

# Faszination Forschung

**TUM Research Highlights**

Technical University of Munich | The Science Magazine

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A close-up portrait of Francis Kéré, a Black man with short hair, looking slightly to the right. He is wearing a dark blue jacket. The background is a blurred office or laboratory setting with white blinds on the right. There are decorative line-art elements in green and white on the left side of the cover.

**Francis Kéré:**  
Architect of Community

**Circuit in the Fly's Brain:** Keep Going or Give Up?

**The Aircraft of the Future:** Flying with Less Fuel

**Neutrinos:** Ice-Cold Detective Work

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**„Stiften  
stiftet  
Zukunft  
an.“**

Prof. Wolfgang A. Herrmann,  
Alumnus und Präsident der TUM



*Dear TUM friends and associates,*

Soon I will be handing over the mantle of president to my successor, Thomas Hofmann. Pride in what we have achieved together and joy over the future course of our alma mater have banished every trace of sadness. On the contrary, I know that TUM is in good hands with Thomas Hofmann and with you, our alumni. You have long been associated with “your TUM”. You are our ambassadors, supporters, friends and promoters.

We aspire to shape important topics of the future at the vanguard of academic research. My farewell issue of *Faszination Forschung* shows you how our scientists are realizing this. It highlights individuals whose appointment at the TUM was a matter of particular interest to me – key people who are preeminent in their field and will certainly continue to command attention in the scientific world.

Elisa Resconi peers deep into the universe. Together with an international team of researchers she has succeeded for the first time in identifying a radiating source of neutrinos in the cosmos: a blazar 5.7 billion light-years away.

Neurobiologist Ilona Grunwald Kadow studies fruit flies to learn how the brain makes decisions and which neurons are involved in the process. Together with mathematician Julijana Gjorgjieva, she has identified a neural circuit that controls motivation and perseverance in the quest for food.

Mathematical models devised by our Humboldt professor Andreas S. Schulz have found interdisciplinary applications. His algorithms are used for solving a wide range of problems: from the setting up flight schedules to operating high-bay warehouses to distributing aid in disaster areas.

Sami Haddadin, who accepted an appointment at TUM instead of going to Stanford or MIT, is involved in multi-disciplinary research. The director of our new Munich School of Robotics and Machine Intelligence, which combines our long-standing cutting-edge research in robotics and artificial intelligence, aims to create robots that interact sensitively with humans.

The new Bavarian Nuclear Magnetic Resonance Center (BNMRZ) is opening up unimagined new dimensions in the interdisciplinary field of protein research. Michael



Sattler, one of our most distinguished researchers in the field of structural molecular biology is elucidating complex structures of proteins with a view to identifying targets for the development of new drugs.

Our Master's degree students have clearly shown that our new Department of Aerospace and Geodesy is built on fertile ground. A four-strong team has won the Design Challenge set by the German Aerospace Center (DLR) and the National Aeronautics and Space Administration (NASA) with its design for a fuel-efficient passenger jet.

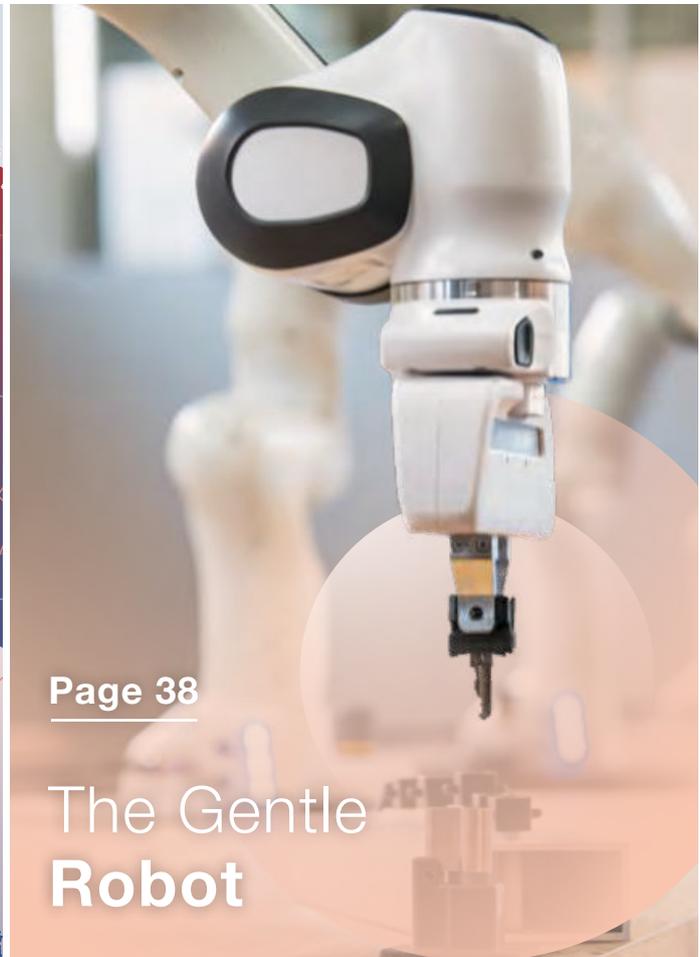
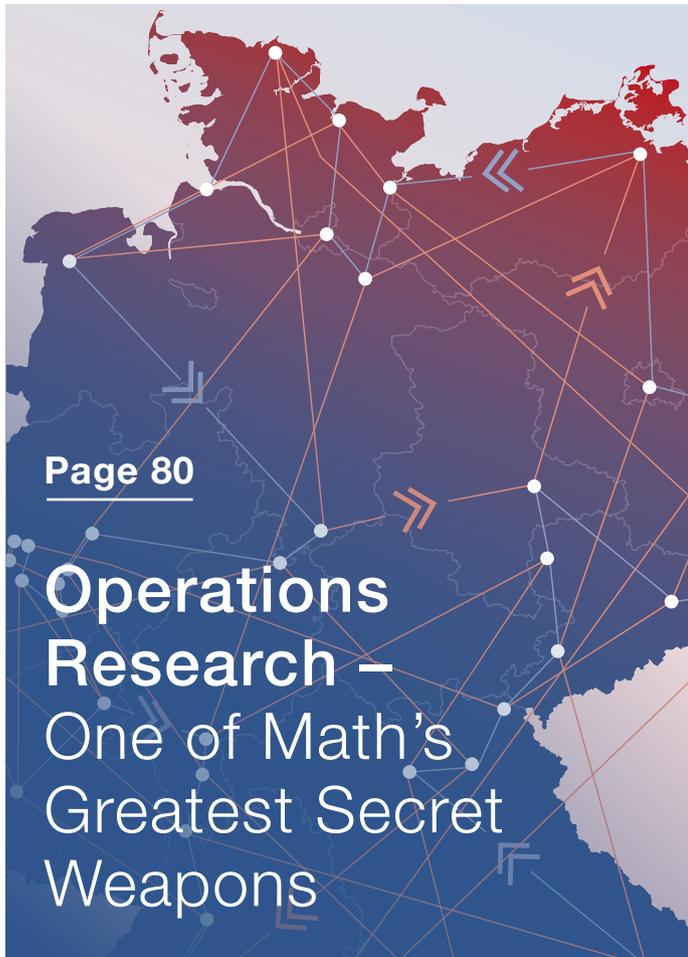
Architect Francis Kéré is both visionary and very down to earth in his approach. In an interview he talks about the importance of architecture for society and about involving people in planning the built environment. Feeling at ease in our environment begins, after all, with the roof above our heads.

I would like to take this opportunity to invite you all to visit the Anniversary Tower designed by this great architect, which we plan to erect on our Garching Research Campus – admittedly an ambitious project. Visible from afar, open and inviting, it will be a place of exchange, an invitation to the intergenerational community of our wonderful university.

One hundred and fifty years of TUM is just a start – but it's a good, promising start!

*Wolfgang A. Herrmann*

Prof. Wolfgang A. Herrmann



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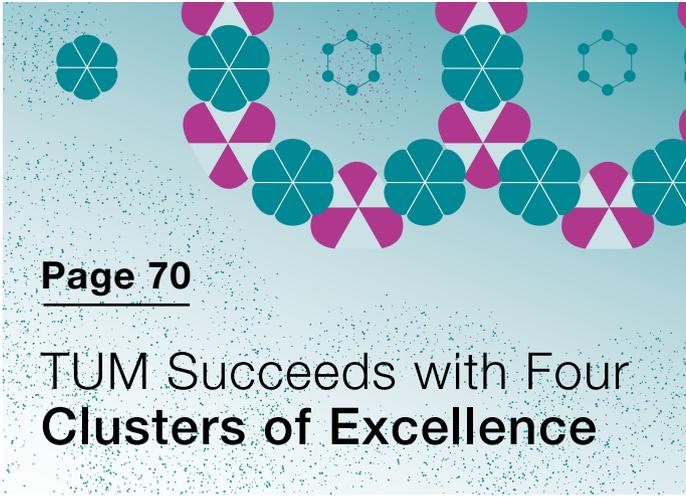
On September 22, 2017, sensors registered a light signal in the Antarctic ice. It put neutrino researcher Elisa Resconi onto something hot: together with colleagues she succeeded in proving that a 5.7 billion years old neutrino had reached Earth.

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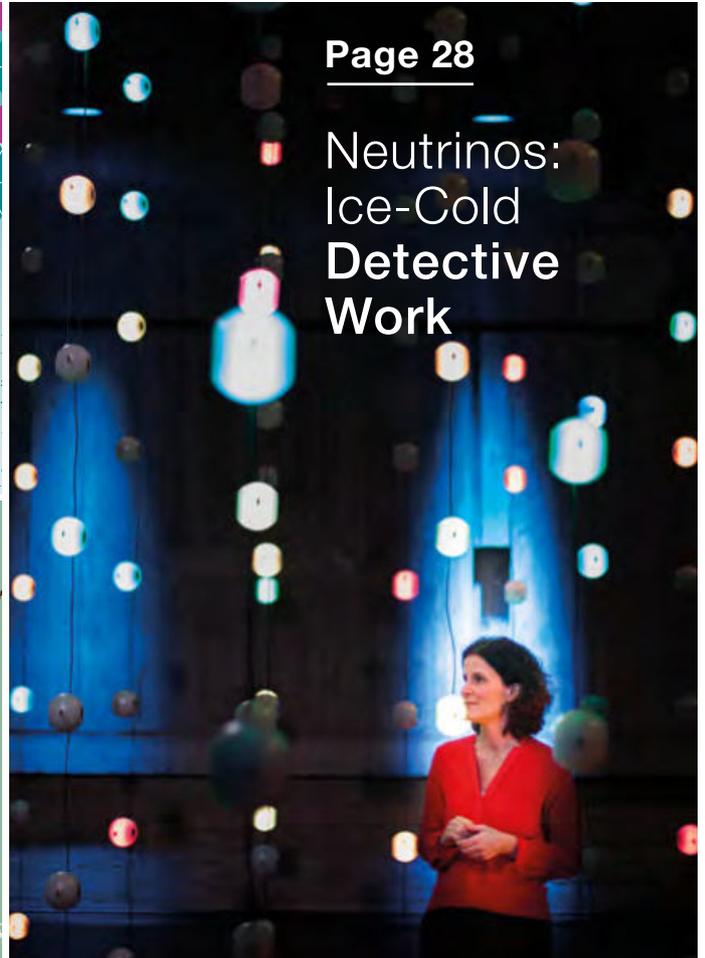
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Picture credits: Astrid Eckert/TUM, Juli Eberle; Graphics: edlundsepp (source: TUM)

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Each research cluster will be financed with up to 50 million euros over the next seven years. The focus is on energy conversion, quantum technology, the origins of the universe, and neurological diseases.

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[www.tum.de/faszination-forschung](http://www.tum.de/faszination-forschung)

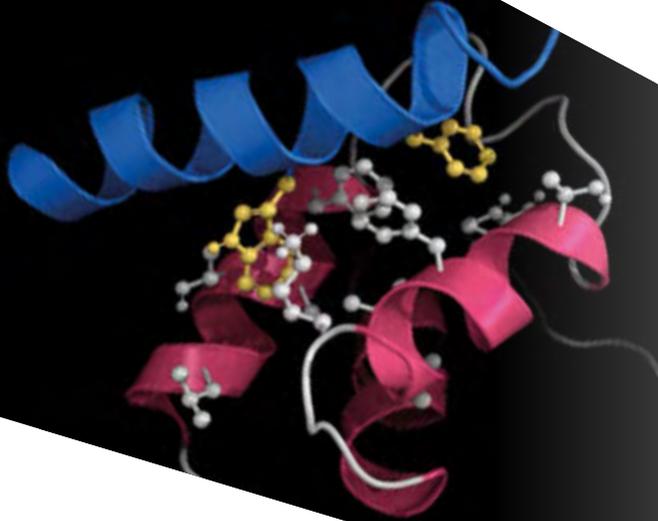


Link

[www.bnmrz.org](http://www.bnmrz.org)

The professors (clockwise) Aphrodite Kapurniotu, Bernd Reif and Michael Sattler are working at the new NMR center to elucidate the structures and functions of complicated protein molecules.

Rings, chains, loops, spirals: Structures like the ones shown here are investigated in the newly erected building of the Bavarian NMR Center at TUM on the Garching research campus.



# How Proteins Work

Protein molecules are made up of chains of amino acids, folded in a complex way. Alongside the sequence of amino acids, this folding is crucial to their function. At TUM's new NMR center, researchers can now gain unique insights into these complex structures.

There are already seven NMR spectrometers in the hall of the NMR Center. Three more will move from other departments, and one of the world's strongest instruments with a frequency of 1.2 gigahertz and a magnetic field strength of almost 30 tesla will be added later.



### Kurzfassung

## Falsch gefaltet

D

Obwohl die Struktur vieler Proteine weitgehend durch die Abfolge ihrer Aminosäuren bestimmt wird, lässt sie sich bis heute nicht vorhersagen und muss experimentell bestimmt werden. Die Kernspinresonanz-Spektroskopie (englisch: Nuclear Magnetic Resonance, NMR) ist hierfür das umfassendste und leistungsstärkste Verfahren. Mit ihr können die komplexe dreidimensionale Raumstruktur und die interne Beweglichkeit von Proteinen exakt vermessen werden.

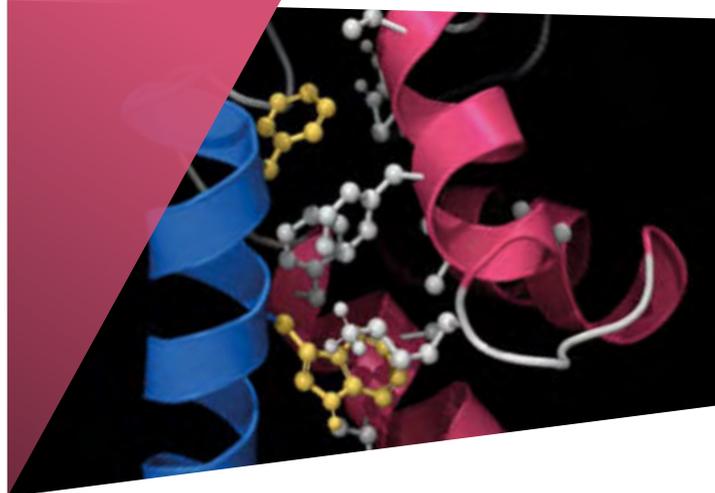
Das neue Bayerische NMR-Zentrum der TUM wurde im Oktober 2018 offiziell eröffnet. Sieben Spektrometer wurden bereits zusammengezogen, drei weitere warten auf den Umzug. Herzstück der Anlage wird in drei Jahren eines der weltweit stärksten NMR-Spektrometer mit einer Frequenz von 1,2GHz sein. Mittelfristig wird es auf der

ganzen Welt nur eine Handvoll solcher Geräte geben. Im Kernresonanz-Zentrum arbeiten Chemiker, Physiker und Biochemiker interdisziplinär zusammen.

So konnte Prof. Michael Sattler zeigen, dass sich auf der Basis der NMR-Spektroskopie Zielstrukturen für neue Medikamente gegen die Chagas-Krankheit ermitteln lassen. Die Professoren Bernd Reif und Aphrodite Kapurniotu sind in einer Reihe von Projekten, zum Teil auch gemeinsamen, auf der Suche nach Wirkstoffen, die sich zur Behandlung von Alzheimer eignen. Die NMR-Spektroskopie bietet hier völlig neue Ansätze, weil sie erstmals erlaubt, die Bindungsstellen, die bei den Fehlfaltungen eine Rolle spielen, mit hoher Auflösung zu betrachten. Wirkstoffkandidaten können so gezielt optimiert werden. □

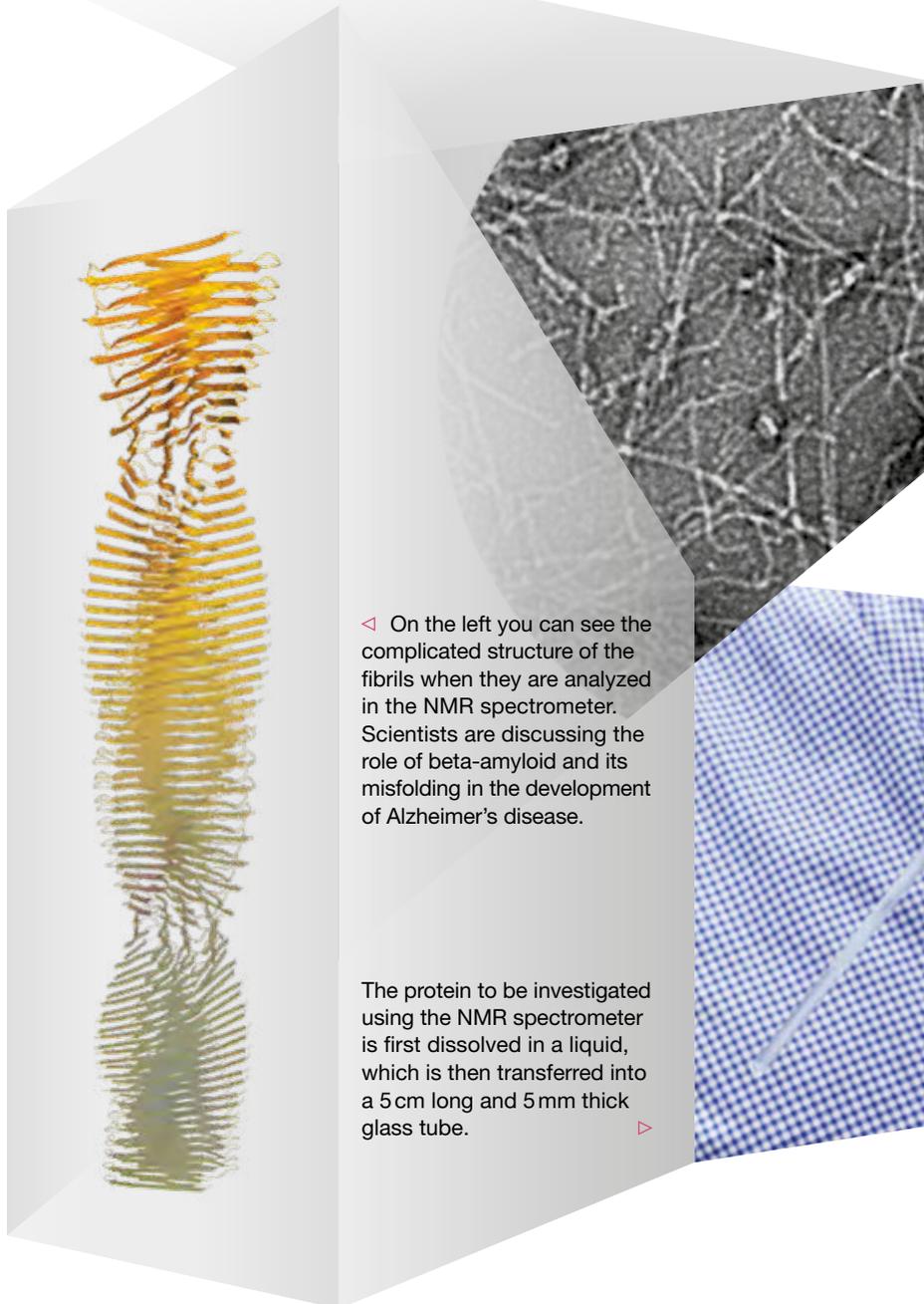
The BNMRZ cooperates closely with the researchers of the Center for Functional Protein Assemblies (CPA), whose new building is currently under construction in the immediate vicinity on the Garching research campus.

The systems are operated from the well-shielded control room attached to the spectrometer hall and all data are collected here.



**P**rof. Bernd Reif holds up a small glass tube around five centimeters in height, but only around five millimeters thick. He shakes it carefully, observing the solution inside, which contains a dissolved protein. The structure of this protein was determined by one of the seven nuclear magnetic resonance (NMR) spectrometers arranged side by side in a 700 square meter measurement hall. This hall is part of TUM's new Bavarian NMR Center (BNMRZ), officially opened in October 2018. Everything in the brand new, dark red building on the Garching campus revolves around nuclear magnetic resonance spectroscopy

– a method that allows the precise measurement of the spatial structure of protein complexes and especially can assess their internal dynamics. One of the most comprehensive and powerful structural analysis methods in chemistry and biochemistry, it enables researchers to take images of the electronic environment of individual atoms and their interactions with neighboring atoms – and thus not only capture the structure but even the dynamics of complex molecules. It is one of the methods that gives atom-level snapshots also of proteins consisting of thousands of atoms. ▶



◁ In Alzheimer's disease, the spatial structure of the beta-amyloid protein changes, causing it to stick together in such long, insoluble strands. At the same time, more and more of the surrounding nerve cells die off.

◁ On the left you can see the complicated structure of the fibrils when they are analyzed in the NMR spectrometer. Scientists are discussing the role of beta-amyloid and its misfolding in the development of Alzheimer's disease.

The protein to be investigated using the NMR spectrometer is first dissolved in a liquid, which is then transferred into a 5 cm long and 5 mm thick glass tube. ▷

Over the last few months, the seven NMR spectrometers previously scattered across various different locations have been brought together at the Bavarian NMR Center. Now widely distributed around the airy hall with its eight-meter-high ceiling, they run around the clock, seven days a week. The fact that this room is so spacious and north-facing makes it easier for the air-conditioning system to keep ambient temperatures stable. The devices each contain a superconducting magnetic core, which must be cooled down to four and sometimes two degrees Kelvin and kept at that temperature with the help of liquid helium. "This is the only way to generate highly homogeneous magnetic fields with the required field strength,"

explains physicist Bernd Reif. The spectrometer hall is also well shielded from external potential sources of interference. Its location at the northwestern tip of the campus was deliberately selected so that neither the subway nor passing trucks would influence the sensitive data collection process.

