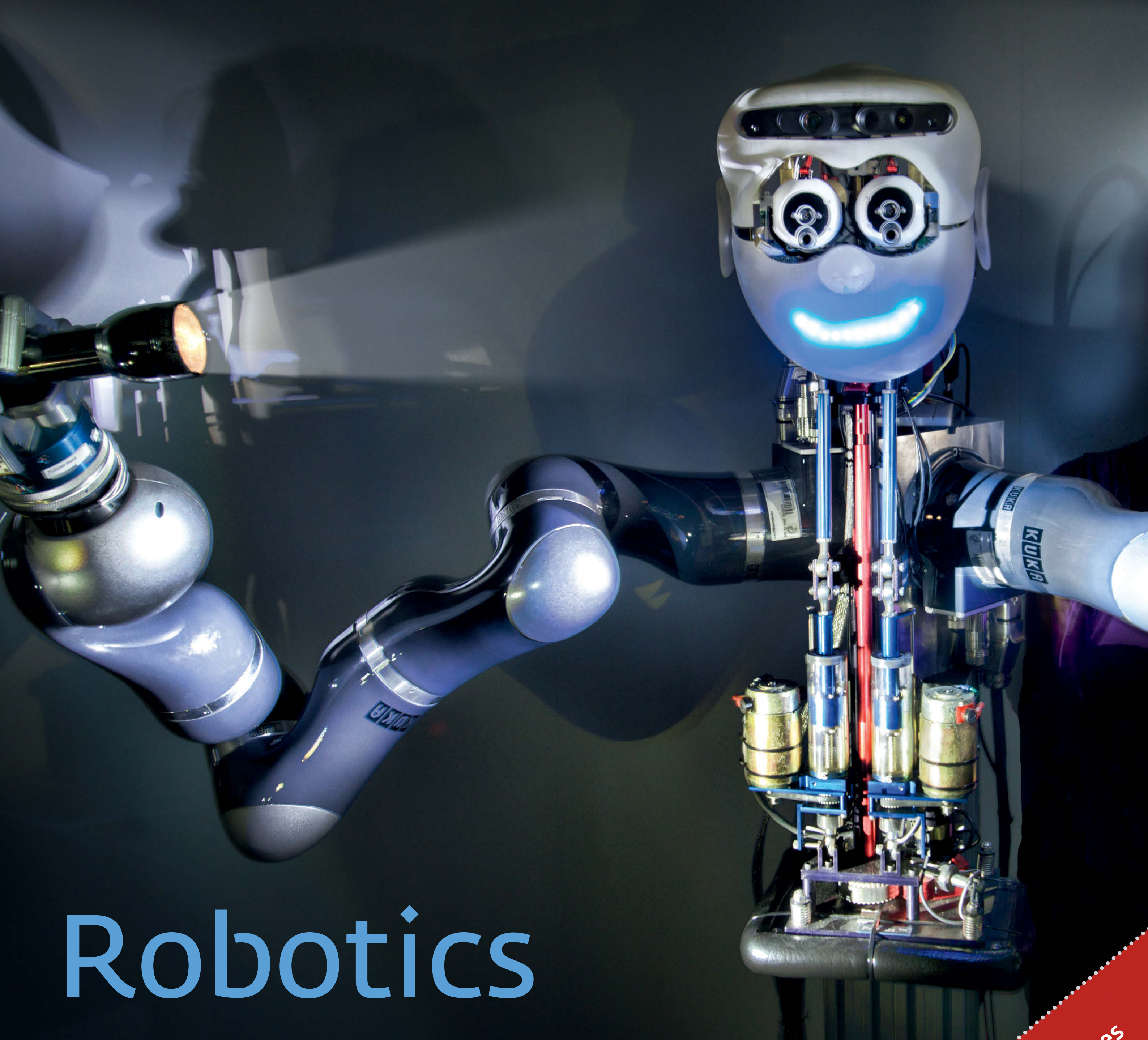
B56133

Max Planck RESEARCH

The Science Magazine of the Max Planck Society

1.2016



Robotics

SOCIAL ANTHROPOLOGY
How Terrorists Are Made

PHYSICS
Counting on Quanta

MICROBIOLOGY
Bacteria Need Partners

Special
Gravitational Waves

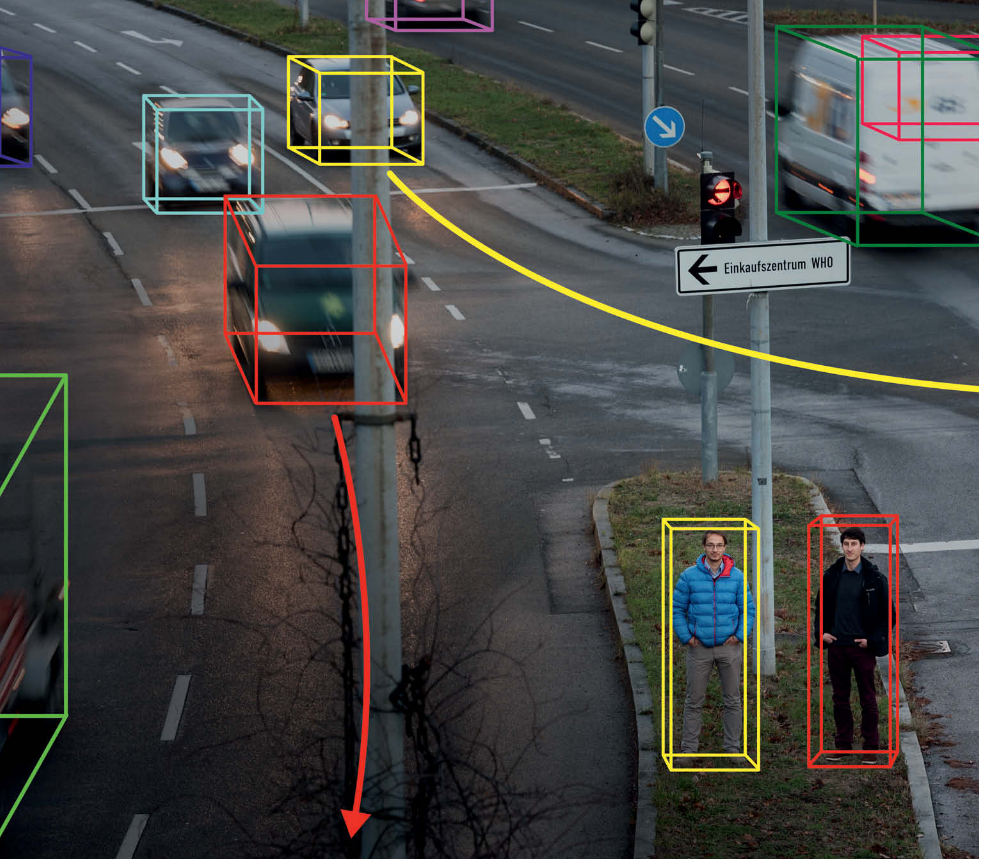

SIEMENS
Pictures of the Future
The Magazine for Research and Innovation
Dossier – Innovation at Siemens
How Innovations are generated – from initial idea to market launch.
siemens.com/pof-innovations

Photo: Boris Unger/HYDRA Institute for Marine Sciences

Naturally Fizzy Water

The water on the shores of the island of Panarea in Southern Italy may not boil, but it fizzes. Large volumes of carbon dioxide from the sea bed flow there right next to Europe's most active volcano, Stromboli. And this is precisely what makes the area very interesting for researchers from a wide range of disciplines. Carbon dioxide (CO_2) is one of the most important greenhouse gases. Since the early days of industrialization, the level of CO_2 in the atmosphere has increased continuously, particularly as a result of the intensive use of fossil fuels like coal, oil, and gas. Reducing the level of CO_2 in the atmosphere thus plays an important role in all attempts to halt or decelerate climate warming. One of the solutions under discussion is a technical one: With carbon dioxide capture and storage (CCS), the aim is to capture the CO_2 and store it away from the air in underground sites. Areas underneath the seabed would also be used to store carbon dioxide. This is already happening in some regions of Europe, for example on the Norwegian coast. But what happens if the CO_2 escapes from such storage sites? How would the high concentrations of CO_2 affect the surrounding marine ecosystems and organisms? These are precisely the questions that the scientists from the Max Planck Institute for Marine Microbiology are investigating in the sea off Panarea. Here, they can compare areas of the sea with strong carbon dioxide release and areas without degassing.

www.youtube.com/watch?v=d1L7ZO-NpHc



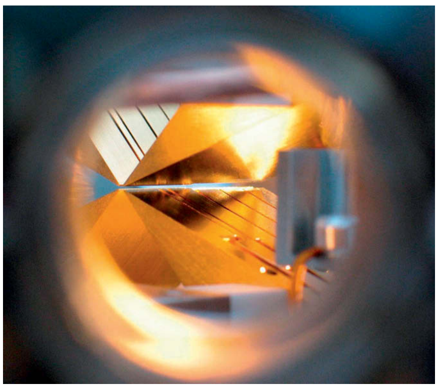
Contents

48 In use: Emmanuelle Charpentier developed a revolutionary method: CRISPR-Cas9.

18 ROBOTICS

ON THE COVER Robots are the heroes of the future. Soon we expect to see them driving cars, helping people in need of care, saving lives in disaster situations, or working as tiny helpers in the body to perform medical tasks. But science still has many hurdles to clear before all this can happen.

Cover: Wolfram Scheible; photos this page: Wolfram Scheible (large image), Hallbauer & Fioretti



SPECTRUM

BIOLOGY & MEDICINE

PHYSICS & ASTRONOMY

ENVIRONMENT & CLIMATE

CULTURE & SOCIETY

REGULAR FEATURES

Gravitational Waves

SPECIAL

Photos: MPI of Quantum Optics, Anna Schroll, Corbis (from left to right)

Teaching Machines How to Learn

Max Planck Center for Learning Systems founded jointly with ETH Zurich

Ceremonial opening: Max Planck Director Stefan Schaal, Swiss Ambassador Christine Schraner Burgener, Max Planck President Martin Stratmann, ETH President Lino Guzzella, Baden-Württemberg Minister of Economic Affairs Theresia Bauer, and Max Planck Director Bernhard Schölkopf (from left to right).

For humans and animals it comes naturally; machines, on the other hand, must acquire it: learning. The aim of the Max Planck ETH Center for Learning Systems in Tübingen, which was jointly established by the Max Planck Society and ETH Zurich, is to create the conditions necessary for this. The Center's researchers will initially investigate the principles of learning. "We first want to understand what lies behind the intelligence of living organisms, allowing them to organize perception, learning, and action, and to operate successfully in a complex environment," says Bernhard Schölkopf, Director at the Max Planck Institute for Intelligent Systems, who, together with Thomas Hofmann from ETH Zurich, will head the Center. The researchers intend to use these fundamental insights into intelligence to further develop machine learning methods.

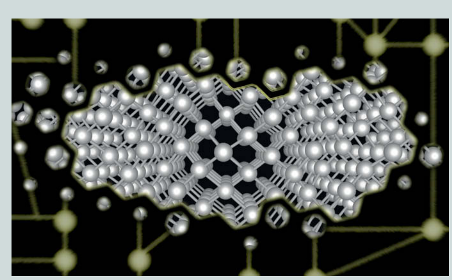
"The Center is a crucial component in the development of the research field of learning and intelligent systems in Baden-Württemberg. Through this cooperation we will ensure that European research in this field remains competitive in the global context," stressed Max Planck President Martin Stratmann at the opening of the Center in late November 2015.

Materials for the Technology of Tomorrow

European Center of Excellence supports the search for new materials

New technical developments are almost always based on better and often completely new materials. This is just as true for the next generation of smartphones as it is for catalysts for producing liquid fuels. Tracking down suitable materials for such wide-ranging applications is the aim of the European Center of Excellence for Novel Materials Discovery (NoMaD). The Center involves scientists from eight research facilities and four high-performance computer centers all over Europe. The EU has provided five million euros in funding for the Center.

"Many materials that could be of scientific and also technological interest are still completely unknown to us," says Max Planck Director Matthias Scheffler, who heads the Center. "Many fascinating characteristics of even known materials remain hidden from us." The materials and their characteristics are "calculated," meaning they initially exist only in virtual form. The cornerstone of this work is a database in which scientists provide general access to their knowledge about basic physical parameters.



Encyclopedia of materials: The Center of Excellence will document the characteristics of unknown substances and the hitherto undiscovered properties of known compounds.

Photos: Wolfram Scheible (top), Christian Carbogno/Fritz Haber Institute (bottom)

“It created peer pressure”

Bjorn Stevens, Director at the Max Planck Institute for Meteorology, on the global climate summit in Paris

Bjorn Stevens

At the UN climate conference in mid-December 2015, the 194 Parties to the United Nations Framework Convention on Climate Change approved a follow-up agreement to the Kyoto Protocol. Bjorn Stevens, Director at the Max Planck Institute for Meteorology in Hamburg, assesses the agreement and explains the tasks facing research in this area in the future.

Professor Stevens, what made the global climate summit in Paris a success?
Bjorn Stevens: I believe there are several reasons for this. Not least is the fact that we’ve been trying to explain the causes of global warming for decades, and research has provided plausible explanations for climate change. Other special circumstances also coincided in Paris. Preparations for the negotiations had begun well in advance and were very thorough, and the chief negotiators were very good. Moreover, the approach involving the nations formulating voluntary contributions rather than having emission reduction targets imposed on them from outside was a success. It created peer pressure, which wouldn’t have happened with a legislative framework. Finally, there was a very cooperative atmosphere in Paris after the devastating terrorist attacks in November.

Will this agreement put an end to climate change?
No, but I am very optimistic nevertheless. What I mean is that the agreement represents a crucial step because the world is taking resolute action to deal with a global problem of this magnitude for the first time. We’re still not on the road to limiting climate warming to a particular temperature, but we have taken the necessary steps to embark on this path.

There were lengthy debates in Paris about whether the temperature rise should be limited to 2 or 1.5 degrees. Aren’t the forecasts too uncertain to allow such precise targets?
Correct, the uncertainty factor associated with calculations for the volume of carbon dioxide that we can release into the atmosphere while ensuring that the global mean temperature doesn’t exceed one of these limits is a factor of two. And the capacity to emit twice as much carbon dioxide is really a lot. So we must observe how the climate reacts to the measures and possibly adapt them. Given that the Earth adapts slowly to change and there is extensive natural variability, this is no trivial matter.

How will climate change, which will definitely happen, impact the planet at a regional level?
A lot of questions remain open here. The most important questions for Europe may be whether the winter storms will move north or south, whether they will become stronger or weaker, or whether they will continue to follow the same patterns for a longer period. The latter is likely what led to the recent floods in the UK. Unfortunately, we still don’t understand enough about the factors on which regional changes in the climate depend.

Should future research be focused on clarifying this?
A lot of resources are currently being invested in producing forecasts for individual regions and calculations as to how a region responds when a certain volume of greenhouse gas is released into the atmosphere. However, when it comes to regional forecasts, we are living in a house of cards that can easily collapse. We are too reliant on the existing models for these kinds of calculations. We would like to believe that the models are viable, but we have little or no proof of this. So we need to take a realistic look at what we know and what we don’t know. If we’re honest, we must invest a lot more in basic research to obtain reliable regional forecasts.

What are the most important factors of uncertainty here?
Because this question touches on my own research, my view on this is somewhat biased. Nevertheless, I think most scientists would agree that we still don’t understand the role of clouds sufficiently well. How do clouds influence the speed and extent of global warming? In addition, the question has recently arisen as to how clouds affect the regional climate and its changes. Another big question is where the carbon dioxide that was absorbed on land has gone to. And whether or not the land masses will retain their enormous appetite for carbon or whether, in the worst case scenario, the carbon that has been absorbed will be released again.

Will the basic researchers have completed their work when they answer these questions?
Certainly not. In my view, the value of basic research lies elsewhere: only basic research provides real surprises. Many people don’t admit to themselves that the limits of their thinking are too narrow. When it comes to broadening our view of the world, there’s nothing more powerful than basic research. And by the surprises we encounter through it, I don’t mean that things turn out differently than we thought, but that things happen that we didn’t expect at all. The greenhouse effect of carbon dioxide wasn’t discovered because a politician said: “Take a look at what happens when we blow carbon dioxide into the atmosphere.” This role was discovered because we wanted to understand the thermal budget of the atmosphere. People were also doing research on ozone in the atmosphere long before the hole in the ozone layer was discovered. The basis for understanding how it came about had already been established. And the ozone hole might never have been discovered if someone hadn’t studied ozone in the atmosphere out of pure curiosity.

Interview: Aaron Lindner and Peter Hergersberg

Photo: David Ausserhofer for the MPI for Meteorology

A Window to the Radio Sky

Max Planck Society contributes to the MeerKAT telescope in South Africa

An ear into space: A MeerKAT radio antenna tunes into the African night sky.

It will be the biggest and most sensitive radio telescope in the southern hemisphere: in a matter of just a few years, 64 individual dish-shaped antennas with a diameter of 13.5 meters will tune into the atmosphere and examine distant X-ray bursts, pulsars, and interstellar clouds within the Milky Way with great precision. This gigantic "ear" known as the MeerKAT is being built around 90 kilometers outside the South African town of Carnarvon on the Northern Cape. There is very little terrestrial interference radiation there in the semi-desert Karoo region, which means that the system's sensitivity can be exploited to the full. One of the telescope's important receiver systems comes from the Max Planck Institute for Radio Astronomy in Bonn. The Max Planck Society is providing 11 million euros for the development and construction of the telescope.

"The MeerKAT project is a milestone in radio astronomy. The installation of this receiver system will give astronomers access to a world-class instrument," said Max Planck President Martin Stratmann at the signing of the cooperation agreement for the project. In addition to President Stratmann, the ceremony was also attended by the South African Minister for Science and Technology, Naledi Pandor.

New Impetus for Open Access

Berlin conference discusses the rededication of funds for academic journals

Open access – free access to articles published in scientific journals – is set to be advanced in a new way. The idea is for academic journals that were previously available on a subscription basis only to now be made freely accessible everywhere. To achieve this, research institutions should invest the money they currently spend on subscriptions in the publication process itself. This was the finding of an international conference that was held in Berlin and organized by the Max Planck Society. Studies carried out by the Max Planck Digital Library had shown that the conversion to open access can be achieved with existing financial resources.

To kick off the conversion process in practice, over 90 representatives of international research organizations in 19 countries came together in Berlin. In the follow-up to the conference, plans are being made to incorporate the outcome of the discussion into a declaration of intent that follows on from the "Berlin Declaration on Open Access to Knowledge in the Sciences and Humanities" of 2004. Accordingly, scientific institutions and funding bodies throughout the world will be invited to sign the expression of interest and contribute to its implementation.

Greater openness: Max Planck Director Ulrich Pöschl (right) and Gerard Meijer, President of Radboud University, organized and chaired the 12th Berlin Conference.

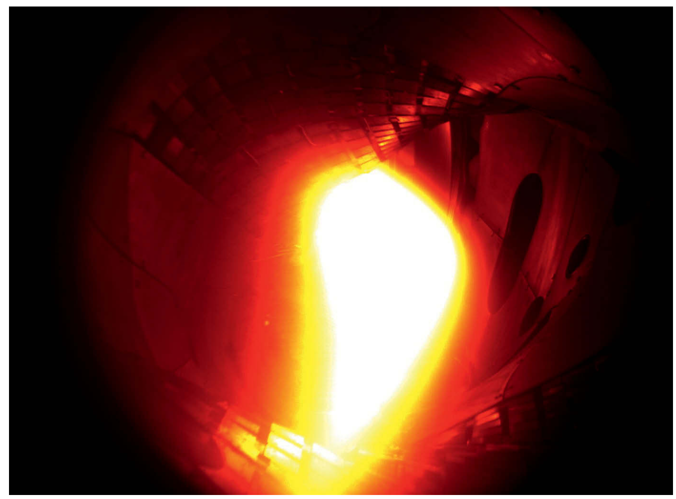
Photo montage: SKA South Africa (March 2014), Georg Botz (CC-BY-SA)

Greifswald Fusion Device Powered Up

A helium plasma was generated in the Wendelstein 7-X for the first time

The plasma researchers' patience and efforts have paid off. A good ten years after work began on the assembly of the Wendelstein 7-X fusion device at the Max Planck Institute for Plasma Research in Greifswald, physicists generated the first plasma in it in early December 2015. "We started with a plasma made from the noble gas helium because the plasma state is easier to reach with helium," explains Thomas Klinger, Director at the Max Planck Institute for Plasma Research and head of the Wendelstein 7-X project: "We won't switch to the actual research object, a hydrogen plasma, until 2016."

In the next stages of the research, the scientists aim to extend the duration of the plasma discharges and study how the helium plasmas can best be generated and heated up using microwaves. In doing this, the researchers are preparing the first experiments with hydrogen plasmas, which is ultimately intended to melt into helium in the fusion experiments. With the Wendelstein 7-X, the world's biggest stellarator-type fusion device, the scientists hope to prove that this model is suitable for use as a power plant.



Shining bright: The first plasma in the Wendelstein 7-X fusion device in Greifswald consisted of helium and reached a temperature of one million degrees Celsius.

On the Net

The Universe on Film
What do the chemical elements in our bodies have to do with the stars? What lies behind exoplanets? What are supernovas? An extraordinary film project provides answers to these fascinating questions from the field of astronomy. Scientists in Heidelberg have teamed up with colleagues from the University of Cambridge to produce seven five-minute films that explain recent discoveries about planets, stars and the Milky Way to a lay audience. Two animated films – "What are stars made of?" and "Why am I like a star?" – are particularly suitable for children of ages 6 to 12. All of the videos can be viewed online and are also available free of charge as a bilingual DVD (German/English).
www.mpia.de/entdecke-unser-universum

Oh, how lovely!
Fascinating! Moving! Thrilling! Who likes what, why and under what conditions? These are exactly the questions that scientists at the Max Planck Institute for Empirical Aesthetics in Frankfurt are seeking to answer. The newly established institute has three departments so far: one focusing on language and literature, another on music, and the third on neuroscience. The institute's website not only provides information about the research carried out there, it also gives interested readers an opportunity to participate in its research. Study participants are constantly being sought for ongoing research projects.
www.aesthetics.mpg.de/en.html

Europe-Wide Success
Each year, the European Research Council awards its Starting Grants to young scientists. Three women and seven men from Max Planck institutes were successful in the second round of applications for 2015. Each grant comes with funding of up to 1.5 million euros. The Max Planck Society was by far the most successful research organization in Germany, ahead of Ludwig-Maximilians-Universität München, which had five successful applicants, and institutes of the Helmholtz Association, with two. The French research organization Centre national de la recherche scientifique (CNRS), which had twelve successful applicants, was the only institution in all of Europe to be awarded more ERC Starting Grants than the MPG.
www.mpg.de/9809717/erc-starting-grants-2015

Photo: MPI for Plasma Physics

How Terrorists **Are Made**

Terrorist attacks like those in Paris leave us fearful and horrified, but above all, bewildered. We're unable – and usually even unwilling – to understand what motivates people to kill others indiscriminately. However, our author believes we should try to understand terrorists. Only then can we combat the causes of violence.

TEXT **GÜNTHER SCHLEE**

The French have a proverb: "*Tout comprendre c'est tout pardonner*" – "To understand everything is to forgive everything." While we hold our neighbors in the highest possible regard, it must be said here that this is a particularly dumb saying. Understanding something and forgiving it are two completely different things. Everyday life is replete with examples that confirm this. It isn't enough for an undercover agent to rationally comprehend the calculating mind of a criminal; he also needs empathy. In other words, he must be able to put himself in the criminal's shoes. He has to "understand" him in the fullest sense of the word, and yet he still hands him over to the police. Likewise, a battered child would do well to model the inner world of the violent father in its mind in order to gauge his moods and alcohol level. This is a question of survival that has nothing to do with forgiveness. The list of examples is endless. *Tout comprendre, ce n'est pas tout pardonner*.

Ever since Auschwitz, we have known that perpetrators of violence are entirely normal people in other contexts

That violent conflicts cause immeasurable suffering is indisputable. There are also measurable effects. Despite the well-founded public interest in climate-related risks, and despite the urgency of economic and currency issues, there are reasons to assume that violence is still the greatest obstacle to development and the most significant cause of suffering in the world. It destroys human potential and infrastructure, wipes out investments and leads to sensible but

War and terror are forcing the population of Somalia to find their own sources of food, such as fish (top image). In the absence of a functioning state, however, terrorists often support the people and so gain their backing. The pickup (bottom image) is bringing al-Shabaab fighters back from a refugee camp, where they distributed aid supplies.

Photo: Reuters (2)

expensive security measures and to fear-based reactions that can be very expensive without being sensible. Consider, for example, the number of road deaths, which always increases when people avoid traveling by plane for fear of terrorist attacks. So an ability to understand violence better, assess it more realistically and, if possible, recognize and forestall a potential escalation is a worthwhile goal. Nevertheless, it is clear that understanding perpetrators of violence has nothing to do with forgiving, let alone condoning, their behavior.

Understanding violence is easier said than done. In our media-saturated environment, which shapes most of us, including political decision-makers, more strongly than science, effects come to the fore that hinder an understanding of violence. One of them stems from the emotions associated with moral outrage. These often lead to a refusal to deal with a matter intellectually. The statement "I just can't understand it!" doesn't express a desire for better comprehension or understanding, but rather implies that the speaker doesn't want to understand. Another effect is pathologization. We classify a phenomenon as pathological, deviant or crazy. From a medical point of view, of course, this should pique our interest in understanding it, but few people share this medical perspective. In most cases, such statements are an expression of exclusion and a desire to distance oneself.

The Islamic Courts were a lifeline in a violence-riven economy

Take, for example, the so-called Islamic State, which currently controls large sections of Syria and Iraq and which has probably unjustifiably arrogated this name to itself, because in the opinion of many Muslims, the organization is profoundly at odds with Islamic values. Its stereotype of the enemy is that of the shameless, promiscuous, profane and capitalistic West, which in turn brands the Islamic State as barbaric and a "terrorist militia." In conflict situations, such mutual insults often reflect the truth one hundred percent, but here we aren't concerned with the inherent truth of these statements. The question, rather, is what effect these verbal exclusory statements have on our cognitive ability to explain violent conflicts in which the Islamic State is involved. My assertion is: certainly no conducive effect.

"Terrorists" are people you want to distance yourself from as much as possible: barbarity was vanquished in Germany 70 years ago, albeit with foreign help, and we want nothing more to do with it. This attitude doesn't help us find out what makes the perpetrators of violence tick – in other words, model their thoughts and actions in our minds. This strong desire to distance ourselves also ignores the thousands of people who support the Islamic State, or at least accept it as the lesser evil (no surprise, considering the available alternatives). They must be quite normal people. Incidentally, ever since Auschwitz, we have known that also the perpetrators of violence are entirely normal people in other contexts. And it ought to be possible to explain the behavior of entirely normal people. Obviously, in many cases there is no serious desire to do so.

Based on such considerations, my colleague, ethnologist Markus V. Hoehne, examined the development of another "terrorist militia," al-Shabaab, in Somalia. Al-Shabaab grew out from the militias of the Islamic Courts in Mogadishu. In the absence of a functional state, the Islamic Courts had developed as a grass-roots initiative and enjoyed widespread acceptance within the population – not because Somalia was suddenly gripped by an atypical religious zeal and moral rigor, but because business people wanted a little security for their property and their transactions and were happy to fund the courts – one of the very rare cases in the history of mankind where business people were happy to pay taxes. The Islamic

Courts were a lifeline in the violence-riven economy that had generally prevailed and in which the key players were major warlords who plundered the country and sold off communally owned assets (fishing rights, for example, and permission to dump toxic waste) to foreigners at bargain-basement prices.

The court militias were perceived as threatening by their opponents – so much so that Ethiopia, with US support, launched a military campaign against them in 2007. The Islamic Court militias then simply disappeared. They weren't created to fight against regular military units equipped with heavy weapons, so they didn't even engage the enemy. The Islamic Courts vanished with them. Only in this way could the internationally recognized government of Somalia be established in the capital of Mogadishu (internationally recognized because it was formed by a "peace process" coordinated by the "international community"). (Incidentally, the author of this paper was involved in this "peace process" as a resource person in 2002 and 2003, but not in a position in which his rather skeptical views could have major political impact.)

The "peace process" was a compromise between the warlords. The internationally recognized government was therefore a government that emerged from organized crime. (Not the first and not the last in human history. Governments that emerge from organized crime are more common than business people who happily pay their taxes.) Now the warlords were in power again, and with the blessing of the international community. Since then, troops of the African Union (AU) have also been in the country. This development led to the radicalization of some of the former Court militias, giving rise to al-Shabaab. Soon they controlled such large swaths of the country that the "legitimate" government that had been formed through the "peace process" and established in the capital with foreign help no longer dared to venture far from the capital. So the "international community" had to step in again. Kenyan troops marched into Somalia in 2011, thus strengthening the alliance between Ethiopia, the forces of the African Union, the US and the government they supported. Al-Shabaab then lost control of the cities and was increasingly restricted to conducting hit-and-run operations from the cover of the rugged terrain.

Al-Shabaab soon regained strength in the north of the country in a craggy, mountainous area on the coast bordering the Gulf of Aden, far from the battle troops in the south. Markus Hoehne has been following the development of the northern state-like formations, Somaliland and Puntland (both recent political creations that don't appear on older maps), for some years. In keeping with the standard of our discipline, he speaks the language of the country, has access to the important players and to the voice of the people who comment on their actions, undertakes careful risk assessments, organizes his security himself, and has repeatedly returned safely from regions that most people have never heard of or whose names conjure up feelings of dread. In this way, he has made a key contribution to the analysis of current conflict situations, all of which have not only global implications, but also significant local ramifications. Zinc and coltan were discovered in this coastal area. There is a strong, rapidly growing and insatiable demand in Asian economies particularly for coltan. The mining rights were quickly sold to an Australian company. The seller was the government of Puntland, a semi-autonomous entity in the northeast of the country. However, the "peace process" had just catapulted the president of Puntland to the president of the whole of Somalia. He then set out claims

The "peace process" in Somalia was a compromise between warlords

Photo: Reuters

on behalf of the Somali federal government, whose rights had not yet been defined. Nor, for that matter, had the rights of the states, whose exact number and form were also unclear. Moreover, this government initially found itself unable to move into the capital, and when it did, it hardly dared to venture out again. Nevertheless, the parties soon settled on a fifty-fifty formula. Only they had forgotten one thing: to ask the local population and allow them to share in the new-found wealth in some way. The clan that settled these coastal mountains (the Warsangeli) was smaller than the clan that prevailed in the rest of Puntland (the Majerteen), but it is part of the same confederation of clans (the Harti). Moreover, the government of Puntland believed it could rely on the brotherhood of all Harti without having to consider the specific rights of the locally ruling genealogical sub-clan (the Warsangeli).

But enough of the clan names. What's important in the present context is this: The local group that would have claimed the resources of "its" land was relatively small compared with the competing clan groups. It launched a spirited armed uprising but soon ran into trouble. It is therefore not surprising that they welcomed help from outside. The local sheikh appealed to Islamic sentiments to mobilize his followers against the infidels. The lines of the alliance that stretched from Puntland to Mogadishu and from there to Ethiopia, Kenya and the US made it expedient to portray the opponents as Islamic apostates in collusion with Christian or even godless powers. After being driven out of the south of the country, al-Shabaab fighters found rhetorical and ideological points of contact here. At some point (Hoehne describes it in more detail than we can here), al-Shabaab then evidently gained the upper hand, and the local sheikh became subservient to it.

Shifting our focus from the local clans and their alliances to the larger, global picture, we see the following: The government, which had sold off the mining rights to natural resources (without being able to guarantee the buyers access to those resources) without consulting the local population, found itself in a global economic web. Other nodes in this web were an Australian mining company and customers in Asia. These relationships were supposed to be cemented by a political-military alliance under the motto "the War on Terror," which included Ethiopia and Kenya in the immediate area and the USA further afield. Faced with this overwhelming configuration, the local population was forced to form alliances with fighters who likewise appealed to global causes: the struggle of "all Muslims" against the "decadent West." The response to large alliances is large alliances or, if these can't mature into formal institutions, at least appeals to global similarities with like-minded individuals.

Simple Somalis became opponents of the West in its "War on Terror"

Another thing we can learn from this story is how terrorists are made. There were terrorists before, too, but what we observe here is an expansion of this category. The business people of Mogadishu, who expected a little security from the Islamic Courts and supported them as the only available peacekeeping power; the inhabitants of the coastal region, who actually only wanted a share of the revenues from mining in their homeland; the simple Somalis, who felt that warlords are perhaps not the ideal officeholders for a government – they were all bundled into this category and branded opponents of the "West" in its "War on Terror."

This case history also illustrates how tightly resource-based conflicts and processes of collective identity are intertwined. Appeals were made to narrow and broad clan relationships, depending on which group of players wanted narrow or broad pop-

Photo: Reuters

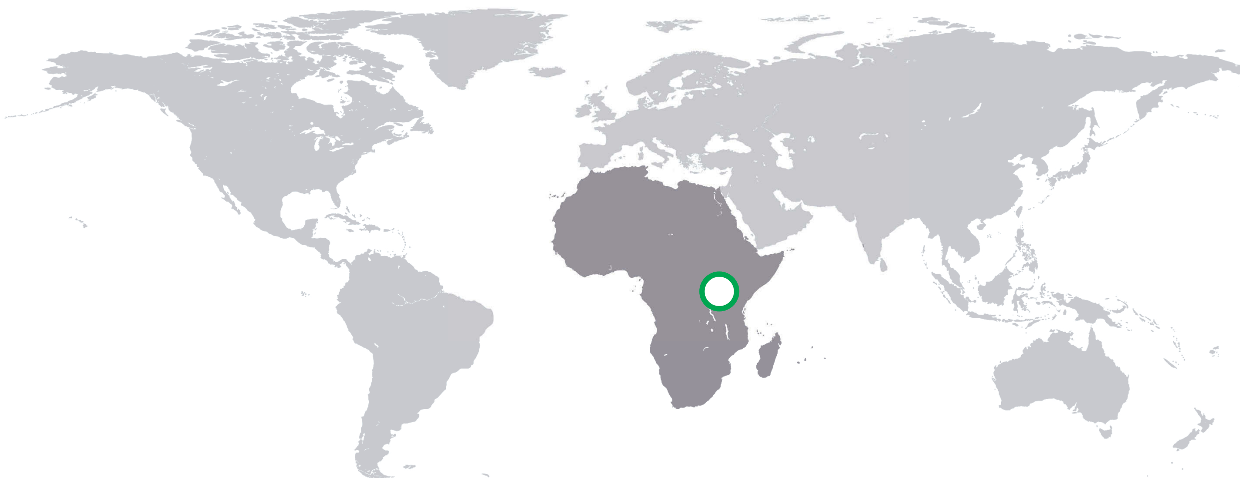
ulation segments to share in the profit from the mining of natural resources. The category "terrorist" also evolved in this context, becoming significantly broader, as did other attributions of self and others.

In general, it can be said that there are no identity-based conflicts versus resource-based conflicts. This distinction, often encountered in English usage, is nonsense, even if some abstruse theories adhere to it, arguing, for example, that identity-based conflict can be implacable while resource-based conflicts are negotiable. Whether a person sees his neighbors as members of a broad clan alliance and shares resources with them, or whether that person sees his neighbors as apostates of Islam in collusion with Christians and atheists and forms alliances against them with Islamists from other parts of the country, it is a resource-based conflict waged through identities (self-descriptions and images of the enemy) or an identity-based conflict with implications for resource distribution – take your pick. The question of identity is a question of subjects – who with whom against whom? – while the question of resources is a question of objects: Who claims what? What is at issue? Every conflict analysis must answer both questions and clarify how the two perspectives are related. ◂

THE AUTHOR

Günther Schlee is a Director at the Max Planck Institute for Social Anthropology. His research focuses on identity and difference, shifting alliances, kinship and friendship. He regularly makes extended field research trips to countries such as Kenya, Ethiopia and the Sudan. His research work is characterized by an "interethnic" approach and a combination of historical, sociological and philological methods.

