p_z p_z\partial_zv_z) \left. \right] + \frac{1}{p_x^2 + p_y^2 + p_z^2} \left[\left(p_x\partial_xp_y - \frac{2p_y^2}{3} \right. \right. \\
 & + \left. \frac{4p_y\partial_y p_y}{3} + p_y\partial_zp_z - \frac{2p_z\partial_y p_z}{3} + p_z\partial_zp_y \right) (p_x^2\partial_xv_x + p_xp_y(\partial_xv_y + \partial_yv_x) + p_y^2\partial_yv_y + p_xp_z(\partial_xv_z\partial_zv_x) + p_y p_z \\
 & + p_z^2\partial_zv_z) + p_xp_y(2p_x\partial_xp_x\partial_xv_x + p_x^2\partial_{xx}v_x + p_y^2\partial_{xx}v_y + p_z^2\partial_{xx}v_z + p_x\partial_xp_y(\partial_xv_y + \partial_yv_x) + p_y\partial_xp_x(\partial_xv_y + \partial_yv_x) \\
 & + p_xp_y(\partial_{xx}v_y + \partial_{xy}v_x) + p_x\partial_xp_z(\partial_xv_z + \partial_zv_x) + p_z\partial_xp_x(\partial_xv_z + \partial_zv_x) + p_y\partial_xp_z(\partial_yv_z + \partial_zv_y) + p_z\partial_xp_y(\partial_yv_z \\
 & + p_xp_z(\partial_{xx}v_z + \partial_{xz}v_x) + p_y p_z(\partial_{xy}v_z + \partial_{xz}v_y)) \left. \right] + \frac{1}{3}((-p_x^2 + 2p_y^2 - p_z^2)(2p_x\partial_y p_x\partial_xv_x + p_x^2\partial_{xy}v_x + p_x\partial_y p_y(\partial_xv_y + \partial_yv_x) \\
 & + p_y\partial_y p_x(\partial_xv_y + \partial_yv_x) + 2p_y\partial_y p_y\partial_yv_y + p_xp_y(\partial_{xy}v_y + \partial_{yy}v_x) + p_y^2\partial_{yy}v_y + p_z^2\partial_{yz}v_z + p_x\partial_y p_z(\partial_xv_z + \partial_zv_x) \\
 & + p_y\partial_y p_z(\partial_yv_z + \partial_zv_y) + p_z\partial_y p_y(\partial_yv_z\partial_zv_y) + 2p_z\partial_y p_z\partial_zv_z + p_xp_z(\partial_{xy}v_z + \partial_{zy}v_x) + p_y p_z(\partial_{yy}v_z + \partial_{zy}v_y)) - \\
 & + p_x^2\partial_{xz}v_x + p_x\partial_zp_y(\partial_xv_y + \partial_yv_x) + p_y\partial_zp_x(\partial_xv_y + \partial_yv_x) + 2p_y\partial_zp_y\partial_yv_y + p_xp_y(\partial_{xz}v_y + \partial_{yz}v_x) + p_y^2\partial_{yz}v_y \\
 & + p_z\partial_zp_x(\partial_xv_z + \partial_zv_x) + p_y\partial_zp_z(\partial_yv_z + \partial_zv_y) + p_z\partial_zp_y(\partial_yv_z + \partial_zv_y) + 2p_z\partial_zp_z\partial_zv_z + p_xp_z(\partial_{xz}v_z + \partial_{zz}v_x \\
 & + \partial_{zz}v_y) + p_z^2\partial_{zz}v_z) \left. \right] \left. \right] \\
 & = - \left[-0.5p_xh_{\perp,y}\partial_zp_y - 0.5p_xh_{\perp,z}\partial_xp_x - 0.5p_xh_{\perp,z}\partial_zp_z + 0.5p_yh_{\perp,x}\partial_zp_y - 0.5p_yh_{\perp,z}\partial_xp_y + 0.5p_y(h_{\perp,x}\partial_zp_y \right. \\
 & + p_y\partial_zh_{\perp,x}) + 0.5p_zh_{\perp,x}\partial_xp_x + 0.5p_zh_{\perp,x}\partial_zp_z + 0.5p_zh_{\perp,y}\partial_xp_y + 0.5p_x(-h_{\perp,x}\partial_xp_z + h_{\perp,z}\partial_xp_x + p_x\partial_xh_{\perp,z} \\
 & - 0.5p_y(-h_{\perp,y}\partial_xp_z + h_{\perp,z}\partial_xp_y + p_y\partial_xh_{\perp,z} - p_z\partial_xh_{\perp,y}) + 0.5p_z(h_{\perp,x}\partial_zp_z - h_{\perp,z}\partial_zp_x - p_x\partial_zh_{\perp,z} + p_z\partial_zh_{\perp,x} \\
 & - p_xh_{\perp,y}\partial_zp_y + 2p_xh_{\perp,z}\partial_xp_x + 2p_xh_{\perp,z}\partial_y p_y + p_xh_{\perp,z}\partial_zp_z + p_x^2\partial_xh_{\perp,z} - 2p_yh_{\perp,x}\partial_y p_z + 2p_yh_{\perp,x}\partial_zp_y + p_yh_{\perp,z} \\
 & - 2p_yh_{\perp,z}\partial_xp_y + 2p_yh_{\perp,z}\partial_y p_x + 2p_xp_y\partial_y h_{\perp,z} - p_xp_y\partial_zh_{\perp,y} - p_y^2\partial_xh_{\perp,z} + p_y^2\partial_zh_{\perp,x} - p_zh_{\perp,x}\partial_xp_x + 2p_zh_{\perp,x} \\
 & + p_zh_{\perp,y}\partial_xp_y + p_zh_{\perp,z}\partial_zp_x - p_xp_z\partial_xh_{\perp,x} + p_xp_z\partial_zh_{\perp,z} + p_y p_z\partial_xh_{\perp,y} - 2p_y p_z\partial_y h_{\perp,x} - p_z^2\partial_zh_{\perp,x} \left. \right] + \nu\gamma\lambda \left[- \right. \\
 & + \left. \frac{(p_x^2 - 2p_y^2 + p_z^2)\partial_y\Delta\mu}{3} + \left(-p_x\partial_xp_y + \frac{2p_x\partial_y p_x}{3} - p_y\partial_xp_x - \frac{4p_y\partial_y p_y}{3} - p_y\partial_zp_z + \frac{2p_z\partial_y p_z}{3} - p_z\partial_zp_y \right) \Delta\mu \right] \\
 & + \Delta\mu\partial_zq_{yz} + \partial_x\sigma_{xy}^{(e)} + \partial_y\sigma_{yy}^{(e)} + \partial_z\sigma_{yz}^{(e)} \left. \right] + \partial_y\Pi
 \end{aligned}$$

The equation for the balance of forces along one of the three spatial directions in living cells or tissues. AI helps find and solve mathematical behemoths like this.

$$\begin{aligned}
 & p_x + p_x p_y (\partial_x v_y + \partial_y v_x) \\
 & + p_x p_y (\partial_x v_y + \partial_y v_x) \\
 & + p_z^2 (p_x^2 \partial_x v_x + p_x p_y (\partial_x v_y \\
 & \frac{\partial_x \partial_y p_x}{3} + p_y \partial_x p_x \\
 & (\partial_y v_z + \partial_z v_y) \\
 & v_x) + 2 p_y \partial_x p_y \partial_y v_x \\
 & v_z + \partial_z v_y) + 2 p_z \partial_x p_z \partial_z v_z \\
 & \partial_x v_y + \partial_y v_x) \\
 & + p_z \partial_y p_x (\partial_x v_z + \partial_z v_x) \\
 & + p_y p_z (2 p_x \partial_z p_x \partial_x v_x \\
 & + p_x \partial_z p_z (\partial_x v_z + \partial_z v_x) \\
 &) + p_y p_z (\partial_{yz} v_z \\
 & - h_{\perp,y} \partial_z p_x - p_x \partial_z h_{\perp,y} \\
 & - p_z \partial_x h_{\perp,x}) \\
 & ,x) + 0.5 \nu \left[- p_x h_{\perp,x} \partial_x p_z \right. \\
 & \left. - p_y \partial_x p_z - p_y h_{\perp,y} \partial_z p_x \right. \\
 & \left. \partial_y p_y - 2 p_z h_{\perp,x} \partial_z p_z \right. \\
 & - p_x p_y \partial_x \Delta \mu - p_y p_z \partial_z \Delta \mu \\
 & + \zeta (\Delta \mu \partial_x q_{xy} + \Delta \mu \partial_y q_{yy}
 \end{aligned}$$

EQUATIONS OF LIFE

TEXT: NORA LESSING

The laws of physics also apply to biological systems. AI, however, generally lacks this foundational knowledge. As a result, there is a risk that it will produce nonsensical results when describing biological organisms. Computer scientist Ivo Sbalzarini and his research group are developing AI that incorporates the laws of physics into the analysis of biological processes, combining biology with mechanics. This allows them to determine how genes influence tissue shape. The technology could also be used to develop more targeted medication in the future.

What is the answer to the ultimate question of life, the universe, and everything? In *The Hitchhiker's Guide to the Galaxy*, a supercomputer stipulates that the answer to this question is “42.” In the novel by British author Douglas Adams, this perplexing result leads to the construction of another supercomputer called Earth, whose goal is to reconstruct the wording of the original question.

Envisioning biology as a gigantic, self-regulating computing system? Ivo Sbalzarini would happily entertain such a concept without hesitation. Sbalzarini is the head of the university department at the Center for Systems Biology Dresden and leads a research group at the Max Planck Institute of Molecular Cell Biology and Genetics. He also holds a professorship in computer science at Dresden University of Technology. One element depicted in Adam's novel which would certainly not meet with Sbalzarini's approval is the lack of transparent data input into and the incomprehensible results generated by the supercomputer. Unlike the novel's protagonists, the researcher and his team understand precisely how the algorithms they developed produce their results. Their algorithms are based on comprehensible mathematical concepts and principles of physics, such as the conservation of mass and the balance of forces. “Because our AI operates within these constraints, it lacks the creativity of language models like ChatGPT. However, its results are easier to interpret, and hallucinations are less likely to occur. This makes it a valuable tool for scientific understanding,” explains Sbalzarini.

Thousands upon thousands of different processes take place in every organism: a growing fish embryo, a blossoming plant, white blood cells killing viruses. As complicated as these processes may be, they are nevertheless predictable. Until a few years ago, however, our ability to predict them was severely limited. Since the 1940s, researchers have been developing algorithms to calculate processes in nuclear physics and fluid mechanics. These were intended to perform functions such as simulating the physics of atomic fission or determining the trajectory of artillery shells. However, living systems require physical descriptions of a different kind. One example of this is the equilibrium assumption often made when describing inanimate matter. According to this assumption, inanimate matter is in thermodynamic equilibrium, or strives to be. This explains why a cup of coffee cools down when left standing, or why a piece of metal does not sponta-

SUMMARY

AI algorithms that describe biological processes must consider the physical laws at play.

To make the algorithms work more efficiently, the researchers have developed a content-adaptive image representation method called adaptive particle representation (APR).

Fusing different biological data using AI can provide new insights into the relationship between genes and organism function, and it can facilitate drug development.

neously start bouncing. Living things, on the other hand, can maintain a constant body temperature and move of their own accord. They can do this because they are supplied with energy through food. The physical description of such non-equilibrium systems differs fundamentally from the laws of equilibrium set out by classical physics. Conventional algorithms are therefore unsuitable for carrying out the associated calculations.

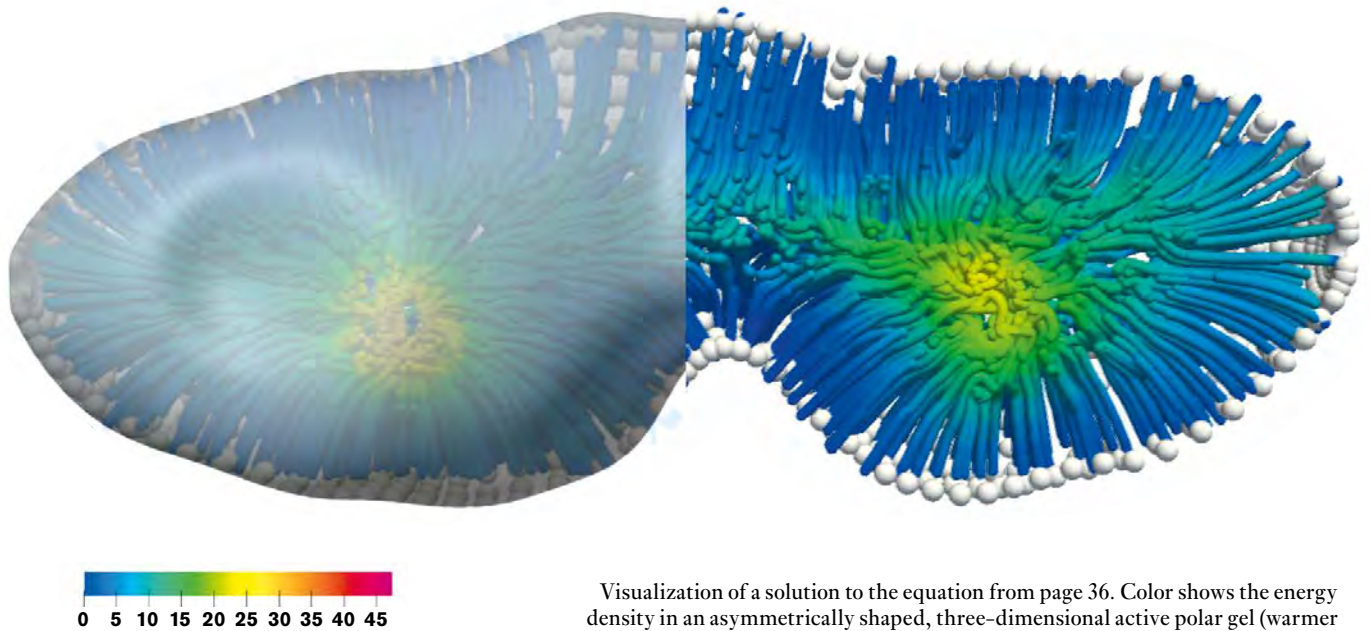
To wrest mathematically computable order from the complexity of life, we need AI algorithms. “We want to decipher the principles of self-organization applicable to living matter—you could also call this the materials science of life,” says

Sbalzarini. The researchers are taking a holistic approach. Rather than examining isolated components, such as proteins, genes, or growth factors, they focus on how these components interact within biological structures, such as cells and tissues. “Mechanics is very important to us here—for example, how soft or fluid the materials are, and which physical principles they must obey.”