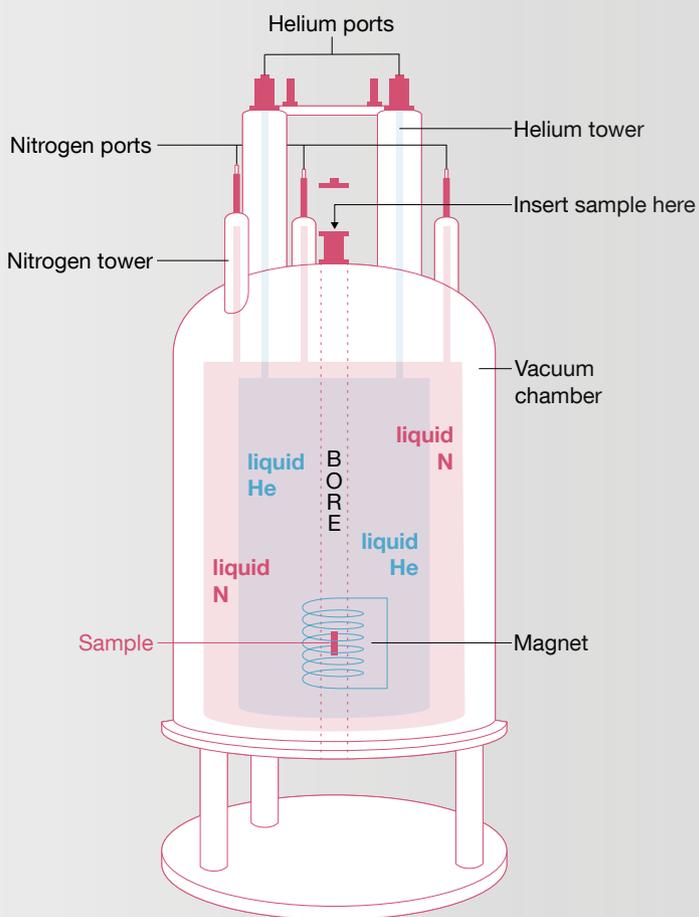
"We wanted a building where labs, offices and equipment are all close by," remarks Prof. Michael Sattler, chemist and Director of the Bavarian NMR Center. Ease of access holds many advantages, enabling closer and more efficient collaboration – not only in terms of research and joint publications, but also when it comes to training students.

### The strongest magnetic field on Earth

Three more spectrometers from neighboring buildings are now waiting to be moved over. The only item missing then will be the core of the center: one of the world's most powerful NMR spectrometers with a frequency of 1.2 gigahertz and a magnetic field strength of almost 30 tesla – the highest permanent magnetic field on Earth to date. “TUM will be the first university in Germany equipped with a high-performance spectrometer of this kind,” Sattler

observes. The device is currently being developed by the company Bruker, with delivery planned in three years' time. It will then enable analysis of even larger and more complex proteins than before: “Higher magnetic fields mean a stronger signal and, at the same time, less background noise that would otherwise interfere with our measurements,” explains Reif. ▶

### NMR magnet



Compared to the sample, the NMR system is huge: The superconducting coil for generating the magnetic field works close to absolute zero. For cooling, it is surrounded by liquid nitrogen on the outside and liquid helium on the inside. However, the NMR sample is measured at room temperature.



The Garching location is an enormous well of expertise, promoting the development of new methods and acting as a central hub specialized in the chemistry of biological macromolecules. In his office, flooded with midday sunlight, Bernd Reif is discussing the broad spectrum of potential applications with Michael Sattler and Aphrodite Kapurniotu, a chemist at the TUM School of Life Sciences Weihenstephan. In highly simplified terms, NMR spectroscopy exposes molecules to a strong homogeneous magnetic field that aligns the nuclei of atoms like compass needles. Short pulses of radio waves are then applied, disrupting this order. During their reorientation, the nuclei release part of the previously absorbed energy as a radio frequency that decays over time, which is measured and then analyzed further by computer. "Each atomic nucleus behaves differently here due to its environment, so in the

end we can assess the exact molecular structure of the protein," reveals Reif. The data provide important information about the form and thus also the function of the molecule, such as how it interacts with other molecules. Not only is this an important step along the path to understanding how diseases develop, it can also be used to pinpoint targets for the development of new drugs. By way of example, Sattler highlights a new drug candidate for Chagas' disease. Findings from a joint study on this with scientists at Helmholtz Zentrum München and Ruhr University Bochum were recently published in "Science" magazine. Chagas' disease is caused by trypanosomes, single-celled parasites, transmitted by blood-sucking insects known as "kissing bugs". It damages many of the body's organs, and around ten percent of cases still prove fatal. The drugs currently available have major side effects and are not able to destroy



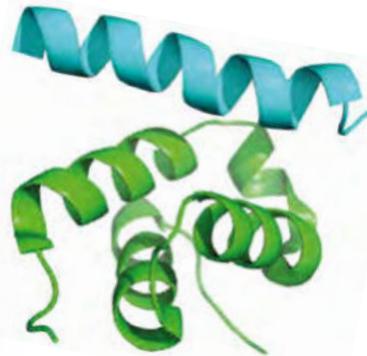
Due to the complexity of the protein structures, the researchers are using state-of-the-art technology, such as VR glasses, with which the spatial arrangement of the individual components can be visualized and intuitively better recognized.

*“Each atomic nucleus behaves differently here due to its environment, so in the end we can calculate the exact molecular structure of the protein.”*

*Bernd Reif, professor and expert in solid-state NMR*

Trypanosomes, unicellular parasites that transmit Chagas' disease, require enzymes for their metabolism, which they take up with the help of a special protein complex. The two proteins PEX14 and PEX5 have to bind to each other. A cartoon representation of the structure of this complex is shown here.

Pex14/Pex5

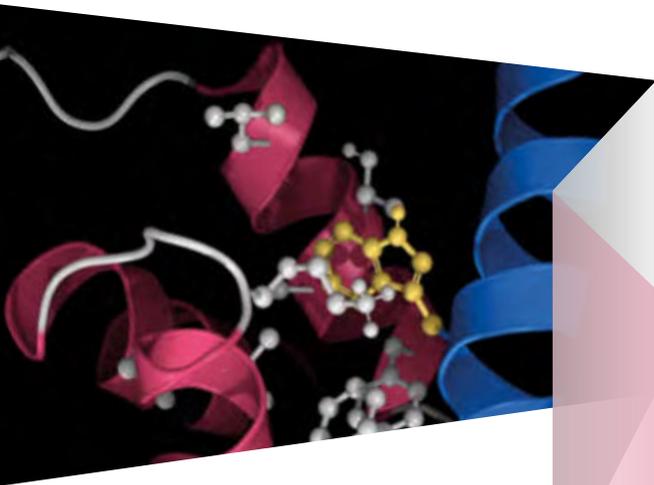


#### Folding is important

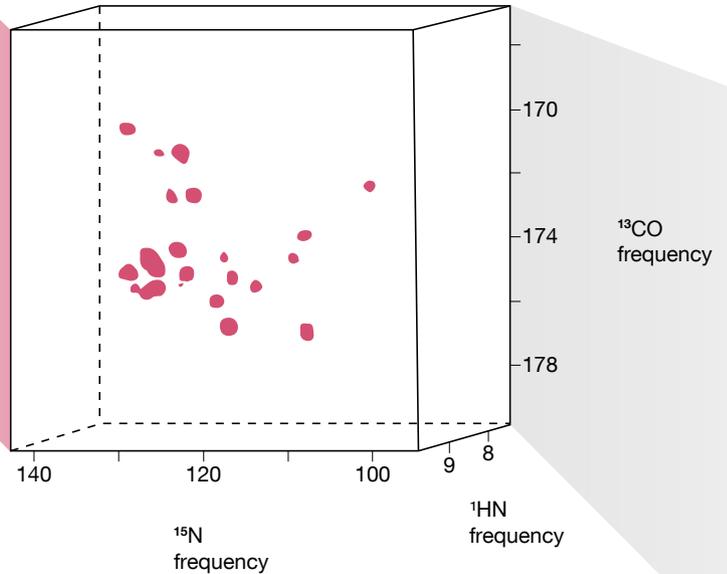
Proteins are made up of amino acids. When two amino acids join together, this is called a dipeptide, and a chain consisting of fewer than ten amino acids is an oligopeptide. Chains of between fifty and two thousand amino acids are referred to as polypeptides or proteins. In simple terms as a basic building principle, a protein can be viewed as a long chain on which various amino acids are strung together.

The exact sequence of amino acids determines the identity and function of the protein. However, proteins can only fulfill their biological function if they have been folded into a specific, complex spatial structure. This folding process takes place after their synthesis – or sometimes during it – due to interactions between amino acids within the molecule. In some cases, enzymes or certain auxiliary proteins, known as chaperones, are required for proper folding. Depending on which amino acids interact with each other, structures can form within the protein that look like spirals or leaflets.

A protein's three-dimensional structure in space is crucial for it to function correctly. If this is disrupted, diseases can occur.



From 3D spots to protein structure: The measurement results provided by the NMR spectrometer are as shown below. Using complicated algorithms, the researchers are able to calculate the three-dimensional structure of proteins.



the pathogens completely. However, it is known that the single-celled organisms contain specific organelles called glycosomes that metabolize sugar, which is essential for the organism's survival. In order to achieve this, the glycosomes must first import certain enzymes with the aid of a special protein transport complex. And it is this mechanism that Sattler and his colleagues chose to examine more closely. Since they knew that the PEX14 and PEX5 proteins have to bind together to enable this transport, they used NMR spectroscopy to identify their precise structure.

With this as their basis, they identified and gradually optimized a small molecule that specifically binds to PEX14, thus preventing it from interacting with PEX5. As a result, Sattler explains: "This blocks the metabolism of the pathogens, so the trypanosomes starve to death." The next step is to continue developing the drug candidate and ultimately bring it to clinical trials. "Market-ready medication is still a long way off," acknowledges Sattler. "But we have been able to show that blocking the PEX14 protein is a promising novel concept for new agents to combat trypanosomes."

### When folding goes wrong

The function of a protein depends not only on the precise sequence of its amino acids, but also on its folding – its exact spatial structure (see box). Some diseases are associated with incorrectly folded proteins that form clumps inside or between cells. Over thirty of these protein misfolding disorders have been identified to date, with Alzheimer's probably the most prominent. While clusters of this kind are difficult to access with established methods of structural biology, they lend themselves well to in-

vestigation using NMR spectroscopy. In Alzheimer's disease, the spatial structure of the beta-amyloid protein changes, causing it to stick together in long, insoluble strands. At the same time, more and more of the surrounding nerve cells die off. Although this has long been a topic of discussion, it remains unclear what role beta-amyloid and its folding play here and what causes the nerve cells to die. And there are still no drugs to prevent the process. ▶



Based on the protein structure of PEX14 and PEX5, the researchers finally developed a chemical agent that binds optimally to PEX14 and prevents interaction with PEX5. This makes PEX14 inactive.

*“We have been able to show that blocking the PEX14 protein is a promising novel concept for new agents to combat trypanosomes.”*

*Michael Sattler, Director of the Bavarian NMR Center*



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**Prof. Aphrodite Kapurniotu**

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## Researcher with international outlook

Prof. Aphrodite Kapurniotu studied chemistry in Athens (Greece). After obtaining her degree in 1984 and her doctorate in 1990 in Tübingen (Germany), she moved to the US, spending 2 years as a postdoc at Rutgers University and another 1 year as a senior scientist at the Picower Institute for Medical Research (US). Returning to Germany, she was a group leader at the University of Tübingen between 1994 and 2002, while completing her postdoctoral thesis in biochemistry. From 2002 through 2007, she led a biomedical research group at RWTH Aachen University, before becoming Professor for Peptide Biochemistry at TUM in 2007.

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**Prof. Bernd Reif**

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## From Berlin to Munich

Prof. Bernd Reif studied physics at the University of Bayreuth (Germany), obtaining his degree in 1993. After completing his doctorate in 1998 at Goethe University Frankfurt, he pursued his studies as a postdoc at the Massachusetts Institute of Technology (MIT) in Cambridge (US) until 1999. He then returned to Germany to lead an Emmy Noether Junior Research Group at TUM until 2002. From 2003 through 2010, he worked at the Leibniz Institute for Molecular Pharmacology in Berlin-Buch, while also holding a professorship at the Charité university hospital in Berlin. In 2007, he became Coordinator at the Leibniz Graduate School of Molecular Biophysics in Berlin. He took up his position at TUM in 2010, and has also led a working group at Helmholtz Zentrum München since that time.

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**Prof. Michael Sattler**

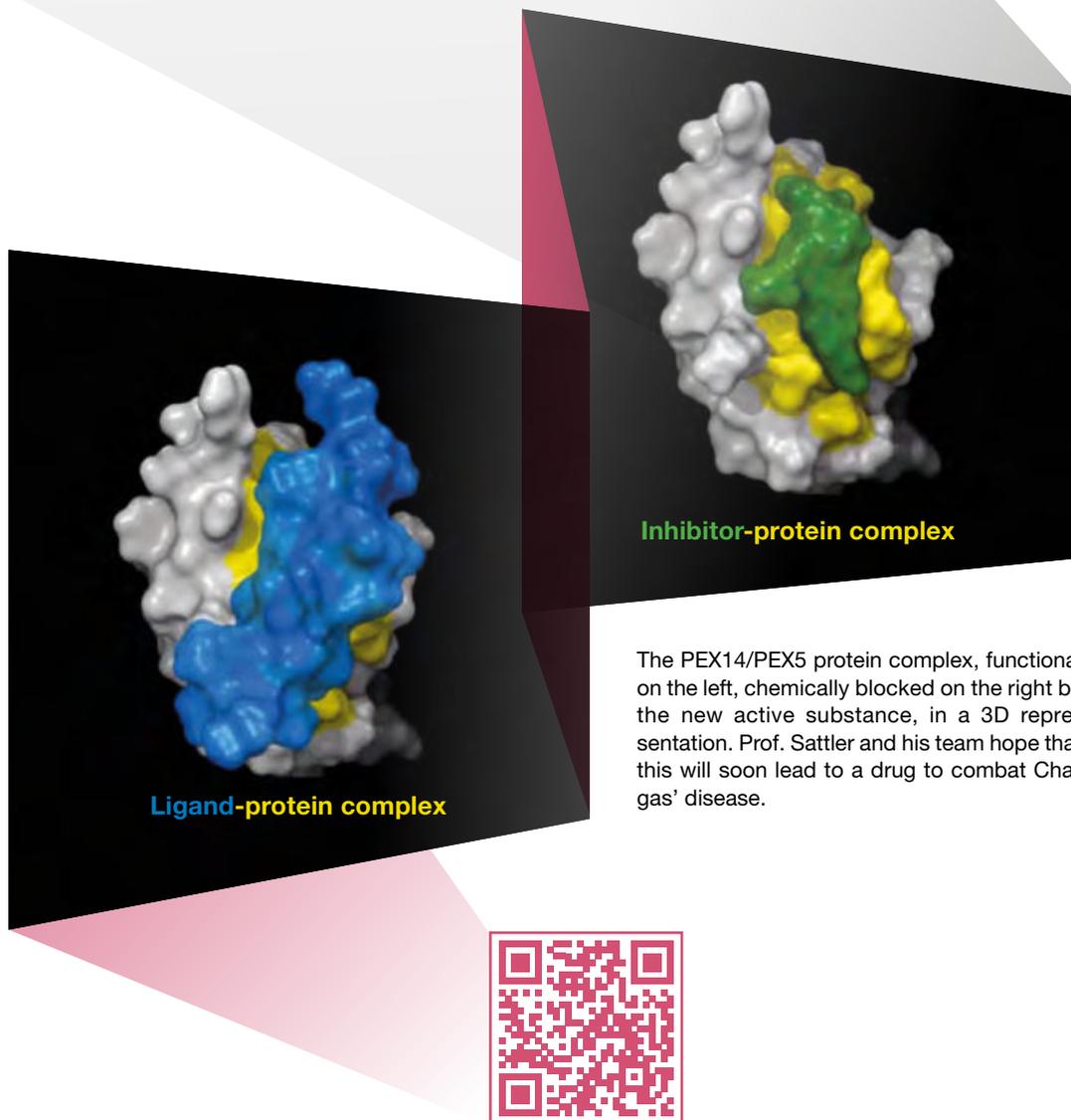
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## An NMR researcher from the very start

Prof. Michael Sattler studied chemistry at Goethe University Frankfurt (Germany), where he received his degree in 1991 and his doctorate in 1995, focusing on the development of NMR methods. He then spent two years in the US, working as a postdoc at Abbott Laboratories – a global pharmaceutical company. Back in Germany, he led a research group at the European Molecular Biology Laboratory (EMBL) in Heidelberg from 1997 through 2006. He has been Director of the Institute of Structural Biology at Helmholtz Zentrum München since 2007, while at the same time holding TUM's Chair of Biomolecular NMR Spectroscopy. He is also Director of the Bavarian NMR Center.

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What we do know is that healthy cells usually have enough clean-up workers on hand in the form of specialized proteins, which ensure that folding errors are corrected immediately or that the affected molecules are taken out of circulation. Bernd Reif is investigating their interaction with beta-amyloid protein. Meanwhile, his colleague, Aphrodite Kapurniotu, is focusing on chemical synthesis and developing molecules intended to block the misfolding and clump formation of beta-amyloid.

“NMR spectroscopy helps us to understand beta-amyloid interactions and thus continue improving the properties of potential aggregation inhibitors,” Kapurniotu explains. In the future, the two professors intend to take results from the test tube further along the path towards medical applications. They are also keen to find out whether their results could be applied to other diseases associated with misfolded proteins. ■

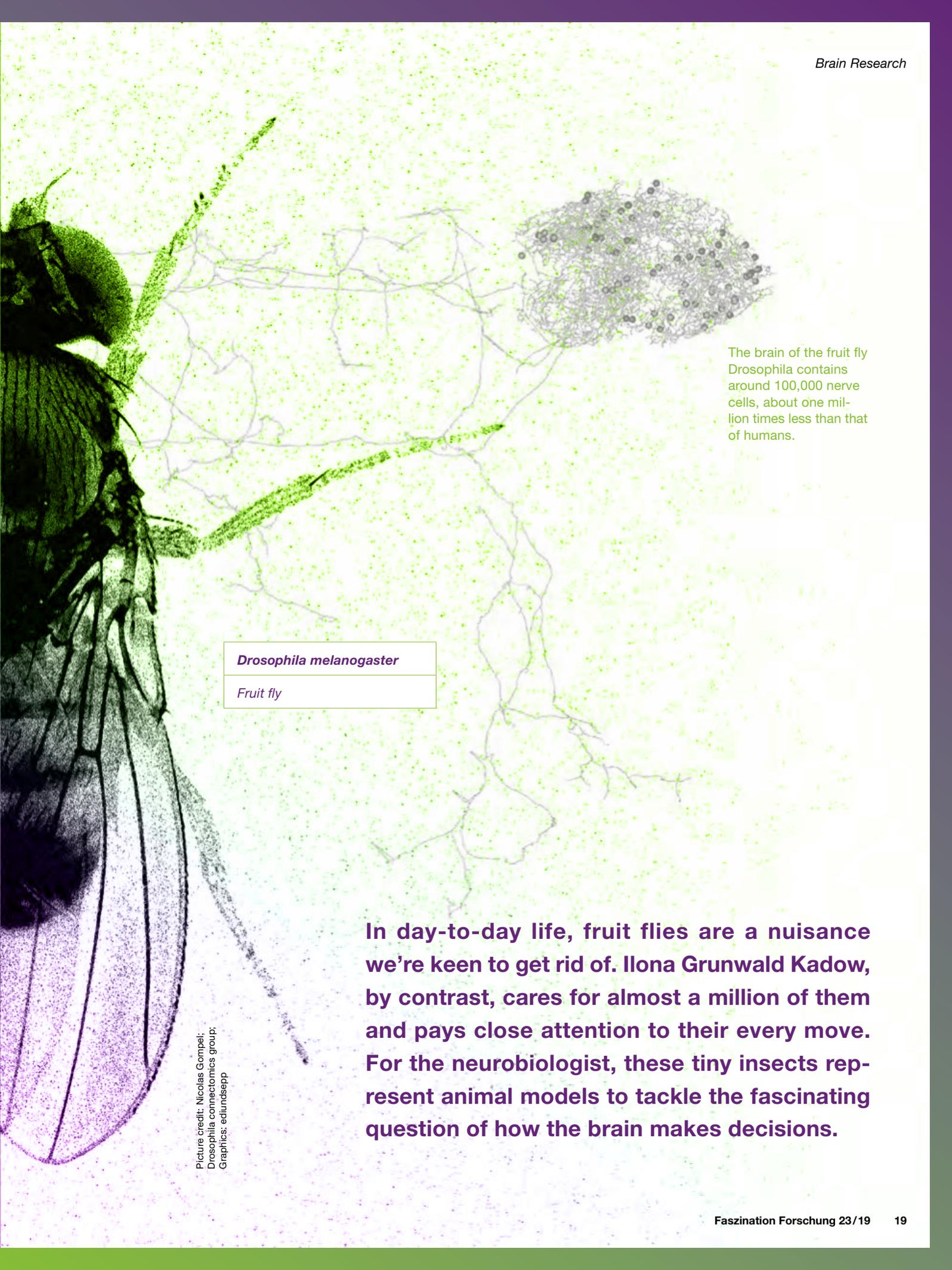
*Karoline Stürmer*

Links

[neuro.wzw.tum.de](http://neuro.wzw.tum.de) | [cns.wzw.tum.de](http://cns.wzw.tum.de)

# Keep Going or Give Up?





*Drosophila melanogaster*  
Fruit fly

The brain of the fruit fly *Drosophila* contains around 100,000 nerve cells, about one million times less than that of humans.

In day-to-day life, fruit flies are a nuisance we're keen to get rid of. Ilona Grunwald Kadow, by contrast, cares for almost a million of them and pays close attention to their every move. For the neurobiologist, these tiny insects represent animal models to tackle the fascinating question of how the brain makes decisions.

Picture credit: Nicolas Gempel;  
*Drosophila connectomics* group;  
Graphics: edlundsepp

## Aufgaben oder Weitermachen?

D

Entscheidungen, wie beispielsweise über die Futtersuche, beruhen auf sensorischen Eindrücken, aber auch auf früheren Erfahrungen und dem inneren Zustand eines Tieres oder Menschen. Wo im Gehirn werden solche Entscheidungen getroffen? Welche Nervenzellen sind daran beteiligt und wie bestimmen sie das Verhalten? Diesen Fragen gehen die Neurobiologin Ilona Grunwald Kadow und die Mathematikerin Julijana Gjorgjieva an der TUM School of Life Sciences in Weihenstephan auf den Grund. Als Modell dienen Fruchtfliegen. Mithilfe von Experimenten und Computermodellen haben die beiden Professorinnen einen neuronalen Schaltkreis im Fliegengehirn identifiziert, der Motivation und Durchhaltevermögen bei der Futtersuche steuert.

Julijana Gjorgjieva entwickelte mit ihrem Team ein mathematisches Modell, das dieses Verhalten simulieren kann. Mittels hochauflösender Elektronenmikroskopie konnte Ilona Grunwald Kadow zusammen mit Kollegen in den

USA und in England dann die entsprechenden anatomischen Strukturen im Fliegengehirn identifizieren. Experimente mit gentechnisch veränderten Fliegen erlaubten es schließlich, die beteiligten Nervenzellen gezielt an- und auszuschalten.

Der Schaltkreis liegt im Lern- und Erinnerungszentrum des Fliegengehirns. Er wird von zwei gegenläufig wirkenden Botenstoffen – Dopamin und Octopamin – angetrieben bzw. unterbrochen. Dopamin existiert auch im menschlichen Gehirn, und Octopamin hat seine Entsprechung in Noradrenalin. Die Verhaltensprogramme zur Nahrungssuche haben sich vor vielen Jahrmillionen entwickelt. Deshalb vermuten die Forscherinnen, dass sie beim Menschen einer ähnlichen neuronalen Kontrolle unterliegen wie bei den Fliegen. Die neuen Erkenntnisse könnten zu einem besseren Verständnis von Essstörungen beitragen.