Photo: Norbert Michalke



Time Flows Very Differently Here

Max Planck scientists cooperate with partners in around 120 countries around the globe. Here they relate their personal experiences and impressions. Psychologist Monika Zaba is a member of the Molecular Psychotraumatology Research Group at the Max Planck Institute of Psychiatry in Munich. As part of her doctoral studies she works in one of Uganda's largest refugee camps.

Africa has always been a dream of mine. I came to Uganda, where I feel very welcome – everybody wants to get to know you and get in touch with you. Here I can be free and feel at home at the same time. This is quite surprising considering that, in my research field, I am confronted daily with life at its cruelest – in one of Uganda's largest refugee camps. Here, more than 80,000 people who have been driven out of their homes, who fled, were mistreated and very often suffered from sickness and starvation, seek protection and a future for themselves and their families. All who come here have experienced unimaginable violence and hardship.

As part of my thesis project, I study how each individual shows different manifestations of symptoms of post-traumatic stress disorder, depression or dissociative disorders, and whether the likelihood of developing these symptoms is also apparent on a molecular level. Another question I am trying to answer is why a large number of study participants, who have all had to endure horrific events in their lives, never developed trauma symptoms.

My hope is that these results can one day be used to develop personalized treatment options for trauma patients. One of the main problems in this field is that the traditional concept of psychological disorders is heavily influenced by aspects that are specific to Western culture, where the concept was developed. As a result, there are many reasons why it can't be readily applied in other cultural contexts where people may have, for example, a different understanding of these same psychological symptoms.

In order to overcome these inadequacies in trauma research and therapy, we conduct in-depth interviews with the people living in the camp to find out more about their past and their current situation, and we also take hair and saliva samples, which are later analyzed in Germany. Our participants come from the Democratic Republic of Congo, Rwanda and Burundi and speak a wide variety of languages and dialects. That is why one of the first challenges we often face is to explain

Graphic: iStockphoto

Monika Zaba, 29, is from Poland and has been living in Germany for eight years. She completed a three-month internship in Rwanda while she was still working toward her psychology degree in Dresden. Since 2011 she has been working in the Molecular Psychotraumatology Research Group headed by Ulrike Schmidt at the Max Planck Institute of Psychiatry in Munich. Her travels to Uganda are part of a sub-project for her doctoral thesis.

– with the help of our interpreters and language mediators – to the participants how our research is intended to help trauma victims, and that taking samples is a completely pain-free procedure.

Furthermore, taking hair and saliva samples is associated with traditions rooted in superstition. Yet as soon as we explain that sampling is completely anonymous and that we send the samples to Germany, we are able to quickly dispel any worries the participants may have and gain their trust.

Shops, stores, churches, schools and bars – you could say that the refugee camp has everything you would find in any normal African city. You can tell the settlements apart, because the older ones have sturdy huts while the newer ones are still made up of tents. But the electricity supply is still not sufficient, and because our samples need to be cooled, we researchers live outside the camp. Yet many aid organizations are active on site and working tirelessly to improve the situation.

Apart from the scarcity of resources and food, another major problem for the people living here is boredom, because there isn't enough work for everyone. Most of our interpreters and language mediators are refugees themselves, providing their services in an effort to build a future for themselves and their families. Working with us is one of the very few opportunities they have to earn money in the refugee camp.

Processes of any kind take much longer over here; in fact, time flows very differently than in Europe. That is why I had to learn to adjust my research activities to the general pace of everyone around me. And sometimes I find it difficult to understand why certain things are done in a certain way. That is why it is all the more important to have a network – to get to know people who can explain to you how the world works over here, and who can introduce you to others. What's more, everyone must take good care of themselves and make sure they don't reach their breaking point.

For that very reason, our team gets together every day after the interviews to discuss and internally process what our respective participants just told us – after all, the trauma has an effect on us as well – and then we close the case and look for activities to help us unwind and distract ourselves. And I have also come to realize something else: Hey, you can achieve a lot even if you don't always give 100 percent, sometimes 60 or 70 percent is just fine. Free time is a rare and precious gift here, so when you are tired, you rest. And the first question people typically ask at the start of a conversation here is just one of the many reasons I feel so welcome in Uganda: "Did you sleep well?"

Photo: Private collection

Robots **Go to School**

As domestic help, healthcare assistants or emergency response units: robots are suitable for these jobs only if they are capable of learning and acting independently, at least to a certain extent. **Stefan Schaal** and the members of his Autonomous Motion Department at the **Max Planck Institute for Intelligent Systems** in Tübingen are teaching machines to become flexible and autonomous.

TEXT **PETER HERGERSBERG**

Truth be told, Apollo doesn't exactly look like a Greek god. With that trusting gaze coming from his big, round eyes, he's more reminiscent of Shaun the Sheep than of the immortal being who struck fear into the hearts of his foes. At best, Apollo, from the laboratory of the Max Planck Institute for Intelligent Systems, could be compared to a demigod, considering that his upper body rests on a massive column rather than on a chiseled abdomen and legs. And the feats he accomplishes are, well, really the simplest of the divine exploits: if all goes well, he can securely grasp different objects, balance a rod on his hand or even mount a wheel on an axle.

That may not sound very impressive for a god, but the Apollo stationed in the laboratory of the Max Planck Institute for Intelligent Systems in Tübingen is a robot. And for a robot, he is actually capable of performing a surprisingly wide range of tasks. Perhaps most importantly of all, he learns a lot – and he does so in a way that might one day enable him, or rather his two-legged

The Director and his student: Apollo is one of the robots that Stefan Schaal and his team are teaching to move autonomously.

Photo: Wolfram Scheible


hand
Model BH8-280
KUKA
KUKA
KUKA
KUKA

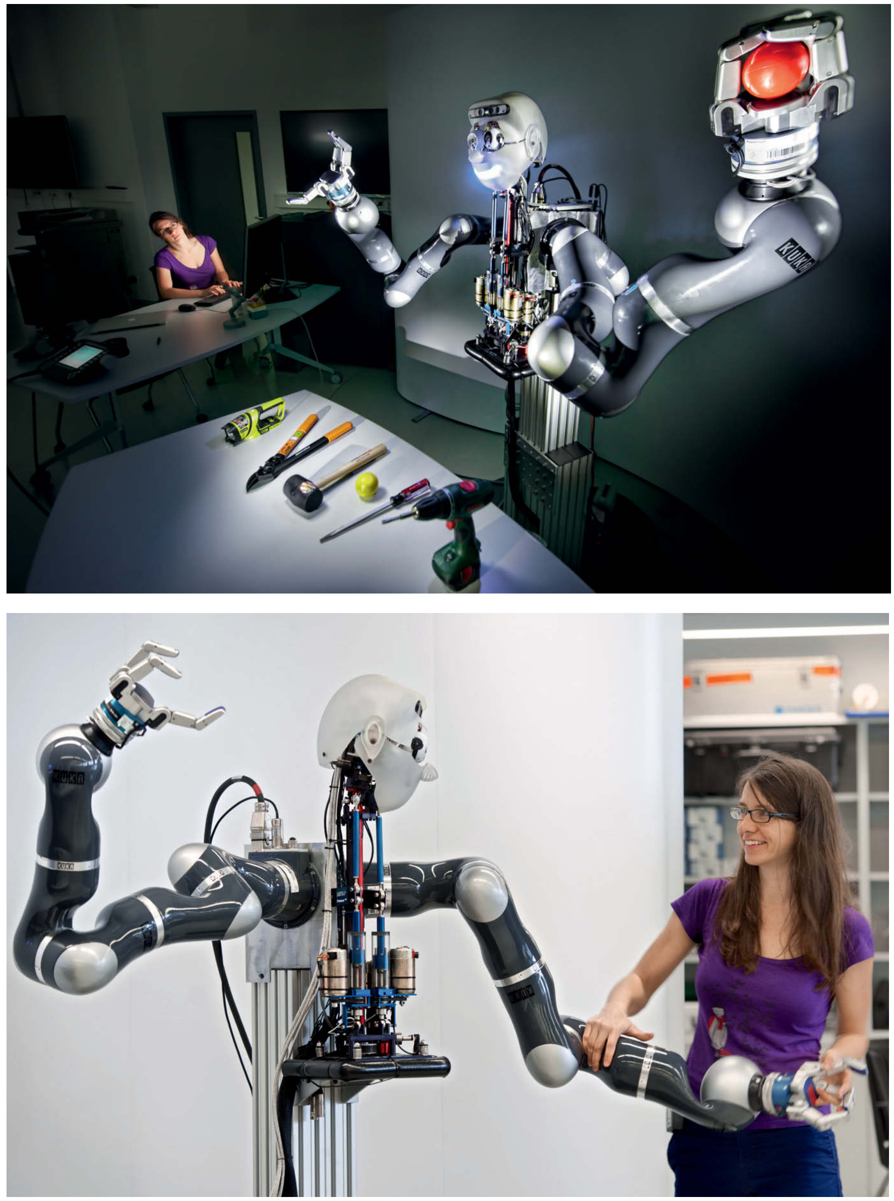
descendants, to autonomously move around in unfamiliar surroundings and independently solve difficult tasks.

Robots need to be able to learn new things if, for instance, they are to serve as emergency response units at a damaged industrial complex or rescue injured persons following an accident and are suddenly confronted with an unexpected obstacle. Also as domestic help or even as healthcare assistants, robots would need to be capable of continuously adapting to new situations and unforeseen events.

Stefan Schaal, Director at the Max Planck Institute in Tübingen, and his team have made it their mission to help these mechanically engineered beings achieve that degree of autonomy. To provide an idea of how much work still needs to be done in this field, Stefan Schaal shows some video footage taken at the Darpa Robotics Challenge. In this competition, robots must drive a golf cart and walk across sand to reach a building where they must close a valve. What we mostly see here, however, is rescue machines, accompanied by heroic-sounding music in the background, stumbling and falling down in various ways: as they get out of the golf cart, as they stagger across the sand, or as they attempt to push open the door and instead end up losing their balance and falling over.

The reason most modern-day robots falter in unknown terrain is because they have a one-track mind, in the truest sense of the word. An industrial robot that is programmed to screw doors onto a car chassis will execute that particular task perfectly – but only that one task, and only for a particular car model, at least as long as its software is not reprogrammed to carry out a new command.

And even the learning robots that already exist can only be taught one task each, for example by having a human trainer take and guide the robot's arm to help it carry out the desired motion, similar to what physiotherapists do with stroke patients in the early stages of rehabilitation. When the machine is then able to emulate a movement on its own, it receives positive or negative feedback until the robot can perform the task correctly, which it then does. But watch out if something unexpected interrupts it. "Today's robots are not robust," says Stefan Schaal. "They have a really hard time compensating for disruptions." If a robot learned to grab a hammer by the handle, for example, it would already consider it a disruption if it were handed the hammer head first.



Coming to grips with it all: Jeannette Bohg teaches Apollo to plan the right way to grasp different objects based on visual input.

"We want to achieve robustness by using various methods to introduce machine learning into the field of robotics," says Stefan Schaal, whose department focuses on perception-action-learning loops. When a machine – meaning a computer, which makes up the brain of every robot – learns something, a software program is trained to perform a particular task by feeding it large amounts of data. By using nu-

Photos: Wolfram Scheible

» It would easily take a robot an entire lifetime to gain enough experience in order for it to become fully independent of human commands or intervention.

merous photos of people taken from different angles and in a variety of settings, for example, image recognition programs can be taught to reliably recognize faces – even when the latter are partially obscured or visible only in semi-profile.

This is the principle the researchers in Tübingen have been applying at their school for robots, which they have been running for almost three years now and which Apollo also attends. Yet the school could be considered more of an experimental educational institution because, unlike regular teachers, the Tübingen-based scientists don't teach their students existing knowledge, but rather start by determining what and how robots learn best.

One of the researchers involved in machine education is Jeannette Bohg. She trains the machines' visual perception in such a way that their visual sense provides them with the information they need for planning actions in a sensible manner. One of the goals, for example, is to teach the robots to analyze an unknown setting and then quickly and reliably find objects they need to solve a particular task.

When searching for a laptop, for example, software programs will use a bottom-up approach to look for conspicuous pixel clusters, or they will analyze all objects located in a given setting. However, computing all that information takes so much time that a robot can hardly complete the task within a reasonable period.

That is why Jeannette Bohg models her teaching on the top-down search strategy that humans use: "We know exactly where to look for something and where not to look for it because we have the necessary background information," the researcher explains. "If we were looking for a laptop, for example, we would expect to find it on a table, but not on a wall." A wall is where we might expect to find a clock, which, however, a person could also be wearing around his or her wrist as a watch. Looking at a scene and narrowing down the number of locations that would be worth searching is helpful for a robot, not least because it can then approach those locations and examine them more closely – just as we humans often do.

In order to teach her mechanical students these human search techniques, Jeannette Bohg researches the best way to model this human strategy with software. She then trains the software using the tracked eye movements of 15 participants who were asked to examine 400 pictures and look for a clock or a laptop, for example. This data allows the robot to acquire the experience that teaches a human where a particular object is most likely to occur.

ROBOTS WORLDWIDE COULD SHARE THEIR KNOWLEDGE

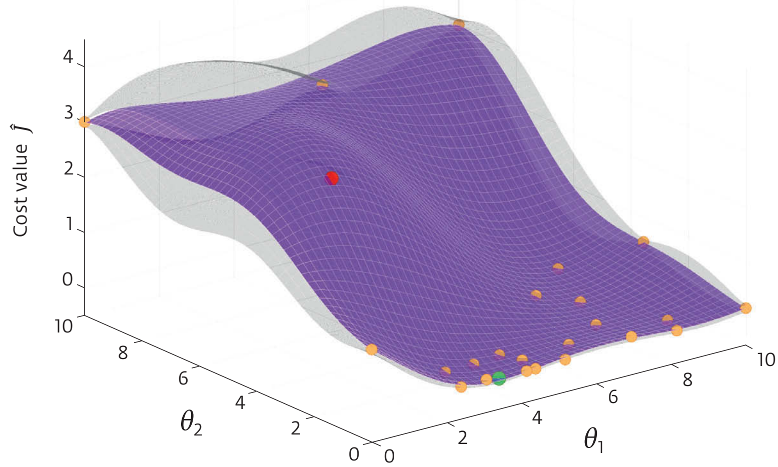
"Following the training sessions, our search algorithm is already quite good at locating clocks and laptops," says Jeannette Bohg. However, this technology is not quite as reliable at finding individual objects as methods that analyze the whole picture. "But bear in mind that, when using 400 pictures, the data set for the training is still rather limited," says Bohg.

Collecting sufficient data and drawing the right conclusion from it in order to be ready for all the contingencies of an autonomous existence is a general problem that machines face: Gaining enough useful experience to allow them to be independent of commands or interventions would easily take up a robot's entire lifetime, which is just as finite as the existence of a computer, a car or a human being. A single electronic brain would hardly be capable of processing such an enormous volume of data. "We might be able to solve this problem using cloud robotics," says Stefan Schaal. Similar to the way in which countless computers are already linked to solve large tasks, robots the world over could unite to altruistically share their knowledge – provided, of course, that their programs are compatible.

For now, each robot is left to its own devices to gather and process all the knowledge it needs to act in a halfway independent manner – for instance to correctly plan which grip to use when they see a particular object. This is another of Jeannette Bohg's areas of research.

In the past, robotics researchers programmed robots in such a way that the robot would first compute which points of an object its fingers needed to touch in order to grasp it securely. "Researchers proceeded on the assumption that the robot had internalized a detailed geometric model of both itself and the object, allowing it to compute and precisely reach the right points on the object in order to grab hold of it," explains Jeannette Bohg. The robot then used these models to plan how to grasp the object without it falling to the floor.

"But it turned out that these assumptions aren't realistic," says Jeannette Bohg. Not only because a robot's software doesn't include a model for each and every thing it could possibly grasp, but also because its controls weren't yet precise enough to reach the computed points on the object, especially since the data coming from the sensors it uses to control its movements is often incomplete and noisy. As a result, machines would often clumsily and unsuccessfully try to get hold of an object. Jeannette Bohg wants to change that, and once again her work takes its cues from humans, who are capable of reliably grasping even objects they have never seen before. >



Affordable control: The mathematical cost function describes how well a robot balances a rod; it does so particularly well when the cost value is low. The cost function depends on the parameters θ_1 and θ_2 of the feedback control algorithm the machine uses to control its movements. When Apollo balances a long rod on his hand, the controller that worked well for the short rod (red dot) proves unsuitable. With the help of a learning algorithm, Apollo then systematically tries out new controllers (yellow dots) until he finds the one best suited for solving the new task (green dot).

The computer scientist has built up a database into which she entered models of more than 700 objects – from hammer to toy doll. In order for the robot to learn how to successfully grasp these objects, she simulates countless possible gripping techniques on her computer. In the process, she also takes into account that an object's position might shift if the robot touches it with its fingertips first instead of with its palm, which might move the object as the robot tries to grasp it. That might just cause the object to slip into the robot's hand, or it might not.

The aim is that one day, based on the experience the software gains from these simulations, robots will be able to grasp not only things they were taught to recognize, but also unfamiliar objects – even if their sensors provide them with only incomplete or noisy information.

Helping robots grab hold of things is also the goal of Ludovic Righetti, a Research Group Leader at the Max Planck Institute in Tübingen. While Jeannette Bohg works on teaching robots to use visual information to develop a plan for grasping an unknown object, Ludovic Righetti and his team approach this challenge from a different angle: among other things, they teach students like Apollo to grasp objects more sensitively. The aim is for a robot hand to be able to grab hold of an object even if the hand doesn't make contact at the right points.

Such actions are regulated by a feedback control system – a computer program that creates a feedback loop between the information collected by the sensors and the motions performed by the actuators. In Apollo's case, the feeling of "I've got it" or "I didn't get it" is expressed as data measured by the force sensors in his hand. The control unit in his brain translates this data into a command directed at the actuators in his fingers. The sensors then report whether the fingers really did end up in the planned location. If not, the software corrects the robot's motions. This type of control engineering is always based on a model that expresses the design of a robot and the interaction between its control unit and actuators as mathematical formulas.

FEEDBACK CONTROL SOFTWARE LEARNS INDEPENDENTLY

Developing the correct model for a tin man or woman is in fact a highly complex affair: "The physics of a robot are extremely nonlinear," says Stefan Schaal. In other words, small deviations from the model's assumptions, for example with regard to sensor sensitivity or actuator force, can have dire consequences. The robot might go completely haywire; in any case, it won't do what it is supposed to do. The main reason is because a full-body robot has around 40 degrees of freedom: it can move its various limbs with the help of 40 independent joints.

But the actual problem doesn't even lie in the physical model on which the robot's controls are based; the model can be controlled despite any adverse circumstances. "I can develop a good model of my robot, but not of unfamiliar surroundings," explains Schaal.

That's why part of Righetti's team is using machine learning to teach robots to develop a more flexible model for solving a particular task, such as grabbing hold of a cup. "This way, the robot learns how an action is supposed to feel at any given point in time – that is, what the force sensors in its wrists, the haptic sensors in its fingers, and the camera eyes are supposed to be registering," says Righetti. "This is a relatively simple form of learning." If the grip turns out to be wrong, Apollo and his fellow students can correct it using their adaptive controls. "Ultimately, we hope to develop more general models that can be applied for a wide range of tasks."

The approach used by Righetti's team involves models that know, or at least should know, which actuator force leads to which movement. The researchers then control the exerted force

Graphic: Alonso Marco/MPI for Intelligent Systems

» Robotics must not follow just one single path when developing autonomous machines designed to serve as household assistants or emergency response units.

and thus the actions performed by the machine. Most robotics scientists, in contrast, currently employ control systems whose commands explicitly specify which position a robot's hand or foot is supposed to assume.

While this might sound like a mere technical detail, it impacts the overall implementation: if control systems measure their success in terms of whether or not a hand reached its target position, for example, the hand won't let anything – not even a human – stop it from carrying out its orders. If need be, the robot will apply even more force to assert itself. In the case of industrial robots, which typically use particularly high levels of force, this could lead to serious accidents.

If, however, the exerted force is regulated, the machine can be programmed to be more sensitive – an indispensable prerequisite for interacting with humans. "Our force-controlled robots are able to act in a much more compliant manner without compromising their precision, because we use controllers that are robust to imprecise models," says Righetti. "This approach opens up a range of new possibilities and is sure to become more widely adopted in the future."

Another researcher working on improving feedback control in robots with the help of machine learning is Sebastian Trimpe. You could say he develops the class materials that help robots learn how to balance a rod, for example, much like children learn to balance a stick on just one finger. "That is a relatively simple task," says Trimpe. "But once we understand how a robot best learns how to solve it, we may also be able to teach it to learn more sophisticated skills." For instance, standing and walking on unfamiliar and uneven terrain.

ROBOT CURIOSITY IS GUIDED BY METHODS OF PROOF

Apollo can balance a rod thanks to his internal feedback control algorithm, which analyzes the sensor information that indicates the rod's current position and movement, and translates this data into control signals directed at the actuators. So if the rod is about to tilt to the right, for example, the controller intervenes and corrects Apollo's movement to prevent the rod from tipping over.

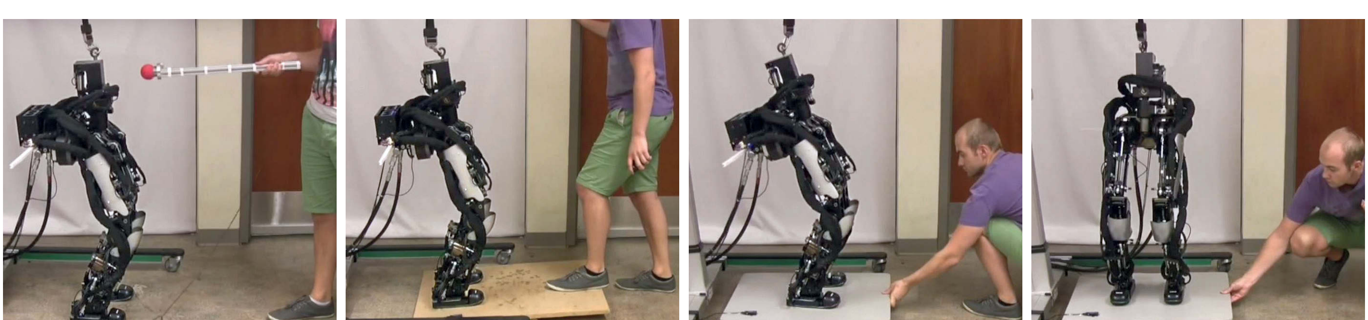
In fact, Apollo's teacher even makes the task a bit more challenging by having him first balance a shorter rod. It's more difficult to balance a shorter rod than a longer one, because the short rod has less inertia and is therefore more likely to tip over sooner, making quick corrective action necessary. But Apollo balances the short rod with ease, even though his first attempts at doing the same with the longer rod fail miserably.

Sebastian Trimpe isn't surprised by the unsuccessful attempt: The corrective action needed depends on the length of the rod, which the controller takes into account. However, the researchers hadn't yet adjusted the control algorithm when they handed Apollo the longer rod. This means the feedback control that worked fine for the short rod fails for the long rod, as it causes Apollo to move his arm much too abruptly.

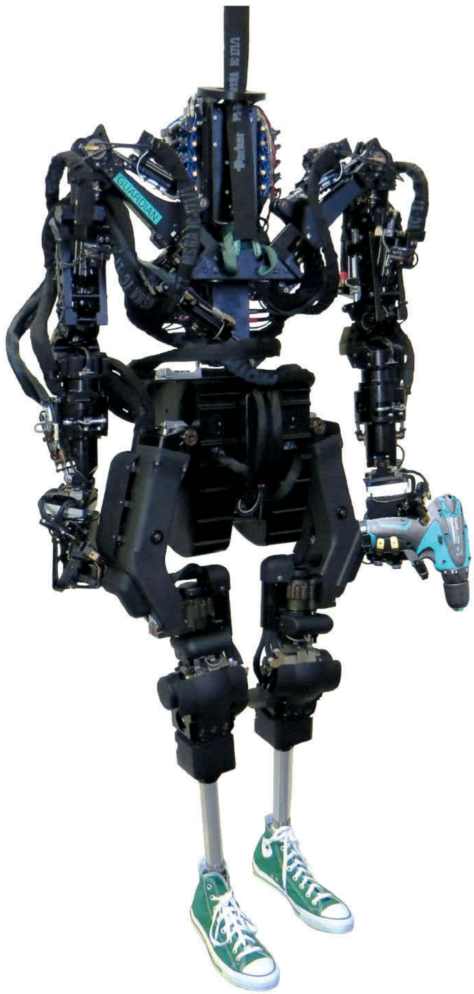
"Instead of programming a new algorithm for each new rod, we adjusted the control software to allow it to learn independently," says Sebastian Trimpe. With the help of machine learning, the robot can therefore autonomously adapt to a new situation without this being preprogrammed into its system. In control engineering, a domain of classical engineering, this is a relatively new approach.

Furthermore, the researchers have programmed instructions that train Apollo to independently learn the best controller in as few attempts as possible. "The algorithm automatically suggests the controller that offers the great-

A sure footing: Ludovic Righetti's team has optimized Hermes' controls so that the robot quickly corrects its posture when it has lost its balance. This prevents the robot from falling down even if it is pushed or is standing on shaky ground.



Film stills: MPI for Intelligent Systems



A Goddess in Chucks: Athena uses hydraulics to move her limbs when handling a tool or walking. She may not have a head, but she's wearing trendy sneakers.

est learning effect," explains Trimpe. In the early stages of the learning process, these could be controllers that differ significantly from the original controller. That's why Apollo's second and third attempts at balancing the rod appear even clumsier than the first, which doesn't faze the robot. After that, however, the learning curve rises steeply.

"In contrast to typical machine learning applications, such as image recognition, for example, learning in robotics is a dynamic problem," says Trimpe. The data set the software uses to recognize faces doesn't change. A robot, on the other hand, constantly gathers new information and gains new experience as it moves through and interacts with the world around it. That's why learning should be a lifelong process for a robot. Yet that very goal puts it in a predicament time and again.

"In order to learn new things or improve, the robot must try out new behaviors," says Trimpe. That can also mean that it performs more poorly for a period of time. To prevent the robot from getting up to nonsense or even becoming damaged in the event of a fall, the researchers must integrate guarantees into the learning algorithm. Using mathematical proof techniques, they guide the robot's curiosity to ensure that the behavior it learns is not only flexible, but also sensible and robust.

In an effort to make a robot's controls more robust, meaning less prone to failure, Ludovic Righetti focuses on more than just the machines' ability to learn. His work is a prime example of modern robotics not pursuing just one single path in developing machines that could one day serve as domestic help or emergency response units.

POSTURE CORRECTED IN JUST A FEW MILLISECONDS

"We want to take the approach in which a robot develops models based on experience, and combine it with a different control engineering approach," says Righetti. He and his team program the flexibility needed to quickly correct the robot's posture directly into the algorithms of the control unit that creates the feedback loop between the sensor data and the commands for the actuators. Whether or not this results in a sensible action, such as grabbing hold of a cup or balancing on shaky ground, can, from a control engineering point of view, be formulated as a mathematical optimization problem, the solution to which identifies the most suitable controller for the particular task at hand.

A controller can often be optimized before the robot is put into operation. When that is not the case due to unforeseen circumstances – for example, if the robot trips or is pushed – the controller must be improved mid-action, for example while the robot is walking. "We have developed strong algorithms for this purpose," says Ludovic Righetti.

Not only do the methods reliably compute how the controller must be adjusted to accommodate for unexpected events, but the software is also very fast – an absolute must, especially if the robot is to walk across uneven terrain. "In that type of situation, the robot has only a few milliseconds to correct its posture once it starts losing its balance," says Ludovic Righetti. If the robot fails to do so, it will fall to the ground.

Righetti and his team use Hermes as proof of how well a machine is capable of using its control system to maintain its balance. In a way, Hermes is Apollo's counterpart, as he consists of only a lower body and two legs. And there is a good reason why he has only two legs: while a robot does in fact have a more secure footing with four or more legs or even wheels, there are many obstacles that it can overcome only by climbing over them using two legs and two arms.

Stefan Schaal and Ludovic Righetti experiment with the two-legged Hermes at the University of Southern California, where they both conducted research before joining the Max Planck Institute in Tübingen. When the researchers throw Hermes out of balance by pushing him, for example, he corrects his posture using distinctly human-like movements.

The new control system is catching on: "The same techniques are now being used with many robots," says Righetti. The mechanism will also help the newest addition to the Tübingen-based institute's Mount Olympus maintain her balance: Athena, the first robot to fly from the US to Germany while sitting in a normal passenger seat. She,

Photo: Sarcos Corp.

Robotics necessitates mathematics: Ludovic Righetti (left) and Sebastian Trimpe discuss the control algorithms that help Apollo and his fellow students learn to act autonomously and flexibly.

too, doesn't quite live up to the expectations associated with the goddess after whom she was named. Her bulky torso, strong arms, hydraulics tubes and machine head, which she doesn't even always wear, make her about as graceful as a transformer. But at least she has both arms and legs.

The research conducted by Ludovic Righetti and his team will now focus on identifying the best way for Athena to coordinate her limbs while attempting to solve several tasks simultaneously. They also seek to answer the question as to how she sets the right priorities when trying to grasp an object while walking or standing on uneven ground. After all, the machine initially doesn't know that it's more important to stay upright than to unconditionally try to grab the object in front of it. A robotic assistant is suitable for day-to-day tasks only if it is capable of making sensible decisions.

It will take some time before robots are independent enough to be able, for instance, to help people in need, as the field of robotics still needs to make significant adjustments to many points in the perception-learning-action loop. That's why Stefan Schaal doesn't believe that, 30 years from now, we will be cared for by beings made of tin, plastic and electronic components – not only owing to technological issues, but also because of society's possible reluctance to accept it. "But I hope I live to see the day when robots help us with our domestic chores, even if only by picking up a book when told to do so because we can't bend down anymore," says the scientist. ◀

TO THE POINT

- **Modern-day robots aren't yet capable of flexibly adapting to new tasks and unexpected situations. Moreover, they are prone to error.**
- **Using machine learning and other methods, Max Planck researchers in Tübingen aim to teach robots to perform such tasks as quickly and reliably finding objects in unfamiliar settings, securely grasping previously unknown objects and independently learning the most suitable control system for solving new tasks.**
- **In order to help robots gain a surer footing and a more stable gait, the researchers also program the controls in such a way that the machines continuously optimize their actions and thus react to disruptions or unforeseen events.**

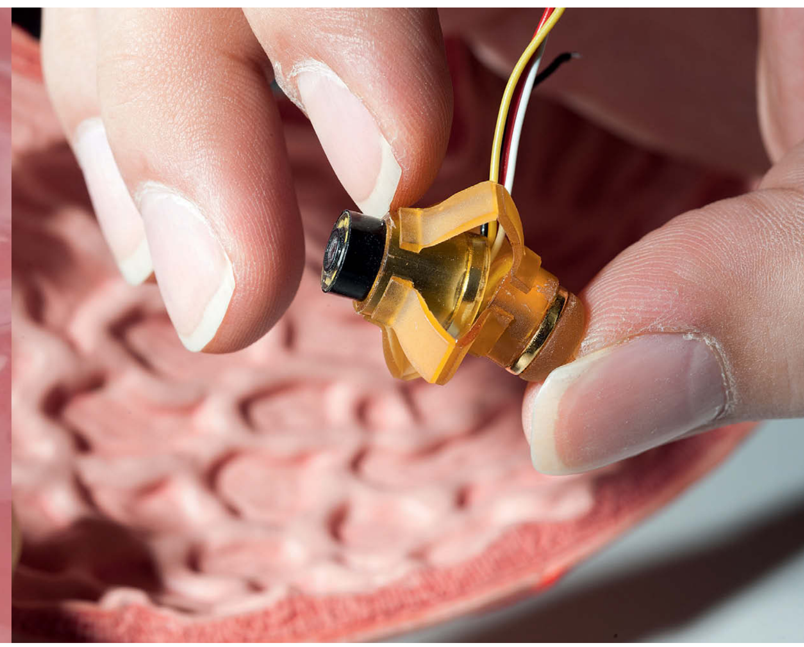
GLOSSARY

Machine learning: Using large amounts of data, a software program learns examples of a particular type of task and can subsequently carry out this task in a general manner. A large number of pictures in which faces are specially indicated, for example, tell a software program which features are essential for facial recognition. The program is then able to identify faces on pictures it has never seen before.

Feedback control: When a machine uses data collected by sensors to issue a command for a certain action to be performed, and when it uses this sensor data to monitor the execution of the command and, if necessary, correct the action being carried out, this is known as a feedback control system. Open-loop control systems don't include this feedback function.

Photo: Claudia Däfler/MPI for Intelligent Systems

Diagnostics with a Stomach Pill



Gastroscopy usually requires patients to swallow an endoscope tube. Although camera-carrying capsules are also suitable for the task, it is still not possible to control them. Scientists at the **Max Planck Institute for Intelligent Systems** in Stuttgart plan to change all that. And their tiny capsule-shaped robots can do a lot more than merely take snapshots of the stomach's interior.

TEXT **TIM SCHRÖDER**

Photos: MPI for Intelligent Systems (left), Tom Pingel (right)

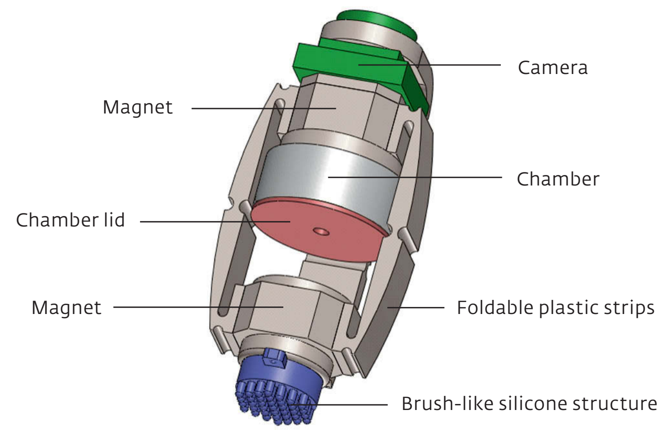
Left to right The MASCE capsule endoscope that Max Planck researchers in Stuttgart are developing is 24 millimeters long. It can be flattened so that it's unable to leave the stomach. MASCE is guided through the stomach with the help of a magnet, as demonstrated here by Donghoon Son.

Photos: Tom Pingel (2)

Gastroscopy is an unpleasant procedure. Anyone who has had to undergo diagnostic gastroscopy because of persistent abdominal pain will know how strange it feels to swallow a long tube. The tube, called a gastroscope, contains a fiber-optic cable that transmits images from a camera at the tip of the tube to a monitor outside the body. Gastroscopy today is a routine procedure. Doctors use it to search for inflammation or tumors in the stomach and duodenum. For patients, it is always a cause of distress.

For the past ten years or so, doctors have therefore resorted to a small high-tech alternative in individual cases – capsule endoscopes: miniature cameras the size of a lozenge. Patients only need to swallow the capsule to launch it on a journey through the gastrointestinal tract, during which the camera snaps hundreds of photos, which it transmits wirelessly to a storage device that the patient attaches to his or her belt for a few hours.

Doctors use capsule endoscopy when blood occurs in a patient's stool and the wound can't be located by gastroscopy or colonoscopy. In such cases, the bleeding source is often in the small intestine, which can't be reached from outside the body. Capsule endoscopy is ideal for examinations in the narrow confines of the small intestine. However, in the relatively large stomach or colon, it is a matter of luck wheth-



Above MASCE is fitted with a camera (green). Two magnets, one at either end, help to guide the capsule endoscope and also to open the lid (red) of the chamber in which drugs or micro-grippers are transported. The latter can be used to take tissue samples. A brush-like silicone structure (blue), to which the micro-grippers stick, collects the samples.

