MAX PLANCK
GESELLSCHAFT

HIGHLIGHTS 2019

FROM THE YEARBOOK
OF THE MAX PLANCK SOCIETY

DEUTSCHE VERSION→

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 suitable work or project from their scientific activities, as far as these have reached a certain degree of completion, and outline the relevant findings and conclusions. The yearbook contributions of all Max Planck Institutes are published online 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 for non-experts.

Among the highlights of the 2019 yearbook are, for example, research findings that make it possible to predict the frequency of malaria parasites in a local mosquito population. They provide the basis for new biotechnological strategies to combat malaria – an almost Herculean task in view of steadily growing insecticide resistance and the sheer size of the world's malaria regions.

Using data from the social network Facebook, researchers have tracked migration movements from Puerto Rico to the USA following Hurricane Maria in the autumn of 2017. In doing so, they gained new information that traditional data sources such as statistical authorities cannot provide. And that the development from an assisted to a fully automated vehicle might not progress so quickly is shown by studies into research for motion analysis, which is considered a likely component of future autonomous vehicles. Researchers found that even small interfering signals confuse it, thus reducing the reliability with which a vehicle can navigate in its surroundings.

We hope you will enjoy reading our highlights 2019!

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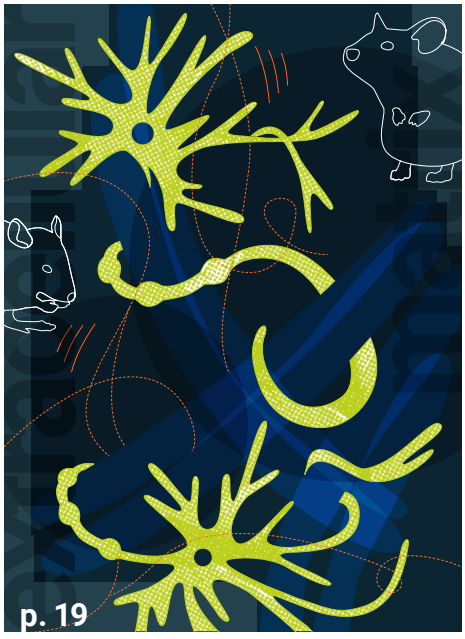
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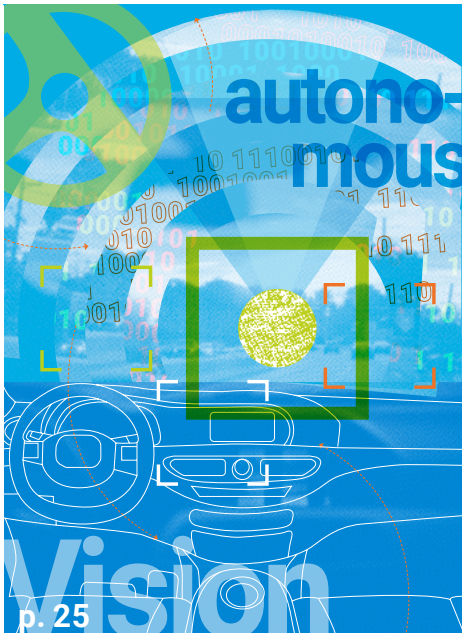

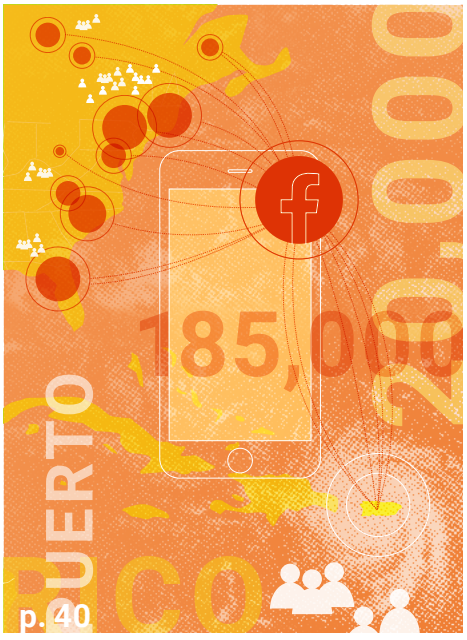

1 The portrait of a black hole

J. ANTON ZENSUS
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Black holes are exotic objects that spark the imagination of researchers and science fiction authors equally. But despite many indirect indications of their existence, these celestial giants in space have so far eluded observation. Only with modern technology has the invisible become visible. The Event Horizon Telescope – a combination of seven radio telescopes spread across half the globe – has produced the first image of a black hole at the centre of the galaxy Messier 87. More than 30 employees from the Max Planck Institute for Radio Astronomy in Bonn contributed to this success.

The fact that black holes must exist results from Albert Einstein's general theory of relativity. This describes gravity as the curvature of space and time. Black holes are an extreme example of the curving of space-time. An extreme amount of mass is concentrated within such a small region of space that not even light can escape the gravitational well. The outer limb of a black hole is referred to as event horizon. Anything that crosses this event horizon can no longer escape. As its name suggests, a black hole appears black to observers. Although these objects can be recognised and characterised by their gravitational interaction, they only become visible against a bright background and can cast a "shadow". We have taken advantage of this fact.

Supermassive black holes contain billions of solar masses and reside at the centres of all galaxies. Matter flows towards these gravitational wells and finally falls into it. Before the matter crosses the event horizon, an enormous amount of energy is released; this is converted into radiation. This process results in extreme luminosities of radio galaxies. The radio galaxy Messier 87 (M87), some 55 million light years away, was theorised to contain such a supermassive black hole – which is why it was selected as a target of observation.

M87 also exhibits a prominent jet of relativistic plasma that can be traced back to the location of the black hole. Discovered in optical light more than a hundred years ago, M87's jet has been studied intensively for decades across the electromagnetic spectrum. The technique of Very Long Baseline Interferometry (VLBI) allows us to peer down the jet to regions very close to black holes at radio wavelengths.

Since the 1970s, the Max Planck Institute for Radio Astronomy has played a leading role in the expansion of VLBI networks around the globe and the development of technology to facilitate observations at ever higher frequencies. Through years of painstaking work, a worldwide collaboration of astronomers has created a VLBI

network that can produce images with unprecedented sharpness of detail. This Event Horizon Telescope (EHT) can achieve a resolution of 20 microarcseconds. With this, one could – neglecting the curvature of the earth – read a newspaper in Central Park in New York. The EHT observed the galaxy M 87 with seven radio telescopes at five different locations. An eighth instrument at the South Pole helped with the calibration.

All telescopes observe simultaneously to one billionth of a second

Our Institute is involved in the Event Horizon Telescope. Our radio antennas and technical equipment have made important contributions to the observations. We built the APEX telescope in the Chilean Andes and equipped it with the same instruments as the ALMA observatory stationed there as well as the IRAM 30-metre telescope in Spain. The analysis of the resultant data was carried out on supercomputers (called correlators) which are housed and operated at the Max Planck Institute in Bonn as well as the MIT Haystack Observatory. Finally, the Effelsberg radio telescope provided important additional information through supporting investigations at longer wavelengths.

Using the power of the VLBI technique, all seven EHT telescopes observed the galaxy M 87 simultaneously to one billionth of a second. The data measured were first stored separately and then compared and combined with each other using supercomputers. The images thus achieved a detailed resolution determined by the

View of a supermassive behemoth: this picture is the first direct visual evidence of a black hole. It's at the center of Galaxy Messier 87 and was captured with the Event Horizon Telescope (EHT).

Researchers at EHT have shown that supermassive black holes are central "engines" powering the luminous hearts of galaxies.

greatest distance between the radio telescopes and the frequency of the waves received. For the observations at 230 gigahertz (corresponding to a wavelength of 1.3 millimetres), only a period from 5 to 11 April 2017 was available. We were extremely fortunate that the weather on these days was excellent at all locations.

EHT has produced the first direct image of a black hole and its immediate surroundings. A dark central area, the "shadow" can be seen. Because of the effects of light bending in the gravitational field of M87's black hole, it actually appears larger than the black hole itself. You can also see the far side of the black hole's environment, so to speak. The brightness variation of the glowing plasma ring around this shadow is caused by the rotation of hot gas around the black hole. Where the gas moves toward us, it appears somewhat brighter, and where it moves away from us, the emission is weaker. This beaming is a well-known relativistic effect.

The first image of the immediate vicinity of the event horizon is consistent with the predictions of general relativity within the limits of the observed accuracy. It has also been shown that supermassive black holes are indeed the central "engines" powering the luminous hearts of galaxies. The EHT thus opens up a new instrument for future investigations of black holes and offers the possibility of testing general relativity in the very strong gravitational range.

The black hole in M87 is about 55 million light years away. The centre of our Milky Way is only 26,000 light years away. There is also a supermassive black hole associated with the compact radio source Sagittarius A* (Sgr A*). The fact that this must be a black hole can be deduced from observations of stellar orbits made in particular at the Garching Max Planck Institute for Extraterrestrial Physics in the group around Reinhard Genzel. From the motion of the stars around Sgr A*, the mass of the black hole has been determined to be about four million solar masses.

In the meantime, precise measurements of stellar motion very close to Sgr A* have become possible, thereby allowing meaningful tests of general relativity. Therefore – in contrast to M 87 – the mass of the gravity trap in our Milky Way is precisely known. In the future, it could be measured even more precisely by the discovery of nearby pulsars. By combining this previous knowledge with a possible image of the shadow of Sgr A*, we could then subject the general theory of relativity to further – and more precise – tests. The EHT collaboration is currently working on the creation of an image of Sgr A*. Unfortunately, this object is subject to brightness fluctuations. As expected, these are much faster than those in M 87 because of its much smaller mass. This makes the calculation of the image more difficult but also more exciting. o

2 A deadly bite

ELENA A. LEVASHINA
↘ *Max Planck Institute for Infection Biology, Berlin*

Most mosquitoes are no more than a nuisance. But the bite of an Anopheles mosquito can be fatal, if it contains malaria parasites. By studying the interactions between the vector, pathogen, and the host, we want to build up scientific bases for interruption of disease transmission.

Malaria is one of the most common infectious diseases globally. According to estimates from the World Health Organisation, the disease was responsible for more than 400,000 deaths worldwide in 2018, almost 70 percent of which were children under five years of age. The disease is caused by a microscopic single-celled organism living in a person's blood. The Plasmodium parasite is transmitted between people by a bite of an infected female Anopheles mosquito.

It has been known for some time that lower mosquito numbers generally result in fewer cases of the disease. Mosquito herds in malaria regions of Italy were wiped out by pesticides, the toxins that specifically target the insects. These vector-oriented efforts successfully rolled back the disease: at the beginning of the 20th century, Malaria was claiming 20,000 victims every year; since 1973, Italy has been malaria-free.

However, this success was jeopardised: not only are medicines for the disease itself becoming less effective; the same is also true for insecticides. Since 2010, Anopheles mosquitoes in over 70 countries have become resistant to at least one of the most commonly used insecticides. The situation is even worse in 27 of these countries where mosquitoes are resistant to all major types of insecticides. It is clear that we urgently need new methods of fighting the disease.

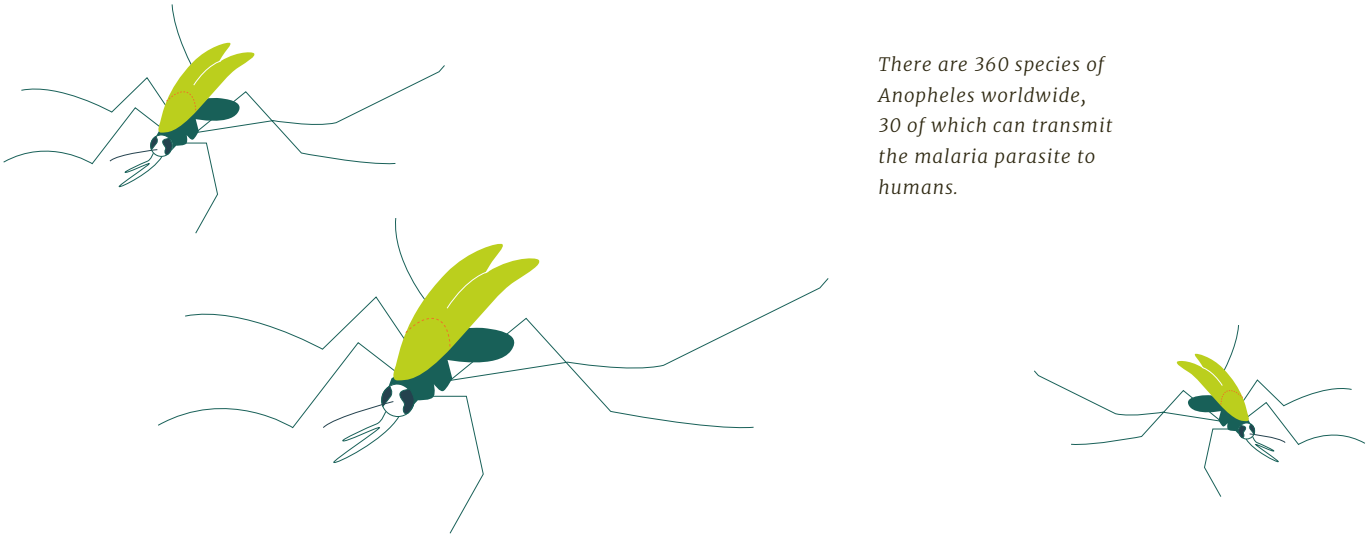
The prevalence of the mosquitoes could be reduced if we were to genetically modify them to make them unable to reproduce. Such interventions would reduce mosquito numbers and lessen parasite transmission. However, released genetically modified mosquitoes would cross-breed with their unmanipulated counterparts in the wild. After just a few generations, the percentage of infertile mosquitoes would be much too low.