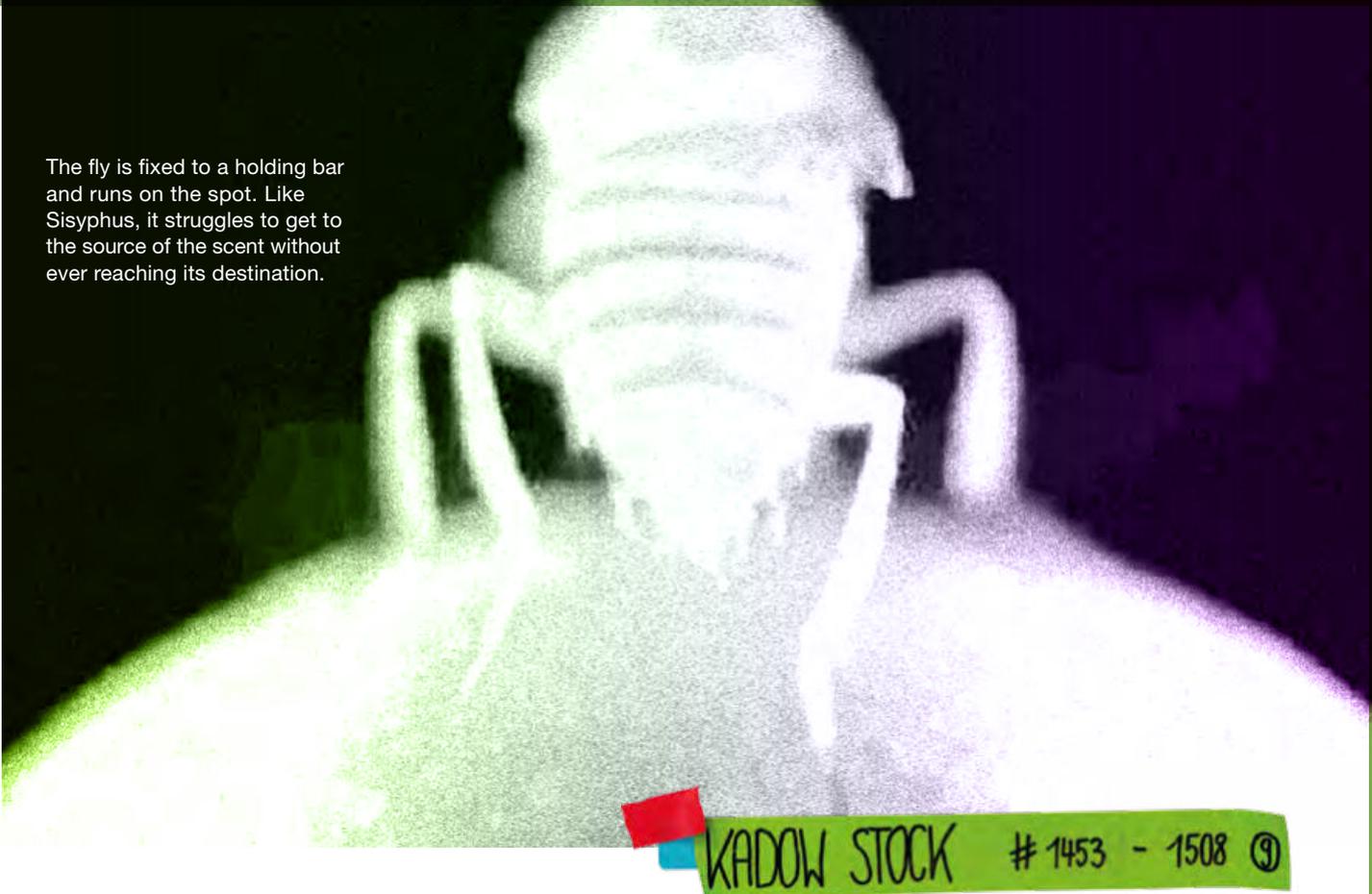
□



For her complex experiments, Ilona Grunwald Kadow needs a large number of transgenic fly strains that differ in important properties. To keep them apart, the flies are kept at a controlled temperature and humidity in carefully labeled plastic tubes with nutrient medium.



The fly is fixed to a holding bar and runs on the spot. Like Sisyphus, it struggles to get to the source of the scent without ever reaching its destination.

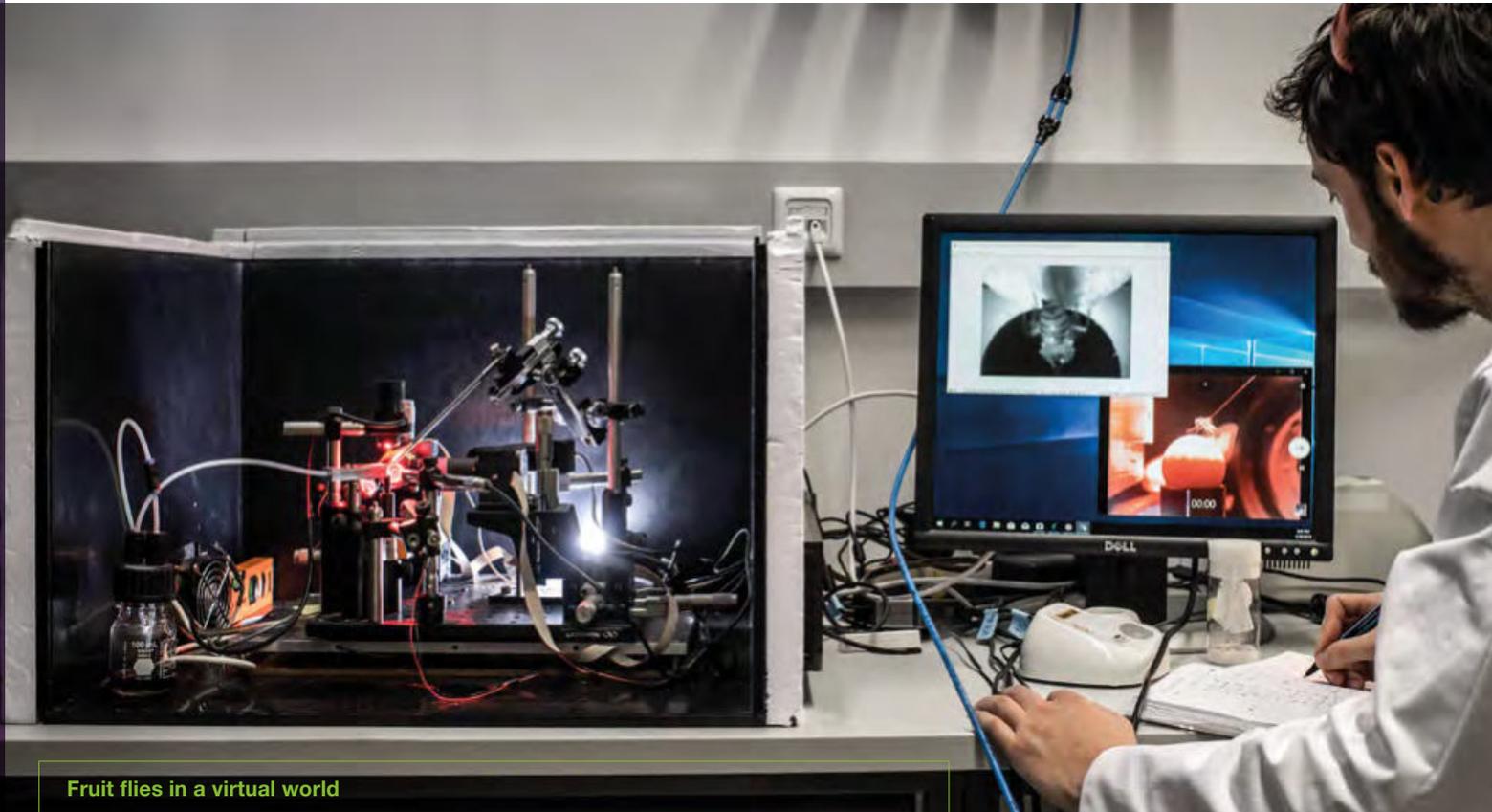


Picture credits: Astrid Eckert/TUM; Sercan Sayin

As lunchtime approaches, everyone agrees: it's time to eat. Work is put on the backburner as everyone moves – as one – to the canteen for the far more important matter of lunch. “In this respect, people and flies are pretty similar,” reveals Prof. Ilona Grunwald Kadow. And the neurobiologist should certainly know, since her lab at the TUM School of Life Sciences in Weihenstephan is

home to roughly one million flies of the *Drosophila* genus. Kept at an ideal temperature and provided with plenty of food, each fly does exactly as it pleases: flying or eating; crawling or fighting; grooming or mating. “Behavior differs greatly between individuals when they have no common objective,” reports Grunwald Kadow. “But that changes when everyone is hungry. Then they suddenly have a shared motivation and pursue the same goal: finding food.”

Looking beyond hunger and thirst, triggers that guide the behavior of flies and humans alike include sensory impressions, emotions, experiences and internal state. Where in the brain does this information converge? Which nerve cells (neurons) are involved and how do they determine behavior? Grunwald Kadow is searching for answers in her fruit flies. “A fly’s brain has almost a million times fewer nerve cells than our own, so it’s easier to find out what a single neuron does,” the biologist explains. And the tiny insects are very suitable for her experiments in other ways, too. Similar to us humans, a hungry fly will drop everything to look for something to eat. As soon as it smells the scent of food, it heads straight for the source. And on reaching its destination, it stops and eats. ▶



### Fruit flies in a virtual world

The experimental setup, shown in real on the left and schematically on the right: In order to decipher how the brain controls the motivation of a fruit fly, the animals are placed in a darkened box in a kind of “virtual reality”. There, they are allowed to run on a moving ball (here in the center, illuminated in red) and a delicious scent is blown in front of their noses. So they imagine that they are moving towards food. In fact, however, they are glued to a holder on their back and are running on the spot. This trick allows the experimenter to observe individual flies from the workstation on the right, either on the monitor or under the microscope.

In the process of searching for food, it displays perseverance, even if it doesn't immediately find anything.

“Using this behavior as a model, we are trying to gain an understanding of basic processes in the brain. We ask ourselves questions such as: How does the nervous system keep the fly on task even if it doesn't immediately achieve its goal? And how can it suddenly abandon this goal and engage in a new, contrasting behavior as soon as it finds food – even though the scent of food, which previously triggered the food search, is still there?” explains Grunwald Kadow. This requires a flexible yet reliable neural mechanism capable of triggering the appropriate behavior and suppressing other behaviors in every

situation. Hence, there is a kind of hierarchy within the nervous system – and the prevailing response depends on the situation, objective and internal state.

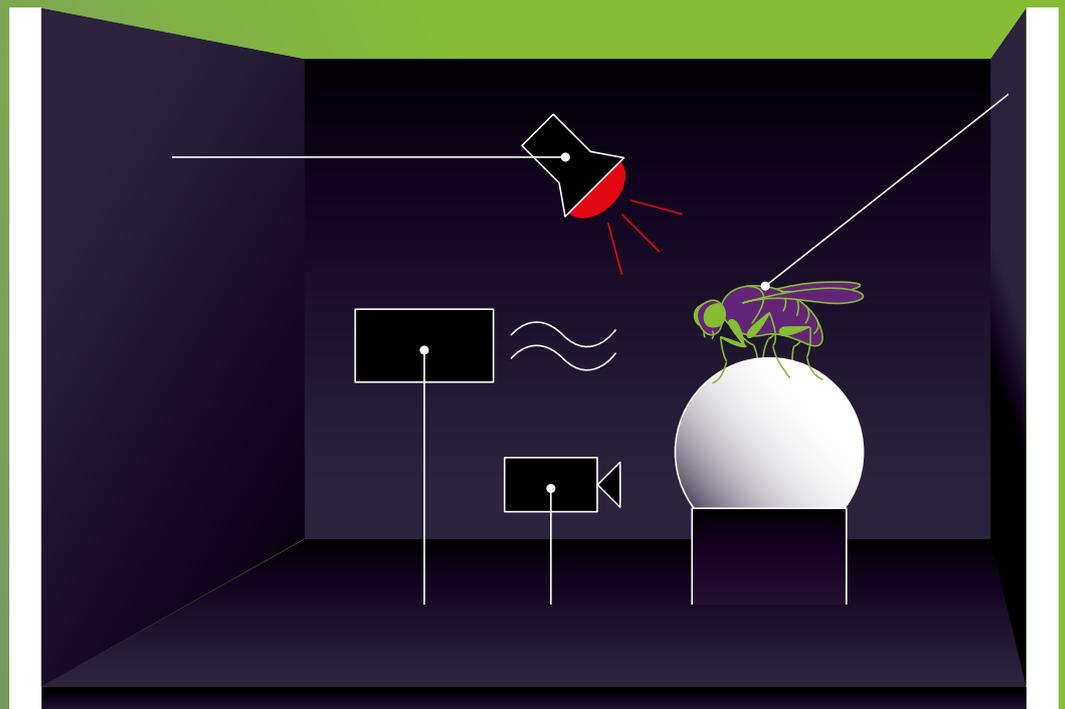
To find out how this works, the flies in Weihenstephan are placed into a type of virtual reality situation. An appetizing scent is wafted in front of their noses as they run on a moving ball in the belief that they are on course to find food. In fact, their backs are glued so that they are running on the spot. This trick enables the researcher to observe individual flies running at full speed on a monitor or under the microscope. “This shows us that hungry insects run after a food scent for longer and in a faster and more targeted way than ones that are already full,” explains ▶



*“We suspect that behavioral programs are subject to a fundamentally similar neural control process in flies and humans.”*

*Ilona Grunwald Kadow*

The schematic experimental setup: A fruit fly, stuck to a holder, runs on a moving ball. From the left, food scent flows towards it, while at the same time it is illuminated with red light so that its food neurons are activated. A camera transmits its behavior to the monitor.

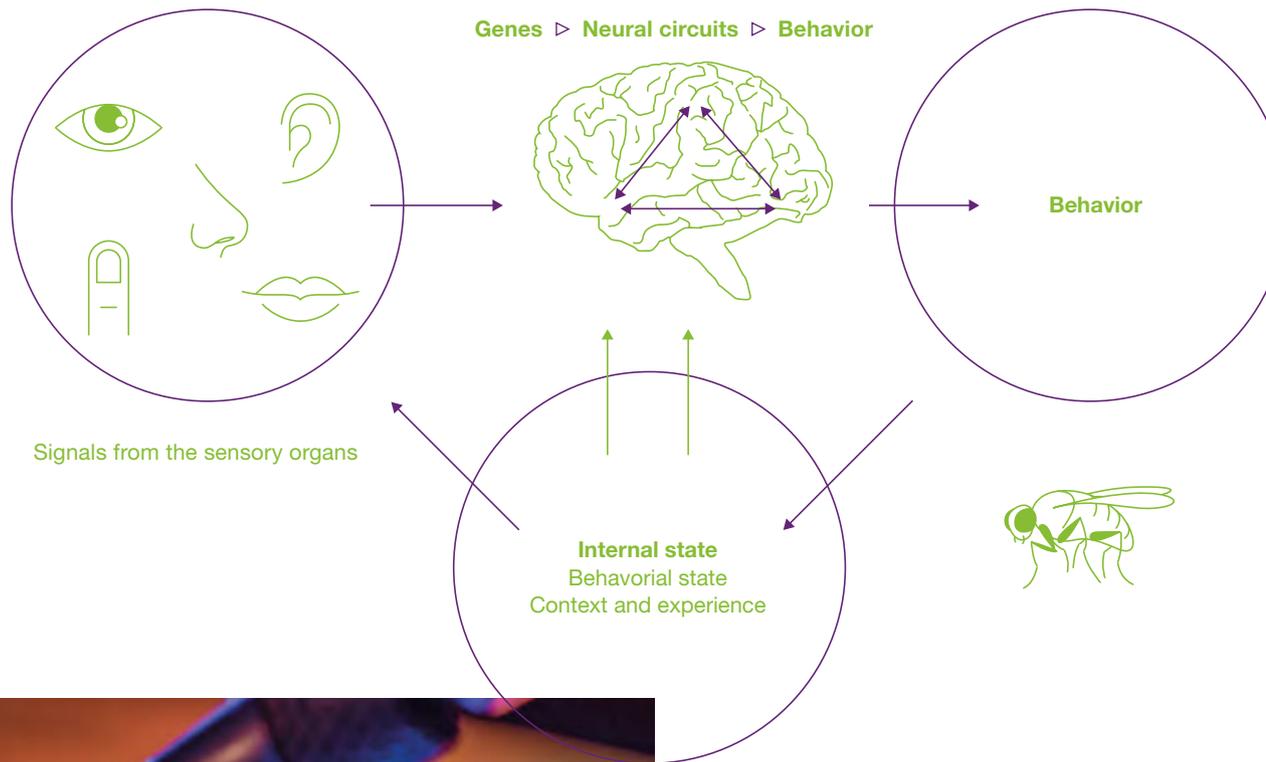


lead investigator Grunwald Kadow. That is hardly unexpected. But the more surprising finding is that, even after ten unsuccessful attempts, hungry flies do not give up. While full insects slacken quickly, the hungry ones try harder and harder each time. The “run and find” program seems to intensify each time as a result of their internal motivation.

“The easiest way to explain this is that there’s a kind of feedback loop in the brain. So, we looked for corresponding brain structures in the flies,” the neurobiologist continues. It was in the brain’s learning and memory center – known as the “mushroom body” on account of its shape – that the TUM team made its finding: “Thanks to electron microscope images from our colleagues in the US and UK, we can see which neurons “talk” to each other. Thus,

we were able to identify a two-way connection between neurons that communicate with the help of dopamine – a neurotransmitter or chemical messenger also found in humans,” she reports. These “dopamine cells” not only communicate among themselves, but also with input and output cells, which respond to incoming scent signals and make the flies run. Cells sensitive to sugar and other taste stimuli also play an important role here. These “food neurons” communicate with the output cells via the messenger substance octopamine, whose function is similar to noradrenaline in humans.

At this point, Prof. Julijana Gjorgjieva enters the picture. The computational neuroscience expert has developed a mathematical model to replicate the flies’ behavior based on interactions between the three types of neurons.



The team anesthetizes the flies with cold or CO<sub>2</sub> and uses tweezers and micromanipulators to position them under the microscope. They are glued into place with UV-cured dental adhesive, which hardens extremely fast.

*“We were able to identify a two-way connection between neurons that communicate with the help of dopamine.”*

*Ilona Grunwald Kadow*



By contact with red light, certain neurons of the genetically modified flies can be switched on and off. These flies are kept in blue light so that this only happens during the experiments.

The model is able to simulate how hungry insects ramp up their efforts to reach food after each unsuccessful attempt. And it explains how food stimuli cause the flies to switch from “run and find food” to “stop and eat” mode. The two messenger substances play a decisive role here, exerting an opposite effect on the output cells: dopamine fuels the feedback loop, while octopamine inhibits it. “Mathematical models help us to unravel the complexity of neural circuits. Ultimately, though, they have to stand up to real-world behavioral responses,” emphasizes Julijana Gjorgjieva.

The reality check here takes place using genetically modified flies, where very specific types of nerve cells have

been selectively manipulated. This is done by inserting genetic elements into the flies’ DNA that respond to temperature increases or light stimuli, either switching off or activating the relevant neurons. “We generate some of these transgenic *Drosophila* strains ourselves and obtain others from colleagues,” reveals Grunwald Kadow. Her team uses these specially adapted flies to turn on and off all of the elements in the neural circuit of interest, one step at a time – in the living insect. In some flies, the researchers block the suspected feedback mechanism within the dopamine or output cells. To achieve this, they need only increase the temperature in the room by a few degrees Celsius. The transgenic flies are equipped

with a heat-sensitive protein that prevents the release of dopamine in the targeted nerve cells, and therefore avoids activating the recipient neurons – but only at temperatures of 30 degrees or above. Therefore, flies that receive this heat-sensitive protein then lack the dopamine-driven feedback loop and thus receive no feedback about previous unsuccessful attempts. Instead of stepping up their efforts each time like regular flies, they always run at the same speed and give up faster.

Other flies are genetically engineered so that their food neurons contain a light-sensitive protein channel. When exposed to red light, which penetrates from the outside through the fly's body tissue, the channel opens. This allows sodium and potassium ions to pass through the membrane of the nerve cell, triggering an excited state that leads to the release of octopamine. Since this messenger substance inhibits the output cells, these insects stop running – even if they are hungry and can smell food.



Julijana Gjorgjieva (on screen) develops mathematical models to decipher the complexity of neural circuits. Via Skype she discusses the results of her computer simulations with her colleague Ilona Grunwald Kadow.



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**Prof. Ilona Grunwald Kadow**

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## Geneticist at the forefront of brain research

After studying biology in Göttingen (Germany) and San Diego (US), Ilona Grunwald Kadow completed her doctorate in neuroscience at the European Molecular Biology Laboratory and the University of Heidelberg (Germany). Following a postdoc at the University of California in Los Angeles (US) and at the Max Planck Institute (MPI) for Neurobiology in Martinsried, Munich (Germany), she spent eight years as an Emmy Noether and then a Max Planck research group leader at the Martinsried MPI. She took up the newly created professorship for Neural Circuits and Metabolism at the TUM School of Life Sciences in Weihenstephan at the start of 2017.

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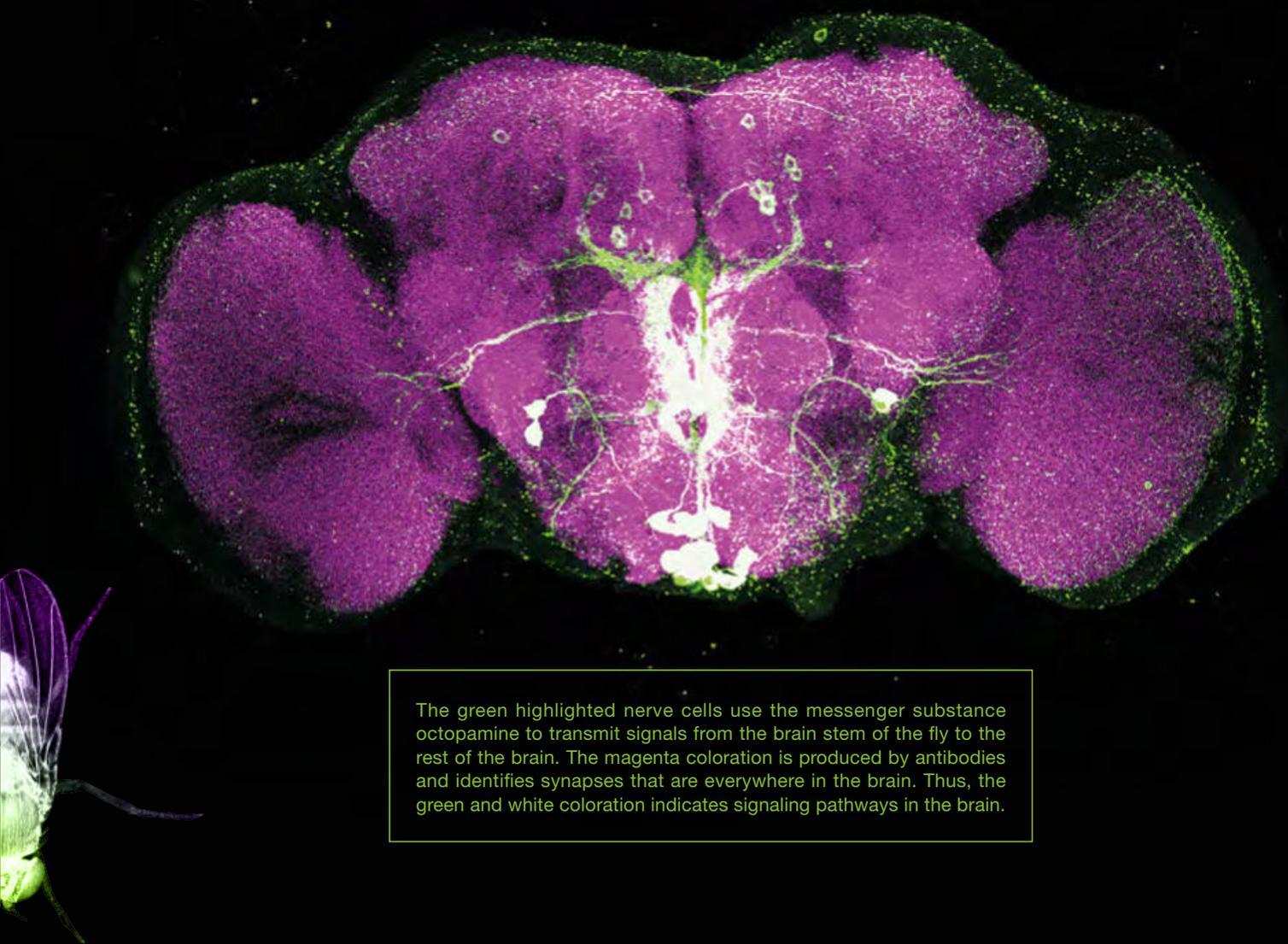
**Prof. Julijana Gjorgjieva**

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## Young leader with interdisciplinary focus

Born in Macedonia, Julijana Gjorgjieva completed her Master's in mathematics and her doctorate at the University of Cambridge (UK). Two summer schools sparked her interest in systems biology and neuroscience, initially taking her to the Center for Brain Science at Harvard and then to Brandeis University (US) as a postdoc. She has been leading a research group at the Max Planck Institute for Brain Research in Frankfurt (Germany) since 2016 and also holds a professorship in Computational Neuroscience at the TUM School of Life Sciences in Weihenstephan.