Right-hand page Metin Sitti heads the Department of Physical Intelligence at the Max Planck Institute for Intelligent Systems in Stuttgart. He is developing robots whose abilities reside in their construction or material.

er the diseased tissue actually falls in the camera's field of view. Moreover, the images tend to be blurred in those organs, as the distance from the capsule to the wall of the organ changes constantly, and are only coincidentally in focus. The problems arise because, unlike a camera at the tip of a conventional endoscope, capsule endoscopes can't be controlled from outside.

For some time now, scientists have therefore been working on capsules that patients can swallow like pills. Such capsules should be guidable, making them suitable for investigations of the stomach and colon. Within the framework of an EU project that ended four years ago, experts at a number of companies and scientific institutions developed a robot capsule that moves through the stomach and intestine like an insect on tiny legs. However, the crawling movement consumed so much power that the robot's on-board energy supply was soon depleted.

Other research teams therefore prefer robot capsules containing magnetic particles or components that allow them to be controlled by magnetic fields outside the body. As the magnetic field moves, the round capsule follows the magnetic field, rolling slowly along in the stomach. As tests in the lab have shown, this mode of locomotion works very well.

Metin Sitti is also developing capsule robots that can be controlled by means of external magnetic fields. He calls them millibots. Measuring only a few millimeters in length, they are initially being optimized for exploring the stomach. Doctoral student Donghoon Son and other members of Sitti's team have guided the millibots, which are in the shape of drug capsules, through artificial silicone stomachs and real pig's stomachs for many hours.

ABILITIES INHERENT IN THE CONSTRUCTION OR MATERIAL

Getting such machines to move about is one of Metin Sitti's fields of expertise. He has developed long-legged robots that glide across the surface of puddles like pond skaters, and flying machines that flutter about like butterflies. For many years he taught mechanical engineering at Carnegie Mellon University in Pittsburgh, and for the past year he has headed the new Department of Physical Intelligence at the Max Planck Institute for Intelligent Systems in Stuttgart.

Physical intelligence – the term initially sounds like an oxymoron, because a robot's mind is usually thought to reside in its software. "Physical intelligence means that a machine's intelligence or abilities reside primarily in its construction or material – not just in its control system," explains Metin Sitti; for example the pond skater, which distributes its weight through its long legs in such a way that it floats on water, using surface tension to support it.

Sitti and his coworkers are extremely creative in finding new materials to make their robots better adapted for specific applications than would be possible with conventional robots composed of steel, plastic and electronic components. Their millibot capsules are a prime example. Unlike conventional capsule endoscopes, they don't have a hard shell. Instead, the 24-millimeter-long devices are held together by strips of soft polyurethane plastic, a material that is used in a similar form for the soles of running shoes. The capsules, which are egg-shaped like rugby balls, are fitted with small magnets at the top and bottom.

Graphic: MPI for Intelligent Systems

Photo: Tom Pingel

Thanks to their flexible shell, the small rubber capsules have the unusual ability to contract. Each polyurethane strip has a fold running across its width, so that an external magnetic field can cause the strips to fold together, flattening the capsule. To this end, an external magnetic field first pulls the capsule against the stomach wall in an upright position. When the researchers increase the strength of the magnetic field, this causes the capsule's internal magnets to move toward each other.

Because the material is elastic, as soon as the magnetic field decreases, the polyurethane strips return to their original shape, and the millibots regain their capsular form. Sitti calls the tiny machines MASCE, short for magnetically actuated soft capsule endoscopes.

A robot that can be squashed like a rubber ball doesn't sound very high tech. But the deformable millibots are special. Capsule endoscopes can usually only roll sideways or tumble while taking photos. Due to their deformability, however, they are in command of a very different kind of movement, which gives them completely new abilities.

Metin Sitti and his colleagues have developed a tiny chamber that opens when MASCE is compressed in a magnetic field – and closes again when the magnetic field diminishes. In the laboratory, the researchers have thereby been able to release tiny amounts of ink, spurt for spurt.

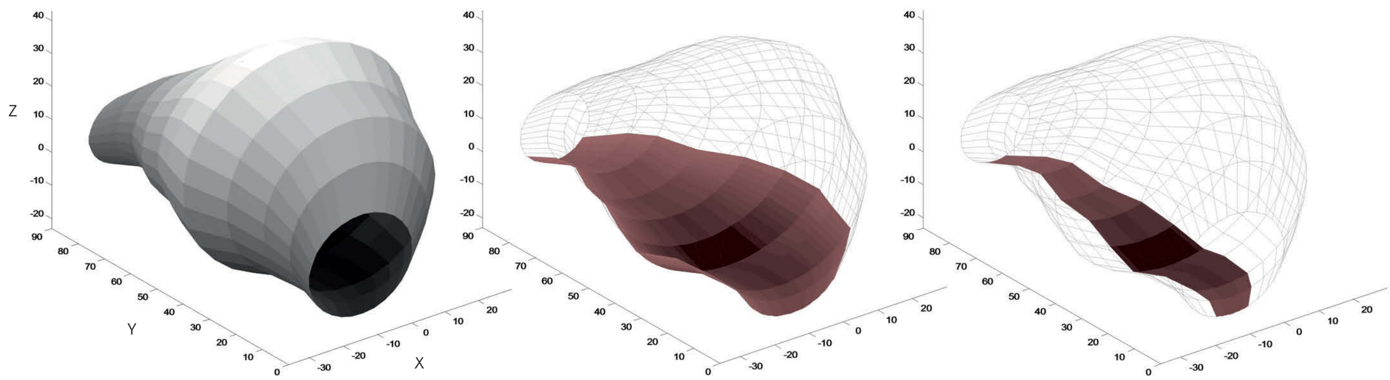
MASCE RELEASES SMALL AMOUNTS OF ACTIVE SUBSTANCES

"We imagine that in the future doctors will be able to release small quantities of drugs, for example to target inflammation or individual tumors," says Sitti. Many people, especially elderly patients, don't tolerate medicines when they swallow them.

"MASCE can release small quantities of drugs directly at the desired site in a much more targeted manner," Sitti says. This would reduce stress to the patient. It is even conceivable for MASCE to dwell in the stomach for several days in order to treat an inflammation or a tumor over an extended period.

Normally, objects pass through the outlet of the stomach, the pylorus, into the duodenum after a short time. The MASCE capsule would be no different. In order for it to release drugs to target an inflammation or tumor for an extended period, the researchers have therefore developed a second type of egg-shaped capsule that can be compressed into a thick disc-like shape by an external magnetic field. It then keeps that shape until the magnetic field is switched off. The capsule can thus remain in the stomach for several days. This MASCE variant contains namely two magnets – one at either end of its longitudinal axis – whose strength is not normally sufficient to compress the capsule. However, an external magnet can move the magnets toward each other so that their attractive force is sufficiently strong without help from outside.

Conversely, as soon as the treatment is completed, an external magnetic field can weaken the attractive force between



the capsule magnets. The capsule then snaps back to its original shape and is able to pass through the pylorus.

Together with the research group headed by materials scientist David Gracias of Johns Hopkins University in Baltimore, Sitti has integrated another important function in the MASCE millibot – the ability to perform biopsies. Doctors usually take samples of the mucosa during gastroscopy in order to examine suspected tissue for inflammation or cancer in the lab. To do so, the doctor pushes a kind of wire with small forceps into the gastroscope.

MICRO BIOPSY GRIPPERS BITE INTO TISSUE

Until now, capsule endoscopes have not been able to remove tissue samples. By contrast, the MASCE millibot can. Together with David Gracias, Metin Sitti had the idea of equipping MASCE with tiny grippers only a few micrometers in width. These micro-grippers resemble small stars whose points draw together like claws and bite into surrounding tissue when they warm up to body temperature. The prongs consist of a metallic layer and a polymer layer that expand at different rates as the temperature rises, causing the prongs to bend.

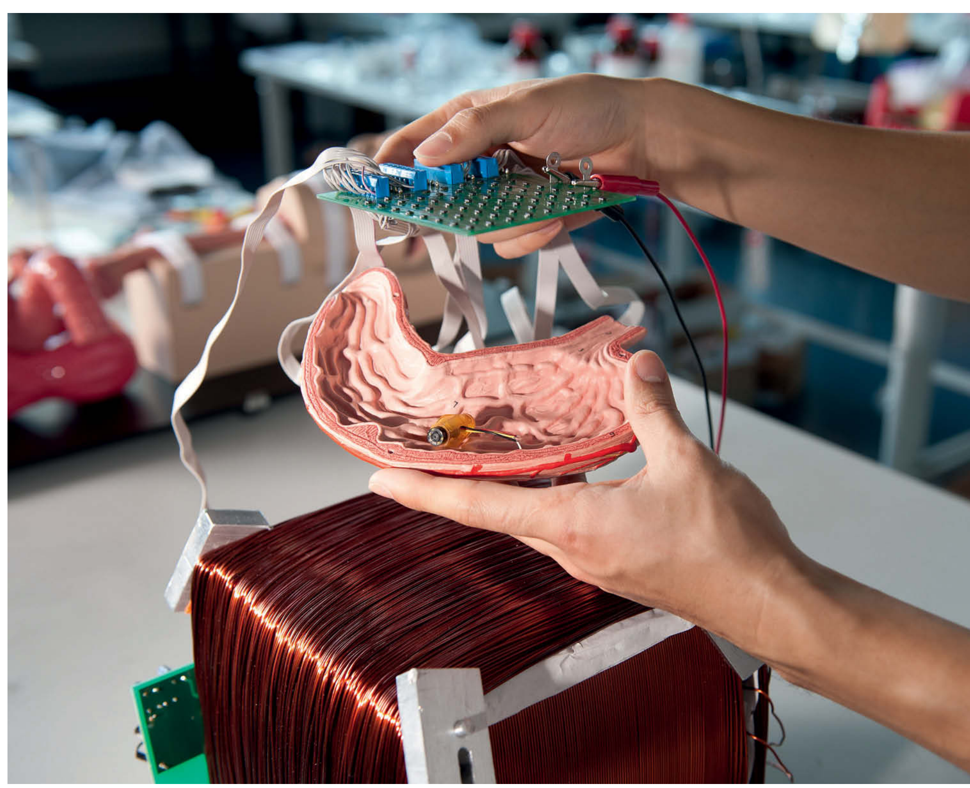
The skill lies in triggering the minuscule grippers at the right place, for example not until the capsule reaches the stomach. A biopsy experiment

Above Regardless of the patient's position, a capsule endoscope only reaches part of the stomach. The size of the working space (middle and right) depends on the ratio between the capsule weight and the strength of the guiding magnetic field. For the entire organ to be examined, the patient has to change position several times.

Below MASCE is controlled by means of a copper wire coil that generates a magnetic field. The magnetic particles of a sensor, visible as metallic dots on the green plate, determine its position and orientation.

Right-hand page To reconstruct the spatial structure of the stomach wall, Mehmet Turan (right) guides a stereo camera with a tube through the stomach model. Meanwhile, Donghoon Son (left) checks the quality of the resulting 3D image.

Graphic: IEEE Transactions on Robotics, vol. 28, no. 1, February 2012; photo: Tom Pingel



proved successful. Metin Sitti filled the small chamber of the MASCE with micro-grippers and positioned it with the help of a magnetic field on a piece of pig's stomach. When the capsule was compressed in the magnetic field, the micro-grippers fluttered down onto the tissue. When the researchers increased the temperature, the micro-grippers snapped shut.

"For a while, we wondered how we could collect the micro-grippers again. Finally, we happened on the idea of coating one end of the MASCE capsule with a brush-like silicone structure to capture the micro-grippers," Sitti explains. That, too, proved successful in experiments. The researchers manipulated MASCE into an upright position in a magnetic field and pressed the capsule endoscope, together with its silicone brush, firmly against the tissue. Some of the micro-grippers were indeed caught in the silicone and were then transported away with MASCE. Of course, Sitti admits, a micro-gripper can only collect a small amount of tissue. However, he believes the quantity is sufficient for laboratory analyses.

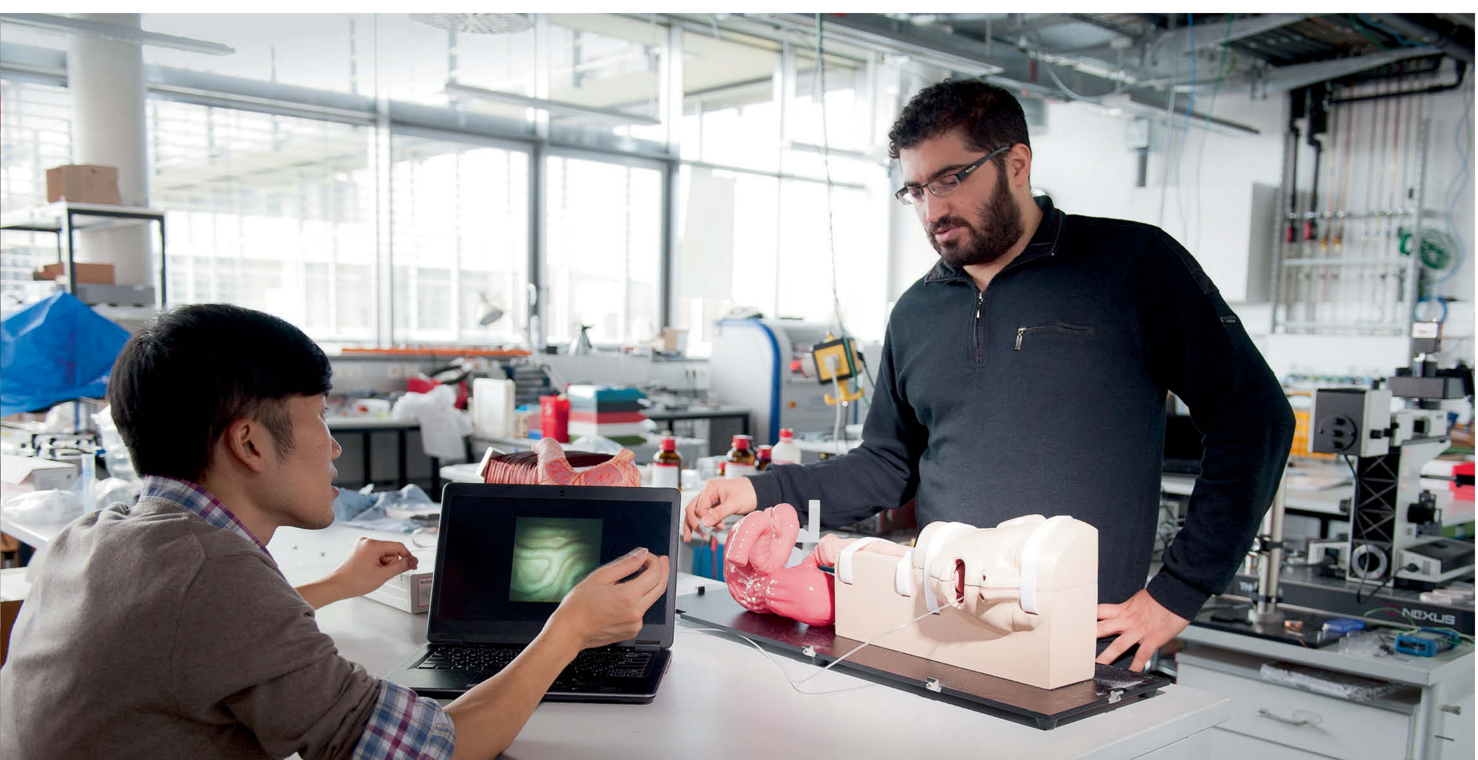
Metin Sitti can also imagine using the micro-grippers in the colon in the future. The problem is that they would have already snapped closed before reaching the colon, having travelled through the body for several hours. However, they could be heated by means of an external magnetic field, Sitti says – similar to the way in which a pot is heated on an induction cooker.

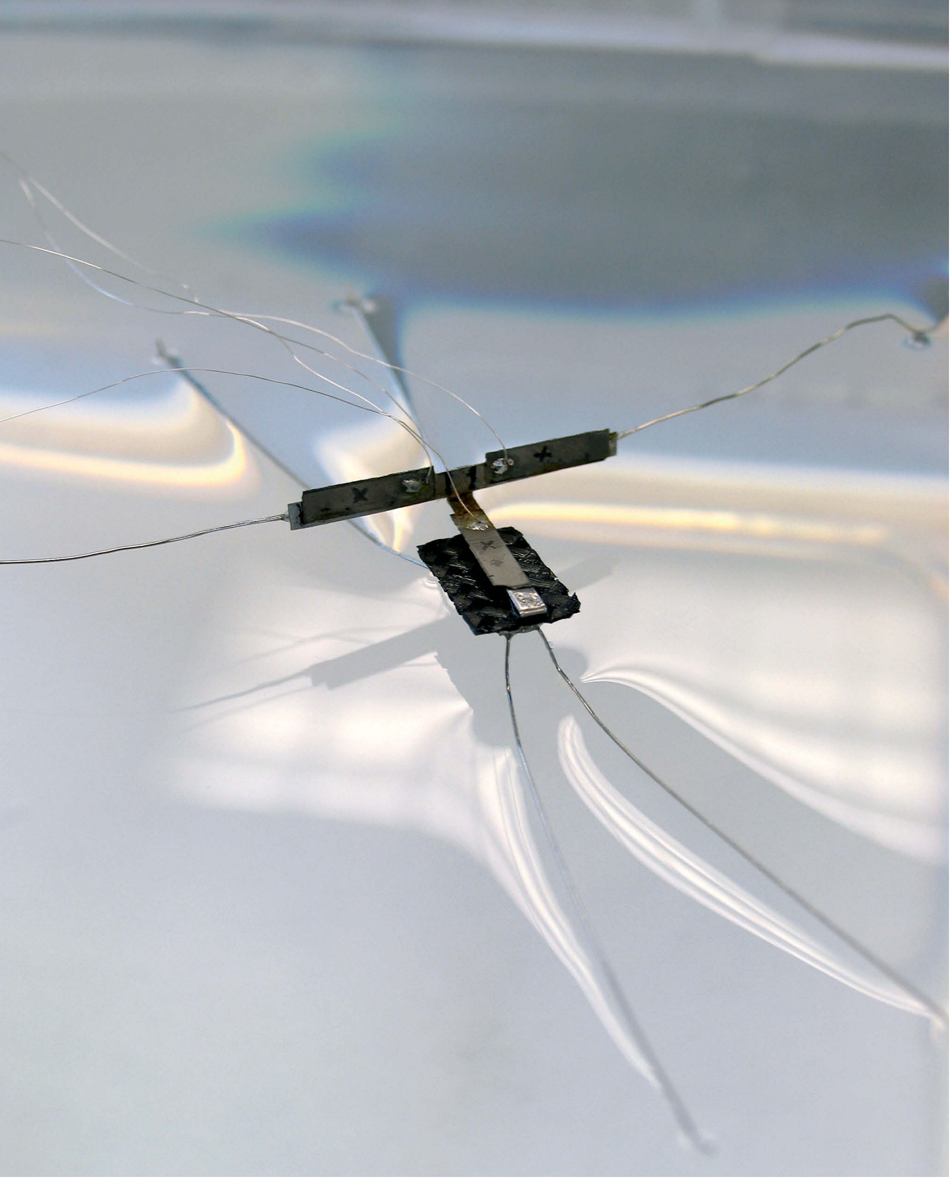
MASCE is still not refined enough for use in patients, but Metin Sitti has already shown that the intelligent polyurethane capsule endoscopes can do a lot more than their conventional precursors, which can only take photographs. Nevertheless, several challenges remain.

Later use in patients presupposes the ability to position MASCE with pinpoint accuracy. To do so, it must be possible to move the magnetic field and the capsule it controls very precisely. The future user must also be able to tell from the camera image which part of the stomach is actually being viewed. Today, a doctor using a conventional gastroscope navigates by rotating the camera at the end of the long tube back and forth.

But how can you know what a capsule is viewing as it tumbles through the stomach? "Ultimately, we want to develop a system that a doctor can use

Photo: Tom Pingel





The capsule endoscope is just one example of how the Stuttgart-based Max Planck researchers use design and material properties to impart abilities to a robot. Guided by these principles, they have also developed an artificial pond skater.

in real time to view the stomach or other parts of the gastrointestinal tract, as with a conventional gastroscope," says Mehmet Turan, a doctoral student in Sitti's department who is in charge of analyzing the images from MASCE.

The image quality, however, is still too poor to achieve that: the small MASCE camera has a resolution of only 250 x 250 pixels, and many of the images it produces are blurred. The problem is compounded by reflections from the moist, shiny mucosa, which disrupts the image, and the peristaltic movements of the stomach.

Mehmet Turan's task is to overcome MASCE's weaknesses. Turan studied electrical engineering and computer science and is an expert in computer vision. He is currently concerned with the question of how robots are able to perceive and analyze their environment – and especially how even poor images can be utilized with the help of computers. "I'm trying to solve the problem by having the computer analyze and merge many individual images, or frames. In this way, we can overcome weaknesses in an image by means of information contained in other images."

A PRECISE 3D MAP OF THE INTERIOR OF THE STOMACH

Mehmet Turan's ultimate future goal is to produce a precise 3D map of the interior of the stomach for every patient, allowing doctors to use MASCE to navigate accurately. The map should resolve structures smaller than one millimeter. Tumors and inflamed areas should also be clearly distinguishable. "To target tumors with drugs using a capsule endoscope, doctors must know precisely where the diseased tissue is located. This is only possible if we coordinate the magnetic field control with the image produced by MASCE," says Turan.

The researcher's task is difficult, not least because the gastric mucosa looks the same everywhere. "When a machine views a landscape, there are clear objects or structures it can use for orientation. There are no such landmarks in the stomach." Turan is therefore trying to extract landmarks from multiple frames to help the computer orient itself. Experts speak of distinguishable features, or corners. In the stomach, these can be particularly prominent folds in the mucosa or blood vessels.

Another advantage of such landmarks is that the computer is able to fix a position more quickly. That's important if the images are to be analyzed and relayed later in real time. A major challenge is estimating depth. As is generally known, animals have two eyes because stereovision enables them to better recognize how far away objects are. Each eye views a distant scene from a slightly different perspective.

However, the camera currently installed in MASCE has only one lens. It is therefore difficult to judge from its images how deep structures, for example folds, lie within the gastric mucosa. Turan also plans to solve this problem in the coming months with the help of machine learning. During analysis of the frames, the computer will take its bearings from landmarks in the organ, for example folds or other elevations. Multiple frames taken from various angles will then be compared to calculate the three-dimensional topology of the surface.

That will be important in the future in order to release micro-grippers or drugs with millimeter precision. As the

Photo: MPI for Intelligent Systems

capsule travels through the body, the locations of landmarks will be tracked to enable the computer to determine how far the capsule has moved relative to each landmark.

Turan will also apply the method of structured lighting to model the 3D topology of the inside of the stomach. In this method, a projector shines a pattern of uniform parallel stripes on an object. The object's three-dimensional shape distorts the striped pattern. By taking images of the distorted pattern with a camera from various angles, it is possible to calculate the 3D structure.

DETECTING DISEASED TISSUE WITH MACHINE LEARNING

Mehmet Turan knows that it's a challenge to project such a striped pattern on the MASCE, which measures only a few millimeters across. First of all, he needs a stripe mask that produces stripes of light less than one millimeter in width.

The camera manufacturer has constructed one especially for the Stuttgart-based research group. Whether it works remains to be seen, as the striped pattern must be cast on the stomach wall with razor-sharpness. "To achieve this, we need very sharply focused light, which in turn requires a lot of current and a high-capacity on-board battery," says Turan. Nevertheless, the Max Planck scientist is confident that the stripe projection experiment will be successful.

In the future, it will be essential for doctors to be able to distinguish healthy tissue from diseased tissue in order to position MASCE precisely at a tumor or focus of inflammation. Once again, the computer can provide assistance. Turan is also using machine learning to recognize diseased tissue and plans to teach the computer using images of healthy and diseased tissue. "However, we still don't know what features in the MASCE images the computer is best able to use to distinguish tissue types. That is also part of the learning process," Turan says. He gives an example: If you want to teach the computer to distinguish between a man and a woman, it first has to learn that "has two eyes" is not a suitable characteristic for determining gender.

Turan believes that specific color features of the mucosa – for example, saturation, brightness or hue – may be suitable for differentiating between healthy and diseased tissue. "Ultimately, we will feed our algorithms a whole series of parameters," he says. "The task of the computer is then to identify those features that give the strongest indication as to whether the tissue is healthy or diseased."

As far as the medical applications of Metin Sitti's work are concerned, the MASCE system is currently the most advanced. As a robotics specialist, however, he is also pursuing other approaches. One of them is to make robots smaller than the MASCE millibot, shrinking them to the micrometer scale. "Our vision is to develop systems that are so small that they can operate not only in the intestines and stomach but throughout the interior of the body."

Such tiny robots face a fundamental problem. The smaller they are, the less energy they can store to drive them. Limits are quickly reached with batteries reduced to the micrometer scale. As with MASCE, Sitti is therefore pinning his hopes on drive systems that don't require electrical energy. Here, too, Sitti's coworkers are experimenting with magnetic fields.

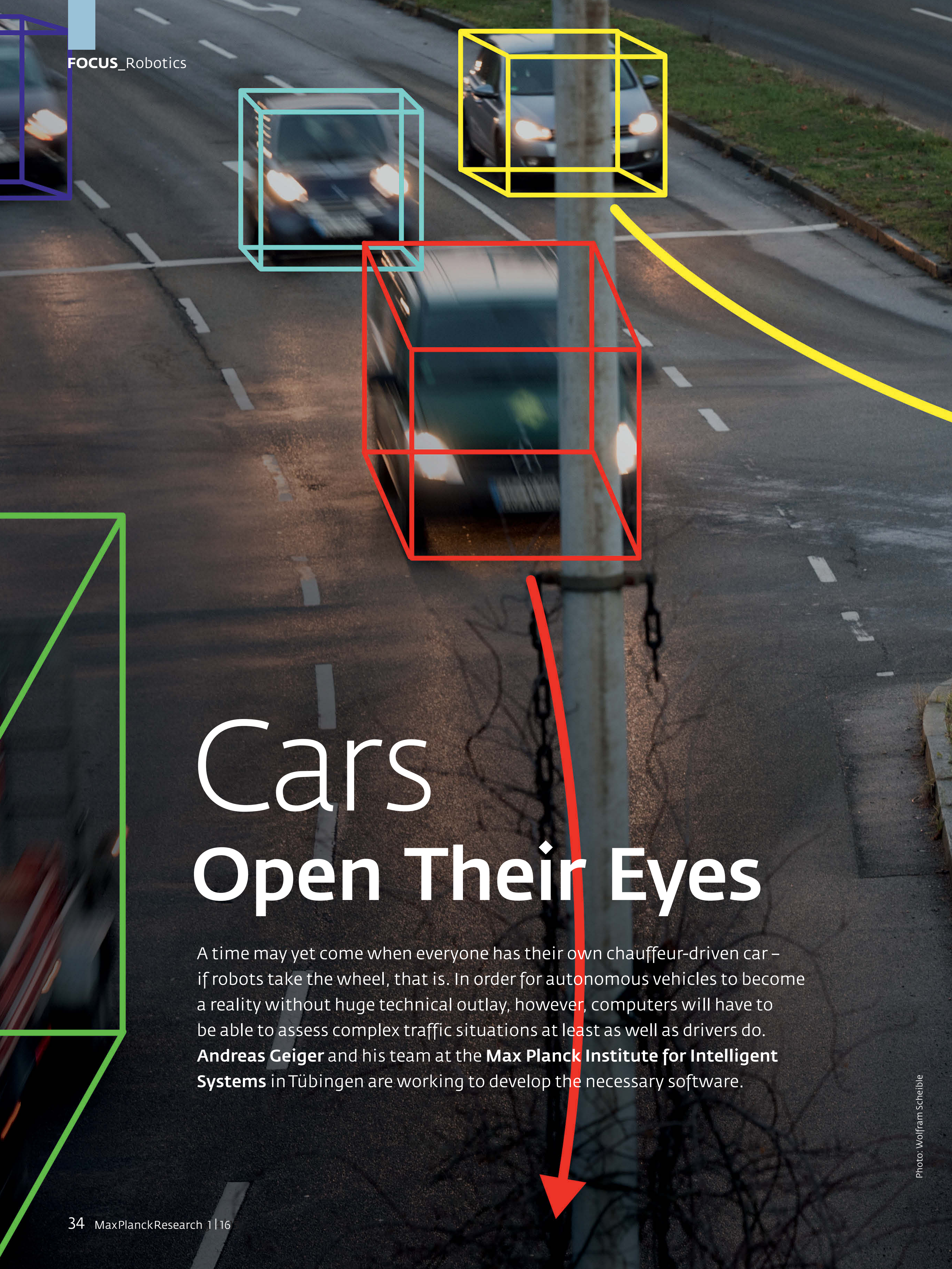
The researchers are pursuing an entirely different idea with micro-robots driven by bacteria. For example, Sitti's team has succeeded in fixing bacteria driven by small whip-like tails, called flagella, to the surface of tiny beads. When the scientists entice the bacteria with nutrients, they start to swim towards the nutrient source, pulling the bead with them.

It is conceivable that drugs could be transported through the body to a specific target in this way – for example, by using bacteria that react to the chemical signals of cancerous tissue. "Such approaches are extremely interesting, because they would help us overcome the limitations of conventional robotics," says Metin Sitti. "But of course that's still a long way off."

He believes though that MASCE is already quite a bit more advanced: "I could imagine it being used in clinical applications in just a few years." ◂

TO THE POINT

- **Gastroscopy causes distress to patients, who usually have to swallow an endoscope tube. Today's capsule-shaped endoscopes can't be controlled and therefore only deliver sharp images of disease foci by accident.**
- **Researchers at the Max Planck Institute for Intelligent Systems in Stuttgart are therefore developing a capsule-shaped robot (magnetically actuated soft capsule endoscope, or MASCE for short) that can be controlled by means of an external magnetic field.**
- **The millibots can be designed to release drugs at the site of an inflammation or tumor over a protracted period. In other variants, they can release micro-grippers that remove tissue samples.**



Cars
Open Their Eyes

A time may yet come when everyone has their own chauffeur-driven car – if robots take the wheel, that is. In order for autonomous vehicles to become a reality without huge technical outlay, however, computers will have to be able to assess complex traffic situations at least as well as drivers do. **Andreas Geiger** and his team at the **Max Planck Institute for Intelligent Systems** in Tübingen are working to develop the necessary software.

Photo: Wolfram Scheible

TEXT **CHRISTIAN J. MEIER**

In today's world, technology has eyes practically everywhere. Webcams can be had for just a few euros; smartphones often have multiple cameras, and stereo cameras in many luxury cars map their surroundings in three dimensions, not unlike humans. In this way, increasingly affordable image sensors are becoming an inescapable part of everyday life, and all kinds of life circumstances and situations are captured on photo or video. Every second, another 48 hours of video material is uploaded to YouTube, while Instagram, the online photo-sharing app, is growing at a rate of 20 million images per day.

For many, these ubiquitous cameras open new windows onto the world. But they mean even more to Andreas Geiger of the Max Planck Institute for Intelligent Systems in Tübingen: to him, cameras are the eyes of computer systems, enabling them to actually perceive and understand the world around us.

"Perception is an essential component of intelligence," explains the computer scientist, and illustrates his statement with an example: "We humans often give things striking shapes and colors to help us find our way in the world. Think of road signs, for in-

Object recognition: A kind of world knowledge helps software identify people and cars, even when they are partly obscured from sight. It also makes it possible for programs to predict the behavior of road users.

Stereoscopic images for modeling: In order to estimate distances, the program locates corresponding points on two images taken from different angles, and uses this information to reconstruct the scene with depth information. The white patches represent areas for which no information was available, as they were hidden from the camera.

Graphic: Andreas Geiger/MPI for Intelligent Systems

stance." As it is hoped that computers will find their bearings in the human world more easily in the future and move autonomously in applications such as domestic robots and autonomous vehicles, they must first learn to perceive their environment as humans do.

There is a problem, though. Computers don't understand images, which they see as a chaotic mosaic of millions of varicolored pixels instead of a scene containing houses, trees, cars or curbs. People, in contrast, recognize objects and are able to grasp complex situations, anticipate movements and estimate distances. "Computers are still a long way from that goal," says Geiger. "Many treasures remain hidden to them for now, lurking in the deluge of images."

If a computer is to guide a driverless car through traffic, it must be able to assess whether the vehicle in front is going to turn or keep going straight, or whether a child on the curb is going to run onto the road. "This is why we're developing systems that can perceive situations as humans do and react accordingly," explains Geiger.

The process of teaching computers to detect objects and interpret scenes is an arduous one. "They have to convert the light that has been captured into meaning," as Andreas Geiger puts it. To this end, a program must first reconstruct the three-dimensional world that has been captured as images in just two dimensions. Geiger and his research group of four are developing the software required for this kind of task. Objects such as cars, tables and even the human body with all its complex movements can now be represented in computer language. The virtual world contains three-dimensional models of people, monsters and Formula One racing cars. In computer games, such models meet, fight and compete with each other: in short, the computer simulates highly complex scenes within a 3D virtual reality.

AMBIGUITIES IN TWO-DIMENSIONAL IMAGES

Gamers, however, see only two-dimensional images as their graphic cards continually project the complex three-dimensional model world of the game onto their flat screens. "The software does an amazingly good job of converting the spatial model of the virtual world into a two-dimensional image," affirms Geiger. The challenge now is to achieve the opposite, namely to take two-dimensional camera images and compute a model of three-dimensional reality.

"One of the problems with this is the issue of ambiguity," says Geiger. An image that contains a thick tree trunk can be interpreted in different ways by the computer. The thick trunk could actually be a thin trunk that is close to the observer. Two different 3D models, one with a distant, thick trunk and another with a close-up, thin trunk, would generate a similar image on the camera.

As a two-dimensional image lacks depth, it is not possible to conclusively differentiate between the two options. This is why computers use stereo images, as humans do, to estimate distances and detect the spatial structure of a scene. But even then ambiguities may arise, as Geiger shows using two images of a residential street lined with old houses, with vehicles parked along both curbs. The images show the same scene captured from slightly different angles, as if seen using the right and left eye of a human observer. The human brain would then generate a spatial impression using the data from both perspectives.

Computer software can estimate distance in a similar way, by measuring the displacement of a feature such as a window frame in one image compared to the other. If the displacement is large, the object is close to the camera. If the images reveal only minor displacement of the feature, then it is located far away. This principle can be observed by looking at a close object and closing the left and right eye alternately. The object will appear to move back and forth in relation to the background. The computer converts this displacement data into actual distance values in meters.

The computer goes about this by comparing the individual pixels in both images. For each pixel in the first image, it looks for its counterpart in the second, meaning the pixel that represents the same point in the real scene. It does so by analyzing the color values of the pixels.