A technique known as gene drive, using CRISPR/Cas9 gene editing, promises greater success. The gene editing ensures that with each generation, all offspring carry the infertility gene. This causes the modified genes to spread rapidly amongst the mosquito population.

Data of 17,000 mosquitoes enable predictions of parasite frequency

Unlike insecticides, however, this gene drive-based application is very specific and will target a single species. As only 30 out of the 360 known species of Anopheles can infect people with malaria, we need to target the major malaria mosquitoes. However, most areas in Africa are concurrently occupied by several species that differ in their capacity to transmit the parasites.

My team and I wanted to find out the species and other factors that play a key role in transmission. In 2014 and 2015, we spent two rainy seasons in Mali collecting mosquitoes every day. We now have data on more than 17,000 mosquitoes.



There are 360 species of Anopheles worldwide, 30 of which can transmit the malaria parasite to humans.

We then investigated which factors – for example, temperature, total number of mosquitoes or the ratios of different mosquito species – influence the prevalence of Plasmodium parasites. We used the Granger causality test – a statistical hypothesis test normally used by economists to forecast stock market prices. With the help of this test, we succeeded to predict the prevalence of malaria parasites in a local mosquito population based on the proportion of one mosquito species out of two inhabiting this area.

Genes makes some types of mosquito more resistant to malaria

The results were surprising: only one species, Anopheles gambiae, correctly predicted infections in mosquitoes. Previously, Anopheles gambiae and its close relative Anopheles coluzzii both had been considered vectors for the disease. However, our results show that Anopheles gambiae is more permissive to the parasite, whereas Anopheles colluzii plays a much more minor role. But since this species is much easier to breed in a laboratory, it has been substantially better characterised and all current gene drive technologies have been also developed for this species.

But why are some mosquito species better vectors for malaria? One of the differences between A. gambiae and A. colluzii is the TEP1 gene. In Mali, A. colluzii has a variant of this gene that makes the mosquito more resistant to malaria. But this is not the real purpose of this variant. Instead, the variations in TEP1 allow the mosquitoes to adapt to regional climatic conditions. We are currently looking for other genes that may influence the development of the parasites and explain the observed differences between the two species.

To reproduce, a female mosquito requires a nutrient-rich meal: the blood. When she bites a person infected with malaria, the pathogens lodged inside the red blood cells enter the insect gut. In order to reproduce in the mosquito, the parasites need energy, which they obtain from their insect host.

Using mathematical modelling, we have investigated the influence of the mosquito's diet on reproduction and virulence. In our model, the virulence of the parasites increases if they highjack nutrients intended for the mosquito's reproduction. If the mosquitoes consume all nutrients, the picture is different: the parasite numbers are reduced and the few developed parasites are unable to infect a next host. We have confirmed the results of our modelling experiments with mosquitoes in the laboratory.

These discoveries are important for the development of gene drive-based strategies. Inhibition of mosquito reproduction will release more nutrients to the parasites and make them more virulent to humans, as our modelling results show. In addition, the effectiveness of gene drive applications depends on the choice of targeted species: if a wrong mosquito species were removed from an ecosystem – for example, A. coluzzii in the area of our study in Mali – it could very quickly be replaced by the more dangerous A. gambiae.

Italy's success story is unlikely to be so easily repeated. An increasing resistance to insecticides and the size of malaria regions worldwide make the fight against the disease a Herculean task. The future belongs to new biotechnological strategies that use multiple interventions. However, their success relies on a fundamental understanding of what makes mosquito species a potent vector. Only when we truly understand the vectors of malaria, we can tailor our efforts in fighting them. o

3 Combating online bullying

FABIAN WINTER
↘ *Max Planck Institute for Research on Collective Goods, Bonn*

Threats, coercion, discriminatory statements and insults have become an everyday occurrence on the Internet, particularly in social networks. The question of whether the escalating number of hate comments can be scaled down is a frequent subject of public discussion. Experiments conducted by our research group have provided a clear answer to this question.

As a German saying goes, "At sea and before the courts, we are in God's hands". Whether a higher power can really be held responsible for surprising court judgements is rather debatable, but they are frequently cause for consternation. One example is the ruling made by the Berlin State Court in the case of Renate Künast in the summer of 2019. The politician had requested that the court release the names and addresses of people who had made derogatory and profanity-laced comments about her online. To the surprise of both laypeople and legal experts, the judges deemed these hate comments to be objective contributions to a debate, which were therefore protected by the freedom of expression laws. However, the court later partially revoked the judgement.

Hate comments are not only directed at well-known public figures, of course. The ever-expanding digitalisation of our communication means that broader sections of society are also affected. Increasingly, migrants, religious and sexual minorities are becoming the target of online abuse. While the phenomenon of online hatred is widely acknowledged, little research has been conducted into the precise mechanisms behind its spread. In the past few years, we have therefore taken a closer look at a series of such mechanisms in the "Mechanisms of Normative Change" research group at the Max Planck Institute for Research on Collective Goods in Bonn.

Following a largely unregulated initial phase in social networks such as Facebook and Twitter, abusive hate comments have now become a focus of public debate. A key issue here is how to handle these comments in order to prevent their further spread. Can communication be given free rein, in the hope that the online community will establish its own rules of behaviour and that users will recognise major breaches of standards and call out the authors of such comments? Or should the social network operators intervene and take down perpetrators by deleting the comments or even blocking user profiles?

Users take their cue from the negative tone of an online debate

In order to compare the impact of these different approaches, we set up an online forum especially for this purpose, where we were able to determine what type of


HATE
SPEECH

comments users would get to see. In an extensive series of experiments, we observed that users do, in fact, take their cue from the negative tone in online debates. Many of them post further negative comments, for example against minorities. When hate comments were posted, the hate-filled statements following such posts were even more negative. In other words, the intensity of the hate comments kept increasing. Interestingly, this behaviour did not change when other users reproached the individuals posting abusive and hate-filled comments. A further deterioration of the debate culture was only prevented when derogatory, discriminatory and abusive statements were deleted.

Social norms are called into question when their validity is shaken by extraordinary events.

Social norms of civil behaviour therefore appear to depend significantly on the behaviour of others. Here, so-called "descriptive norms" appear to have a particularly strong impact, and are derived from the specific behaviour of others. However, the deterrent effect of informal sanctions – in the case of social media, the counter-comments by other users – appear to be far less effective.

In general, social norms are often called into question when their validity is shaken by extraordinary events. We can observe this when horror stories are circulated in the media. Against this background, we conducted a further study, comparing the situation shortly before and shortly after two Islamic terror attacks in Germany in the spring of 2016. In this context, we made arrangements to set the tone of the debate in such a way that for users who visited our online platform, only positive or neutral statements on minorities could be seen, while in others, individual hate comments were also shown. While deleting the hate comments before the terror attack only had a minor impact on the debate culture, the difference in the comments after the attack was clear: negative examples were accepted to a far greater degree and exacerbated the extreme comments even further.

Major changes often lead to a feeling of normlessness

We have turned to a classic concept in sociology in order to explain this effect. Émile Durkheim's "Theory of Anomie" states that major structural changes in a society frequently go hand in hand with a general feeling of disintegration or disappearance of norms and values. On a small scale, this sense of "normlessness" can also be observed in the case of the terror attacks. While before the attacks, anti-discrimination norms were widely accepted, after the attacks, many people questioned whether these still applied. In order to obtain information about their validity, people refer to their social environment for orientation. If they observe mainly positive or neutral statements about foreigners, the pendulum swings towards validity. However, seeing repeated cases when this norm is broken has precisely the opposite effect. The norms appear not to apply as strictly as they did before, so that those who previously did not make statements against migrants now felt justified in doing so.

Our research has delivered valuable results in many ways. On the one hand, it sheds light on a topic that is of current relevance in society: it identifies situations in which standing up against discrimination has a key impact, and shows ways in which this can be done. On the other, when researching social norms, it is important to understand how normative insecurity, or "anomie", affects a shift in social norms. Finally, our research also shows how experimental methods can be used to analyse social debates, and in this way, how quantitative approaches can be combined with questions that are frequently qualitative in nature. ○

4 Protective microbes at the root

THORSTEN THIERGART, FELIX GETZKE, STÉPHANE HACQUARD
↘ *Max Planck Institute for Plant Breeding Research, Köln*

Probiotic foods and microorganisms which produce compounds that are beneficial to human health are becoming increasingly popular. Similar to animals, plants also live in intimate association with huge numbers of microorganisms that profoundly impact their health. My group and I want to identify health-promoting microorganisms that associate with plants and characterise the mechanisms by which they promote growth or protect from diseases.

Fungal diseases cause considerable damage in agriculture. Farmers usually combat them with antifungal agents, so-called fungicides. Alternatively, they rely on plant varieties that are resistant to disease-causing fungi. But perhaps a more sustainable solution could come from under the ground.

Soil is home to a large number of different microorganisms, including bacteria and fungi. Some of these microbes are able to colonise plant roots and to carry out beneficial functions for their hosts. Nitrogen-fixing bacteria called rhizobia and arbuscular mycorrhizal fungi are among the best characterised of these "good" root-associated microorganisms: they invade the root cells of specific plant hosts such as legumes and crops, respectively, and facilitate plant uptake of mineral nutrients via the development of specialised symbiotic organs (i.e. the nodule and the arbuscule). However, plants are also continuously threatened by pathogenic microorganisms, and as a consequence, they have developed an immune system that can recognise pathogens and keep them in check. Unlike animals, plants do not have an adaptive or specialised immune system and therefore exclusively rely on a limited number of extracellular and intracellular receptors that recognise and mount immune responses against microbial pathogens.

Could the "good" microorganisms act as an additional protective barrier against microbial pathogens, and if so, how? My team and I want to find out whether and how the interaction of different microorganisms in plant-associated microbial communities influences plant health. We have studied this question in thale cress *(Arabidopsis thaliana),* a model plant popular among plant biologists.

Different root microbes in pure cultures

We investigated the bacteria, fungi and so-called oomycetes, which are closely related to brown algae and are often referred to as water molds. In a first step, we isolated the majority of microbes that colonise plant

Microorganisms of a plant root under the electron microscope.