This requires a mathematical view of the world. People experience the environment through their senses. For example, they might rub dry earth between their fingers, bite into a juicy apricot, or marvel at the sight of

“If neural networks can only learn models that do not violate basic physical principles, a lot of unnecessary computing and unrealistic results can be avoided.”

IVO SBALZARINI



Visualization of a solution to the equation from page 36. Color shows the energy density in an asymmetrically shaped, three-dimensional active polar gel (warmer colors = higher energy density). The lines represent the orientation of the material within the body (e.g., of cytoskeletal molecules). The left half of the image shows the surface of the body in semi-transparent gray. The right half shows the body cut open.

bizarrely shaped mushrooms. Sbalzarini and his team, however, also view life from another perspective. They assume that nature is a thoroughly predictable affair. Hidden behind the diversity of nature, they discover mathematical equations that model complex biological processes. The researchers from Dresden thus transform the sensory experience into a world of numbers. Their newly developed AI algorithms help them to achieve this.

The development of a roundworm embryo can be used as an example to illustrate the principle of how Sbalzarini and his team work. Biologists use light-sheet microscopy to study how the embryo grows and forms new structures during its development. Based on such data, an AI created by Sbalzarini's team finds the equations that mathematically describe this development and the forces at work. This also allows them to predict how further development will proceed. What's more, AI could also describe gene activity or cell movement in an embryo. "We are looking for the laws that govern development. Finding them allows us to describe the process and predict how it will continue," Sbalzarini explains. Using experimental data from their project partners' laboratories, he and his team can verify the accuracy of the algorithmic predictions. New AI algorithms have greatly increased the success rate here.

However, it has not yet been possible to find equations for many biological processes. For some, though, it has. However, the equations found by AI are sometimes so complicated that they are difficult to solve. Another new algorithm that was "made in Dresden" can help with this. Sbalzarini's team can now solve the equations that describe the growth and autonomous movement of living tissues. Living tissues behave like materials known as "active polar gels." These materials can move on their own (i.e., "actively"), but are neither liquid nor solid. A non-active example is Silly Putty. When this material is shaped into a ball and thrown on the floor, it bounces away like a rubber ball. But if you leave it on the table, its shape slowly melts. "Living tissues behave in the same way; if quickly deformed, they return to their original shape. If a tissue is slowly deformed, it adapts. And it's active, too," explains Sbalzarini.

Solutions to Equations

The physical principles that describe the mechanics of active polar gels have been known for over 20 years. Until now, however, the resulting complicated mathematical equations could only be solved in a few special cases. After years of research, Sbalzarini's team recently presented an algorithm that can solve these equations in all



Cell nuclei under the microscope. The original image is at the top; the image pixels are shown as individual dots in the center panel. Their color represents brightness.

Below is the same image in the new content-adaptive representation. The dots are of different sizes depending on how dense the information in the image is at that location (smaller dots = denser information).

The image thus represented is visually indistinguishable from the original, yet requires only a fraction of the memory and computing power.

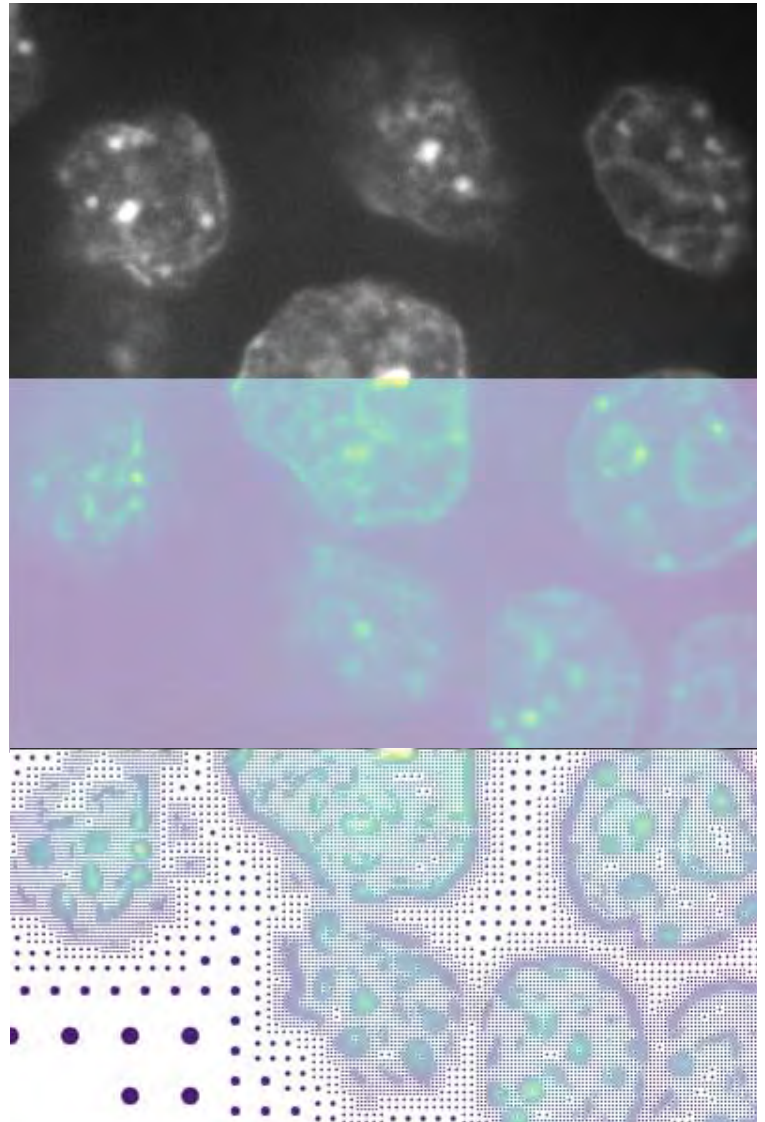


IMAGE: JOEL JONSSON AND BEVAN CHEESEMAN, SBALZARINI GROUP

cases. This allows the three-dimensional shape of living materials and the distribution of forces within them to be calculated. The researchers are now aiming to expand the algorithm's capabilities to encompass processes in moving or growing biological structures.

- 40 However, when the AI derives physical models from light-sheet microscopy images, it needs to process enormous amounts of data. This is often unmanageable using conventional methods. To address this problem, Sbalzarini's research group has developed an algorithm that allows images to be stored and analyzed more efficiently. Until recently, analyzing 3D images of living biological tissue represented a technical challenge. In light-sheet microscopy, a laser successively excites the fluorescent molecules in individual, wafer-thin layers of the examined object to make them glow. The images from these different layers are then combined to form a 3D image. The resulting images are highly detailed, but can generate terabytes, sometimes even petabytes, of data. "This means that uploading the images from the microscope to a server requires a great deal of patience. During this time, the expensive microscope cannot be used for anything else. Once the data arrives on the server, the images are so large that they won't fit into the memory of any graphics card, so you can't even look at them. It's like a Ferrari that can only drive on dirt tracks and gets stuck in the mud every few meters."

This spurred Sbalzarini and his team to develop a technology that can process large images much more efficiently, making them compatible for use with AI. Images created using this adaptive particle representation (APR) technology have the same quality as conventional pixel images, but crucially, require only a fraction of the storage space and computing time. Unlike

conventional images, the new method only stores information where it is present. In an image of a fruit fly embryo against a black background, for example, each pixel requires the same amount of memory, even though it is the embryo and not so much the background that is of interest to researchers. "In most cases, not all pixels in an image are relevant to the information it contains," explains Sbalzarini. APR identifies the relevant areas within an image and only saves brightness and color within them. Unlike compression algorithms, which can be used to save disk space when storing images, APR images do not have to be decompressed, i.e. unzipped, before being processed. This

not only saves disk space but also computing time. Additionally, it relieves the graphics card's video memory so that images can be viewed and analyzed faster than the microscope can acquire them. "In other words, we have built the Ferrari a highway so that it can now drive at maximum speed. And the content-adaptive APR also helps the AI, because it is not hindered by having to first learn where the relevant information is hidden in the image."

With the help of Max Planck Innovation, the Max Planck Society's technology transfer office, Sbalzarini applied for a patent for APR-based microscopy. Two former members of his research group founded a start-up in Oxford, UK, which aims to make APR commercially available for all forms of fluorescence microscopy. However, this technology could also be useful for other imaging methods in the future, such as radio astronomy. Biologists outside of Dresden are already using APR to analyze images from their high-performance microscopes. This improves utilization of the microscopes and saves compute resources, time, and electricity. At the same time, it allows 3D images to be displayed in virtual reality in real time. For example, researchers in Geneva, Switzerland, only needed 1 hour and 20 minutes of computing time to create a 3D fluorescence microscopy image of the nerve cells in a complete mouse brain. Without the new technology, this would have taken four days.

Thanks in part to APR imaging, AI has already made considerable progress in the physical description of life. Sbalzarini is convinced: "AI equipped with a knowledge of physics will enable significant advancements in systems biology in the coming years. If neural networks can only learn models that do not violate basic physical principles, a lot of unnecessary computing and unrealistic results can be avoided." At the same time, this would make AI models more explainable, reliable, and resource efficient.

Small Data Sets, Huge Data Points

However, developing AI to analyze biological processes remains a colossal task. Part of the problem is the data itself. "There are gigantic data sets used for the development of language models. However, the individual data points, e.g. word groups, are small. In systems biology, it is often the other way around: the data sets are small, just a few microscopy images of the development of an embryo. The individual data points, the single images, on the other hand, are huge. This is what makes training AI systems for spatial biology so difficult." In the coming years, Sbalzarini and his team want to bring AI, physics, and biology even closer together. In line with this, the Max Planck Society, in cooperation with the Boehring-

er-Ingelheim Foundation and the Dresden University of Technology, has created an additional department for biomedical AI at the Center for Systems Biology Dresden. The Boehringer-Ingelheim Foundation has contributed EUR 20 million to the project; the Max Planck Society, the Dresden University of Technology, and the state of Saxony have contributed an additional EUR 20 million. After ten years, the Max Planck Society will assume the costs itself. The scientific concept for the new department was largely authored by Sbalzarini. The goal is to combine data sets using physical principles to make them compatible for use with AI. "Genetics, biochemistry, cell biology, and developmental biology, to name just a few disciplines, have amassed an enormous body of knowledge. For instance, we know the complete inventory of proteins in an organism, the activity of its genes, and the changes in shape during development. So far, however, no one has succeeded in linking these data sets together in order to understand the overall system. Because these data sets are so large, heterogeneous, and complex, we can only achieve this goal with the help of AI." The Dresden researchers want to find a common language for microscopy images, protein concentrations, and gene data, and bring them all together using AI. It sounds as if life could be transferred to the digital world this way, and "digital twins" of biological processes or even organisms could be created. However, that is not the actual goal. "Fusing different types of data could help us understand the relationship between genes and the function of an organism. The connection between genotype and phenotype remains unclear," says Sbalzarini. This could also be a significant advancement for pharmaceutical research. If AI makes biological processes predictable, targeted active pharmaceutical compounds could be developed more efficiently.

What is clear is that many algorithms do not need to be reinvented because they already exist. Life itself produced them long ago—in the form of biochemical networks in cells. Like algorithms, these networks evaluate information from their environment, learn, and react dynamically to change. "However, unlike digital computers, they have more than just the voltage states 0 and 1. The number of ways in which you could combine concentrations of tens of thousands of proteins is immeasurably large. In some sense, life on earth functions like a gigantic quantum computer," Sbalzarini summarizes. This is a comparison very much in the spirit of Douglas Adams and his novel.

 www.mpg.de/podcasts/ki-und-biomedizin (in German)



Tina Lüdecke enjoys traveling in foreign countries. It's one of the reasons she became a geoscientist. Today, she works at the cutting—or even biting—edge: at the Max Planck Institute for Chemistry in Mainz, she analyzes fossil teeth to determine how our early ancestors ate millions of years ago, shedding light on human evolution.

TEXT: NORA LESSING

The air shimmers in the morning heat. Grassland and savanna woodland stretch all the way to the horizon. The helicopter thunders, beneath it a herd of elephants passes by, kicking up red dust. The pilot nods to Tina Lüdecke, who saves the GPS coordinates in her satellite phone. Then the helicopter climbs higher and veers off. A few kilometers away, it sets the team down at the starting point of today's exploratory tour. The researchers then begin their trek through Mozambique's Gorongosa National Park in search of fossils and sediments millions of years old, crossing sand dunes and dry riverbeds, passing towering acacia trees. The team must make their way back to the GPS coordinates—the pickup spot—by 5:30 PM, or else face the prospect of a night in the savanna. "The helicopter isn't allowed to fly after dark. So of course, we're back by four," says Lüdecke, laughing. She loves this kind of fieldwork. But after many years of camping in the bush, she now prefers a refreshing shower and the comfort of a soft hotel bed.

