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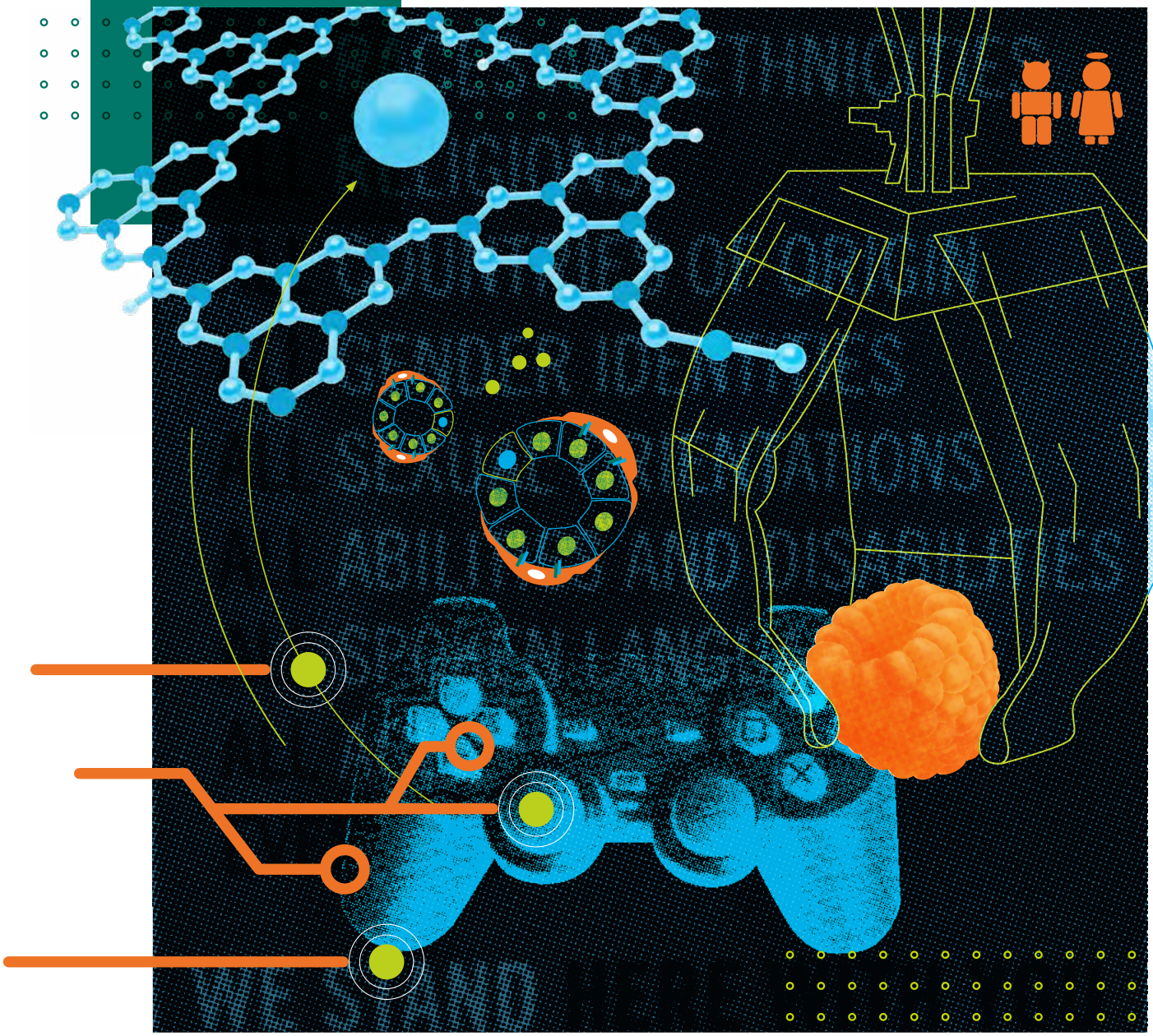


HIGHLIGHTS 2021

FROM THE YEARBOOK
OF THE MAX PLANCK SOCIETY

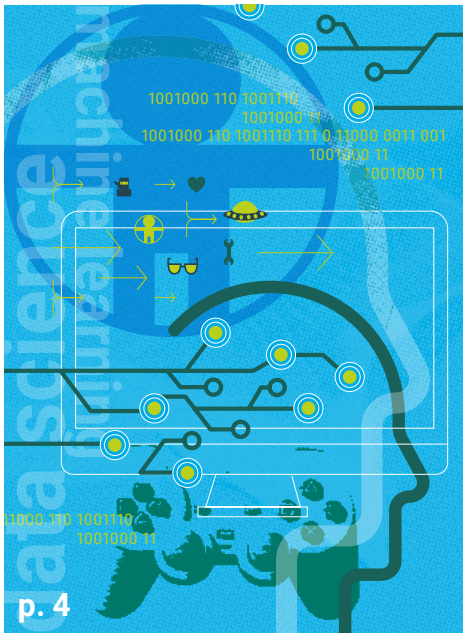
Editorial

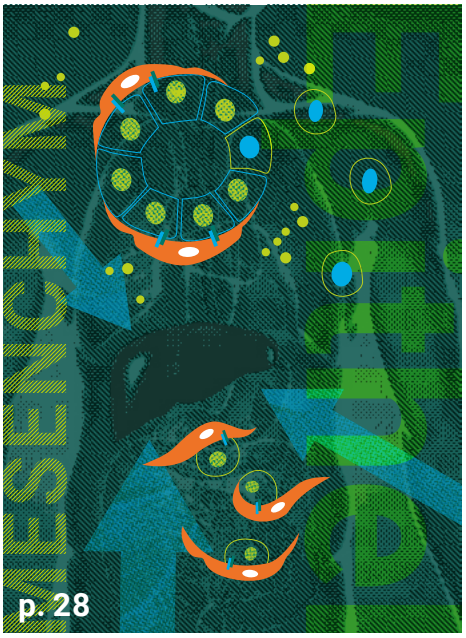
Each year, the Max Planck Society submits a scientific research report in the form of a yearbook to render account of the scientific research performed at its Institutes to the public and its funding providers. The central questions addressed are: where do we stand, and where do we want to go? The Max Planck Institutes are asked to select a work or project from their scientific activities that is suitable for presentation in the yearbook, as far as these have reached a certain degree of completion. All contributions of the Max Planck Institutes are published on our website at www.mpg.de/jahrbuecher.

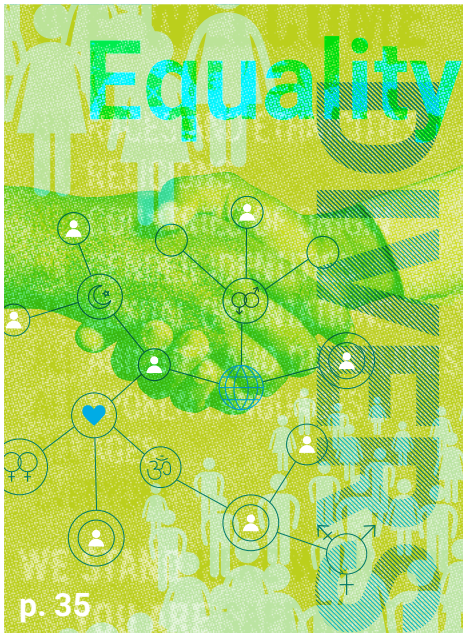
For this printed collection, 15 articles were selected and edited in a journalistic manner, which seemed particularly suited for publication from a science communication perspective and especially interesting also for non-experts. The highlights of the 2021 Yearbook shine a spotlight, amongst others, on the extent to which computer technologies have found their way into research – whether as a methodological tool or as an object of study in itself. For example, a research group at the Max Planck Institute for Biological Cybernetics is using the complex worlds of computer and video games to find out why humans still perform better than the best computer algorithms currently available, especially when it comes to creative processes. At the Max Planck Institute for Informatics, researchers are developing software to integrate optical switches in cloud data centres instead of the usual electronic switches. This is because optical data traffic between servers could make the work of data centres more efficient. And at the Max Planck Institute for Human Development, researchers are investigating the effects of artificial intelligence on social, cultural, political and economic processes. A central question here is how the behaviour of machines influences human morality.

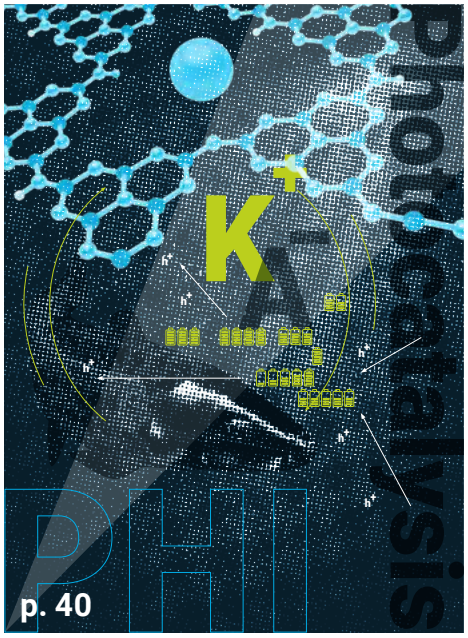
We hope you will enjoy reading our Highlights 2021!

Content









1 A beginning without errors

TOMMASO CAVAZZA, LENA WARTOSCH, MELINA SCHUH

↘ Max Planck Institute for Multidisciplinary Sciences, Göttingen

Only about one in three fertilisations leads to a birth. Many embryos resulting from fertilisation do not develop further because they have the incorrect number of chromosomes. This is one of the main causes of miscarriages and infertility. In many cases, the egg cell had the incorrect number of chromosomes to begin with. However, our latest research has revealed that errors are also often imminent after fertilisation, when the genetic material of both parents is combined. This process, which is fundamental to the emergence of new, healthy life, is astonishingly inefficient.

Once an egg has been fertilised by a sperm, the genes of the father and the mother are combined. Both contribute one copy each of the 23 chromosomes that contain the genetic information encoded by the DNA. The embryo thus inherits a complete set of chromosomes.

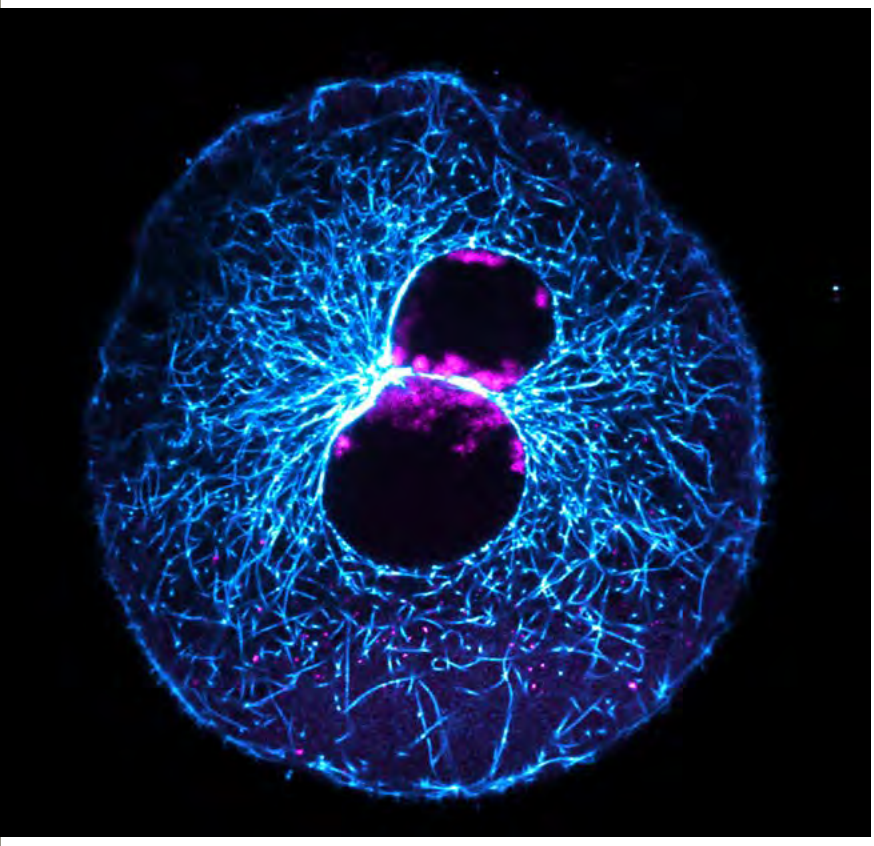
The precursor cell of an egg cell still contains two copies of each of the 23 chromosomes. In order for eggs to be produced from this cell, half of its 46 chromosomes must be removed. This happens during meiosis, which is a particularly error-prone process. Even in young women, ten to 20% of the eggs have too few or too many chromosomes. For women over 40, it is even more than 50%. This is because a woman's immature eggs are produced before she is even born. A 40-year-old woman thus has 40-year-old eggs. The older the woman and her eggs become, the more likely the mature egg will have too many or too few chromosomes. This is one of the main causes of miscarriages and infertility.

We have already discovered several factors that contribute to the high error rates in egg cells. The spindle apparatus, a cellular machine, ensures that a maturing egg contains the right number of chromosomes. This apparatus consists of protein fibres that attach to the chromosomes during meiosis. These fibres pull one copy of each pair of chromosomes to one of the two opposite poles. After that, the cell divides. Surprisingly, our studies show that the spindle apparatus in human egg cells is quite unstable and often attaches incorrectly to the chromosomes. This leads to errors in chromosome separation. We recently discovered that human egg cells lack a motor protein (KIFC1); this makes the spindles unstable. By artificially introducing the motor protein into the egg cell, we were able to stabilise the spindles and reduce errors in chromosome separation.