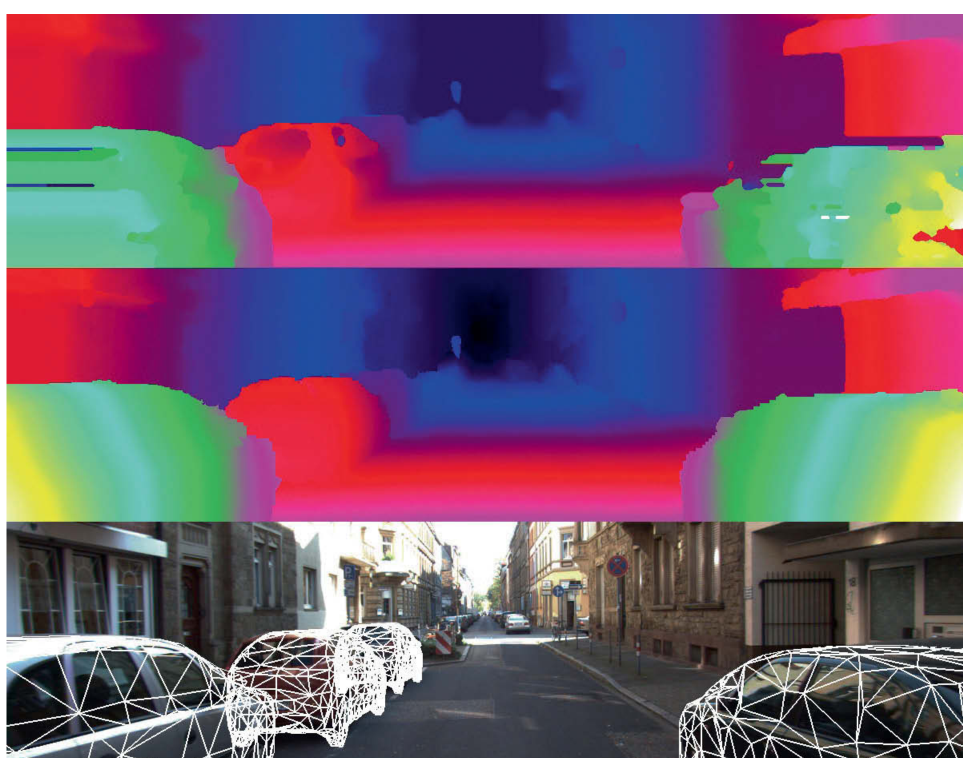
"Edges such as window frames are easy to pinpoint in this way," says Geiger, as they show an abrupt transition from one color to another, and this is easily recognizable in the second image. Paint on a car door, on the other hand, is generally monochrome and all pixels have a similar color value. This means that, for each pixel in one image, there are many candidates in the second image that would have to be considered as possible counterparts. Existing procedures for calculating depth maps are unable to handle this level of ambiguity. In the worst case, it leads to miscalculation of depth – and in a system that is relevant to safety, this could have fatal consequences.

Geiger illustrates the problem with the image of a scene in which depth is represented by false colors. Green dominates for close objects, with violet and red further back, and everything that is far off appears blue. Vehicle contours can be detected on this depth map, but many colored specks appear around car doors. "In those cases," explains Geiger, "the computer was either unable to assess the distance or miscalculated it."

OBJECT KNOWLEDGE HELPS MAKE SENSE OF DISTANCE

In order for their computer to estimate distance reliably in spite of these difficulties, the Tübingen-based researchers feed the software with information about the image, called object knowledge. In other words, they turn a collection of pixels into a scene with objects as a human would perceive them. Adaptive software can identify cars on the basis of multiple sample images, and then consistently mark the places in new images where cars are located. In this way, the computer learns to detect the presence or absence of cars in a given image.

Geiger describes object knowledge as mid-level knowledge, or "knowledge of a medium level of abstraction." It is helpful, he says, to build a scene up from pixel-based low-level features such as those window frames and divide it into different items, just as a person detects tables, chairs and cupboards within the home. >



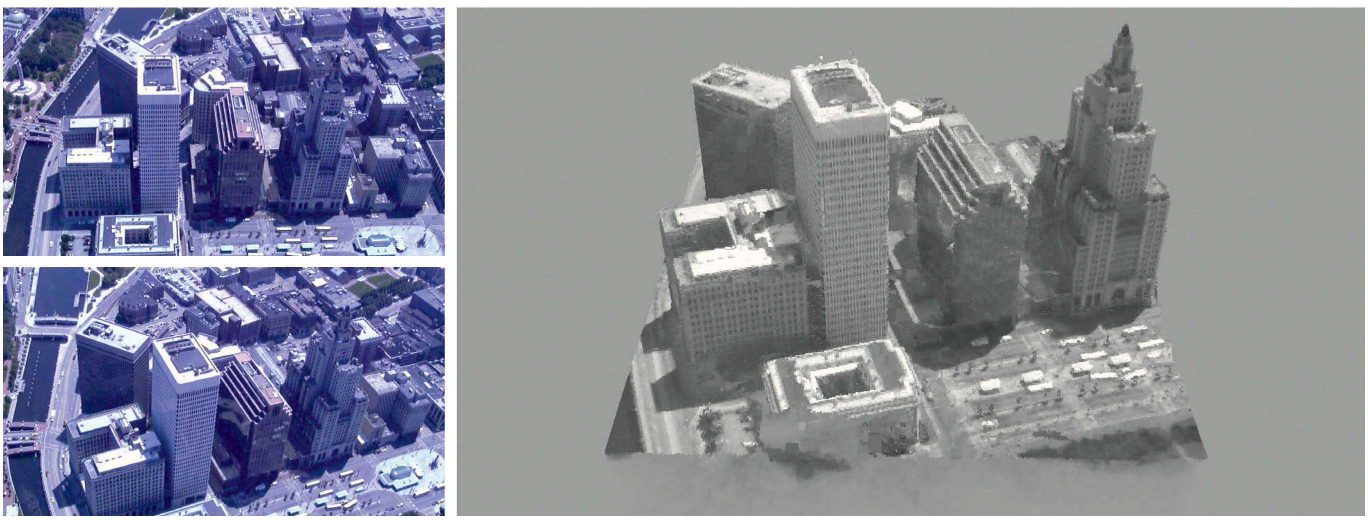
Top A depth map codes distances using different colors (yellow – near; blue – far).

Bottom The software calculates distances with the help of information on the geometry of objects such as cars. Relevant models are stored in its memory.

Graphic: Andreas Geiger/MPI for Intelligent Systems

Right-hand page Built on probabilities: Osman Ulusoy, Joël Janai and Andreas Geiger (from left) discuss the algorithm they are using to reconstruct 3D models from stereoscopic images. The background image shows them the algorithm's confidence level in relation to depth information for the Capitol in Providence. White dots on the image mean the assessment is fairly reliable, unlike the black dots, which indicate that the algorithm has depended more on prior knowledge, for example about the general shape of buildings.

Below Downtown Providence poses: Osman Ulusoy uses aerial photos taken from different angles (left) to compute a 3D reconstruction of his hometown in Rhode Island (US). The reconstruction can then be used to observe the city center from different perspectives not provided in the original images (right).



Geiger's team uses software that reconstructs scenes virtually using geometric 3D models of cars, generating a 3D simulation with virtual cars in a row. Modern graphics cards accurately convert these scenes into depth maps without any data gaps around the car doors, as they are based on complete 3D models.

However, this still doesn't deliver a totally unambiguous result. It is not clear from the photos how many cars are parked along the curbs, or whether they are parked parallel to the curb or at an angle. Consequently, there are thousands of simulations with different numbers of cars and different parking orientations that reconstruct the image of the streetscape with varying degrees of accuracy.

The research team's program tests all these variants for consistency with the corresponding image data. So, for example, it compares the depth map generated by the simulation with that produced using only pixel comparison with no world knowledge. The software also measures how well the artificial image reproduces the areas where cars are located in the real image. "This allows us to filter out the most probable hypotheses," explains Geiger. The method doesn't deliver any hard and fast certainty, but it does achieve a more consistent and meaningful interpretation of the image.

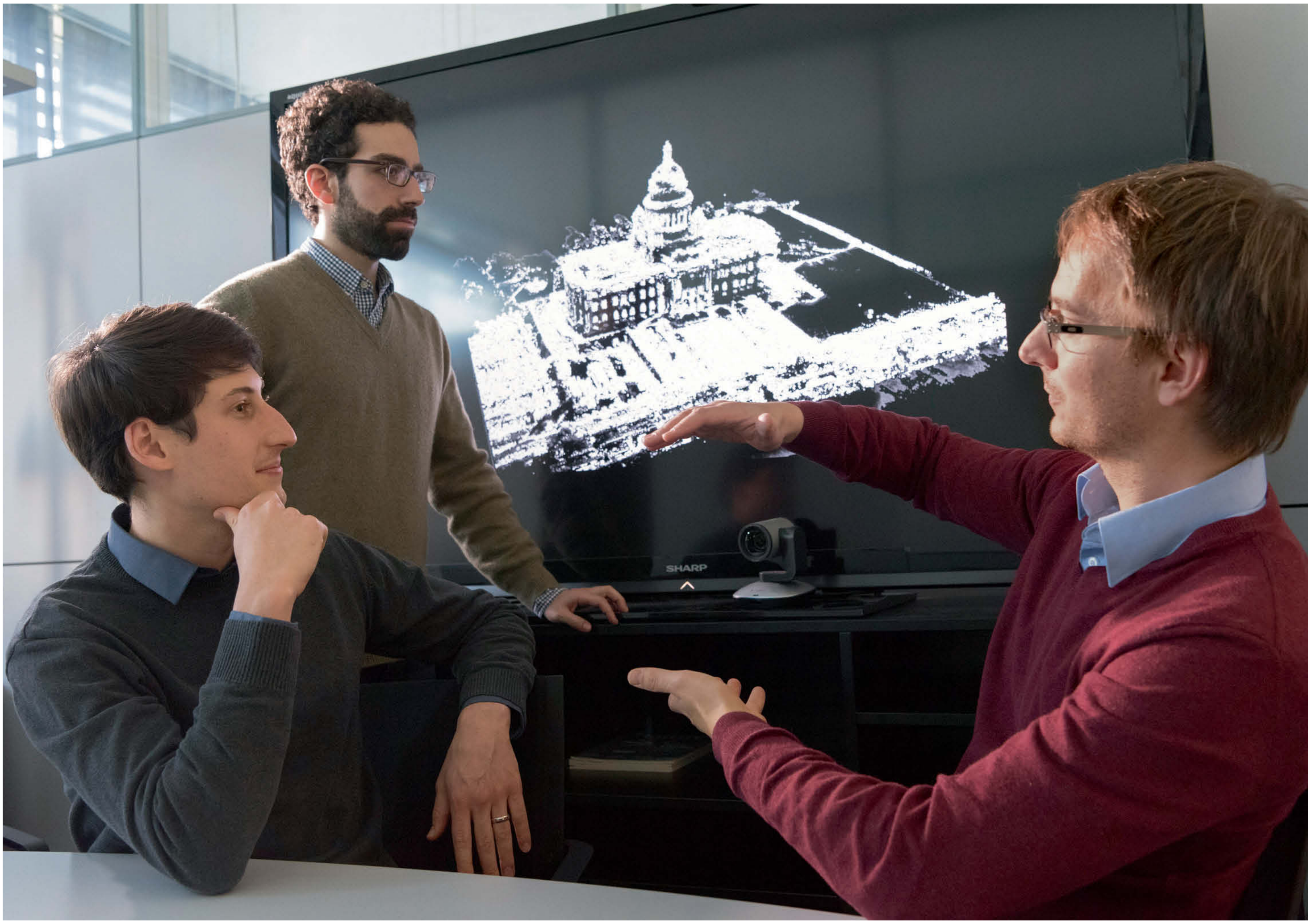
AERIAL PHOTOGRAPHS YIELD 3D CITY MODELS

Osman Ulusoy, one of Geiger's team colleagues, demonstrates a similar principle using aerial photographs of his hometown of Providence in Rhode Island (US). "Photographs taken from different angles can be used to generate a 3D model of the city center," he explains. However, reflecting surfaces are difficult for the computer to reconstruct, since reflections throw the calculation of distance into confusion.

"We feed *a priori* knowledge into the computer to close the gaps," says Ulusoy. This is a kind of world knowledge in terms of the characteristics and structure of things in general; for example, the fact that reflecting surfaces are generally smooth. This enables the software to complete the model in spite of ambiguous observations. "This could be of interest to urban planners," surmises the computer scientist. "It would enable them to document the development of the city in 3D."

Indoor scenes can be virtually reconstructed too, as Andreas Geiger shows using an image of a room with a bed, chair and cupboard. "The model recognizes the shapes and sizes of typical pieces of furniture," he ex-

Graphic: Ali Osman Ulusoy/MPI for Intelligent Systems



plains, adding that it can detect a chair even if the image shows only a side view of the chair back. Again, the researchers feed *a priori* knowledge into the system for the virtual reconstruction of the scene. "Cupboards, beds and sofa are generally positioned up against a wall," says Geiger. Furthermore, objects do not intersect each other. As in the scene with parked cars, this knowledge limits the number of possible hypotheses to a range that the computer can run through in a shorter time.

The virtual reconstruction of indoor areas may be useful for robots that need to maneuver safely in a domestic setting. It could also help architects and designers produce more realistic drafts and develop ergonomic designs, Geiger believes.

As the computer uses the object knowledge supplied, it learns to detect objects in new images. "Still, it's important to approach the problem as a whole and not just focus on the individual components," warns the group leader.

HIGH-LEVEL KNOWLEDGE FOR INTERPRETING THE IMAGES

The team in Tübingen relates the objects in an image to each other by inputting high-level knowledge into the computer, that is, knowledge involving a high degree of abstraction. This includes the above assumption that pieces of furniture do not intersect one another, or that they are generally positioned against a wall.

It is this high-level knowledge that enables the computer to assign meaningful interpretations not only to static images, but also to moving ones. Here, Geiger uses the term "3D scene flow," which means an estimate of the three-dimensional movement of all objects in the scene. His team attempts, for instance, to derive the best data from the rather limited perspective of traffic scenarios as captured by a car's on-board cameras, say at the junction of two busy streets in the city center.

A fixed bird's-eye view would be the best perspective for understanding this type of situation, as only the vehicles would move and it would immediately be clear which lanes they were driving in, what traffic lights are located at the junction, and how the traffic light phases alternate. "From a height of 1.60 meters, which would be typical for a car's stereo cameras, it's much harder to deduce that information, and it involves a greater degree of uncertainty," says Geiger. In fact, the built-in cameras are often unable to detect whether the traffic lights for their own lane are red or green. >

Photo: Wolfram Scheible

Two parts, one person: Andreas Geiger demonstrates a scene that computers do not initially understand. They do not grasp, namely, that there is only one scientist in the photo, not two. Geiger's team is working to train software to reach this conclusion on its own.

Photo: Wolfram Scheible

Despite this incomplete and unreliable information, the team in Tübingen hopes to make autonomous vehicles a reality by increasing the intelligence of on-board computers: they aim to teach them to accurately detect and interpret scene flow.

OBJECT RIGIDITY REDUCES THE NUMBER OF MODELS

The first problem: the identification of other road users. To a computer, a street scene is initially just a swarm of moving pixels. We humans, on the other hand, know that many of the scenes we observe, including road traffic scenes, consist of a small number of rigid objects. Cars don't suddenly change shape, but move as a compact whole.

Then again, there is only a small number of vehicles at a junction at any given time, and not hundreds. "So we tell the computer to break the scene down into the smallest possible number of rigid components," says Geiger. Rigid objects have less freedom to move than, say, the human body. They can move along three planes: forward and backward, left and right, up and down. They can also turn on three axes, while the complex movement of a human body involves hundreds of variables, including the rotational angles at each joint.

"So this assumption of rigidity greatly restricts the model of the scene," says Geiger. The computer has fewer variants to test for plausibility and resolves ambiguities with better results. Furthermore, the command to identify the smallest possible number of objects excludes many other hypotheses, for example that a car on the far side of a lamppost be misinterpreted as two separate objects. Rigidity, then, is a simple criterion with far-reaching effects.

Once Geiger's software has detected individual vehicles at a junction, it follows them for a time. Do they drive straight ahead? Do they turn right or left? This is where machine learning comes into play. Using many sample images, computers learn to recognize certain elements. If a computer is trained with thousands of images of human faces, it can ultimately detect faces in new photos by itself.

CAMERAS AND INTELLIGENCE REPLACE EXPENSIVE TECHNOLOGY

In similar fashion, the software designed in Tübingen is trained to use traffic flow data and road markings to detect the lanes for driving straight and turning right or left, and to infer traffic light sequences. "Different types of traffic light configurations are linked with different phase sequences," explains Geiger. "Our computers learn those sequences on the basis of large volumes of data, and then use that knowledge to improve how they relate road users to each other."

The junction surroundings are also subjected to scrutiny: the location of buildings, the orientation of the streets, etc. The computer uses all this information to reconstruct a digital map of the junction and run a virtual 3D film that reduces the scenery captured by the cameras to a bare minimum. The autonomous system can build on that to reach the right decision; and it does so ad hoc for each new junction it comes across.

"If autonomous vehicles were to combine cameras and intelligence, they would manage without the expensive technologies of today's prototypes, like laser scanners and radar," affirms Geiger. The highly accurate satellite navigation and laboriously produced digital maps such as those used for current systems would not be necessary, and in the transitional period when only a small number of autonomous vehicles are on the road, there would be no intelligent infrastructure available to support the new class of car.

There is currently still a problem with the software for analyzing complex scenes: relatively speaking, it still makes many mistakes. It mistakes a sofa for a bed, or a piano for a table. It slips up at junctions, partly because machine learning in the area of road traffic is more arduous than for facial recognition, for instance. A very high volume of data is required to train it, but there are far fewer video sequences containing cars than photos of faces. Not only that, but people have to overlay the training data with information, for instance by showing the computer where to find faces in the images. "This kind of annotation is very labor-intensive in the case of traffic junctions," says Andreas Geiger.

The pitfalls of digital photography pose a further obstacle to the researchers. Bright sunlight can blind the sensors, trees can obstruct a view, and large contrasts between light and dark can make it impossible to capture a scene on camera. In such cases, the accuracy of the virtual reconstruction suffers or is rendered impossible.

ACCEPTANCE OF THE TECHNOLOGY WILL COME

Again, the researchers intend to tackle these technical problems using *a priori* knowledge. "In the case of houses in a development, we can assume that they are similar to each other," says Geiger. This assumption of similarity helps the computer to virtually reconstruct an entire residential street, even if it is lined with trees or the camera is hampered by the sun.

Think of it like this: The system logs the facade of one house, the left external wall of another, and the right wall of a third. Since the houses are assumed to be similar in structure, these three pieces of the puzzle can be combined to generate a typical house for that street. "The model is flexible enough to allow the extrapolation and interpolation of different geometries," says Geiger. This means it can generate houses that have not actually been observed but fit perfectly into the development based on their appearance.

However, even if the software continues to become better at assigning meaning to billions of pixels, those interpretations of the images it captures are still just approximations. And even the most probable hypothesis is only a hypothesis and not a certainty. But surely certainty is the one thing needed in situations involving road traffic?

"Even a good driver can only estimate how the car in front will behave," counters Geiger. It is true, he admits, that computers are not yet as good as drivers in making such estimations. "Acceptance for this kind of technology will come as soon as the systems make significantly fewer mistakes than human drivers." ◂

TO THE POINT

- **Initially, computers perceive images only as a series of meaningless pixels. Andreas Geiger and his team at the Max Planck Institute for Intelligent Systems train them to understand images of complex traffic situations and to anticipate the behavior of road users.**
- **When a program uses two-dimensional images to construct a three-dimensional model of a street scene, ambiguities arise in areas such as the evaluation of distance. To resolve this issue, the team input data of a medium level of abstraction into the software, helping computers to recognize individual objects such as cars.**
- **The software uses knowledge with a high level of abstraction to understand how individual objects relate to each other. This specifies, for example, that solid objects do not intersect one another.**
- **When computers have analyzed many traffic situations using machine learning, they can anticipate traffic flow at junctions.**

The Genetic Legacy of Farming

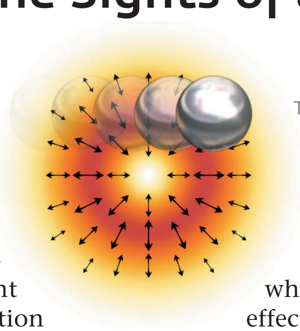
Agriculture and livestock farming leave their mark on the genes of Europeans

Agriculture and livestock farming spread across central Europe around 7,500 years ago. The associated selection processes are reflected in the genome of today's Europeans. Based on the analysis of genetic data from different periods and regions, an international team of researchers headed by Wolfgang Haak and Johannes Krause from the Max Planck Institute for the Science of Human History has shown that agricultural knowledge from Anatolia in today's Turkey made its way to Europe. This knowledge spread because Stone Age farmers from the region migrated to different parts of the continent. According to the study, the gene mutation that enables adult humans to tolerate milk occurred for the first time between 4,200 and 4,300 years ago. It had previously been assumed that this happened shortly after the domestication of cows 8,000 years ago. The researchers also succeeded for the first time in demonstrating the adaptation of genes that play an important role in the immune system. This became necessary as a result of close contact with domestic animals and their pathogens. As the Anatolian migrants were considerably lighter-skinned than the original European hunters and gatherers, the skin of the Europeans also became lighter. This resulted in an improvement in their vitamin D supply, as paler skin allows more light to penetrate. (Nature, November 23, 2015)

On the trail of Europe's first farmers: The genetic data of an adult male from the Salzmünde culture in the district of Saalekreis (Saxony-Anhalt) were incorporated into a study on the spread of agriculture. This grave is between 7,100 and 7,400 years old.

Speeding Particles in the Sights of a Laser

A mysterious phenomenon from the quantum world is acting as a model for a new kind of motion sensor. Researchers from the Max Planck Institute for the Science of Light use the entanglement of the polarization and the spatial distribution of the electromagnetic field in a radially polarized laser beam to track the movement of objects. In this kind of laser beam, the oscillation planes of the light waves arrange themselves like the spokes of a wheel. Entanglement is known from quantum physics, where it causes the properties of two particles to influence each other without exchanging any information, even if they are located at a considerable distance from each other. The entanglement with which the Erlangen-based physicists are working, however, is not all that spooky, as what is involved here is not a quantum physical effect but a classical one in a laser beam. It enables the determination of the position of a particle flying through the beam based on relatively simple measurements of the polarization. Because the polarization can be determined several billion times in a second, a particle moving as fast as a bullet can also be tracked without difficulty – something that is surely of interest for research applications. (Optica, September 28, 2015)



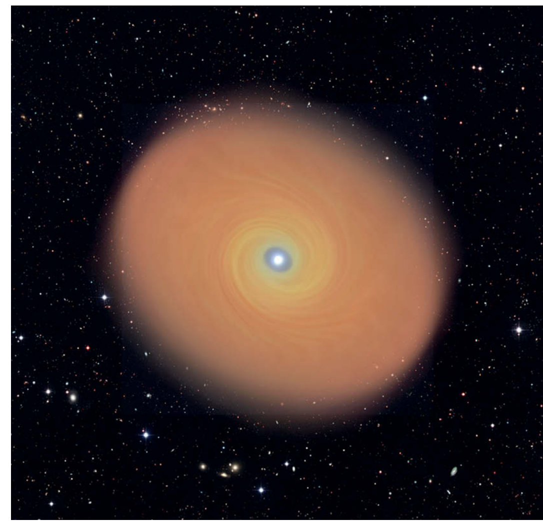
The path of a metal ball that flies through a radially polarized light beam can be reconstructed from the measurements of the polarization. The arrows show that the oscillation planes of the light waves in the beam arrange themselves like spokes of a bicycle wheel.

Photo: Juraj Lipták, LDA Sachsen-Anhalt (top); illustration: Optica 2015, MPI for the Science of Light, p. 43 (bottom)

How Stars Grow into Heavyweights

Astronomers find a stable disk around a massive young sun

Stars come in both lightweight and heavyweight form. They are all born in clouds of gas and dust; however, the more massive a baby star, the earlier nuclear fusion ignites in its core. The radiation pressure produced in this way should actually purge its surroundings, and thus prevent the infall of matter that would enable the star to grow bigger. Despite this, some stars manage to reach masses of over one hundred times that of our Sun. Stable flat disks – like those that the researchers from the Max Planck Institute for Astronomy have now found around a young star in the Centaurus constellation – appear to play a key role in this process. A stable disk like this can, on the one hand, direct enormous volumes of matter onto the nascent star; on the other hand, it presents a very narrow profile to the radiation pressure and thus a smaller area of attack than gas, which surrounds the star like a spherical shell. In this way, the star can continue to accommodate mass and grow into a heavyweight. (Astrophysical Journal Letters, October 29, 2015)



A star gains weight: This artist's impression shows the disk of gas and dust around the massive sun AFGL 4176.

The Origin of the Very First Species

A model provides a possible explanation for the origin of the first biological species, from which all of today's life forms descended

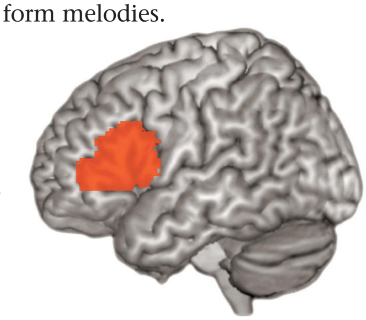
When life emerged, probably around 3.8 billion years ago, the first biological species did not suddenly exist on Earth. Instead, it is likely that there was a big genetic muddle in the first cells due to the promiscuous exchange of genetic material between unrelated individuals via horizontal gene transfer. It took quite some time for the first biological species that reproduced over many generations with more or less the same genome and had a relatively functional biochemical apparatus to develop. A team of researchers headed by Marc Timme at the Max Planck Institute for Dynamics and Self-Organization in Göttingen used a theoretical model to investigate how this might have occurred. According to this model, life fluctuated back and forth between a genetically highly mixed state and a partially unmixed state. Over time, the entire population became biologically fitter on average and the importance of horizontal gene exchange and the genetic mix probably declined. The first species, from which all subsequent species emerged, may have formed in this way. (Physical Review E, November 13, 2015)

Dual Challenge for the Brain

If you listen to music while reading a book, the brain does not cleanly separate the two tasks. A new study shows that there is an area of the brain that processes both tasks simultaneously: Broca's area. A research team headed by Richard Kunert from the Max Planck Institute for Psycholinguistics in Nijmegen carried out a series of tests on this, in which the participants' brain activity was measured with the help of functional magnetic resonance imaging. The researchers discovered that the two tasks influence each other: "When we played a particularly complicated series of notes to the participants, they found it more difficult to process the structure of a sentence," reports Kunert.

These new insights also support the theory that Broca's area is not responsible for language processing in general, but specifically for combining different elements to form an overall image. During language processing, individual words must be combined to form sentences, and in the case of music, individual notes are combined to form melodies.

(PLOS ONE, November 4, 2015)



Broca's area has long been known as an important part of the brain's language center. However, it also plays a key role in processing music.

Illustration: K. G. Johnston and ESO (top), MPI for Psycholinguistics (bottom)

Dispatches from the Middle Ages of the Universe

MAGIC telescopes measure gamma radiation from a remote galaxy

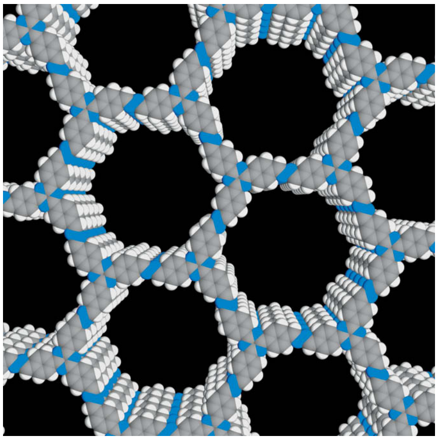
Researchers using the MAGIC telescope on La Palma have detected high-energy gamma radiation at a distant active galaxy for the first time. The center of this quasar, which is called PKS 1441+25, contains a high-mass black hole that is surrounded by a luminous disk of matter. The activity of the quasar is extremely variable: the most energy-rich gamma rays detected were around 250 gigaelectronvolts. This means that the outbursts are up to 100 times stronger than the normal gamma radiation profile. Astronomers are still unable to explain the reasons for this vast range. However, they discovered that the outbursts arise many billions of kilometers away from the active core. And yet another aspect: because the universe was born around 13.8 billion years ago and the light from PKS 1441+25 has been en route to Earth for around 7.6 billion years, its observation also provides insights into the "middle ages" of the universe. (Astrophysical Journal Letters, December 16, 2015)

Massive monster with radiant power: The PKS 1441+25 galaxy belongs to the group of quasars. A black hole at the center of the galaxy attracts matter, some of which is hurled outward in the form of jets at the speed of light.

Let There Be Hydrogen

An organic framework acts as a catalyst for photolytic conversion of water into hydrogen

Hydrogen is part of a climate-friendly energy mix, but only if it is produced regeneratively – that is, using energy from sunlight. Scientists from the Max Planck Institute for Solid State Research in Stuttgart and from Ludwig-Maximilians-Universität München have developed an innovative catalyst that produces this energy source from water and light. The material consists mainly of a covalent organic framework, to which, however, platinum nanoparticles and a compound that donates electrons must be added. Although the catalyst doesn't yet fulfill all requirements for technical use, it has the advantage that its properties can be chemically tuned at the molecular level. (Nature Communications, September 30, 2015)



Covalent organic frameworks are able to produce hydrogen. They form a regular structure with a large surface, which is required by technical catalysts (gray – carbon, blue – nitrogen, white – hydrogen).

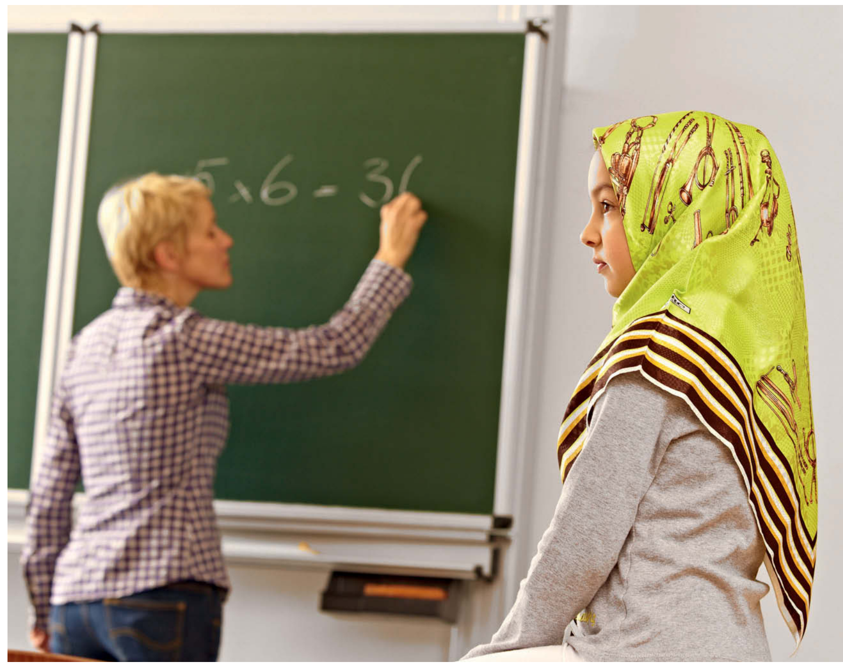
Touchless Touchscreens

Touchscreens are practical, but touchless ones would be even better. Touching wears out screens and spreads bacteria and viruses. In order to avoid this, a team of researchers headed by Bettina Lotsch at the Max Planck Institute for Solid State Research in Stuttgart and Ludwig-Maximilians-Universität München developed a layered nanomaterial, comprising antimony, phosphorous, oxygen and hydrogen, whose electrical conductivity changes when it absorbs water. The material even reacts to the moisture released by a finger that comes anywhere near it, thus fulfilling an important requirement for touchless displays. (Advanced Materials, September 23, 2015)

Illustration: M. Weiss/CfA (top), Nature Communications/Macmillan Publishers (bottom)

Poverty Linked to Bad Grades

Compendium provides overview of ethnic inequalities in education and training



Discrimination by teachers is not a major factor when it comes to explaining ethnic educational inequalities. Social background is more significant in this case, as well.

Performance gaps between children and young people from migrant and non-migrant backgrounds are observed throughout their educational careers. However, this is due mainly to social factors. Although migration-related reasons, such as language difficulties, are immediately observable, they are less significant. A volume co-edited by Christian Hunkler from the Max Planck Institute for Social Law and Social Policy provides an up-to-date overview of the current state of research in this field. According to the research, there are clear differences in the performances of children from different ethnic groups: children and adolescents of Turkish origin generally achieve much lower results than, for instance, pupils from the former Soviet Union. One of the reasons for this is the targeted recruitment of low-skilled guest workers from Turkey in the past. Their families still tend to have a low education level. Overall, the percentage of educationally disadvantaged families is disproportionately high among children with a migration background. (SpringerVS, 2015)

Following Their Noses to Lake Victoria

Without sense of smell, lesser black-backed gulls are unable to compensate for deviations from natural migratory route

Lesser black-backed gulls (*Larus fuscus fuscus*) are often on the move: In the fall, birds from Russia and Finland fly across the western Black Sea and the Nile Delta to Lake Victoria in East Africa. They spend the winter there and fly back north again to breed.

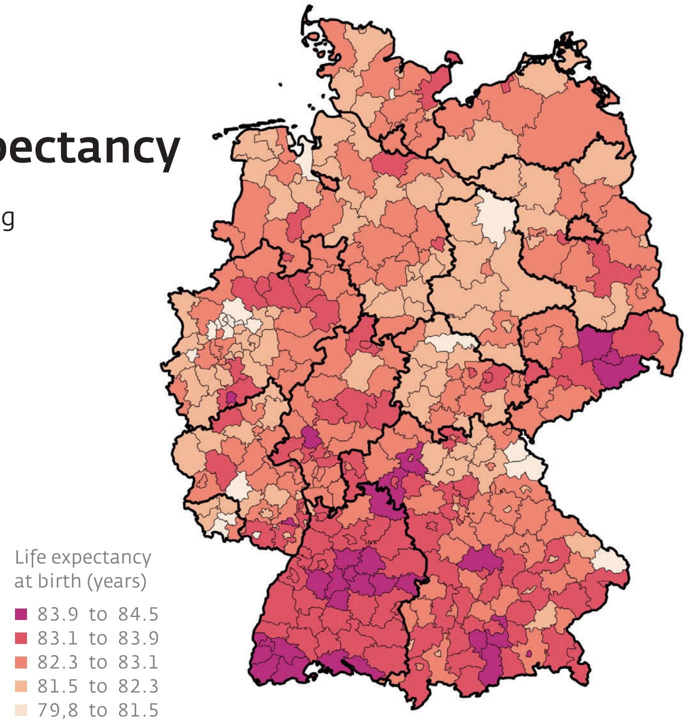
Photos: allesalltag (top), fotolia (bottom)

There's not much you can teach seagulls about navigation: they cover thousands of kilometers and reach their final destination with pinpoint accuracy. Exactly how they do this has not yet been fully explained. Together with colleagues from other research institutes, scientists from the Max Planck Institute of Ornithology in Radolfzell have provided further proof that some birds also use their sense of smell to navigate on their migratory journeys. The scientists used GPS transmitters to track the movements of lesser black-backed gulls whose olfactory nerves had been severed; the nerves grow back together again after a few months, so the birds aren't permanently impaired. Without their sense of smell, the gulls failed to reach their wintering area on Lake Victoria in Africa. The researchers have not yet identified the smells the birds follow. Individual olfactory cues along the route, such as the Black Sea and the Nile Delta, probably provide an indication of the general migratory direction. The lesser black-backed gulls do not, however, appear to use the Earth's magnetic field for navigation. (Nature Scientific Reports, November 24, 2015)

South-North Divide in Life Expectancy

Economically weak regions in western Germany falling behind in life expectancy

Twenty-five years after reunification, the once considerable differences between life expectancy in eastern and western Germany have almost disappeared. Instead, as scientists at the Max Planck Institute for Demographic Research discovered in an analysis of regional trends in life expectancy, the divide today is more along north-south lines. Southern Germans live longest: women in Baden-Württemberg have a record life expectancy of 83.6 years, followed by their counterparts in Saxony, Bavaria and Hessen. At the bottom of the list for the first time is a western German state, Saarland. Overall, the life expectancy map increasingly resembles a patchwork quilt. Economically weak areas in the west are falling behind. The regions with the shortest lifespan for women are now concentrated in North Rhine-Westphalia. The demographers see migrant flows as the cause of this. Highly developed areas attract people with a high level of education, who live considerably longer. (Kölner Zeitschrift für Soziologie und Sozialpsychologie, September 21, 2015)



The patchwork quilt of life expectancy: The fact that life expectancy in the east once lagged clearly behind that in the west – as was the case in the immediate aftermath of unification – is hardly noticeable now, at least among women. Instead, regional economic performance increasingly determines the length of life. Men in the east also now live only 1.4 fewer years than those in the west.