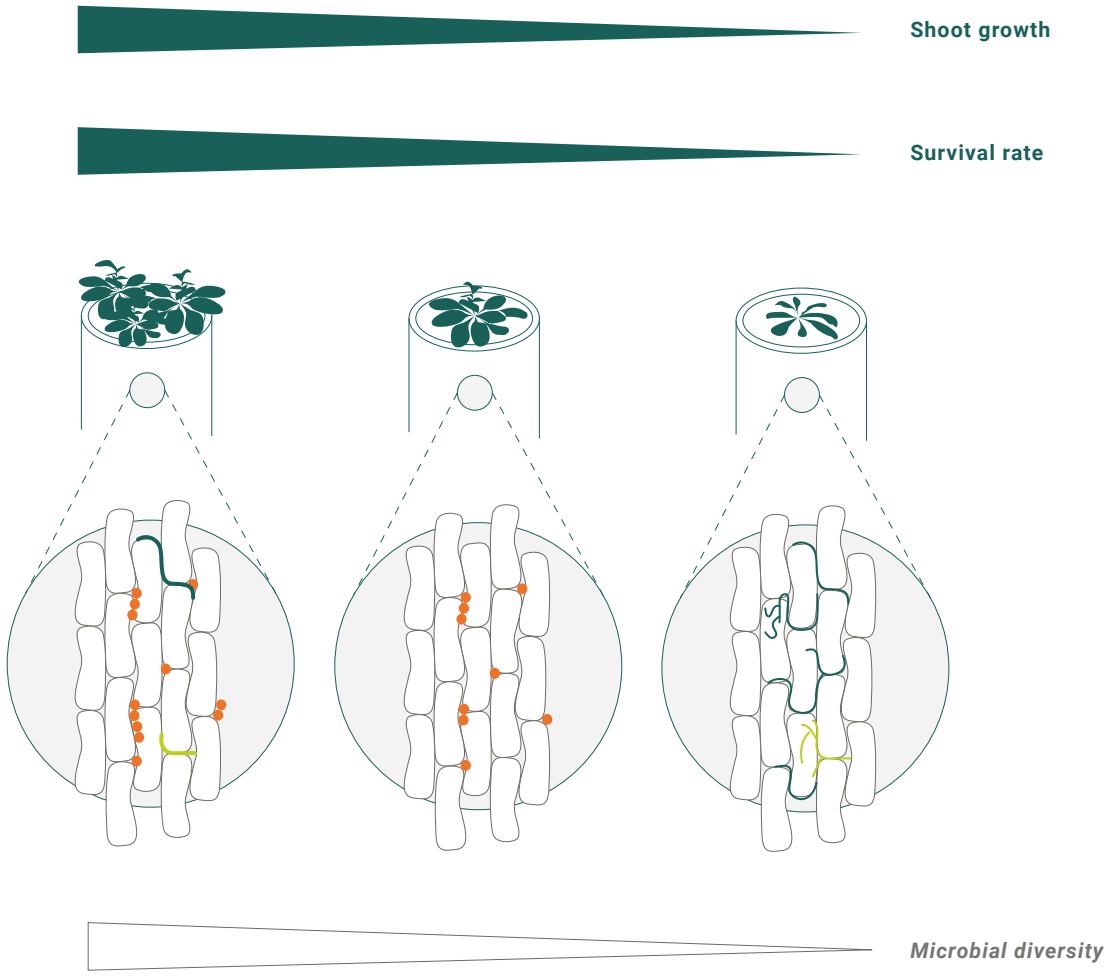
roots as pure cultures. Next, we grew the individual microorganisms together with sterile plants in different combinations. This allowed us to determine the effect of each combination under controlled laboratory conditions and to find out whether an imbalance between the different microbial groups (bacteria, fungi, oomycetes) affects the growth and survival of the plants.

Bacteria hinder the growth of fungi and other microbes

Our test plants were only able to survive potentially harmful fungi and oomycetes in the presence of bacteria. The bacteria appear to hinder the emergence of the fungal and oomycetal communities at the root zone, thereby promoting the growth and survival of the host plant. This protective function appears to be widespread among bacteria.

Our experiments show that the plants' immune system alone is not sufficient to protect it against harmful

If the roots of sterile plants are recolonised only by fungi and oomycetes (right), the plants grow worse than when additional bacteria grow on it (left).



fungi and oomycetes. Thus, bacteria from plant roots or their surroundings are, in a sense, an extension of the plants' immune system. Interestingly, plants grow better when all three groups of microorganisms are present. Bacteria, fungi and oomycetes therefore appear to have complementary properties that likely act synergistically to promote plant health in nature. In order to understand and make use of this natural protective function for plants, we now aim to determine how these bacteria restrict the growth of pathogenic fungi and oomycetes.

Our research has paved the way for combining different bacteria in ways that can keep harmful organisms at bay. The development of such "synthetic bacterial communities" represents a promising strategy for microbiome manipulation in the field that could significantly increase productivity in agriculture while reducing the application of fungicides. ○

5 I'm the bus stop!

STEPHAN HERMINGHAUS
↘ *Max Planck Institute for Dynamics and Self-Organisation, Göttingen*

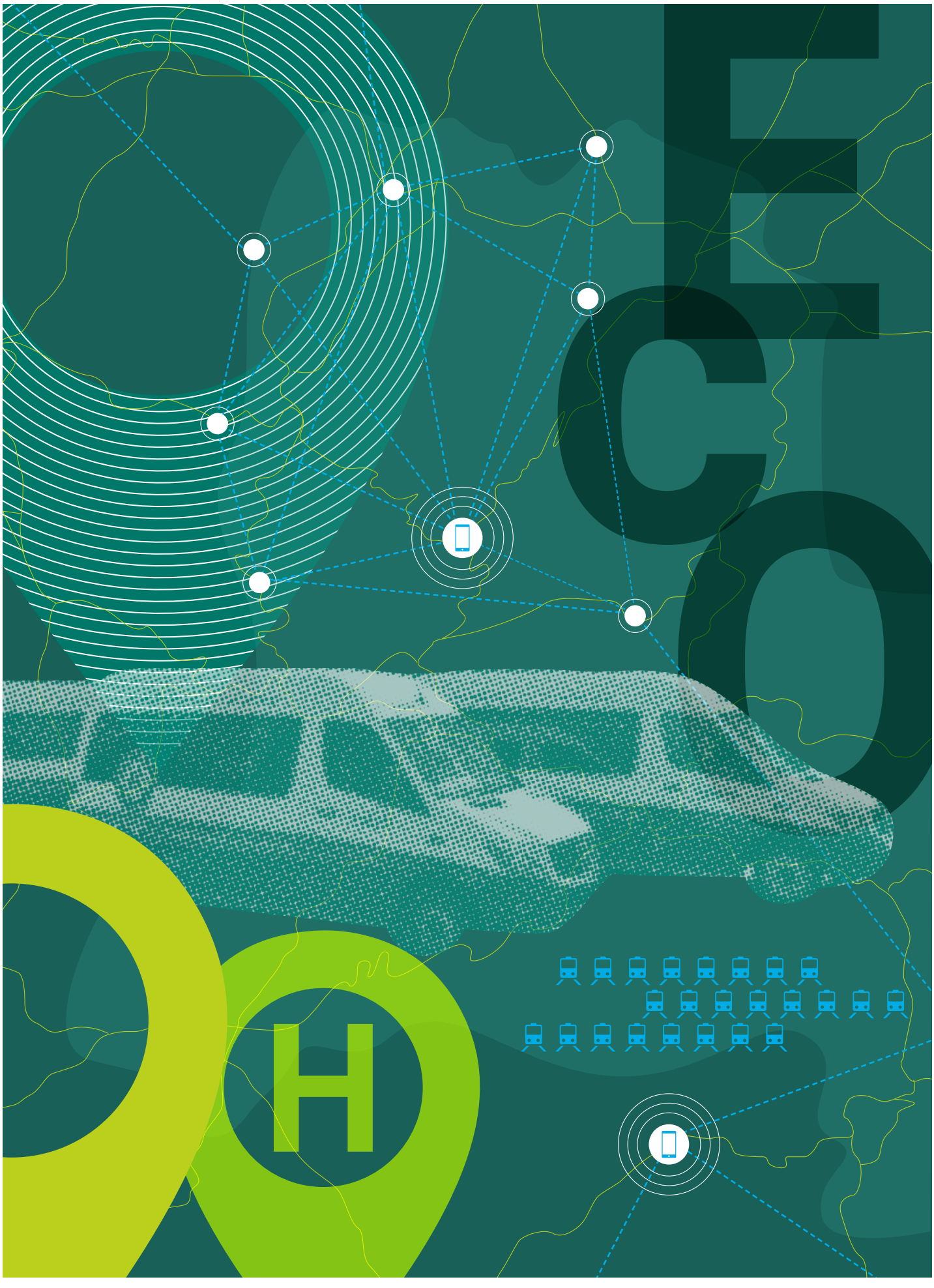
Imagine a bus that picks you up at your door and brings you to your destination – whenever and wherever you want. Although this sounds complicated and uneconomical, it could help solve our mobility problems. The Ride-Pooling-System EcoBus that was developed theoretically by our group has proven itself in initial practical tests.

Cars have stood for individual mobility for decades. But carbon dioxide, nitrogen and particulate matter emissions as well as the increasing density of traffic, particularly in our cities, are causing more and more headaches. This is why traffic planners are looking for new mobility concepts that are a practical alternative to private cars and at the same time spare the environment. Our group at the Max Planck Institute for Dynamics and Self-Organisation has come up with a Ride-Pooling-System called EcoBus that could replace part of private transportation in future. We began with its theoretical development and then put it through its paces in real test campaigns. Based on the experience gathered with these, we believe the EcoBus has the potential to reduce private transportation and at the same time strengthen public transport.

In our ride pooling system, small buses carry passengers along routes that are determined solely by the passengers' needs. Before every journey, passengers enter where they want to be picked up and dropped off in an app or over the phone as well as the desired collection time. The system calculates the best routes for small buses based on these requests so as to collect the passengers where they are, and at the requested time, and bring them exactly to where they want to go. There are no fixed bus stops – each passenger is his or her own stop. The tickets cost the same as the public transport rates.

The Ecobus aims to get people on to public transport

The idea behind ride sharing is not actually new. Transport services such as UberPool, MOIA, CleverShuttle or door2door are also based on ordering vehicles per smart phone at any time and to any place. The problem with this kind of service, however, is that it puts more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vehicles on the road. This does not ultimately relieve road traffic; instead, these services steal guests from the eco-friendlier public transport services and shift transportation to a larger number of cars. The EcoBus wants to do just the opposite: it aims to get people out of cars and on to public transport. We have achieved this by docking the routes of the EcoBuses onto the public transport network and timetables. EcoBus supplements the existing network and acts as a feeder to regular services, wherever this is possible and sensible, thus making these much more competitive.

The ride pooling system is related to the classic mathematical "Travelling salesman problem" from the 1930s: the problem here was to find the shortest route between different cities a travelling salesman has to visit. The more cities there were, the greater the number of alternative routes.

Route planning has to take into account regular services so as to allow their combined use.

The 15 biggest cities in Germany, for example, can be connected by 43 billion different combinations of routes. Nowadays there are plenty of algorithms to help solve this optimisation task. These are used, amongst other things, in sat-nav systems.

In ride pooling, we are not dealing with just individual travellers but a number of passengers who want to be picked up and dropped off. What is more, we have to coordinate the routes of several buses. For example, a bus travelling in one direction should not pick up passengers whose destination is in the opposite direction. In addition, routes are constantly changing because new passengers are constantly sending new requests. And finally, the route planning has to take into account regular services and networks so as to avoid parallel services or allow their combined use as far as possible.

Methods of statistical physics to develop a ride pooling system

One big problem was the speed at which the system has to decide, because passengers should receive a reply on their smart phones within a few seconds. All of these requirements taken together make the system very complex. Our more than twenty-strong team needed a good two years to investigate the problem theoretically, to develop the route optimisation algorithm and write the apps (iOS and Android) for customers, drivers and the call centre.

Our group was able to fall back on theoretical methods of statistical physics for this complex problem, methods we had put to successful use in the past for different line services, but nevertheless related problems such as flows of plankton swarms. Motor traffic is also a flow: vehicles follow a certain direction, as in a flow, but they can actively deviate from this main direction. Although plankton organisms are transported in a certain direction by large flows of water, they can also vary their direction by rowing motions. In these cases, one talks of active fluids.

Our theoretical results were tested practically in several pilot projects, in each of which we were able to gain valuable new research findings. The first two were

The intermodal optimised service leads to a significant increase in the number of passengers.

carried out with up to nine vehicles between June 2018 and February 2019 in and around Bad Gandersheim, at the same time as the open air theatre festival *Gandersheimer Domfestspiele,* as well as in Upper Harz in the rural districts of Goslar and Göttingen. The biggest issues here were the low population density in the area, the weather (winter in Harz) as well as the topography and poor cell-phone reception. The Ecobus had already been planned to enable connecting trips to and from trains in certain towns as well as to regional and urban buses, but otherwise it was a standard on-call bus service.

All three test projects were very well received by inhabitants

The "full version" has been in operation since mid-October 2019 in a suburb to the north of Leipzig under the name Flexa: small buses and regular services have been integrated into a complete system. Initial analyses already show that this intermodal optimised service is not only very popular amongst customers but has also led to a significant increase in the number of passengers on the different routes.

All three projects were very well received by inhabitants; the number of registered customers has risen steadily. At the end of the seven-month project in Upper Harz, for example, the service had a market share of well over ten percent. Because of the limited number of vehicles, our system's capacity was reached at just over 250 trips a day. In the quite sparsely populated Upper Harz region, we achieved this with nine vehicles, in the current pilot project in the suburban area of Leipzig, only four small buses are needed. The full capacity was reached here in only two weeks.

The average number of passengers in each small bus, a crucial figure for the system's profitability, corresponded to our theory's prediction within the tolerances. In Upper Harz, we could have covered the entire mobility needs within the area served with around ten times the number of vehicles, with a cost coverage factor that is normal for public transport. But as explained above, our goal was to develop the overall intermodal system of regular services and small buses as a service for the "final mile", as is being tested in Leipzig. We hope to be able to enter the market with this system in the near future. o

6 Helping damaged nerves to re-grow

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Severed nerve tracts are very difficult to treat. If at all, the damage so far can only be repaired through complex operations. At the Max Planck Institute for Polymer Research, we have developed materials that stimulate damaged nerves into growth. Results from initial tests on mice show that nerve tracts can regenerate this way.