Age-related changes

Errors also occur because of age-related changes in the chromosomal architecture: they fall apart prematurely even before they are separated.

Chromosome segregation errors happen not only in the egg but also in the early embryo of mammals. The time immediately after the union of sperm and egg – the zygote stage – appears to be an extremely critical phase for healthy development. We wanted to find out why this is the case. For our investigations, we analysed videos of human zygotes recorded by colleagues at the



New life emerges: the paternal and maternal genetic material (magenta) shortly after fertilisation of an ovum of a cow in two separate so-called pronuclei. Before the genetic material unites, the chromosomes gather at the contact surface. (Blue: a part of the cytoskeleton)

Bourn Hall Clinic in England. There, microscopy videos of human zygotes are routinely recorded for fertility treatments.

However, especially for ethical reasons, studies on human zygotes are quite limited. We therefore set out to find a new model organism that could be used to study early embryonic development in greater detail. Together with researchers at the Institute of Farm Animal Genetics at the Friedrich-Loeffler-Institute, Neustadt, we have developed methods to observe the first divisions of a bovine zygote live. Bovine zygotes are quite similar to those of humans (e.g. in terms of chromosome arrangement and spindle organisation). The frequency of chromosome separation errors during the first cell divisions is also similar in both organisms. Another advantage of the "bovine model system" is that we can obtain the egg cells for fertilisation from slaughterhouse waste.

Lost chromosomes

In the laboratory, we fertilised the bovine egg cells in vitro and used high-resolution live cell microscopy in order to follow how the parental genetic material combines. After fertilisation, the parental chromosomes are initially present in two separate nuclei, the pronuclei. Under the microscope, we observed that the parental chromosomes accumulate at the interface of the two pronuclei. However, in some zygotes, individual chromosomes did not accumulate. As a result, these were lost when the genetic material was united. The newly formed cell nuclei thus had too few chromosomes. As expected, these zygotes then showed developmental disorders. The assembly of the chromosomes at the interface of the two pro-nuclei thus appears to be an extremely important step. If this accumulation of chromosomes is not successful, errors occur, and the embryo does not develop correctly.

But why do the chromosomes not accumulate correctly? Our results show that motor proteins and components of the cytoskeleton control the movement of chromosomes within the pronuclei. These are the same elements that ensure that the two pronuclei move towards each other. The unification of the parental genome is thus based on two closely linked processes. However, these often go wrong. Whether an embryo develops correctly depends on a remarkably inefficient process.

Our findings could be important for the successful in vitro fertilisation of human eggs. For example, we showed that defects in human egg cells can be reduced by introducing the motor protein KIFC1. This could improve the success of fertility treatments. o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2 Computers are learning how to be curious

ERIC SCHULZ

↘ Max Planck Institute for Biological Cybernetics, Tübingen

Although computer games are made for entertainment purposes, my team and I are using them for behavioural research. This is not only opening up new approaches in the field of psychological research; our research results are also helping to improve artificial intelligence (AI) algorithms.

Curiosity is one of the key characteristics of the human species, and is especially evident in children. It is curiosity that prompts the eponymous heroine in "Alice in Wonderland" to follow a white rabbit down a hole, which leads to a dreamlike, magical world. Thanks to her childlike sense of wonder and her love for exploration, Alice learns to assert herself in this new world and comes up with ever new solutions to a series of conundrums.

Experimental psychologists usually employ quite simplistic scenarios to study the root causes of human behaviour, such as curiosity. For example, to study the principles of intelligent action, test subjects are asked to repeatedly choose between two options, or to compare the length of two lines.

Simple experimental set-ups such as these do not reflect the complexity of the real world. In terms of dealing with complexity, machine learning theories are already far superior to human learning theories. The capabilities of Artificial Intelligence (AI) algorithms have also increased dramatically during the past decade. One of the main reasons why computer capabilities have increased to such an extent in such a short period of time is that the focus has shifted: increasingly, computers have been optimised to cope with multiple environments and to learn more complex behaviours. The results are impressive: computers running artificial intelligence algorithms have even beaten human world champions in "Go", a centuries-old board game, and are able to solve difficult mathematical problems.

The goal of my research group is to make a similar transition in our understanding of how humans learn: we use complex computer and video game environments to study human behaviour in realistic environments. In particular, we focus on those behaviours in which humans still outperform the best computer algorithms, such as creative processes.

Playing with the elements

One of the games we use is Little Alchemy, which can be played for free online at https://littlealchemy.com/. Players start with four simple elements, earth, water, air, and fire, any two of which can be combined on a virtual screen to create a new one (e.g., combining water and fire produces the new element "steam"). A total of 720 "elements" can be created, from simple ones such as clay and grass to more complex ones such as humans and "ice cream for astronauts". The remarkable thing is that although there are no prizes for creating elements, thousands of people play the game every day. Why do they do so, and how can their behaviour best be described in scientific terms?

In a collaboration with the game's inventor, we studied and mathematically modelled the behaviour of about

We are attempting to develop algorithms that are capable of playing this game as well as humans.

30,000 players in more detail and found that players try to create elements from which they can create as many other elements as possible. This kind of curiosity is known as aptitude.

Our findings lead us to conclude that people act like this because they enjoy being able to create more and more new elements whilst simultaneously learning more and more about the game. Our current goal is to programme the characteristics that typify human curiosity into an AI algorithm.

We use a more complex online game to explore how large groups of people discover one another and interact creatively. Players form groups and develop new technologies in the game One Hour One Life (http://onehouronelife.com/) whereby each player is "born" into a random family and scenario, and age by a year every minute.

Family members explore their surroundings together and – just as in Little Alchemy – can combine existing elements to form new ones. Even complex objects, such as cars or aeroplanes, can be created from stones and sticks, whereby each player only makes a minor contribution to the development of the entire family over several generations. At the time of writing, the oldest family line extends over 800 generations.

Success in the game

We analysed the behaviour of approximately 30,000 players in 6,300 families to gain an understanding of what distinguishes successful, highly innovative groups from less successful ones and found that successful groups share two primary characteristics: first, people are able to join in an efficient and purposeful manner, i.e., they can quickly adopt roles for which there is a current demand. Second, all members in these groups share information frequently. In mathematical terms, collective curiosity, which can be thought of as a directed search process, can be plotted on a graph that encompasses all the elements in play. We are currently attempting to develop algorithms that are capable of playing this game as well as humans, or can at least collaborate with them.

We believe that the complexity of games will enable us to construct more realistic models of human behaviour. If we can discover the assumptions that players tend to make in advance, then it should be possible to program me them into machine learning algorithms to make them more efficient. Presumably, computer games could also be used to investigate the limits of human learning.

Our research could bring about a paradigm shift in psychology. In the future, methodologies from the fields of data science and machine learning could enable the study of theories in cognitive and learning psychology. Like Alice in Wonderland and our playful test subjects, we will have to stay curious to effectively combine both disciplines. o

3 The surprising history of our oral bacteria

CHRISTINA WARINNER, JAMES FELLOWS YATES, IRINA VELSKO

↘ Max Planck Institute for Evolutionary Anthropology, Leipzig

Thanks to ancient DNA from early human history, scientists are constantly gaining new insights into how our ancestors once lived. Together with an international research team, we now succeeded in reconstructing the oral microbiomes of Neanderthals, primates, and humans, including the oldest oral microbiome ever sequenced from a 100,000-year-old Neanderthal. The results provide new insights into human evolution, health, and diet.

Living in and on our bodies are trillions of microbial cells belonging to thousands of bacterial species: our microbiome. These microbes play key roles in human health, but little has been known about their evolution until now. In a multidisciplinary international research study, we investigated the evolutionary history of the hominid oral microbiome by analysing the fossilised dental plaque of humans and Neanderthals spanning the past 100,000 years and comparing it to those of wild chimpanzees, gorillas, and howler monkeys.

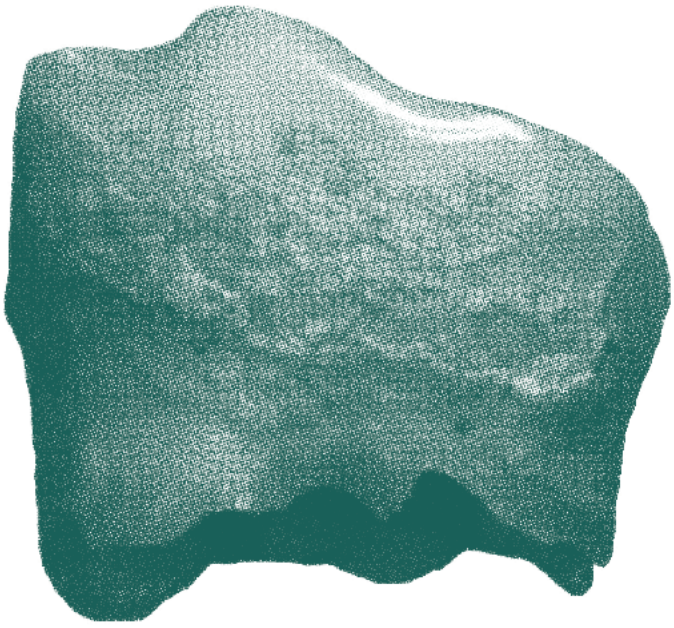
Researchers from 41 institutions in 13 countries contributed to the study, making this the largest and most ambitious study of the ancient oral microbiome to date. Our analysis of dental calculus from more than 120 individuals representing key points in primate and human evolution has revealed surprising findings about early human behaviour and novel insights into the evolution of the hominid microbiome.

Working with DNA tens or hundreds of thousands of years old is highly challenging, and like archaeologists reconstructing broken pots, archaeogeneticists also have to painstakingly piece together the broken fragments of ancient genomes in order to reconstruct a complete picture of the past. For this study, we had to develop new tools and computational approaches to genetically analyse billions of DNA fragments and identify the long-dead bacterial communities preserved in archaeological dental calculus.

Dental plaque of Neanderthals

Using these new tools, we were able to successfully reconstruct human microbiomes from the Pleistocene onwards, including the 100,000-year-old oral microbiome of a Neanderthal from Pešturina Cave in Serbia, the oldest oral microbiome successfully reconstructed to date by more than 50,000 years. The tools and techniques developed in this study have opened up new opportunities for answering fundamental questions in microbial archaeology, and will allow the broader exploration of the intimate relationship between humans and their microbiome.

A surprising number of oral bacteria are so understudied that they even lack species names.



Teeth from ancient human remains – more precisely, the fossilised plaque on them – provide far-reaching insights into the oral microbiome of our ancestors.

Indications of starchy foods

Within the fossilised dental plaque, we identified ten groups of bacteria that have been members of the primate oral microbiome for over 40 million years and that are still shared between humans and their closest primate relatives. Many of these bacteria are known to have important beneficial functions in the mouth and may help promote healthy gums and teeth. A surprising number of these bacteria, however, are so understudied that they even lack species names. That many of the most important bacterial species are poorly characterised came as a surprise. Oral microbiologists say these results have given them new targets for future research on oral health and disease.

Although humans share many oral bacteria with other primates, the oral microbiomes of Homo sapiens and Neanderthals are particularly similar. Nevertheless, there are a few small differences, mostly at the level of bacterial strains. When the researchers took a closer look at these differences, they found that ancient humans living in Ice Age Europe shared some bacterial strains with Neanderthals. Because the oral microbiome is typically acquired in early childhood from caregivers, this sharing may reflect earlier human-Neanderthal pairings and child rearing, as has also been already indicated by the discovery of Neanderthal DNA in ancient and modern human genomes. We found that

Jaws with teeth from archaeological finds are first carefully cleaned in order to discover ancient dental plaque (left).

Grauer's gorilla specimens showing typical dark deposits on the teeth likely as a result of their herbivorous diet.

Neanderthal-like bacterial strains were no longer found in humans after approx. 14,000 years ago, a period during which there was substantial population turnover in Europe at the end of the last Ice Age.

Among the biggest surprises was the discovery that a subgroup of Streptococcus bacteria present in both modern humans and Neanderthals appears to have specially adapted to consume starch early in Homo evolution. This suggests that starchy foods became important in the human diet long before the introduction of farming, and in fact even before the evolution of modern humans. Starchy foods, such as roots, tubers, and seeds, are rich sources of energy, and previous studies have argued that a transition to eating starchy foods may have helped our ancestors to grow the large brains that characterise our species.

Rapid evolution of bacteria

Reconstructing what was on the menu for our most ancient ancestors is a difficult challenge, but oral bacteria may hold important clues for understanding the early dietary shifts that have made us uniquely human. Bacterial genomes evolve more quickly than the human genome, which makes our microbiome a particularly sensitive indicator of major events in the distant and recent human evolutionary past.

It's important food for thought – the humble bacterial plaques that grow on our teeth and that we carefully brush away every day hold remarkable clues not only to our health, but also to our evolution. ○

4 Joints for collaborative robots

CHRISTOPH KEPLINGER, PHILIPP ROTHEMUND

↘ *Max-Planck-Institut for Intelligent Systems, Stuttgart*

Robots will soon be operating autonomously in unstructured enviroments and working closely with humans. Conventional robots made of rigid, metallic components and motors are not suitable for these tasks. Instead, we are developing components from soft and intelligent materials. We were recently inspired by a spider leg joint.

Robots today are constructed mainly from solid components and driven by electric motors made of metal. They are well suited for stationary use as industrial robots in car factories and recycling centres. However, when dealing with humans, such robots can be clumsy or even dangerous. They are also expensive and not well suited for unpredictable terrain. In contrast, nature relies on soft materials such as muscles and skin. That's why human hands are much more dexterous, agile, and adaptable than those of robots. With their flexibility, hands have an intrinsic intelligence because they can adapt to different shapes and contact forces without targeted control. The objective of our research is to use soft materials to construct robots. We take an interdisciplinary approach that combines insights from soft matter physics and chemistry with advanced engineering techniques. We can thus develop materials that not only enable the construction of intelligent machines but also mimic the remarkable abilities of natural organisms.