Colorful Birds

Plumage color in male and female birds from a single species can evolve separately only to a limited extent

The magnificent plumage of many male birds is the result of sexual selection: success in the mating game is limited to the males with the most beautiful plumage. In many bird species, however, the females are also strikingly colored. Scientists from the Max Planck Institute for Ornithology in Seewiesen analyzed the plumage of almost 6,000 species of passerine birds and found that the coloration of the males and females of a species is closely linked. Surprisingly, strong selection pressure on males reduces plumage coloration in females more than it increases it in males. Thus, the fact that high selection pressure can lead to major differences in coloration is mainly due to the fact that the females become less colorful. The analysis also revealed that birds in the tropics are more extravagant in their appearance than elsewhere because the competition for resources there is greater. Large tropical birds have the most magnificent plumage – big birds are less likely to fall prey to predators there and can afford to be more brightly colored. Colorful females occur above all in species with long-lasting partnerships and breeding communities. The competition between females for the opportunity to reproduce is higher in these cases. (Nature, November 4, 2015)

The differences in color are not as striking between all male and female birds as they are in the white-winged fairy wren (*Malurus leucopterus*) from Australia.

Graphic: Max Planck Institute for Demographic Research; photo: Kapar Delhey, Monash University, Australia

Infectiously Fertile

A gene makes male mosquitoes more fertile and also increases the females' susceptibility to malaria

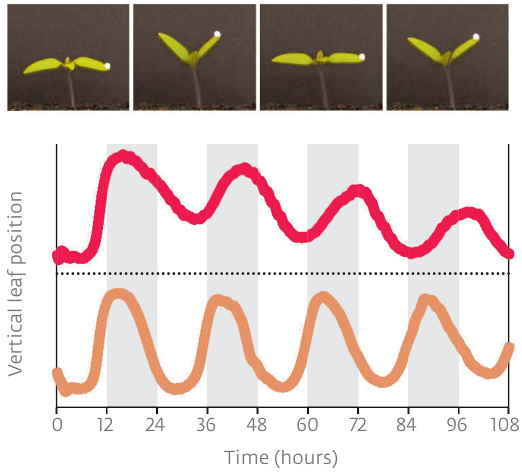
The TEP1gene influences whether female *Anopheles* mosquitoes can fight infection with malaria pathogens. In male mosquitoes, in contrast, it controls fertility.

Malaria is one of the most common infectious diseases in the tropics. Infected female Anopheles mosquitoes transmit the single-celled parasite from human to human through biting. According to researchers from the Max Planck Institute of Infection Biology in Berlin, the susceptibility of the females to the malaria pathogens also depends on the males. The mosquitoes have different variants of the TEP1 gene, as it is known. The corresponding TEP1 protein variant in the blood of the females attacks the malaria pathogens with varying degrees of success. The TEP1 protein is also active in the male testes. There, it removes low-quality sperm, increasing fertility. However, the most effective protein variant for this makes the females particularly susceptible to malaria. Consequently, that which benefits the males damages the females. Which of the variants spread among the mosquitoes depends on whether a higher rate of reproduction or protection against malaria is more important.
(PLOS BIOL., September 22, 2015)

Tomatoes with Jet Lag

Domestication altered circadian clock of wild tomato plants

When we travel to different time zones, our internal clock often lags behind. Not only in humans – plants, too, have an internal clock that synchronizes such processes as leaf movements with the natural circadian rhythm. Researchers from the Max Planck Institute for Plant Breeding Research in Cologne have now discovered that the circadian clock of cultivated tomato plants ticks more slowly than that of wild tomato plants. The cultivated forms apparently adapted to the longer summer days at higher latitudes when they were transported from their original home in Ecuador to Europe during the course of domestication. Summer days in Naples, for example, last more than three hours longer than in Ecuador. During domestication, gene variants must have arisen that are responsible for the altered rhythm. According to the researchers, these variants affect only two genes. One of them, EID1, enables plant cells to perceive light stimuli. It is not yet known whether the circadian clocks of other crops have also changed through domestication.
(NATURE GENETICS, November 16, 2015)



An internal clock controls the leaf movements of tomato seedlings over the course of a day. The leaves of the cultivated tomato (red) move more slowly than those of the wild ancestor (orange).

The Curious Body

Robots could gain a lot of knowledge from babies – for example, how they learn their first movements. Children explore the world through play, and in the process, they discover not only their environment, but also their own bodies. As Ralf Der, a researcher at the Max Planck Institute for Mathematics in the Sciences, and Georg Martius, a scientist at the Institute of Science and Technology in Klosterneuburg, Austria, have now shown in simulations with robots, the brain of a mechanical being, or even that of a human, doesn't necessarily need a high-level control center to generate curiosity. Curiosity arises solely from feedback loops between stimuli input from sensors that convey information about interactions between the robot's body and the environment, and commands for new movements. From initially small and even passive movements, the robot develops a motor repertoire without specific higher-level instructions. Up to now, robots with the capacity to learn have been set specific goals and are rewarded when they achieve them. Researchers have also tried to program curiosity into the robots. (PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES, November 10, 2015)

Photo: Christine Panagiotidis/MPI of Molecular Cell Biology and Genetics (top); photos and graphic: Niels Müller/MPI for Plant Breeding Research (bottom)

An Artist in **Gene Editing**

Sometimes a single discovery can change a whole life. For **Emmanuelle Charpentier**, deciphering the functioning of an enzyme previously known only to experts was such a moment. The trio comprised of one enzyme and two RNA molecules and known as CRISPR-Cas9 made headlines far beyond the world of science. Since then, a lot of things have changed in the French woman's life. She became a Director at the Berlin-based **Max Planck Institute for Infection Biology** in early October 2015.

TEXT **UTA DEFFKE**

It's one of the last hot days of summer 2015. Emmanuelle Charpentier sits in her office in Braunschweig, deep in concentration. She taps her foot. The dainty French woman is on the move again: after two years at the Helmholtz Centre for Infection Research, she is now moving to the German capital. In Berlin, she will be appointed Director at the Max Planck Institute for Infection Biology.

Her new institute stands on historic ground in the middle of the city: on the grounds of Charité, Berlin's renowned teaching hospital. This is where Robert Koch, at the Prussian Institute for Infectious Diseases, began his battle against the tuberculosis bacterium at the end of the 19th century – an appropriate location for a microbiologist and one of the most important scientists of our time.

For Charpentier, it wasn't just the temperatures that made it a hot summer. She seems a little stressed from all the fuss that has surrounded her and her discovery over the last two years. The list of prizes she was awarded in 2015 alone includes several prestigious science awards, among them the Princess of Asturias Award for Scientific and Technical Research, the Louis Jeantet Prize for Medicine, the Ernst Jung Prize for Medicine, the 2015 Breakthrough Prize in Life Sciences and the 2016 Leibniz Prize.

A SCALPEL FOR RESEARCHERS

As the many awards and prizes show, Charpentier's discovery is one of science's most remarkable success stories. The main protagonist in the story is part of the immune system of bacteria and goes by the unpronounceable name of CRISPR-Cas9. When viruses attack a bacterium, enzymes cut out a piece of the viral DNA and integrate it at a very specific location in the bacterial genome: the CRISPR sequence. The cell then transcribes this sequence into an RNA molecule, the CRISPR-RNA. The protein Cas9 then cuts the genome of invading viruses, thus incapacitating the pathogens.

In 2011, Charpentier described the new mechanism in NATURE, showing that three components are involved in the process: two RNA molecules – known as CRISPR-RNA and tracrRNA – and an enzyme initially named Csn1 and now known as Cas9. In 2012, Charpentier and her colleagues published a paper in SCIENCE outlining their discovery that tracrRNA is also involved in the DNA cleavage process. Cas9 is guided by the two RNA molecules to cut the viral DNA at the location defined by the CRISPR-RNA. Emmanuelle Charpentier had already foreseen that her discovery could open up new ways of specifically targeting genes and treating human genetic disorders.

Charpentier's group in Umeå, Sweden worked with Jennifer Doudna's

Photo: Hallbauer and Fioretti

Finally here: Emmanuelle Charpentier moved to the Berlin-based Max Planck Institute for Infection Biology in October 2015. Her objective was to begin working on her research as soon as possible after the move.

group in Berkeley, California to combine the two RNA molecules into one molecule. This step simplified the application of the CRISPR-Cas9 tool, since it meant that researchers only needed to program one RNA molecule in the gene sequence that Cas9 was to cleave.

In order for the DNA to be cut at a desired location, only the relevant gene sequence needs to be known and a matching RNA molecule manufactured. Researchers can then insert a new DNA snippet at the cut and thus switch genes on or off.

Since the discovery of the CRISPR-Cas9 mechanism, the molecular scissors have taken laboratories by storm: in 2012, 127 publications covered the subject of CRISPR-Cas9; by 2013 the figure had risen to 277. In 2015, the number skyrocketed to almost 500, and could rise to more than 1,100 studies this year. Scientists from all over the world are now taking a closer look at CRISPR-Cas9 and want to develop it further. But they are using it mainly as a tool to study genes. As it is much more precise, efficient and cost effective than previous methods, it is already a vital addition to many labs.

To date, all experiments involving plant, animal and human cells have been successful. CRISPR-Cas9 therefore has the potential for an extremely diverse range of applications: from plant breeding and the breeding of transgenic laboratory mice to treatments for a multitude of diseases. Doctors could use it to correct mutations and cure genetic diseases. It is already being used in HIV and malaria research. >

An immune mechanism in bacteria, until recently known only to hardcore microbiologists, could soon become a medical treatment for millions of patients. CRISPR-Cas9 is therefore a prime example of one of Charpentier's core beliefs: "Basic research is essential for progress," she stresses at every opportunity – a view that resonates perfectly with the Max Planck Society, of course.

The driving force behind Charpentier's research is, above all, an unquenchable curiosity about the world and its complex relationships, a characteristic that she displayed even as a child. Charpentier grew up south of Paris, where she was exposed to a multifaceted range of interests. Her mother worked in psychiatry; her father was responsible for planning green spaces in the city. One of her sisters began her studies at university just as Emmanuelle started school, and from then on, one thing was clear to her: she wanted that, too. Even more so than school, university seemed to her to be the place of learning and intellectual debate.

FROM MUSIC TO BIOLOGY

That she would one day be a biologist, however, wasn't determined until later. "According to my mother, when I was 11 or 12 years old, I told her that I would work at the Pasteur Institute – and that is where I actually did my doctorate," she recalls with a smile. "But I actually enjoyed all my subjects at school. So I could have also followed a very different path."

In her spare time, Charpentier enjoys art, music and dance. She played the piano and practiced ballet and modern dance for several years – a good exercise, not least for discipline and creative power. As she herself says: "Art has had a significant influence on my scientific career: you need to be rigorous, but you also need to be able to let yourself go." But she didn't want to make a career out of this talent: not only because it is difficult to make a living from it, but, for dancers in particular, their active years are soon over. Scientists, on the other hand, can always keep making progress, even as they get older.

Biology, with its complexity and direct relationship with people, was the area that fascinated her most. Biochemistry was the area she initially focused on, but bacteria soon took over the main role in her life as a researcher. In her doctoral thesis, she examined mechanisms that lead bacteria to develop resistance to antibiotics. It was already apparent back then that the number of multi-resistant pathogens would rapidly increase.

At the same time, there was a growing awareness that we could also learn a lot from them. Thus, the research that was conducted on bacteria in the 1970s resulted in important new laboratory techniques, such as the gene cloning.

Photo: Hallbauer and Fioretti

Left The researcher and the object of her study: Bacteria have Charpentier's full attention. She wants to understand how the microbes cause infections and protect themselves against infections.

Right Top: The Cas9 enzyme needs two RNA molecules to find its target: the so-called CRISPR-RNA, with a recognition sequence for a certain DNA sequence (red), and tracrRNA.
Center: The two RNA molecules can be merged – this makes it easier to use CRISPR-Cas9 for research purposes.
Bottom: The CRISPR-RNA, together with its recognition sequence, attaches itself to a suitable DNA sequence, identifying the interface for Cas9. This is how genes can be cut out or new ones inserted.

It is surprises like these that she finds so exciting in her discipline. This is also what motivated her at an early stage, following her studies and her doctoral work, to continuously embark on new adventures – both geographically and in terms of subject matter. She began her scientific pilgrimage with a postdoctoral position in New York. On the day she arrived, she found out that her working group would be moving to Memphis, Tennessee. "At that moment, I remembered something that my aunt, a missionary, had once predicted for me as a young child: that I would have an adventurous life with constant change. Up to then, it didn't mean very much to me. But since my arrival in New York, I have actually been constantly on the move."

This is also a source of inspiration for Charpentier. After all, leaving different places also means constantly leaving her comfort zone, scrutinizing and tweaking her own work. "This is probably exactly what I need for my work," she says, also recommending it to her students. Similarly, she didn't want to restrict herself in terms of subject matter, even if that was sometimes viewed critically by scientific colleagues. After all, in the scientific world, it's important to find one's niche.

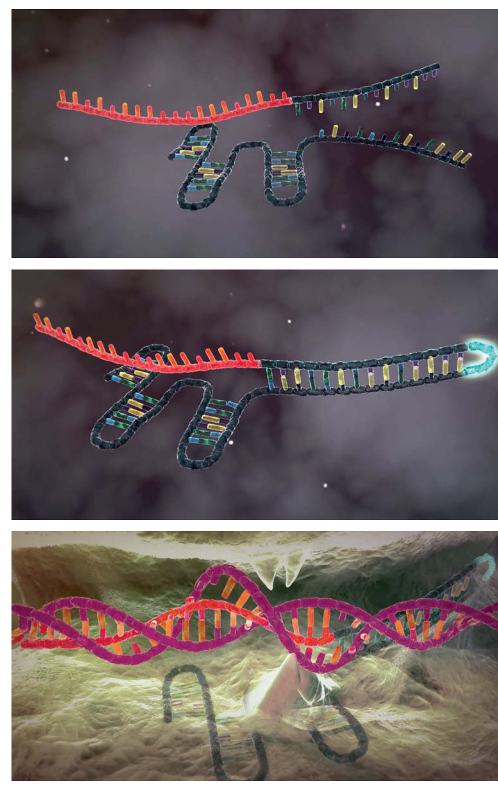
Leaving home initially also meant leaving her bacteria. Charpentier turned instead to their hosts, and carried out research on mice, focusing on skin development and how microorganisms trigger skin infections. In doing so, she learned how arduous it was to modify the mouse genome in such a way as to make the animals suitable as model systems for diseases. This experience ultimately brought the researcher back to bacteria, as they were frequently a starting point for new gene manipulation tools.

After six years of postdoctoral work in the US, she was offered the opportunity to establish her own research group in the Biocenter at the University of Vienna. This was a real incentive to return to Europe. "Vienna offered strong basic research and outstanding colleagues, and I could choose my own subjects and work completely independently. I learned to think on a larger scale, to apply for research funding, as well as to manage with scant resources."

In 2009, Charpentier moved from Vienna to Umeå University in Sweden. More than a few people thought she was a bit crazy at the time. "The move to Umeå was certainly risky," she admits. "But ultimately it was exactly the right decision." Not least because she came up with the radical idea of bringing together CRISPR and RNA while on the plane during her initial commutes between the two locations.

It then took her almost a year to find a student who also wanted to implement her idea in the lab. Her master's student Elitza Deltcheva played an important role in encouraging other colleagues in the group to take an interest in CRISPR-Cas9.

Charpentier has now been researching in Germany since 2013. The country has always been a presence in her life. Her parents experienced the Second World War, she herself learned



German at school, and as part of a student exchange, she got a taste of life in the country by living with a German family in a small town in the Rhine region for two weeks. Many of her friends and colleagues in the US, Austria and Sweden were also from Germany.

The Helmholtz Centre in Braunschweig and the Hannover Medical School enticed her with, among other things, an Alexander von Humboldt professorship. The connection with the

Graphic: Massih Media for the Max Planck Society

Hannover Medical School gave Charpentier access to clinical practice – a connection that she would now like to build on in a similar way at Charité. But she still stays in touch with her colleagues in Hanover.

LEGAL FRAMEWORK ABSENT IN MANY COUNTRIES

In addition, two of the companies that she co-founded are driving the development of CRISPR-Cas9: CRISPR Therapeutics was set up to make the technology commercially viable as a method of treatment for genetic diseases. The company wants to remove cells from patients, treat them with CRISPR-Cas9, and then return them to the body. Alternatively, CRISPR-Cas9 could also be inserted into the body via specific transport containers, such as fat bubbles or nanoparticles. Charpentier also helped co-found ERS Genomics, and has transferred the licenses for use on other organisms to the company.

However, it will still be a few years before humans can be treated with CRISPR-Cas9. Before that, more clarity about potential risks is needed. Although CRISPR-Cas9 is considerably more precise than other techniques, it still makes mistakes and occasionally cuts the genome at the wrong place.

Added to this are ethical issues that the use of CRISPR-Cas9 could raise. Chinese researchers recently modified the genes in human embryonic stem cells. While the embryos weren't viable, the experiments nevertheless show that society and policy makers urgently need to dictate what is and isn't allowed. "CRISPR-Cas9 can deliver huge benefits to humanity, but of course we need to handle it responsibly. Interventions into the human germline, for instance, which would influence the genome of future generations, is something that I and most of my colleagues refuse to do," clarifies Charpentier. Ultimately, it is the responsibility of policy makers to ensure that the enormous potential of the DNA scissors isn't abused to create designer babies.

Charpentier is looking forward to the new challenge at the Max Planck Institute in Berlin. The location offers the ideal conditions for her research: "I have always looked for a place where I can freely develop my ideas and practice science under excellent conditions. And I have always dreamed of working in a major city like Paris, London or Berlin." In particular, the unconventional spirit of the city on the Spree River resembles her own, and could inspire her research.

For the time being, however, the daily commute to the institute may well have to suffice, as she will have very little time to enjoy the cultural life of Berlin in the coming months. After all, it's full steam ahead for the establishment of her new "Regulation in Infection Biology" department, and it's something that will require a huge amount of energy: labs will be modified, and some of her colleagues who are coming with her from the Helmholtz Centre will be busy setting up the labs so that the research can continue as seamlessly as possible. At the same time, she also wants to cultivate contacts with colleagues from the neighboring institutes of the two universities in Berlin and Charité.

In terms of subject matter, understanding regulation mechanisms in pathogens will continue to be the focus of her attention. First and foremost, she wants to finish what she started with CRISPR-Cas9. Her main objective is to gain an even better understanding of the biochemistry, specificity and efficiency of the system: "We can see that it works and we understand the fundamentals, but we're still studying the details of how the DNA sequences are identified and how the cutting works." She also wants to investigate other CRISPR-Cas systems, as there may be other cutting tools in the realm of bacteria that are even more suitable for studying genes.

On top of all that, Charpentier wants to strengthen the field of microbiology at the institute and attract excellent junior scientists to this biological discipline. This is also a matter of urgency, as many microbiologists will be retiring in the coming years. Compounding this is the fact that microbiology isn't exactly seen as a discipline with a great future. Charpentier is convinced this is an error of judgment – one that she hopes to correct. ◂

GLOSSARY

CRISPR-Cas9: CRISPR stands for "Clustered Regularly Interspaced Short Palindromic Repeats" and describes a genome sequence in bacteria. Cas9 is an endonuclease – an enzyme that cuts DNA. In viral infections, the bacteria cut sequences out of the viral genome and insert them into the CRISPR sequence. The bacteria can use the resulting transcribed CRISPR-RNA and an additional RNA molecule to identify the viral genome if it attacks again. They can cut through it, incapacitating the pathogens. In this way, the CRISPR-Cas9 system provides the bacterial immune system with a kind of memory.

RNA: The DNA molecule contains the assembly instructions for all proteins in an organism. These instructions aren't translated directly into proteins, but rather are first transcribed into individual, much shorter RNA molecules. The chemical structure of RNA, which is a single-stranded nucleic acid, is somewhat different from that of DNA. There are various types of RNA molecules: some serve as a template for the production of proteins, while others control gene activity.

Aus dem Hause
DIE ZEIT

Wer begleitet mich auf meinem Karriereweg?

Die Antwort:
academics.de, der führende Stellenmarkt für Wissenschaftler

academics.de – das Ratgeber-Karriereportal mit Stellenangeboten, Themen-Spezialen und Services für die berufliche Laufbahn in Wissenschaft und Forschung. Inklusive Ratgeberinformationen zu Berufseinstieg, Gehälter in der Wissenschaft, Promotionsberatung, Alternative Karrierewege für Forscher u.v.m.

Sie suchen neue Mitarbeiter?
Informieren Sie sich jetzt unter academics.de/arbeitgeber

academics.de/maxplanck
Das Karriereportal für Wissenschaft & Forschung

Sie möchten eine **Anzeige schalten** und wünschen eine individuelle Beratung? Das academics-Team freut sich auf Ihren Anruf.
Telefon: **+49 (0)40/320 273-50** // E-Mail: **anzeigen@academics.de**

Counting on Quanta

Modern quantum physics holds quite a few promises in store: quantum computers and simulators will be able to trawl through huge quantities of data at lightning speed, accelerate the development of new drugs or facilitate the search for materials for, say, energy engineering. The research being carried out by **Ignacio Cirac**, Director at the **Max Planck Institute of Quantum Optics** in Garching, is helping to fulfill these promises.

TEXT **ROLAND WENGENMAYR**

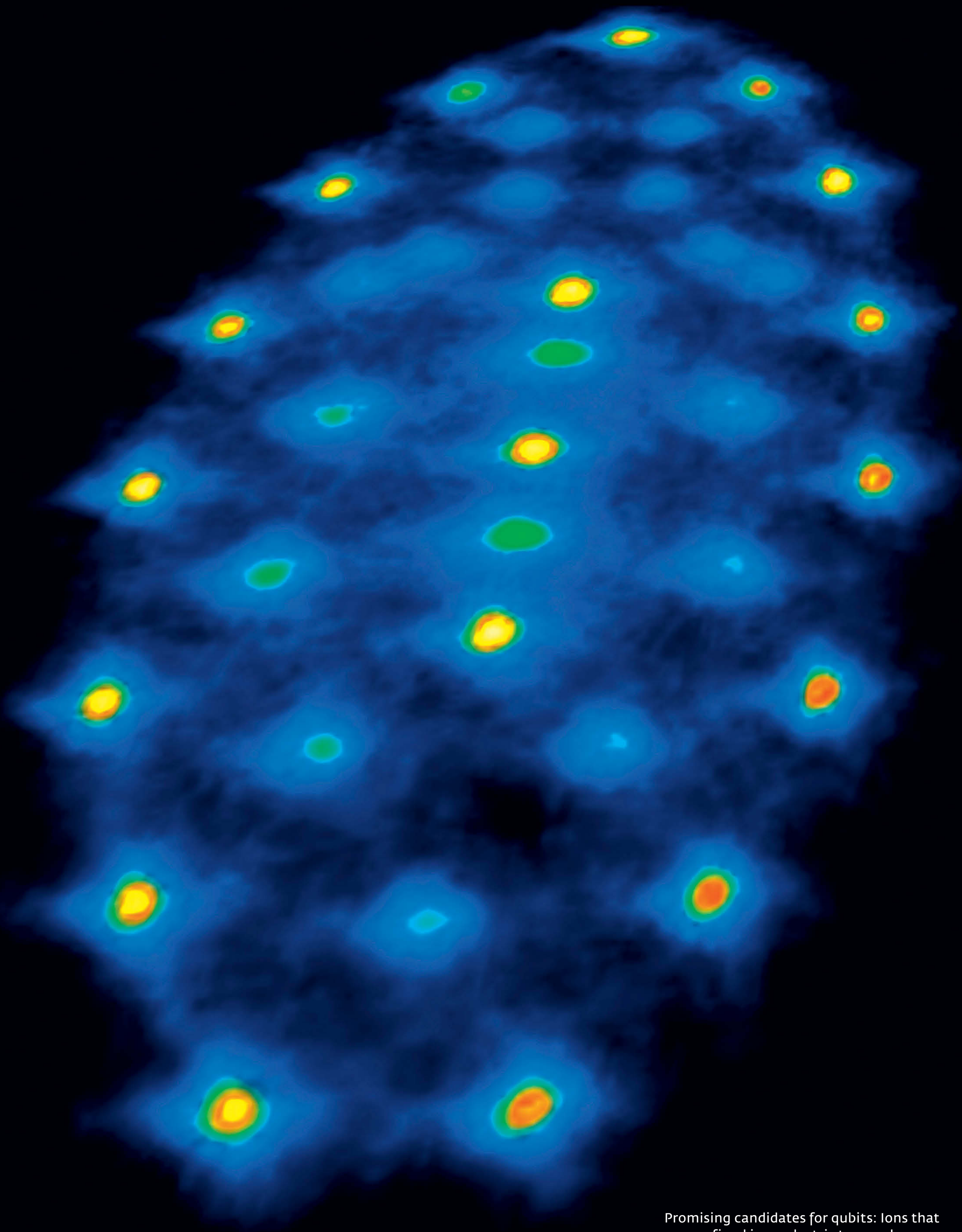
This story starts with a train delay, requiring a phone call to Ignacio Cirac's office while en route. Fortunately, the Director at the Max Planck Institute of Quantum Optics in Garching can move our meeting to a slightly later time. We plan to talk about his research field, quantum information, which holds the keys to allowing the world of physics to realize a number of promising future technologies.

The call made via the cellular network is a good reason to consider how much physics has already made its mark on modern communications technology. Quantum physics is involved in just about everything: from semiconductor electronics to the laser that enables connections across the world at the speed of light via the global fiber-optic network. How much more will future quantum technology change our lives? No one can predict this today, as physicists like Cirac are still in the process of laying the foundations.

IMPORTANT FOUNDATIONS FOR THE QUANTUM COMPUTER

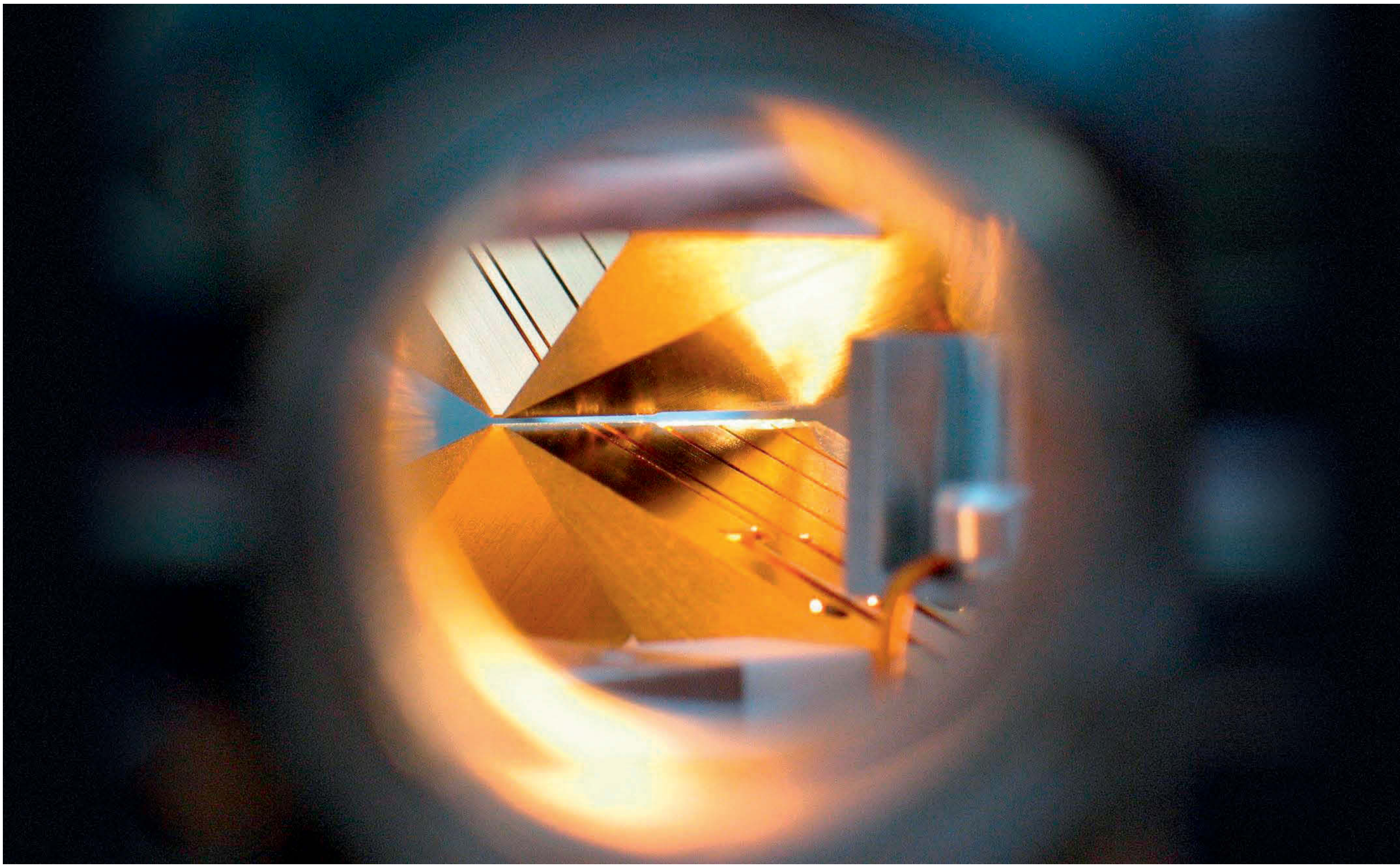
The stress of the journey is quickly forgotten in the relaxed atmosphere in Cirac's office. The Spaniard prefers a quiet, thoughtful environment. We are sitting in the warm September sun, surrounded by light quanta, and move our thoughts into an abstract microcosm. This is where our intuition, which is shaped by relatively large objects, quickly comes up against its limits. Cirac is one of the pioneers of a discipline that has brought such ideas as quantum computers, quantum simulators and quantum cryptography (cf. MaxPlanckResearch 2/2015, p. 60) into the world. He is just as interested in technology as he is in mathematics and the basic questions of quantum physics, and the field of quantum information is the ideal setting for him to combine these three passions.

In the 1990s, Ignacio Cirac and Peter Zoller jointly developed important foundations for a possible quantum computer technology. Zoller, a professor of theoretical physics at the University of Innsbruck, was a scientific mentor of the young Ignacio Cirac, who, between 1996 and 2001, likewise conducted research at the University of Innsbruck. Cirac then became Director at the Max Planck Institute of Quantum Optics. >



Promising candidates for qubits: Ions that are confined in an electric trap and appear here as bright spots can serve as elementary computing units in a quantum computer.

Photo: MPI of Quantum Optics



Trapped in a Paul trap: Ions are ensnared in an alternating electric field generated by four electrodes. Ignacio Cirac and Peter Zoller proposed the charged particles as qubits.

The big moment in Cirac's life as a researcher came in 1994. At the time, he was working as a postdoc with Zoller at the University of Colorado in Boulder, at the Joint Institute for Laboratory Astrophysics. Zoller and Cirac listened to a talk given by Artur Ekert. This Polish-British physicist is now well known for a protocol he developed that can be used to transmit quantum-cryptographically encrypted messages that can't be intercepted. "He talked about quantum computers and how fantastic it would be to be able to build them – but nobody knew how," recounts Cirac.

IONS WERE THE BEST CANDIDATES FOR QUBITS

This gave Cirac and Zoller the crucial idea. As theoreticians, they worked with a technique that was tried and tested in atomic clocks, and that they then remodeled into a fundamental tool kit for quantum computers. The approach is based on individual ions – electrically charged atoms – that are confined in ion traps by electric and magnetic fields.

The trap technology was already so advanced in the early 1990s that the ions trapped inside them could be controlled extremely well. This made them the best candidates available for quantum bits, or qubits for short. Qubits are the equivalent to the bits of conventional computer technology. In the paper they published in 1995, Cirac and Zoller showed that, with sophisticated trap control and precisely tailored laser pulses directed at the ions, the particles can be addressed as qubits, and quantum logic operations can be carried out.

Only three months later, one of David Wineland's teams at the National Institute of Standards and Technology, likewise in Boulder, demonstrated experimentally that Cirac's and Zoller's theoretical proposal works in principle.

But what on earth would quantum computers be good for? They promise to solve a few tasks whose complexity is too much for today's supercomputers. "These are complicated problems that each require a great many equations to be solved," explains Cirac: "The design of chemical compounds, for example, or new materials – and maybe even equations that are contained in such applications as weather forecasts." Powerful computers are used for modeling in all these fields, but they can't provide an exact solution of the equations because their computing power is limited. So they have to work with greatly simplified approximation methods, meaning with compromises that are often unsatisfactory. Quantum computers, in contrast, can theoretically solve some of these problems through "quantum parallelism" – quantum-doped massively parallel computing, as it were – in an acceptable time frame.

"Quantum computers are specialists," emphasizes Cirac. They won't be replacing the computers on our desks. "In principle, they can solve the same tasks as conventional computers," ex-

Photo: MPI of Quantum Optics

» In principle, quantum computers can solve the same tasks as conventional computers, but they use different natural laws than normal computers.

plains the Max Planck Director, "but they use different natural laws than normal computers."

COMPUTERS USE ELECTRON CLOUDS

The basic concepts of modern computers and quantum computers are indeed similar at first sight. Established computer technology uses bits – zeros and ones – mainly in the form of electron clouds, but increasingly also in the form of photons, or light quanta. It executes logic operations using logic gates and stores the intermediate results in registers. Quantum bits, quantum logic gates and quantum registers will work in a similar way in a quantum computer.

The fundamental difference is evident when a qubit is examined in greater detail. Qubits are typically individual electrons, photons or atoms. They are therefore much smaller than digital bits. This ultimate miniaturization automatically immerses one in a strange microworld. "The logic of quantum mechanics rules here," explains Cirac with a smile, "and its laws are slightly unusual." Quantum computers can thus achieve things that conventional computers aren't capable of.

A qubit has two quantum states, which correspond to the zero and the one of a conventional bit. As a quantum particle, it can additionally be in a superposition of these two states, and that is the crucial difference. Physicists also call this the state of Schrödinger's cat – in remembrance of a thought experiment proposed by Erwin Schrödinger. It involves a radioactive atom that can decay randomly, triggering a poisoning mechanism that kills a poor cat in a box. As long as the lid of the box is closed, no information is available as to whether the atom has decayed or not – that is, whether the cat is dead or alive. From a quantum mechanical point of view, the two cat states in the box are superimposed.

The qubit therefore has an infinite number of intermediate states – in contrast to the two states of the digital bit. But this applies only as long as its state isn't measured in the classical sense, meaning by opening Schrödinger's box. As soon as that happens, the qubit jumps into one of the two fundamental states, which represent zero or one. It is now known whether the cat is still alive or not. Consequently, if one wants to use the added value of qubits from quantum information technology, the cat must first remain undisturbed in the box.

But the superposition of the two states within a qubit is just the beginning. Even a Ronaldo can't score a soccer goal all on his own – it takes a well-coordinated team. A crucial key to the computing power of future quantum computers, in turn, is the ability to prepare several qubits in a shared quantum state – in a superposition of the superposition, so to speak. This complex collective state is called entanglement, and it is the reason for some of the eccentric properties of quantum mechanics.

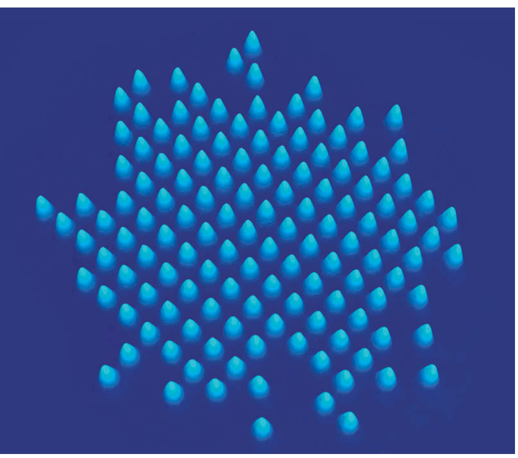
In the quantum computer, entanglement must operate as a quantum mechanical arithmetic unit. The operation can be imagined in simplified form as follows: The task is written into a set of qubits and then the entangled quantum system is left to work in peace. In principle, the enormous computing power of the quantum parallelism of entanglement contains all possible solutions to the task and runs through them. In this way, even relatively small numbers of qubits can develop a computing power that beats all conventional computers.