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The green highlighted nerve cells use the messenger substance octopamine to transmit signals from the brain stem of the fly to the rest of the brain. The magenta coloration is produced by antibodies and identifies synapses that are everywhere in the brain. Thus, the green and white coloration indicates signaling pathways in the brain.

Picture credits: Astrid Eckert; Nicolas Gompel; Anja Friedrich

“Thus, the flies behave exactly as our model predicts. That is a very strong indication of the existence of this circuit,” Gjorgjieva sums up.

What, then, can we learn from *Drosophila* flies? “Hunger is a major area of similarity between flies and humans. The associated behavioral programs evolved millions of years ago. Therefore, we suspect that they are subject to a fundamentally similar neural control process in both species,” explains Grunwald Kadow. The fact that this control does not always work properly can be seen in patients with eating disorders: Some are unable to stop

eating long after they are actually full, while people with anorexia are no longer able to respond to their hunger signals and, in extreme cases, can even starve themselves to death. “Something is way off track there. A program that is definitely flawed has managed to suppress a program vital to survival, which is actually supposed to be dominant. We want to understand how and where in the brain that happens and how we could potentially intervene,” the TUM researcher concludes. And now that she knows how the brain circuit works in the fly, she is another step closer to that aim. ■ *Monika Offenberger*

Link

[www.ph.tum.de/research/groups/group/TUPHECP](http://www.ph.tum.de/research/groups/group/TUPHECP)

# Neutrinos: Ice-Cold Detective Work

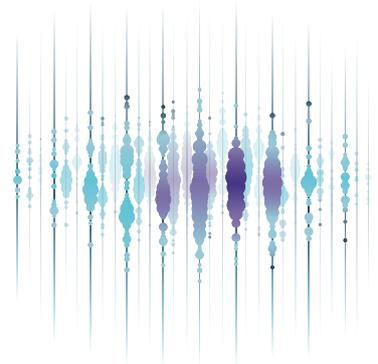


While searching for neutrinos as part of the IceCube experiment in Antarctica, Prof. Elisa Resconi and her team of researchers came across an extremely high-energy particle. Tracing it back, they realized they were dealing with an object that is 5.7 billion years old.



Physicist Elisa Resconi in a walk-in installation by conceptual artist Tim Otto Roth. The spheres symbolize the detectors of the IceCube experiment. The lights simulate the impact of a neutrino, similar to the measurements in the image below.

Picture credit: Jüli Eberle; Graphics: eclundisepp (source: IceCube)



Kurzfassung

## Physikalische Detektivarbeit: Herkunft hochenergetischer Neutrinos geklärt

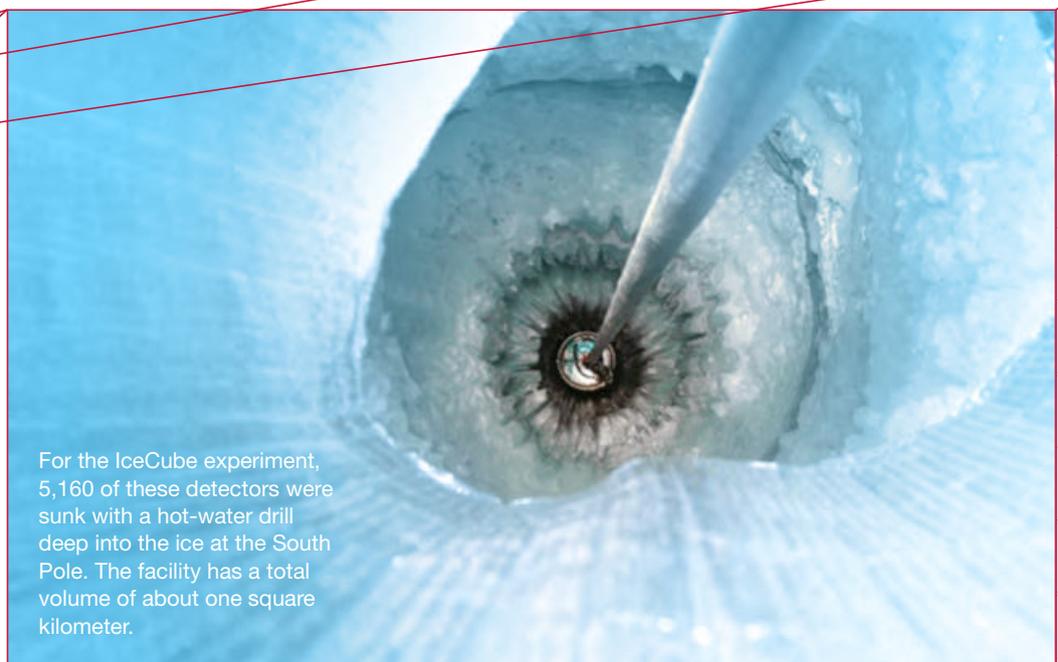
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Am 22. September 2017 registrierten Sensoren im Experiment IceCube in der Antarktis ein hochenergetisches Neutrino. Seine Einfallsrichtung führte die Forscherin Prof. Elisa Resconi auf eine heiße Spur: Gemeinsam mit einem internationalen Forscherteam gelang es ihr nachzuweisen, dass das Neutrino von einem 5,7 Milliarden Lichtjahre entfernten Blazar stammte. Das Ergebnis erklärte *Science* zu einem der „Breakthroughs“ des Jahres 2018.

Neutrinos haben keine Ladung und sind fast masselos, durchdringen Materie mühelos und werden von Magnetfeldern nicht abgelenkt. Für die Suche nach ihnen wurde im Eis der Antarktis das IceCube South Pole Observatory errichtet. Es weist Neutrinos indirekt nach: Stößt eines von ihnen mit einem Atomkern zusammen, kann ein Myon entstehen. Dieses sendet entlang seiner Flugbahn Photonen aus. 5160 Detektoren, die in einem Quadrat-

kilometer Eis versenkt sind, detektieren diese. Aus den Messwerten berechnet man die Energie des Neutrinos und die Richtung seines Einfalls. Das am 22. September 2017 registrierte Teilchen hatte demnach eine Energie von 290 Tera Elektronenvolt (tausend Milliarden) und stammte aus Richtung des Sternbilds Orion.

In Zusammenarbeit mit Astronomen gelang es den IceCube-Forschern, den Herkunftsort des kosmischen Neutrinos zu lokalisieren: den Blazar TXS 0506+056, ein Schwarzes Loch im Zentrum einer aktiven Galaxie. Er erzeugt einen „Jet“ hochenergetischer Strahlung, der auf die Erde gerichtet ist. Mit den Messungen konnte erstmals bewiesen werden, dass ein Blazar während Phasen erhöhter Aktivität nicht nur Röntgen- und Gammastrahlen, sondern auch hochenergetische Neutrinos erzeugt. □



For the IceCube experiment, 5,160 of these detectors were sunk with a hot-water drill deep into the ice at the South Pole. The facility has a total volume of about one square kilometer.

Via cables, the signals passed through the eternal ice from the detectors to the computer.



*September 22, 2017*

**O**n Friday, September 22, 2017, 20:54 UTC, sensors near the South Pole detected a faint, bluish glow at a depth of more than 1,500 meters. Just a few minutes later, an alert popped up on Prof. Elisa Resconi's monitor in the TUM Department of Physics, 15,000 kilometers away.

The physicist still has a vivid recollection of the precise moment when she got the news: "I had been at a meeting and opened the mail as soon as I got back to my office. The data clearly indicated that the sensors in the IceCube South Pole Observatory had found evidence of a high-

energy neutrino." She certainly waited a long time for this moment, having spent over twenty years tracking the tiny particles, which have barely any mass or charge, and pass through matter with ease. Along with research teams from twelve different countries, Elisa Resconi was involved in the IceCube project right from the start.

IceCube is the most unusual telescope in the world. The detector consists of 5,160 optical sensors, suspended from a total of 86 wires that are submerged into the Antarctic ice at depths of 1,500 to 2,500 meters. The sensors are connected by cable to the surface. The sensor field spans one cubic kilometer of ice (see *Faszination Forschung* 16, July 2015).

This Antarctic instrument can detect neutrinos indirectly. If one collides with an atomic nucleus in the ice, a muon can form. This charged elementary particle continues the trajectory of the neutrino, emitting a bluish glow due to Cherenkov radiation. The optical sensors in the ice detect the photons, and specially developed algorithms analyze the measurements. The number and intensity of photons can be used to determine a neutrino's energy, while the Cherenkov radiation trace indicates the direction from which ▶

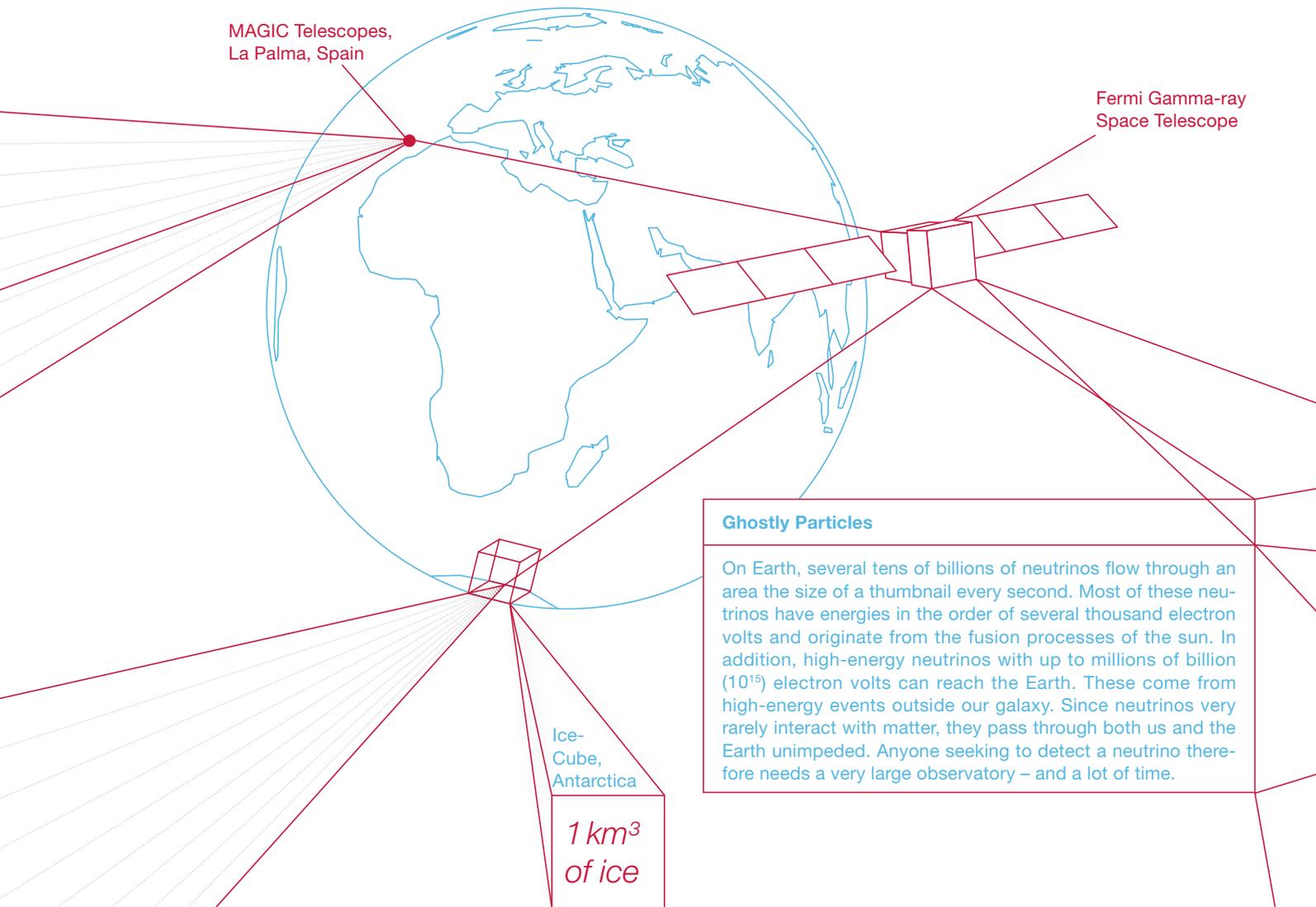


*“It had long been suspected that blazars were a source of high-energy neutrinos but no-one had been able to prove it.”*

*Elisa Resconi*

*5,160  
detectors*

In IceCube's laboratory building, the signals were collected and then sent all over the world. They also went to Paolo Padovani (top left) from the European Southern Observatory, to Paolo Giommi, then at TUM, and to the MAGIC Observatory in La Palma.



### Ghostly Particles

On Earth, several tens of billions of neutrinos flow through an area the size of a thumbnail every second. Most of these neutrinos have energies in the order of several thousand electron volts and originate from the fusion processes of the sun. In addition, high-energy neutrinos with up to millions of billion ( $10^{15}$ ) electron volts can reach the Earth. These come from high-energy events outside our galaxy. Since neutrinos very rarely interact with matter, they pass through both us and the Earth unimpeded. Anyone seeking to detect a neutrino therefore needs a very large observatory – and a lot of time.

a neutrino came. The majority of neutrinos originate from the sun and have energies in the order of up to several million electron volts. In addition, high-energy neutrinos with up to millions of billion ( $10^{15}$ ) electron volts – peta eV for short – reach the Earth. But only very rarely might one collide with an atomic nucleus in the exact cubic kilometer of Antarctic ice where the IceCube detector is located – as was the case on September 22, 2017.

Elisa Resconi stayed late in the office that evening. While she was busy scrutinizing the measurements, a dozen telescopes around the globe interrupted their routine programs due to the alert and set their sights on the Orion constellation. Calculations indicated that it was the source of the neutrino radiation. And so the interdisciplinary

detective work began: “Searching for the origins of high-energy neutrinos is like sifting through circumstantial evidence in a criminal case,” discloses the physicist. Observations by the Fermi Gamma-ray Space Telescope and the MAGIC gamma-ray telescope on La Palma (Canary Islands, Spain), and other telescopes pointed to a prime suspect: blazar number TXS 0506+056. This is located in the precise area of space from which the IceCube neutrino originated. Blazars are active galactic nuclei, black holes, which devour matter and produce jets of high-energy particles and electromagnetic rays directed towards Earth. On September 22, 2017, the jet of blazar TXS 0506+056 was particularly noticeable due to its increased radiation intensity. ▶

“That gave us a hot trail to follow,” Resconi reports. “It had long been suspected that blazars were a source of high-energy neutrinos but no-one had been able to prove it.”

A single neutrino, however, was obviously not enough to provide the necessary proof. So the researchers trawled the IceCube archive, looking for other evidence of particles coming from the same direction that were previously disregarded because their energy was lower. “When the data analysis results appeared on our screen, we all pretty

much freaked out,” recalls the physicist: “Over a dozen particles all pointed to the same place of origin.”

But did they really come from blazar TXS 0506+056? To answer this question, Resconi needed to draw on the support of astronomers. “It was a lucky coincidence that two blazar researchers happened to work nearby at the time: Paolo Padovani, who works at the European Southern Observatory (ESO), and Paolo Giommi, then a fellow at TUM’s Institute for Advanced Study.”



July 13, 2018



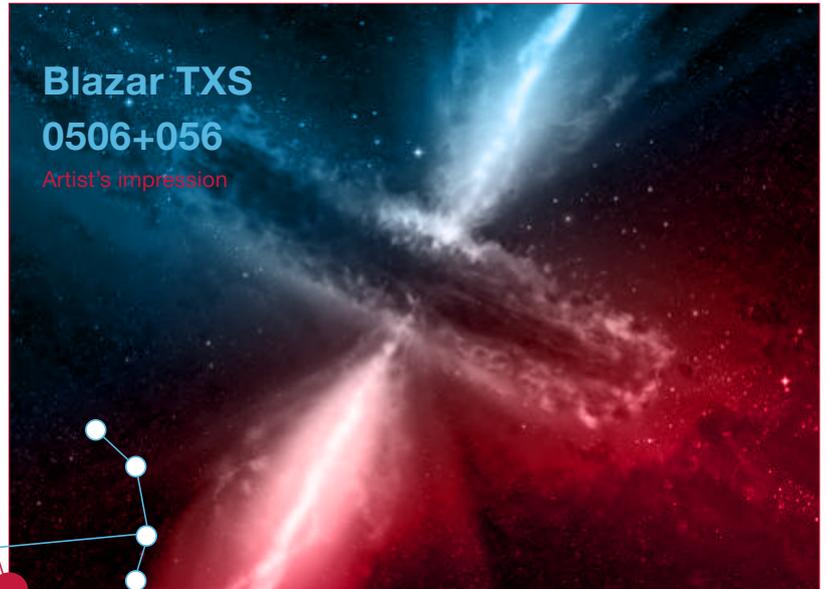
Prof. Elisa Resconi

## A physical detective working on neutrinos

Elisa Resconi didn't have to think too hard about the career path she should take: "I've always been fascinated by how things work – so becoming a physicist was the natural choice for me," the 47-year-old now recalls. Her career as a neutrino researcher began after her studies in Milan and Genoa, with her doctorate at the Laboratori Nazionali del Gran Sasso (Italy). She has been involved in the design and construction of the IceCube experiment for the past 18 years.

In Germany, Resconi was a Marie Curie Postdoctoral Fellow at DESY-Zeuthen, then continued her work at the Max Planck Institute for Nuclear Physics in Heidelberg and as a visiting professor at the University of Erlangen-Nuremberg (FAU). She has been a professor since 2011 – and Equal Opportunity Officer of the Physics Department since 2018.

Picture credits: Science Magazine, Cover, July 13, 2018.  
Reprinted with permission from AAAS; Juli Eberle;  
ESA/NASA/the AVO project/Paolo Padovani; Graphics: edlundsepp



## Blazar TXS

0506+056

Artist's impression

5.7

billion light  
years away

Orion

Finally, it turned out that the neutrino came from the blazar with the catalog number TXS 0506+056 in the constellation of Orion.



The news went around the world: "Science" put them on the front page and called this the "Breakthrough of 2018"; NASA made a movie about the discovery (see QR code).

The team combed through current measurement data and archives from numerous telescopes. "Comparing data from the Fermi Gamma-ray Space Telescope with the various IceCube measurements showed a clear connection between increased blazar activity and high-energy neutrino radiation," reveals Resconi. "So, for the first time, we were able to assign that radiation to a cosmic object – 5.7 billion light-years away." The findings were published on July 12, 2018, as the cover story in "Science" magazine. Not long after, "Science" named the IceCube researchers' discovery one of the biggest breakthroughs of 2018.

"High-energy neutrinos are now opening up a new window into the universe, allowing us to identify and research sources of high-energy radiation," sums up Resconi – while admitting that this obviously still requires a lot more measurement data. That is why, together with teams from Canada, Russia and Europe, she is currently planning a global network of neutrino telescopes: "Implementing the planetary neutrino telescope (PLENUM) project will be a lot easier than all of our work thus far – because now we know what we are looking for." ■ *Monika Weiner*

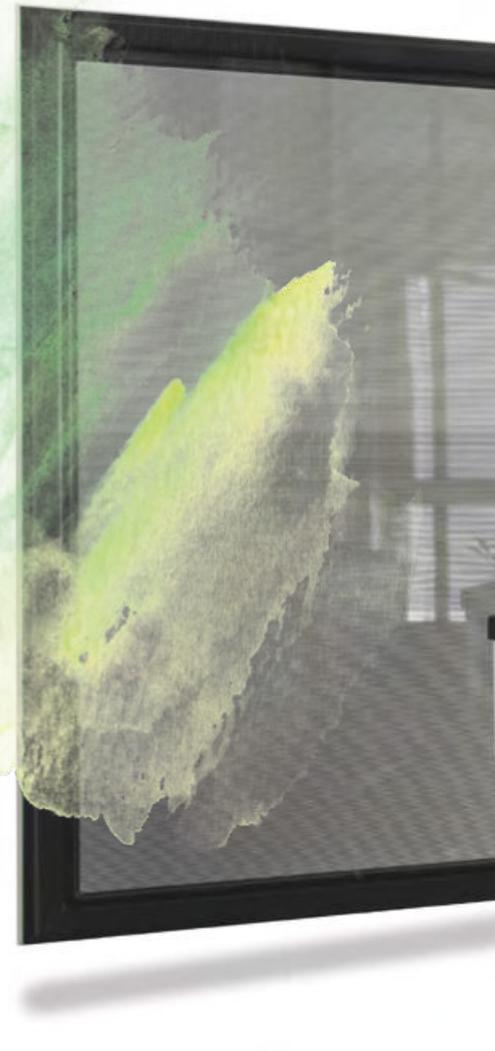
# Indoor Greens Go Hightech

**The relatively young enterprise Agrilution is bringing vertical farming to the kitchen with a smart greenhouse cube for the home. The device provides the ideal conditions for healthy cultivation of salads, microgreens and herbs.**

**A**s more and more people move to urban areas, farmland is gradually giving way to concrete. At the same time, the global population continues to rise. The combined effect of these trends means that land for crops will soon be in short supply. Yet many consumers want food that is fresh, crunchy and free of pesticides. Against this backdrop, interest in vertical farming has been rising in recent years. Instead of growing crops on vast stretches of land, vertical farming stacks cultivation spaces on top of one another, for instance inside buildings.