Lots of grass and a small forest: that's the first image Google Maps brings up when you search for Lüdecke's birthplace. The village of Barchel lies in Lower Saxony's Elbe-Weser triangle, between Buxtehude and Bremerhaven. There are no elephants here, but plenty of cows—and about 660 people. Many of the people here work in agriculture, making a living from milk and meat production. "My parents are originally from Göttingen and moved to Barchel three years before I was

born," says Lüdecke. Her father became the village schoolteacher; her mother worked as a secretary before staying home for several years to raise their two daughters. "The next town is called Bremervörde and has maybe 20,000 inhabitants. My parents still talk about the first time they drove through it. They saw an arrow sign pointing to the town center, so they thought they were almost there. Then, suddenly, the arrow pointed the other way—they had already passed right through without realizing."

Lüdecke was born in 1983 and was a curious, athletic child. She began equestrian vaulting at the age of five, eventually moving on to dressage and show jumping as she grew older. "Up until my early teens it was the best way to grow up. We played tennis on the main street and got annoyed when the neighbor drove home half an hour early from work," recalls the researcher. "We spent the whole day outside, played by the stream, or hung out at the neighbors' house." As a teenager, however, life in the quiet village of Barchel eventually began to feel dull. She dreamed of faraway countries, different cultures, and exotic foods. "Even back then, I had this deep love of traveling. I've always loved being on the move."

The first photo of Lüdecke as an aspiring geologist was taken by her parents during a summer vacation on Lake Constance: in her bathing suit, the then ten-year-old bangs stones together on a beach, trying to discover fossils. It was a few years later that a lecture by an engineer convinced her to study geosciences. "She was building wells in Indonesia and travelled a lot. That was exactly the kind of job I wanted." So, Lüdecke went to Hannover, studying soils, minerals, and dune formation. She was especially fascinated by geochemistry and the methods used to analyze stable isotopes—variants of elements with lighter or heavier atomic weights. These techniques, for example, can reveal which types of plants once grew in a particular soil.

→

VISIT TO

TINA
LÜDECKE



IMAGE: KATRIN BINNER, MPG

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A bike called Emmy: with her first paycheck as leader of an Emmy Noether research group, Tina Lüdecke treated herself to this road bike—and gave it a fitting name.



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An early passion: as a child, Tina Lüdecke used to knock stones together on the beach hoping to find fossils in them. Today, as a geoscientist, she studies fossil teeth to reconstruct the diets of animals and prehistoric humans. In the photo on the right, she tests her method by sampling the tooth of an elephant that died a few years ago.

For her diploma thesis, Lüdecke took part in her first major research trip—to Turkey. As the only woman in the team, she had to grit her teeth on more than one occasion—for instance, when locals in the rural interior mistook her for a prostitute because she was travelling unmarried, and only reluctantly rented her a room. “At three in the morning the police burst into my room to make sure I wasn’t doing anything illegal.” It was an uncomfortable experience, but Lüdecke wasn’t discouraged. She remained focused on tracking down carbonate deposits in the soil. “These carbonates are typically white, one to two centimeters in size, and look like popcorn,” the scientist explains. This “popcorn of the soil” forms over many years. Rainwater seeps into the ground and mixes with the remnants of decomposing plants. As the water moves into deeper layers, the dissolved carbonate eventually precipitates—as carbonate nodules that Tina Lüdecke and her team bring back to the surface through excavation.

The carbonate nodules carry a distinct chemical signature that reflects the types of plants that once decayed at the site. The key lies in photosynthesis: plants preferably absorb one of two stable carbon isotopes into their biomass, depending on the type of photosynthetic pathway they use. Three types of plants can be distinguished in this context: C3, C4, and CAM. Each group follows a different photosynthetic pathway, leaving behind distinct isotopic signatures in the soil. From these, researchers can reconstruct the vegetation that once grew at a given site. Robust savanna grasses, for example, which withstand both extreme heat and long dry seasons, belong to the C4 group and tend to absorb more of the heavier carbon isotope carbon-13 (^{13}C). This variant of the carbon isotope has a mass number of 13. In contrast, C3 plants, which include most trees and shrubs in African savannas, prefer the slightly lighter ^{12}C atoms—carbon with the mass number 12. “By analyzing the ratio of ^{12}C to ^{13}C in a soil sample, we can determine whether an area was once dominated by open grassland or forested landscapes.”

For her PhD, Lüdecke moved to the Senckenberg Biodiversity and Climate Research Centre in Frankfurt am Main. She had barely settled in before setting off



on her next major field expedition. This time, the destination was Malawi. “My goal was to reconstruct the environmental conditions from roughly 2.4 million years ago using soil carbonates,” the researcher explains. “What wasn’t clear, however, was whether the soil in Malawi actually contained any carbonate nodules at all.” Lüdecke teamed up with Heinrich Thiemeyer, an experienced soil scientist who had already conducted several field trips to Malawi. “Together, we spent weeks trekking for many miles across fields, grassland, and ancient riverbeds with an incredible amount of drinking water on our backs.” Laden with several kilograms of precious carbonates, Lüdecke finally returned to Frankfurt. As an additional bonus, she had three fossil antelope teeth in her luggage.

Carbonates are not the only clues to prehistoric ecosystems: fossils, especially the bones and teeth of long-extinct animals also offer valuable insights. “Teeth are 95 percent mineral—almost like having a piece of rock in your mouth,” explains Tina Lüdecke. “Their incredible geochemical durability makes them a fantastic material for detecting all sorts of signals, even millions of years later.” Among these signals are carbon isotope concentrations, similar to those in the soil carbonates. Using a den-

tal drill, Lüdecke extracted fine tooth powder from antelope teeth, then analyzed it with a mass spectrometer. This allowed her to determine which kinds of plants the animals had eaten millions of years ago during their lifetimes. The results were so promising that she extended her drilling to additional fossils from the Senckenberg collection. Little by little she examined the teeth of long-gone herbivores that had once roamed the savanna in Malawi—ancestors of zebras, for example, as well as wildebeests and warthogs. “That meant I was able to reconstruct what the savanna looked like back then.” But it wasn’t only animals that inhabited those ancient African landscapes: early humans did as well. “So naturally, my next goal was to examine hominin teeth too.”

Hominin fossils are virtually the crown jewels of paleoanthropology—exceedingly rare and carefully curated in museums. In Malawi, after years of searching, researchers have recovered just four hominin fossils: two isolated teeth, a fragment of upper jaw, and a lower jaw. So, Lüdecke had to do a great deal of persuading before she was allowed to drill a small hole in the precious specimens. However, her efforts paid off. “From these fossils, I was able to reconstruct which plants early hominins of the genera



Homo and *Paranthropus* consumed 2.4 million years ago.” She showed that *Paranthropus boisei*, long believed to have had a specialized diet, was in fact surprisingly adaptable: in open savannas these hominins lived mainly on grassy resources, whereas in wooded regions they turned to fruit and other tree-based foods. By analyzing oxygen isotopes in the teeth, Lüdecke also discovered how much fresh water the different hominin species drank and to what extent they relied on puddles and other stagnant water to quench their thirst.

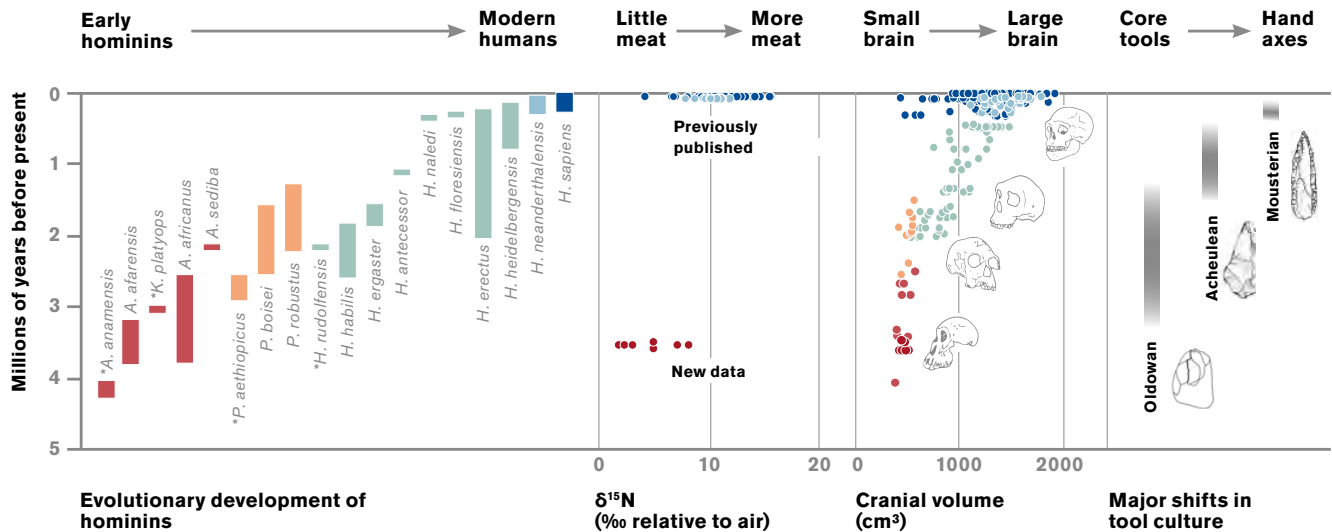
Yet for a long time, Lüdecke was unable to comment on one of the most evolutionarily important aspects of the early-human diet: meat. “In all my publications, I wrote, ‘We can’t say anything about meat consumption.’ That was incredibly frustrating for me. After all, many researchers believe that the evolution of the human brain is closely tied to eating meat.” Early humans probably developed a taste for meat between two and four million years ago. Fossil skeletons from that period already show anatomical changes compared to earlier hominins. “You can see that the brain becomes larger while the digestive tract gets shorter.” The prevailing hypothesis: a larger brain demands more energy, and hominin

taxa that began supplementing their plant-based diets with calorie-rich meat likely had an evolutionary advantage. Their shorter digestive tract supports this theory, as meat is easier to digest than fibrous plant matter. “Various findings show that by one million years ago at the latest, meat was a crucial part of the human diet. But what exactly happened in the two million years before that is still a mystery.”

Chemical analyses of nitrogen isotopes in fossil teeth could help fill this gap in our understanding of early human diets. The principle behind this is simple: as animals process nitrogen, they tend to excrete the lighter nitrogen isotopes—through sweat, urine and other waste—while the heavier isotopes accumulate in their bodies. The higher an animal is on the food chain, the more “heavy” nitrogen it stores. Plants exhibit the lowest quantities of heavy nitrogen isotopes, whereas carnivores display comparably high quantities. But there is a catch: tooth enamel binds nitrogen extremely tightly, making it hard to access. “That is actually a good thing, because it is precisely why teeth record the past so reliably,” comments Lüdecke. “But this same stability, and the fact that enamel contains extremely little nitrogen, poses a challenge for research.” Lüdecke solved this prob-

Revealing tooth enamel: several australopithecines lived more than two million years ago, making them some of our earliest proto-human ancestors. Based on the ratio of nitrogen isotopes ($\delta^{15}\text{N}$) in tooth enamel, *Australopithecus* (red) from the Sterkfontein Caves in South Africa had a predominantly vegetarian diet—unlike modern humans (dark blue) and Neanderthals (light blue). This dietary shift from mostly plant-based to increasingly animal-based foods may have gone hand in hand with the evolution of a larger brain. At the same time, hominins gradually developed more sophisticated tools, beginning with Oldowan implements, then progressing through the Acheulean technology, and later the Mousterian culture.

*
A. = *Australopithecus*
H. = *Homo*
K. = *Kenyanthropus*
P. = *Paranthropus*



lem together with her colleagues Jennifer Leichter and Alfredo Martínez-García from the Max Planck Institute for Chemistry in Mainz. The latter runs a laboratory that is equipped to analyze even trace amounts of nitrogen. The team first experimented on the teeth of recently deceased mammals with

topes,” says Lüdecke. “If fresh meat was eaten, the isotopic concentration in some of the amino acids should, for instance, differ from that of putrid meat. And if all goes well, we’ll eventually be able to detect milk consumption, or even the intake of specific plant sources.”

“It would be amazing to pinpoint the time when some of our ancestors started eating meat regularly—and to find out which species made this shift.”

known diets. The data checked out—so they moved on to fossilized animal teeth, and finally, to those of early hominins. After chemically preparing the samples, they fed them to specialized bacteria that releases the nitrogen bound within the tooth enamel and converted it into nitrous oxide, better known as laughing gas. A mass spectrometer then measured its isotopic signature. “To reconstruct the meat consumption of early humans, we are effectively analyzing bacterial farts,” Lüdecke says with a grin.

In 2021, the researcher established an Emmy Noether Group at the Max Planck Institute for Chemistry, funded by the German Research Foundation. The team’s focus: the onset and evolution of meat consumption among our ancestors, who lived in Africa between 4.2 and 1.4 million years ago. The group quickly produced exciting results, including evidence that early hominins of the genus *Australopithecus* likely followed a vegetarian diet. In collaboration with Cajetan Neubauer from the University of Colorado Boulder and Rani Bakkour from the Technical University of Munich, Lüdecke’s team also secured additional funding from the Human Frontier Science Program, co-financed by the European Union. “In this project, we’re taking things one step further and breaking down our samples by amino acid type,” Lüdecke explains. The human body uses 20 amino acids—the fundamental building blocks of all proteins—many of which are also incorporated into tooth enamel. Some of these amino acids must be obtained directly through diet, as the body cannot produce them on its own. As a result, the nitrogen stored in teeth carries a diet-specific chemical signature. “We’ve already succeeded in isolating individual amino acids from modern tooth enamel, now we’re working on measuring their nitrogen and carbon iso-

At the same time, Lüdecke is collaborating with scientists from the Czech Republic studying roughly 7,000-year-old burials in Oman. “Dozens of people were buried in a desert hill alongside stone tools, shells, and shark teeth that were likely worn as pendants. It makes you wonder what they ate.” To find out, Lüdecke measured the nitrogen isotope composition in the teeth—and could hardly believe her eyes. “The nitrogen isotope values for these people in Oman were in fact much higher than anything I have seen so far—even higher than those of lions or hyenas.”