Have you ever tried holding a pen without using your thumb? Then you will know how difficult this is. What may seem like an interesting finger exercise is for many a bitter reality. If nerve tracts are damaged or completely severed as a result of a traffic accident or occupational injury, individual limbs or even entire body parts can become numb and often can no longer be moved. In the past, the only chance to restore their functionality has been through surgery. Some operations involve removing nerve strands from another part of the body and reinserting them in the damaged spot. In this way, the damaged nerve endings can grow back together again, restoring a certain degree of movement to the affected part.

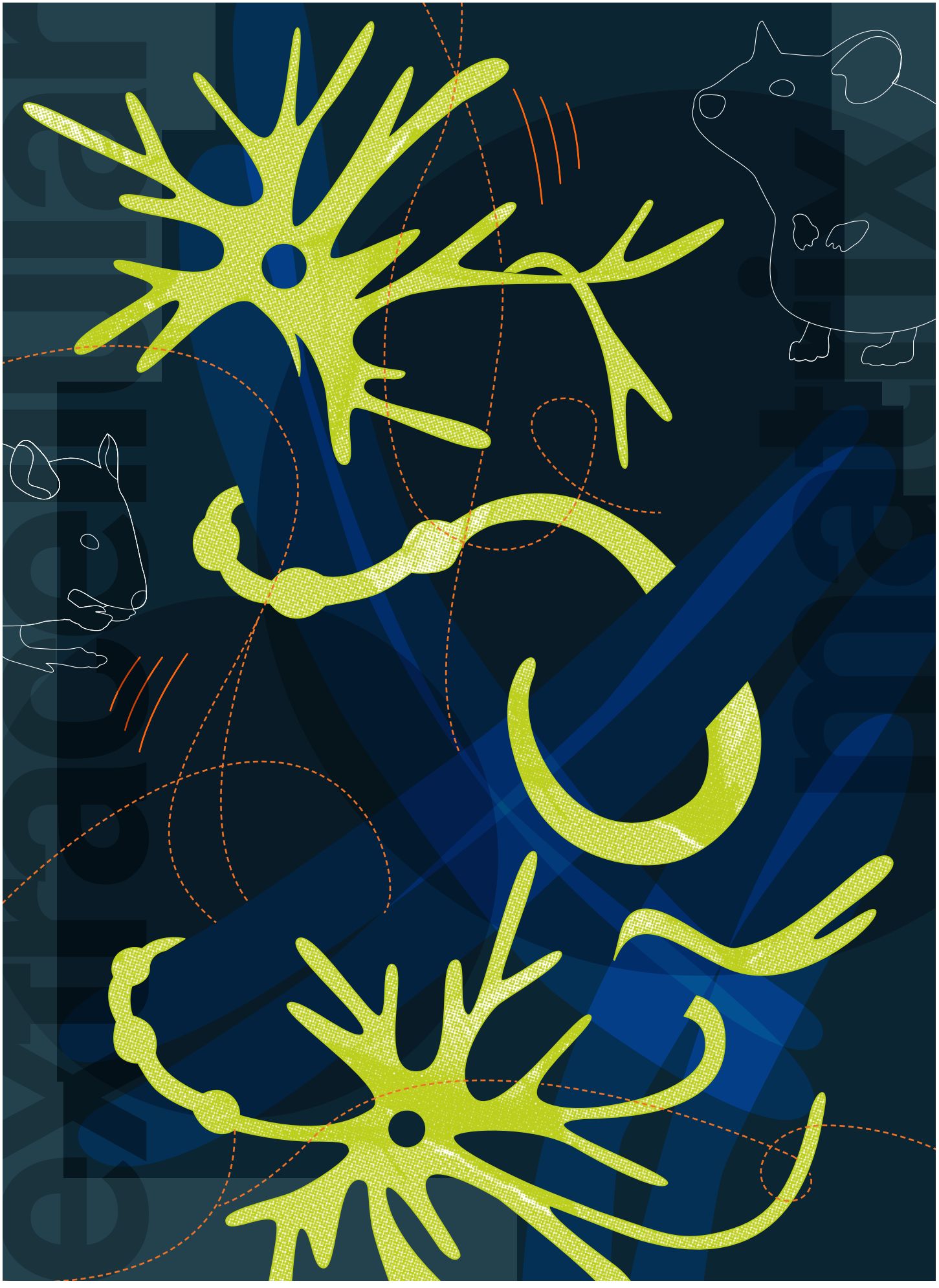
Growth requires structure

Although nerves may be able to bridge a severed connection, the process is extremely complex and not always successful. In addition, a framework of proteins surrounds healthy nerves, and injured nerve fibres depend on this framework remaining intact. However, injuries often damage not only the nerve tract itself but also this framework. This so-called extracellular matrix forms the scaffolding for nerve tracts. Just like tomato plants need a trellis, nerve cells need this matrix to grow alongside. At the Max Planck Institute for Polymer Research, we have developed a material consisting of endogenous building blocks, which can be used to replace this matrix. And as was shown, the artificial framework helps the damaged nerves to regenerate themselves.

The natural matrix consists of particular proteins: long chain molecules folded like balls of wool. Large numbers of these tiny balls of wool align themselves to form long fibres. These various fibres form a web – the extracellular matrix – that the nerve cells can latch onto.

Lego-build fibres

In order for these proteins to form, numerous complex biochemical processes have to take place within the body – too complex to be recreated in a test tube. Our research takes a different approach: although we use the same basic materials that make up the extracellular matrix, we assemble them in a simpler form. We use short-chain molecules known as peptides, which, like



We are confident that our artificial extracellular matrix can help healing minor injuries to nerve tracts.

proteins, are composed of amino acid building blocks. We produce these peptides with chemical precision, allowing us to determine the exact position of each individual building block.

To use an analogy, our precise chemical design creates 'studs' and corresponding 'holes' on the molecules, similar to Lego bricks. Two peptide molecules synthetisised in this way will naturally align themselves so that stud and hole meet. This then creates a stable structure. We were able to use this technique to produce long fibres that – despite their differing microscopic structure – strongly resemble the fibres of the nerve's extracellular matrix in shape and chemical composition.

From test tube to mouse

How do nerve cells behave when they are to grow on this artificial extracellular matrix? How do these growth characteristics change when we alter the peptides originally used? We investigated these questions in collaboration with our partner Bernd Knöll, Professor at the Institute of Physiological Chemistry at Ulm University. We produced various peptide structures, deposited them on glass substrates, and cultivated nerve cells on them. While the nerve cells on some fibre structures barely grew at all, on others we saw the rapid formation of axons, thin protrusions that create the connections to other nerve cells.

Together with our colleagues at Ulm University, we then used animal models to test the fibre structure that supported the best nerve cell growth. We surgically severed the facial nerve of a mouse on one side, which controls the movement of its whiskers. We then took the fibre-forming peptides and injected them into the gap in the nerve. After 18 days, the mouse was able to move its whiskers again to some extent; the nerve tracts had apparently grown back together.

Since the peptides used our artificial fibres resemble the natural proteins in the extracellular matrix, we are hoping that while the material remains in place during the healing process, the body can then break it down over time. So far we have been able to show that the material remaining at the injection site is slowly decreasing. However, whether this is due to biological degradation or the distribution in the body requires further investigation.

Pioneering properties

As shown by the laboratory experiment in mice, initial damage to nerve tracts can be repaired using our artificial matrix. Before using the material in clinical applications, however, further optimisation is required since the nerve cells on our material do not grow as well yet as they do in the natural matrix. They also grow in a quite disordered manner in all directions. Our next step will be to embed so-called growth factors into the artificial matrix to further accelerate the healing process. Furthermore, we want to orient the injected fibre structures to assist the nerve cells to grow in a specific direction.

We are confident that our artificial extracellular matrix could represent a good alternative to complex surgery for minor injuries to nerve tracts. Further research might also lead to a method of treating not just injuries to the peripheral nervous system but also to the central nervous system. ○

7 Synapses rely on regional products

SUSANNE TOM DIECK, ANNE-SOPHIE HAFNER, PAUL DONLIN-ASP, VIDHYA RANGARAJU, ERIN SCHUMAN
↘ Max Planck Institute for Brain Research, Frankfurt am Main

Anyone who has ever learned to ride a bicycle generally retains the skill for a lifetime. But however permanent learned abilities can be, the molecules which support learning processes are extremely short-lived. The production of new proteins at the synapses – the nerve cell communication sites – plays a crucial role here. We have been investigating such newly formed proteins in order to better understand the cellular processes of learning and memory.

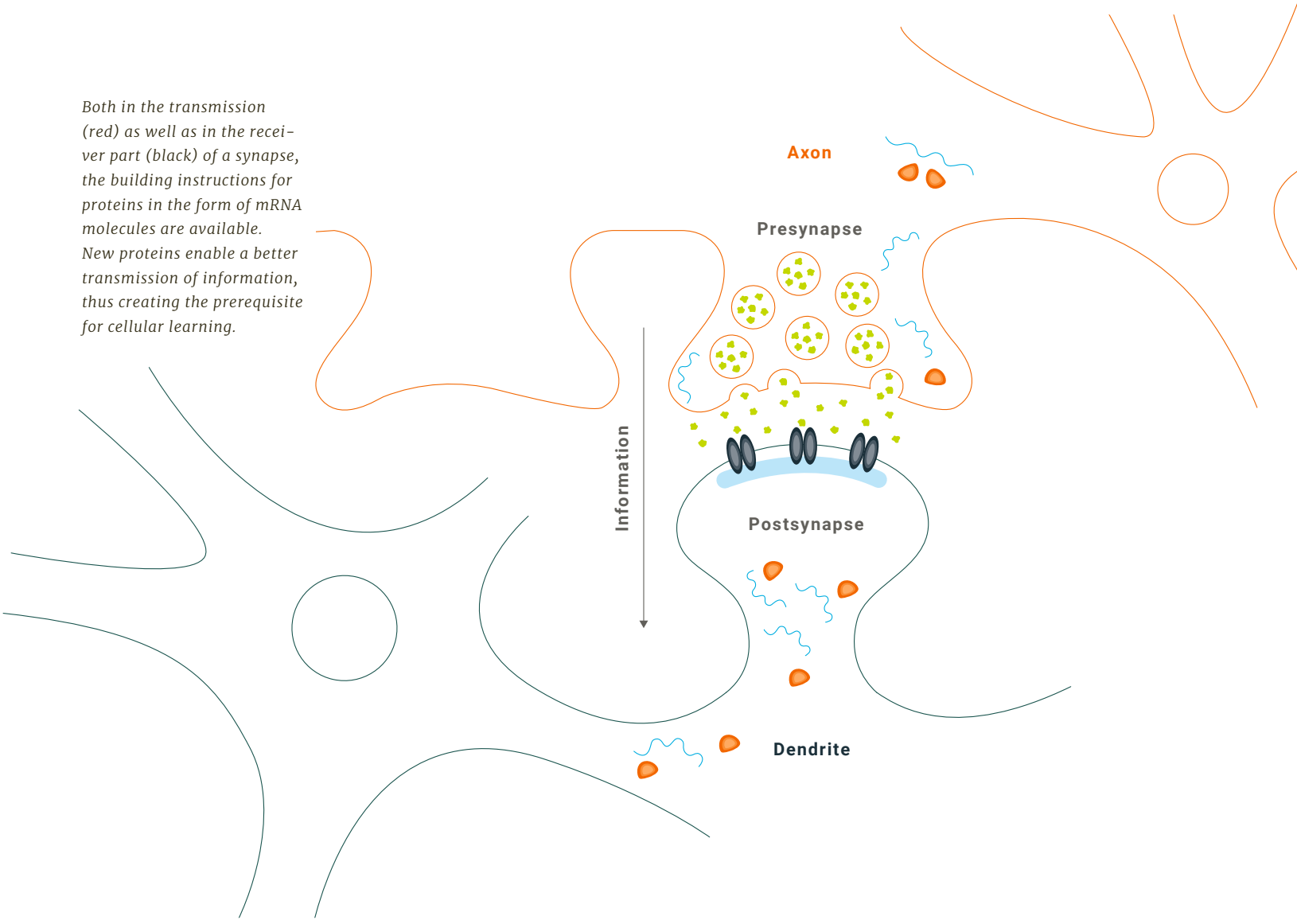
Nerve cells receive signals via thousands of synapses: junctions which transmit information not by means of electrical impulses but via messenger substances. They are able to individually amplify or reduce the strength of a signal – an ability known as synaptic plasticity. They can also form completely new synapses.

To enable the signals to bridge great distances, nerve cells have an unusual structure: the spherical cell body has tree-like spurs (dendrites) for receiving and a long protrusion for sending signals branching out from it. In vertebrates, an axon such as this can reach a hundred millimetres in length. In the case of a nerve cell in the musculoskeletal system, which have the longest axons, this means that if the cell body were the size of a table-tennis ball, its furthest synapses would be almost 400 metres away.