We recently developed artificial muscles together with researchers from the University of Colorado in Boulder. Because these muscles are based on an interplay between electrostatics and hydraulics, we have named them Hydraulically Amplified Self-healing Electrostatic (HASEL). These actuators work according to the following principle: a polymer bag is filled with a liquid dielectric (i.e. a material that is polarised in an electric field). In the simplest case, we use vegetable oil. We line the opposite sides of the bag with electrodes. If we apply a voltage to these, an electric field is created between the electrodes. The electrostatic force exerted on the structure redistributes the liquid locally, thereby deforming the bag. The trick is to connect the bag to a mechanism so that the mechanism can be moved as desired. In this way, we have constructed lightweight artificial ankle joints and biceps muscles. The frequency with which these actuators tension and release can be controlled by switching the voltage on and off. We have so far been able to achieve more than 100 cycles per second.

Inspired by spiders

We have now used this technique to develop a joint that mimics that of spiders. Spiders have their own biohydraulic system. Their legs have seven joints, two of which are without muscles. This is possible because arthropods have an open blood vessel system. Haemolymph flows freely from the arteries into the tissue and accumulates in the interstitial spaces. Contraction of the spider's anterior increases the haemolymph pressure in the legs, thereby causing them to stretch. An integrated hydraulic joint makes the leg movable and gives spiders considerable jumping power.

Based on the model of this tibia-metatarsus joint, we built a joint based on the HASEL technology. We use this Spider-inspired Electrohydraulic Soft-actuated joint (SES) in many different configurations – including


ARACHNOBOT

in the development of spiderlike Arachno-Bots. Building on an initially bidirectional joint, we then developed a multi-part limb. This was well-suited to construct a gripper with three fingers. This soft robotic hand can easily pick up, move, and set down even a fragile object – such as a raw egg – without damaging it. The gripper hand is a successful example of how soft robotic elements can be effectively combined with hard ones – a highly active field of research worldwide.

Powerful and cost-effective

The SES joints can rotate up to 70 degrees. This makes them quite agile and dynamic. The degree of the rotation can be precisely adjusted via the voltage applied. The joints are also quite robust – for example against blows. Despite their simple design, the lightweight joints are quite powerful. They allow a small robot to jump up to 10 times its height. Unlike the joints of hard robots, all this happens without gears and the other bulky and heavy components that make a robot immobile and slow. This makes these joints ideal for robotic systems that have to move quickly and operate in a cluttered environment. They also consume little energy and are simple and cost-effective to produce. For example, here we use plastics also used to package food. The production of the joints would therefore be easily scalable. These criteria are decisive in the design of versatile robots.

For our soft joints, we generally need materials that are sensitive and durable to the electric fields yet mechanically robust. Even when constructed from commercially available plastics, the joints can withstand more than one million cycles. Industry has also developed many high-performance films for special applications. We can either use these or develop our own high-performance material systems. During our investigations, we also came across material properties (e.g. of the oils used) that contradict previous knowledge. For example, some oils still function at voltages 10 to 100 times higher than expected. In order to understand this, we still need to conduct fundamental basic research. We expect that the resulting knowledge will allow us to substantially improve the performance of our artificial muscles.

Example of a soft robotic hand, whose design is based on HASEL actuators. The gripper is gentle enough to handle raspberries without crushing them.

A control mechanism that corrects errors

Finally, soft robots require control mechanisms that are different from those used in rigid systems. With their soft skin, human hands often do not grip quite precisely. Our brain has learned to deal with this inaccuracy and avoids or corrects errors. In the same way, soft robots will need intelligent, adaptive control. We are therefore working together with colleagues at the Sub-Institute in Tübingen, who specialise in machine learning.

We are convinced that robots with bio-inspired actuators will be increasingly integrated into our lives – from disaster control to medical and everyday robotics to wearable systems and lifelike prosthetics. Even if there is still a long way to go, we are approaching a world in which humans and machines will interact with each other in a way that has so far been seen only in science fiction. It is not a question of if – but rather when – this will happen. ○

5 Swarming phagocytes

TIM LÄMMERMANN

↘ *Max Planck Institute of Immunobiology and Epigenetics, Freiburg*

Neutrophilic granulocytes are among the "scavenger cells" of our immune system. These cells (also called neutrophils) circulate through our blood vessels. At the onset of inflammation or infection, they enter the tissue as first responders to eliminate pathogens. For this purpose, these phagocytes form impressive cell swarms and attack the pathogens in a coordinated manner. Our research shows that neutrophils have evolved a molecular start-stop system for their coordinated action. They control their swarming activity in order to effectively eliminate bacteria in body tissues without producing negative side effects.

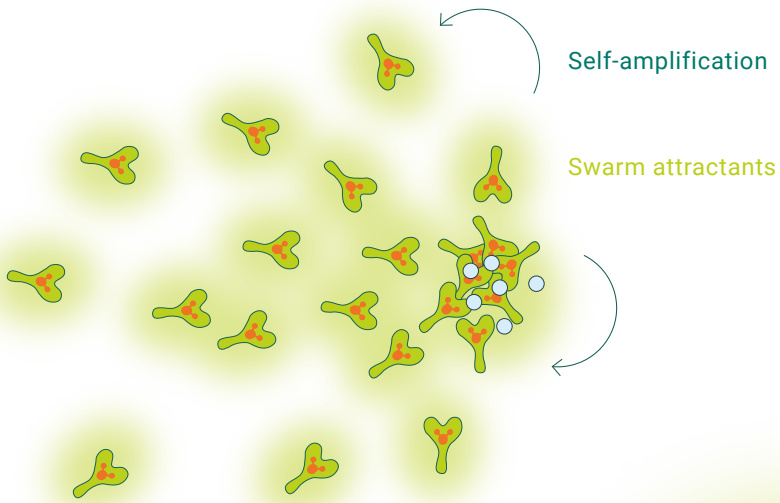
Our body is largely protected from invading pathogens by the skin. However, pathogens can enter the body through wounds and cause serious infections. In such cases, our innate immune system takes over the first line of defence with an effective arsenal of different cellular weapons. Neutrophilic granulocytes fight in the front line. They enter the injured tissue from the bloodstream within a few hours. There they identify and destroy the intruders.

Neutrophils in the blood patrol almost all areas of our body. With the help of molecular sensors on their cell surface, they are specialised in recognising the alarm signals of those cells that have been damaged by injuries or by invading microbes. As soon as individual neutrophils recognise these signals, they use chemical messengers to call other neutrophils to their aid.

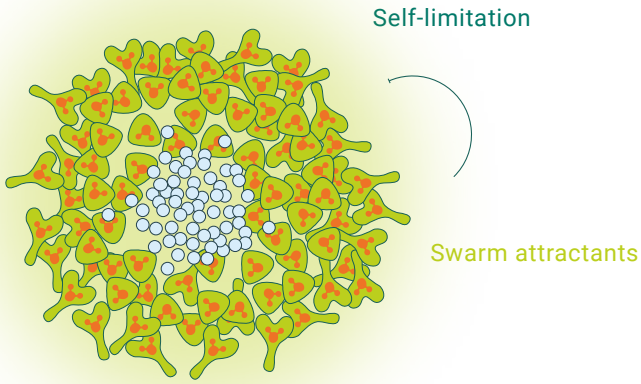
Our research shows that a special substance called Leukotriene B4, which is secreted as a messenger substance during inflammation, plays a crucial role in the communication between neutrophils. Leukotriene B4 is secreted by activated neutrophils in order to give direction to other neutrophils to follow. In this way, neutrophils form imposing swarms, some of which comprise several hundred cells and act together in a finely tuned manner in the tissue like a cell collective.

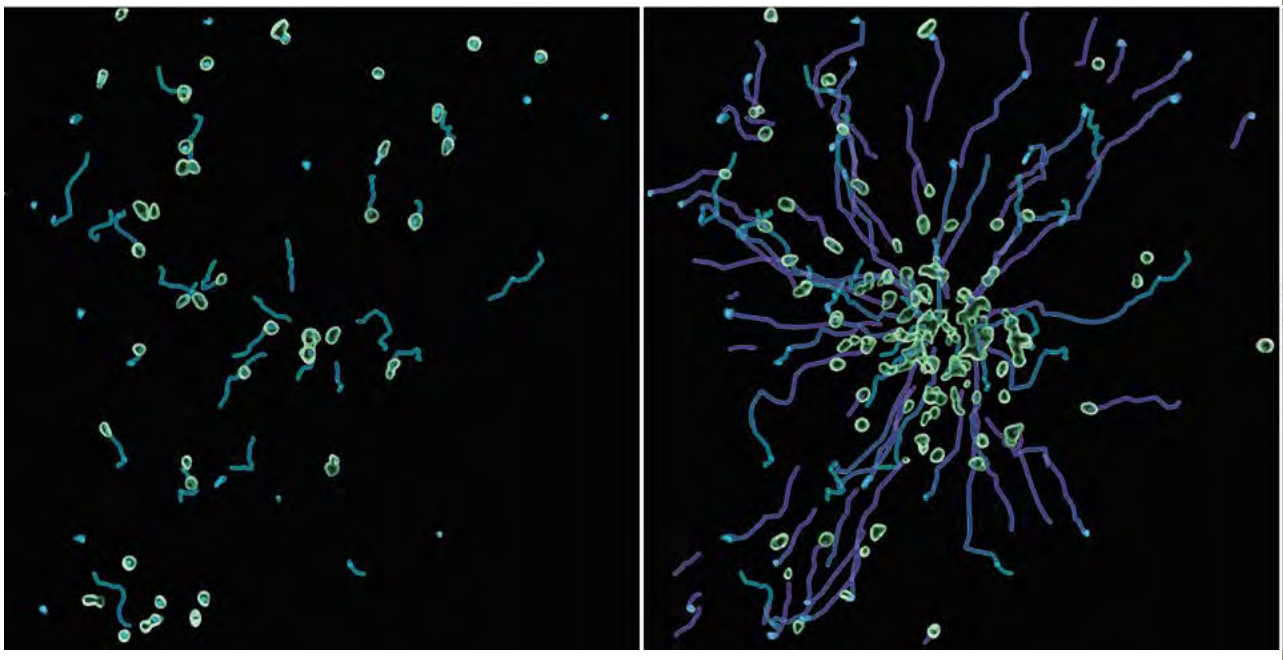
Dangerous contents

The fine balancing of their activity is necessary because neutrophils contain several antipathogenic substances inside their cells. However, when these substances are released from the cell into the surrounding environment, they can be harmful to the surrounding tissue scaffold. Such an excessive inflammatory reaction would result in massive tissue damage and become a danger to the body. This is often observed in severe inflammatory reactions and could be one of the causes of lung damage in severe courses of Covid-19.



Neutrophils release signalling substances that attract more and more cells. If the concentration of signals exceeds a certain threshold, the scavenger cells stop to migrate (s. below). The resulting swarm can destroy invading pathogens (circles) and fight them.





Scavenger cells (green) build swarms and gather at places where they have to remove damaged cells or pathogens. The lines in the individual images show the movements of the cells at different times (right: 30 minutes)

Neutrophils can control their swarming behaviour themselves, thus establishing an optimal balance between the search for and the destruction of pathogens.

Controlled swarm resolution

In recent years, many new insights have been gained into the triggering mechanisms of neutrophil swarms. However, it is still not known which mechanisms control the resolution of the swarms. We therefore asked how to prevent the uncontrolled accumulation of neutrophils in the tissue and thus the harmful inflammatory reaction associated with this.

Our studies show that neutrophils can control their swarming behaviour themselves and thus establish an optimal balance between the search and destruction phases in the fight against pathogens. These findings are surprising because it had always been assumed that external signals from the tissue environment dampened or stopped the activity of neutrophils at the end of an inflammation. However, by using special microscopy on living tissue, we observed that, over time, swarming neutrophils become insensitive to their own signals (e.g. Leukotriene B4) with which they originally initiated the swarm.

Molecular brake

The swarming neutrophils become desensitised because of a molecular brake with which they stop their movement as soon as they perceive excessive concentrations of the accumulating attractants. The protein mediating the braking effect is called “G-protein coupled receptor kinase 2”. It ensures that the cells no longer respond to these signals at high concentrations. In experiments with neutrophils that lack the start-stop mechanism, we observed that these cells circulate unchecked in the tissue and thus seek out bacteria in much too large tissue areas. However, this prevents them from combating the pathogens, which tend to grow more locally. Neutrophils act much more effectively when they swarm around an infected cell and remain there. In this way, they form a barrier that prevents not only the multiplication of pathogenic bacteria but also the further spread of them.

Our results have deciphered an important aspect of neutrophil biology that is particularly relevant to the immune defence against bacteria. Our unexpected findings on the hunting strategies of immune cells may provide important impulses for new therapeutic approaches. Furthermore, the mechanisms described here for the swarming behaviour of neutrophils could also advance research into the collective behaviour of other cell assemblies – right up to the collective behaviour of swarming insect species. o

6 The virtual fusion power plant

FELIX WARMER

↘ *Max Planck Institute for Plasma Physics, Greifswald*

Making the sun's energy source usable on earth is the ambitious goal of fusion research. There are currently two possible variants for realising a power plant: tokamak and stellarator. For years, we have been developing a simulation platform with which both the physical and technical requirements of a stellarator can be simulated "holistically". This digital twin is intended to describe the interaction of all system components in order to develop a fusion power plant more quickly and bring it to market maturity.