The explanation: compared with the terrestrial food chain, which consists of plants, herbivores, and carnivores, the marine food chain is significantly longer. As a result, marine apex predators can accumulate a far higher concentration of heavy nitrogen isotopes than carnivores on land. Acting on a hunch, Lüdecke tested the shark teeth from the graves. Sure enough, their nitrogen isotope values were just below those of the humans. “That strongly suggests that Neolithic people in Oman systematically hunted and ate enormous bull sharks.”

Even as her list of discoveries grows, Tina Lüdecke will not run out of research topics. First, though, the geoscientist hopes for a permanent position—her Emmy Noether funding runs out in fall 2027. Looking ahead, she wants to sink her teeth even deeper into the story of our ancestors, for instance by examining when they first began to cook their food. “It would be amazing to pinpoint the time when some of our ancestors started eating meat regularly—and to find out which species made this shift.” The ultimate goal: using geochemistry to reconstruct how food shaped our evolution. “If we can really pull that off, it would be absolutely fantastic.”





DOUBLE TAKE

*MAX PLANCK INSTITUTE FOR
MULTIDISCIPLINARY SCIENCES*

This still frame from an MRI video shows the mouth and throat of Berlin Philharmonic horn player Stefan Dohr as he plays his instrument. MRI recordings like these are only possible thanks to a technique called Flash2, which enables the visualization of movements inside the body in real time. Flash2 is based on a sophisticated mathematical image-reconstruction method that allows up to 100 frames to be captured per second. It represents an enormous advance in terms of medical diagnostics, as it allows for the direct observation of actions such as joint and speech movements, the processes associated with swallowing, and the beating heart.

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A QUANTUM TWIST ON HYDROGEN

TEXT: FINN BROCKERHOFF

Hydrogen is supposed to help many areas of the economy become independent from fossil fuels. Researchers at the Max Planck Institute for Chemical Physics of Solids in Dresden are using the quantum properties of catalysts to make the electrolysis required for producing hydrogen more efficient.

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Green hydrogen is considered the key to the energy revolution. It can be generated from water using climate-friendly power provided by solar and wind energy. As an energy source, it is expected to provide an alternative to coal, oil, and natural gas and make processes in the steel and chemical industries, among others, more environmentally-friendly. There are still many hurdles for establishing a hydrogen economy, however, including the possibility of creating green hydrogen using electrolysis efficiently, and thus inexpensively. But according to a team at the Max Planck Institute for Chemical Physics of Solids, that can be changed by reexamining the quantum physical procedures that take place during electrolysis.

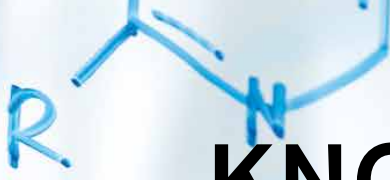
“The electrolysis takes place in two partial reactions,” explains Xia Wang, head of the Topological Catalysis Group at the Institute in Dresden, “In one reaction, water molecules split into oxygen, protons, and electrons. In the second partial reaction, these electrons are used to generate hydroxide ions and the desired hydrogen from additional water molecules.” Simply put, the electrons in this process are regarded as simple electric charges, as is generally the case in chemistry.

“Chemistry often ignores the fact that the electrons have a second property in addition to their electric charge. This second property is also significant for chemical reactions,” explains Wang. She is referring to electron spin. According to quantum physical models, this spin can be imagined as the rotation of the electron around its own axis, and it can exist in two different orientations—usually symbolized by two arrows: one pointing up for “spin up” and another pointing

down for “spin down.” This difference appears simple, but it has important effects on the organization of the electrons in an atomic shell and thus on the process of chemical reactions.

“These influences were not well understood for a long time, but we now know considerably more about the role spin and other physical concepts play in chemistry,” says Claudia Felser, Director at the Max Planck Institute for Chemical Physics of Solids. The spin orientation influences the formation of reaction products during water electrolysis: “Only when the spins of the electrons forming the molecular bonds are parallel—in other words, pointing in the same direction—will the first half-reaction produce the desired oxygen more efficiently,” Wang explains. However, if the spins are antiparallel, that is, pointing in different directions, unwanted substances like hydrogen peroxide can form. Normally, both spin orientations occur during electrolysis, which

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Catalysis

high ee

Homochirality

KNOWLEDGE FROM

PHYSICS & ASTRONOMY

A good hand: Max Planck researchers in Dresden are developing catalysts that, like hands, exist as mirror images of one another. These kinds of reaction accelerators are particularly efficient when water is split into oxygen and hydrogen, for instance.

makes producing hydrogen less efficient in practice than it could be due to side reactions.

Chiral Catalysts

“That is why my group is pursuing the approach of using quantum physical properties like spin as active control parameters in chemical reactions,” Wang says. Specifically, she and her team are researching how the spins of the electrons involved in a reaction can be influenced in a targeted manner to generate the desired reaction products. Wang and her team use special catalysts for this purpose: in general, catalysts accelerate a certain reaction so that a desired product is generated in much greater quantities than any by-products. What is special about the catalysts used by Wang’s team is that they consist of materials with a certain intrinsic chirality. “You can see what that means using our two hands,” Wang says, “Just as our left and right hands are mirror images of each other, some molecules and crystal structures occur in two variants that are mirror images of one another. They are constructed of atoms of the same elements, but they demonstrate opposite spatial arrangements that cannot be aligned through rotation.”

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Chirality is of critical importance for catalysis when crystal structures are involved. This is because it influences electron spin behavior, as Felser explains, “The spins become polarized in crystals whose chiral structures resemble a helix. That means they all point in the same direction.” Therefore, as catalysts, crystals like these can uniformly orient their electron spins so they are parallel during a reaction. In the case of water electroly-

sis, a significant quantity of oxygen—and a comparatively small quantity of hydrogen peroxide—is produced as a result.

To exploit this effect, other research groups have simply covered the surface of normal catalysts with chiral molecules. “In contrast,” Wang explains, “the chiral structures of our catalysts are an intrinsic component of the entire crystal structure.” The researchers achieve this by producing their catalysts from topological materials that are especially well suited to be catalysts owing to their intrinsic chiral crystal structure and exceptional electron properties. Examples include combinations of the elements palladium and gallium (PdGa) or rhodium, bismuth, and sulfur (RhBiS). “We can grow large single crystals of

SUMMARY

Electron spin influences how certain chemical reactions proceed.

In topological materials with homogeneous chirality, the spins of the electrons are predominately parallel.

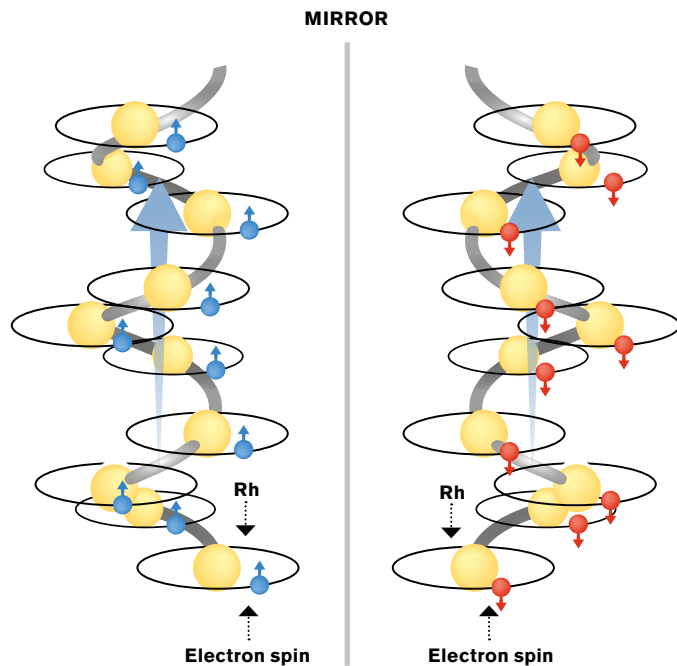
Chiral topological catalysts make water electrolysis and fuel cell reactions, for example, more efficient.

these chiral materials. To do so, we search for an extremely small single crystal in the material samples—we call it a chiral seed. We melt the bulk material in a container, introduce the seed into the molten mixture, and fi-



IMAGE: SVEN DÖRING / MPG

Catalysts with a twist: Claudia Felser (left) and Xia Wang use the quantum properties of chiral topological catalysts to control chemical reactions.



Spinturbo for hydrogen electrolysis: the rhodium atoms form a spiral that rotates either clockwise or counterclockwise in a chiral catalyst. If a current flows through the catalyst during the electrolysis of water (blue-gray arrow), the spins of certain rhodium electrons are aligned with or against the direction of the current. That favors the formation of oxygen.

nally generate a much larger single crystal with homogeneous chirality using a controlled heating and cooling process that involves slow lifting and rotating.”

In a study that appeared at the end of 2024 in the specialist journal *Nature Energy*, Wang and her team researched the suitability of different materials as catalysts for oxygen evolution during water electrolysis, including three topological single crystals with homogeneous chirality. The latter demonstrated a considerably higher reaction rate compared to the non-chiral catalysts, says Wang: “They catalyzed oxygen formation much better. The material RhBiS even performed 200 times better than one of the established standard catalysts.”

The researchers have also shown that single crystals made of heavy elements like rhodium or bismuth tend to be advantageous for catalysis. “This supports our hypothesis that the selective effect of our catalysts is based not only on the polarization of their spins; the complex relativistic interactions between the electrons’ spins and their orbits around the atomic nucleus also play a role,” says

Wang. In quantum physics, this effect is known as “spin-orbit coupling,” and has a particularly strong impact on reactions involving heavy elements with many electrons in the atomic shell.

The concept of spin-controlled catalysis has also proven successful in the reverse of water electrolysis: the fuel cell reaction. In this process, hydrogen and oxygen react in a controlled manner across two electrodes, proceeding through half-reactions to form water and generate electricity. As researchers working with Wang reported in a paper published in the magazine PNAS at the beginning of 2025, their homochiral catalyst of PdGa demonstrated a conversion rate that was 100 times higher than that of a non-chiral catalyst made of the same elements. “Traditional catalysts often produce undesired hydrogen peroxide as a by-product,” says Felser. “Our homochiral PdGa single crystal was virtually able to suppress the formation of hydrogen peroxide entirely, as a result of which the reaction continued to be produce water in a targeted manner.”

The experiments in both research projects were primarily feasibility studies. However, Wang believes that the ap-

proach could be attractive for technical applications. Be that as it may, the team’s best catalysts are less suitable for industrial hydrogen production because of their rare and expensive components, Felser adds. She is nevertheless certain that more efficient and sustainable catalysts can be developed for industrial applications based on the studies performed by her group. “We’ll gladly leave that to others,” she says, laughing. “We want to improve the fundamental understanding of catalysis by bringing chemistry and physics closer together.” Both researchers nonetheless hope that they can make a long-term contribution to the development of the hydrogen economy by doing so.

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GLOSSARY

CHIRALITY

describes a property of objects that are mirror images of each other, like two hands. These mirror images cannot be superimposed onto each other.

SPIN

designates the intrinsic angular momentum of elementary particles, such as electrons, in quantum physics.

TOPOLOGICAL MATERIALS

are materials whose physical properties, such as electrical conductivity or magnetism, are determined not only by their chemical composition, but also by the geometric and topological arrangement of their atoms. These structures enable quantum mechanical effects, such as robust surface states or superconductivity, arising from interactions between crystal symmetry and electron behavior.

Valorizing waste: plans are afoot for plastic waste to serve as a feedstock in a chemical circular economy. A Max Planck team in Magdeburg is developing methods to reuse polyamide, such as from discarded fishing nets.



CIRCULAR CHEMISTRY

TEXT: KARL HÜBNER

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Over the coming years and decades, the chemical industry will have to forego the use of fossil feedstocks—not only to reduce greenhouse gas emissions, but also to avoid waste. At the Max Planck Institute for Dynamics of Complex Technical Systems in Magdeburg, researchers are supporting this transformation through numerous projects.

We are not at the mercy of climate change. Kai Sundmacher is one of many who hopes that the rise in the concentration of CO₂ in the atmosphere will one day be halted—and perhaps even reversed. But how could this be achieved? The answer is to dispense with fossil feedstocks. It is important to note that defossilization is

by no means equivalent to decarbonization—that is, a move away from carbon-based products such as plastics and paints. Or a move away from fuels that will still be needed, at least in aviation and sea transport. All of these chemical products contain carbon that is set to be kept in circulation. But before we get to that point, says Sundmacher, there is still a long way to go. Nevertheless, the process engineer's research group is participating in various projects in order to get closer to achieving that goal.