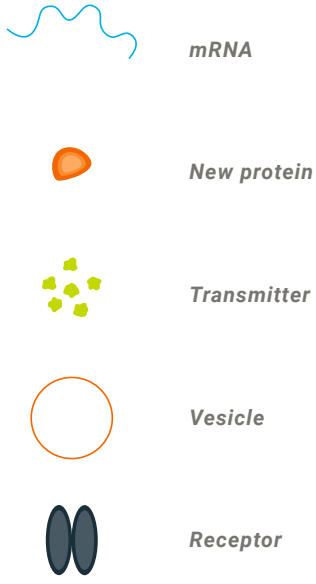
There are, therefore, often great distances from the synapse to the cell body. Within the cell body we find the nucleus, and usually also the instructions for building proteins. These are indispensable for learning processes in the synapses: without the production of new proteins, the transmission strength at the synapses cannot continue to be adjusted, and nothing new can be learned. We now know that a synapse contains on average around 50 molecules of a given type of protein. There are up to 500 different types, giving a total of 25,000 proteins per synapse. Since a nerve cell has on average 10,000 synapses, this means that after a few days, up to 250 million proteins need to be replaced due to their short life span.

Usually, proteins are formed according to the instructions created in the cell body – the messenger RNA molecules, or mRNA – and then distributed around the cell. How does the nerve cell achieve the task of rapidly transporting these large numbers of proteins to individual synapses despite their size and complexity? How do proteins identify their destination? And how can the cell target change at one particular synapse among thousands?

Back in the 1990s, we found out that new proteins can be produced in a decentralised location, i.e. close to the synapses, if they are active. Consequently, we discovered thousands of mRNAs in axons and dendrites,



Both in the transmission (red) as well as in the receiver part (black) of a synapse, the building instructions for proteins in the form of mRNA molecules are available. New proteins enable a better transmission of information, thus creating the prerequisite for cellular learning.



far from the cell body. Building on this exciting result, we have now isolated the mRNA from the part of the synapse responsible for sending signals to the next cell. We discovered a whole collection of building instructions for proteins that organise the release site of these messenger substances.

How locally are the proteins produced at the synapses?

But what is the local protein production process in detail? To use an analogy: does 'local' mean producing for the whole federal state of Hesse, or just for the city of Frankfurt? Where exactly is the decentralised factory? Which products are being manufactured at a given point in time, and where does the energy come from?

First, we concentrated on the question of where exactly the proteins are formed. Researchers can normally answer this question with the help of a microscope. In our case, however, this was something of a challenge, as the distances between the possible production sites

Without the production of new proteins, the transmission strength of synapses cannot continue to be adjusted and nothing new can be learned.

lie at the boundaries of optical microscopy. We also required a method of identifying newly formed proteins.

Once we had developed a technique to do this, we combined it with a small trick: we embedded nerve cells into a matrix which absorbs moisture and swells like a nappy. If we fix the proteins to this matrix before the swelling process, then, in an ideal case, all the original structures expand equally. Using this method, we were able to achieve roughly a fourfold expansion of the matrix, making the desired structures visible under an optical microscope.

Each type of cellular learning produces proteins at different sites

We then wanted to know whether proteins were manufactured in the transmitting or receiving part of a synapse. We treated the nerve cells with substances which induce various types of cellular learning. Astonishingly, for each type of cellular learning, there appears to be a dedicated constellation of sites for protein production.

Nerve cells need a great deal of energy, including for cellular learning. This is generated in specific cell organelles known as mitochondria. We observed these cell factories live under a microscope and discovered that their behaviour differs between axons and dendrites: in dendrites, mitochondria stay in one location in clusters of around 30 micrometres; in axons they form tiny mobile bundles.

In an experiment, we targeted individual clusters of factories, putting them out of action. It emerged that, under normal conditions, a local failure does not influence protein production. But the synapses in the region of the disabled factories were no longer able to power up the protein production necessary for cellular learning. Learning was no longer possible.

Clarifying these details is important because faulty mitochondria and problems with protein production are typical in neurodegenerative illnesses such as Alzheimer's or Parkinson's. Disruptions in synaptic plasticity are directly associated with disorders of the nervous system such as depression, anxiety and addictive behaviours. Communication and plasticity at the synapses need to function faultlessly to enable rehabilitation after brain injuries. Our research can contribute to distinguishing cause and effect in brain injuries, and help correct malfunctions. ○

8 Attack on autopilots

MICHAEL BLACK
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How fast the development from assisted to fully automated vehicles will progress is uncertain. One crucial factor here is the reliability with which a vehicle can navigate in its surroundings and react to unforeseeable incidents. Our group at the Max Planck Institute for Intelligent Systems showed that methods for motion analysis based on deep neural networks – likely components in future autonomous vehicles – can be confused by small patterns designed to "attack" these networks.

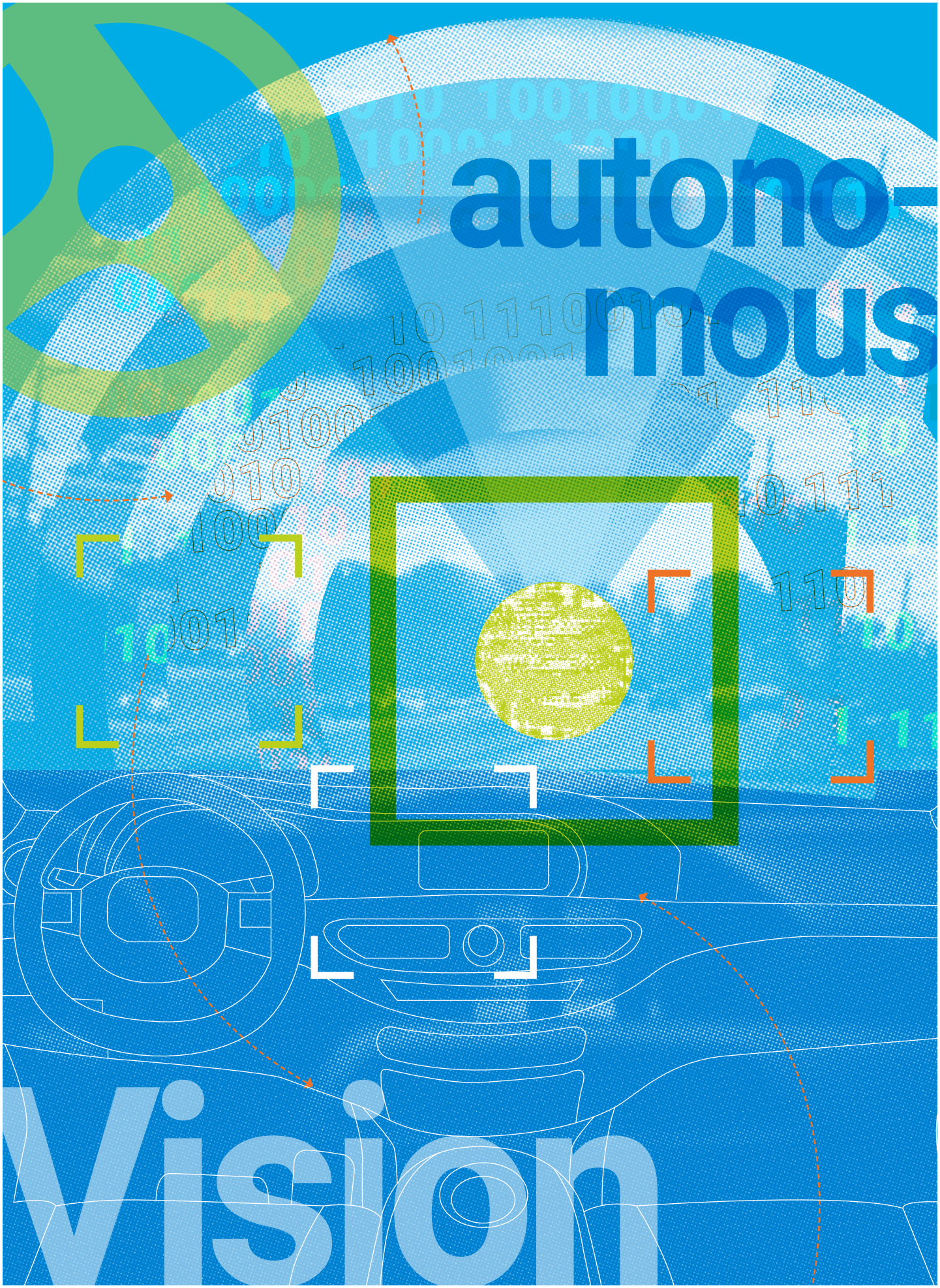
Self-driving or semi-autonomous cars perceive their surroundings with different sensors. To analyse a scenario, manufacturers use, amongst others, optical flow, the two-dimensional motion of pixels between video frames. This is used in robots, in medicine, in special effects and in navigation, to name but a few examples.

The optical flow describes the various movements in a scene that are perceived by humans with their eyes and cars with on-board cameras. If you drive or walk somewhere, static objects such as trees, houses or pylons appear to drift in the opposite direction. The speed of movement allows us to judge the distances to the objects, amongst other things: Whereas a nearby tree rapidly disappears behind us, distant objects such as clouds or mountains appear to be standing still. We also see people or animals moving on their own.

In order to analyse the various movements, the on-board cameras record numerous images of the scene in rapid succession; a computer deduces the movement of the individual objects from the differences between the images with complex mathematical methods. It calculates a speed vector for each pixel that indicates how fast and in what direction the world surface at the pixel moves through the image. One important aspect here is that both the movement of the vehicle and the movement of the surrounding objects, persons or other cars, cause an optical flow. The on-board computer thus has to be able to distinguish its own movement from that of other objects – a very complicated task.

Easy to produce colour patterns can disturb motion analysis

The latest progress in machine learning has led to faster and better methods to calculate such movement. In a joint project involving our Department for Perceptive Systems at the Max Planck Institute for Intelligent Systems in Tübingen and the Autonomous Vision research group of the University of Tübingen, we have demonstrated that these kinds of methods are susceptible to carefully constructed attacks: if, for example, a simple, colourful pattern appears in the scene, either by accident or purposefully positioned in the image data by a hacker attack. Even if the pattern does not move, it can lead to incorrect calculations by deep neural networks, as are currently widely used to calculate optical flow –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The objective was to inform the manufacturers of automated cars of the threat.

the network suddenly calculates that large parts of the scene are moving in the wrong direction. Sometimes the blotch of colour can even disrupt the complete system. Such a blackout could be very risky.

The danger that existing vehicles currently available on the market are affected is low. Nevertheless, to be on the safe side, we informed a number of car manufacturers who are currently developing self-driving models. The topic of attacking neural networks is actively discussed at the leading conferences on machine vision, but we are the first to show that optical flow networks can be attacked. The goal of our project was to warn manufacturers of self-driving vehicles of the potential threat and to develop new methods that are robust to attack. Our work can help manufacturers to train their systems to withstand such disturbances.

We tested five freely available systems for optical attacks in our research work. To this end, we built five colour patches to attack these systems. It turns out to be relatively easy to come up with such patterns with a few hours of computation.

We positioned these colour patterns at random points in a scene during our test runs. To our great surprise, it was very easy to disturb all five neural networks. In our test, even a small patch, making up less than one percent of an overall image, was enough to confuse the system in such a manner as to affect half of the image area. And the larger the patch, the more disastrous the consequences. The colour patches are thus very effective. We used these patches to analyse what was happening inside these networks and found systematic biases in the networks that people were unaware of. This gives a path to improving both the robustness and accuracy of such methods.

These neural networks are loosely inspired by the way our brain works. Incoming data is analysed in the network with weights and simple computations. The system's weights are trained so that the network learns to output the correct motion of the scene. If the network makes mistakes, this can be compared to optical illusions that can also trick the human eye.

The neural network itself is unable to change the prioritisations it has been taught, which can lead to misjudgements. However, it should be possible to retrain it so that it is no longer tricked by these kinds of illusions.

Reliable neural networks will make autonomous driving safer

The fact that neural networks still require improvement was demonstrated by a very simple test. We showed the system two identical images. Although there was no movement or change in either of them, the network identified a difference. This should not happen. And these problems show that optical flow networks are not yet sufficiently mature for autonomous vehicles. Our research work should help raise awareness of this problem.

If neural networks are reliable, they will make autonomous driving safer. This will also be aided by cars using not only cameras but other sensors to "find their way around". On the other hand, on-board computers in cars should be able to analyse street scenarios more easily when more autonomous vehicles are on the roads that can communicate with each other. In this case, a car is not only dependent on the signals of its own sensors, but also receives data on its position and speed from other vehicles. We are convinced that autonomous driving can make road traffic safer despite the technical weakness that we are disclosing here. After all, human error is still the cause of 90 percent of all accidents. ○

9 Human rights versus economic law – the case of Latin America

ARMIN VON BOGDANDY, MARIELA MORALES ANTONIAZZI, FRANZ CHRISTIAN EBERT

↘ *Max Planck Institute for Comparative Public Law and International Law, Heidelberg*

When international economic law interacts with national or regional constitutional guarantees, conflicts can arise. Taking Latin America as an example, our project analyses relevant tensions and explores solutions that may potentially also be of interest for debates in other regions of the world.