After a certain time, the quantum arithmetic unit is stopped and the result read out. If the timespan and the programming were selected with skill, the solution to the task will have been obtained.

A FURTHER CONCEPT: ATOMS IN AN OPTICAL LATTICE

Today, various concepts for the architecture of quantum computers are being investigated. These concepts differ in the details of how they work, but the picture described here conveys a basic sense of the operating principle of quantum computers.

In 1998, Cirac and Zoller published a second influential concept, which physicists today are putting to the test in many other variants besides ions in traps. In this proposal, a cloud of electrically neutral atoms is cooled to a few millionths of a degree above absolute zero. A three-dimensional lattice made of laser beams is then laid through this cloud. The individual atoms are drawn to the points of intersection much like



Atoms are arranged in an optical lattice like eggs in an egg carton. Such a system could also serve as the computing core of a quantum computer.

eggs slip into the wells of an egg carton. Arranged in this way, they can be manipulated as qubits.

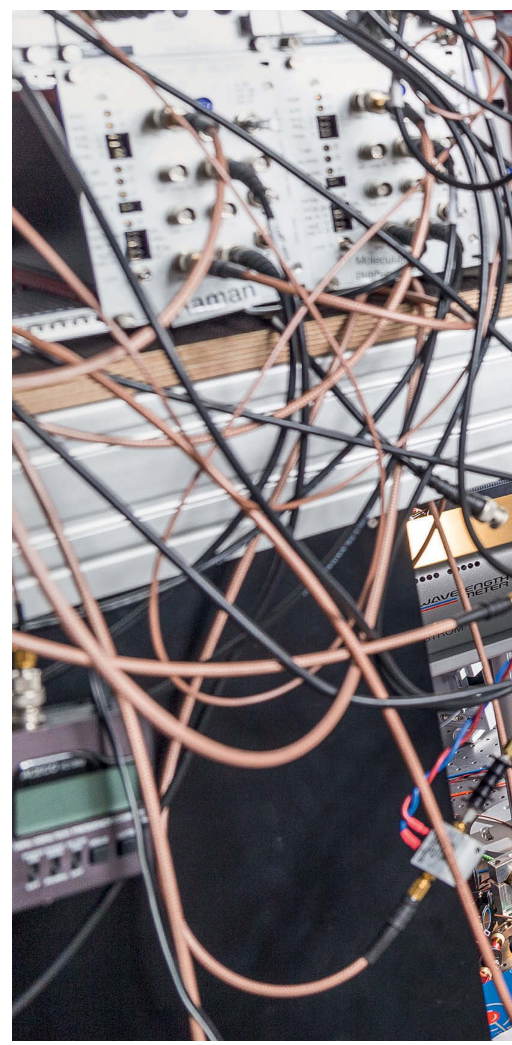
The optical lattice has the advantage over ion technology that it can control many thousands, even hundreds of thousands of qubits simultaneously. However, they can't yet be controlled as well as trapped ions. The ion technology, in contrast, long resisted combining a larger number of qubits, as the ions repel each other electrically. Now, however, both technologies are increasingly overcoming their weaknesses and coming closer to each other.

Despite the promising approaches, there is still a long way to go before we have true quantum computers, regardless of the promises made by the first commercial suppliers and the millions invested in their development, also by companies like Microsoft, IBM and Intel. "I am convinced that they will be built," says Cirac, "but it may take another ten, twenty or even fifty years."

The situation is different for quantum simulators – specialized, slimmed-down versions of the quantum computer. The department of Immanuel Bloch, a fellow Director in Garching with whom Cirac closely collaborates, is already carrying out the first quantum simulations with optical lattices. The quantum simulator goes back to an idea that American physics Nobel laureate Richard Feynman presented in the early 1980s. He – and not only he – was bothered by a fundamental problem with which physics still struggles today: although it can generate the exact equations for the behavior of complex systems made up of many quantum particles, it can't provide an exact solution for them. "We even fail for a system of just one hundred electrons," says Ignacio Cirac.

ONE QUANTUM SYSTEM IS MODELED USING ANOTHER ONE

Feynman came to a radical conclusion: the behavior of a quantum system can only be modeled efficiently by using another quantum system. Electrons, for example, determine the properties of matter. But they're not readily accessible, so it is difficult to investigate their behavior. A quantum simulator, however, could simulate it using qubits that can be controlled directly. Even with only a few dozen qubits, a quantum simulator could thus reproduce the properties of many fundamental building blocks of matter very accurately. Quantum simulators therefore promise to revolutionize the development of new materials. They



Not just a theory: The concepts developed by Ignacio Cirac's group are also implemented experimentally in the laboratories of Immanuel Bloch's department at the Max Planck Institute of Quantum Optics. Here, Cirac stands next to a laser bench with numerous optical instruments that are used to generate optical lattices.

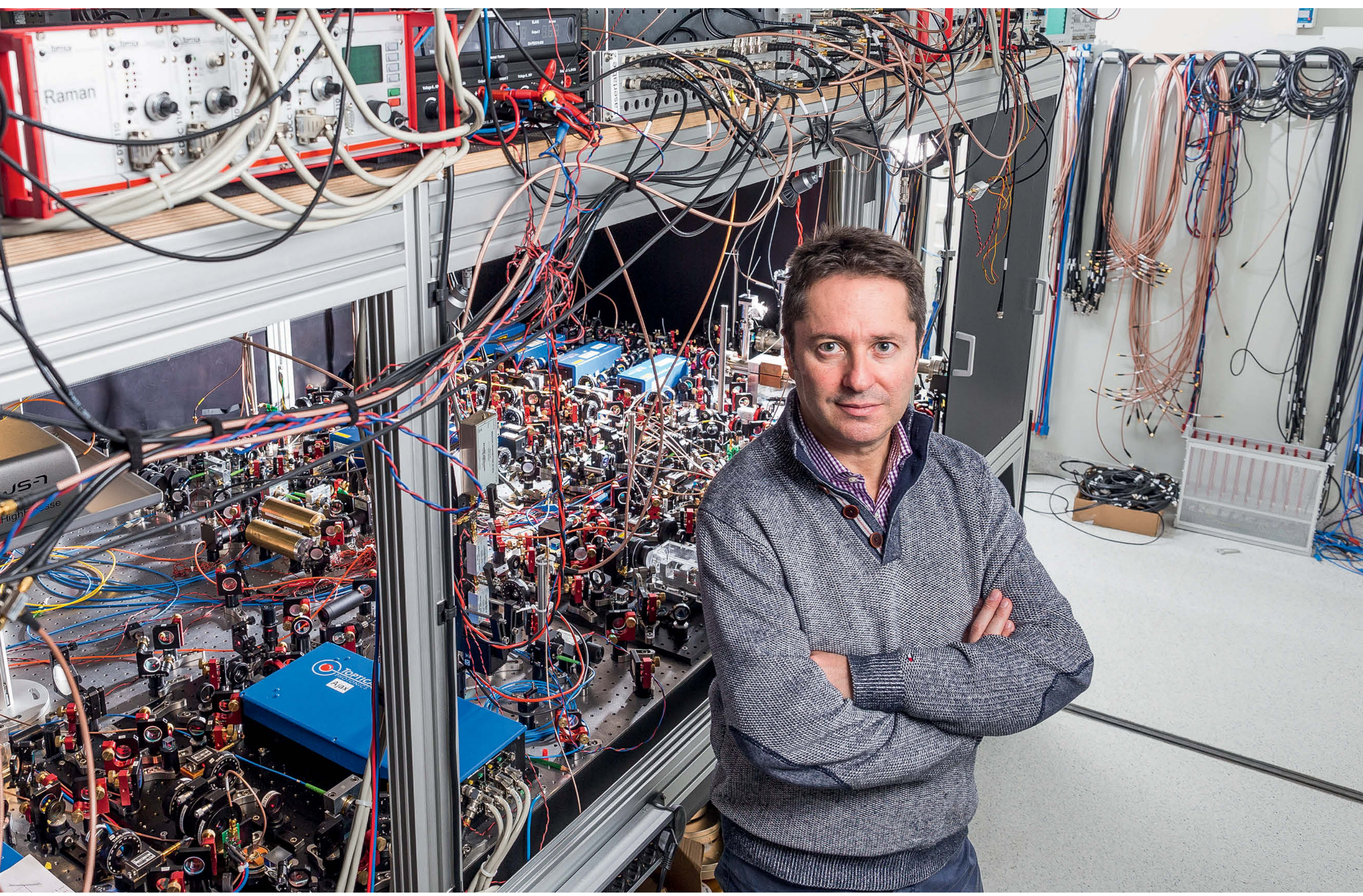
Photo: MPI of Quantum Optics

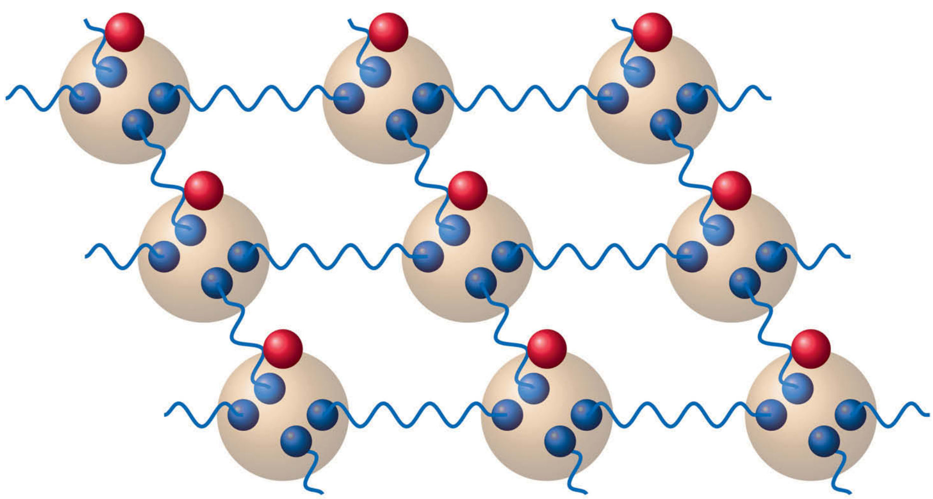
» Cirac's team is primarily interested in using quantum information methods to advance physics in other fields.

Photo: Axel Griesch

could assist in solving the mystery of high-temperature superconductivity, for instance, and in developing better superconductors.

Quantum simulators and quantum computers are the hardware, and quantum algorithms are their software. In 1994, when Cirac and Zoller had the idea of quantum computer components, American mathematician Peter Shor had just developed such an algorithm. Quantum computers can use it to factorize numbers much faster than modern computers. Factorization is the reverse of multiplication. This means it involves division, but in a way that results in prime numbers. For example, 15 is split up into 3 and 5. This example is trivial, of course. "But just imagine this for a number with 200 digits," says the





Left Determining the properties of a quantum system of real particles (red spheres) is as complicated as it gets, as all particles interact among each other. The physicists in Garching therefore describe each real particle with four virtual particles (blue spheres), each of which is entangled with a virtual particle of a neighboring particle (indicated by the wavy lines). Because the virtual particles are projected onto the real particle (indicated by the large beige-colored spheres), physicists call this "projected entangled pair states" (peps) – one example of a tensor network.

Right-hand page Ignacio Cirac talks with András Molnár and Yimin Ge (left to right) about how tensor networks can be used as algorithms to simulate an unknown quantum system by means of a known one.

physicist: "All of today's supercomputers taken together would fail."

What looks like academic mental acrobatics has a very topical practical significance. Most of today's common encryption methods for messages rely on eavesdroppers being unable to crack the number codes used for encryption in this way, or at least not in a viable time span. Functional quantum computers could thus crack these encryption methods. There is a good reason why secret services are extremely interested in quantum information technologies.

ACCELERATED SEARCH IN UNORDERED DATABASES

But also other technical applications are conceivable today: the so-called Grover algorithm, for example, would accelerate searches in unordered databases enormously. IT experts see this as making great progress, given the vast and ever-increasing amounts of data now being processed in many computer applications.

Cirac's team is interested primarily in using quantum information methods to advance physics in other fields. In addition to the physics of condensed matter – materials research within physics – the main focus of interest is particle physics, which is carried out in the large accelerator facilities. Here, too, the important thing is to understand complex quantum effects involving large numbers of particles in order to gain a deeper understanding of the origin of matter and forces.

In all these fields, a new mathematical method from quantum information could be of assistance – the so-called tensor networks. Cirac is counting on these. One of his teams has just developed a new quantum algorithm on this basis. The doctoral students András Molnár from Hungary and Yimin Ge from Austria struggle to provide a graphic explanation. "Imagine a chain of one hundred spheres that can be either red or blue," explains Ge. But all the colors of the spheres in the chain are superimposed. "Even on a computer screen, it's not possible to display what this would look like," says the mathematician.

ALGORITHM FOR A MANY-PARTICLE SYSTEM

Tensor networks, however, can precisely describe the behavior of the chain of spheres. Their color superposition is an illustrative image for the superimposed states of one hundred qubits, of course. The Garching-based researchers can now use their algorithm to compute how such a complex system develops over time if the spheres are allowed to change color. They can use rules to adapt their algorithm to the typical behavior of real quantum systems of many particles – such as a semiconductor crystal.

This is how physical systems minimize their energy bill, which is why water freezes to ice as the temperature drops. "For our spheres, for example, we

Graphic: Thorsten B. Wahl

could introduce the rule that it costs ten virtual euros if two neighboring spheres ultimately have different colors," says Ge. With this rule and the instruction to be economical, the chain of spheres will, over time, approach a state of uniform color, just as many quantum systems transition into a collective quantum state at low temperatures.

Although the result was easy to predict intuitively in this simple example, the path to the solution is difficult to describe in a mathematical model. Similarly, the scientists in Garching can also train their system for a physical behavior whose outcome can't be easily anticipated. They could, for instance, simulate as yet unknown properties of new materials.

At present, no one can say what impact this basic research will have on our culture. But looking at the key role physics developments play in today's information and communications technology suggests that the impact could be very significant indeed. ◂

Photo: Axel Griesch

TO THE POINT

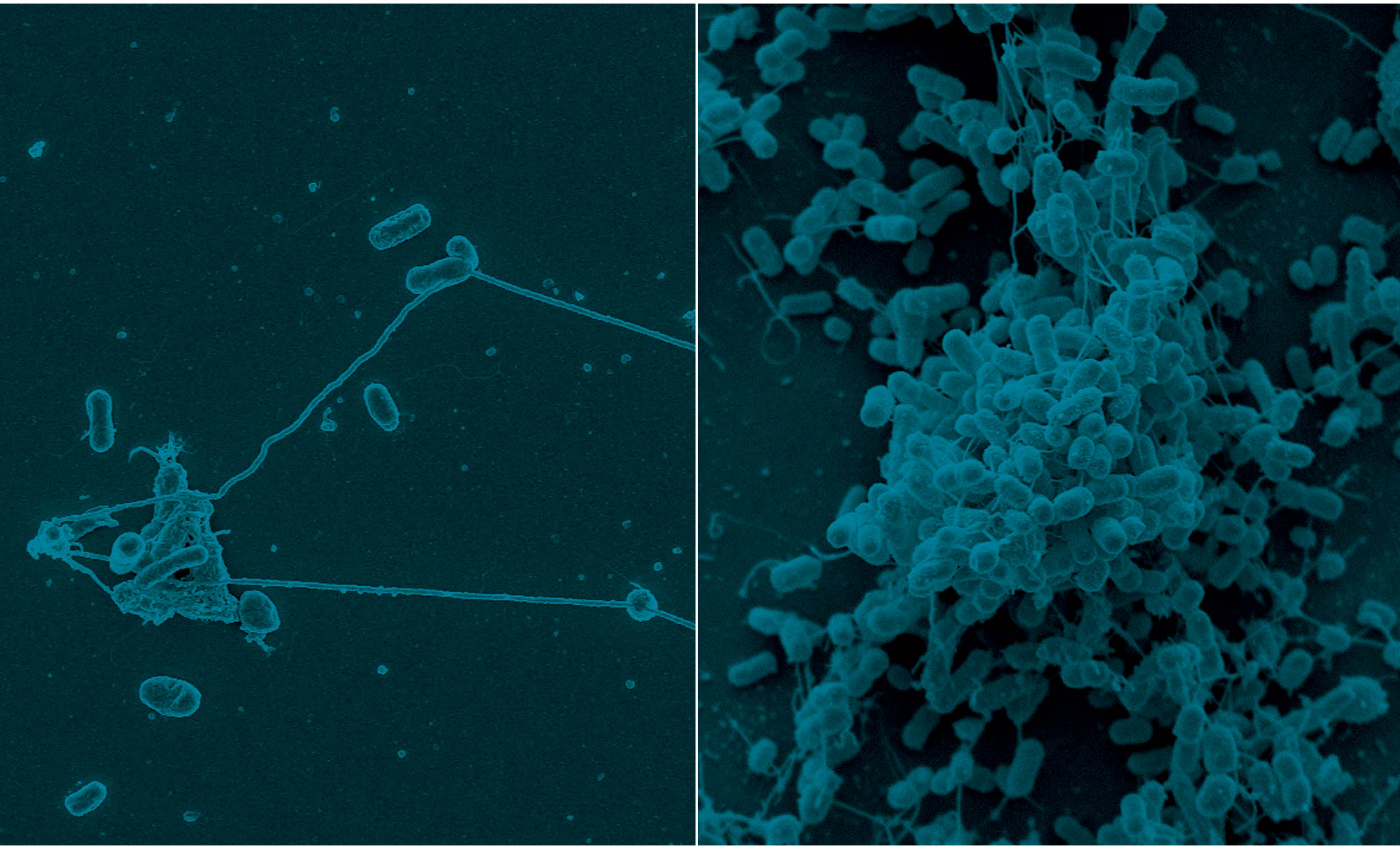
- **Quantum computers can manage tasks that would overwhelm even today's supercomputers in practicable computing time, as they can carry out massively parallel quantum computations with the aid of the quantum physical entanglement of qubits.**
- **In the near future, quantum simulators – simpler versions of a universal quantum computer – could already be solving complex physical problems and assisting in the development of new materials.**
- **Max Planck scientist Ignacio Cirac, together with Peter Zoller from the University of Innsbruck, has proposed two concepts for the practical design of quantum computers and simulators: with ions in electromagnetic traps or with atoms trapped in lattices made of laser beams.**

GLOSSARY

Qubit: Like a conventional bit, a quantum bit, or qubit for short, has two states that represent zero and one; unlike a bit, however, it can also assume all superposition states in between.

Tensor network: A mathematical method to describe the state of a quantum system consisting of many particles. Tensors, which are mathematical functions, serve here as building blocks that, when put together, provide a description for the desired state.

Entanglement: When two or more quantum particles such as atoms are entangled with each other, they are in a superposition state of one property before a measurement. With the measurement on one particle, this property is then fixed not only on the measured particle, but immediately also on the particles with which it is entangled.

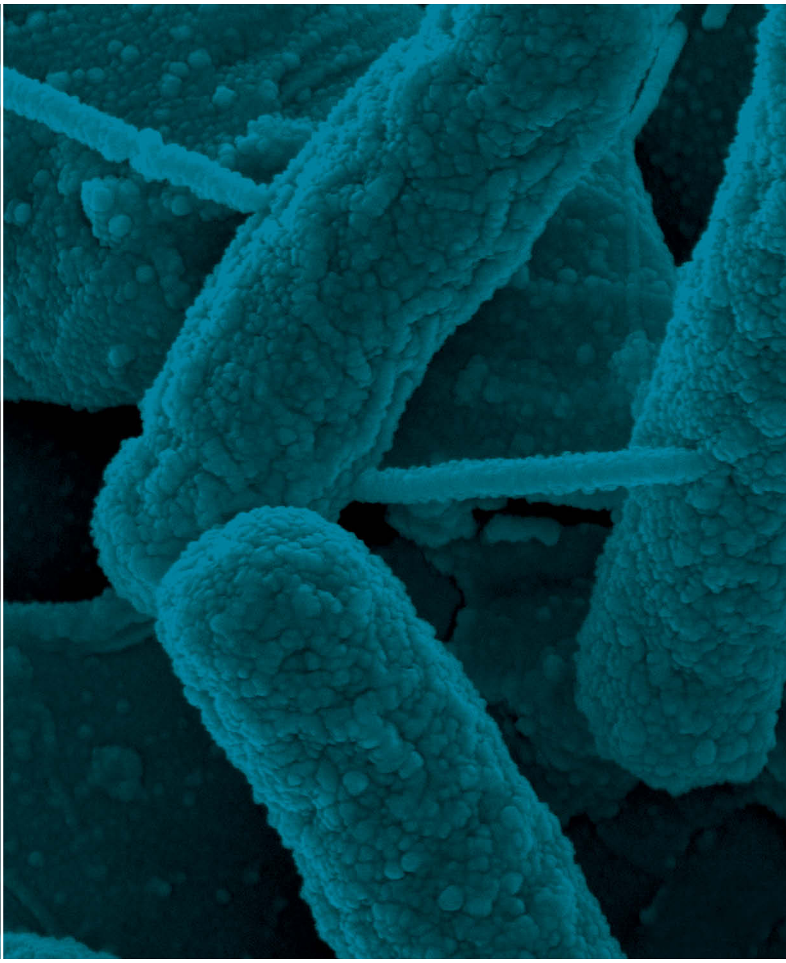


Bacteria Need Partners

Bacteria are individuals that always operate in isolation? Not at all, says **Christian Kost** of the **Max Planck Institute for Chemical Ecology** in Jena. In fact, he thinks bacteria frequently can't help but cooperate. His team is using cleverly devised experiments to test this hypothesis.

TEXT **KLAUS WILHELM**

Photo: MPI for Chemical Ecology (2)



Networking bacteria: The electron microscope reveals the tubular connections between genetically modified *Escherichia coli* and *Acinetobacter baylyi* bacteria. The microbes use these tubes to exchange amino acids.

"When I saw it, my first thought was that we must have made a mistake." Shraddha Shitut, a doctoral student at the Max Planck Institute for Chemical Ecology in Jena, looks at her boss Christian Kost and laughs. Kost, in contrast, a biologist and Leader of the Experimental Ecology and Evolution Research Group, was "immediately sure that everything had worked out just fine and we had discovered something fundamentally new."

Still, Shraddha Shitut repeated the experiment over the following days with her colleagues Lisa Freund and Samay Pande. And then once again, just to be sure. "But we always saw the same thing under the electron microscope," she says. The instrument, which can reveal even the tiniest structures measuring a millionth of a millimeter, showed that small channels called nanotubes linked individual bacteria together.

NANOTUBES TRANSPORT NUTRIENTS

Bacteria use these tubes to reciprocally exchange certain nutrients that are vital for their growth, but that they can no longer produce on their own. Without the missing amino acids, both partners would die. "They depend on each other," says Kost. "In fact, you could say they literally cling to one another for survival."

"I believe in my staff, otherwise I'd be lost," says Christian Kost. He is a team player – and team play is the focus of his professional career, too. After all, the researcher is studying the social life of bacteria and how they cooperate. The social life of bacteria? Although it seems bizarre, Kost believes this concept holds the key to life in general.

When he talks about his hypothesis, he does so with passion and conviction, backed up by the findings of his cleverly devised and carefully controlled experiments. "It's always better to cooperate than to live on your own," he says. Always? A brief

Photo: MPI for Chemical Ecology (2)

Photo: Anna Schroll

Left-hand page To increase confidence in their data, the researchers must repeat their experiments several times and grow different cell types in separate culture vessels. This results in stacks of petri dishes.

Above Shraddha Shitut (left) counts the bacterial colonies (right) that have grown in the petri dishes to determine how successfully they have reproduced.

pause. “Nearly always! And that’s true for all organisms, from bacteria on up to humans.”

The 40-year-old scientist is challenging cherished principles. In contrast to common beliefs, he thinks that “bacteria can’t help but work together.” He believes that the assumption that bacteria always function as independent units is incorrect.

REPRODUCING ON THE DOUBLE

Kost is an evolutionary biologist, so he thinks in the patterns and principles that have shaped the science of life since the times of Charles Darwin. It follows that his hypotheses must stand up to the most fundamental assumption of the theory of evolution: that cooperating organisms reproduce in greater numbers than selfish ones. However, it is virtually impossible to demonstrate this unequivocally under natural conditions.

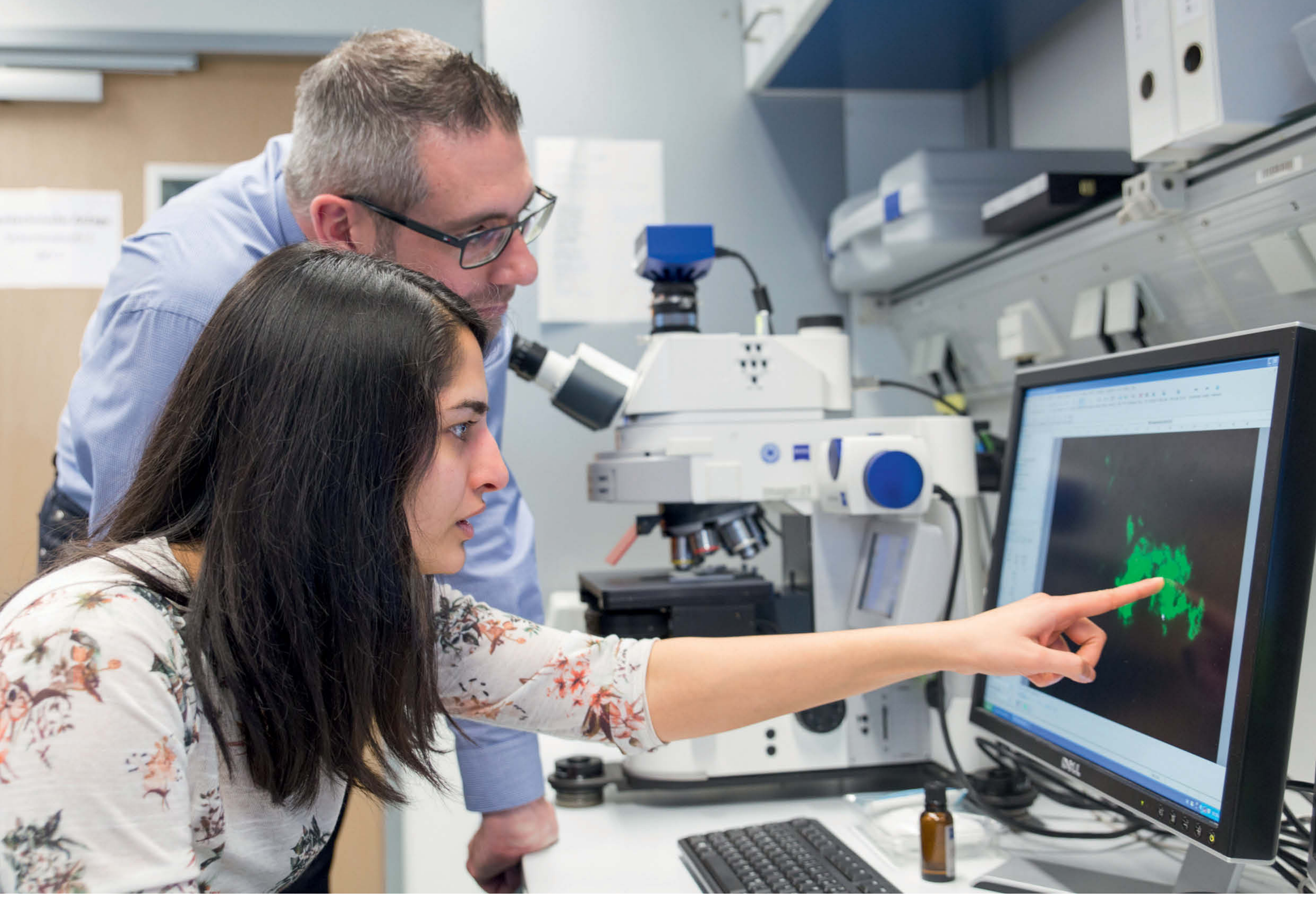
Still, it should be possible to mimic evolutionary processes under laboratory conditions, including the evolution of cooperation, reasons Kost. “Observing the process of evolution in real time and monitoring it scientifically over the course of mere days or weeks – that fascinates me,” he says. This type of experiment is possible because some species of bacteria divide every 20 minutes, so they produce offspring very quickly. Moreover, it is also possible to turn off specific genes in a single day, and to control environmental conditions at will.

Based on those premises, the Jena-based scientists came up with a laboratory experiment. They took the gut microbe *Escherichia coli* that is very popular among scientists and switched off a gene that is responsible for producing an essential amino acid A. A second mutation caused the bacterium to produce an increased amount of amino acid B. The researchers also modified another bacterial strain with a converse set of mutations, such that it produced excess amounts of A, but not B. Both populations were then put together into a culture medium to see how they would develop.

IT PAYS TO WORK TOGETHER

Rather than dying, the bacteria reproduced 20 percent faster than *Coli* strains that could autonomously produce all amino acids. The two mutants that lacked two genes each must therefore have supplied each other with the missing amino acids. This demonstrates that cooperation is advantageous, also in terms of Darwinian evolution. >

Photo: Anna Schroll (2)



As a consequence, those bacterial strains that can produce all metabolites autonomously should be at a disadvantage within bacterial communities. Why? Because producing the full range of amino acids consumes more energy than sharing the workload with other individuals. Ultimately, cells are thrifty by nature – even if it costs them the freedom of living independently.

But how do cooperating microbes exchange nutrients? This is a serious issue, because if they simply release the amino acids into the environment, other microbes that are not investing in the partnership could benefit as freeloaders, putting the whole venture at risk. A direct connection, on the other hand, would be ideal – a closed pipeline for passing nutrients between cooperators.

Again, the researchers switched off genes for the production of certain amino acids, this time using the soil microbe *Acinetobacter baylyi* as well as *Escherichia coli*, because even bacteria of different species can get along. “It’s most probably very widespread in nature,” says Kost. The results of this experiment showed that, as expected, the strains that were cultivated together in the medium grew best.

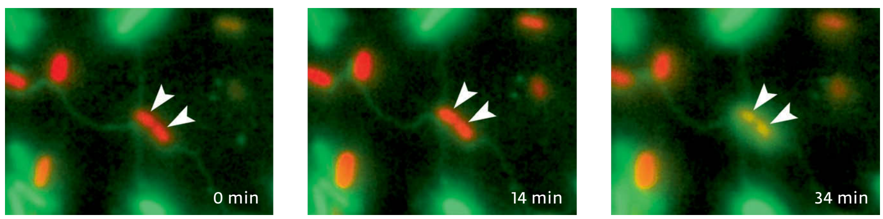
PHYSICAL CONTACT IS NECESSARY

In another test, the cooperating microbes were separated using a filter that allowed amino acids in the medium to pass, but prevented direct contact between the two genetically modified strains. Without contact, none of the microbes were able to grow. “This means the microbes in the partnership need physical contact in order to exchange nutrients,” explains Shraddha Shitut.

Examining images under the electron microscope, Shitut then noticed that, on their outer cell envelope, the *E. coli* bacteria had formed small tubes that were stretching over to the *Acinetobacter* cells: the nanotubes. Presumably one cell taps into the other to access a nutrient, but the partner can also use the channel itself. For motile bacteria such as *Escherichia coli*, producing nanotubes is worth the effort. As soon as they “smell” a potential food source, they presumably move toward it and establish the tube. However, for a microbe such as *Acinetobacter* that can only move passively – for example in flowing water – producing nanotubes is probably not worthwhile, unless a cell that can fill its nutrient gap just happens to be right next to it.

In order to verify their results, the scientists performed another experiment. This time, they supplemented the culture medium with all the required substances, including the amino acids that the genetically manipulated microorganisms could not produce on their own. In this case, the production of nanotubes stopped. “So the formation of these structures obviously depends on how hungry a

Photo: Anna Schroll



Left-hand page A fluorescence microscope helps Shraddha Shitut and Christian Kost study the nanotubes. A green fluorescent dye indicates that the tubes are made from the same material as the bacterial cell membrane.

Above Dyes unveil the exchange between genetically modified *Acinetobacter baylyi* (red) and *Escherichia coli* (green). At the start of the experiment, both species contain the dyes originally administered (left). Gradually, the green pigment moves through a tube from an *Escherichia coli* cell to an *Acinetobacter* cell (middle). After about 30 minutes, the two pigments have become so mixed that the cell appears yellow (right).

cell is," says Christian Kost. And on how many nutrients they release into their environment.

ONLY HUNGRY CELLS FORM NANOTUBES

If enough amino acids are released, there is no need for the tiny tubes, as the cooperators can simply absorb the nutrients they need from their environment. "Because," explains Kost, "forming these tubes likely consumes energy."

Further investigation will be required to determine whether these nanotubular structures are formed solely to enhance efficiency or whether there are other reasons, for example if some types of bacteria use them to parasitize others. Another question that remains unclear is whether the bacteria can actively choose the cells to which they attach, since the microbe at the other end of the tube could potentially contain harmful substances.

Christian Kost interprets the formation of these cooperative communities as evidence of "a principle of self-organization." This can be observed when bacteria are inoculated onto an agar plate. Obtained from algae, agar combined with sugars provides a culture medium for microorganisms.

Once again, the Max Planck scientists in Jena generated double mutants of *Acinetobacter baylyi* and *Escherichia coli*, each strain lacking the ability to produce one particular amino acid, yet producing excessive amounts of another one. This time, however, the bacteria released the amino acids into their environment. The two groups were then pipetted onto an agar plate along with auxotrophic microbes that also required amino acids to grow, but that did not contribute to their production.

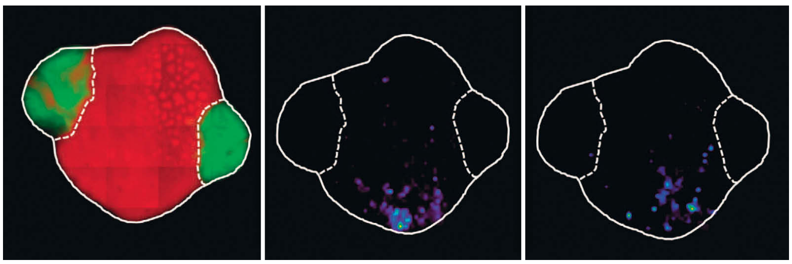
At the onset of the experiment, all cells were perfectly mixed. However, after just 24 hours, says Kost, "we could see a clear spatial distribution." Initially, a small number of double mutants happened to be side by side. Since both types released their surplus amino acids into the environment, double mutants in the immediate vicinity benefited most.

Where non-cooperating bacteria were nearby, the growth rate of the cooperative double mutants was reduced. Over time, auxotrophic cheaters were pushed farther out toward the edge of the colony – like outsiders in human societies. This spatial separation seems to stabilize the system evolutionarily.

Intuitively, one might assume that the system should collapse, because non-cooperating bacteria derive benefits without contributing, thus sucking the cooperators dry. "Not so." says Kost. "Our results show that the colony settles and stabilizes at an equilibrium such that all participants can coexist."

Still, the cooperating partners fare better than the parasitic loners. In reality, they are all dependent on each oth-

Photo: Nature Communications



As shown on the left, selfish bacteria (green) can only exist on the edge of cooperating bacterial colonies (red). High concentrations of the amino acids histidine (middle) and tryptophan (right) occur only where cooperating microbes are located, and not around the selfish cells.

er; freedom in the sense of independence seems to be a truly rare condition. "It doesn't make sense to do everything for oneself. It's always better to divide the labor," says Kost.

EVOLUTION FAVORS COOPERATION

He sees this as only logical in light of the latest research results. The driving force is the loss of functional genes, and gene loss is inevitable because genes face constant mutation pressure. In this process, the probability that a gene will be destroyed is significantly higher than the probability that a new, beneficial gene will emerge. Given this context, bacteria can't get around entering into obligate interactions with each other. They are thus compelled to cooperate.