Generating energy from the fusion of hydrogen (more precisely: its heavy variants deuterium and tritium) is a long-pursued dream. With an almost inexhaustible fuel reservoir and CO_2-free operation, this technology could become one of the pillars of a sustainable energy supply. With their large electrical output, fusion power plants would primarily serve the base load and thus ideally complement the wind and solar power plants that depend on the weather.

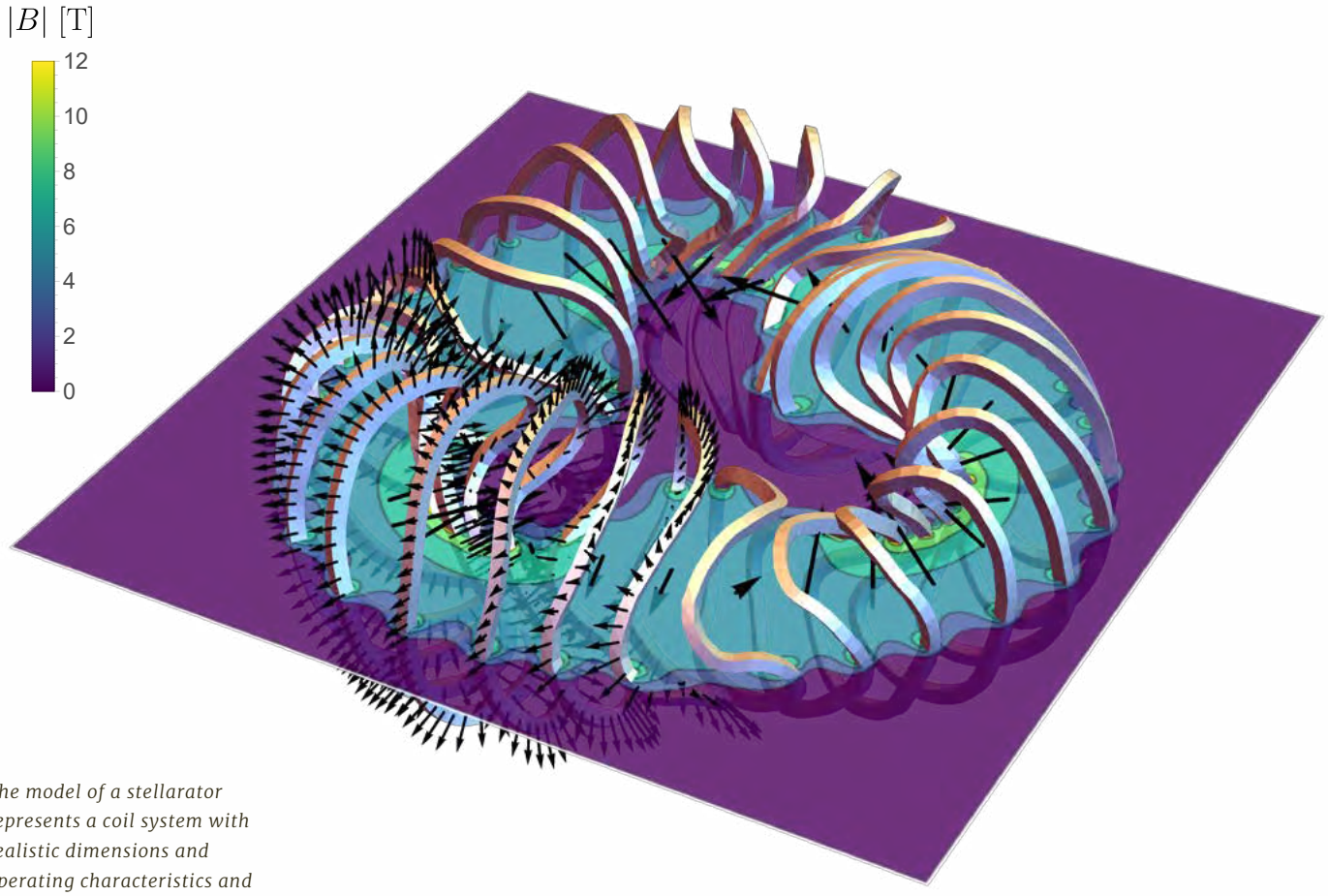
The ITER experimental reactor is currently being built in Cadarache in southern France. It is intended to demonstrate for the first time on a large scale that this type of energy generation is technically feasible. ITER is based on the principle of the tokamak. In it, the plasma, which has a temperature of around one hundred million degrees, is confined in a magnetic field cage. However, this is generated in such a way that a tokamak can operate only in pulsed mode (i.e. with regular interruptions).

Because of this limitation, another concept for fusion energy production called stellarator is being researched in parallel. It offers an attractive alternative because stellarators can operate continuously. The largest and most successful experimental facility of this type is Wendelstein 7-X, which has been operating in Greifswald since 2015.

The stellarator concept initially seemed more challenging because much more complex-shaped magnetic coils are needed to confine the plasma than in a tokamak. Wendelstein 7-X has proven that such coils can be produced with the required precision. This system holds the stellarator world record for the fusion product of temperature, plasma density, and energy confinement time. It indicates how close we are to the values for an independently burning plasma.

The goal: an economically attractive power plant

The computer programme used for the planning of the stellarators were developed in the 1990s. They calculate the magnetic field that encloses the hot fusion plasma and the coils that generate the field. However, there has so far been no systematic framework that takes into account other technical requirements important for operation. Building on the previous successful codes, we have developed new models in recent years – for the first time worldwide – that incorporate precisely these boundary conditions in a simulation platform in order to describe all details of technical subsystems holistically. Our ambition is to create a flexible digital twin of a fusion power plant on a computer. Such a system can be used to investigate the effect of new methods, physical findings, and uncertainties on the design and create an



The model of a stellarator represents a coil system with realistic dimensions and operating characteristics and takes into account the technical boundary conditions. The colour code indicates the magnetic field strength in Tesla. The small arrows represent local electromagnetic forces on the coils, the large arrows show the direction and, qualitatively, the strength of the summed forces for one coil.

optimal concept for a stellarator fusion power plant. This digital twin optimises not only the physical but also the engineering aspects of such a system.

The scientific challenge in developing a power plant concept is to combine the physical findings from ongoing stellarator experiments such as Wendelstein 7-X with current technical developments in order to derive an economically attractive power plant design. It is particularly demanding to harmonise all the technical components (superconducting coils, support structure, cooling systems, and many other systems must be coordinated with each other) and leave enough space to allow for remote maintenance access. Our simulation platform opens up new ways to virtually represent and overcome such technological challenges.

Tests for different stellarators

Wendelstein 7-X has already proven by experiment that the stellarator concept works. However, a future reactor can be built in many different shapes – and the optimal spatial geometry has yet to be found. We therefore applied our code called Process to different stellarator

We need to incorporate all the physical and technical aspects in the digital twin.

In 2016 and 2017, 8000 graphite tiles were installed in the plasma chamber of Wendelstein 7-X. Data that researchers have collected in the facility since then also flow into the virtual model of the stellarator.

concepts. We first simulated three reactor-sized stellarators with different aspect ratios. We have also calculated three coil sets with a different number of coils. Here, the volume and surface area of the plasma play an important role when it comes to further calculations of the fusion power, the fuelling rates, or the material load. Process takes into account the material properties of superconductors and technical boundary conditions in magnetic field calculations (e.g. the rules for a rapid shut-down of the coils). The model thus produces a functional coil system with realistic dimensions and operating characteristics. These simulations allow for the first time the comparison of different stellarator configurations within the same holistic system code and thus contribute to stellarator optimisation.

Another highlight of Process is its speed: the results are available after only a few seconds. This allows us to investigate an almost endless number of alternative designs in parallel and to decisively narrow down the large parameter space. In designing the codes, we consider computational speed – with a trade-off between high accuracy and speed. Once we have narrowed down an optimal range with Process, this configuration can be investigated in more detail with high-resolution simulations. This is done within the EU project EUROfusion. It currently unites 30 research institutions in 25 EU Member States plus Switzerland, the United Kingdom, and Ukraine. It is coordinated by the IPP Garching. This research network gathers experts who have specialised in specific sub-aspects and can simulate them in detail. We cooperate intensively with these experts. This research therefore generates strong synergy effects and promotes transnational exchange and cooperation.

So far, not all technical aspects of a stellarator power plant have been covered. We are currently working on models that can predict the mechanical stresses in the coils and their support structure with sufficient accuracy. Such tensions are caused mainly by the strong electromagnetic forces between the coils. We ultimately need to incorporate all the physical and technical aspects in our digital twin. We are convinced that our strategy can help drive the development of a stellarator power plant. o

7 When intelligent machines are bad advisors

NILS KÖBIS, IYAD RAHWAN

↘ Max Planck Institute for Human Development, Berlin

Machines powered by artificial intelligence take on ever more social roles in society. To study this new class of actors, their behavioural patterns, and ecology, we describe Machine Behaviour—an emerging approach that applies concepts and methodologies from across the behavioural sciences to intelligent machines. One key question is whether machine behaviour can corrupt human morals. To find an answer, we evaluate the risks of AI advisors and AI agents acting as bad role models.

Machines powered by artificial intelligence are increasingly becoming integral parts of human life. Today, machines advise humans on which purchases to make and which employees to hire. They recommend medical treatments and judicial sentencing. They offer psychological counseling and provide companionship to the elderly and infirm. In short, they're taking on ever more roles previously reserved for humans. Our machines are being transformed from a mere medium for data processing and storage into agents that act in the world—a shift with enormous social, cultural, economic, and political implications. Which raises the question: how best to study them?

In 1969, Nobel Prize laureate Herbert Simon wrote: "Natural science is knowledge about natural objects and phenomena. We ask whether there cannot also be 'artificial' science—knowledge about artificial objects and phenomena." Adopting Simon's vision, we established a new interdisciplinary academic field: Machine Behaviour. It refers to the scientific study of intelligent machines, not as engineering artifacts and passive objects, but as a class of actors with particular behavioural patterns and ecology. Overlapping with, but distinct from, computer science and robotics, Machine Behaviour draws on concepts and methodologies from across the behavioural sciences.

In the newly founded Center for Humans and Machines in Berlin, we use a Machine Behaviour approach to conduct pioneering conceptual and empirical research on AI at work in the world. The research focuses on two broad aspects: (a) how intelligent machines behave and the outcomes that emerge as they interact with humans; (b) how humans perceive the behaviour of machines, and how this perception shapes their expectations and judgment of both the machines' actions and their own behaviour. One key question is how such machines influence human morality.

Are machines corrupting morals?

There is an emerging concern that intelligent machines might have a corrupting influence on human behaviour, swaying their decisions away from adhering to ethical rules towards more self-serving actions. We assessed the empirical validity of these fears based on the available evidence from behavioural science, human-computer interaction, and AI research. The review reveals that the risk of machines corrupting human morals crucially depends on the role that these machines take in society.

In some roles, the worry appears to be, at the moment, largely unwarranted. For example, although concern grows that people might blindly copy unethical behaviour from AI role models—think of children


eXeAI
Replika
Cogito

imitating their intelligent virtual assistants — little empirical evidence exists for such worries. That is not to say that such risks won't increase as technology becomes more sophisticated.

However, when intelligent machines fulfill other social roles, they warrant more immediate concern—for example, when acting as advisors. Consider that already millions of people consult their AI-based chatbot friend Replika for guidance. The voice-controlled personal assistant Alexa – already in the homes of more than 100 million people – could assume a similar function in the future. Amazon's chief scientist aims to turn the role of Alexa "from more of an assistant towards an advisor."

An AI-based sales advice system can autonomously detect that deceptive strategies pay off.

Also in the working life, the number of AI advisors increases – already, call-center sales agents get recommendations from AI agents such as Cogito and Gong.io on how to conduct their work.

Without some form of oversight, these AI advisors may encourage an unethical course of action. For example, an AI-based sales advice system can autonomously detect that deceptive strategies pay off and subsequently suggest such strategies to the employees. A large-scale online experiment with more than 1500 participants confirms this worry. Participants received short written advice on how to solve an ethical dilemma between adhering to ethical rules or breaking them for financial profit. The results showed that, while people neglect advice to be honest, they follow the advice to be dishonest for profit. Strikingly, it makes no difference whether this advice comes from a fellow human or was autonomously generated by a natural language processing algorithm. Even informing people that an algorithm, not a human, advised them does not reduce this corrupting influence.

AI can also have a positive influence

Yet, much like other technological innovations, intelligent machines serve dual purposes. As much as AI advisors can corrupt people, they can also be used in different contexts to promote ethical behaviour, reduce loneliness and create a sense of belonging. The new behavioural science of machines helps minimise AI harm and reap its benefits on human life. ○

8 Collisions in an artificial star cluster

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All known black holes belong to only two groups: stellar black holes (comprising up to several dozen solar masses) and supermassive black holes (with millions to billions of solar masses). There are presumably also intermediate-mass black holes. Using computer simulations, we found that this population grew through the collisions of stars and stellar black holes in the extremely dense star clusters of the early universe.

In the 1930s, Julius Robert Oppenheimer discovered how a black hole is formed. When a large, massive star has depleted the fuel inside of it at the end of its life, energy production stops. The core region then collapses, and the outer gas shell is blown off and flashed brightly as a supernova. If the central part weighs more than about two and a half solar masses, nothing can stop the force of the increasing gravity. The collapsing star theoretically contracts itself to a material point. The space around it closes and builds a trap from which nothing – not even light – can escape. A stellar black hole is born.

Until the first gravitational wave measurements a few years ago, it was possible to "weigh" only around 20 black holes in our Milky Way using sophisticated methods. These range from about 2.5 to 15 solar masses. There are also supermassive black holes at the centres of galaxies. Reinhard Genzel from the Max Planck Institute for Extraterrestrial Physics and Andrea Ghez from the University of California have been awarded the 2020 Nobel Prize in Physics for studying an object weighing four million solar masses at the heart of our Milky Way.