Latin America is the world's most unequal region, as confirmed by the United Nations Economic Commission for Latin America and the Caribbean. In many countries, large sections of the population are excluded from the main social systems, including health and education. At the same time, the region is prey to structural violence and insecurity, often as a result of weak state institutions. One avenue to overcome these inequalities is seen in what has been termed transformative constitutionalism. This form of constitutionalism interprets and applies constitutional and related legal norms so as to engender profound social change, in particular with a view to combating systemic deficits. In this regard, NGOs have been important in using the instruments of strategic litigation – often combined with broader awareness-raising campaigns – to support a more effective implementation of human rights at both the international and national level. The improved enforcement of human rights, especially those of marginalised groups, is also intended to foster more inclusive democratic processes in the countries concerned.

Transformative constitutionalism has emerged in many Latin American countries, often after periods of prolonged dictatorships. Despite the fact that the form and content of transformative constitutionalism has acquired different trajectories in different countries, a trend can be observed: a close network of human rights guarantees has developed, which are based both on the respective national constitutions as well as on international agreements such as the American Convention on Human Rights. These provisions are put into concrete terms by the case law of domestic constitutional courts and the decisions of the Inter-American Court of Human Rights. In this regard, broad opening clauses contained in the constitutions of many Latin American countries have given international human rights guarantees a status within the domestic legal order that goes far beyond what many European legal orders grant to the European Convention on Human Rights. Often transcending the individual case before it, the Inter-American Court of Human Rights has influenced numerous political processes in the region. Among others, the Court has provided important impulses for the development of indigenous peoples' and migrants' rights as well as in the area of socio-economic rights. Similarly, domestic constitutional courts have also played a crucial role in shaping

The relevance of international economic law has increased significantly in the past few years.

developments in transformative constitutionalism. In Colombia, for example, invoking the right to health enshrined in the country's constitution, the constitutional court issued orders so as to address structural deficiencies of the public health system. In conjunction with pressure from civil society, this led to a series of reforms regarding the Colombian health system that have resulted in significant improvements.

The extraction of lithium puts at risk the livelihoods of the indigenous population

Our project posits that this constitutionalisation process can, however, be significantly hampered by instruments from other areas of law. As a first step, we analyse where such conflicts arise. The focus here is on international economic law, the relevance of which has increased significantly in Latin America in recent years. This can be seen in the numerous free trade agreements and bilateral investment treaties that have been concluded by countries from the region. Economic growth and development are high on the agenda in Latin America, and while the strive towards a prosperous economy is legitimate, it often comes at the cost of individual and collective human rights. A case in point is the extraction of natural resources. For example, 70 percent of the world's lithium deposits are said to be found at the border triangle between Argentina, Bolivia and Chile. While lithium is needed, among others, for the production of batteries for electric cars, the extraction of these resources puts at risk the livelihoods of the indigenous population in the region, thereby often disregarding their rights. Domestic constitutional courts and the Inter-American Court of Human Rights can only enforce the interests of the rights holders to a limited extent if, for example, awards by investment tribunals force the state in question to pay damages to investors that run into the millions for measures taken to protect human rights. Furthermore, international institutions such as the International Monetary Fund and the World Bank influence the economic and political situation of the respective countries through the conditions attached to their financial assistance programmes, often with palpable human rights implications.

The World Bank could fulfil its responsibility as a specialised agency

Secondly, we look into potential ways of resolving these conflicts. The key question here is how mechanisms of international economic law can be aligned with transformative constitutionalism such that they aid the enforcement of human rights rather than to the contrary. In our view, the World Bank, for example, should continue to move away from its neo-liberal approach to financial assistance and give greater consideration to the human rights *acquis* of the Latin American region. These concerns should also be reflected in the legal framework for the World Bank's activities so as to foster an approach to economic policy-making that is sustainable both socially and in terms of human rights. This would also enable the World Bank to better fulfil its responsibility as a specialised agency of the United Nations.

In addition to the law governing international financial institutions, we have also looked into other key subjects such as world trade law, bilateral free trade agreements and the regulation of transnational corporations. Of special relevance here is international investment law, which is particularly controversial in Latin America. Here too, we believe it is necessary to make changes to the various legal instruments, and in particular their interpretation, in order to prevent or cushion the negative effects of international investment law on the principles and objectives of transformative constitutionalism. Additional thought is being given to how the actors and instruments of economic law can contribute to strengthening these principles. In a follow-up project, we intend to expand the project's conceptual framework and apply it to additional sub-domains of international economic law. ○

10 Caterpillar droppings scare off moths

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The females of the tobacco hornworm (Manduca sexta) choose their egg laying sites carefully to avoid competition for their offspring. They are guided not only by the scent of the plant but also by the smell of the caterpillars' legacies. At the Max Planck Institute for Chemical Ecology, our research group is investigating what triggers this behaviour.

The bright green caterpillars of the tobacco hawkmoth develop on nightshade plants, which include tomato, eggplant and pepper in addition to tobacco. Nightshade plants usually protect themselves with different kinds of toxins, including nicotine, against larval frass. However, hawkmoth caterpillars tolerate these toxins and even accumulate them in their body as a chemical weapon against predators.

In contrast to the caterpillar, the full-grown moth is rather unremarkably coloured. With its buzzing flight behaviour it resembles a hummingbird. It lives on plant nectar and contributes significantly to the plants' pollination.

The caterpillars are extremely voracious: In the course of their development, a single animal often eats all the leaves of its host plant. Then it looks for another plant and eats it completely bare. It repeats this several times until it is fully grown and pupates in the soil.

If a female moth lays an egg on a plant on which a caterpillar is already growing, its own offspring may not be able to grow large enough to reach its next host plant. But how does the moth know which host plants are still free from other caterpillars?

We know already that female moths recognise caterpillar infestation by changes in the scent pattern of the plants. However, it was previously unclear whether a moth also takes into account scent information from caterpillars that already live on a given plant and would be competitors for the moth's own offspring.

The presence of other caterpillars deters female moths from laying eggs

When caterpillars grow on a plant, they produce huge amounts of larval frass. In experiments we have checked whether ovipositing moths also pay attention to odours from these legacies. We offered the moths plants that were either prepared with caterpillar droppings or were untreated. Our experiments revealed that the female moths prefer to lay their eggs on plants where no larval frass is present and by that avoid the presence of caterpillars. We could furthermore show that the moths' decision is mainly driven by the carboxylic acids 3-methylbutyric acid and hexanoic acid, which are released from the excretions.

To smell caterpillar droppings, the moths use olfactory receptors that are located in their antennae. The sense of smell is particularly strong in insects, and accordingly, there is a huge number of olfactory receptors

One day it might be possible to deter insects from fields with odorous substances.

that each detect a different subset of odorants, ranging from ten olfactory receptor genes in head lice to more than 300 in ants. Which and how many olfactory receptors an insect expresses, determines which odorants the insect will be able to smell. The different receptors also differ in terms of the chemical and electrical signals processed in the insect's brain and the behaviour they trigger.

An olfactory receptor controls the response of the moths to caterpillar faeces

In the tobacco hawkmoth, almost 100 genes for different kinds of olfactory receptors are known. Using the CRISPR/Cas9 gene scissors, we have created genetic variants in which specific individual receptor proteins were switched off. Switching off some of the receptors did not affect the animals' ability to smell and avoid the caterpillar excretions, suggesting that they are not involved in the detection process.

When we, however, switched off the so-called ionotropic receptor 8a (IR8a), we found that this receptor controls the avoidance reaction to caterpillar droppings. Moths lacking IR8a are unable to recognise and avoid the caterpillar faeces. Hence, we elucidated a signalling pathway involved in competition avoidance down to its molecular details.

The interaction between plants and insects is diverse and highly complex. It has developed over millions of years in the course of evolution and has been repeatedly adapted to new environmental conditions. For example, the smell of caterpillar droppings can also attract enemies of the caterpillars and thus protect the tobacco from being eaten. On the other hand, as we now know, the scents in caterpillar droppings govern oviposition avoidance in moths.

Thanks to new techniques such as CRISPR/Cas9, we are able to study the odour-controlled behaviour of tobacco hawkmoths and other insects in even more detail. We are particularly interested in additional factors guiding the insects to their host plants: Flower scents, moisture or carbon dioxide? Which signalling proteins control the reactions to scents, and which genes are involved in this behaviour?

Answers to these questions could contribute to finding alternatives to insecticides. One possibility would be, for example, to specifically deter insects from a field with odorous substances or to attract their enemies. In addition, we must meet the challenges that the climate crisis will bring for agriculture. ○

11 Break-in forecasts on probation

DOMINIK GERSTNER
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"Preventing crime before it happens"— this is the phrase used to attract interest in what is known as "predictive policing software". We conducted the first scientific study on how well this software really works with a pilot project in Baden-Wurttemberg. There, the police used software to predict a higher degree of probability for house break-ins in certain areas.

Predictive policing means that software is used to create forecasts about future crime by evaluating data and applying statistical methods. The goal is to take police action on this basis in order to prevent these predicted criminal acts in the first place. The forecast methods can range from simple statistical analyses to the use of artificial intelligence and can cover different areas of crime. The focus here is always only on predicting probabilities and not on specific crimes. Although a very wide range of predictive policing strategies are already being used in many countries, some of which are now highly contentious, there are almost no scientific studies on their degree of effectiveness. Our evaluation of the predictive policing pilot project in Baden-Wurttemberg is the first scientific examination in this area on the European continent.

As in other regions in Germany, in Baden-Wurttemberg the number of domestic burglaries increased significantly between 2007 and 2014. To counteract this development, the pilot project was initiated by the federal state police, headed by the Baden-Wurttemberg Federal Police Agency. Commercial computer software was used in the Karlsruhe and Stuttgart police districts. This software predicts whether there are increased probabilities of break-ins in certain areas. If this is the case, an alarm is generated to which the police respond with specific measures. The forecasts use simulation-based "if-then decisions" and not artificial intelligence. The goal was to prevent so-called "near repeat crimes", in other words, break-ins that frequently occur shortly after the first break-in and geographically close to it.

Two test phases with online survey and expert interviews

On behalf of the Baden-Wurttemberg Federal Police Agency, we conducted a scientific study to determine how successful this approach has been. In two test phases in 2015/16 and 2017/18, we analysed process-generated data on the one hand. On the other, we obtained new information about the practicality and degree of acceptance among the police stations involved through an online survey with around 700 respondents and expert interviews. In the second evaluation phase, we also introduced an experimental research design in order to be able to better determine the degree of effectiveness of the forecasts. Here, alarms based on predictions were randomly assigned to an experimental or control group, enabling a comparison between the two groups.

The findings provide insufficient evidence to assess whether the use of predictive policing software is worth its while, however. While some positive evidence is available that the method can contribute to a reduction in burglaries, the impact appears to be limited.

On the one hand, this is reflected in the assessments of the police stations involved. There, opinions vary as to the benefits of the method. In the online survey, which obtained views and experiences of the police officers, around half of the respondents regarded the trial predictive policing model as being potentially beneficial, while the other half held the opposite view. Above all, the officers who were confronted with a particularly large number of alarms felt that the model promised little improvement. This may be due to the fact that the computer forecasts reduce the level of autonomy to act, or that the measures have a preventive impact as a result of the forecasts, and the benefits are therefore difficult to assess.

In contrast to urban areas, rural areas hardly benefited from predictive policing.

On the other hand, several important conclusions can be drawn from the evaluation of the case data. Near-repeat crimes, i.e. burglaries committed shortly after a previous break-in and occurring close by, mainly take place in towns and cities. Here in particular, it is therefore possible to define relevant forecast areas in which the number of follow-up crimes can be reduced accordingly. In rural areas, however, the relevant forecast areas were limited. On the whole, therefore, only a small number of break-ins occurred in these areas. In the district of Calw, for example, where most people live in villages, this applied to only three of 70 break-ins during the winter months of 2015/16. By contrast, in Stuttgart, the figure was 260 cases out of 424 in total.