"Cooperation and the division of labor are powerful principles in evolution," says Kost, and explains that the genomes of more than a thousand species of bacteria have now been decoded. Remarkably, only about 35 percent of those possess *all* genes they need for survival.

"That's only the tip of the iceberg," suspects the biologist, "because to date we have mostly sequenced the genomes of bacteria that can be cultivated in the laboratory, and those represent less than one per mill." It seems that losing genes is no problem for bacteria, because the resulting cooperation requires less energy.

In natural ecosystems, such cooperation may give rise to multicellular units comprising representatives of different species – colorful networks that are more than the sum of their parts, along the lines of "my neighbor, my savior!" The group gains new benefits from the interactions between different microbes. "And the more we study it, the more we realize that this occurs in natural conditions, too," says Christian Kost. ◂

TO THE POINT

- **For many years, bacteria were thought of as purely individualistic organisms, but they are well able to cooperate, thus compensating for gene loss.**
- **Many bacteria are part of a network that even connects them to bacteria of other species.**
- **Cooperation is a basic principle of life and a driving force for the development of biological complexity. Individuals combine to form superorganisms ("holobionts") in which the dividing lines between individuals are blurred.**

GLOSSARY

Auxotrophy: Auxotrophic organisms are unable to produce one or more vital substances for themselves, and must obtain them from their environment instead. Auxotrophy arises when a mutation deactivates a gene required for the production of an essential nutrient.

Evolution: According to the neo-Darwinist theory of evolution, natural selection can only work at the level of the individual. British biologist Richard Dawkins believes selection starts with even smaller units, namely genes. This means that a gene is prioritized for passing on to the next generation if it is of benefit to the individual. It provides its carrier a selective advantage, increasing its evolutionary fitness. However, this does not rule out the possibility of group selection. Under certain conditions, evolution favors whole groups; cooperation between different species of bacteria is an example of this.

The ISME Journal (2015)

Für Forscher, Entdecker, Wissenschaftler – und solche, die es werden wollen:

Junge Wissenschaft

Das einzige europäische Wissenschaftsmagazin mit begutachteten Beiträgen junger Nachwuchsforscher.

Wissenschaftliche Erstveröffentlichungen und das Neueste aus Mathematik, Informatik, Naturwissenschaft und Technik.

Nur im Abo. Viermal im Jahr News aus Forschung und Technik, Veranstaltungen, Porträts, Studien- und Berufsprofile.

Vorteilsabo sichern!

abo@verlag-jungewissenschaft.de
Stichwort: „Vorteilsabo"

Leseprobe anfordern!

leseprobe@verlag-jungewissenschaft.de
oder per Fax 0211 / 74 95 64-29

Vorteilsabo

nur 20,-€*

für Schüler, Studenten, Referendare und Lehrer (4 Ausgaben für 20,00 EUR statt 30,00 EUR)*

*zzgl. Versandkosten

www.verlag-jungewissenschaft.de

Bedtime Stories or Bali?

Decisions follow a script all their own. Sometimes current facts play a role, sometimes utility is the driving force – and sometimes they are rooted deep in human evolutionary history. **Ralph Hertwig**, Director at the **Max Planck Institute for Human Development** in Berlin, studies the dynamics of choice, uncertainty and risk. And he advises grandparents to help look after their grandchildren.

TEXT **MARTIN TSCHECHNE**

Perhaps it is of no great importance that Susanne has been to Italy, has accounting experience and previously worked at Lidl. She speaks Dutch and has a friendly nature. Maybe that's more important. Every piece of information could be the one that makes the difference. Anna also speaks Dutch, but she worked at Aldi, has advertising experience, lived abroad in Sweden and radiates authority. Anika Josef and Thorsten Pachur, psychologists at the Max Planck Institute for Human Development in Berlin, haven't made it easy for the participants in their study. They asked women and men from a variety of age groups to decide who is better suited for a job, then inundated them with information about fictitious applicants: Susanne and Anna, Julia and Carmen, Franziska, Melanie and Vera; their foreign languages, previous employers and areas of special expertise, biographical details and character traits. In reaching a decision, the participants must either tolerate uncertainty or eliminate it. So which candidate is the best?

Is this a realistic situation? Sure, says Thorsten Pachur: processes such as organizing our personal lives; dealing with the growing complexity of the work environment, the rapid changes in technology in both domains, and the demands of an increasingly compartmentalized market; and choosing between insurance policies, investments, and even green energy or telecommunications suppliers; all require detailed knowledge of facts, a good memory and keen judgment. In his dissertation nine years ago, Pachur already examined how the outside world is reflected in our minds. And, as doctoral student Anika Josef points out, things don't become any less demanding with age.

DIFFICULT DECISIONS AMID INFORMATION OVERLOAD

The team of neuroscientists, economists, philosophers, biologists and mathematicians headed by psychologist Ralph Hertwig at the Max Planck Institute in Berlin is breaking new ground in the research field of adaptive rationality: How can the world be expressed in terms that can inform decisions? What level of precision is required? And how much uncertainty can be tolerated, or may even be help-

Photo: Corbis

To jump or not to jump? Some decisions depend primarily on an individual's risk-taking propensity.

» Not many 60-year-olds will expose themselves to the risks of bungee jumping. Simply because, at their age, it's no longer necessary.

ful, when time is short, information is incomplete, or – as some of us have already noticed – it becomes increasingly difficult with age to remember names and other details? Research on adaptive rationality addresses how real people navigate the real world – a world that isn't rationally structured and manageable down to the last detail, a world inhabited by people who are sometimes overwhelmed by the sheer abundance of choices.

But wasn't it this Institute that attracted so much attention, well beyond scientific circles, by identifying strategies that empower people to make good, or at least satisfactory, decisions even under significant constraints? Namely by applying simple heuristics such as the recognition heuristic, which states that if better information isn't available or retrievable, or if the amount of information is overwhelming, it may be sufficient to choose the option you're more familiar with, the one you recognize or have heard before. Which city is larger: Detroit or Milwaukee? Regular readers of the financial pages may rack their brains weighing up the declining automotive industry on the one hand and the prospering brewing trade on the other – and come to the wrong conclusion. Whereas simply choosing the more familiar name from a European perspective, without putting great thought into details and background information, will deliver the right solution: Detroit, of course.

And wasn't it this Institute that developed the adaptive toolbox, full of easy-to-apply solutions that confirm that we really don't need to weigh up every little detail in day-to-day life in order to select a decent meal from a menu, for example? Or to get a sense of which candidate is suitable for a job after just a few moments, a few words, taking only sparingly selected data into account, based only on our experience and understanding of human nature? Surely someone who's worked in an HR department for 20 years is able to perform this feat with their eyes closed?

YOUNG ADULTS GET THE MOST HITS

"I worked long and hard on the adaptive toolbox with Gerd Gigerenzer," says Hertwig. "We're still working on it." The solutions Gigerenzer proposed – fast and frugal, quick and easy – retain their alluring elegance, an almost aesthetic quality, but to establish their validity, researchers now need to explore their limits. "What do you think more people in Germany die of today: cholera or botulism?" asks Pachur, with an enigmatic smile. Even the friendly hint that "botulism" means "food poisoning" doesn't stop his interviewer from backing the wrong horse. After all, we've all heard of cholera; we all have a mental picture of the terrible epidemic that wiped out millions, even if we practically only ever read about in history books. But when was the last time you heard of a case of botulism? There you go then. Or not? Cholera is the wrong answer. Hertwig gives a satisfied nod.

And it's precisely here, he says, that his research into adaptive rationality steps in. The goal is to pave the way for widespread risk literacy – that is, the ability to recognize, accept and react appropriately to everyday uncertainties. It is against this background that Anika Josef and Thorsten Pachur asked their study participants in the Institute's research lab to perform tasks requiring mature judgment and a keen memory: Which lottery drum is the better bet? Which is more appealing – one where almost every ticket promises a small prize or one offering a large win with a frequency that can be determined through trial and error? If there are just two drums, the solution may emerge quite quickly; if there are eight, however, the numbers begin to dance. And older participants typically do less well.

"Fluid intelligence," explains Pachur, "is the ability to adjust flexibly to the demands of a new situation, to identify the key elements and be able to recall them. It peaks in young adulthood and declines steadily from then on." This finding has long been recognized in the cognitive sciences. But the declining ability to adapt to new situations is often offset by crystallized intelligence. Experience, mature knowledge of the world and a rich and nuanced vocabulary: all of

Right or left? We constantly have to make decisions, often in complex situations, under time pressure and without all the necessary information. Ralph Hertwig, Director at the Max Planck Institute for Human Development, studies which strategies people use to make these decisions.

this helps older adults to spot patterns, separate the important from the unimportant, and develop efficient strategies – provided that the task corresponds to the experiences of the world they have gradually constructed, continually revised and cleverly arranged over time. Provided, in other words, that the world doesn't consist of eight lottery drums with different chances of winning.

And yet sometimes it does. Sometimes none of our routines can help – as anyone who has ever despaired of installing the latest apps on their smartphone is painfully aware.

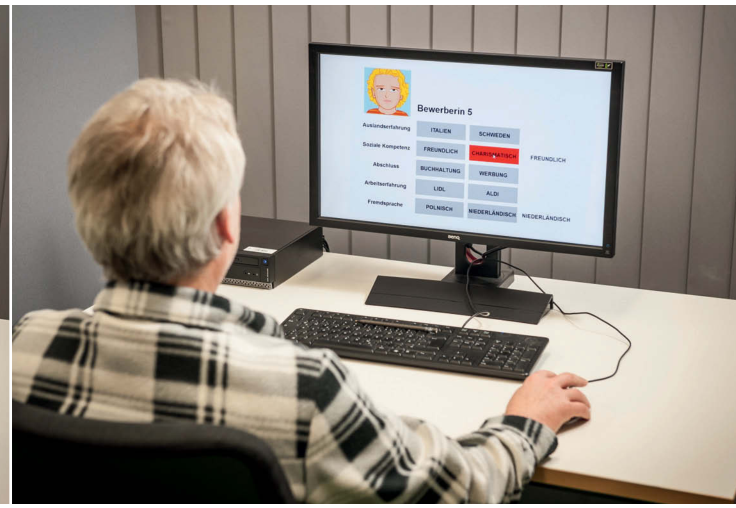
The experiments being run in the lab facilities at the Max Planck Institute for Human Development are thus also putting a myth to the test: an airbrushed version of aging, according to which everything gets better, bigger and freer after the age of 50 or 60. Secure pensions, grandchildren gurgling with delight, the freedom of long trips, the programmability of mental and physical fitness: perhaps even the image of old age itself is a product of selective, strategically chosen information.

DECISIONS ROOTED IN EVOLUTION

"Are you familiar with the list of the most influential people in the world?" asks Ralph Hertwig. "Their average age is 61." Is that a scandal? Or an indication that long-tested techniques can outperform the pep and the mental agility of younger generations? Either way, it challenges science to examine different strategies and risk preferences as a factor of age: How do people of different ages deal with uncertainty? And could it be that their approach to it has a function of its own – for instance, in situations where courage or coolness in dealing with risk or uncertainty promise to boost prestige? "Not many 60-year-olds will expose themselves to the risks of bungee jumping," explains Hertwig. "Simply because, at their age, it's no longer necessary."

This raises a hypothesis that could explain many differences in observable behaviors: decisions for or against taking a risk are often rooted deep in human evolutionary history. Young men have to bungee jump (or think they have to) in order to present themselves as strong and daring providers on the mating market. Older men are more relaxed in this respect. And women tend to avoid risks and dangers in order to protect their offspring. In

Photo: Norbert Michalke



other words, the different propensities for risk in different phases of life correspond to functional differences in human developmental history.

LIFE CIRCUMSTANCES DETERMINE HOW WE DEAL WITH RISK

These findings are echoed in today's more or less rationally structured society – in results from experiments with lottery drawings or fictitious job applicants, in the statistics compiled by, for instance, vehicle accident insurers, or in the analyses of data amassed in the context of SOEP, a socio-economic panel survey run by the German Institute for Economic Research (DIW Berlin), which has been surveying more than 30,000 people annually for the last 30 years. SOEP participants are also asked about their attitudes toward risk, making the dataset a valuable resource for the research team at the MPI in Berlin. An additional resource, as Ralph Hertwig emphasizes.

This data source is particularly valuable because it allows researchers to track individual and age-related changes over a period of up to ten years. "We can look at change and stability in the risk-taking propensity of people of different ages over time," says Anika Josef. The data also differentiates between different areas of life. People who report taking risks in their leisure time – jumping off bridges secured only by a rubber cord, for example – may describe themselves as rather more cautious in the work context or in their interactions with other people. Such differences needn't be preprogrammed and they may change with time. But they offer insights into personal motivations, individual structures of beliefs about how the world works, and how life events such as marriage, the birth of a child or retirement impact risk preferences.

"Our aim for future studies is to integrate the different data sources on risk behavior," reports Hertwig. Will someone who describes himself as cautious and socially reserved in the panel survey also be more likely to behave that way in the controlled situation of a game that requires mutual trust and cooperation to succeed? And will he show a similar level of risk tolerance when asked to choose between a lottery with a high hit rate but low winnings and one with a big but improbable jackpot?

"The participants in our experiments, no matter their age, have to learn," says Hertwig. "They learn the probabilistic structure of the world – or at least of a very specific situation. They learn the possible outcomes of their choice, and the probability of those outcomes occurring. That knowledge allows them to succeed." Of course, he concedes, this is a reduced representation of reality: "In real life, we can usually only guess at probabilities. Sometimes we don't even know which outcomes could possibly occur." It is then that our own system of beliefs comes into play: our willingness to take risks, our mental representations of logical relationships from similar situations, our knowledge, experience and crystallized intelligence. What Hertwig's colleagues Anika Josef and Thorsten Pachur simulate on their computer monitors are world models of greatly varying complexity. And what they calculate are greatly varying ways of responding to that complexity.

DEEPLY ROOTED PROGRAMS PLAY A PROMINENT ROLE

So what do you do when you realize that the mass of information is too much for your memory, your mental flexibility, your no-longer-quite-so-fluid intelligence? You choose another

Photo: Norbert Michalke (2)

International experience or computer skills? Study participants are given a number of fictitious applicants with various profiles to choose from and a limited time to make their choice. The researchers analyze how the participants deal with the glut of information.

strategy. Reduce the amount of information, search for familiar patterns and cues, block things out. And you rely on convention and habit, and if necessary on luck and instinct. As the researchers in Berlin found, relative to the younger participants in their studies, older participants were satisfied with half as many draws from the lottery drums before deciding on one of the lotteries. As a result, they lost out, going away empty handed as often as less educated younger participants with lower fluid intelligence. Taking risks may sometimes be a thrill, an ostentatious display of courage and good health – but sometimes it is the only option left. And sometimes an overly hasty choice from a mass of options is evidence only that we are aware of the limits of our capacities.

In major orchestras worldwide, it is now standard practice to have applicants for open positions audition behind a screen to ensure that evaluations of their musical talent and skill are not contaminated by knowledge of their age, gender or skin color. Literature Nobel laureate Günter Grass chose not to find out which of his friends had denounced him to the East German *Stasi*, but to leave his file closed. And physicians are constantly wrestling with the question of whether and why they should burden seriously ill patients with the full truth. Intentionally blocking out information – deliberate ignorance – can be a conscious, even clever strategy to maintain peace of mind when nothing can be changed anyway, to focus on what matters rather than being distracted by redundancies, or to keep confusing emotions under control. Psychological research confirms that older people tend to have better balanced emotions. "If I could reliably predict the date of your death," Hertwig offers as a thought experiment, "would you want to know?" Across all age groups, he continues, 90 percent of those asked so far have said no – with a clearly increasing tendency to shield oneself from information whose mental costs can far exceed the benefits the older we grow. And it's here that the researchers touch on wisdom ….

After all, it's always a matter of knowledge, its utility, its economics and strategies for applying it – which can also be a form of knowledge: higher-order knowledge. And deeply rooted programs always play a surprisingly prominent role, be it in the choice of a lottery, an investment, a car or a retirement plan. Or in the fundamental decision as to one's role and place in life.

"What we are doing here is basic research," clarifies Hertwig – and yet it's no surprise to him that people whose position and situation forces them to make and commit to choices often ask him about the results of his research – managers, HR consultants, legal experts, physicians. And grandparents. Here again, Hertwig takes an evolutionary perspective.

GRANDPARENTS' BEHAVIOR INTERPRETED AS AN INVESTMENT

Grandparents' investment decisions aren't necessarily a key area of his work at the Institute in Berlin, he admits, but an area in which the courses of life paths are set and where distinct constellations of expectations and experiences can be observed. "We humans are a unique species in that there is no other species of mammal where there is such a wide gap between the end of the reproductive phase and statistical life expectancy." Demographic change, driven by healthier lifestyles and a highly developed system of social and medical care, means that the period in which humans no longer have to look after their own children often spans 30 or 40 years or more. In this context, decisions on relation-

Photo: Norbert Michalke (2)

Head or gut? With their concept of adaptive rationality, Director Ralph Hertwig (center), doctoral student Anika Josef and senior researcher Thorsten Pachur are challenging the dominant economic and psychological ideas that human decision makers always act rationally – or are plagued by irrational biases.

ships, responsibilities and personal commitments can truly take on the character of life choices.

"What first brought our attention to this area," explains Hertwig, "was the so-called grandmother effect, the observation that maternal grandmothers tend to display stronger emotions, invest more time and make greater sacrifices for their grandchildren than, for instance, paternal grandfathers." This effect has been observed in all cultures – including enlightened, modern-day Europe – and it can be explained from an evolutionary perspective: a mother's mother knows for a fact that she really is related to her grandchild, but a father's father can't be so certain. He has the most cause to question whether his investment will benefit the right person.

What is new about the researchers' approach is that they interpret grandparents' behavior as an investment, and view caring for grandchildren as the product of a decision: bedtime stories or Bali? And if both, then in what proportion? There's no disputing, concedes Hertwig, that social, economic and cultural factors are becoming increasingly important for life in the post-reproductive phase. At the same time, there is no disputing that the decision to assume some degree of responsibility for others – whether they be grandchildren, neighbors, asylum seekers or people in need or nursing care – has a positive impact on our health, satisfaction, intellectual capacity and longevity. ◂

TO THE POINT

- **Researchers are studying how people make decisions in complex situations and in the face of information overload.**
- **Young people are usually better cognitively equipped to cope with these conditions than older ones, who have to manage the information overload by blocking out information.**
- **In addition, younger people increase their chances of success by taking more risks than older people. At the same time, older people are better balanced emotionally because they can block out information that would negatively impact their feelings.**

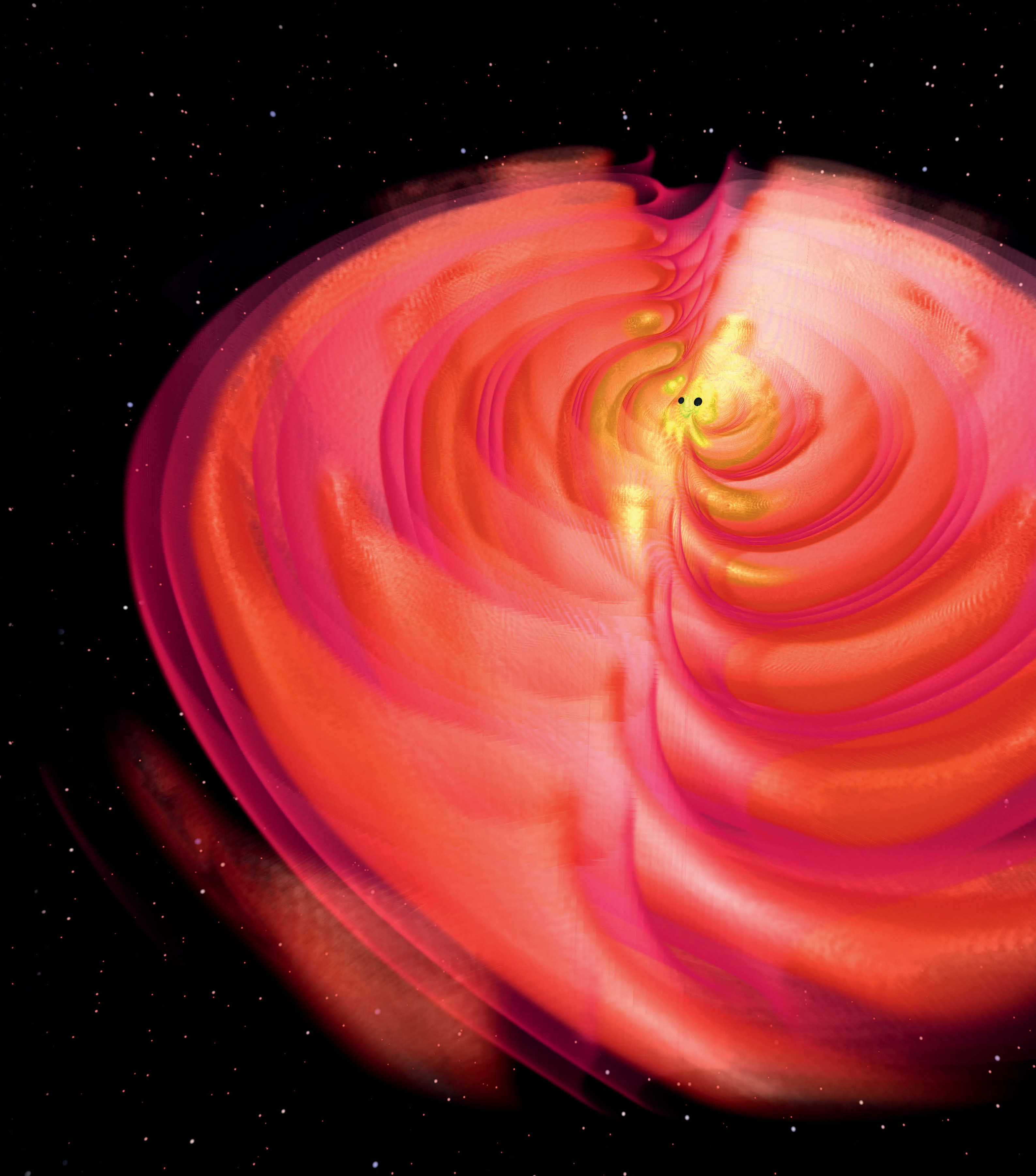
Photo: Norbert Michalke

Wissen Sie, wie man „Berufungsliste“, „Blockseminar“ oder „Präsenzstudium“ ins Englische übersetzt?
Oder welche Entsprechung der Ausdruck „die Anerkennung von Studien- und Prüfungsleistungen beantragen“ im Englischen findet? Dirk Siepmann | **Wörterbuch Hochschule** | Forschung, Lehre und Management | Deutsch – Englisch | Englisch – Deutsch

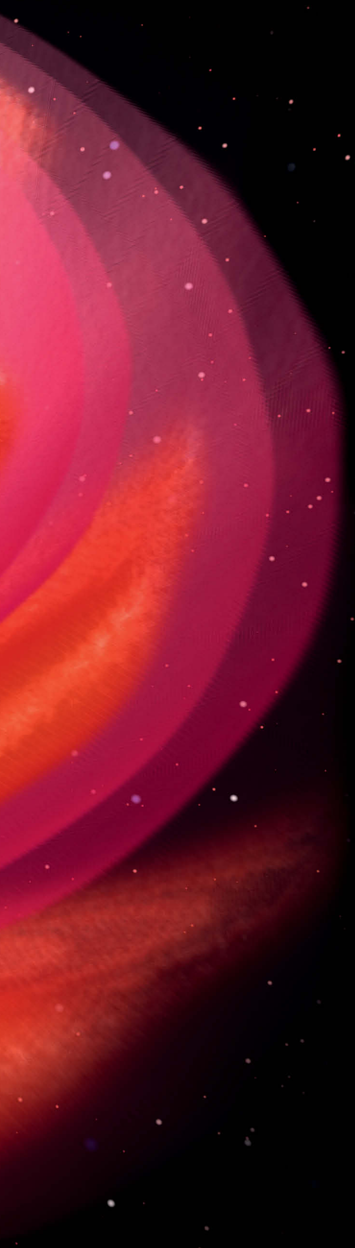
Gebundene Ausgabe, 2015, 476 S., 19,90 € (D) inkl. Porto, für DHV-Mitglieder zum Sonderpreis von 17,90 € inkl. Porto | **Zu bestellen über:** Deutscher Hochschulverband, Rheinallee 18-20, 53173 Bonn,
Tel. 0228 902 66 66, Fax 0228 902 66 80 oder per Mail: dhv@hochschulverband.de

Dirk Siepmann ist Professor für Fachdidaktik des Englischen an der Universität Osnabrück. Er verfügt über eine jahrzehntelange Erfahrung in Fremdsprachendidaktik, Übersetzungswissenschaft und Lexikographie.

DEUTSCHER
HOCHSCHUL
VERBAND



Cosmic collision: The first gravitational waves ever observed originated from two merging black holes around 1.3 billion light-years from Earth. Researchers at the Max Planck Institute for Gravitational Physics simulated the scenario on the computer.



Numerical-relativistic simulation: S. Ossokine, A. Buonanno (Max Planck Institute for Gravitational Physics)/scientific visualization: W. Benger (Airborne Hydro Mapping GmbH)

The Quaking **Cosmos**

Albert Einstein was right: gravitational waves really do exist. They were detected on September 14, 2015. This, on the other hand, would have surprised Einstein, as he believed they were too weak to ever be measured. The researchers were therefore all the more delighted – particularly those at the **Max Planck Institute for Gravitational Physics**, which played a major role in the discovery.

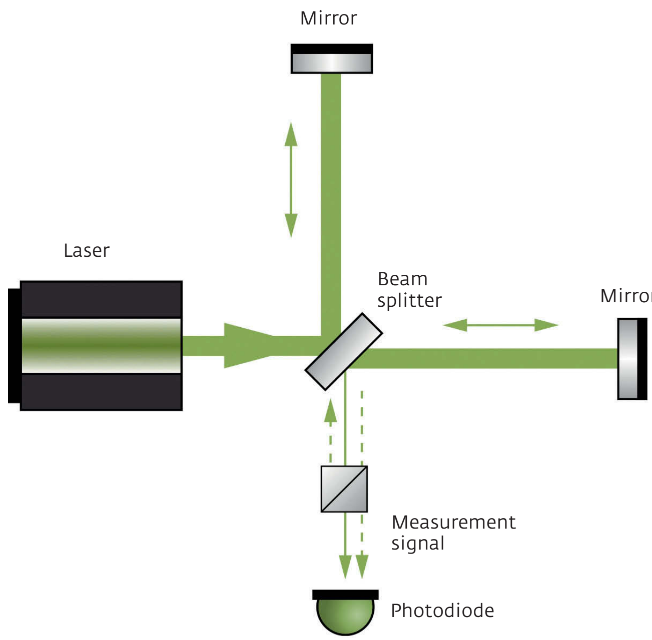
TEXT **HELMUT HORNUNG**

On that memorable Monday in September 2015, the clock in Hanover stood at 11:51 a.m. when Marco Drago at the Max Planck Institute for Gravitational Physics first saw the signal. For around a quarter of a second, the gravitational wave rippled through two detectors known as Advanced LIGO. The installations are located thousands of kilometers away in the US, one in Hanford, Washington, the other in Livingston, Louisiana.

Drago initially thought the signal had been slipped in deliberately to test the scientists' response, as has happened many a time in the past. But Advanced LIGO wasn't even in regular operation yet, so Drago informed his colleague Andy Lundgren. Both agreed: the curve looked perfect; the signal appeared to be real. The Max Planck researchers had an inkling that they had just become witnesses to a historic moment.

The discovery represents the current pinnacle of the history of gravitation – the general theory of relativity has now passed its final test with flying colors. In addition, the measurement opens up a new window of observation, as almost 99 percent of the universe is in the dark – that is, it doesn't emit any electromagnetic radiation. With gravitational waves, in contrast, it will be possible for the first time to investigate cosmic objects such as black holes in detail. And in the future, the researchers will even be able to "hear" almost as far back as the Big Bang.

But what exactly are these waves from outer space? The roots of modern gravitational research lie in Switzerland. There, in 1907, a "technical expert second class" at the patent office in Berne was giving some intense thought to gravity: Albert Einstein. He simulated gravity using acceleration, since acceleration also generates forces



Left Crossed paths: In the gravitational wave detector, a laser beam is split at the beam splitter. From there, the two partial beams run perpendicular to one another along the arms of the interferometer. At the ends of the arms, the partial beams are reflected, sent back to the beam splitter and superimposed there to form the signal beam. This then strikes the photodiode. The change in brightness measured by the photodiode is a measure of the relative change in length of the light paths.

Right Field research: One of Advanced LIGO's detectors, which stretches out its four-kilometer arms in Livingston, Louisiana. Its heart is the building in the center that houses the laser system. The second, practically identical LIGO detector is located in Hanford, Washington, some 3,000 kilometers away.

as occur, for instance, in a rapidly accelerating elevator. If the elevator car were soundproof and lightproof, the passengers might think that terrestrial gravity had suddenly increased.

EARTH BENDS SPACE AS IT ORBITS THE SUN

The realization that gravitation is at least partially a question of one's system of reference led Albert Einstein to the revolutionary ideas he presented in his general theory of relativity in the fall of 1915, after eight years of work. It was ultimately a field theory. It states that the accelerated motion of masses leads to perturbations that move through space at the speed of light – gravitational waves.

If you jump up and down on a trampoline, for example, you lose energy and generate these waves in space-time. They are immeasurably small, because a human being has a low mass and jumps relatively slowly. Space, on the other hand, contains very large masses – and even a trampoline: space-time. Everything is in motion here, as not a single celestial body remains at rest in one place. Earth bends space as it orbits the Sun, radiating gravitational waves with a power of 200 watts. But even these gravitational waves are still too weak to be tracked down with a detector.

Fortunately, there are also much stronger tremors of space-time in the universe: when two neutron stars or black holes orbit each other extremely quickly, or even collide with each other. Or when a massive star explodes as a supernova. Such cosmic events generate gravitational waves with an energy of around 10^{45} watts.

Gravitational waves change the separation between the objects in space perpendicularly to the direction of propagation. This is extremely difficult to measure, which is why Albert Einstein thought it would be impossible to detect them. And yet scientists have come up with instruments that have now succeeded in doing just that. The first-generation instruments of the 1960s consisted of aluminum cylinders weighing many tons and equipped with sensitive sensors. Pulses of gravitational waves should have caused them to oscillate like the clapper of a bell. But despite sophisticated amplifiers, these resonance detectors produced no results.

The researchers thus designed receivers that were even more sensitive, known as laser interferometers. Here, a laser beam impinges on a beam splitter, where it is split into two beams; one continues on in a straight line while the other is deflected to the side. At the end of each path is a mirror that reflects the light back to the beam splitter. This mirror now deflects the beams in such a way that they are superimposed on each other – that is, they interfere – and strike a photodiode.

WAVE CREST MEETS WAVE TROUGH

In the case of unperturbed measurement paths, the light waves arriving at the photodiode oscillate not in phase, but out of phase: wave crest meets wave trough, the light waves extinguish each other. If a gravitational wave perturbs the system and thus changes the measurement paths, the light waves lose the beat. The receiver no longer remains dark – a signal appears.

In 1975 a group working with Heinz Billing at the Max Planck Institute for Physics and Astrophysics built the prototype of such an interferometer with a

Graphic: MPI for Gravitational Physics

Photo: Caltech/LIGO Laboratory

path length of 3 meters; in 1983 they built one with a 30-meter path length. The foundations were thus laid for all subsequent installations of this type. The scientists have developed innovative technologies – for instance for the suspension of the mirrors or to stabilize the laser – particularly for the GEO600 detector, which has been stretching out its 600-meter arms in a field near Hanover since the mid-1990s.

"Seen in this light, Advanced LIGO is our detector as well," said Karsten Danzmann on February 11 in Hanover, on the occasion of the official announcement of the discovery. After all, the two structurally similar facilities in the US are full of technical know-how from Danzmann's team. When they detected the tremor in space-time, the length of the laser paths, each four kilometers long and arranged perpendicular to each other, had changed by only a tiny fraction of the diameter of an atom.

In order to discover the gravitational wave signals in the pile of data, the researchers had to know what they were looking for in the first place. The researchers in Bruce Allen's department in Hanover are therefore working on programs to see and analyze the signals. And Alessandra Buonanno's group in Potsdam-Golm developed the models they use to better understand the sources of the waves.

The signal detected on September 14, 2015 told of the merger of two black holes with 29 and 36 solar masses, 1.3 billion light-years away from Earth. The close interplay of experiment, simulations, analytical calculations and data analysis allows the scientists to illuminate the dark corners of the universe. The ripples in space-time will shed light on the astronomy of the future. ◂

"The signal caught our eye immediately"

The discovery of gravitational waves on September 14, 2015 was the crowning moment of a search that had lasted decades and employed ingenious methods. The **Max Planck Institute for Gravitational Physics**, with its branches in Potsdam-Golm and Hanover, played a crucial role in this success. There, researchers are working not only on innovative technologies, but also on theoretical models, virtual simulations and data analysis. We discussed this work and the importance and consequences of the discovery with Directors **Bruce Allen**, **Alessandra Buonanno** and **Karsten Danzmann**.

Mr. Allen, Ms. Buonanno, Mr. Danzmann: As members of an international network of gravitational wave detectors, the LIGO Virgo collaboration, you and the staff at your institute played a significant role in the very first measurement of gravitational waves. Congratulations!

All three: Thank you!

Did you expect to make the discovery at this point in time?

Karsten Danzmann: No, not at all. It was a complete surprise. In mid-September 2015, the American LIGO detectors – designed along the lines of a Michelson interferometer like our GEO600 detector – were still only in test mode after undergoing a rather long upgrade phase. The plan was for the scientific measuring operation to begin a few days later. The scientists were still checking whether the instruments were working as planned. They were indeed. But that they were operating so well and would be able to receive a gravitational wave signal right at the start – nobody expected that.

Bruce Allen: The signal arrived late in the morning of September 14, 2015 Central European Time. It was night time in the US and our colleagues there were asleep. So it was two members of the Max Planck Institute for Gravitational Physics who were the first to see it on their monitors a few minutes after the detectors had been triggered. They analyzed the data for several hours and then sent an initial e-mail to the collaboration. We couldn't believe it at first, especially since the signal was so strong and looked so perfect that we first asked ourselves whether it was actually real.

Karsten Danzmann: It must be said here that we regularly simulate the impact of gravitational waves on the detectors for test purposes. This allows us to test the operability of the instruments, and also to check the detection chain and establish that the scientists are working independently of each other.

Bruce Allen: In the first few weeks after the discovery, we actually did have concerns that someone might have mistakenly injected an artificial signal or forgotten to tell us about it. We expended a lot of effort to rule out this possibility. In the end, however, it was clear that the signal originated from outer space. We had become witnesses to the fact that, in a distant galaxy, two black holes had collapsed into one another!

What does such a signal look like?

Alessandra Buonanno: The signal swept through the LIGO detectors for around a quarter of a second. It looked remarkably simple! A sine wave of about 10 to 15 cycles whose amplitude first grew, then reached its maximum and eventually died out. In the meantime, its frequency increased more and more until it reached a constant value. This characteristic signal can be explained as follows: As the two black holes orbit each other, they lose energy because of gravitational wave emission. Therefore, they come closer and closer until they collide with each other and merge. This forms a more massive black hole that then rings like a bell for a little while before settling down. Before merger, the signal's frequency is proportional to the orbital frequency, and its amplitude to the characteristic velocity of the binary star, which is almost the speed of light during the last stages of the evolution. Once the new black hole forms, it rings down, emitting gravitational waves at a constant frequency.

Bruce Allen: I didn't expect that the very first detection would enable us to deduce the event so directly from the waveform. I had assumed that the first detections would be much weaker and that we would need our analysis programs to fish them out of the data. And also that it would be difficult to understand what is really happening there. The fact that it stands out so clearly in the raw data, and is even visible to the human eye, is remarkable.