Company founders Maximilian Lössl and Philipp Wagner seized on this idea and developed it through their startup Agrilution, launched in 2013. They now offer a smart plant cube for private households, enabling anyone to grow their own greens. “We have created a completely new device category and are thus the first provider of this kind of greenhouse box worldwide,” states Lössl. “We give people all over the world the opportunity to harvest fresh, healthy, aromatic vegetables for themselves at home on a daily basis – also giving them access to a wide selection of established, new and international plant varieties. At the same time, we uphold the highest environmental standards.”

The “mini vertical farm” has been available since the end of 2018 from upmarket kitchen providers, major electronics retailers and online suppliers. It is a recyclable cube with eight drawers into which seedmats can be placed. These are made of recycled fabric remnants, with the seeds already inserted at appropriate intervals.



The young company offers a smart plant cube for private households, enabling anyone to easily grow their own herbs, salads and microgreens.



Maximilian Lössl and Philipp Wagner founded the company Agrilution, located in the west of Munich, in 2013. The company now has 25 employees.



Watering and climate control



Internet connection



Control via app



Seed mat

Automated irrigation



The nutrients required by the plants are included in water supplied from a tank, so there is no need for soil at all. The manufacturers guarantee that they do not use genetically modified seeds. And since the cube is not accessible to pests, it can also grow proven older varieties that have no chance of thriving in open fields. The company is currently conducting research to expand its offering to up to one hundred new plant varieties.

The greenhouse box is connected to the Internet and uses an app to determine which plants the user has inserted where. Plant-specific parameters are stored in the cloud for the various species to ensure optimum growth. The cabinet accesses these parameters so it knows how much water, light and heat to provide and when. Users can even leave the device to run autonomously for up to three weeks, for instance if they are on vacation.

“Bringing a new kitchen product to market, from vision to series production, is quite an undertaking,” underscores

Wagner, who studied mathematics with a minor in economics at TUM. “The device is extremely complex as it has to control and maintain all the ambient factors for the plants. Aligning hardware and software with biology to obtain predictable, repeatable results was a major challenge.” The young company’s concept has been endorsed by several awards: In 2018, it won the Green Product Award; in 2015, the Ecosummit Award; and in 2013, the Thought For Food Challenge.

In its early days, the startup received support from UnternehmerTUM during the launch phase and was involved in the Kickstarter program. At the same time, it participated in the Climate-KIC accelerator – again backed by UnternehmerTUM. Additionally, the company worked with the University’s Chair of Industrial Design as part of the Design Enterprise program. Agrilution has now brought strong investors on board and the team has grown to over 25 full-time staff. ■

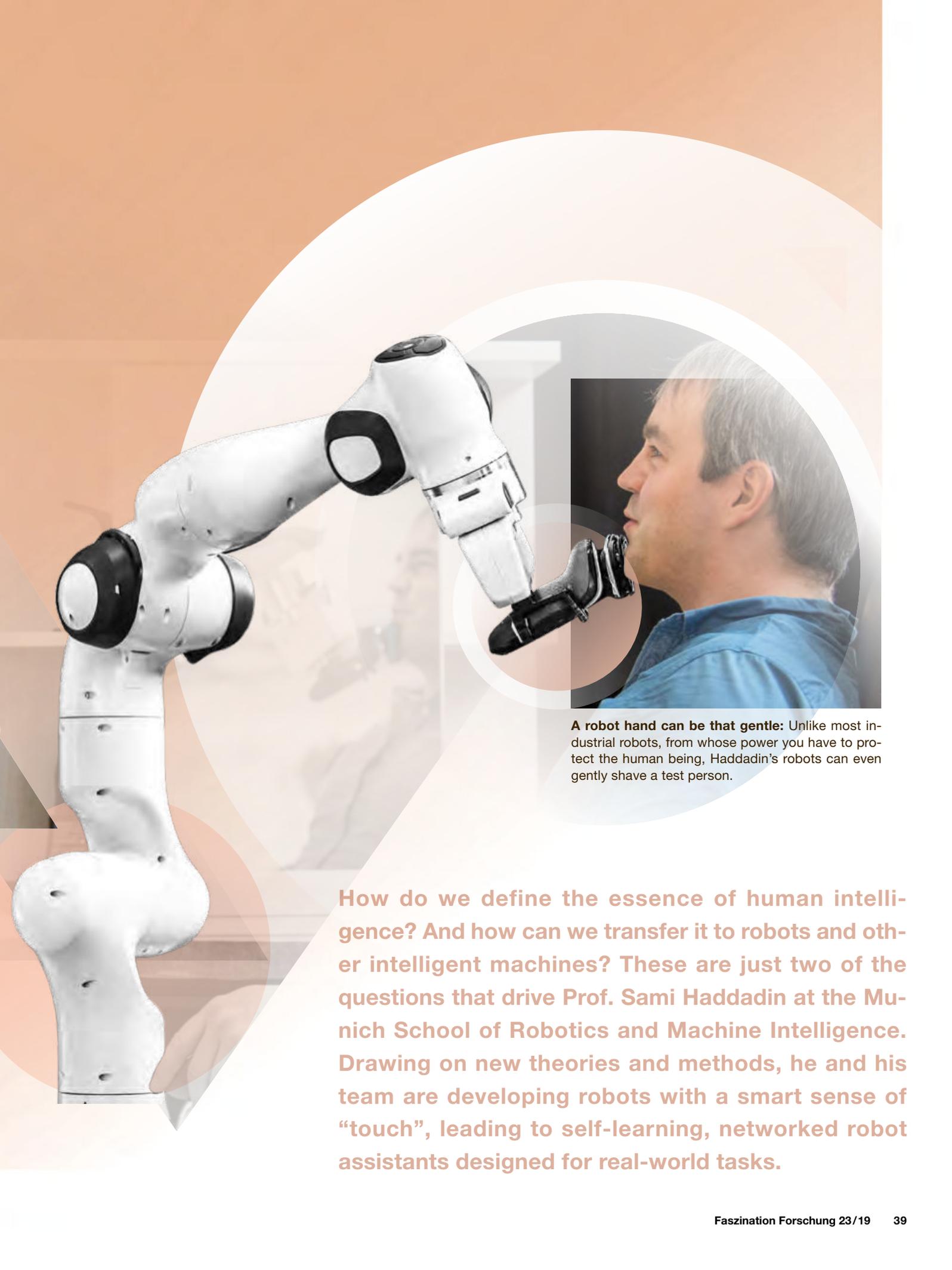
*Brigitte Röhlein*

# Munich School of Robotics and Machine Intelligence – **The Gentle Robot**



Link

[www.msrm.tum.de/rsi/lehrstuhl-fuer-robotik-und-systemintelligenz](http://www.msrm.tum.de/rsi/lehrstuhl-fuer-robotik-und-systemintelligenz)



**A robot hand can be that gentle:** Unlike most industrial robots, from whose power you have to protect the human being, Haddadin's robots can even gently shave a test person.

How do we define the essence of human intelligence? And how can we transfer it to robots and other intelligent machines? These are just two of the questions that drive Prof. Sami Haddadin at the Munich School of Robotics and Machine Intelligence. Drawing on new theories and methods, he and his team are developing robots with a smart sense of “touch”, leading to self-learning, networked robot assistants designed for real-world tasks.

## Kollektiv lernende Roboter

D

Maschinelle Intelligenz soll Roboter feinfühlig und intelligent machen, wie es der Mensch ist. Die Maschinen werden künftig auch in der realen Welt mit Menschen in Kontakt treten und müssen daher nicht nur intuitiv zu bedienen, sondern auch sicher sein.

Die TUM will diese Entwicklung maßgeblich mitgestalten. Mit der Gründung der Munich School of Robotics and Machine Intelligence (MSRM) beschreitet sie neue Wege, um maschinelle Assistenten reaktionsfähiger und „schlauer“ zu machen.

Direktor des neu gegründeten Instituts ist Professor Sami Haddadin, einer der bedeutendsten Wissenschaftler auf dem Gebiet der Robotik und Systemintelligenz. TUM-Präsident Wolfgang A. Herrmann hat den Topwissenschaftler nach München geholt und damit die Eliteuniversität Stanford und das MIT in Massachusetts ausgestochen.

Haddadins aktuelles Vorzeigeprojekt sind durch kollektives maschinelles Lernen kooperierende Roboter, die binnen kürzester Zeit und bei geringstem Rechenbedarf nahezu verzögerungsfrei neue Fertigkeiten erlernen. Der Prüfstein bei diesem Forschungsprojekt ist eine Schlüssel-Schloss-Einheit: Ein Roboter lernt, Schlüssel in verschiedene Schlüssellöcher zu stecken und das Schloss zu öffnen – eine für einen erwachsenen Menschen gera-

dezu triviale, für eine Maschine aber höchst komplexe Handlung. Das gelernte Wissen können über die kollektive Künstliche Intelligenz andere Roboter weiter nutzen. Für Haddadin hat die Robotik sehr viel damit zu tun, wie der Mensch funktioniert. In seinen Robotern sieht er eine Art „Testbed“, um die Grundprinzipien intelligenten Verhaltens zu studieren und den menschlichen Bauplan in seinen Robotern technisch-systemisch nachzubilden. Auf diese Weise können Roboter auch viel besser mit Menschen in Kontakt treten.

Drei gesellschaftlich relevante Themen bilden aktuell die praktischen Forschungsschwerpunkte: In der „Zukunft der Gesundheit“ geht es um die Unterstützung älterer Menschen durch Robotik und Künstliche Intelligenz, in der „Zukunft der Arbeit“ stehen kollektiv lernende und sichere Roboterassistenten im Mittelpunkt, und in der „Zukunft der Mobilität“ sollen autonome Teams von Transportsystemen entwickelt werden. Begleitet wird Haddadins Forschung von ethischen Diskursen. □

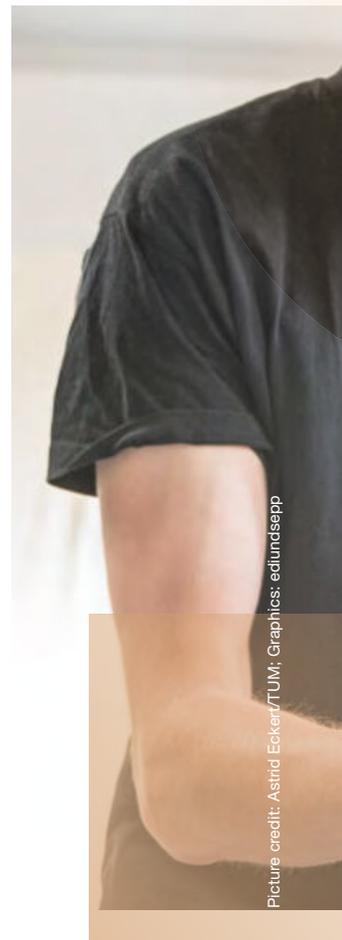
280

million euros will be provided by the Bavarian State Government for the Artificial Machine Intelligence Competence Network by 2023

54

professors work on robotics related topics at TUM

Alexander Tödtheide (left), here in a discussion with Prof. Sami Haddadin, develops a prosthetic hand with artificial muscles.

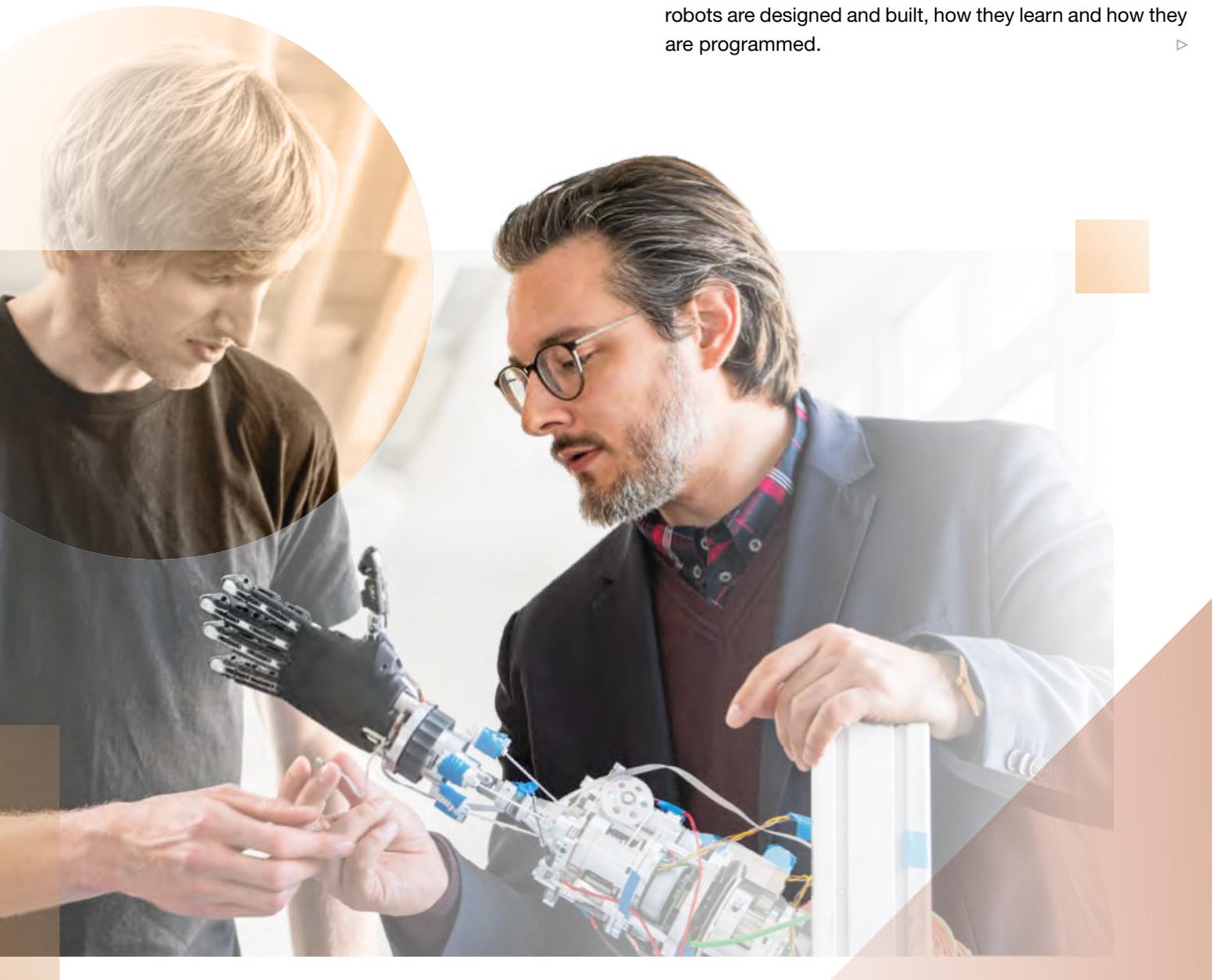


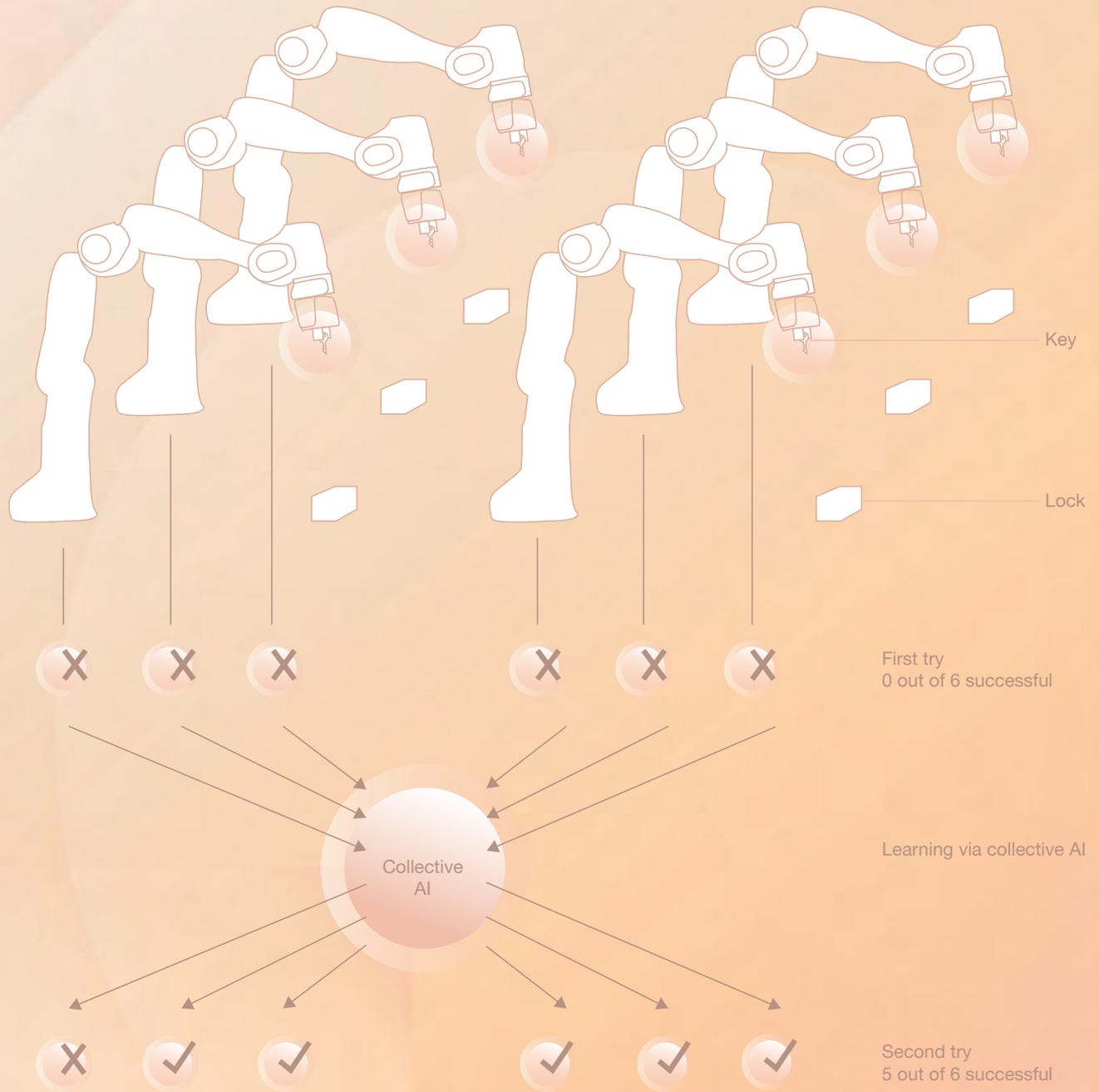
**R**obots and intelligent machines are set to transform the way we live and work over the coming years. On the one hand, machines will be as capable of learning as humans. On the other hand, however, we need to draw clear lines between technical systems and their human archetype. As machines evolve, they will increasingly collaborate with people – so safe, intuitive interaction is a must.

TUM is set to play a key role in shaping the evolution of human-robot interaction and has strengthened its position by welcoming Prof. Sami Haddadin – one of the most prominent scientists in the field of robotics and systems intelligence – to its ranks.

Since April 2018, the 38-year-old researcher has been Director of the newly founded Munich School of Robotics and Machine Intelligence (MSRM), located in the former buildings of the paper technology research institute PTS in the Schwabing district of Munich. MSRM aims to explore new ways of making robots and other machines smarter, building on the latest artificial intelligence developments and further pushing the boundaries.

TUM President Wolfgang Herrmann was instrumental in attracting the robotics luminary to Munich – thus outpitching elite institutions such as Stanford University and Massachusetts Institute of Technology. This was a major coup for TUM, since Haddadin's research into human-robot interaction is generally considered to be groundbreaking. His work opens up a completely new perspective on the way robots are designed and built, how they learn and how they are programmed. ▶





**Collective learning:** A robot learns how to insert keys into various keyholes to open a lock. Then the robot can pass its knowledge on to its “colleagues” via the collective AI. They have access to the increasing pool of knowledge that all machines have fed into.

Prof. Haddadin’s current flagship project involves robots cooperating through collective machine learning, enabling them to acquire new skills almost instantly and with minimal computing power. Proof-of-concept at the heart of this research project is a lock and key: A robot learns to insert keys into various keyholes to open the lock. For an adult human, this would be a straightforward task, but it is a highly complex operation for a machine.

### **Machines that can “sense”**

Inserting a key into a lock requires a sophisticated degree of sensory skill – and equipping robots with this capability is anything but simple. To enable the robotic hand to move with similar dexterity to a human hand, Prof. Haddadin created a completely new mechanism, inspired by human motor skills. “This level of sensitivity brings us to the limits of what is technically feasible for machines today,” he confirms. “Children only develop this level of sensory-motor ability when they are three or four years old. If you use other robots for this challenge, they will damage either the lock or the key. You could call us the creators of robotic fine motor skills.”

The dexterous sense of touch is considered a central tool in robotics – it is essentially the interface between the robot’s mind and its surroundings. And it was more or less the hand that brought Sami Haddadin to his current field of research. “In my very pre-student days, robots were still fairly crude machines – and I wasn’t particularly interested,” he recalls. “However, even before the end of the nineties, I saw something that really caught my attention at the Hanover trade fair: a robotic hand. I was fascinated by the notion that science had created a technical system inspired by the human hand that actually came very close – as I thought at the time – to the human model.” This connection between man and machine led Haddadin work on biological systems from an early stage.

### **Robot collectives learn like toddlers**

These tactile sensory skills are only a means to an end, however. The real highlight of the project is the fact that the robot can pass lessons learned on to other robots; its peers have access to the collective pool of knowledge that all of the machines have fed into. “Not only can robots pick up and pass on this knowledge, they can also put it to constructive use – with the result that learning is suddenly massively accelerated through networking-based avalanche effects,” Haddadin explains.

And he is already looking beyond the simple lock-and-key proof-of-concept. Convinced that the current system can be built out, he plans, for instance, to expand the use case to bimanual scenarios and develop new hands that have additional capabilities based on better insights into human building principles and sensory-motor abilities. ▷

**Torque sensors in the joints** in combination with an artificial central nervous system allow the robot to feel how it has to position the key correctly.



Haddadin's ultimate vision is a global network of interconnected robots. "A few thousand networked robots will be able to pick up the skills of a small child within a blink of an eye – no need for complex big data algorithms running on supercomputers and eating up massive computing power over years. Instead, the systems intelligence in the innovative AI algorithms is all the robots need to learn the skills in just a few steps, like humans do. I see almost infinite possibilities in these technologies. It is then up to us humans to use them properly and responsibly for the benefit of society."

### Learning through creation

For Haddadin, robotics has a lot to do with the way that human-embodied intelligence works. "Understanding the basic principles of human intelligence is actually what drives me," he reveals. Just as Newton's laws or Maxwell's equations offer universal explanations of the physical world, Haddadin also sees basic principles in intelligent systems, which work in the background to determine systemic behavior. One such basic principle lies in the answer to the question of how the human hand reaches for an object. This influences the design of both robots and intelligent learning algorithms. As a result, operating the robots becomes child's play and requires no programming knowledge whatsoever. To teach the robot something, you need only demonstrate what you want it to do. The machine then learns from this and can independently apply the acquired knowledge to other challenges – a skill that conventional industrial robots do not possess.

Prof. Haddadin's work is not limited to any one particular type of intelligence – intelligent systems might be artificial, biological or hybrid. He views his robots as a type of test-bed for studying the basic principles of intelligent behavior and simulating the human blueprint at a technical/systemic level. "Learning through creation" is his motto. If human-inspired artificial systems are able to approximate the performance of biological systems, this is at least an indication that we have understood something essential about humans themselves. So, for Haddadin, artificial systems are also attempts to explain intelligence in humans or other biological systems – explanations that previously eluded us.