While rural areas hardly benefited from predictive policing at all, the forecast software was at least partially able to reduce the number of burglaries in urban areas. A specification given for the pilot project was to intensify police patrols for a week within a radius of 500 meters around the first break-in site when the software issued an alarm, and to conduct measures to prevent and combat burglaries. Overall, however, this only had a moderate impact. In the second evaluation round in 2017/18, we were able to compare an experimental group which followed this specification with a control group which acted in the normal way after the break-in. In the group that used predictive policing, the number of follow-up crimes was reduced by just 0.3 burglaries on average, with police density and other structural parameters such as proximity to a major road as control factors. Therefore, in the pilot project we were unable to determine any noticeable downward trend in burglaries that could be traced to the use of the forecast software. ○

12 Gamma rays from space

MORITZ HÜTTEN, MARTIN WILL
↘ *Max Planck Institute for Physics, Munich*

In January 2019, the two MAGIC telescopes on La Palma (Canary Islands) measured the most energetic gamma-ray burst to date. It was thus possible to gain new insights into these mysterious cosmic events. We hope to find many more celestial bodies in the highest energy range. Therefore, the future Cherenkov Telescope Array (CTA) consisting of more than 100 individual telescopes is currently under construction on La Palma and in Chile.

What we see with our naked eyes in the night sky corresponds to only a small section of the electromagnetic spectrum – which ranges from long radio waves to high-energy X-rays and gamma rays. We have known for only about 30 years that cosmic objects also emit radiation that is billions of times more energetic than visible light. This is radiation with an energy in the teraelectronvolt range. One electronvolt is the energy that an electron receives when passing through an electric field with a voltage of 1 V; a teraelectronvolt is one trillion electronvolts.

This radiation is completely absorbed by the atmosphere. Nevertheless, it can be observed indirectly from the ground using a clever trick: when a gamma particle enters the atmosphere, its interaction with the atoms in the air triggers a shower of secondary particles that travel for kilometres through the atmosphere. This produces bluish Cherenkov light, which can be detected using special mirrors and light sensors. By the way, the secondary particles move at superluminal velocity – which is no contradiction to Einstein's postulate, which only applies to a vacuum; in a medium like air or water, the speed of light is lower. The charged particles in the cosmic showers have almost vacuum light speed and therefore travel at a speed greater than the speed of light in the atmosphere.

Under the leadership of the Max Planck Institute for Physics, scientists from 12 countries have been operating the two MAGIC telescopes on La Palma for 16 years. An important goal for the construction of MAGIC – Major Atmospheric Gamma Imaging Cherenkov Telescopes – was the observation of gamma-ray bursts from the very beginning. These are sudden bursts of radiation, each lasting fractions of a second to minutes, which reach us from the depths of the cosmos. The phenomenon of gamma-ray bursts has been known for more than 50 years. However, their origin has not yet been fully clarified.

Gamma-ray bursts are the most luminous events in space and are visible at distances of billions of light years. They are thought to arise when a massive star collapses at the end of its life or when two compact

Successful duo: with GRB190114C, the two MAGIC telescopes observed the first gamma burst on the Canary Island La Palma. It also had the highest energy known so far.

objects – such as neutron stars – fuse together. Because it is impossible to predict when and where in the sky these short gamma-ray bursts will occur, they can be detected only by space telescopes that scan the sky around the clock. But these satellites are not capable of measuring teraelectronvolt radiation. This spectrum can only be observed with ground-based telescopes. However, it is precisely the detection of radiation in the highest energy range that makes a significant contribution to understanding the processes in a gamma-ray burst.

In order to capture the ephemeral events, the MAGIC telescopes were built in such a way that they can be swiftly pointed in the direction of such a burst. MAGIC was thus able to slew to gamma-ray burst GRB190114C within only 25 seconds after an alarm was triggered by two space telescopes on the evening of 14 January 2019. Immediately after starting the measurement, MAGIC detected gamma radiation in the teraelectronvolt range. Never before have we observed such high-energy radiation from a gamma-ray burst. The analysis of the signal and comparison with data from other telescopes ultimately revealed that GRB190114C was probably a massive star that collapsed into a black hole in a giant supernova explosion.

Particles in magnetic fields emit synchrotron radiation

The gamma radiation came from the afterglow of the explosion when the matter that was ejected into space crossed the interstellar medium. According to our models, such astrophysical shock waves generate gamma radiation. Here, charged particles that are accelerated to high energies move in strong magnetic fields and emit synchrotron radiation. However, this method does not produce gamma radiation with the highest energies. Therefore, in the case of GRB190114C we suspect that

MAGIC observed the effect of inverse Compton scattering. In the process, the high-energy particles transfer part of their energy to the nearby synchrotron photons. This mechanism is known in other objects; it has long been suspected – but never proven – that it also occurs in gamma-ray bursts.

The burst was in not too great a distance and therefore appeared particularly bright

Interestingly, the total energy released by GRB190114C over all observed wavelengths was not exceptionally high. However, its distance was quite small on cosmic scales. This is why the burst appeared particularly bright and why MAGIC was able to register such high gamma energies. The question therefore remains whether the telescope has observed a very special stellar collapse or whether inverse Compton scattering always starts in the afterglow of gamma-ray bursts. This can be answered only if we observe many more – and even more distant – gamma-ray bursts in the teraelectronvolt range.

The Cherenkov Telescope Array (CTA), which is currently under construction, offers great opportunities for this. CTA will consist of more than 100 individual telescopes. These will be set up at two locations: in the Southern hemisphere in the Chilean Atacama Desert and in the North on La Palma, right next to the MAGIC telescopes. Three types of telescopes are planned. Eight Large-Size Telescopes (LSTs) have been optimised for seeking out gamma-ray bursts. Their mirrors each have a diameter of 23 metres and the telescopes can be repositioned almost twice as fast as MAGIC. In combination, the LSTs will be able to measure gamma-ray bursts only one tenth as bright as those that can be measured by MAGIC. CTA thus may be able to detect radiation from gamma-ray bursts that flare up for only a maximum of a few seconds before afterglow. These short gamma-ray bursts are particularly interesting because they are probably triggered by the same events as gravitational waves are.

The Max Planck Institute for Physics is involved in the construction of the LSTs. The first such telescope on La Palma was inaugurated in October 2018, and initial measurements were successful. Construction of the three additional LSTs on La Palma is expected to begin in the summer of 2020; we expect them to be completed in a few years. At the same time, all the other telescopes will be constructed on La Palma and in Chile. By 2026, the entire CTA park should be in place. By then at the latest, the new Cherenkov telescopes will provide us with exciting new insights into the most energy-rich radiation phenomena in the Universe. ○

The question therefore remains whether the telescope has observed a very special stellar collapse.

13 Sustainable alloys for demanding applications

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↘ *Max-Planck-Institut für Eisenforschung GmbH, Düsseldorf*

Materials in wind turbines, aircraft engines and steam turbines have to withstand high mechanical loads at high temperatures. At the Max-Planck-Institut für Eisenforschung, we have developed alloy concepts that not only meet such requirements, but which are also more cost-effective and sustainable than materials previously used. Together with our industrial partners, we are optimising these manufacturing processes.

Offshore wind turbines generate environmentally friendly electricity under inhospitable conditions such as salty and humid sea air, weather fluctuations and extreme temperatures. However, many wind turbine components wear and corrode over time and, therefore, the turbines must be replaced after about 20 years. Pipelines in biomass power plants, engines in aircraft, or compressor blades in steam turbines must withstand similar conditions. In order to increase the sustainability and cost-effectiveness of these applications, robust yet cost-effective materials are required. At the Max-Planck-Institut für Eisenforschung, we have developed alloys that meet exactly these requirements.

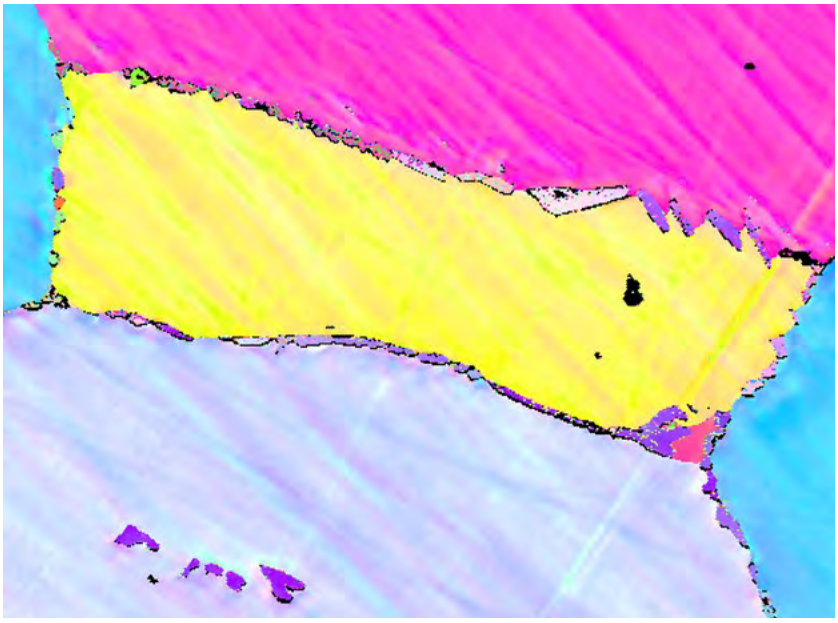
Iron aluminides are corrosion-resistant, wear-resistant and light

Alloys based on iron and aluminium – the two most common metals in the earth's crust – are proving to be particularly sustainable. Such alloys may also contain other additives such as boron in smaller quantities. These iron aluminides have several properties that are of particular interest to industry: they are highly corrosion-resistant, have a high wear resistance and are particularly lightweight because of their low density. Furthermore, they do not require additional expensive alloying elements to improve material properties and can be produced in conventional process routes such as casting, rolling and forging.

Iron aluminide alloys have been available since the 1930s. They were tested in major applications such as industrial furnaces, steam turbines and in the chemical industry as early as the 1950s. However, besides their many advantages, these alloys have had one decisive problem so far: they were not strong enough at temperatures above 700 °C. It has therefore not yet been possible to use such alloys in aircraft engines and biomass power plants or as brake discs in wind turbines.

At the Max-Planck-Institut für Eisenforschung, we have designed our new alloys so that they can be used at high temperatures and still retain their other advantages. Supported by the Federal Ministry of Economics and Energy (BMWi), we are working together

Example of the microstructure of an iron aluminide material: the different colours reflect the different orientations of the grains that make up the structure. The boundaries between the grains show fine precipitates that give the material its high strength.



with Siemens, Rolls Royce Deutschland, Leistritz Turbinentechnik and Otto Junker as well as the Karlsruhe Institute of Technology and the Access Research Centre associated with the RWTH Aachen University in order to optimise our alloys for industrial processes and applications.

High strength at high temperatures

To this end, we are developing processes with which the microstructure of a material can be designed for specific applications. Apart from the chemical composition of the structural constituents, the properties of a material are largely determined by the size, shape, and distribution of these components as well as by the interfaces between the individual constituents. The alloy design enables us to tailor the properties of such a material for different applications so that it is suitable for use at high temperatures yet still highly resistant to mechanical stress.

We achieve the mechanical strength of such an alloy at high temperatures by adding small quantities of other elements. We can then distribute these in a targeted manner in the structural constituents or introduce them into the material in the form of fine particles with a different chemical composition. Their size and distribution can be adjusted via specific temperature programs or mechanical processing. For example, it is possible to distribute extremely fine, nanometer-sized particles evenly on the interfaces between the microstructural constituents and thus tailor the properties of a material to the respective application.

A special heat treatment makes the components particularly strong

For components that we produce by casting, we can, for example, add boron to deposit fine precipitates of boron compounds evenly along the interfaces in the material. This makes a component more ductile, especially at low temperatures. This property is particularly important if the materials will be regularly exposed to large temperature differences. For example, brake discs for wind turbines heat up to 900 °C on the surface when the rotor brakes.

Other components such as turbine blades, which are subject to high mechanical stress, are best produced by forging. Here, we specifically combine forging temperature and formability. If necessary, we also subject the product to a special heat treatment so that an additional, finely distributed intermetallic compound is created within the alloy, thus giving the components the desired strength.

Cost-effective and sustainable

The industry expects savings in the double-digit percentage range if comparatively expensive nickel-chromium steels or even more expensive nickel-based alloys can be replaced with our iron aluminide alloys. And what is even more important: our alloys are also more durable thanks to their high wear and corrosion resistance. Finally, they are also recyclable and more lightweight. We are currently working with our project partners to determine the optimum alloy concepts for the various process routes. In addition to our expertise in alloys, the high-resolution characterisation methods available at the Max Planck Institute are decisive factors for our industrial partners.

Our low-cost and sustainable iron aluminide alloys could thus replace high-alloy steels and nickel-based alloys in future applications – especially when used at high temperatures in harsh environments. o

14 How Facebook is helping to measure migration

EMILIO ZAGHENI
↘ *Max Planck Institute for Demographic Research, Rostock*

It is almost impossible to rapidly obtain figures on migration movement following natural disasters, especially using only traditional sources such as government statistics. Data from social networks such as Facebook is opening up completely new possibilities. This enabled us to track migration movements from Puerto Rico to the USA following Hurricane Maria in the autumn of 2017.