Sundmacher is Director of the Process Systems Engineering Department at the Max Planck Institute for Dynamics of Complex Technical Systems in Magdeburg. When presenting his vision, he likes to show a diagram illus-

trating the various pathways of carbon within the future cycle. The centerpiece is a block headed “Smart Process Systems.” He hopes that these systems will be the ones used in the future to manufacture all our products. Crucially, the feedstocks in these systems are no longer fossil-based, meaning they no longer come from coal, crude oil, or natural gas. Instead, plastic waste and renewable (biogenic) residues are used. Carbon dioxide is also incorporated into the overall recycling system. Rather than allowing the greenhouse gas to continue driving global warming, the plan is to capture it from exhaust gases or extract it from the air and feed it into chemical reactors. Much of this is entirely new to the chemical industry. →

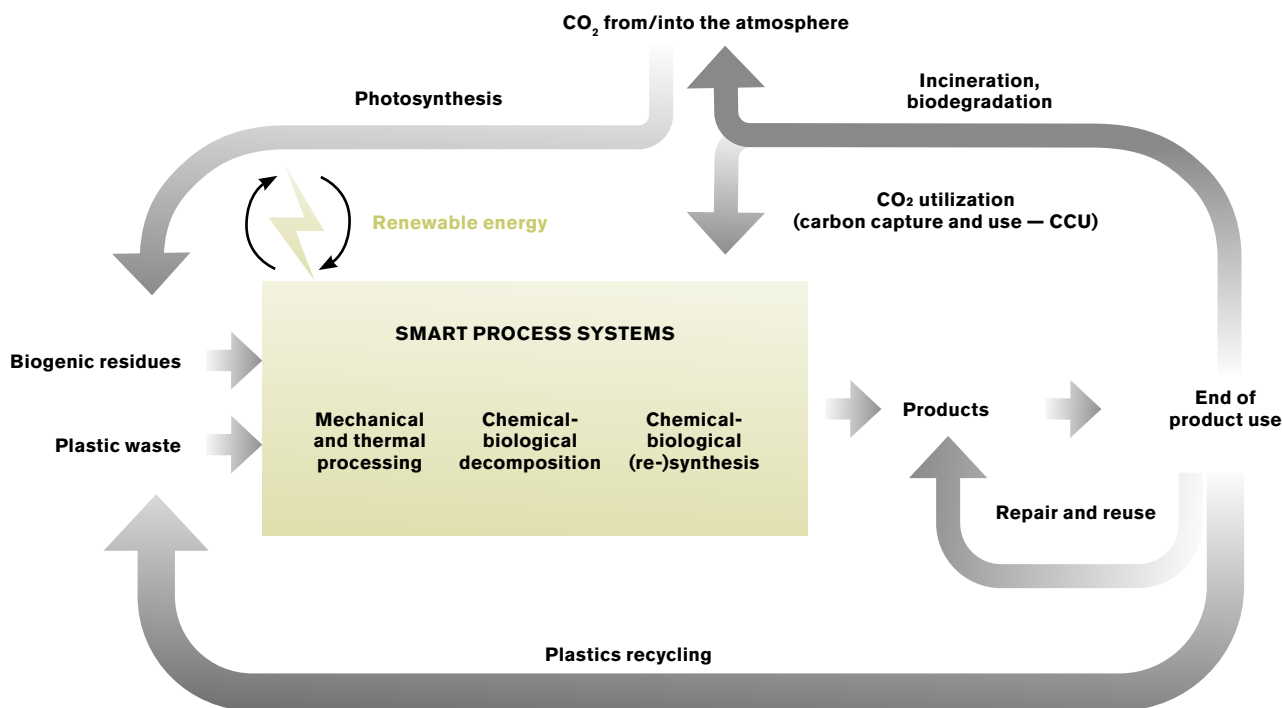


DIAGRAM: GCO, BASED ON THE WORK OF KAI SUNDMACHER AT THE MPI FOR DYNAMICS OF COMPLEX TECHNICAL SYSTEMS

Moving away from fossil feedstocks: in the future, the chemical industry plans to draw its carbon from biomass, plastic waste, or even carbon dioxide. Researchers at the Max Planck Institute for Dynamics of Complex Technical Systems are working on smart process systems to enable just this kind of circular chemical economy.

One path in Sundmacher’s flow diagram is particularly broad—“plastic recycling.” And it’s no wonder: every year, over 400 million metric tons of plastic are produced worldwide, about 90 percent of it from fossil feedstocks, with much of it, such as packaging, quickly becoming waste. Some 14 percent of production occurs in Europe and just under 3 percent, namely 11 million metric tons, in Germany. Around 6 million metric tons of plastic end up as waste in Germany each year. The largest portion is used for energy recovery—which is to say, it is incinerated to generate heat and electricity. True chemical recycling, which converts polymeric waste into basic chemical components that can be reused as raw materials, is in its infancy; just 0.2 percent of Germany’s plastic waste was chemically recycled in 2023.

Recovering plastics from waste in near-pure form remains challenging, even

with public waste-separation and recycling programs. There are approaches for breaking down mixed plastics to serve as raw material for new polymers. One such approach is pyrolysis, in which polymers are heated in an airless environment and broken down into shorter molecular fragments. However, in Kai Sundmacher’s view, this is something of a brute-force method—and one that typically yields complex product mixtures, the separation of which is highly energy intensive.

Artificial Intelligence and Lab Testing

He and his team envision something more like a scalpel. “We are working on selectively isolating a single type of plastic from mixtures,” explains Ruben Goldhahn, a scientist at the Magdeburg Institute. As part of his doc-

toral research, he focuses primarily on polyamides—which are known to consumers under brands such as Nylon and Perlon. In Germany, around 600,000 metric tons of polyamide were produced in 2023 and processed into fabrics, hoses, cords, or ropes. “The synthesis of polyamides from petroleum feedstocks is very energy intensive and generates a lot of waste,” says Goldhahn. For that reason, establishing a circular system for this class of plastics would be especially worthwhile.

One typical waste stream containing polyamides mixed with various other polymers comes from end-of-life vehicle recycling. Those polyamides can come from fuel lines or heat-resistant covers in engine compartments. But how do you find a solvent that dissolves polyamides? How can you then separate it from other polymers in the mixture? Evidently, you could investigate these questions through lab-

based experiments and endless trials. However, in keeping with the Magdeburg Institute's systemic research approach, the scientists there use computer-based methods to seek solutions. Only then do they test the most promising solutions in the lab. This approach is more targeted—and also saves the time and money that would otherwise need to be spent on elaborate lab experiments.

However, computers need input data to produce results. Fortunately, there are databases of key parameters that describe the solubilities of many substances—and there is artificial intelligence. The researchers train artificial neural networks on the available data and thus deduce how those substances behave in other solvents. In practice, however, this is not as simple

as it sounds. For one thing, with polymers—whose molecular chain length distributions are often unknown—it is not always clear which solvent will be able to dissolve them. Moreover, the databases currently contain very little background information on polyamides. Consequently, Goldhahn still has to put on his lab coat and safety goggles from time to time and measure solubilities. From those measurements, the Magdeburg team can then infer the parameters needed to train the neural network.

There is another crucial, though unfortunately not self-evident, factor that the researchers must consider: once polyamides have been dissolved, it must also be possible to precipitate them again so that they can be fed into the production process in pure form.

It's at this point that an approach that had hitherto looked promising can fail. The Magdeburg team experienced this firsthand: the researchers came across a solvent that was initially working well. However, it consisted of three components, and because the subsequent separation and recovery of the individual solvent components was extremely labor intensive—and essential for a complete cycle—the candidate was ultimately ruled out. "It isn't enough to simply find a good solvent. We also have to make sure that it doesn't cause problems further along the process or harm the environment," Sundmacher explains. The Head of Department speaks of this as the "integrated molecular and process design approach"—the "philosophy" of his group, as it were. After restarting their search, the team has since found a new candidate for dissolving polyamide, and it works without the need for any compromises.

Lignin for Adhesives and Plastics

Test case with pure materials: initial dissolution trials for polyamide 6 are carried out on the pure polymer. Any promising solvent must then prove its effectiveness in experiments with mixed plastics.



IMAGE: UNIVERSITÄT MAGDEBURG / JANA DÜNNHAUPT

According to Sundmacher, plastic waste is not the only feedstock for the circular chemistry of the future. Another pathway in his diagram shows residuals from biogenic resources. It is important to Sundmacher that residues are used for this purpose. He wants to avoid reserving additional agricultural land specifically for the chemical industry, at the expense of food production. In his view, these residuals might include straw or by-products from food production. Or the large amounts of lignin—still seldom valorized into high value products and often incinerated—that is left over from processing wood into pulp.

Lignin, present in trees, shrubs, and grasses, would be a superb feedstock for the chemical industry. This macromolecule is considered the largest renewable source of "aromatic compounds"—substances that can serve as precursors for the synthesis of adhesives or plastics. These compounds are currently almost exclusively produced using petrochemicals. Thus far, technological obstacles have pre-

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vented this renewable lignin from being put into use. The pulping method used most widely, the Kraft process, chemically alters lignin in a way that hinders further processing.

Solvents Produced by Chemical Evolutions

This is where Sundmacher's department steps in. "We are developing a process to extract lignin from biomass before pulp production and to separate it from the other wood components, cellulose, and hemicellulose," explains Liisa Rihko-Struckmann, who heads the Life Cycle Assessment team in Sundmacher's department. In for-

mal terms, this task is similar to extracting polyamides from a plastic mixture—which is why the approach was so similar, too. The team first trained an artificial neural network with data on the solubility of lignin in more than 3300 different solvents. From this base, the group used computers to predict how additional substances would dissolve. To avoid testing compounds at random, the Magdeburg researchers combined the neural network with an evolutionary optimization tool called PSEvolve.

"We start with a given substance and then let the tool automatically modify it from one generation to the next—for example, by gradually removing or adding bonds, inserting chemical

groups, and so on," explains Rihko-Struckmann. After each change, the neural network predicts how well the resulting compound is likely to dissolve lignin. If its ability improves compared to the previous molecule, the next structural change is made—until the process converges on an optimal solvent for lignin.

This solvent must satisfy additional criteria. It must be chemically compatible with the additives that protect lignin from chemical changes, such as those that occur in the Kraft process. "Of course, it must be possible to manufacture such a solvent later on without adverse environmental effects, and the solvent must be non-toxic," Sundmacher emphasizes. Chemists



Lab tests for AI training: Ruben Goldhahn and Ann-Joelle Minor first attempt to dissolve a plastic in a temperature-controlled ultrasonic bath. They then measure thermodynamic data, which is used to train artificial neural networks.

are already able to extract lignin very effectively from biomass using dioxane—a solvent that is however classified as “likely carcinogenic.” Collaborating with a research group in Lausanne, the Magdeburg team has already identified several promising alternatives to dioxane with this approach. Their calculations with the neural network and PSEvolve have produced a number of nitrogen-containing compounds that dissolve lignin effectively. The next step is to test these theoretically developed candidates. To that end, the scientists hope to collaborate with companies in Saxony-Anhalt whose processes generate large amounts of lignin as a residual material—lignin that is currently burned or used as tire filler.

Looking again at the flow diagram and its depiction of the cycle, it shows a third input pathway for the smart conversion processes: CO₂. To serve as a feedstock for syntheses, it must be captured either from air or from exhaust gases. Many groups worldwide, including Sundmacher’s department, are researching suitable CO₂ utilization processes (see MaxPlanck-Research 03/2021 and 04/2022). The current focus is the production of methane and methanol from CO₂ and green hydrogen, which is obtained by

SUMMARY

In the future, instead of relying mainly on crude oil to produce plastics, adhesives, and dyes, the chemical industry will have to use waste such as plastic scrap, biogenic residues, and CO₂.

Researchers at the Max Planck Institute for Dynamics of Complex Technical Systems are using computer-based methods, particularly artificial intelligence, to find solvents that selectively dissolve polyamides from mixed plastic waste or lignin from lignocellulosic biomass.

Digital twins make it easier to control demanding processes, such as maintaining the temperature when CO₂ reacts with a fluctuating supply of green hydrogen to form methane.

water electrolysis using electricity from renewable sources. Facilities of this kind could be built right next to wind or solar farms.

Ask Sundmacher exactly what his team is investigating, and he’ll gladly lead you straight to the Institute’s pilot plant. There, Sundmacher stops in front of a fume hood—a glass cabinet with a through-flow of air—that houses a slim, vertical tube about two meters tall, although its exact shape is hidden beneath layers of insulation. “Hydrogen and carbon dioxide are fed

into this reactor from above, where they react on catalyst pellets. Methane and steam emerge at the bottom.” If things really were as simple as Sundmacher describes, his team wouldn’t have to deal with this particular issue. The team first had to develop a special catalyst design that prevents the reactor from overheating (see MaxPlanckResearch 3/2024).

Temperature management itself is a major concern. After all, things can’t be allowed to get too cold, either. For the Power-to-X process to run optimally—a process which releases a great deal of heat—the reactor has to be kept within a narrow temperature range. A challenging proposition in a process that is often subject to load fluctuations. These fluctuations arise because renewable electricity, whether wind or solar, is not available continuously, and neither is the green hydrogen derived from it. In theory, the hydrogen could be stored and then fed in on a continuous basis. “But that kind of storage is expensive, so we would prefer to avoid it,” Sundmacher explains.

Like many reactors, the Magdeburg tube is cooled from the outside. The temperature inside is controlled by adjusting the coolant’s temperature. Yet because the conditions inside change constantly depending on the load, the coolant has to be pre-conditioned to a different temperature over and over again. Luisa Peterson, a doctoral researcher in Sundmacher’s department, describes the special challenge: “The system doesn’t respond immediately to abrupt changes in load. The coolant temperature is adjusted with a delay.” That means that if the coolant is supposed to reach a certain temperature at any particular time, the thermostat has to be set a few minutes beforehand.