Several arguments speak for the existence of intermediate-mass black holes. For example, the two gravitational wave detectors Ligo in the US and Virgo in Italy have observed two black holes weighing 85 and 66 solar masses, respectively. The existence of these cannot be explained by classical theory. Moreover, the observation of black holes weighing billions of solar masses less than a billion years after the birth of the universe raises unanswered questions about how they were generated. Are there perhaps intermediate-mass black holes as predecessors that were formed in a non-classical way?

Simulations on supercomputers

Young massive star clusters could be the cradle of this hypothetical population. In such clusters, stars are packed several million times more densely than in the Milky Way. Stars and already formed stellar black holes can therefore collide with each other in the cluster and grow into larger bodies. Together with an international team, we have investigated the interactions between these bodies using supercomputer simulations.

We started with 110,000 simulation particles corresponding to young stars in a cluster with a radius of about three light years. As assumed, these had a chemical composition corresponding to the early universe and covered a range of 0.08 to 100 solar masses with the corresponding known frequencies; 10% of them were in binary systems. The virtual stars then evolved according to known models (i.e. the more massive the star, the shorter its lifetime). Whilst the heaviest stars exploded as supernovae after only a few million years and collapsed into stellar black holes, the lighter ones lived much longer.

We simultaneously observedd how the members of the cluster moved under the influence of gravity, repeatedly colliding. In addition to the interactions of the stars, we also considered the emission of gravitational waves from two orbiting black holes, which ultimately led to the merging of the two bodies as observed with the Ligo/Virgo gravitational wave detectors.

Black holes are created in several steps

In total, we ran 80 simulations with different initial conditions over a period of 300 million years. According to the simulations, all stars with at least eight solar masses had collapsed into black holes. These extremely accurate simulations were run with the NBODY6++GPU software on the supercomputers at the Max Planck Computing and Data Facility in Garching and JUWELS at the Jülich Supercomputing Center.

In fact, intermediate-mass black holes weighing up to 350 solar masses did form in these ultra-dense artificial star clusters. This often happened in several steps. Initially, primarily binary systems collided, thereby giving rise to massive stars. These, in turn, collided with each other and with the first stellar black holes, which became heavier as a result. Intermediate-mass black holes were thus created in several steps. According to our models, the dominant process for the formation of this weight category of gravity traps is the collision between an extremely massive star and a stellar black hole.

But even if all the massive stars have disappeared from the cluster, the intermediate-mass black holes can still moderately increase in mass by colliding and merging with stellar black holes and smaller stars. Our most compact models record about 300 collisions within 300 million years; 40% of these occurred in the first 15 million years. In one case, we watched how, in three steps, two black holes with initially 17 and 28, then 25 and 45, and finally 68 and 70 solar masses merged to form a giant with almost 140 solar masses. This happened within 90 million years – a mere blink of an eye in relation to the 13.8-billion-year history of the universe. However, the rate of mergers has declined over the past billions of years because the density of the star clusters has decreased through various processes.

Our simulations take into account the laws of stellar evolution; however, they cannot provide a detailed calculation of the physical processes involved in a collision. Instead, these processes need to be parametrised. In particular, it is not entirely clear what happens when a star collides with a black hole. Does the black hole lose out if the star is torn apart in the collision? Or does it completely engulf the stellar mass? In order to estimate this uncertainty, we ran the simulations with different "destruction efficiencies". There are three possibilities: either the black hole engulfed no matter at all, only 50%, or the entire star. This showed that only in the last two cases, intermediate-mass black holes were created.

The mass distribution of the merging black holes calculated with our simulations can readily explain the previous results of gravitational wave events measured with the Ligo/Virgo detectors. There are also conjectures and a few uncertain observational indications that intermediate-mass black holes weighing a few thousand or ten thousand solar masses could also exist. In order to verify this, we plan to simulate dense star clusters with several million stars in which more collisions and mergers could take place. ○

Virtual doppelganger: this computer-simulated compact globular cluster looks strikingly similar to a natural object. The central region is so densely populated that stars and stellar black holes collide and merge with each other inside of it. In this way, a series of intermediate-mass black holes are eventually formed.

9 Patent rights in pandemic times

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One of the biggest challenges of the Covid-19 pandemic has been the provision of sufficient quantities of vaccine over months. While rich industrialised countries ordered huge quantities early on, poorer states suffered from a glaring shortage. Against this background, several of them have requested among other things the temporary suspension of patent rights at the World Trade Organization (WTO). Our team has analysed the legal situation.

At first glance, the idea of waiving legal protection in order to speed up the production of patent-protected vaccines may seem plausible. When considered in more detail, however, the focus on patents as the cause of the vaccine shortage during the Covid-19 pandemic proves unhelpful and short-sighted – not least with regard to the fact that innovation will continue to be needed to address health challenges in the future.

Drugs and vaccines are enormously expensive to develop. What is more, both research and market approval require investors to have staying power. Success is never guaranteed. If a market approval is granted, a company needs a certain amount of time to recoup its costs and of course to generate some revenue – even if, in an exceptional situation such as a pandemic, other considerations may play a role. Patents ensure market exclusivity, create legal certainty and are therefore a prerequisite for investments to be made in the first place.

Nonetheless, patents alone are not sufficient: investments are made not to obtain a patent, but to generate profits. So we should not deceive ourselves into thinking that there is any easy substitute for market-based incentives, though patent law is a key factor in terms of the latter's impact. In the case of the Covid-19 vaccines, too, the lion's share of the costs was covered by the private sector. Years before the outbreak of the pandemic, individual investors were already betting on the potential of mRNA technologies – at a time when no state would have been prepared to spend taxpayers' money without any certain prospect of a concrete benefit.

Complex product facilities

What is more, the idea that it is enough to be allowed to use a protected technology in order to be able to manufacture and distribute the relevant products in sufficient quantity in no way corresponds to reality, especially in the case of mRNA vaccines. These are high-tech products that cannot simply be produced in any chemical factory. Highly complex and specialised production facilities are required, including personnel with specific expertise. In addition, it takes special raw materials with limited availability, which effectively limits the production volume from the outset.

Even having production sites in countries with a high demand would not be enough. Vaccines require regulatory approval where they are to be marketed. Irrespective of whether the original manufacturer has been granted such approval, each independent producer must prove of their own that their products meet the requirements. The only exception here is in the case of

production under licence, i.e. with the consent of the patent holder: in this case, the patent holder's approval extends to the products manufactured this way. Contractual licences usually involve the transfer of knowledge and technical support. All this saves valuable time that would be lost if only patent protection were waived.

Consequently, the most efficient way forward lies in collaborations. The current willingness of the pharmaceutical industry to grant licences even to competitors is unprecedented. However, patents are an indispensable prerequisite for precisely this purpose. Only patents make it possible to determine in a legally secure manner what should be permitted to whom within the framework of a collaboration. If this possibility were to disappear in the event of a suspension of IP rights, the current willingness to cooperate would immediately cease. In the absence of support from the patent holders, the market might even see the launch of inadequate and ineffective vaccines, which would be of no use to anyone.

The proposal to waive patent rights, among other things, is directed against the fundamental obligation of the member states of the World Trade Organization (WTO) to comply with the minimum standards of protection provided for under the so-called TRIPS Agreement within the framework of their national legislation. However, this agreement already allows member states to permit certain uses by third parties under certain conditions, even against the will of the rights holders concerned. In particular, they may grant compulsory licences for patents, whereby each individual country can specify this option in more detail in its national laws.

A flexible legal framework

Of course, this is primarily of use if there are at all local companies that are capable of manufacturing the required products – though this is no different when it comes to waiving IP rights. If this requirement is met and a patent holder unjustifiably refuses to grant a licence to a company, that company can sue for permission to use the patent before national courts. This can be costly and time-consuming, however. For this reason, member states are also free to grant rights of use directly to local industries without the need for the latter to litigate. This would allow entire patent groups to be covered, thereby achieving a similar effect to that of the proposed suspension of patent protection.

The international legal framework therefore does not lack flexibility. The problem is more likely to lie in the fact that national law in a number of countries has not been adequately designed to take account of the extraordinary circumstances of a pandemic. If this were to be made swiftly, this alone should motivate patent holders to grant contractual licences so as to avoid compulsory measures and thus a loss of control.

Note: An agreement among WTO member states was in the offing at the time of printing of this article. Under this agreement, the options for the use of vaccine patents as set out in the TRIPS Agreement are to be extended for a limited period of time. In addition, such options are to be permitted under certain conditions, even if national law does not explicitly provide for this. ○

Patents create legal certainty and are insofar a prerequisite for any investment to be made in the development of vaccines and medicines.

10 Contacts in the liver

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↘ *Max Planck Institute of Molecular Cell Biology and Genetics, Dresden*

In order for body tissue to be able to renew itself, there must be sufficient cell proliferation. But if cell proliferation is uncontrolled, cancer develops; if it is insufficient, the tissue may no longer be able to function properly. By studying liver organoids that we have developed, we have discovered how the cells maintain this fine balance.

The liver is a fascinating organ. Even after major injuries, it can regenerate itself almost completely. Already the ancient Greeks knew about this ability. The legend of Prometheus tells how his liver grows back despite daily attacks by an eagle until Heracles finally rescues him.

Molecules, tissues, and organs all need to renew themselves so that their structure and function can be restored. In tissues that are continually renewing themselves (e.g. the intestinal epithelium or the skin), the cell programmes for proliferation and differentiation are always active. However, most tissues are in a "dormant" state. For damage to be repaired, the regeneration programmes must first be switched on. Then the tissues can return to their dormant state. The liver is an excellent model for tissue regeneration in mammals. The intricately structured liver lobules consist of many different cell types. In addition to the actual liver cells, the tissue contains tiny bile tubes lined with hepatic duct cells. These cells work together with the supporting cells of the connective tissue to maintain tissue function. In the liver lobules, there are various interactions between the same and different cells over the entire life span of the organism.

Disrupted interactions

In the case of damage (e.g. by toxins), these interactions are disrupted. In chronic injuries (e.g. drug or alcohol abuse), a dysfunctional tissue develops. This results in either scar because of a hardening of the connective tissue or in a completely opposite state, the indefinite propagation of cells that try unsuccessfully to recover the tissue, ultimately leading to cancer. However, the mechanisms responsible for this – especially the interactions between different cell types – are still poorly understood.

Our research group at the Max Planck Institute of Molecular Cell Biology and Genetics works with a multi-level and interdisciplinary approach. We are particularly interested in which mechanisms control the renewal of tissues. Unfortunately, it is impossible to study these cellular interactions and their dynamics directly in living animals. We therefore need to mimic at least some of the interactions in vitro. Almost a decade ago, we developed the first three-dimensional liver cultures. However, these lack the supporting connective tissue. Now, together with colleagues at the University of Cambridge,

IN VITRO

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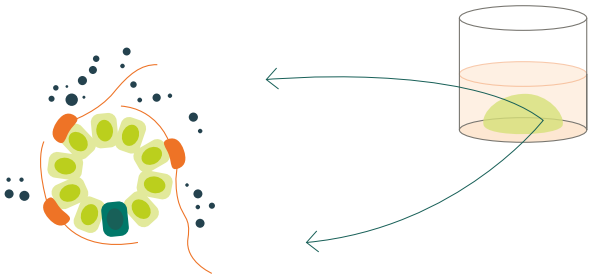

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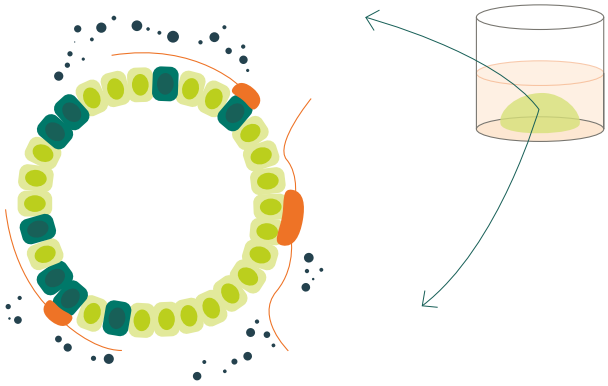

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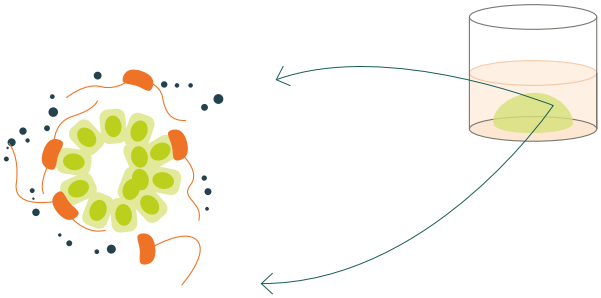

Top: If one connective tissue cell (red) comes into contact with three hepatic duct cells (green) in a cell culture, almost every duct cell is contacted by a connective tissue cell. The duct cells then are in a resting state (light green), as in a healthy liver.

Middle: A lower ratio of 1:10 corresponds to that in a damaged liver. Under these conditions, the duct cells proliferate (dark green) and most of them lose contact with a connective tissue cell.

Below: At a higher ratio of 1:2, the duct cells stop multiplying. Some of the cells are even rejected into the interior of the liver duct so that the duct becomes smaller again and the cells return to their resting state. This corresponds to the state inside a liver after an injury has healed.

Connective tissue cell Signalling factors Hepatic duct cell Growing duct cell

we have improved that system to also contain supporting connective tissue. These liver organoids reproduce both the tissue architecture and the interactions of the liver duct and connective tissue cells in vitro.