Hurricane Maria raged in parts of the Caribbean in September 2017. The island of Puerto Rico, an incorporated territory of the United States, was hit particularly hard: countless houses were destroyed, the electricity and water supply collapsed and the medical infrastructure suffered severe damage. As a result, almost 3,000 people died in Puerto Rico alone.

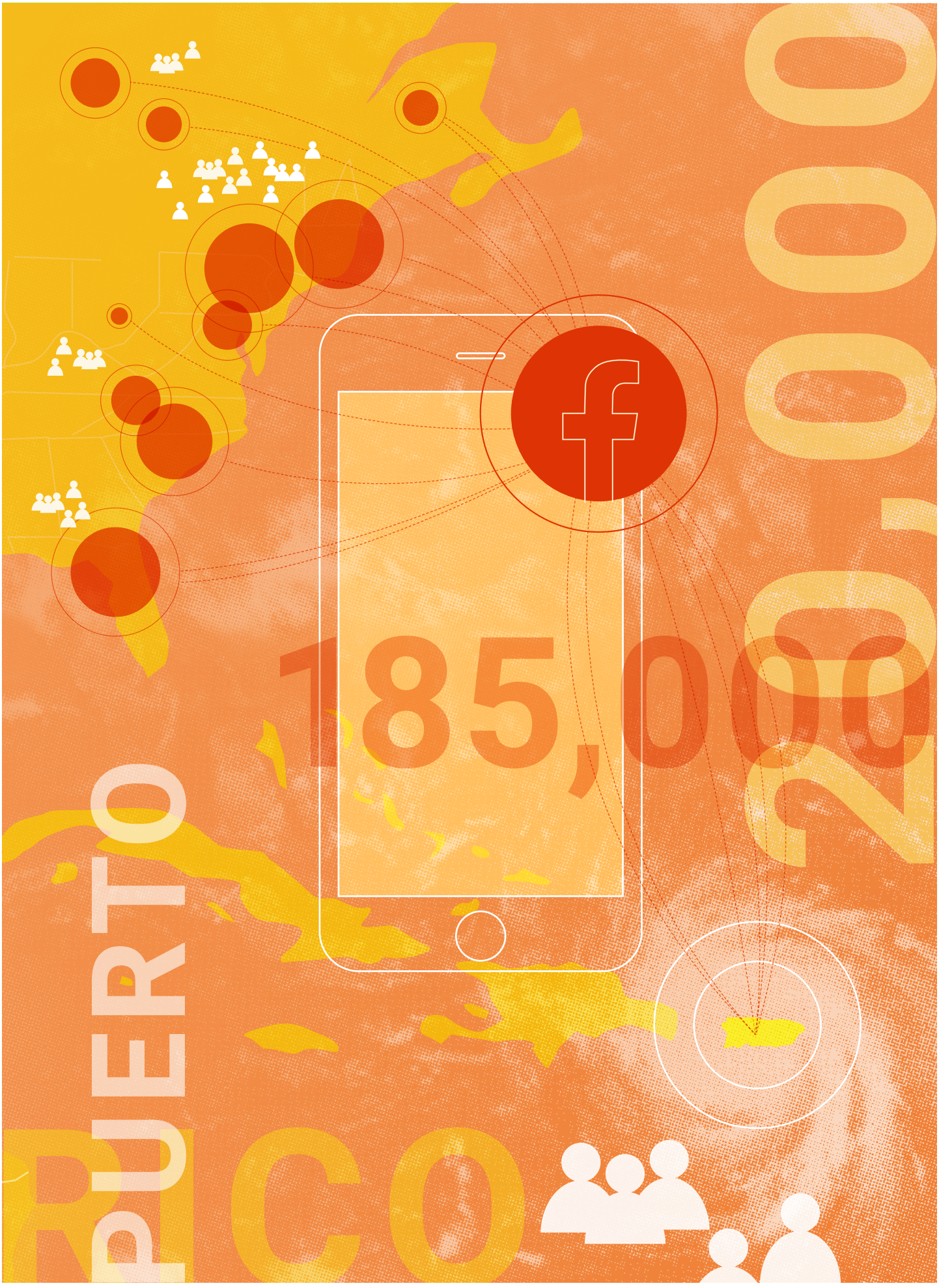
Natural disasters such as these frequently cause part of the population to emigrate. But until now, it has been difficult to track who goes where and when, and particularly to do so in a timely manner. However, for authorities and aid organisations to be able to support those affected, this data would be important, whether or not they want to remain, begin a new life elsewhere or return home. These questions cannot be answered using only traditional data sources such as official statistics. Particularly, the authorities in the USA do not keep monthly records of migration within US states and US territories such as Puerto Rico. Yet this is precisely what would be required to track disaster-related migration and displacement.

This is why, together with Monica Alexander from the University of Toronto and Kivan Polimis from the University of Washington, we exploited an alternative data source: Facebook. In addition to the counts of those concerned, anonymised Facebook data, which is collected regularly for advertisers, provides precise demographic data on the genders and ages of migrating users. This enabled us not only to track how many people moved following Hurricane Maria, but also whether as many men as women emigrated and their ages at that time. Even compared to other unconventional sources such as passenger lists and mobile phone data, this is an additional benefit.

This social network is mainly used by younger people

Our team had already started to collect data from the Facebook advertising platform in January 2017, so we already had data on migratory movement prior to the natural disaster when Hurricane Maria struck Puerto Rico the following September and we were able to collect further data during the following period. This is important, as Facebook data is only revealing valuable information if trends are observed over a long period and in comparison with other countries.

Another factor must be taken into account when working with Facebook data: this social network is mainly used by younger people, whereas older people are underrepresented in relation to their share of the


PUERTO
RICO
185,000
200,000

Force of nature: in September 2017, Hurricane Maria devastated the island of Puerto Rico. Many people fled the country or emigrated. With the help of Facebook, researchers have gained a whole range of demographic information about those who migrated.

total population. We therefore used a suitable statistical model to correct for this distortion of the data, after which we could clearly see a sharp increase in migration from Puerto Rico to various US states in the immediate aftermath of the natural disaster. We found that about 185,000 people , which is more than five percent of the population, had emigrated from the island to continental US by January 2018. These were primarily young people aged between 15 and 30 years. We also found that, for the most part, these young adults migrated to US states with pre-existing Puerto Rican communities such as Florida, Connecticut and Pennsylvania, which saw the biggest increases in Puerto Rican population.

Conversely, this means that it was mainly older people who stayed put. Our data generally confirms findings from other studies, according to which people require a certain amount of resources to be able to react quickly to a disaster. Being able to emigrate depends on one's health and financial situation. Regardless of how devastating the situation is, the frail and the poor remain behind.

Furthermore, we analysed data from the Facebook advertising platform for the year after the disaster and discovered that around 20,000 people returned to Puerto Rico between January and March 2018. This trend to return to the old home emerged once the worst effects of the hurricane were under control. Using traditional data sources would not have enabled us to track this migration movement.

Reliable data support relief efforts in the event of a catastrophe

A sound grounding in statistics and programming skills are prerequisites for compiling and evaluating such unconventional data, so our project involved a collaboration between researchers from the fields of demography, data science and statistics. We jointly developed new methods before using additional data sources to independently verify our results.

The post-Hurricane Maria migration example demonstrates that Facebook advertising data in conjunction with statistical models are an effective tool to track migratory movements. Our approach enables us to provide rapid reliable migration data to those responsible in the event of a disaster and thus to support relief efforts. ○

15 Building with DNA

KERSTIN GÖPFRICH
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Life on Earth developed from inanimate components. Can we recreate this process in the laboratory, and what tools do we need for this? Using DNA origami, the art of folding at a scale of just a few millionths of a millimetre, we are able to reconstruct individual cellular components. They may be capable of taking over important tasks in our bodies in future.

A living cell consists of separate yet connected functional units: a cell envelope, organelles, metabolism and the genome. "What I cannot reconstruct, I cannot understand" – this statement by the physicist and Nobel laureate Richard Feynman holds true for living cells.

It is still impossible to create an artificial cell from scratch. But history teaches us that what was unimaginable yesterday and may become reality tomorrow: at the beginning of the 19th century, for example, most chemists were convinced that urea could not be created artificially from inanimate matter. They believed that a "vital spark" was required to produce an organic substance such as this component of urine. In 1828, the chemist Friedrich Wöhler then manufactured urea from ammonium chloride and silver cyanate.

For the first time, humans were able to create a substance in a test tube which had previously only been known from living organisms. Today, synthetic biology may stand at the point where organic chemistry was before artificial urea synthesis. But a cell is far more complex than the chemistry of ammonium salts.

Therefore, the recipe for success in synthetic biology is simplification: Researchers select only the most important components and put them together in cell-like compartments. In a so-called bottom-up approach, they create minimal modules, each of which copies one specific function of a living cell: One module can, for instance, convert light into chemical energy, another one responds to stimuli, while a third enables movement. But putting together the modules to form a complete functional synthetic cell is still very difficult because it is not always clear how exactly they fit together. In addition, their interactions are extremely complex.

Artifical cells should be programmable and independent

Perhaps it would be more straight forward to change perspectives. Instead of combining existing modules to reconstruct the original as accurately as possible, researchers could use new tools and materials. This leaves room for creative solutions. My team and I are applying such a "de novo" approach to build an artificial cell from human-made components. Instead of copying life as we know it, we aim for a unique original. Our

What is life, and could it look completely different?

artificial cell should be programmable and act independently – like a miniature robot, as a link between the animate and the inanimate world.

But what tools and what materials are suitable for building such synthetic components? In any case, they have to be programmable precision tools which can provide a high number of copies of molecular units, precisely engineered for various different functions.

Letter sequence determines the form of DNA molecules

In our opinion, one suitable tool is DNA origami, the art of folding with DNA. In this approach, DNA is not used for hereditary information storage like in nature, but as a building material. The spiral-shaped DNA double helix is unwound and split into individual strands. One long individual strand can now be folded into a desired shape using many short, artificially created DNA sequences. We calculate the required DNA sequences based on a 3D drawing and then combine them in a test tube. This process creates trillions of identical copies of the previously designed shape in a drop of water, each only a few millionths of a millimetre in size.

It may sound like magic, but it's simply physics: due to the prescribed base pairings, the DNA strands self-assemble to maximise their fit and create the designed three-dimensional structure, which can take over a specific task in a cell. In this way, we have produced artificial membrane pores from DNA – components which are difficult to isolate from cells.

But it does not always have to be complicated structures. Even a single, chemically modified DNA double helix is sufficient to connect two components in a cell. Nature often uses hundreds of linker proteins – for example, to tie the cytoskeleton to the cell membrane. It appears highly challenging to isolate them individually and integrate them into synthetic cells. That's why we have chosen to take a short cut and use DNA as an artificial link. This link can be broken and reformed based on external stimuli such as temperature changes.

At the end, we need to combine the different components inside a compartment in order to mimic a cell. We are already able to divide such cell-like compartments. Yet assembling it in the first place is not easy,

A cell consists of a variety of components and organelles. These include, for example, the elongated mitochondria (drawn in orange) and supply the cell with energy. The spherical cell nucleus (olive green) contains the genetic material and the reticular endoplasmic reticulum (light blue) is surrounded by a membrane envelope.

because the cell envelope is particularly fragile. Once the membrane, which consists of a thin fatty acid layer, has been formed, the insertion of components becomes challenging.

A boundary layer of droplets as artifical cell envelope

That's why we have developed a method which superficially resembles cocktail shaking: we first layer the components on top of each other in a test tube and then shake them to create a droplet emulsion. An artificial cell envelope forms at the boundary layer of the droplets and encapsulate the components. In this simple way, we can include many different components. Also microfluidics and 3D printing are helpful tools. With them at hand, we can dedicate ourselves to the next challenge: the development of an information storage system for synthetic cells.

The emergence of life on Earth took billions of years. When will the laboratory experiment be successful? Humans could be much quicker because, instead of waiting for a series of lucky coincidences like in natural evolution, we pursue clear goals with synthetic biology. This gives us hope that an artificial living model system may soon become a reality. Then, at the latest, an ancient question will gain new meaning: what is life, and could it perhaps look very different? ○

The Max Planck Society

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Max Planck Institutes work in research areas, which are particularly innovative and require a special commitment in terms of funding or time. Their research spectrum is constantly growing. New Institutes or departments are set up and existing ones rededicated in order to find answers to seminal scientific questions. This process of constant renewal preserves the Max Planck Society's leeway to pick up quickly on new scientific developments. It was set up in 1948 as the successor organisation to the Kaiser Wilhelm Society, which had been in existence since 1911. Since then, 17 male Nobel Prize winners and one female Nobel Prize winner have been produced from its ranks. As well as five Institutes abroad, the Max Planck Society runs a further 20 Max Planck Centers with research facilities such as Princeton and Harvard University in the USA, Science Po in France, University College London / UK or the University of Tokyo in Japan. Funded in equal measure by the Federal and State Governments, the Max Planck Society enjoys a total annual budget of 1.86 billion euros.

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