For several years now, Peterson has been working on predicting the reactor’s temperature changes ahead of time. To that end, she has created a digital twin—a virtual model of the reactor and its internal processes that exchanges data with the plant, yet always stays one step ahead of it. To train her model for deployment in, say,

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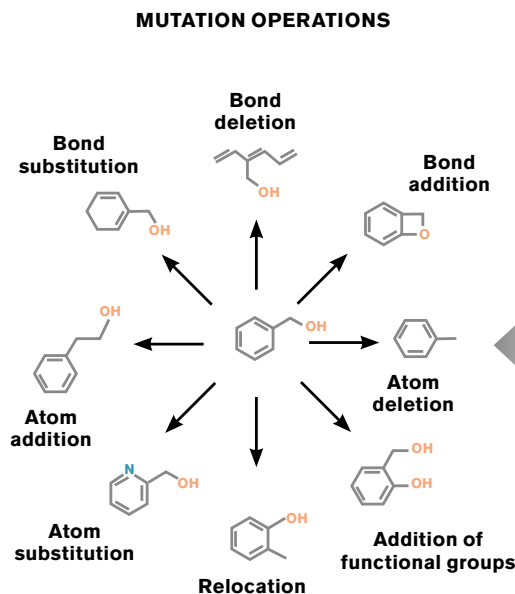
a wind farm, where hydrogen concentrations fluctuate, Peterson uses local wind forecasts. The forecasts reveal precisely how much power the wind turbines will supply for water electrolysis at any given moment and how much hydrogen will flow into the methanation reactor.

Researchers from the Numerical Methods in Systems and Control Theory Department, headed by Peter Benner, have also played a key role in this development. Most importantly, Ion Victor Gosea offered Peterson comprehensive support on theoretical methods, including machine learning ones. The digital twin is now highly advanced. Benner regards the still-new digital-twin approach as a blueprint for other processes. “Thanks to data-driven methods, we are now increasingly able to find dynamic models for such twins and can therefore optimize, monitor, and control technical systems in real time,” the mathematician explains.

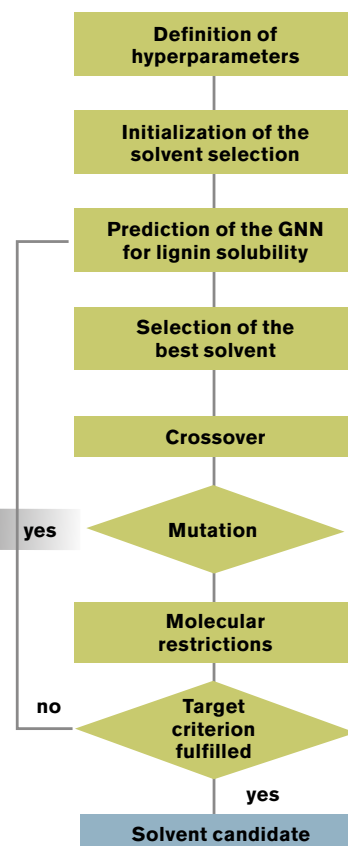
Biogenic and Biodegradable

From solvents for plastic recycling and lignin extraction, to the efficient conversion of green hydrogen with carbon dioxide—all these examples show that computer-aided modeling is essential for chemistry’s green transformation. Across many other projects, the staff of the Institute in Magdeburg are developing similar models. One project led by Achim Kienle’s group focuses on optimizing the biotechnological production of polyhydroxyalkanoates (PHA). These PHAs are regarded as a particularly sustainable alternative to conventional plastics, because they can be produced from bio-based feedstocks. And unlike many other plastics, they are biodegradable. Even so, a number of questions still have to be answered before such processes can operate in practice.

The researchers in Magdeburg will scarcely be short of projects in the future. Nor will they be short of ideas. And they certainly won’t be short of



ALGORITHM FOR SOLVENT DESIGN



Using an AI algorithm, the Magdeburg team is developing organic solvents for lignin and other applications. The method combines evolutionary principles of mutation and selection with a graph-based neural network (GNN) that predicts lignin’s solubility.

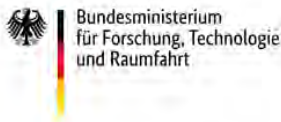
young talent either. Sundmacher meets some of that potential talent regularly just a stone’s throw from his Institute—in the lecture hall at Otto-von-Guericke University, where he holds the Chair of Process Systems Engineering. Just recently he illustrated the scale of the chemical industry to his students: every year it takes about 100,000 tank wagons to move the products of the oil refinery in Leuna, a good 100 kilometers away. The volumes of waste, particularly in the form of end-of-life products from chemical production, are of a similar magnitude. Sundmacher then sets out his vision for the future of chemical production; it’s his view that this type of waste should be seen as a valuable resource—for a circular chemical economy. ←

GLOSSARY

DEFOSSILIZATION refers to moving away from fossil feedstocks such as crude oil and natural gas. It is not a synonym for decarbonization. Decarbonization involves abandoning carbon-based substances and materials altogether, which is impossible in the chemical industry, unlike in road transport or steel production.

ARTIFICIAL NEURAL NETWORK is an approach used in machine learning. It imitates the way the brain works by processing data in artificial neurons that are interconnected and usually arranged in layers.

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ADVERT

Excitement on the sidelines: games can be won with a new strategy and the active support of fans.



DEMOCRACY IN THE PLAYOFFS

TEXT: MICHAELA HUTTERER

Established democracies are under mounting pressure—and they are beginning to crumble. The process of erosion begins slowly, almost imperceptibly, before suddenly accelerating at a terrifying pace. What are the most corrosive forces at play, and how can society counter the slide? These are the questions driving Ralph Hertwig’s research at the Max Planck Institute for Human Development. One fact is undeniable: watching passively from the sidelines will do nothing to stop the erosion.

The score is 88–91. It might sound like a tight basketball game, but this is actually the current tally in the global game between democracies and autocracies. The tally was calculated by the Varieties of Democracy (V-Dem) Institute in Gothenburg for the 2024 season. This is the first time in 20 years that democracy has fallen behind; last year, the score was 91–88.

Currently, many more people live in autocracies than in democracies: 72 percent of the world’s population. In 2024, only 29 countries—including Japan, Switzerland, and some EU states such as Germany, Sweden, and Denmark—met the criteria for liberal democracy, such as separation of powers, free and fair elections, and civil rights (last year it was 32). This is fewer than at any time since the end of the Cold War.

For V-Dem’s democracy report, researchers evaluated 202 countries based on 600 parameters. Countries can rise or fall in the rankings depending on the degree to which the separation of powers is effective, free-

dom of expression is guaranteed, and elections are free and fair. The V-Dem Institute found no signs that “the wave of autocratization is cresting or even slowing down.”

A Matter of Time

Of course, falling behind in sports doesn’t automatically mean defeat. The possibility of a comeback depends on all kinds of things, but chief among them is how much time is left on the clock. The best coaches have a feel for what to try. Is it time for substitutions, a revised lineup, fresh tactics, or a new defensive strategy? But beyond any play that can be sketched

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out on a whiteboard, there's something essential and intangible: the will to win—in the team, in each player, and even in the crowd. Do they still have it in them to turn the game around, or have they given up?

“In a democracy, we are often both players and spectators,” says Ralph Hertwig. He leads the Center for Adaptive Rationality at the Max Planck Institute for Human Development in Berlin. As a psychologist, Hertwig studies human behavior and decision-making. He researches the cognitive tools we use to make decisions, particularly under challenging conditions such as time pressure, uncertainty, and information overload. Few areas of life require as many decisions as the digital world, whether on social media platforms such as X and Facebook, in comment sections on news sites, group chats, or internet forums. “In the digital world, we are always spectators, but we're often players too,” Hertwig says. How do we shape our digital interactions? What content do we consume? What do we share? And when do we decide to quit a platform or leave a group chat?

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“Many people are experiencing an erosion of democracy, along with high

levels of dissatisfaction and exhaustion.” We are in a state of polycrisis, with challenges like inflation, economic inequality, climate change, worries about the future, artificial intelligence, and workplace disruptions combining to fuel doubts about the performance of democracy and leading to a dangerous slump. As in sports, attitude and mindset are decisive in a democracy. How resistant are we, as a society, to the allure of seemingly simple solutions to complex problems served up by populists around the world? Do we have enough fundamental trust in a system where political decisions are based on compromise, rather than the decrees of individual rulers and their followers?

Learning from High-Security Systems

“We were looking for a scientific model that could identify shifts in political cultures. We wanted to know how endangered our democracy is, and what options we have to take countermeasures,” Hertwig explains, describing the starting point of a new research project. A model used in risk re-

search—in contexts such as nuclear power plants, oil rigs, and rocket missions—provided answers. “Although systems like these are equipped with multiple layers of safety precautions and designed to be fault tolerant, the system can still drift into a danger zone and crash,” Hertwig explains.

The drift-to-danger model was developed by power plant expert and accident researcher Jens Rasmussen. According to the model, every system is characterized by goals and constraints to which individuals must adhere for the system to function safely. “It operates in an abstract space defined by three hard limits. If the system crosses one of these limits, it collapses. There can be many reasons for this,” says Hertwig. One limit is economic viability—any system without sufficient financial resources or profitability will fail. A poor budget situation and inflation can increase the risks. Another limit is technical failure, which can also cause a system to collapse. The third limit is defined by people—more precisely, their capacity to maintain and service the system, as well as their willingness to actively contribute to the good of the system. In the model, the system reacts to pressure and can drift into a danger

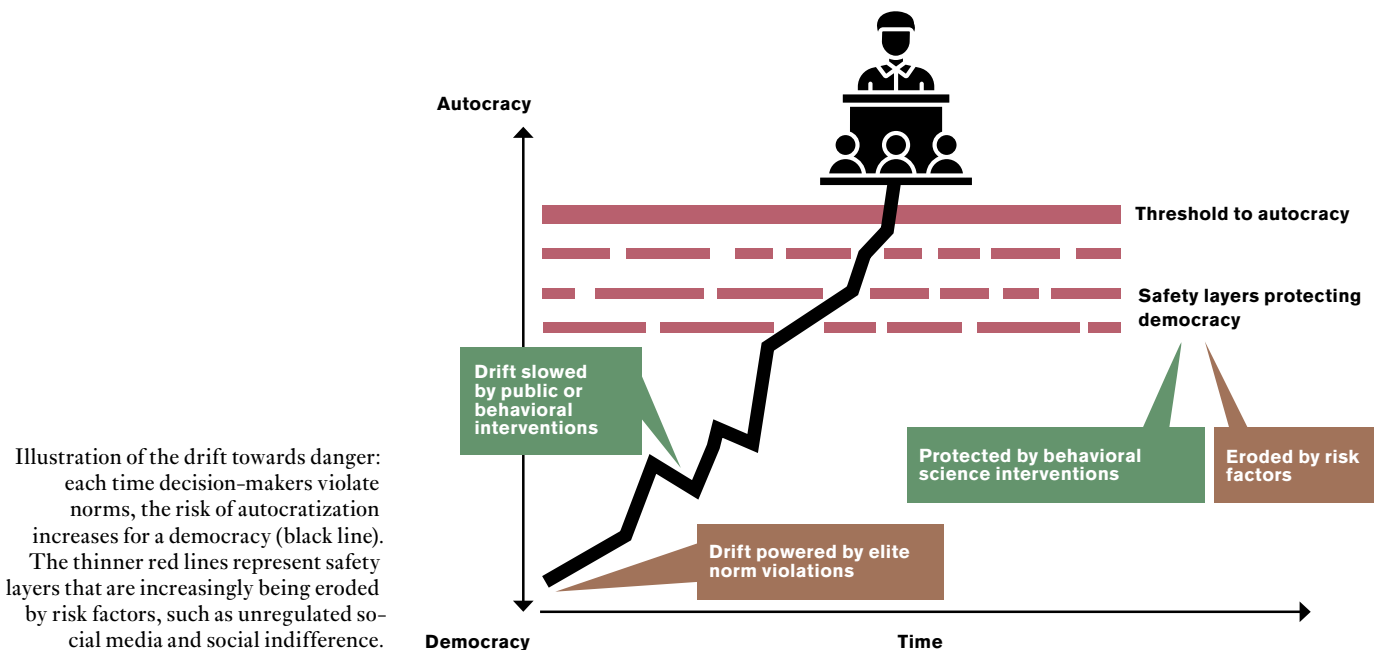


IMAGE: NICO WÖHRLE / MPG



Ralph Hertwig is a psychologist and Director at the Max Planck Institute for Human Development in Berlin. His research has shown that under some circumstances people act as if they underestimate the probability of rare events and their consequences.

zone. And that isn't a linear process, but an abrupt one, similar to the sudden shifts seen in the movement patterns of particles in Brownian motion. When the core of the Unit 2 reactor at the Three Mile Island power plant near Harrisburg, Pennsylvania, melted down in March 1979, the post-mortem revealed a long chain of failures that, in their sequence and sum, had hollowed out the reactor's ability to function—all in a slow, creeping, and unnoticed process of decay.

Instructive Near Misses

As history shows, democracies are no different. They don't collapse overnight; they erode. "There are gradual processes, often difficult to perceive, that bring a secure system to a critical state, which can then abruptly lead to system failure," explains Christoph Abels, a political scientist at the Uni-

versity of Potsdam. He and Hertwig have analyzed seven near-meltdowns in recent history. These are cases in which a backslide to autocracy was prevented at the last minute. One example is Finland in 1932, when key military officers did not join the Mäntsälä uprising of the nationalist Lapua movement. The rebels were severely punished by judges, and a cross-party alliance was formed as a counter-initiative. Another example is Spain. In February 1981, an attempted coup by anti-democracy forces ended with the intervention of King Juan Carlos I. He was not intim-

For example, not lying habitually and systematically.