In order to bring the cells into contact with each other, we work with semi-liquid hydrogels. Using the microfluidics technique, we encapsulate the cells in numerous hydrogel droplets. In the limited interior space of the droplets, the cells establish the typical cell contacts – a prerequisite for in vitro tissue development. We have now refined our liver organoid cultures so that further cell types can be integrated and complex microstructures can be created. This allow us now to examine these live under the microscope and thus observe the processes directly and in real time.

When we first filmed the interactions, we discovered a completely unexpected behaviour of the organoid tissue. It shrank when it came into contact with connective tissue cells but grew when there was no contact. This paradoxical behaviour corresponds to the reaction of injured tissue after it is damaged. We hoped that the cell contacts would provide insight into why the tissue either grows or stops growing during the regeneration process.

After we managed for the first time to make the contacts between the cells visible in our organoids, we were now able to find that it is not the number of hepatic duct and connective tissue cells that determine how many cells are produced to repair the damaged tissue – but rather the number of contacts they have with each other.

Organoids offer the unique opportunity to recreate the development of human organs.

Number of cell contacts controls repair

In intact tissue, the connective tissue cells appear to keep the liver tissue in a resting state. A certain number of contacts between the cell types signals that the hepatic duct cells should not propagate but rather simply retain their status quo and remain as they are. In the event of injury, the duct cells proliferate first. This reduces the number of cell contacts with the neighbouring connective tissue. Once the injury is over, the connective tissue cells proliferate until the original number of contacts is restored and the damage is repaired. In turn, more contacts through connective tissue cells cause fewer or no new hepatic duct cells to be formed, and cell proliferation stops.

This control could be of crucial importance because a missing stop signal for the duct cells would lead to cancer. Similarly, if the connective tissue cells proliferate unchecked, this can result in scarring and cirrhosis of the liver.

So far, our research has focused on the interactions between cells in the liver. We now want to better understand the fundamental principles that govern the proliferation and maturation of cells in organs and tissues. The mechanisms we observed could also work in other tissues (e.g. lung or breast tissue) that also react to chronic damage by producing too little or excessive cell division so that either fibrosis or cancer develop.

Organoids offer the unique opportunity to recreate the development of human organs in a system that is remarkably similar to natural development. We therefore plan to develop organoids with other cell types. Our long-term goal is to activate or improve the regenerative capacity of tissues and thus alleviate debilitating diseases. o

11 Optical data traffic in the cloud

YITING XIA

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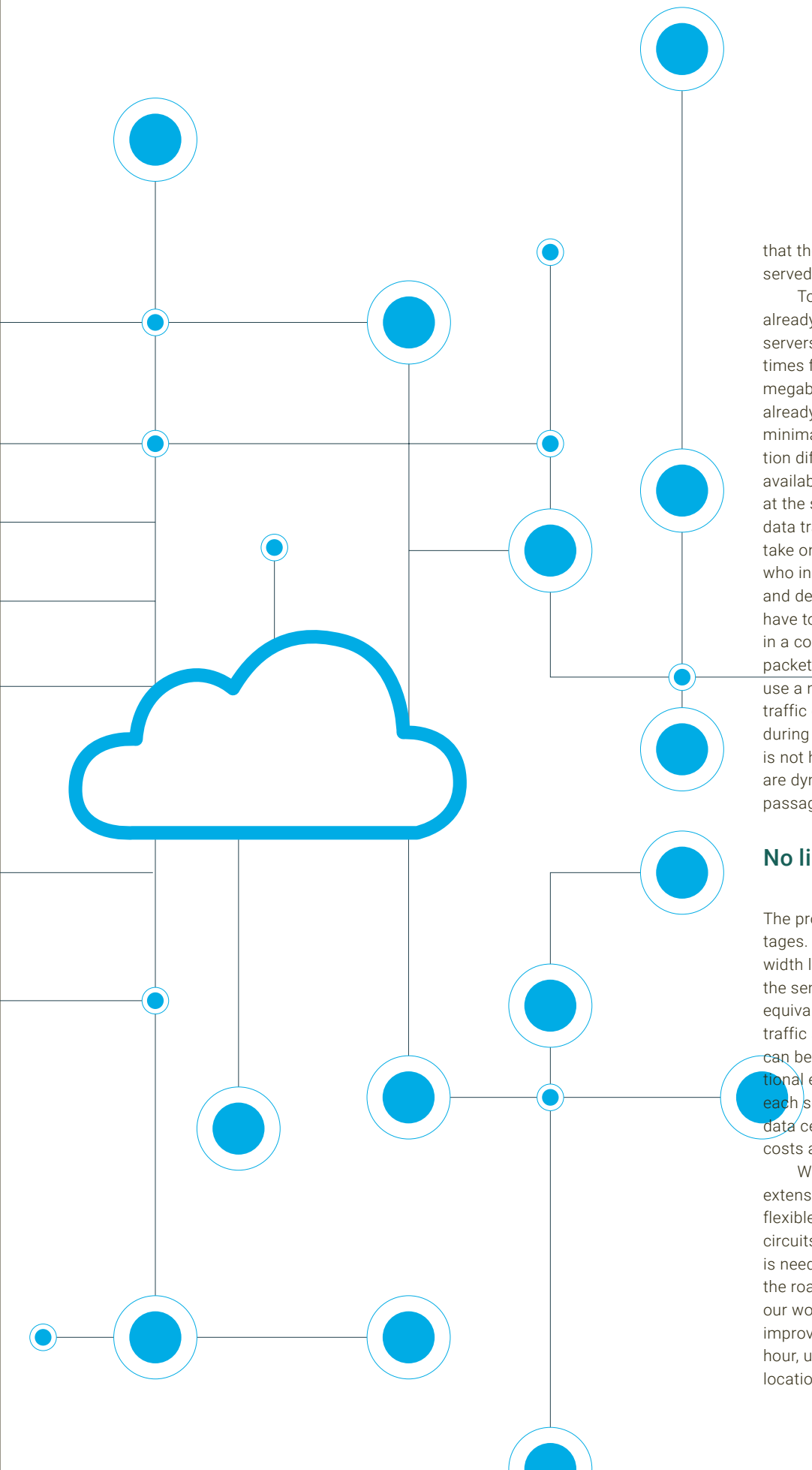
Most online services today are hosted in cloud data centres where applications run on many servers. Optical data traffic between these servers could make the work of the data centres more efficient. We are developing software to integrate the necessary optical switches, which work in a fundamentally different way than the common electronic switches, into the data centres. In addition, we are testing the optical switches and the software in a real environment

Search engines, social networks, online shopping or video streaming – almost all the online services we use today are hosted in cloud data centres around the world. These services require sophisticated computations that far exceed the processing power of one single computer. Data centres provide hundreds of thousands of computer servers, which run in coordination to render the services. A powerful network, the so-called data centre network, interconnects these servers to enable high-speed data communication among them.

The data centre network is similar to an inter-city express highway network. In this analogy, the servers in the data centre correspond to cities, the network links to highways, the electrical network switches to the interconnection points between different highways, and the data transmitted over the network links to the traffic on the highways. The switches control the data exchange to avoid delays in data processing, for example, due to congestion in the connections.

As annual traffic increases exponentially with the growing number of users and services, data centre networks are constantly being upgraded with servers, network connections and network switches to enable more bandwidth. A key factor in this over the past decade has been that the bandwidth of electronic switches has doubled every two years at the same cost and power. More recently, however, the bandwidth of electronic switches has expanded more slowly, making switches a bottleneck as data centre networks evolved. This problem could be solved by optical networks with optical switches, which are much more powerful and energy-efficient than electronic switches and also allow data centres to operate more cost-effectively. In the Cloud and Network Systems Research Group at the Max Planck Institute for Informatics, we are researching how optical data traffic can be realised in data centres and, above all, how data processing must be adapted to the special properties of optical switches. In this way, we want to help ensure



that the growing demand for cloud services can also be served in the future.

Today, the components for optical data centres are already available, sending data back and forth between servers at rates of 400 gigabits per second. That's 8,000 times faster than the typical DSL home internet at 50 megabits per second at home! Optical switches also already exist. These are passive devices that consume minimal power during operation. In principle, they function differently from electronic switches: these allow the available bandwidth to be used by different data packets at the same time and intervene in an orderly manner if data traffic becomes congested. Electric switches thus take on a similar role for data traffic as police officers, who in some places regulate traffic on crowded roads and determine when cars get to drive and when they have to stop. Optical switches, on the other hand, work in a completely different way: they assign each data packet a precise time window in which it can exclusively use a network connection. It's like being able to drive in traffic on a private lane you have all to yourself, but only during an assigned time period. However, the schedule is not handled as inflexibly as it sounds. Rather, there are dynamic schedules that reserve data packets a free passage over a network connection even at short notice.

No limit of bandwidth

The properties of optical switches bring many advantages. Unlike electrical switches, they have no bandwidth limit, and their capacity is determined solely by the sending speed of the connected servers. This is equivalent to a never-congested highway that can carry traffic as fast as cars can go. In addition, more servers can be connected to optical switches than to conventional electrical switches, so the cost of connecting each server is lower. As recent studies show, optical data centre networks can save about 50 percent of costs and 75 percent of power consumption.

What is more, optical data centres are highly extensible to future demands. And ideally, they are very flexible. This is because optical switches can build circuits on-demand, wherever the data transmission is needed. Imagine a flexible highway system where the roads can be moved around as needed. In some of our work, we have taken advantage of this feature to improve the performance of the network: during the rush hour, under-utilised roads can be moved to a jammed location to speed up traffic. And even if a road breaks

Optical communication between servers could make the work of cloud data centres more efficient. To this end, Max Planck researchers are developing the appropriate software.

down, unused roads can be moved there instead of forcing cars to take detours.

However, optical networks in data centres not only bring many advantages, but also fundamental changes in data transmission. This is because the exclusive connections between data sender and receiver make conventional network concepts, which are designed for shared bandwidth, unusable for optical data centre networks. We are developing software for the network connections, which are made on demand. Specifically, we are investigating how to coordinate servers across the network to know when they can talk to whom and for how long. This is as difficult as informing all the drivers in a town of the road schedule and ensuring their clocks are all accurate.

In order to test our software and the function of optical data centre networks under real conditions, we are also building an optical network in which servers are also integrated. Since these have not been included in tests so far, many potential problems are still unknown. With this, we want to resolve a chicken-egg dilemma: without complete testing, cloud providers will not be convinced to deploy optical data centre networks. But without deployment under real-world conditions, many practical problems cannot be uncovered, so the technology cannot be improved.

Software as open source code

As soon as optical data centre networks have proven themselves under real conditions, we believe that cloud providers will probably introduce them gradually. Optical components must therefore increasingly be able to be integrated into existing network hardware. It should also be possible to operate optical components together with electronic hardware despite their fundamentally different mode of operation. On the one hand, we are researching the fundamental principles of optical data centre networks and redesigning communication software to maximise the performance of today's network hardware. On the other, we are integrating these changes into existing servers to adapt them to the novel optical network infrastructure. Once these two sides meet, we will open-source our software system to enable cloud providers and academic research groups to easily deploy optical data centre network in production and lab environments. In this way, more problems will come to light and new insights will be gained that can be used to further optimise the technology over time. o

12 Are organisations open to diversity?

SANJA BÖKLE, KAREN SCHÖNWÄLDER

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The political presence and representation of immigrants is a controversial topic in German society. Increasingly, marginalisation and discrimination are no longer being accepted as the norm. But to what extent are advocacy organisations, important actors in a democracy, willing and able to represent the interests of the migrant population, to open up to them, and to ensure their participation on an equal footing? These are the questions we explored in our research project.

Plenty of organisations exist in our society that advocate for specific interests and causes: be it climate protection, patient rights, the interests of tenants or artists – advocacy organisations intervene in public discourses to promote the interests of the people they represent. How do these organisations respond to the fact that immigration is transforming society? Do they react with openness, defensively, or proactively? Are the organisations themselves changing at all?

These are some of the questions we and other researchers from the Ludwig Maximilians University in Munich and Humboldt University in Berlin have been exploring in the ZOMiDi research project, funded by the Federal Ministry of Education and Research. We looked at a number of organisations, including the Federal Association Lebenshilfe e. V., the united service unionVerdi, the Lesbian and Gay Federation in Germany (LSVD), and Deutsche Aidshilfe e. V. (DAH), which represent the interests of disabled people, service sector employees, sexual and gender minorities, and people who might face discrimination due to illness.

Advocacy organisations may be seen as providing a network that both organises civil society and links it with policy makers. They therefore play a central role in our democracy and society. Yet which concerns and interests are voiced in public and in political circles and are considered for example, in public funding programmes and laws, very much depends on them. For example, does an organisation that advocates for disability rights also call for the interests of refugees with disabilities to be taken into account? Do lesbian and gay organisations ensure that immigrants can also access counselling and support services? Who actually sets the agenda within these organisations and decides which campaigns to launch and what should be the key demands? Do the members, staff, and directors reflect the diversity of our society?

Minorities are underrepresented

To answer these questions, we used document analyses and interviews to reconstruct the development of the aforementioned organisations in detail. What we found was that all four are open to welcoming and representing the rights of immigrants, in principle. This does not necessarily apply to all civil society organisations in Germany. We took the conscious decision to study organisations that themselves represent a marginalised group and should, one would assume, therefore be sensitive to other forms of exclusion, such as those related to migration processes and racism.


Equality

A corporate entity that emphasises unity and a shared identity hinders the recognition of difference.

But not even these organisations have made a sustained effort to recruit people from migrant backgrounds. Not all organisations have departments or persons responsible for ensuring that the concerns of people with a migrant background are continuously and effectively integrated into their operations, and where these do exist, they are inadequately equipped.