Even though the gravitational wave signal in this case is obviously easy to see with the naked eye, it is imperative to undertake a sound data analysis. How is this done and what role does the Max Planck Institute for Gravitational Physics play in it?

Karsten Danzmann: While the detectors are running, the measurement data is automatically trawled continuously for signals. If something is found, the scientists are notified by e-mail.

Bruce Allen: The foundations for the algorithm that detected the latest signal were laid by colleagues at the University of Florida. This algorithm searches the LIGO detectors for a deflection at the same frequencies so that the events in both detectors match. In our working group we have spent years developing and improving this code in order to specifically filter out from the data the signals from binary systems with black holes of moderate mass. These improvements were one of the reasons that the latest event was discovered. And as far as the algorithm for the precision analysis applied after the detection is concerned, the colleagues at our institute belong to one of only two groups of experts in the world.

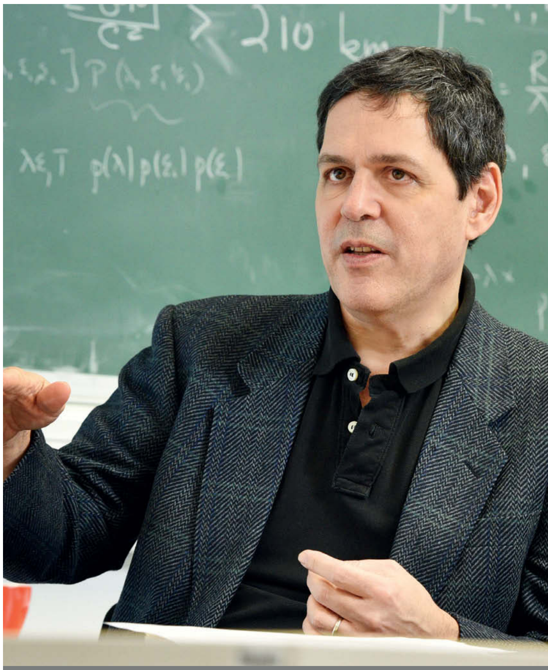

Bruce Allen

Photo: Frank Vinken

» Toward the end of the next measuring period we will have around 20 such detections.

Where are the calculations done?

Bruce Allen: Most of them are done on the ATLAS computer cluster here in Hanover. It has roughly the same capacity as the rest of the collaboration together has available.

Karsten Danzmann: After excluding all other external perturbations including, for instance, earthquakes, the signal is compared with synthetically generated waveforms. This is how we determine the properties of the astrophysical source emitting the gravitational waves.

How are those wave signals modeled and implemented in your search?

Alessandra Buonanno: First we developed sophisticated, analytical approximations to describe the two-body dynamics and gravitational radiation during the phase in which two black holes come ever closer to each other. Then we used the re-

Alessandra Buonanno

And afterwards, you can say precisely what the system you found really looks like?

Alessandra Buonanno: Having identified the signal in the data, we used our waveform models to run follow-up analyses and infer the astrophysical properties of the source. We found that the binary system was composed of two black holes that had 36 and 29 solar masses, respectively. The two black holes merged into a single, rotating black hole with a mass of around 62 times the mass of the Sun. The binary system was 1.3 billion light-years away. Furthermore, the signal was quite loud, making it possible to also use our waveform models to look for violations of Einstein's general theory of relativity. No deviations were found!

» Having identified the signal in the data, we used our waveform models to run follow-up analyses and infer the astrophysical properties of the source.

sults of numerical-relativity simulations of binary black holes to model the merger and ring-down signal. It is not possible to employ only numerical-relativity waveforms in searches and follow-up analyses because it takes one month or more to simulate the last 15 orbits of a binary black hole coalescence. The waveform models we have developed were also implemented and employed in the continuing search for binary coalescences in the LIGO data. This search observed the black hole merger known as GW150914 with sufficient significance to be confident in the detection.

Apart from the signal strength, was this system a surprise in any other way?

Alessandra Buonanno: We didn't know if black holes exceeding 20 solar masses existed, but we did know that if they existed, they would be the strongest gravitational wave sources for LIGO. They proved to be the golden sources we always dreamed of! Because with such massive binary black holes, the merger signal lies in the detector's sweet spot – its most sensitive region – and it is at merger that the signal is strongest.

Which frequencies are these?

Karsten Danzmann: Between 60 and 250 hertz. In this range, the LIGO detectors are now almost ten times as sensitive as before the upgrade. Incidentally, this is something we are particularly delighted about: almost all the developments that have made Advanced LIGO so much more sensitive were developed or tested out at GEO600. At higher frequencies where we expect the signals from two merging neutron stars, for example, the instruments are currently a factor of three better than before. However, this is expected to be increased to a factor of ten in the coming months. The dominance of seismic effects is too great at very low frequencies. In the future, however, this gap will be closed by the VIRGO detector in Italy, which is also a member of our network. Its technology is also currently being modernized and is set to resume operation next year.

And what is the situation with GEO600 in Ruthe near Hanover?

Karsten Danzmann: It's smaller, so it's not sensitive enough for such signals at low frequencies. Its strength lies at higher frequencies. But the main thing we have here is decades of tradition in developing technologies. All innovations that have had their origins here can now be found in the other detectors in the network; they include special systems for suspending mirrors, and also the laser technology and the optical layout of the interferometer in general. We provided the hardware for the pre-stabilized laser systems used with Advanced LIGO. Advanced LIGO is our detector as well!

The discovery has shown that the calculation that the new measurement sensitivity of the detectors would finally enable us to mea-

Photo: Sven Döring

» We suddenly have a new tool at our disposal with which to study the dark side of the universe.

sure gravitational waves directly proved to be correct – and even earlier than was hoped for. What further developments and observations do you expect in the near future?

Bruce Allen: In the immediate future it could become particularly exciting. We have now observed one system very well. I estimate that during the next six months of scientific operation following a further, brief update phase over the course of the year, we will see a system like this every three or four days. Toward the end of the next measuring period we will have around 20 such detections. We will be able to see what the mass spectrum of such systems is. And we will learn something about the evolution of such systems, because some of them will be close while others are more distant, which means they formed at an earlier point in time. This will tell us something about the proportion of heavy elements in the universe during the various eras, for example, because this has a considerable impact on the formation rate of massive stars and black holes in particular. And then we naturally hope to also find all the other types of sources that are to be expected – the merger of two neutron stars or combinations of a neutron star and a black hole.

What does the discovery mean for physics in the broader sense?

Karsten Danzmann: I think it has enormous significance for physics and astronomy. Not so much because gravitational waves have finally been detected – nobody doubted they would be! But because gravitational wave astronomy has now become mainstream astronomy. We suddenly have a new tool at our disposal with which to study the dark side of the universe. We have to realize that more than 99 percent of space emits no light and no electromagnetic radiation. All we know about this part at the moment is that it is subject to gravitation. The great hope now is that it will be possible to investigate it.

Bruce Allen: But first and foremost we have shown that we can measure gravitational waves directly. We can now use this to do research. And we are now in a position to test the general theory of relativity in strong gravitational fields. Until now, it has proved primarily that Einstein's theory is completely correct. So I don't think this will tell us something fundamentally new about physics that we don't already know. But we have a wonderful method for checking these laws.

Alessandra Buonanno: It is such an enormous discovery that it is difficult to immediately anticipate all the repercussions for gravitation, fundamental physics and astrophysics, but its echoes will be reverberating in those fields for many, many years. And it's fantastic that the announcement takes place shortly after the 100-year anniversary of Einstein's publication of the paper in which he predicted the existence of gravitational waves! We now have a new tool to probe the universe and unveil its dark, most extreme side. We have discovered that stellar-mass black holes exist, that they exist in pairs – that is, in binary systems – and that they can be quite massive. And yes, the observation of binary black hole mergers provides us with the remarkable opportunity to see how gravity operates at such extreme conditions and test whether Einstein's general theory of relativity still holds. So far, so good!

Karsten Danzmann

Bruce Allen: I also think back to the centenary anniversary of the general theory of relativity, which we celebrated in autumn 2015 in Berlin: because even Einstein himself didn't believe that it would ever be possible to measure gravitational waves, since they are so weak. Nor did he believe in black holes. We have shown that he was wrong on both counts. But I don't think this would have bothered him. I think he would have been delighted! ◂

Interview: Felicitas Mokler

Photo: Frank Vinken

The Search for the **Gentle Tremble**

Gravitational waves are some of the most spectacular predictions of the 1915 general theory of relativity. However, it wasn't until half a century later that physicist Joseph Weber attempted to track them down. In the early 1970s, **Max Planck scientists** also began working in this research field, and developed second-generation detectors. The groundwork laid by these pioneers meant the waves in space-time ceased to be just figments of the imagination: in September 2015 they were finally detected.

TEXT **HELMUT HORNUNG**

Albert Einstein is beset by doubt: it will never be possible to detect gravitational waves – the tremble in space-time is simply too weak! Yet it was he himself who had postulated their existence, which follows from the general theory of relativity he put forward in November 1915. A short time later, in 1916 and again in 1918, he devotes a paper to this phenomenon.

Two decades later, he suddenly has a change of heart: "I have been working with a young colleague [Nathan Rosen] and we have come to the interesting conclusion that gravitational waves do not exist," Einstein writes to his colleague Max Born. In 1936, he submits a manuscript to the renowned journal Physical Review; it is returned to the author by a reviewer who considers it to be unsuitable. Albert Einstein is fuming about this embarrassment, but must concede that his argumentation is indeed flawed. His doubts were unfounded.

And the physics world? It barely pays any heed to gravitational waves. The same applies to the general theory of relativity overall, which has been eking out a rather miserable existence since the 1920s. It is only after Einstein's death in 1955 that people begin to take an interest in it. Astrophysicists are now starting to turn their sights toward black holes and quasars, exotic objects that can't be explained without Einstein's equations. This renaissance of relativity ultimately benefits gravitational waves, too, which strike a chord with at least one physicist: Joseph Weber.

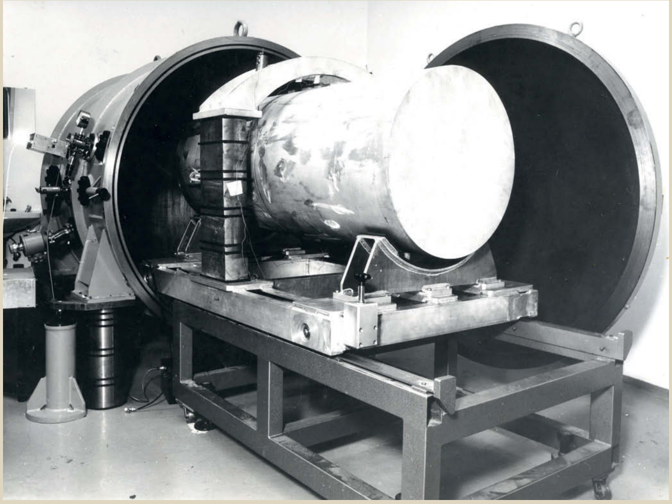
Born in 1919 in New Jersey, the researcher at the University of Maryland has an idea for a simple experiment: he suspends an incredibly heavy aluminum cylinder – 1.5 meters long and 60 centimeters across – in a steel wire loop and attaches piezo sensors to its middle to register oscillations. The whole test rig is housed in a vacuum chamber.

But why can gravitational waves cause a solid metal cylinder to tremble? Because they stretch and compress space perpendicularly to their direction of propagation. Let's imagine that gravitational waves impinge on a spherical balloon: within a matter of milliseconds, they would first deform it into the shape of an egg and then elongate it into the shape of a sausage.

Weber thinks gravitational waves originate primarily from cosmic catastrophes within our Milky Way – a supernova, for instance. This is when a star explodes and ejects great amounts of mass into space at the same time as its inner regions are collapsing in on themselves. What remains is a neutron star or a black hole. We now know that these objects themselves can also generate gravitational waves – whenever they are formed in pairs on close orbits and merge with each other. The waves registered in September 2015 originated from this type of event: two black holes with a mass of around 29 and 36 solar masses each that merged with one another in a galaxy approximately 1.3 billion light-years away.

The reach of Weber's cylinder extends only to a small region within our Milky Way. It is unlikely that a supernova will explode here, especially since there are thought to be only two to four such events per century in the entire galaxy. Nevertheless, Joseph Weber reports success in 1969. His detectors in Maryland and at Argonne National Laboratory 1,000 kilometers away are said to have actually registered gravitational waves, and even several per week!

Other scientists remain skeptical, including those at the Max Planck Institute for Physics and Astrophysics in Munich. In 1970, this becomes the birthplace of gravitational wave research in



Weighty experiment: In the early 1970s, Max Planck researchers used a massive aluminum cylinder like the one shown here in their search for gravitational waves.

Photo: MPG archive

Germany. “We decided back then to repeat Weber’s experiment as precisely as we could with refined technology and sophisticated data processing,” remembers Walter Winkler, one of the ambitious Max Planck researchers. The group working with Heinz Billing builds the world’s most sensitive cylinder detectors in Munich and in Frascati, Italy. They are capable of registering changes in length of 10^{-15} centimeters. The experiments run from 1972 until 1975. The result: nothing!

The Weber detectors fall out of fashion – and make room for a new method: interferometry. This idea originally came from German-American physicist Albert A. Michelson. In 1881, he wanted to use such an instrument in Potsdam to measure the speed of the Earth relative to what was then thought to be the ether. Ninety years later, Philip Chapman, Robert Forward and Rainer Weiss suggest using this type of instrument as a detector for gravitational waves. The light source is to be a laser. But a lack of money prevents the three US researchers from getting any further.

Once again, the group from the Max Planck Institute for Physics and Astrophysics comes onto the scene. They are the only people in the world to begin working with this new technology. Its principle is simple: a laser beam impinges on a beam splitter, where it is split into two beams; one continues on in a straight line while the other is deflected to the side. At the end of each path is a mirror that reflects the light back to the beam splitter.

GEO, November 1985

» Researchers at the Max Planck Institute of Quantum Optics in Garching aim to use a three-by-three kilometer “antenna” to detect gravitational waves from distant galaxies.

This mirror now deflects the beams such that they are superimposed on each other – that is, they interfere. However, the light waves arriving at a photodiode oscillate not in phase, but out of phase: wave crest meets wave trough – the light waves extinguish each other. If a gravitational wave runs through the system, it compresses and elongates space, thus changing the measurement paths. The light waves are no longer out of phase. The receiver no longer remains dark – a signal appears.

In 1975, the researchers in Munich – working with Heinz Billing are Walter Winkler, Albrecht Rüdiger, Roland Schilling, Lise Schnupp and Karl Maischberger – build a prototype with an arm length of 3 meters. The light of a 3-watt argon laser is reflected 150 times. But this second-generation detector also has its problems: the frequency of the laser light must be extremely stable, and its basic power is too weak. Moreover, fluctuations in the geometry of the beam lead to undesired error signals and allow tremors to shake the mirrors.

To reduce all these unwanted effects, the physicists develop innovative technologies that no modern gravitational wave trap can now do without. From 1983 onward, they continue their pioneering work with a second prototype with 30-meter arm length. This is really short, because in the thousandth of a second that it takes a gravitational wave to traverse the measurement path, the light covers 300 kilometers. The laser beam would therefore have to be en route over the same length in order to observe the wave completely. The researchers avail themselves of a trick they call “delay line,” which consists in “folding” the beam path and reflecting the beam backwards and forwards between the mirrors many times, as described above.

New technology: Lasers form the heart of the second generation of detectors. Here, Walter Winkler (background left) and Karl Maischberger are working on the prototype of such an interferometer in 1977.

Nevertheless, the longer the measurement path, the better. “So in 1985, we submitted an application to build a detector with an arm length of 3 kilometers,” says Walter Winkler. “But in Germany there was no interest at all in the project, so it wasn’t approved.” A British group suffers the same fate. It had been undertaking similar research since 1977 at the University of Glasgow and had built a detector with 10-meter arm length in 1980. In 1986, the Scottish application for a large interferometer fell on deaf ears.

But similar fates bring people together, so three years later, the two teams decide to collaborate. Only a short time later, they submit joint plans for a detector to be built in the Harz Mountains in Germany, again without success. The breakthrough finally comes in 1994: the construction of a German-British detector with each arm measuring 600 meters finally becomes reality just outside Hanover. “Herbert Welling from the University of Hanover managed to convince his colleagues to bring the installation to Lower Saxony,” says Winkler.

Karsten Danzmann, then Group Leader in Garching and now Director at the Max Planck Institute for Gravitational Physics, is appointed and given funding by the Federal State of Lower Saxony, the university and the Volkswagen Foundation. With not much money but a lot of hard work – also by the British colleagues – the researchers get the project off the ground.

The first groundbreaking ceremony is held on September 4, 1995. Since 2002, the detector has been operated by the Center for Gravitational Physics, of which the Max Planck Institute is a member, together with Leibniz Universität Hannover and Glasgow and Cardiff Universities. The facility serves primarily as a test laboratory for technologies that are incorporated in other detectors all over the world. Even David Shoemaker, leader of the Advanced LIGO project, was a member of the Max Planck Group for a while. This American facility with German technology is now the first to have measured gravitational waves and crowned the decades-long search for the gentle tremble from space.

Photo: MPG archive

A Diplomat with Plenty of Energy

Max Planck Society honors Reinhard Jahn with the Communitas Prize

Honored: President Martin Stratmann (left) presents Reinhard Jahn with the MPG's Communitas Prize. Professor Jahn is a Director at the Max Planck Institute for Biophysical Chemistry and a particular advocate of career support for junior scientists.

The Max Planck Society presented its Communitas Prize to Reinhard Jahn, a Director who consistently implements structural improvements in science, particularly in the area of support for junior scientists.

He is a man who gets things moving – calmly but doggedly, until changes are made. Just where the neurobiologist from the Max Planck Institute for Biophysical Chemistry in Göttingen finds the energy is a mystery to many. Reinhard Jahn is a man in perpetual motion, and one who has worked tirelessly for the Max Planck Society since 1997, as Max Planck President Martin Stratmann explained at the award ceremony before the Scientific Council. And he has done so with success and impact, connecting with people on an empathetic level, but without making a lot of noise.

When Professor Jahn left Yale to take up his appointment in Göttingen, his attention was initially focused on the conditions at the new location: "There was little interaction with the neighboring university, and it was hard to attract good doctoral students," he recalls. However, in his research partner at the university – Kurt von Figura, who later became president of the university – he found a counterpart who likewise wanted to clear away the barriers.

As a result, the establishment of two doctoral student programs, further assisted by Erwin Neher, evolved into the first International Max Planck Research School (IMPRS), which was launched in 2000. The IMPRS is now an award-winning model of structured graduate training from master's degree through to doctorate, as is the offshoot the Göttingen Graduate School for Neurosciences, Biophysics, and Molecular Biosciences (GGNB) co-developed by Reinhard Jahn. It is the embodiment of exemplary and efficient cooperation between the Max Planck Society and the university, and played a major role in Göttingen's success in the 2012 Excellence Initiative. The GGNB currently involves four university faculties, three Max Planck Institutes and a Leibniz Institute, offering twelve doctoral student programs.

Since 2013, Reinhard Jahn has focused – initially at the request of President Stratmann's predecessor Peter Gruss – on improving conditions for junior scientists throughout the Max Planck Society. That sometimes takes effort, the 65-year-old admits – after all, old habits must first be broken to allow new ones to take their place. At the moment he is using the Max Planck Society's internal online platform maxNet to canvass opinions on new draft guidelines for the support and supervision of postdocs. As President Stratmann pointed out in his speech, this makes the Max Planck Society transparent and shows that everyone is taken seriously. In Reinhard Jahn's eyes, it is an exercise in democratic behavior.

He likes working with young people. "It is a privilege as one gets older," he observes. As a doctoral student himself, he also experienced how easily scientific projects can fail. So career support for junior scientists is high on his list of priorities. He likes to be an instigator, listening and encouraging where necessary – his choice of words gives a hint of the philanthropist that colleagues see in him.

Does that explain where his energy comes from, considering that he also expends it in his involvement with the European Research Council and as initiator of the panel of experts at the German Research Foundation (DFG)? President Stratmann, at least, has found an answer: in presenting the Communitas Prize, he concluded his speech with the remark, "Some suspect that Professor Jahn's DFG water bottle with the telling label 'Thirst for Knowledge' actually contains a magic potion."

Photo: Amac Garbe/MPG

Ten Starting Grants

The European Research Council (ERC) has awarded 291 Starting Grants valued at 429 million euros. In this second round of calls under Horizon 2020, the EU Framework Programme for Research and Innovation, ten scientists – three women and seven men – at Max Planck Society institutes were successful with their applications and will receive funding.

Starting Grants are awarded annually by the ERC. Scientists who received their doctorates between two and around seven years previously are invited to take part in the competition provided that they intend to carry out their project at a European research institute. Each grant is worth up to 1.5 million euros. In this round, the Max Planck Society was by far the most successful institution in Germany, well ahead of the Ludwig-Maximilians-Universität München with five grants and the Helmholtz Association institutes, which received two grants. The French research organization Centre national de la recherche scientifique (CNRS) was the only institution in Europe to attract more funding, garnering twelve grants.

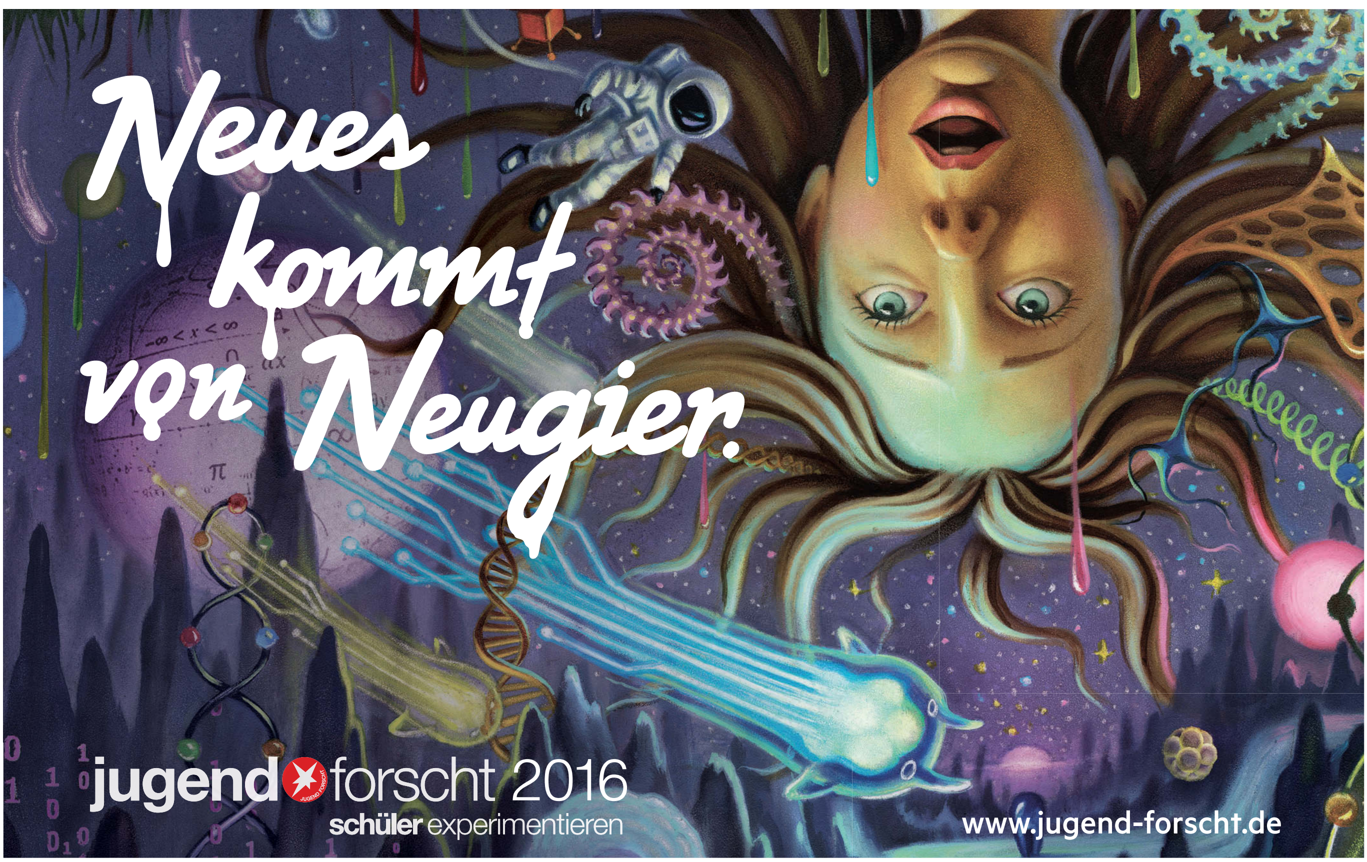
The following applicants can look forward to receiving funding:

- Catherine Crockford and Amanda Henry (MPI for Evolutionary Anthropology)
- Alexander Stein (MPI for Biophysical Chemistry)
- Anke Henning (MPI for Biological Cybernetics)
- John Travers (MPI for the Science of Light), Jens Bardarson (MPI for the Physics of Complex Systems)
- Fabian Schmidt (MPI for Astrophysics)
- Yaowen Wu and Tom Grossmann (MPI of Molecular Physiology) and
- Christian Groß (MPI of Quantum Optics).

Of the 2,920 applications submitted this year, the physical sciences and engineering accounted for the greatest number, at 1,269, followed by life sciences at 940 and social sciences and the humanities at 711. Around 10 percent of the applications in each category were approved, with the ERC sending the glad tidings to 291 scientists from 38 countries. Of the successful applications, 28 percent were made by women, somewhat fewer than the year before (33 percent). Most grants went to individuals working at research institutions in the United Kingdom (48), followed by Germany (47), the Netherlands (32) and France (29). The overall spread covered 23 European nations.

Applications were submitted by 64 scientists – male and female – at the Max Planck Society. Ten approvals represent an internal success rate of around 16 percent.

However, it is not just the grant recipients themselves who will benefit from the EU program – this funding will enable 291 excellent project leaders to recruit postdocs and doctoral students for their research teams, thus supporting a new generation of scientists.



Exchange of Ideas on Syrian Law

Max Planck Institute employs refugee lawyers – the joint effort also benefits the authorities

Will a marriage entered into by Syrian citizens prior to escaping from the territory controlled by the Islamic State terrorist regime be recognized in Europe? In order to facilitate research into issues such as this, refugee Syrian lawyers are supporting a new research project by the Max Planck Institute for Comparative and International Private Law. In parallel, the researchers are assisting with applications and meetings with authorities. Support for integration meets scientific added value.

Like so many of their fellow countrymen, Ahmad Jarken, Hussam Al-Asmi and Bilal Hajjo fled from Syria and are now trying to settle in Germany. Back home, they studied law or even worked as attorneys, but their qualifications are of little use in Germany – they know about Syrian law, but not German law.

In the newly launched research project on family law in Syria, however, their knowledge of Syrian law is precisely what is needed. Since late January 2016, the three Syrians have been assisting the Max Planck "Changes in God's Law" Research Group. They are paid as interns and work half-days at the Institute – leaving time, as in Bilal Hajjo's case, to attend external courses in German. The 31-year-old, who fled with his wife and child and now lives in an apartment in Hamburg, still prefers to speak English, in which he is more fluent; but "my German is getting better," says Hajjo. "I am very pleased to have this chance to contribute my experiences."

The internship is currently set to last for three months. It is intended to serve as a building block to aid the academics in finding their own perspective, while at the same time offering them the opportunity to actively use their knowledge. "The flood of refugees is presenting European authorities and courts with some very specific issues regarding applicable law in crisis areas such as Syria and Iraq," explains Research Group Leader Nadjma Yassari. Family relationships that would have to be proven as part of the asylum procedure may have been formed under national law, or they may have been created in autonomous territories under external control. How does one treat documents issued in these autonomous areas? How does one assess purely religiously contracted marriages, or for that matter the civil marriages recently introduced in Kurdish territories? Can polygamous marriages be recognized, and are the children of such marriages regarded as legitimate? "All these pieces of information are important when considering requests for subsequent immigration of family members. At the same time, they also afford the authorities insight into a legal system that may seem very alien to them. Our Syrian colleagues aren't just sources of data, they are also mediators of a different understanding of law," emphasizes Yassari.

Data alone is a problem, since the scientists working with Yassari, whose project receives funding from the Max Planck Foundation, usually conduct field research on site. This helps them identify differences between written law and actual legal practice. Given that court records are scarcely available from Syria at present, Bilal Hajjo contributes his own knowledge as an attorney. "With the aid of his legal diary, he is reconstructing and making written records of cases he worked on in Syria," says Dr. Yassari. Ahmad Jarken and Hussam Al-Asmi are carrying out additional research into Syria's patchwork legal landscape. The medium-term aim is to publish the results on a website. Relevant fields of law such as international private law, family and inheritance law and procedural law will be treated systematically and made available to a wide audience. Ideally, this will assist courts and authorities in reaching appropriate decisions. The Institute has long been receiving requests for expert opinions on precisely this subject.

Discussing matters at the Institute library: Research Group Leader Nadjma Yassari with Bilal Hajjo, Hussam Al-Asmi and Ahmad Jarken (left to right).

Photo: Tom Pingel

Research Establishments

- Institute / research center
- Sub-institute / external branch
- Other research establishments
- Associated research organizations

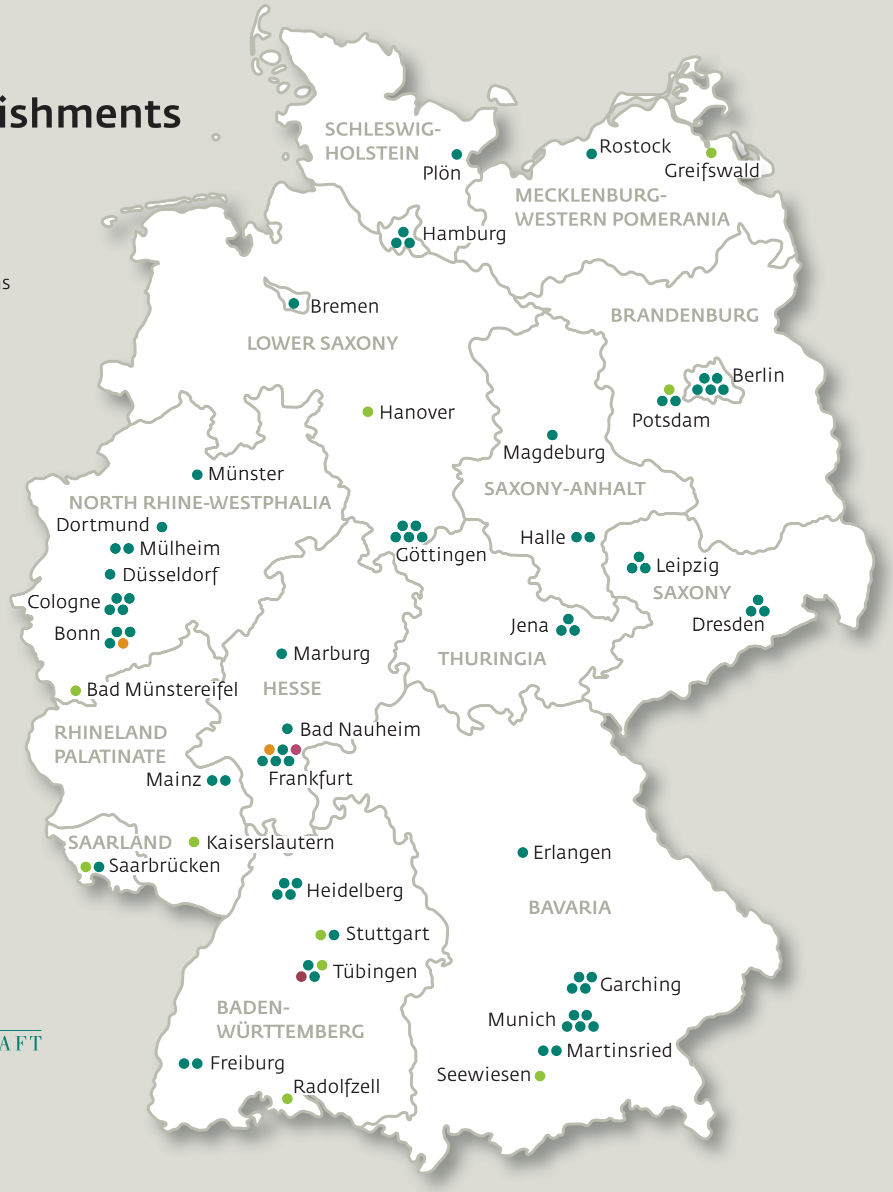
The Netherlands
- Nijmegen

Italy
- Rome
- Florence

USA
- Jupiter, Florida

Brazil
- Manaus

Luxembourg
- Luxembourg



MAX-PLANCK-GESELLSCHAFT

Publisher's Information

MaxPlanckResearch is published by the Science and Corporate Communication Office of the Max Planck Society for the Advancement of Science. Legal headquarters of the Association: Berlin. ISSN 1616-4172

Publisher's mailing address
Hofgartenstraße 8, D-80539 Munich
Tel. +49 89 2108-1719 / -1276 (Fax: -1405)
e-mail: mpf@gv.mpg.de
The magazine as ePaper: www.mpg.de/mpresearch
App for free download: www.mpg.de/mpr-mobile

Content Authority
Dr. Christina Beck (-1276)

Editors-in-Chief
Peter Hergersberg (Chemistry, Physics, Technology; -1536)
Helmut Hornung (Astronomy; -1404)

Editorial Staff
Dr. Elke Maier (Biology, Medicine; -1064)
Dr. Harald Rösch (Biology, Medicine; -1756)
Mechthild Zimmermann (Culture, Society; -1720)

Photo Editor
Susanne Schauer (-1562)

Translation
Baker & Harrison Translations
Ferdinand-Maria-Straße 30, 80639 Munich
Tel. +49 89 8583608-0
e-mail: cb@bakerharrison.de

Art Direction
Julia Kessler, Sandra Ostertag
Voßstraße 9, 81543 Munich
Tel. +49 89 27818770
e-mail: projekte@designergold.de

Lithography
KSA Media GmbH
Zeuggasse 7, 86150 Augsburg

Printing & Distribution
Vogel Druck- & Medienservice GmbH
Leibnizstraße 5, 97204 Höchberg

Advertising
Beatrice Rieck
Vogel Druck und Medienservice GmbH
Leibnizstraße 5, 97204 Höchberg
Tel.: +49 931 4600-2721 (Fax: -2145)
e-mail: beatrice.rieck@vogel-druck.de

MaxPlanckResearch seeks to keep partners and friends of the **Max Planck Society** up to date on the latest research conducted at the Max Planck Institutes. Four editions of the magazine are published in German each year, all of which are translated into English. At present, the English version has a circulation of 10,000 copies (**MaxPlanckForschung**: 85,000 copies). It is free of charge. None of the views and opinions expressed in **MaxPlanckResearch** may be interpreted as representing the official views of the **Max Planck Society** and its associated bodies. Reprint of texts is permitted only with the prior approval of the publisher. Photographic rights may be granted by agreement.

The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. (**Max Planck Society**) comprises 83 institutes and research facilities where around 22,200 employees, including some 6,000 permanently employed scientists, work and conduct research. The annual budget for 2016 is 1.6 billion euros. Research activities of the **Max Planck Society** focus on basic research in natural sciences and the humanities. The **Max Planck Society** is a non-profit organization registered under private law as an incorporated association. Its central decision-making body is the Senate, with members from the world of politics, the scientific community, and the professional public, providing for a well-balanced partnership.

FSC
www.fsc.org
MIX
Papier aus verantwortungsvollen Quellen
FSC® C022953

MaxPlanckResearch is printed on paper from responsibly managed forests and bears the seal of the Forest Stewardship Council (FSC)

Research doesn't have to be **heavy**.

Go paperless!

The Max Planck Society's magazine is **available as ePaper**: www.mpg.de/mpr-mobile

App for immediate & free download

Internet: www.mpg.de/mpresearch

MAX-PLANCK-GESELLSCHAFT