*"You could call us  
the creators of  
robotic fine motor  
skills"*

*Sami Haddadin*

The theoretical background of his work is not an end in itself, however. Rather, these fundamental insights into machine intelligence provide the platform for Haddadin's research projects. "Findings from basic research should flow into practical applications with the ability to let society at large benefit," he declares, outlining his plans. Together with colleagues, industry partners and startups, he aims to test and implement his developments in everyday use cases.

At TUM, there are now over fifty professors focused on machine intelligence across a variety of disciplines – computer scientists, mechatronics specialists and mechanical engineers, medics and physicists. The idea of MSRM is to create an open-minded, creative space for all of them to collaborate with the robotics researchers. The scientists also work closely with industry here, with members of the MSRM Industrial Advisory Board including leaders and board members from Siemens, BMW, IBM, Airbus and other enterprises.

MSRM has currently defined three research strands with a specific innovation focus. "The future of health" explores for example the use of robotics and artificial intelligence to support elderly people. "The future of work" focuses on collective learning by safe robotic assistants. And "The future of mobility" seeks to develop teams of autonomous mobile systems for inspection and maintenance.



### Robotic assistants to help senior citizens

The first of these topics will be tackled at a geriatrics center now being set up in the nearby town of Garmisch-Partenkirchen. In this MSRМ satellite, researchers will develop robotic assistants to enable independent living for the elderly. Currently, the most important project in this area is the two-armed robotic assistant, GARMI. This system is intended to help elderly people with everyday activities such as getting up, making food and clearing the table. Doctors may also connect with the assistant to establish a remote diagnosis, take ultrasound images or prescribe medication, for example.

Another project in this field involves smart rehabilitation robots. Here, specially developed robots for people recovering from strokes or operations reach out and guide them in such a way that these patients learn to carry out various tasks again and gradually regain motor control. Here, too, Haddadin's basic premise applies: "You need to understand humans to purposefully interact with them."

Haddadin is well aware that his research inevitably raises legal and ethical questions. "We need to communicate extensively and make sure we understand what people want, what they don't want, what is useful and what is not – as well as what will and won't be accepted." ▸

Since April 2018, the 38-year-old Prof. Sami Haddadin – one of the most prominent scientists in the field of robotics and systems intelligence – has been Director of the newly founded Munich School of Robotics and Machine Intelligence (MSRM).





To engage in this debate alongside colleagues in ethics, philosophy and the social sciences, Haddadin is participating in the German federal parliament's dedicated study commission and in the European Commission's high-level Artificial Intelligence expert group. He is also in dialog with legal experts to understand the possible legal framework around robotics and AI research.

Despite all the reservations humans may have about robots, "We needn't be afraid," counsels Haddadin. In the future, intelligent machines will relieve people of tedious and dangerous work, nursing staff will be free to devote more time to their patients, and workers can replace monotonous activities with valuable ones. People's work evolves with progress – and the important thing is to set the right course. "I think fear has always been the worst of all advisers – perhaps even the most dangerous." ■

*Klaus Manhart*

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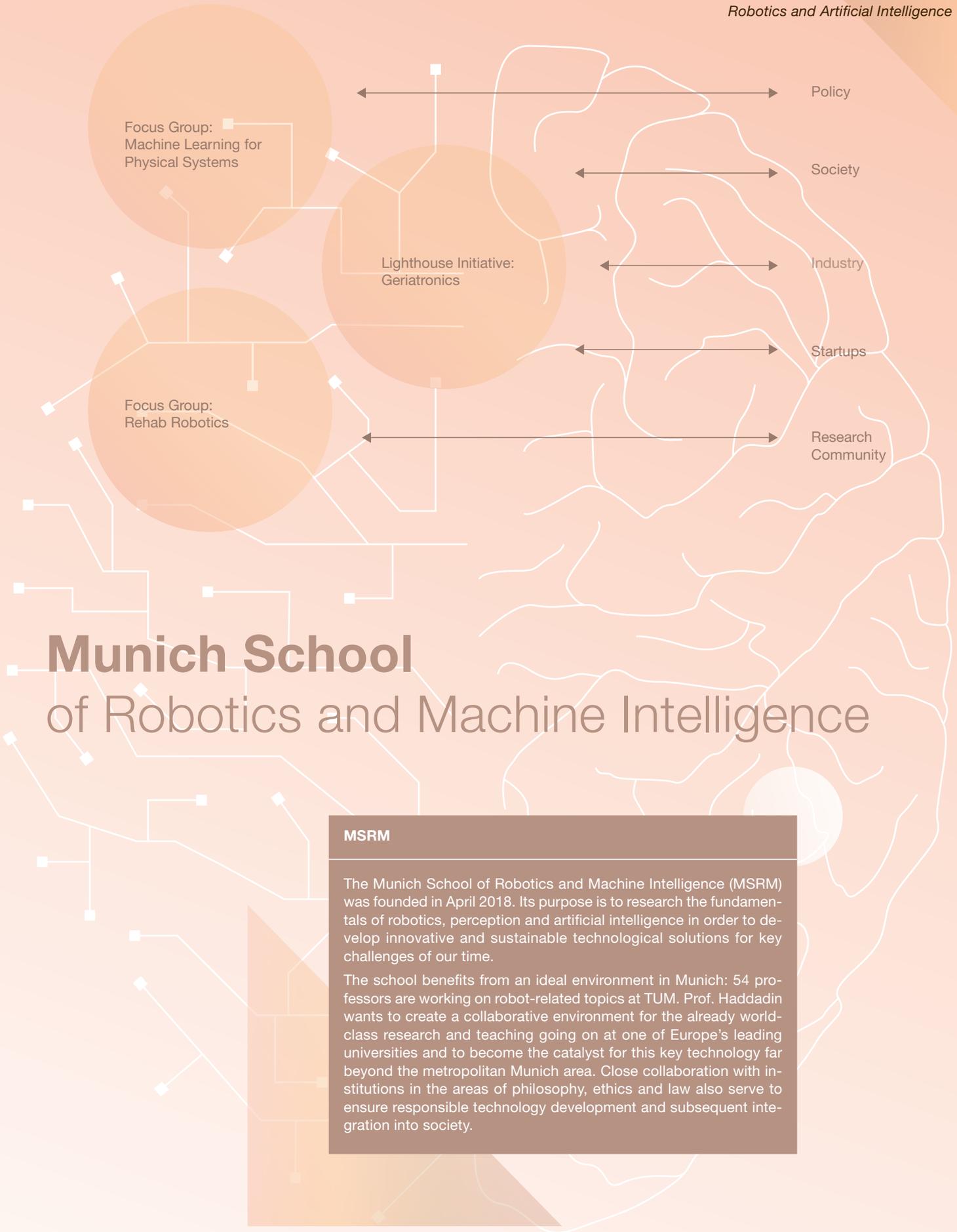
**Prof. Sami Haddadin**

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## Robotics researcher with a raft of scientific awards

Prof. Sami Haddadin studied electrical engineering and computer science at TUM, and technology management at the Center for Digital Technology and Management (CDTM) – a joint TUM and LMU institute. Besides pursuing his doctorate at RWTH Aachen University, he began his research career at the German Aerospace Center (DLR), then becoming full professor at the Gottfried Wilhelm Leibniz Universität Hannover in 2014. Among many other accolades, he received the Early Career Award from the IEEE Robotics and Automation Society and the Alfried Krupp Award in recognition of his research. Together with his brother Simon Haddadin and his colleague Sven Parusel, he also received the German President's Award for Innovation in Science and Technology (Deutscher Zukunftspreis) in 2017. In 2019, the German Research Foundation (DFG) awarded Sami Haddadin the Gottfried Wilhelm Leibniz Prize for his pioneering robotics research. As Founding Director of the MSRM, Haddadin has attracted an excellent team of scientists from the fields of robotics and artificial intelligence.

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# Munich School of Robotics and Machine Intelligence

## MSRM

The Munich School of Robotics and Machine Intelligence (MSRM) was founded in April 2018. Its purpose is to research the fundamentals of robotics, perception and artificial intelligence in order to develop innovative and sustainable technological solutions for key challenges of our time.

The school benefits from an ideal environment in Munich: 54 professors are working on robot-related topics at TUM. Prof. Haddadin wants to create a collaborative environment for the already world-class research and teaching going on at one of Europe's leading universities and to become the catalyst for this key technology far beyond the metropolitan Munich area. Close collaboration with institutions in the areas of philosophy, ethics and law also serve to ensure responsible technology development and subsequent integration into society.

# “Participation is not just a Romantic Idea”



**Prof. Francis Kéré comes from Burkina Faso and has been shaped by the inherently strong sense of community and engagement that he grew up with. This is also apparent in his works – soon to include the Anniversary Tower he is planning for TUM.**

Link

[www.ar.tum.de/en/ap/architectural-design-and-participation](http://www.ar.tum.de/en/ap/architectural-design-and-participation)

**The photo captures Francis Kéré (left) atop a sample roof vault for the Gando Primary School with residents in Gando, Burkina Faso. By demonstrating the stability of the built infrastructure, Kéré builds trust and encourages residents' interest in joining the community building effort.**



## Der Traum vom besseren Bauen D

Schon als Schüler im westlichen Afrika träumt Francis Kéré davon, bessere Schulen zu bauen, damit eines Tages andere freier lernen können. Mit einer Reihe ausgezeichnete Lernorte brachte er sein Heimatdorf auf die Landkarte der internationalen Architektur. Heute forscht und baut Kéré in Europa ebenso wie in Afrika. Bei seinen Projekten praktiziert er das einfache Bauen, wobei er jeweils örtlichen Gesetzmäßigkeiten folgt. Kéré ist ein Realist, für den der Traum ein wichtiger Teil des Entwurfsprozesses bleibt. Sein Bauen ist nachhaltig, da es Nutzer frühzeitig mit einbezieht. Sein künftiger Anniversary Tower der TUM soll ein Ort der Wissenschaftsgemeinde sein und zugleich neue, materialsparende Bauweisen erproben. □

**Education and learning connect your architectural work with your teaching. Your father, chief of Gando village in Burkina Faso, enabled you to attend school and then to study. So what does education mean to you?**

**Francis Kéré:** My dad went without. He made sacrifices for my education and he was ridiculed. People couldn't understand why he would let his firstborn go to school in town instead of getting his help with the field work. But he said to me: "Go and learn how to read and write. Then you can read me the letters that come from the government." Whether he realized it, I can't say, but he was a visionary.

**And what does education mean for society and for architecture as a profession?**

**FK:** Without education, there is no progress. Education empowers people to develop and advance in life. A society without education would have no access to achievements; to the products of science and culture. It would not be in a position to engage with other communities. In colonial times, knowledge was filtered for local citizens. But it is important to have your own access to knowledge. I work in areas where the words "architecture" and "architect" are unknown. Even today, over sixty percent of the population of Burkina Faso cannot read or write. And if you come from a region where specialist knowledge or expertise essentially doesn't exist, then knowledge sharing becomes very important. ▷

**Francis Kéré continues to reinvest knowledge back** into his home country, Burkina Faso. He has developed innovative construction strategies that combine traditional building techniques and materials with modern engineering methods.



**So being an architect also means sharing knowledge? And you realized early on that you have to convince the people around you in order to put your ideas into practice?**

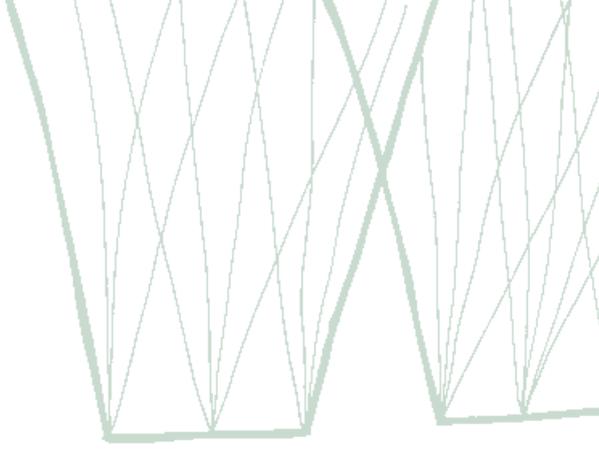
**FK:** You do have to be persuasive. That's how you create the right environment – one where others can step up to certain tasks, so you can progress with new ideas yourself.

**Architects today are at the center of a fine balancing act. They need to be familiar with current building standards, but also with the history of architectural forms; with the possibilities and limitations of materials as well as the expectations of investors and users. What role does education play within this multifaceted framework?**

**FK:** Acquiring a broad knowledge base is essential to gain a solid understanding of architecture in its many different forms and styles. Otherwise you run the risk of confining yourself to one narrow facet of the profession and failing to see the big picture. After all, our role is not just to draw; it's not just to work out how to design a building. Nowadays, we are called on to bridge multiple disciplines and the ability to do that is growing in importance all the time. Education means openness; the desire to know more and gain experiences. It opens up opportunities for exchange and helps us practice our profession today. It used to be a bit different: A master builder would come up with a blueprint, and this was then implemented by craftsmen trained to map shapes and styles. Today, though, dialog is essential.

*“I am convinced that participation can lead to a happier society.”*

*Francis Kéré*



**The radial layout** of the Lycée Schorge classroom modules is wrapped around a central public courtyard. This configuration creates privacy from the main public domain, shelters and protects the inner courtyard from wind and dust, and accommodates informal gatherings as well as formal assemblies.





**The Opera Village in Burkina Faso** (here a model) is based on an idea by film and theater director Christoph Schlingensiefel. After massive flooding damaged the project site and surrounding villages though, the decision was made to pool resources and funds from the opera to introduce additional residential, educational and recreational amenities into the plan.



Picture credit: Kéré Architecture, Hans-Georg Gaul; Graphics: edlundsepp

**In your presentations, writings, exhibitions and installations, you repeatedly emphasize the importance of building as a community activity. You show how people come together to produce something worthwhile. Do we embrace this mindset sufficiently in Western society?**

**FK:** That one is not so easy. There are huge differences between society in Germany and in Burkina Faso. The former is an industrialized nation with a highly developed economy, defined by rationalization and the division of labor. In Burkina Faso, communal effort is the key to success – and a prerequisite for survival. Here, you have experts you can consult. But there are examples of teamwork here in Germany – think for instance of the time-honored Bavarian tradition of putting up the maypole. Collectively, the village can achieve something that would not be feasible for an individual acting alone. And once the pole is up, it serves as a meeting hub for the village.

These principles are difficult to implement in construction. It is true that the different trades work together. But questions of individual liability and responsibility make community action more difficult. This makes private building collectives all the more important, where people come together so they themselves can determine to the greatest extent possible how they want to live within the same building. They look for planners who are able to flesh out their ideas, and they articulate their requirements to the expert. But before building begins, they want to talk it through in detail. ▽

### Why does that seem so difficult?

**FK:** A highly organized society is quickly overwhelmed when faced with the challenge of reducing multiple requirements to a common denominator. Financial viability is the big hurdle. In other societies, people are used to talking and allowing everyone to state their case. When I create something in Burkina Faso, the community element is important to me. The sense of togetherness creates positive momentum. The resulting work is a community achievement, and I step back afterwards. This community spirit is very important for a building project. In Germany, community buy-in or engagement tends to be viewed as a cost factor. It takes a lot of hours to move from “I” to “we” – and unfortunately, every hour here comes at a cost and that puts a brake on a great many things. So architects just don’t have the time to invest in building community spirit.

**Francis Kéré’s very first building** was the Gando Primary School in his home village in Burkina Faso. A clay/cement hybrid was primarily used for the walls, and a dry-stacked brick ceiling allows for maximum ventilation. The walls are protected from damaging rains with a large overhanging tin roof.

**Your educational and cultural buildings such as the Opera Village, which you developed with Christoph Schlingensief, and many other of your projects are supported by foundations. And, of course, you have set up a foundation yourself. Is this a prerequisite for simple, people-centric construction?**

**FK:** I think so, yes. Foundations make these projects easier to accomplish. There are funds, clear rules and a certain traction for this type of project. Foundations seek to promote new ideas and do things differently. They have the courage to look for someone who is capable of realizing their own vision. They have the capacity and are committed to approaching projects in this way. I worked with Christoph Schlingensief because he was concerned that he had no knowledge of Africa. He was convinced that he would fail if he only applied Western ideas. He needed someone by his side who came from Africa and understood the local code of conduct. After all, the Opera Village was intended to achieve something special – and something that corresponded to the ideas and visions of Christoph Schlingensief the artist. Wanting to do things differently is also about exploring. These projects are not born of urgent necessity; there is an element of curiosity, as in research, and a moment of surprise.





**The design for the Burkina Faso National Assembly & Memorial Park** in Ouagadougou, which will be built on the site of the former national Assembly (now destroyed), shows a spirit of transparency and openness. The outer facade of the parliamentary structure is designed to be inhabited by the public. Citizens can climb the stepped pyramidal building and experience an elevated view of the city.

**In English we have the saying “necessity is the mother of invention”. Your work in Burkina Faso is based on the situation on the ground. How can upcoming architects at TUM benefit from this type of approach?**

**FK:** It isn't easy, for sure. But TUM encourages students to think outside the box. Some professors are committed to enabling students to travel in parallel to their studies in Europe, so that they can experience construction in other regions and cultures. We could make this a standard part of the curriculum. Students should be able to develop a sharp eye. How can we accomplish an architectural work that serves users while also allowing students to evolve? How can we develop this approach to produce modern buildings – buildings that have form, function and meaning while still being fit for the future? Students need to learn how architecture takes shape. Ultimately, we are trying to serve people. The art of simple construction work based on resources that are available locally could be more firmly anchored at TUM.

**You are Professor of Architectural Design and Participation at TUM. You describe curiosity, involvement in the construction process, but also critical observations you made in Burkina Faso. How does this differ from our practice in Germany, and how could we embrace participation more actively?**

**FK:** The potential consequences of insufficient participation were highlighted by the Stuttgart 21 railway and infrastructure project. An architect won a fair competition. The political powers that governed there for a long time tried, quite rightly, to implement the outcome of that competition. So far, so good. But it meant felling old and treasured trees. The protest began slowly at first and then spread far and wide. The fact that residents weren't sufficiently engaged led to a political earthquake that changed the balance of power in the city council.

Thus, participation is not just a romantic idea. It may sound utopian, but I am convinced that participation can lead to a happier society. In Germany, I try to use such words with caution. But I think it would be good for all of us if we could see – as part of the participation process – what is in the pipeline for me and my neighborhood. Ultimately, participation has its limits. And we should use them where possible.

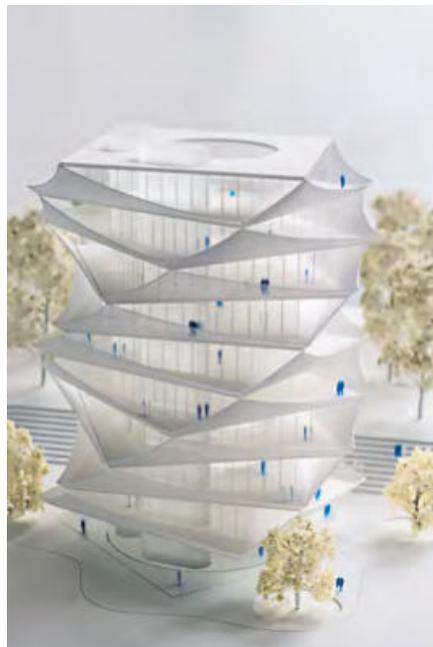


**The TUM Anniversary Tower**, designed by Francis Kéré, will be erected on the Garching campus to mark 150 years since the university's foundation. The idea is to create an inspiring place that builds a sense of identity.

**TUM already has the Oskar von Miller Tower and the Thiersch Tower. Your Anniversary Tower will be erected on the Garching campus to mark 150 years since the university's foundation. What is the underlying vision behind this building?**

**FK:** It will be a heart that beats for TUM. The idea is to create an inviting, inspiring place that builds a sense of identity. The tower is designed to act as a magnet – a place that is always open. It is a place of welcome and a meeting hub that connects people. And all of TUM's faculties and disciplines will feel at home there. At the top there will be a platform – a versatile space for events. Alumni will be able to meet there, and young students can discover what TUM has to offer in terms of study opportunities and partnerships. We will work with warm materials, but also with concrete. This will be a sustainable construction harnessing new processes that use concrete sparingly. And, of course, the facade will be as green as a Bavarian maypole.

■ *Interview by Thomas Edelmann*



**The tower is designed to act as a place of welcome and a meeting hub that connects people.**

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**Prof. Diébédo Francis Kéré**

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## The architect who works with what he's got

During his studies at the Technical University of Berlin, Prof. Diébédo Francis Kéré (born 1965) returned to his native village of Gando to build a primary school there, using local materials and techniques and encouraging the community to participate in the project. In 2004, the work won the Aga Khan Award for Architecture. It was swiftly followed by further school buildings in Gando and many other places. At the same time, the young architect founded the Kéré Foundation and opened his own architecture office in Berlin, receiving prestigious awards and prizes for sustainable construction that contributes to society. Kéré collaborated with Christoph Schlingensiefel to develop the Opera Village in Burkina Faso. Exhibitions showcase Kéré's buildings and design principles, and he spent time teaching at Harvard (US) and Mendrisio (Switzerland). Kéré took up his role as Professor of Architectural Design and Participation at TUM in October 2017.

### Africa Initiative at TUM

The TUM launched an Africa Initiative at the end of 2018. In addition to cooperation in individual projects, long-term partnerships are planned in the key areas of teaching, research and entrepreneurship, which are supported at TUM in a cross-faculty Africa network. The objective is to promote sustainable development of the continent together with local partners.

The symposium “Sustainable Development in Africa” at the Garching campus in November 2018 provided an overview of the planned measures. TUM professors presented the various projects in the fields of health, resources, automotive technologies, architecture and renewable energy systems. The keynote speaker was Prof. Francis Kéré.





Picture credit: Kéré Architecture, Erik-Jan Ouwerkerk; Graphics: edlundsepp

The Lycée Schorge Secondary School sets a new standard for educational excellence in Burkina Faso, and it uses locally sourced building materials in an innovative and modern way.



The masterplan of Kéré's Opera Village at Laongo/Burkina Faso includes classrooms for up to 500 students, a variety of housing types, art and media labs, workshops and dining facilities.

*“You do have to be persuasive. That’s how you create the right environment.”*

Francis Kéré

# The Aircraft of the Future

Link

[www.lis.mw.tum.de](http://www.lis.mw.tum.de)

Picture credit: [M]: Design: A.Frühbeis, J.Held, P.Steb, A.Usbek/TUM;  
CGI: DLR (CC-BY 3.0)



**Four TUM students have blazed a trail in the world of aircraft engineering with a highly advanced cross-disciplinary collaborative project to design the most economical aircraft possible. Featuring a turboelectric propulsion system, their jet won them the 2018 DLR/NASA Design Challenge.**

*eRay*

These four aerospace students jointly won the DLR/NASA Design Challenge in 2018 with their design for a new aircraft concept: Alexander Frühbeis, Isa Held, Artur Usbek and Patrick Sieb (from right).