Have the organisations in question managed to include people with and without a migrant background? Are people with a migration background and those potentially subject to racial discrimination given an equal say? Certainly, in the case of all the organisations we studied, the answer to this question is no. Migrants are underrepresented, especially in the executive boards and usually also among the membership. During the interviews and group discussions, we also heard about experiences of racism and discrimination.

A lack of strategies for increasing diversity

None of the aforementioned organisations systematically collects information on their membership structure. According to our findings, it is only in the Verdi trade union that people with a migration background are probably represented to the same extent as among service sector employees. Verdi is also the organisation where the representation and participation of members with a migration background is formally guaranteed. However, none of the four organisations has a strategy in place for increasing diversity among their employees. There are migrant self-help structures in place in some organisations, but rights of participation are often still of an informal nature. Despite some initial steps towards openness, people with a migration background are still insufficiently involved in all four organisations and severely underrepresented in important positions.

What determines whether or not civil society organisations open up to people with migration backgrounds and play an active role in shaping a diverse society? This is where our project took up and further developed concepts from institutionalist research into the study of organisations.

As postulated in institutionalist theory, the actions of organisations are influenced by the expectations of the social context in which they operate, i.e., the so-called "organisational field". Civil society organisations operate in a continuous dialogue with other stakeholders. For example, they want to influence governments and parliaments or form alliances, to which end they need to be accepted by other stakeholders. If the field in which organisations operate encourages and normalises migrant participation, anti-racism measures, and intercultural openness, non-governmental organisations will tend to adapt accordingly.

Membership numbers as a strong argument

The interests and "functional requirements" of the organisation in question, i.e., those conditions that are essential for its existence and day-to-day activities, also play a role. Taking an active interest in migration issues and actively involving people with a migration background are more likely when this is in line with the interests of the organisation, whereby the need to increase membership numbers is a strong argument in favour of recruiting new members from other demographic groups and, perhaps, for removing existing barriers.

The way a given organisation views itself is also important: organisations whose self-image includes plurality are more likely to be open to differences. A corporate identity that emphasises unity and a shared identity hinders the recognition of difference and favours the neglect of particular concerns.

Members with a migrant background and their social networks can also play a crucial role themselves. Change is less likely if there is no internal pressure. In those organisations that do include members with a migration background, these can use their experience to provide important ideas and mobilise their social networks to push for a more equal participation. o

13 Blood supply for artificial tissue

BRITTA TRAPPMANN

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The implantation of artificial tissue is a future vision of medicine. For successful implantation, blood vessels must be able to penetrate and supply the tissue with nutrients and oxygen. We have developed the first artificial tissue model in which blood vessels can grow.

Thousands of patients are waiting for donor organs. For many, a transplant is the only chance for a cure. However, the number of donor organs available is not nearly enough. Every year, less than half of the patients receive a new organ.

Alternative solutions are therefore being investigated. Many laboratories around the world are producing artificial replacement organs. However, these are still far from being used in the body. An alternative would be to replace the damaged tissue regions in situ with an artificial scaffold. This could then be repopulated by the cells of the surrounding healthy tissue, thereby restoring the natural structure.

Artificial materials would be particularly suitable for this purpose. Unlike natural tissue components, they remain stable in the body long enough for cells to settle on them. But settlement alone is not enough. The materials used must support the function of the tissue-specific cell types and provide space for the ingrowth of blood vessels from the surrounding healthy tissue. This is necessary for a lasting supply of nutrients and oxygen to the tissue.

But what kinds of materials can support the growth of blood vessels? To answer this question, we have developed the world's first cell culture model that replicates the most important processes of blood vessel growth within an artificial material system. At the heart of our model is a sugar-based hydrogel we designed ourselves.

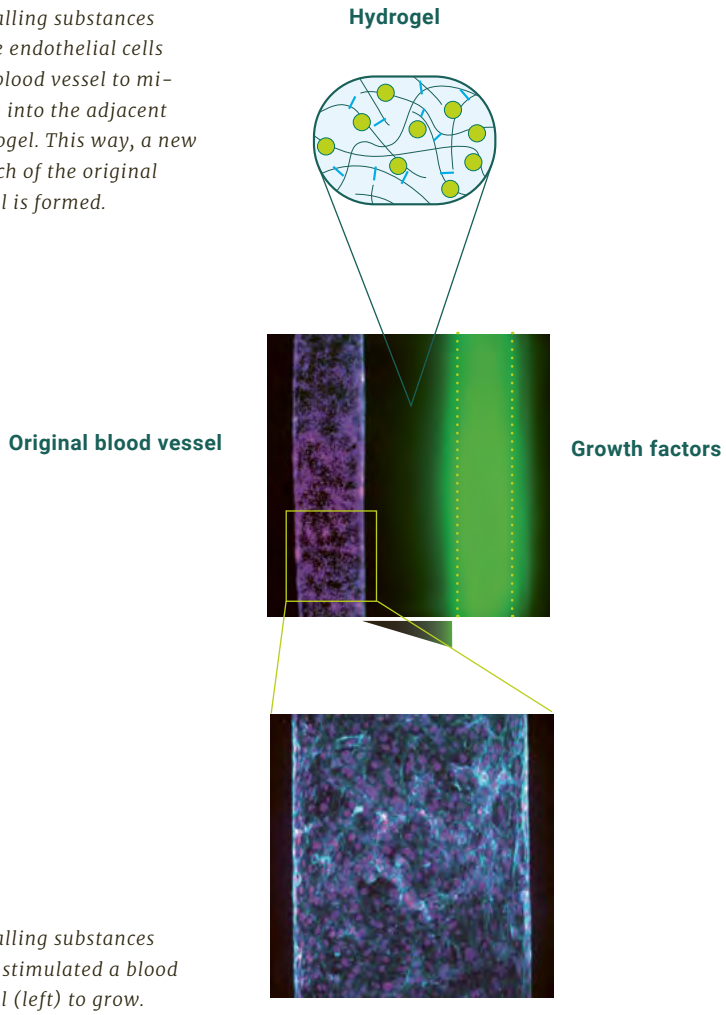
Hydrogels provide shape

Hydrogels contain large amounts of water to keep the cells hydrated; they are also sufficiently rigid to provide shape. We can supply them with nutrients and other substances in order to independently control their properties. The principle is simple: the cells break down the connections between the individual sugar molecules with enzymes and thus migrate through the hydrogel.

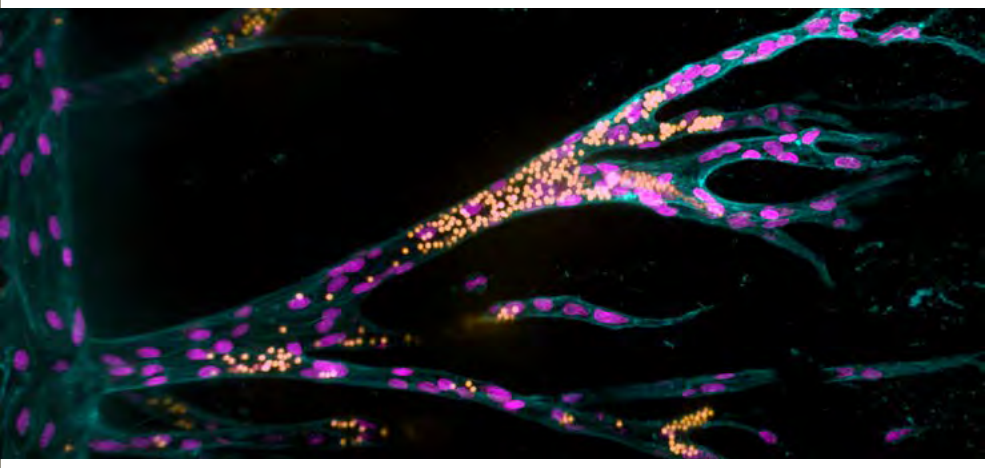
To recapitulate the tubular structures of blood vessels, we use fine acupuncture needles to create two parallel channels (each with a diameter of approx. 0.4 mm) in the hydrogel approx. 1 mm apart from each other. We seed one channel with the same cells that line blood vessels in natural tissues. These endothelial cells do indeed form contacts with each other, attach themselves to the artificial tissue environment in the channel, and form an original blood vessel after about one day.

Through the second channel, we inject a cocktail of the same growth factors that drive the growth of vessels in real tissues. These diffuse towards the endothelial cells in the first channel and thereby trigger the cells to migrate into the surrounding hydrogel matrix. Under the microscope, we can observe how tiny beads labelled with dye flow into the newly formed vessels. The endothelial cells actually form permeable tubes.

Signalling substances cause endothelial cells of a blood vessel to migrate into the adjacent hydrogel. This way, a new branch of the original vessel is formed.



Signalling substances have stimulated a blood vessel (left) to grow. Beads (yellow) have flowed from the original vessel into the new vessel. A permeable connection has thus been created between the two. (Cell nuclei of the epithelial cells in magenta).



Adhesive proteins to hold on to

But what determines whether endothelial cells migrate and form new vessels? And how can we influence the migration of endothelial cells into the hydrogel scaffold? We initially focused on the influence of adhesion proteins (i.e. proteins through which the cells attach themselves to the surrounding tissue and which transmit signals for migration or growth, among other things).

We found that the higher the concentration of these proteins, the more endothelial cells migrate through the hydrogel as coherent strands, as opposed to individually. This collective migration is the prerequisite for the formation of tubes, which are connected to the original vessel.

However, our artificially created vascular structures were initially smaller than those found in natural tissues. We suspected that the components of our hydrogels are harder to break down than natural tissue scaffolds. In order to circumvent this problem, we biochemically modified the hydrogel so that it can be more easily enzymatically cleaved by the cells. Through this optimisation, we were indeed able to grow vascular structures in artificial materials in a controlled manner. These vascular structures not only have the same size but also many of the properties of real blood vessels.

In a next step, we want to expand our model. For example, we plan to use other molecules that transmit important signals to the endothelial cells. Our long-term goal is to replicate the process of natural blood vessel growth as well as possible in cell culture. The experiments described above have provided us with a valuable basis for this. Only if a hydrogel provides the right docking sites and is easily degradable can endothelial cells collectively migrate through it and form blood vessels.

If we know which factors are required for successful blood vessel growth, it may be possible to close the supply gap in transplant medicine using artificial tissue. Anti-rejection drugs would also be superfluous because the organs can regenerate from endogenous cells. ○

14 Versatile storage for light energy

FILIP PODJASKI, BETTINA VALESKA LOTSCH

↘ *Max Planck Institute for Solid State Research, Stuttgart*

Plants show us how it's done: they synthesise sugar with solar energy. However, a chemically robust and versatile carbon nitride can mimic photosynthesis. What's more: it can also store the energy of light electrically. We are working to understand and optimise these processes. They could find application in microrobotics, novel sensors, neuromorphic computers, and solar batteries.

Nature is still setting standards in the use of solar energy. In photosynthesis, plants use solar energy to synthesise chemical energy carriers (i.e. sugar). Regenerative energy carriers such as hydrogen, which plays an essential role in moving away from fossil raw materials, are produced through electrolysis with electricity generated by photovoltaics. However, using artificial photosynthesis, hydrogen can also be created directly with the energy of light, thereby dispensing with the need for electrolysis. This is made possible by carbon nitrides that catalyse the production of hydrogen from water.

Carbon nitrides have been known since the beginning of the 19th century and can be produced cheaply from simple and readily available source materials such as urea. The polymerisation of urea usually produces a chainlike carbon nitride polymer. However, through our research, we have found a way to create layered structures in molten salts. In this two-dimensional carbon nitride – poly(heptazine imide) (PHI) – we observed a property previously unknown in carbon nitrides and other organic materials: PHI can not only convert solar energy directly into chemical energy carriers via photocatalysis but also store this energy for several hours. The electrical charging of the material is visualised by a colour change from yellow to blue. Thanks to this storage capability for electrons, PHI forms a versatile link between solar energy conversion and storage akin to a solar cell combined with a battery. This opens up new concepts for dealing with the fluctuating availability of sunlight.

Photochemically driven microswimmers for medicine

The storage function can thus be used to decouple hydrogen production from the fluctuating availability of sunlight – a concept for which we have coined the term "dark photocatalysis". The addition of a catalyst (e.g. in the form of reusable platinum nanoparticles) in the dark acts like a switch that enables the release of hydrogen virtually on demand. This could lead to applications in which hydrogen can be stored only to a limited extent or where it needs to be produced flexibly and independently of the incidence of light.

We studied the practical implications of dark photocatalysis in a collaboration with the Department of Physical Intelligence at the MPI for Intelligent Systems. In this collaboration, we developed light-driven PHI microswimmers that move autonomously, much like self-propelled microorganisms such as certain bacteria or algae. In order to make this possible, we modified


Photocatalysis
PHI
K+
h+
h+
h+
h+
h+

parts of the swimmer's surface so that photocatalytic reactions can be specifically triggered on different sides of the PHI particles. The redistribution of the reaction products along the particles' surface then creates a thrust and propels the microswimmer.

The accumulation of electrons on PHI particles coated on one side with platinum enables them to charge up under illumination and then to continue to travel even when the light is turned off. Just 30 seconds of charging are enough to enable 30 minutes of directed movement in the dark. Microswimmers driven by photocatalysis could be used to specifically transport medical agents to disease foci such as tumours. This is possible because PHI is not only biocompatible and tolerant of saline environments (present in all biologically relevant media such as blood) but also able to bind drugs quite well, which can be exploited for their transportation. We have also shown that PHI delivers the drugs better when it is electrically charged with light in an oxygen-deficient environment (e.g. in cancer cells). The PHI particles could thus be used as quasi-autonomous drug shuttles that react to their environment. Such medical microbots would release their cargo at the destination through external stimuli such as a change in pH or light.