"What once led to the resignation of ministers and even a US president now seems to be a tool of political competition and governance. Such violations of norms are becoming normalized," says Hertwig. This has serious consequences: "Once a society becomes accustomed to lies being propagated, political opponents discredited, freedom of the press threatened, parliaments bypassed, and laws stretched, a democracy slides into autocracy."

Slow Drift

The exact timing cannot be predicted, but the factors that accelerate this drift (to danger) can: a combination of populism, misinformation, and polarization. "These factors weaken the protective and control mechanisms that normally prevent political decision-makers from undermining central democratic norms," explains Hertwig. The violations occur gradually. "Once a tipping point is reached, it becomes difficult to restore democratic processes through the usual control mechanisms, such as elections and civil society engagement," says Abels. This is not unlike repeatedly skipping safety inspections.

For behavioral researchers, it's no coincidence that established democracies have come under increasing pressure with the rise of social media over the past 15 years. In 2022, a team led by Hertwig showed how the use of digital media—from posts on channels such as X to comments on online articles—relates to key dimensions of liberal democracies. "In autocracies and emerging democracies, online exchange can have positive effects, such as increasing political participation and improving access to information," reports Lisa Oswald, a political scientist and researcher at the Max Planck Institute for Human Development who analyzed around 500 research articles with Hertwig.

"In established democracies, however, there are various dangers. Many stud-

SUMMARY

Liberal democracies are losing ground. Autocracies are on the rise.

When politicians and other decision-makers repeatedly violate unwritten democratic norms without facing consequences from the courts, parliament, and civil society, the risk of autocratization increases.

In the current attention economy, digital media use is associated with societal polarization, populism, and mistrust of democratic institutions and their representatives, particularly in established democracies.

idated by the occupation of parliament, or by tanks on the streets of Valencia—and neither were the Spanish people, who had celebrated the end of the Franco dictatorship just a few years earlier.

"In every example we identified, influential political actors had begun violating democratic norms long before the situation escalated," emphasizes Hertwig. By democratic norms, Hertwig means the essential rules of a democracy. In addition to the rule of law, civil liberties, and the separation of powers, these norms include the unwritten rules and codes of conduct shared by society and political actors.



Autocratization is gaining traction: since 2009, the number of closed autocracies (such as China, Myanmar, and Vietnam) has risen to 35. They often develop from electoral autocracies with a multi-party system that nevertheless have significant deficits in freedom of expression and assembly, as well as in free and fair elections. The decline of liberal democracies (now 29) is reflected in an increase in electoral democracies that no longer meet all the criteria for a liberal democracy.

- Liberal Democracy
- Electoral Democracy
- Closed Autocracy
- Electoral Autocracy

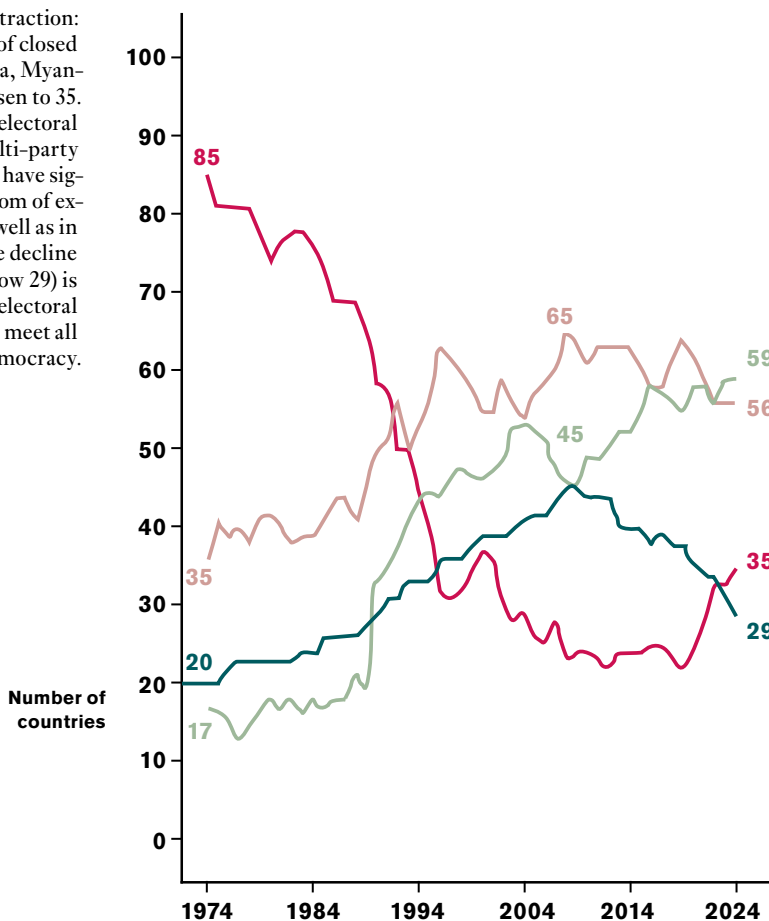


CHART: GCO BASED ON NORD, M., ET AL., 2025: DEMOCRACY REPORT 2025: 25 YEARS OF AUTOCRATIZATION — DEMOCRACY TRUMPED? UNIVERSITY OF GÖTHENBERG, V-Dem INSTITUTE.

ies have found correlations between digital media use and low trust in democracy and its institutions, greater polarization, and support for populist parties,” Oswald says. In 2025, other researchers replicated these findings in studies published up to 2024, confirming the initial results. Polarizing posts typically generate greater reach through a business model that rewards and monetizes attention. “Additionally, the majority of political content on social media is generated by a small, but highly active—and highly visible—minority,” Oswald explains. This can create partisan echo chambers where people with similar views reinforce each other, producing more content more frequently than those in the moderate mainstream, who tend to remain silent.

But democratic near misses also offer valuable lessons: “Clear public support

for upholding democratic norms—even when it goes against one’s own political interests—is an important protective factor for the robustness of liberal democracies. Unfortunately, polarization and populism are increasingly undermining society’s willingness to take a stand,” says Abels.

Boost Yourself!

“We’re witnessing an exhausted society,” says Hertwig. Many people ignore facts, boycott quality news, and rely solely on social media for political information. “Our ability to think critically and question is being pushed to its limits by the flood of news, crises, and rule-breaking.” Hertwig is exploring ways to make better use of our limited cognitive resources and has introduced the concept of the “citizen choice architect.” This suggests that

individuals can shape their immediate environments, especially in the digital world. “There are plenty of small but effective changes we can make to protect ourselves from dangers such as misinformation, manipulation, and the hijacking of our attention online.”

Step one: “We can regain cognitive sovereignty by becoming aware of when and how we are being manipulated by attention merchants, such as digital platforms and producers of misinformation, seeking to exploit what makes us tick,” says Hertwig. For example, we often find content we have seen repeatedly or that aligns with our views more credible,” Hertwig explains. On top of that, content that triggers strong negative emotions is especially good at capturing our attention. “But we can also learn to use that emotional response as a built-in alarm, a signal

to stop and question the truth of the information,” Hertwig says.

Lateral reading—vetting unfamiliar websites or news sources before trusting them—also helps reclaim our autonomy. “We proceed like professional fact-checkers.” Simply open a new browser tab—moving sideways from the original source rather than delving straight into it—and use Google or another search engine to find out who is running the site. There are an astonishing number of slick, reputable-looking websites that are actually fronts for interest groups who want to manipulate their readers, not inform them.

This manipulation can be countered by not sharing content lightly, but instead asking: why am I sharing it? Is it true? Who is it from? Is it important? If we feel powerless in the face of a political development, simply checking the numbers can help: what is the baseline,

or, to be more precise, the absolute frequency from which increases in refugee numbers, spending, or crime rates are calculated? It’s impossible to interpret a headline such as “Number of crimes has doubled” unless you know how many crimes there were last year. Was it two or 2000?

In step two, we can take back control as critical consumers. “When we make small individual decisions that have a large collective impact, we can make a big difference as a society,” says Hertwig, citing the sales figures of a certain electric car manufacturer in the US as an example. People can also regain control of their smartphone use—for example, by moving social media apps to a folder (“out of sight, out of mind”), setting time limits, or using black-and-white mode to make posts, reels, and videos less visually appealing. An app called one sec that asks whether you really want to open Facebook and the like can make you

think twice and prevent endless scrolling.

“Five years ago, the pandemic showed us that we can change our behavior and develop new skills,” Hertwig says. The speed with which many of us acquired medical expertise, adapted to restrictions needed to protect vulnerable people, and developed new ways of working demonstrates our capacity to overcome crises together by acquiring new knowledge and skills, as well as cultivating compassion and solidarity. Inaction favors drift—or defeat in the competition between political systems.

Right now, it’s 88–91. If this 2024 tally were a basketball score, fans would know that a few seconds are all it takes to tie the game. So, let’s call a timeout, bring democracy’s players into a huddle—the spectators, too—and focus on the most important play of all: how do we want to live? ←

ADVERT

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Breath-testing the ground: with 200 measuring stations worldwide, including this one in the Degerö Stormyr nature reserve in northern Sweden, an international research team has determined how much CO₂ the ecosystems of the Arctic Boreal Zone absorb or give out.



CO₂ THAT COMES FROM THE COLD

TEXT: JAN BERNDORFF

For thousands of years, the boreal region and the Arctic have served as a sort of freezer for carbon and so have helped to keep Earth's climate stable. But a new study involving the Max Planck Institute for Biogeochemistry in Jena shows that the region's CO₂ balance sheet is changing as a result of climate change—sooner than expected.

Away from the ice, there is a seemingly never-ending expanse that defines the Arctic landscape: the boreal forests stretch in an evergreen ring around the globe between 50 and 70 degrees of northern latitude as far as the eye can see. The largest continuous forests on Earth cover more than 15 million square kilometers of Eurasia and America—a good ten percent of Earth's land surface and one and a half times the area of Europe. To the north, this sea of green, which is also known as taiga, gradually turns into tundra around the Arctic circle.

Hardly any trees grow here; instead, bushes, grasses, mosses, and lichens dominate. Around a quarter of the taiga and tundra are wetlands, which means they are covered with standing water.

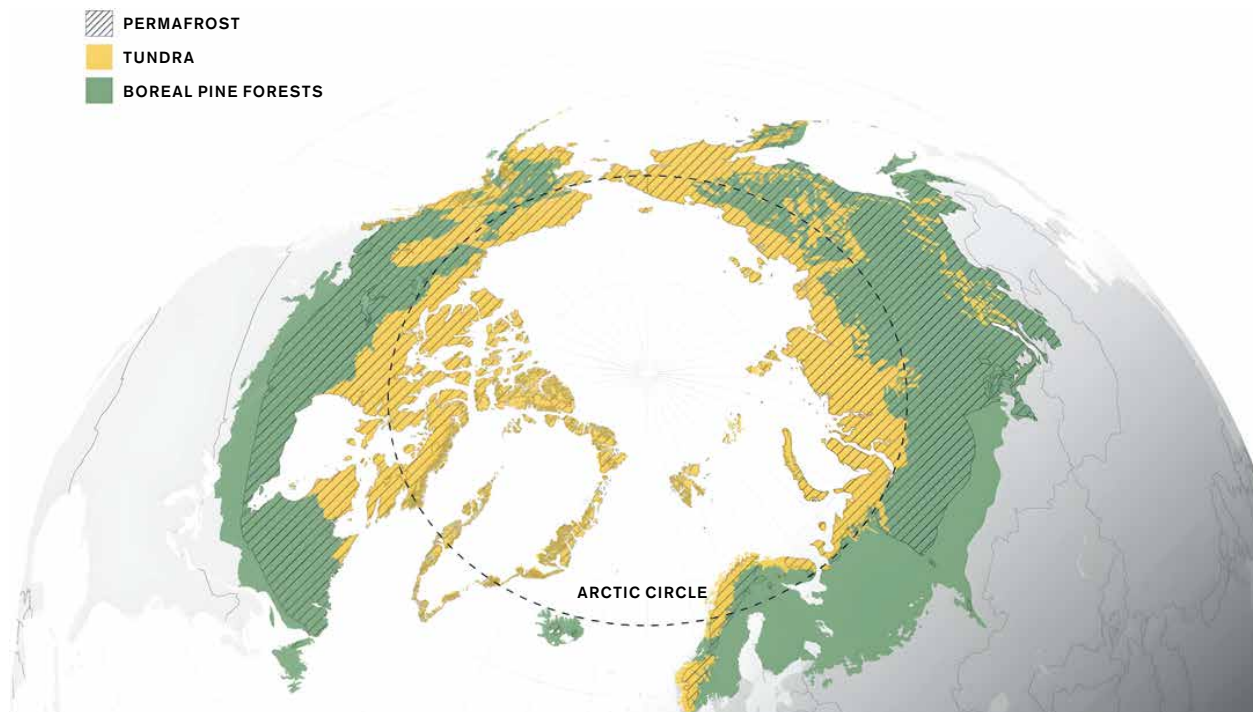
This landscape, which is known as the Arctic Boreal Zone (ABZ), is ice-cold for most of the year, so the water and the ground are both frozen. Below a certain depth, the soil even remains frozen at the height of summer—which is why it is known as “permafrost.” Permafrost exists in around 80 percent of the ABZ. For this reason, the area is only very sparsely populated. And its northern regions are also barely exploited for economic purposes. As a result, the forests, meadows, bushes, and wetlands are largely still in a natural state — unlike in our part of the world.