*Kurzfassung*

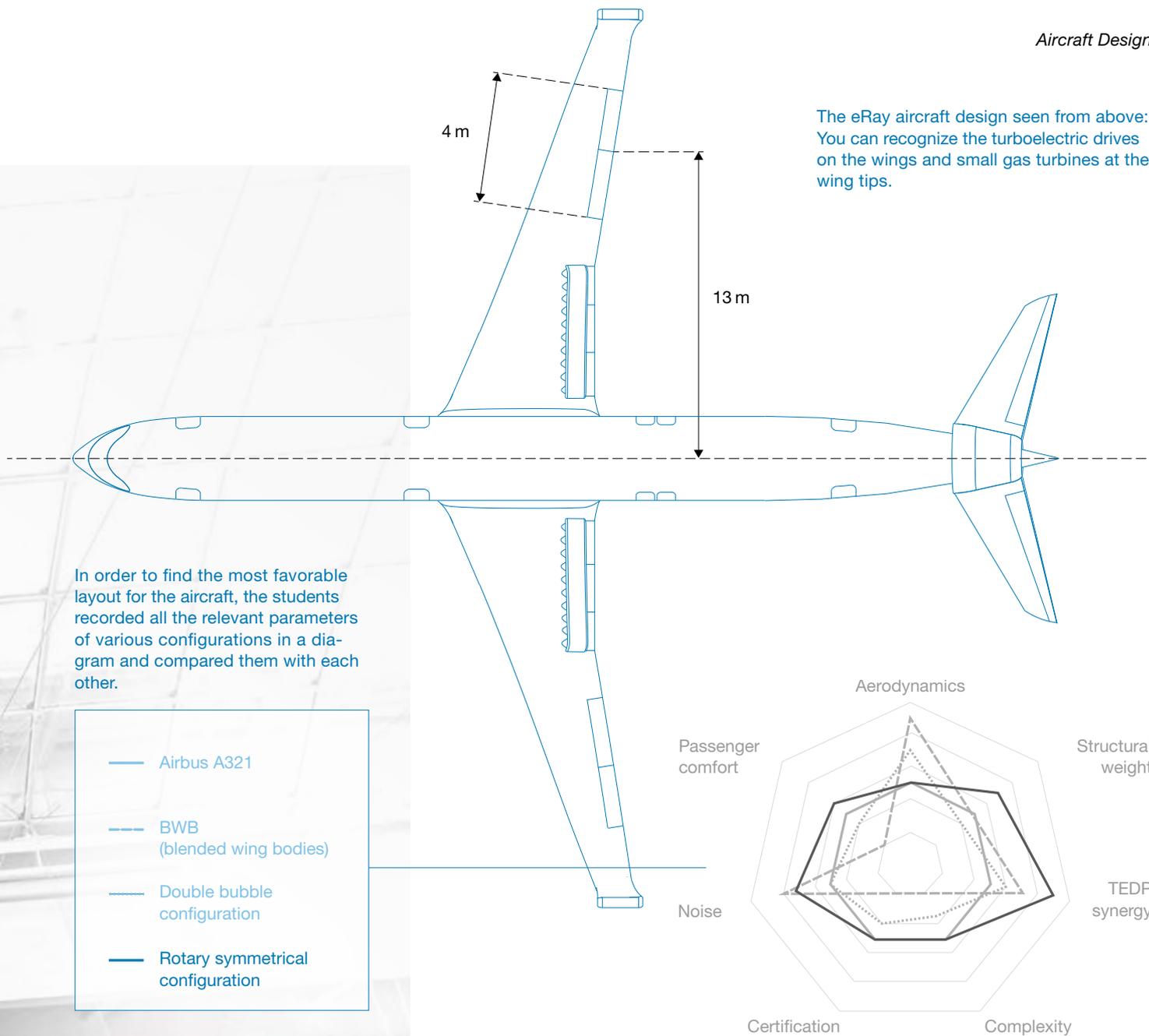
## Das Flugzeug der Zukunft fliegt mit fast zwei Dritteln weniger Treibstoff

D

Den Masterstudierenden Alexander Frühbeis, Isa Held, Patrick Sieb und Artur Usbek gelingt 2018 ein Entwurf für ein Verkehrsflugzeug der Zukunft, der aufhorchen lässt. Mit seinem „eRay“ gewinnt das Team der TUM die DLR/NASA Design Challenge. Das Flugzeug soll im Vergleich zu einem heutigen Airbus 321 bis zu 64 Prozent Energie einsparen und damit entsprechend umweltschädliche Emissionen vermeiden. Sein Ansatz: Synergieeffekte von Neuerungen in den Bereichen Antrieb, Aerodynamik und

Struktur nutzen und damit ein ultraeffizientes Gesamtsystem schaffen. Der fensterlose Jet hat einen Rumpf aus Carbonfasern mit einer größeren Fanstufe am Heck und kleinen, an der hinteren Tragflächenkante angebrachten elektrischen Antriebseinheiten. Mit seiner cleveren Kombination einzelner Verbesserungen ist der „eRay“ leichter, hat einen effizienteren Antrieb und weist weniger Luftwiderstand auf als heutige Verkehrsmaschinen. □

Picture credit: Kurt Bauer, Graphics: edmundsepp (source: A.Frühbeis, I.Held, P.Sieb, A.Usbek/TUM)



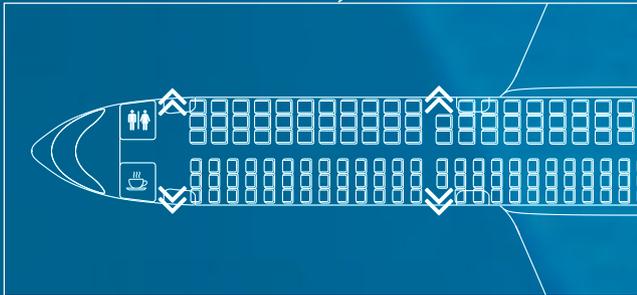
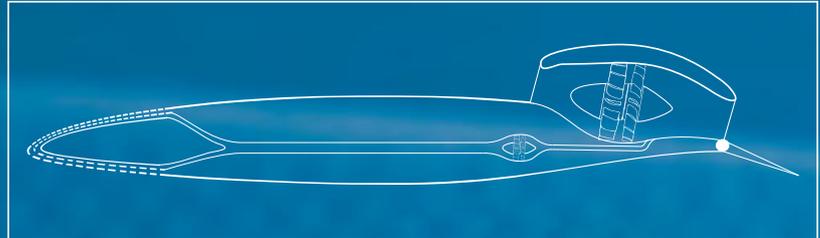
“The world of aviation faces a huge challenge. We all know we’re not doing the environment any favors with ever-growing air traffic and passenger numbers doubling every 15 to 20 years,” declares Alexander Frühbeis. Studying for his Master’s in Aerospace Engineering at TUM, the 24-year-old is convinced that, “Balancing this immense growth with environmental concerns calls for completely new aircraft concepts.”

The German Aerospace Center (DLR) and US National Aeronautics and Space Administration (NASA) launched a joint Design Challenge for German and American university students with the aim of specifically encouraging groundbreaking designs for the future of aviation such as

the one described by Frühbeis. The competition is now in its second round. In the 2018 competition, the focus was on aircraft concepts that radically reduce harmful emissions. The task was to achieve energy savings of 60 percent or more in comparison with today’s Airbus A321-200 with a design offering comparable transport capacity, at least three hours’ range over water, direct connections between small airports, and the lowest possible manufacturing and operating costs. As Frühbeis recalls, “As soon as I heard about this, I knew I would take part, since it unites my two biggest passions: a fascination with flying and the desire to help shape a greener society.”



The aircraft harnesses the boundary layer ingestion effect, in which the boundary layer, which otherwise increases aerodynamic drag, is absorbed by the engines to improve efficiency.



The team of Munich students presented a design for a windowless jet for 200 passengers with a fuselage made of carbon fibers, with a larger electric fan stage at the rear and smaller electric drive packages, attached to the rear wing edges.

Thanks to its electric drive the eRay concept would be quieter during takeoff, flight and landing, as well as on the tarmac.

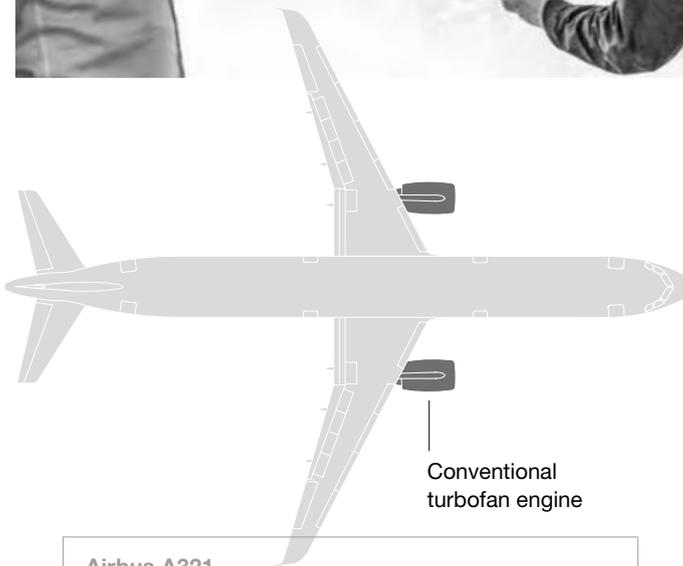
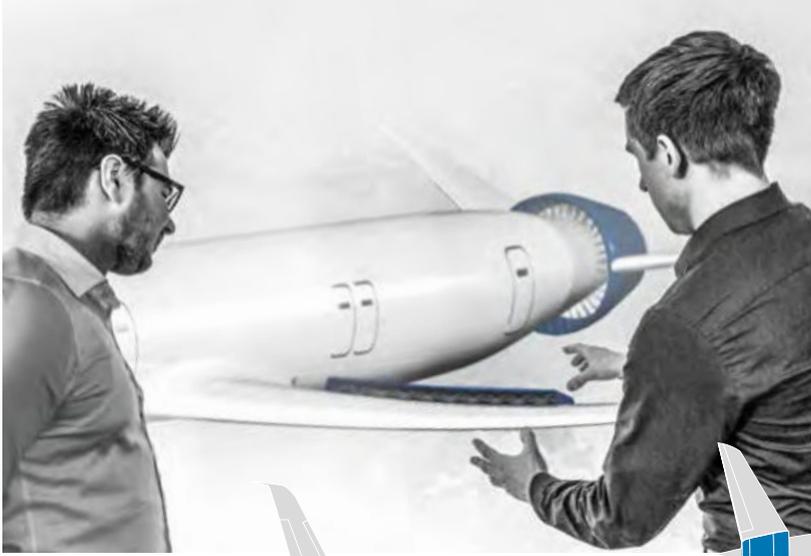


eRay requires only a comparatively small amount of fuel for the two wing-mounted gas turbines. With their generators they produce the electrical energy for the operation of the e-engines.

Interplay between propulsion and aerodynamics: The layer of air slowed down by flowing past the fuselage is sucked in by a large fan mounted on the tail of the aircraft. This increases efficiency by reducing fuselage air resistance.

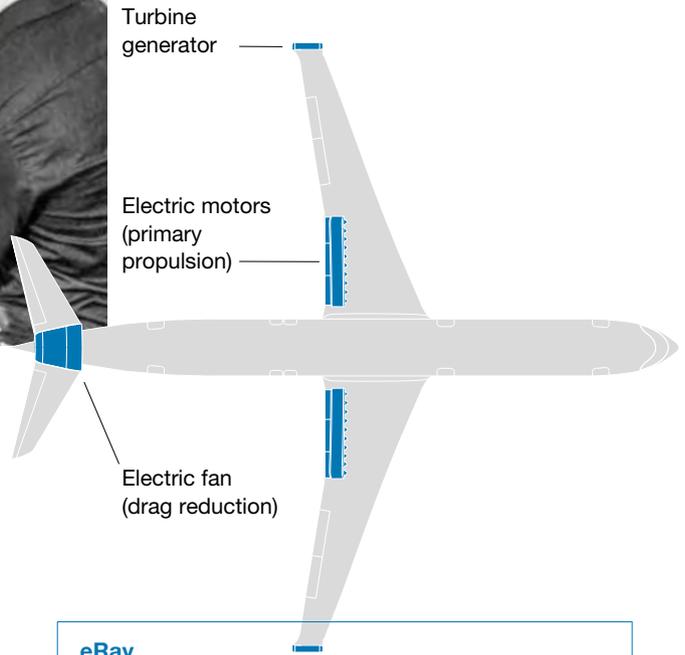
### Flight of the future poised for take-off

In January 2018, what was to be the winning German team first formed at TUM, consisting of Master's students Alexander Frühbeis, Artur Usbek, Isa Held and Patrick Sieb. The first general meeting for all participants across various German universities took place in Hamburg in February. Between that and the final presentation of their concepts in Braunschweig at the start of August – so within only around six months – the team completed their design for an ultra-efficient aircraft, which they christened eRay. Prof. Mirko Hornung, Chair of TUM's Institute of Aircraft Design, and research associate Lysandros Anastasopoulos were on hand to support the students with this competition. The latter outlines the challenges framing the project: "In terms of cruising speed, payload capacity and range, today's jet-powered commercial aircraft are about to reach their technical limits. Recent research has focused a lot on environmental compatibility, aiming to reduce emissions such as carbon dioxide, nitrogen oxides and soot, as well as noise pollution. So even in this area, it now takes considerable effort to realize any significant improvement." ▶



**Airbus A321**

The comparator aircraft for the competition was the 2005 Airbus A321-200 powered by two conventional engines. The task was to develop a concept for an aircraft that consumes at least 60 percent less energy with comparable transport capacity.



**eRay**

The eRay design, which won the competition, is electrically powered and shows a 30 percent reduction in mass and 48 percent improvement in propulsion power compared to the A321, leading to a 64 percent overall reduction in energy consumption.

**Smart use of synergies**

Against this backdrop, the Munich students focused both on improving specific aircraft components and, above all, on harnessing synergy effects across the areas of propulsion, aerodynamics and structural design. Frühbeis and his team presented a design for an electrically powered, windowless jet with a carbon fiber fuselage, featuring a larger stage fan in the tail and smaller electric propulsion units attached to the trailing edge of the wings (turboelectric distributed propulsion, TEDP). Their eRay boasts a lower weight, increased propulsion efficiency and im-

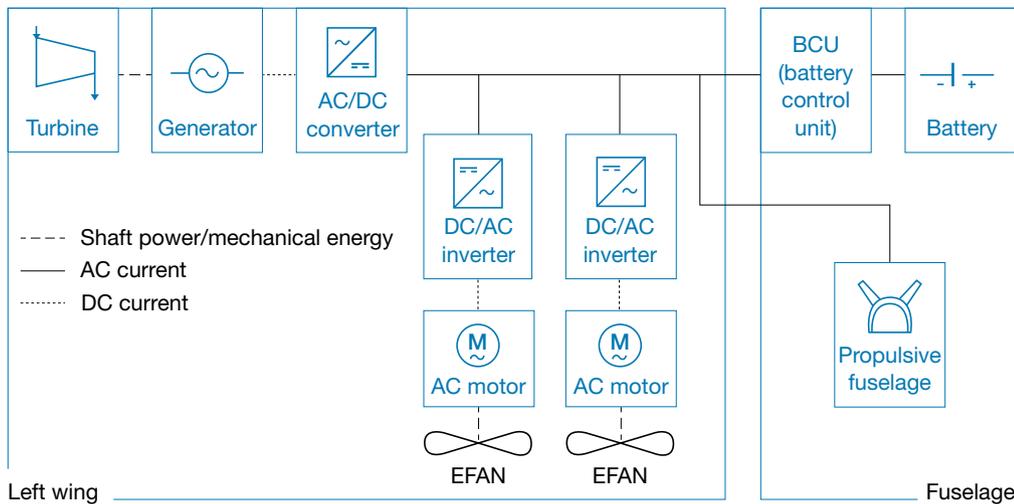
proved aerodynamics – the latter thanks to use of the laminar flow control (LFC) principle as well as a reduced, V-shaped tail surface and active reduction of wind resistance against the airframe. This intelligent overall package came out on top when the Design Challenge winners were announced in August. Rolf Henke, DLR Executive Board Member for Aeronautics Research, commended the winners: “My fellow jury members and I were impressed by the systematic dovetailing of complementary technologies that were a perfect fit for each other.”

### 64 percent fuel saving

The eRay is significantly lighter than an Airbus 321, with just as many passengers on board (although some of them travel standing). This is made possible by the use of new materials, the absence of windows and the comparatively small amount of fuel, which the aircraft only needs to carry for the two gas turbines attached to its wingtips.

These use their generators to produce electrical energy to power the electric engines. Various synergies (see box) are used to reduce aerodynamic drag on the eRay, which also contributes to fuel savings.

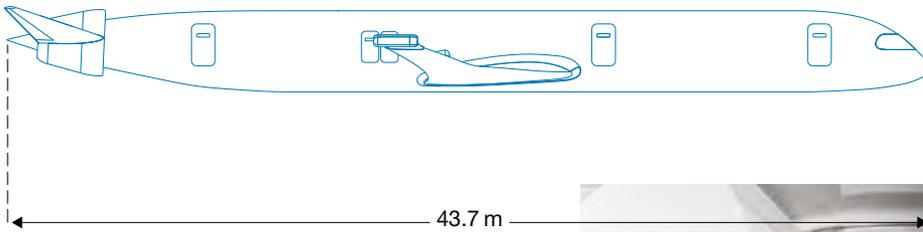
The aircraft is designed to meet the growing demand for short and medium-haul direct flights in Asia, while offering a number of general advantages too. For instance, its electric propulsion makes it quieter during take-off, flight and landing, as well as on the tarmac. The eRay could thus unlock night-flight potential for airports running at full capacity during the day.



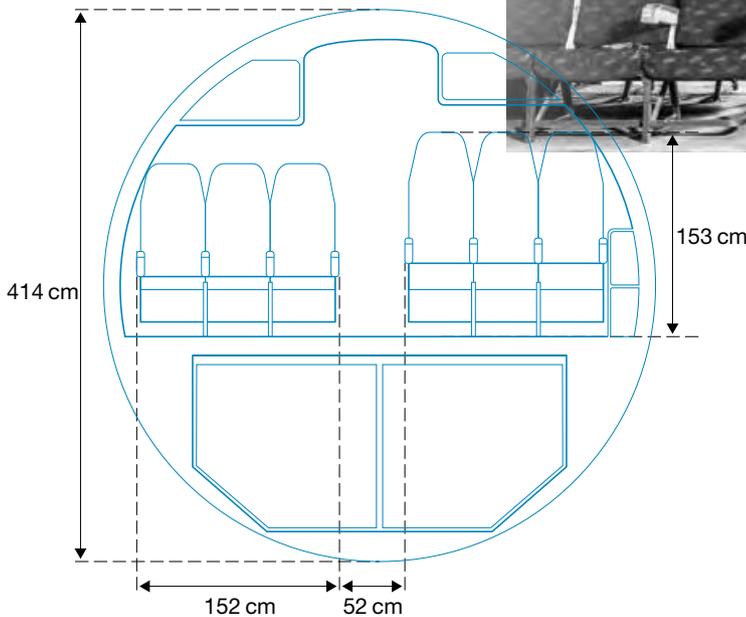
Schematic arrangement of the electric drive system of the aircraft: The gas turbines supply the turboelectric drives and the electric turbines at the end of the fuselage via generators and rectifiers. At the same time, they supply batteries as a buffer for the higher energy consumption during take-off and landing.

To save weight, the outer skin of the aircraft was planned in carbon fiber, as shown here by Patrick Sieb and Isa Held.





The winning design in side view: The entire plane is 43.7 meters long, 1.3 meters shorter than an Airbus A321.



In order to accommodate more air travelers, the students planned to allow some of the passengers to travel standing up.

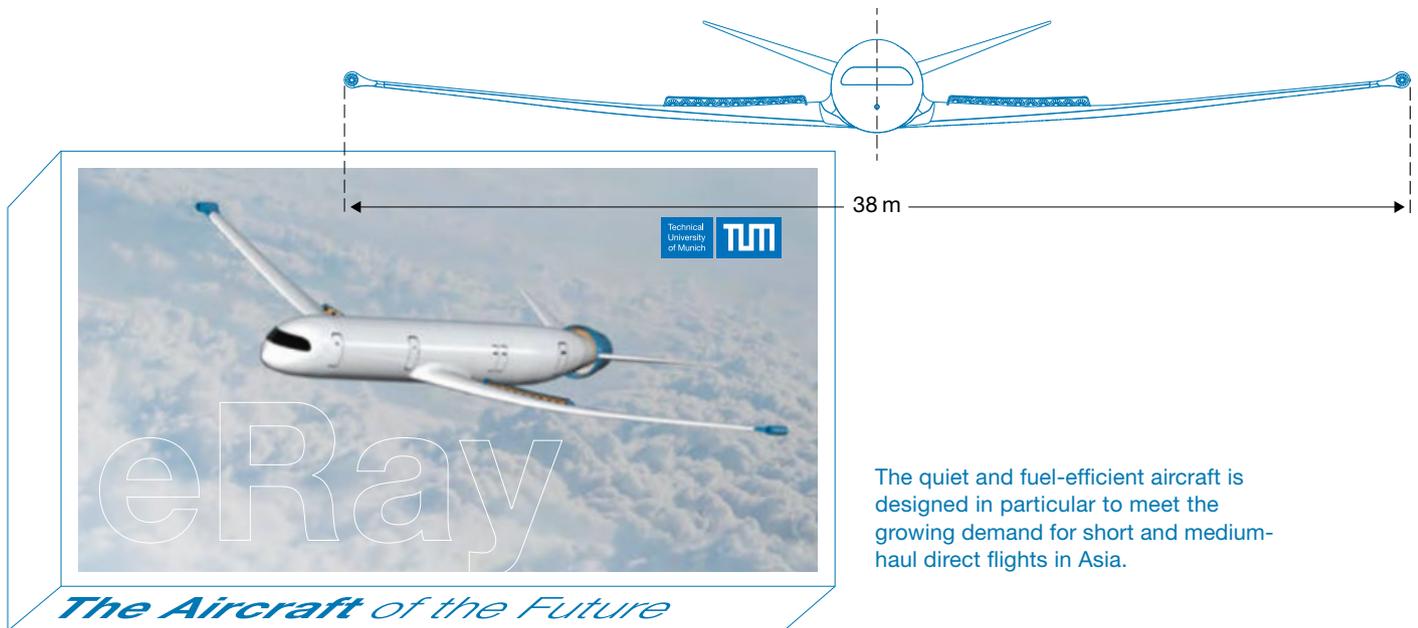
### Getting off the ground

Whether the students' predictions come true and the eRay will really be suitable for everyday use from around 2045 onwards still depends on certain developments. The Munich team's concept relies on rigorous progress in battery technologies (the eRay uses batteries as a buffer for high energy demand during take-off and landing), as well as a significant improvement in flight control systems and certain amendments to regulatory approvals. Equally, the prospect of flying without windows and standing during the flight – both a given in the winning design's most efficient scenario – would have to resonate with passengers in the real world. However, the first virtual windows, which display

images from an on-board camera instead of giving passengers a real view outside, have recently launched in the new first-class cabin of Emirates' Boeing 777-300ER aircraft. TUM's young scientists are optimistic that flying will develop in line with their vision. "What I found most fascinating during the Challenge was the realization that there is still so much room for innovation. The aircraft in its current form is by no means the best imaginable," emphasizes Frühbeis. "The next stage is implementing and testing out these new concepts. Business leaders and policymakers need to be bold in leading the way here and actively embrace innovation. Concepts like the eRay require a high

*“My fellow jury members and I were impressed by the systematic dovetailing of complementary technologies that were a perfect fit for each other.”*

*Rolf Henke, Member of the DLR Executive Board*



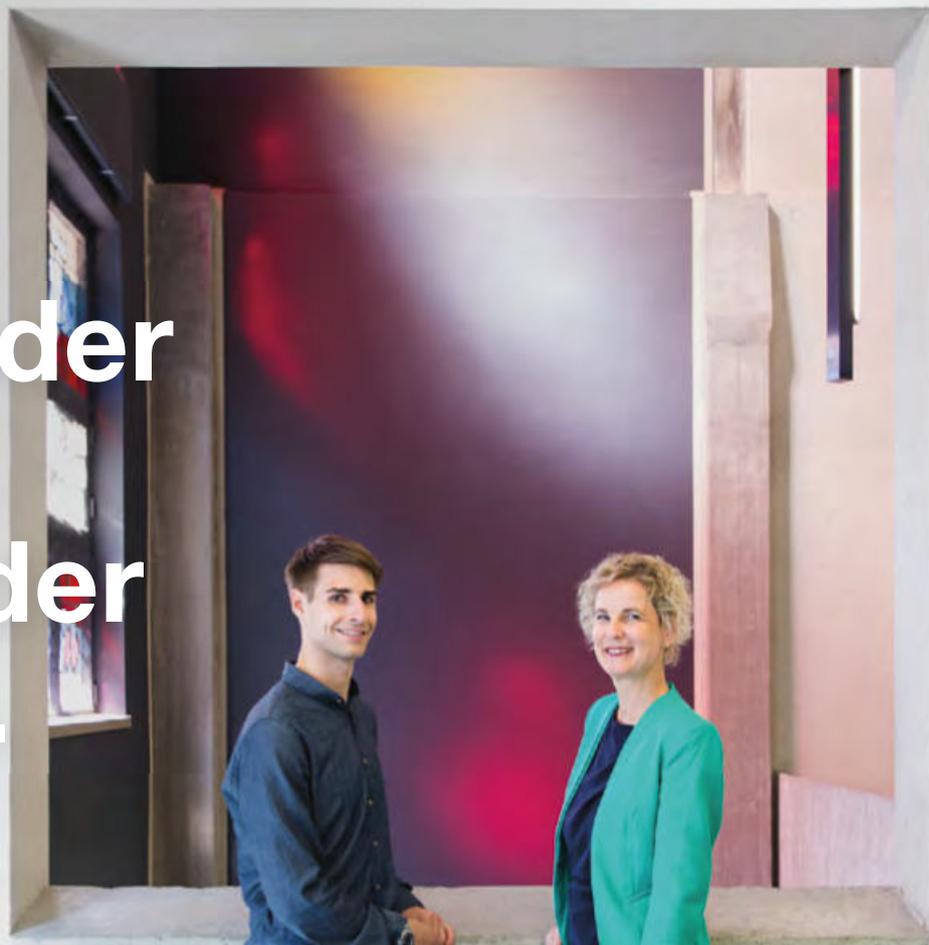
level of cooperation – as we already experienced in our own small team. Aerodynamics experts really have to get to grips with the propulsion system and vice versa. And this is at odds with the strict division of labor in the industry today. In the long term, I want to contribute to driving this transformation.”