PHI forms a link between solar energy conversion and solar energy storage, similar to a solar cell combined with a battery.

Batteries that can be charged directly with light

However, the electrons stored on PHI can not only drive chemical reactions but also be electrically discharged via an electrical contact. This results in a solar battery that can be charged directly with sunlight. This combination of light absorption and charge storage makes it possible to combine the otherwise separate processes of photovoltaic electricity generation and battery-type storage in a compact space. Interestingly, PHI can also be charged purely electrically or by a combination of sunlight and electricity. This allows for novel hybrid concepts of light-assisted energy storage. We are now looking at how to increase the efficiency of PHI as storage for solar energy. It would be particularly interesting as an energy storage system in which a low-cost material is needed and large areas are available.

However, the possibilities offered by PHI are not limited to the generation of chemical energy carriers and the storage of energy. In recent work, we also present novel photomemristive sensor concepts. To do this, we use the capability of PHI to oxidise various organic substances such as glucose under illumination and to store the charge extracted in this process. The degree of charging or its subsequent discharge can thus be used to determine how much glucose was contained in a sample. PHI encodes the analysis result in its charge state. This, in turn, is reflected in the change of various optical or electronic properties. Thus, PHI could not only enable new analytical concepts but also find application in neuromorphic computing. This form of data processing mimics the function of nerve cells by transmitting signals for logical operations not only in binary form (as in today's computers) but also with the help of physico-chemical changes of states in variable strength.

The possible applications presented here, some of which have opened up only after 200 years of knowledge-driven research, reveal the far-reaching potential of carbon nitrides. o

15 Pathways to a green and sustainable metal economy

DIERK RAABE

↘ Max-Planck-Institut für Eisenforschung GmbH, Düsseldorf

Metals have enabled progress in human civilisations for millennia. However, with one third of all industrial greenhouse gas emissions, the metal industry is also the largest single contributor to global warming today. In order to decouple the further increase in demand for metals from the rise in CO_2 emissions, researchers at the Max-Planck-Institut für Eisenforschung are pursuing various approaches. Our goals are green steel production using hydrogen, plasma, and electrolysis as well as sustainable aluminium alloys made from high scrap fractions which are easier to recycle than the current aluminium-based materials

Metals form the backbone of our society. They paved the way for the inventions of human civilisation – from the plough to spacecraft. Only metallic materials have such diverse mechanical properties as strength, hardness, damage tolerance, joinability, and durability, often combined with functions such as corrosion resistance, thermal, and electrical conductivity, and magnetism.

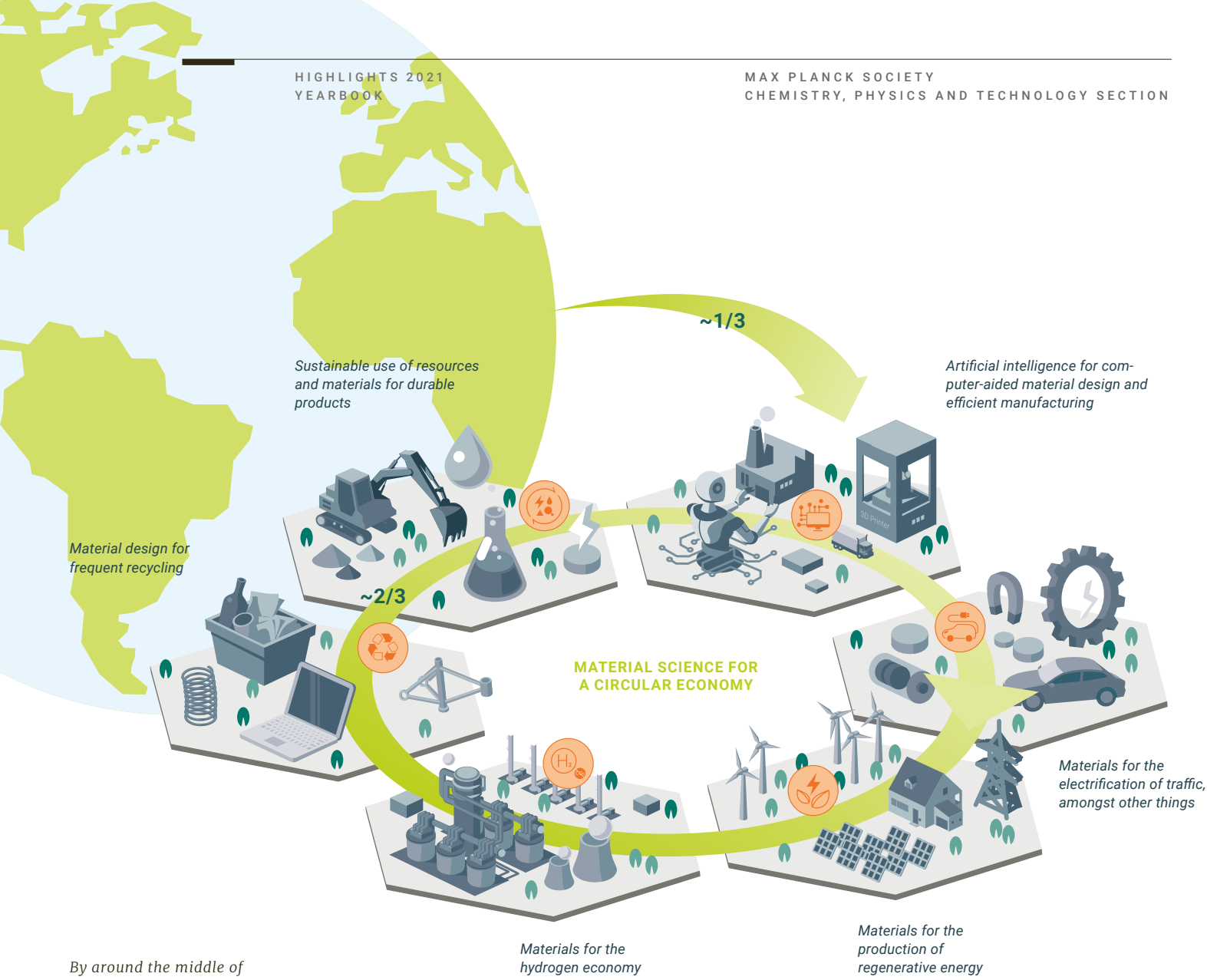
Metals play an ambivalent role in tackling the climate crisis: one the one hand, they play a helpful role as materials that contribute to a sustainable economy in the form of wind turbines, electric motors, and lightweight construction. But on the other hand, they also have a harmful impact, as the main global emitters of greenhouse gases. Metal production consumes eight per cent of the globally used energy and leads to about one third of industrial CO_2 equivalent emissions if only steels and aluminium alloys are considered. As a result of the global growth in industry, transport, energy, and construction, the demand for metals is expected to double over the next 25 years. And unless counteracted with disruptive concepts, greenhouse gas emissions are likely to increase even further. It will not be enough to take small development steps and increase efficiency. Instead, the production of metals will have to be reinvented completely – without the involvement of fossil fuels and reducing agents and with maximum recyclability.

Basic research for sustainable iron and steel production

Steel is the most important metallic material (1.8 billion tonnes are produced annually). It can be recycled by melting down scrap; however, this covers only 30% of demand at most. New iron therefore has to be produced in huge quantities from ores. These ores are freed from oxygen mainly by carbon monoxide in blast furnaces. Parts of the remaining carbon are then removed in converters with oxygen. These processes produce around 2.1 tonnes of CO_2 per tonne of steel. This makes steel production the largest industrial source of greenhouse gases; it accounts for about 28% of all CO_2 emissions.

We are investigating how these huge amounts of CO_2 can be reduced by more than 80%. This is the single biggest lever to combat global warming. Instead of reducing iron ores with carbon, we use electrolysis or carbon-free reducing agents in various forms and can thus almost completely eliminate carbon from the manufacturing process.

Electrolysis, in which iron oxide is reduced in the liquid state together with other oxides, is an attractive method because it is efficient, and sustainable sources of electricity can be used immediately. In particular, the energy-intensive production of an alternative reducing agent (e.g. hydrogen) is avoided. However, electroly-



By around the middle of the century, two thirds of the metals in a sustainable metal economy are to be obtained through recycling, only one third would be newly produced from ores.

sis requires temperatures of about 1600 °C in order to melt the iron oxide. We are therefore researching the basic electrode reactions in electrolysis as well as their intermediate products and suitable electrode materials. We are also investigating low-temperature electrolysis in which the oxide powders are split into iron and oxygen in ionic liquids at low temperatures.

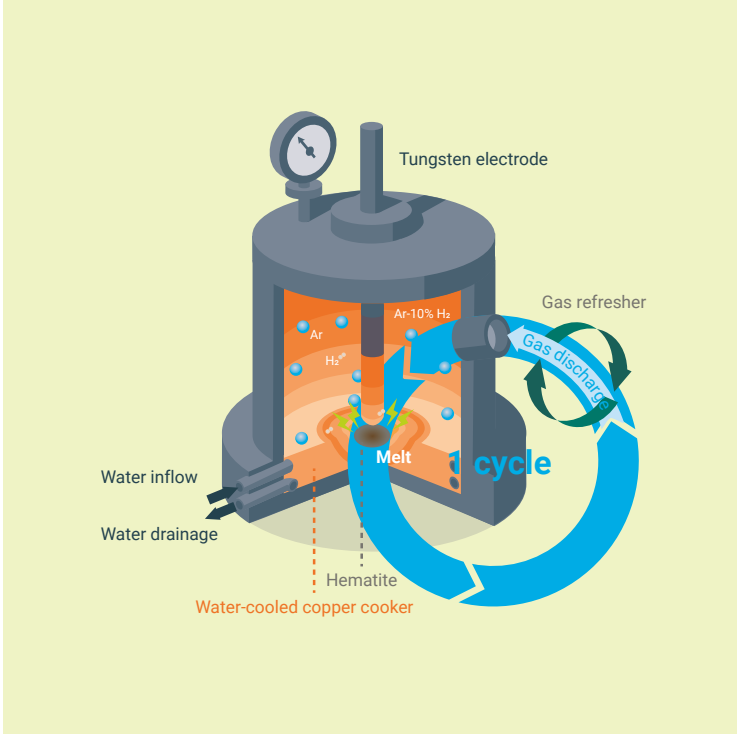
Iron production with hydrogen and hydrogen plasma

Even though green hydrogen or a hydrogen carrier such as ammonia must first be produced using renewable electricity, the direct reduction approach offers advantages over other paths to sustainable steel production. This means that the iron ore does not have to be melted with a high energy input. In addition, systems that are currently used for direct reduction with natural gas can be used for this purpose as well. Finally, 'impure' hydrogen, which is inexpensive, is also suitable for direct reduction. Ammonia as a hydrogen carrier has the advantage over hydrogen that it can be transported in a much more energy-efficient manner than hydrogen itself. This makes it easier for it to reach the steel production sites from sun-rich countries in North Africa or the Arabian Peninsula, which are predestined for the production of hydrogen.

In the direct reduction with hydrogen, we are looking for ways to increase the efficiency of this process. A promising approach here is the use of fine ore, especially because it is the cheapest form of iron ore. However, the reduction must then be carried out in a fluidised bed furnace instead of a shaft furnace. We are trying to understand in detail the chemical and physical processes that are relevant here and are looking for the optimal process of the direct reduction with hydrogen or its carriers under the given boundary conditions.
So far, the community has paid little attention to another reduction process, plasma reduction in the arc furnace,

which could ultimately prove to be the most efficient and cost-effective one in many cases. With this process, iron ores – also mixed with scrap – can be melted in an electric arc furnace with a low hydrogen content and reduced at the same time. The great advantage of this method is that virtually all processes that previously required different systems in huge steelworks could be combined in a single furnace and made sustainable. As promising as these plasma reduction processes are, they are still poorly understood – not least because they involve numerous plasma-chemical reactions and reactive species that have so far eluded measurement and theory. However, a precise knowledge of the processes is essential in order to be able to better control the process and develop industrial plants. In a comprehensive study, we have determined the optimum ratio between the mass of iron ore used and the power of the arc so that the iron ore is completely reduced in only 15 minutes.

During plasma reduction in the arc furnace, a plasma of argon with ten percent hydrogen transforms the molten iron ore hematite into iron.



A recycling gene for aluminium alloys

After iron, aluminium is economically and quantitatively the most important metal. When it comes to sustainability, aluminium has two faces. Because its density is only one third of that of steel, it helps save fuel. However, a lot of energy is required in order to produce it from ores. Although hydropower serves as energy source for some plants, fossil fuels are still used in most cases. Recycling makes aluminium much more sustainable overall. Because aluminium melts at 660 °C, melting aluminium scrap requires only 5% of the energy needed to produce aluminium from its ores. The amount of aluminium available for recycling will roughly double by 2050. This will open up opportunities to bring metal production closer to the goal of a circular economy. However, impurities in aluminium scrap have so far made recycling difficult. Especially because different aluminium alloys are mixed in the scrap, mutual contamination occurs.

Therefore, in a science of 'contaminated alloys', we first try to understand how the various metals from the scrap affect the aluminium. Our investigations have shown how impurities cause or change nanoscopic precipitations in aluminium alloys and thus diminish the mechanical and corrosive properties. Based on these findings, we research which elements can be tolerated in which quantities and how alloys can be designed from the outset so that the highest possible proportion of scrap can be used in production. To this end, we endow these materials with a "gene of recyclability". With this alloy design "gene", we could considerably reduce the CO_2 footprint of aluminium and make another important contribution to a sustainable metal economy. ○

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