These spaces also form enormous carbon sinks with huge significance for the development of the climate. A third of the carbon bound in forests is stored in boreal forests. The majority of this is in the ground: in humus,

roots, fungi, and microorganisms. In the cold and wet, or in frost, microbes are not very active and decompose dead plants and animals only slowly. As a result, carbon has accumulated over thousands of years as humus on the ground—meters thick in some cases—and has largely been trapped in permafrost, meaning it doesn't end up in the atmosphere. Wetlands and the soil of the tundra store more carbon dioxide than the soil of the forest in many regions.

The vegetation of the far North also continues to draw carbon dioxide from the atmosphere during Arctic summers, alleviating the anthropogenic greenhouse effect. Various studies have shown that the ABZ rids the climate of around 550 to 850 million metric tons of carbon each year. Accordingly, this CO₂ sink offsets roughly as much carbon dioxide as Europe emits annually.

However, global warming means that the permafrost is thawing and humus is decomposing at a faster rate. So how long can we count on the ABZ as a CO₂



GRAPHIC: GREG FISKE / WOODWELL CLIMATE RESEARCH CENTER

A band circling the world: the Arctic Boreal Zone stretches around the world near the Arctic circle. Boreal pine forests dominate to the south of the Arctic circle, while tundra prevails to the north. Permafrost can be found in large swaths here.

sink? The new study headed by the Woodwell Climate Research Center in the United States and involving the Max Planck Institute for Biogeochemistry also showed that the ABZ removed an average of around 548 million metric tons of carbon from the climate each year between 2001 and 2020. But the results also show that a good third of the ABZ is already changing from a CO₂ sink into an additional source of CO₂. Counting forest and peat fires, this number increases to as much as 40 percent. “Alaska, for example, emitted 12 million metric tons of carbon dioxide per year,” says Anna-Maria Virkkala, a scientist at the Woodwell Center. The tipping point, she says, has also been reached in northern Siberia. The ABZ is thus following other CO₂ sinks that are now absorbing less carbon—if any at all. Parts of the Amazon rainforest, for instance, have developed into sources of CO₂ as a consequence of deforestation, drought, and forest fires. As a result of drought and pests, German forests now also emit more CO₂ than they absorb.

Contrary Effects

“The balance had been expected to tip later for the ABZ, as the forests there are comparatively untouched and are even expanding as the planet warms,” says Mathias Göckede, Group Leader at the Max Planck Institute for Biogeochemistry. According to the study, the ABZ became greener in almost half of its regions during the observation period. Trees and meadows are becoming denser and are spreading north in particular due to milder temperatures. However, on a net basis, just 12 percent of these areas now absorb more carbon dioxide than before. The positive feedback from a climate perspective—more plants store more CO₂ and slow down warming—is already being largely eroded by other effects.

One of these is the “respiration” of vegetation and the soil: while it is true that trees and other plants take in more CO₂ from the air when they are spreading and growing denser, they

SUMMARY

Until a few years ago, the forests, meadows, and wetlands of the Arctic Boreal Zone absorbed as much CO₂ annually as is emitted in Europe.

Due to global warming caused by human activity, the ABZ’s permafrost is thawing, and microbes are decomposing more organic material, releasing CO₂.

As a result, up to 40 percent of the ABZ is now releasing more CO₂ than it absorbs.

also emit more overnight and in winter as they slow down their metabolism. Higher emissions are now being seen from the soil in particular, because microorganisms multiply better in warm weather and decompose more dead organic matter. This matter is also being released by the thawing of permafrost. More frequent periods of drought, storms, and insect

infestations are also having an effect. These consequences of a warming climate mean that more plants are dying off.

Fire is another important factor: forest fires occur more frequently in the taiga than in deciduous forests in Central Europe and are also more harmful to the climate. First, this is because people often leave these fires to burn, as they rarely threaten settlements or other assets. Second, conifers produce highly inflammable resin, and their needles contain less moisture than leaves. And then there's the soil's high carbon content: boreal forest fires release ten to 20 times more CO₂ than fires in other ecosystems. In these fires it is not only the trees and shrubs that burn, but usually also the ground with its meters-thick humus. Peat fires in boggy areas are not unusual either. "Naturally, if there are twice as many fires as there used to be, fire as a factor is going to play a big role," explains Göckede.

New Approach

The study carried out by Virkkala and her team has shown that, for the first time, parts of the ABZ have now transitioned from sink to source as a result of all these factors. This finding is based on a new type of modeling and

the largest collection of data on carbon flows in the ABZ to date, which resulted in the most comprehensive CO₂ balance sheet ever for the region. To create this, the researchers gathered all available data within a period of around three years and processed it partly with the help of artificial intelligence. Virkkala was assisted by the global "Permafrost Carbon Network", in which over 500 climate researchers—including some from Max Planck—collaborate on topics such as permafrost, carbon budgets, and climate change in the ABZ.

Virkkala collated data collected between 1990 and 2020 over 200 measuring stations in Siberia, Alaska, Canada, Greenland, and northern Scandinavia. She and her team were also able to use satellite data, with a resolution of up to one kilometer, which is more precise than the data from other studies. The researchers combined the data using a machine learning model and compared the results with three other approaches. "We hope this will help us to obtain more reliable results despite the ongoing scarcity of data," Virkkala explains.

Atmosphere models are one example of an alternative approach, with Christian Rödenbeck, project leader at the Max Planck Institute for Biogeochemistry, contributing one of these. "In principle, it observes air currents be-

GLOSSARY

ARCTIC BOREAL ZONE (ABZ) refers to a belt of land around the Arctic circle. It includes the boreal pine forests, wetlands of the taiga, and the treeless tundra.

CO₂ SINK designates an ecosystem that takes in more CO₂ than it releases into the atmosphere, thus alleviating the greenhouse effect resulting from human activity.

tween the measuring stations," he explains. "If there's a high carbon value in the air at one station and a lower one at a second toward which the wind is blowing, there must be a CO₂ sink between the two. The activity of this sink can be roughly quantified." In this way, carbon flows can be reconstructed even in regions for which no concrete measurements exist.

Half a dozen such atmosphere models were used for the study in order to obtain reasonably reliable figures. "It would of course be much better to corroborate these interpreted values using concrete measurements taken on location," says Göckede. In any case, the study provides another good reason to intensify climate protection efforts: "We cannot rely on forests, wetlands, meadows, and bushes as CO₂ sinks if we want to achieve our climate goals," says Virkkala. ←

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IMAGE: ANNA-MARIA VIRKKALA

Research in the field with a measuring chamber: Anna-Maria Virkkala from the Woodwell Center measured carbon flows herself for the most comprehensive CO₂ balance sheet created to date for the ABZ—here she is working near the village of Kilpisjärvi in northern Finland

Max Planck researchers collaborate with partners in more than 120 countries. In this article, they write about their personal experiences and impressions. At the Atto research station in the Amazon, Sebastian Brill from the Mainz-based Max Planck Institute for Chemistry is investigating how fungal spores and other biological particles affect cloud formation in the atmosphere. The researcher tells of life in a rainforest camp, where the trees are home to howler monkeys and caymans appear in the shower.

IMAGE: SEBASTIAN BRILL / MPI FOR CHEMISTRY



Research above the canopy: the Atto tower stands in a clearing in the middle of the rainforest. At a lofty height, Sebastian Brill collects data there to investigate cloud formation processes.

72 It's hard to imagine, but fungi are crucial to the survival of the Amazon rainforest. The jungle trees can only grow there because fungi make nutrients available in the soil through their microscopically fine network. And that's not all: a single fungus can release many thousands of spores into the air—in just one second! In favorable conditions, the tiny particles are carried high up into the atmosphere. There they act as condensation nuclei for clouds, generating rain. This means that fungi play an important role in the water cycle of the Amazon region. In my doctoral thesis, I am investigating the transportation of fungal spores and other biological particles into the atmosphere and analyzing their chemical composition to enable us to understand their effects in detail.

The Atto station offers the perfect conditions for this. Atto stands for “Amazon Tall Tower Observatory” and is a German–Brazilian research project in the middle of the rainforest. It is 150 kilometers as the crow flies to the nearest big city, Manaus—or a half-day journey by car and boat. Far from the influences of human civilization, researchers based there can investi-

gate how the forest, ground, and atmosphere influence each other.

The heart of the Atto is a 325-meter-high steel tower. The tower houses measuring equipment that records meteorological, chemical, and biological data. Some devices are even mounted on an elevator that is permanently traveling up and down. This enables us to create vertical profiles. A spiral staircase with 1500 steps leads to the topmost platform. Anyone who wants to work on the tower must first com-

plete a three-day safety training course. A helmet and climbing harness are also mandatory. Climbing the endless stairs in hot and humid conditions is tiring, but the filters for the particle samples have to be changed daily, and devices need to be maintained regularly and often have to be repaired. It's worth the effort every time: looking out over the sea of treetops really is fantastic!

The station offers space for 15 to 20 scientists. A kitchen, a dining room, sev-



THE ATTO RESEARCH STATION, BRAZIL

eral washrooms, and a shared dormitory are housed in rustic wooden huts with metal roofs. Hammocks serve as beds. They are more hygienic than mattresses and also offer protection against spiders and snakes that might creep into the station at night. There's also a small car repair shop on the site, which is used as a fitness space in the evening. Badminton and beach volleyball are also popular among the researchers.

However, the real sporting highlight takes place on Sundays: on the riverbank around 15 kilometers from the station is a small settlement with a church, a school, and—typical of the Brazilians—a soccer pitch right outside of town. The scientists arrange to meet up there with men and women from the village for joint tournaments. In addition to being good fun, the tournaments also strengthen relationships with local people. While researchers from the Atto station were initially observed with suspicion, we are now seen as part of the furniture, so to speak. We look out for and help each other. Teachers from nearby

schools have also visited us to find out what we are doing, and Atto researchers have organized workshops for the local schoolchildren.

The station is a dream for anyone who loves animals! There are birds, spiders, and insects in all shapes and colors—they all seem three times as big as those at home. Howler monkeys roar from the trees, and agoutis—slender, long-legged relatives of guinea pigs—run around between the buildings. There's even a small cayman that always hangs around the site in the rainy season. During the day it lies about in a puddle, and sometimes it wanders into the shower at night.

The most impressive experience I've had was my encounter with a jaguar: I was walking in the forest close to the tower with a companion. We also had a dog with us. That's probably what attracted the jaguar. We stood a few meters away from the big cat for what felt like an eternity, before it vanished into the undergrowth. Since then, researchers haven't brought dogs with them to the station.



IMAGE: PRIVATE

Sebastian Brill

31, is a biologist who is currently undertaking his doctorate at the Max Planck Institute for Chemistry in the Multiphase Chemistry Department. His career path was set when a childhood gift from his parents—a science kit—gave him the idea to become a researcher instead of a train driver.



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FIVE QUESTIONS

ON THE FUTURE OF THE US DOLLAR AS THE GLOBAL RESERVE CURRENCY

WITH LUCIO BACCARO

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The US dollar has been the global reserve currency since the end of the Second World War. Do you think it might lose this status? If so, do you think this is the aim of the Trump administration?

LUCIO BACCARO Although the US dollar currently has no serious competition as the world's lead currency, the political agenda of the Trump administration could weaken its foundations. The US government is looking to devalue the dollar in order to restore the competitiveness of US manufacturing. At the same time, it wants to preserve the dollar's reserve status. To reconcile these goals, it is pressuring partner countries to increase imports from the United States and to make a financial contribution to the military security guarantees of the United States. The Mar-a-Lago Accord envisions allies swapping short-term US Treasury securities for very long-term, low-interest US debt—such as 100-year Treasury bonds. Tariffs or the threat of withdrawing US military protection are both means of exerting pressure. The Accord is intended to ensure that the United States has access to “cheap” money in the long term.

What are the consequences for the global economy, particularly Europe, if the US dollar weakens?

There is a crucial difference between a gradual weakening of the US dollar and a sudden

loss of trust in its reserve status. The latter would be a systemic threat: US Treasury securities form the backbone of the international financial system. Were investors to sell these securities en masse, this could lead to a global liquidity crisis. Europe would not be spared: European banks are highly dependent on financing in US dollars. A flight from dollar assets in search of safer alternatives would worsen credit terms for banks. This in turn would make loans more expensive for companies and households or—worse still—lead to a huge credit freeze, as seen during the global financial crisis.

Which currency could replace the US dollar—the Chinese yuan or the euro?

The yuan is not a likely candidate, mainly because it cannot be freely converted into other currencies and is still subject to capital controls by the Chinese authorities. It also lacks transparency and predictability. In principle, the euro could take on a larger reserve role, but this would require a change in economic policy and growth strategy within Europe. Reserve currencies must be backed by safe assets such as government bonds. To absorb global demand, either the EU member states would have to collectively take on new debt together through the large-scale issue of joint euro bonds, or else individual countries—particularly Germany—would have to deliberately run higher budget deficits in order to incur new government debt.

Would it be beneficial for Europe if the euro were to take on the role of global reserve currency?

Fundamentally, issuing the global reserve currency is a privilege: it allows the hegemonic country to take on debt across long periods without interest rates rising significantly. However, this privilege also has negative aspects. High demand for the reserve currency tends to increase the exchange rate and asset prices. For the euro to become the global reserve currency, Europe would likely have to move away from the export-led growth model and toward a more debt- and consumption-led one, similar to that of the United States

Could several reserve currencies co-exist in the future?

Yes, in principle this is both possible and desirable: a multipolar currency system in which the US dollar, the euro, and possibly the yuan served as references for different spheres of influence could reduce global dependency on a single reserve currency and distribute both the benefits and the burdens more fairly.

Interview: Elke Maier

Lucio Baccaro is a Director at the Max Planck Institute for the Study of Societies in Cologne and works in international political economy, among other areas.

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