Artur Usbek exemplifies this collaborative approach: The 24-year-old is a student of mechanical engineering, aerospace engineering, management, and product development and engineering design. With four Master’s degrees under his belt, he could envisage working as an engineer focusing on the entire system design of military jets or

engine systems. He concludes: “It quickly became clear to me that developing new aircraft concepts is all about workable compromises. I particularly enjoyed the contact with other aerospace enthusiasts during this competition and would recommend taking part in a project like this to anyone.”

Altogether, over a hundred students participated in the German-US Design Challenge. In September 2018, the two winning groups were honored at a symposium at NASA headquarters in Washington D.C. And TUM is already gearing up for similar competitive challenges later this year. ■

*Karsten Werth*



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# TUM Succeeds with Four Clusters of Excellence

TUM has got off to another successful start in the extremely competitive Excellence Initiative organized by the German government and federal states. Over the next seven years, four research clusters run by TUM and its cooperation partners will each receive up to 50 million euros in funding. Contributing to this great start was the outstanding quality of the TUM researchers and the successful collaboration between different disciplines and various partner institutions.

## e-conversion

The e-conversion Cluster of Excellence focuses on the energy conversion processes of different technologies in the sustainable energy ecosystem – from photovoltaics through (photo-)electrocatalysis to batteries. This cluster uses experimental research to study the underlying mechanisms of energy conversion with a time resolution in the femtosecond range.

## MCQST

The objective of the Munich Center for Quantum Science and Technology (MCQST) is to gain a comprehensive understanding of quantum mechanics phenomena and thus advance basic building blocks, materials and concepts for quantum technologies. Interdisciplinary research extends from the analysis of entanglement in multiparticle systems to quantum chemistry, cosmology and precision metrology.

## ORIGINS

This cluster investigates the innermost structure of the universe and the origins of life. It brings together scientists from the fields of astrophysics, astrobiology, biophysics and particle physics to collaboratively explore, for instance, the connection between planet formation and the emergence of the first molecules that may have been the precursors of living cells.

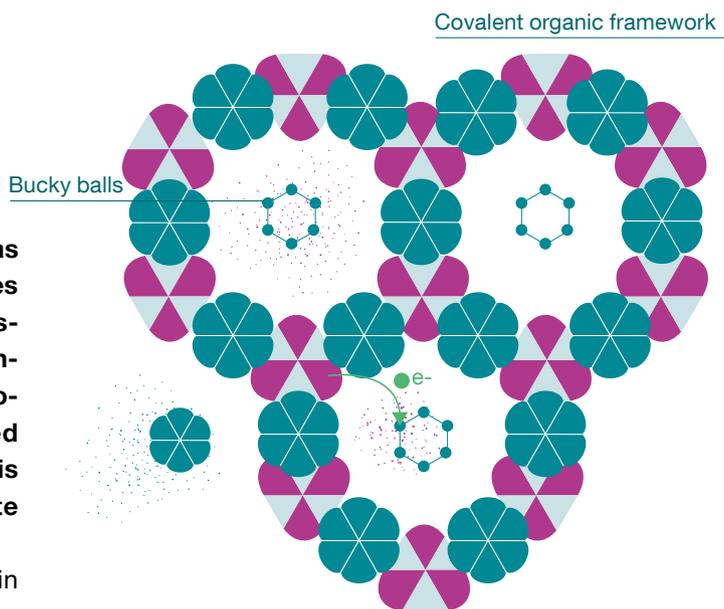
## SyNergy

The Munich Cluster for Systems Neurology (SyNergy) studies the onset of neurological diseases such as multiple sclerosis and Alzheimer's. Given the highly complex nature of the human nervous system, numerous processes interact in the development of these degenerative neurological conditions. At the heart of this Munich-based research engagement lies a whole new interdisciplinary field of science: systems neurology.

# e-conversion – Close-up on Materials for Energy Conversion

**Capturing energy from sustainable sources such as solar power calls for completely different technologies compared to those used with conventional combustion power plants. The focus here lies on energy conversion and storage methods, all based on atomic processes at tailored interfaces between engineered materials. The e-conversion Cluster of Excellence is taking an interdisciplinary approach to investigate these mechanisms.**

**A**lthough the world has seen significant progress in the move towards more sustainable forms of energy through the growing adoption of renewables in recent decades, there are still major gaps in our understanding of the underlying atomic processes. In many cases, we have not even determined the basic properties affecting the nanoscale, femtosecond processes that take place at battery, fuel cell and solar cell interfaces. The effects can reduce the efficiency of the devices they power or compromise stable long-term operation.



Transport of charge carriers  
by energetic excitation  
in model materials

For the researchers, three interpretations of the e in the name of the cluster are significant:

The first e stands for “energy” conversion in general. “The reason we decided to combine all the energy conversion technologies in one cluster was because we realized that we often rely on the same microscopic processes in these – previously largely separate – fields of research,” explains TUM professor Karsten Reuter. “They play a central physical role and set the limits in the current systems.”

Up to now, all these technologies further tended to rely on the same or similar materials. The interdisciplinary e-conversion cluster hopes to find synergies and analogies by bringing together researchers who had previously been working independently on different energy conversion technologies.

The second interpretation of e stands for “elementary”. The limiting microscopic processes in current energy conversion systems mostly occur at the interfaces between materials, predominantly at solid-solid, solid-liquid or solid-molecular material boundaries. So far, very little is known about these fundamental processes. More detailed findings are important, however, because during

operation these processes also change these boundaries to a significant degree.

Solid-solid and solid-liquid interfaces are thereby particularly difficult to study, as unlike at a surface the boundary is then concealed within the system. The central focus of e-conversion is, therefore, to create new model systems that enable a detailed study. “The trick is not to take real systems and somehow simplify them,” TUM professor Ulrich Heiz points out. “Instead, we use the latest developments in nanotechnology to assemble artificial systems more or less atom by atom according to our specifications. Our goal is to create our own ideal models for studying the boundaries and the microscopic processes that take place there.” The researchers hope that this will improve their fundamental understanding of these molecular processes. As an additional benefit, the Cluster of Excellence will forge stronger links between the disciplines of energy research and nanoscience.

A third interpretation of the e is “excitation”. The processes in energy converters always require excitation of the atoms or molecules which form the actual basis for the energy conversion step. With renewables, the process often starts with sunlight as a sustainable source of energy. The processes involved here are also on the research agenda of the e-conversion cluster.

A thorough understanding of the mechanisms at play in the materials will provide a good springboard for work to avoid harmful effects and develop new materials that enable more efficient conversion of energy from sunlight into electricity or synthetic fuels, or lead to long-lasting and safe batteries with high storage capacities.

Alongside LMU and TUM as joint applicants, the Max Planck Institutes for Chemical Energy Conversion (Mülheim/Ruhr) and for Solid State Research (Stuttgart) are also participating in the e-conversion cluster. TUM’s spokespersons are Prof. Karsten Reuter and Prof. Ulrich Heiz (chemistry). ■



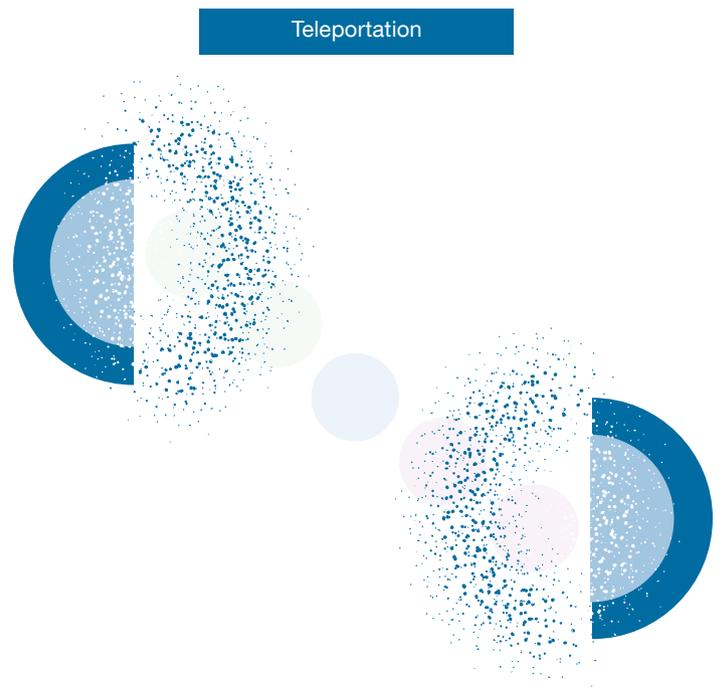
Picture credit: Wenzel Schürmann; Graphics: edlundsepp

Scientists at TUM’s neutron research source FRM II employ positrons to measure the properties of batteries. FRM II is an important research tool in the e-conversion Cluster of Excellence.

# MCQST – The Practical Applications of Quantum Physics

**A new approach to the laws of the quantum realm is paving the way for completely novel technologies, such as better encryption possibilities, data teleportation and quantum computing. This new field of research, which harnesses quantum phenomena for practical use cases, is now being advanced on an interdisciplinary platform at the Munich Center for Quantum Science and Technology (MCQST). The application potential is huge.**

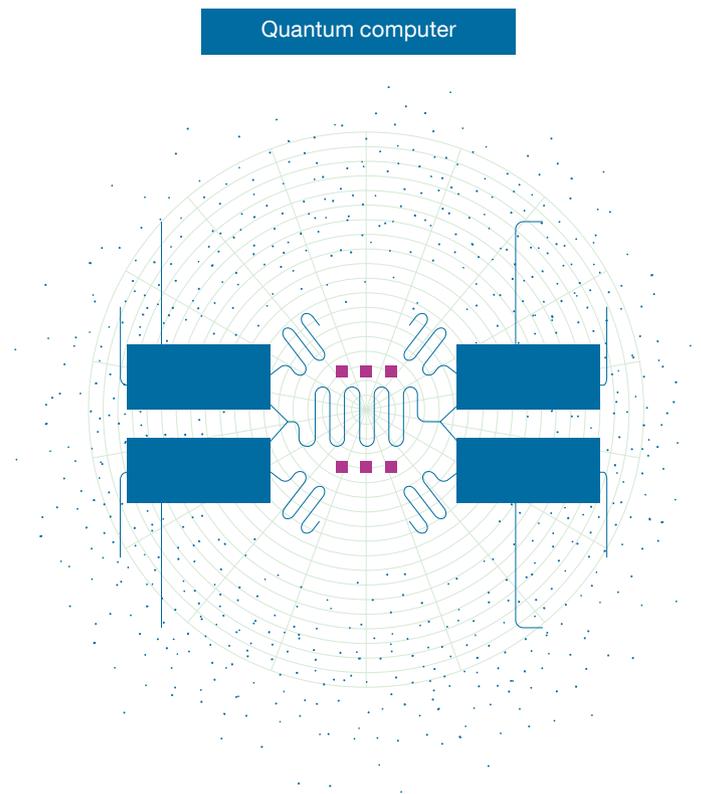
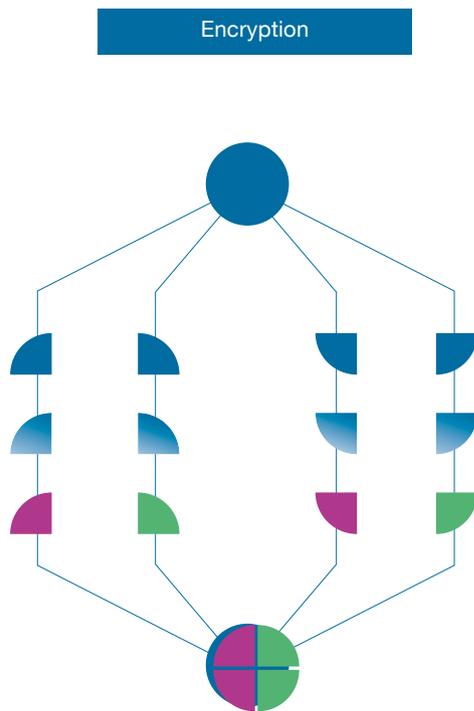
**F**rom computers through lasers to atomic clocks – technologies based on quantum mechanics have already been in use for years across many different application scenarios. This science, developed in the first three decades of the twentieth century, describes physical processes on the very smallest scale – some of which can seem truly bizarre. For a long time, the influences of quantum mechanics were seen as a disruption to classical physics, but there has since been a complete shift in perspective. Now, a new generation of physicists are applying these laws for their own aims and developing brand new applications under the Quantum 2.0 umbrella. Needless to say, the physical laws have not changed, but the way we harness them certainly has.



This center's work is largely based on the use of superposition, entanglement and teleportation of quantum states. Entanglement is the phenomenon described by an incredulous Albert Einstein as "spooky action at a distance". Two quantum objects that are entangled are always correlated, no matter how far apart they are from one another. If the state of one changes after being observed, the state of the other automatically does too, as though bound by telepathic connection. Harnessing this phenomenon in conjunction with teleportation has enabled the development of revolutionary methods for encrypting messages, for instance – which are now on the path to practical applications.

The superposition of quantum states plays an important role in constructing a quantum computer. This concept was first discussed in theory by US Nobel Prize winner Richard Feynman in 1981. In the meantime, we have progressed to initial prototypes, components and the rudiments of suitable software.

The Munich Center for Quantum Science and Technology aims to further our understanding of the principles of quantum information and to harness the effects described. Its interdisciplinary research extends from the analysis of entanglement in many-particle systems to quantum chemistry, cosmology and precision metrology. A new research building is under construction at TUM's Garching campus, jointly funded (to the tune of 40 million euros) by the federal government and the state of Bavaria. Alongside TUM and LMU as joint applicants, the Max Planck Institute of Quantum Optics, the Walther Meißner Institute of the Bavarian Academy of Sciences and Humanities, and the Deutsches Museum are involved in MC-QST. TUM's spokespersons are Prof. Rudolf Gross (physics) and Prof. Ignacio Cirac (physics/MPI of Quantum Optics). ■



# ORIGINS – How Did the Universe and Life Originate?

**The development of the cosmos – from the Big Bang to the emergence of life – is still one of science’s greatest mysteries. The ORIGINS research alliance builds on twelve successful years of work by the Universe Cluster of Excellence, which drew to a close at the end of 2018. The focus of the new cluster is on understanding the structure of the universe as well as the origin of life, on Earth and on possibly other planets.**

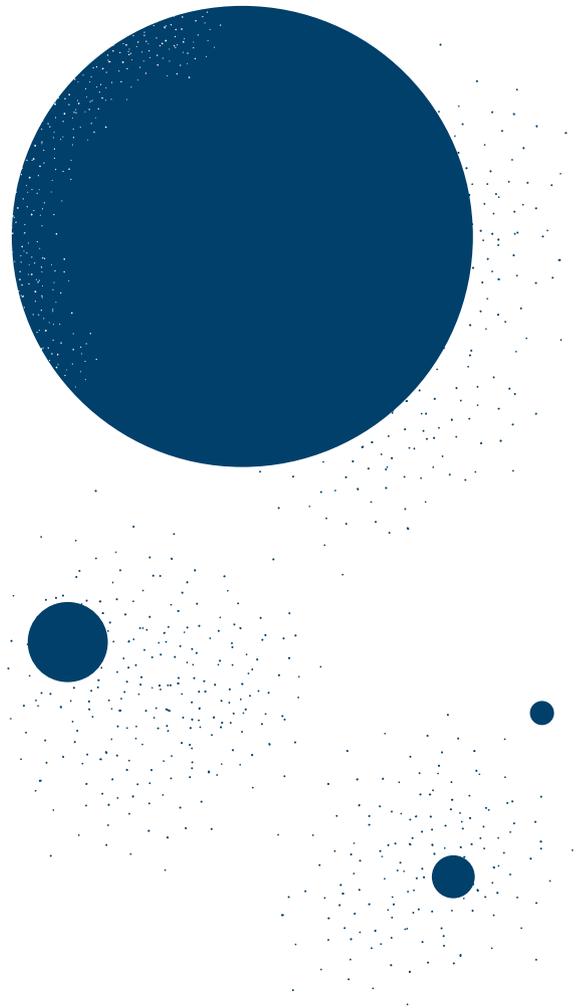
**S**cience has already revealed a great deal in recent decades about the origins of the universe and its development up to the present day. We now understand much better how stars and galaxies are formed from gas clouds and nebulae, and have discovered a myriad of exotic phenomena in the skies, some of which have now been explained. Nonetheless, fundamental questions remain unanswered. One of the most important is how life develops – and originally emerged – in the vastness of the universe, as well as on Earth. Closely linked to that is the search for exoplanets that could possibly be home to living structures. Researchers can get closer to the answers by investigating in retrospect what conditions were once necessary for the emergence of life on Earth.

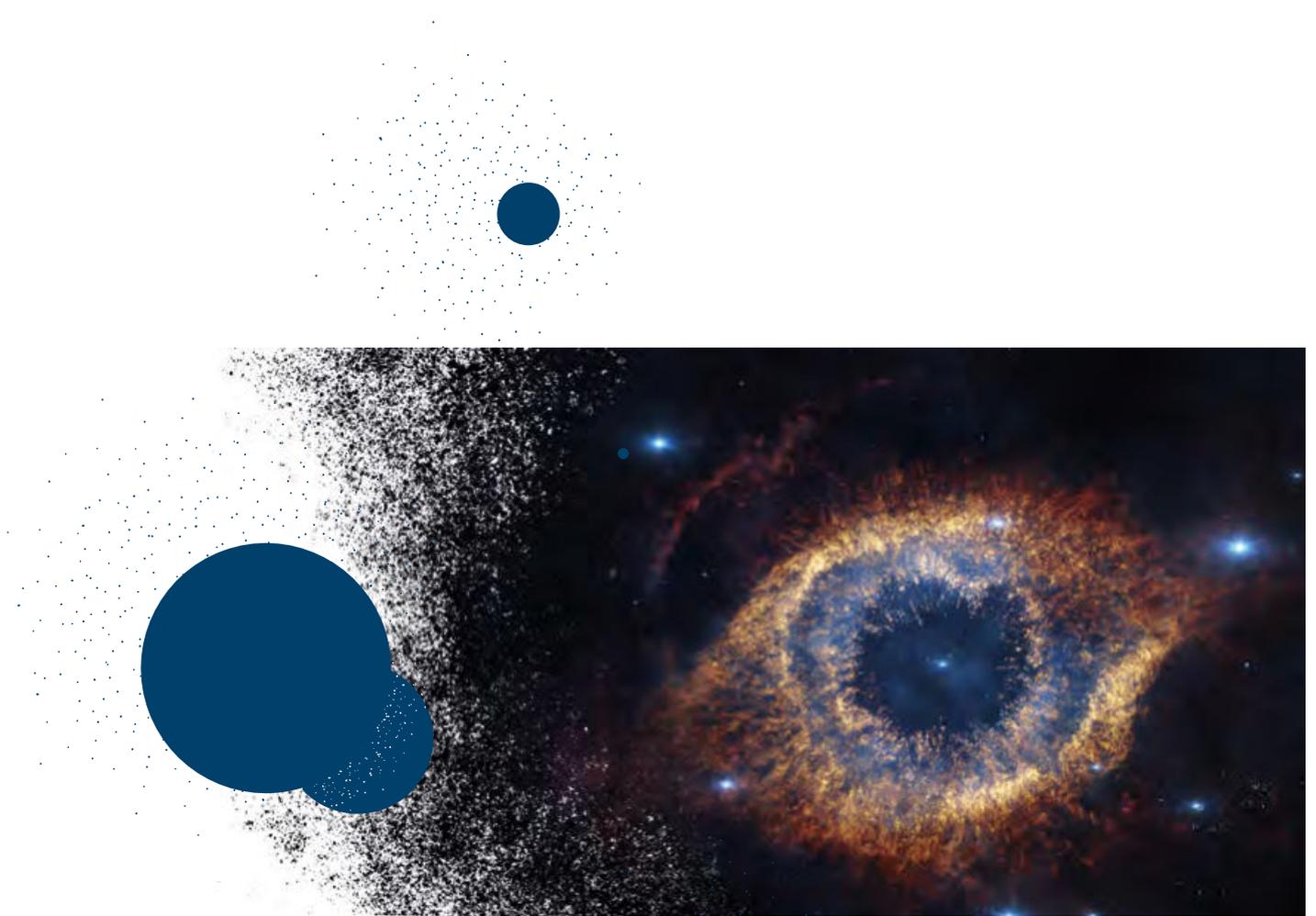
Responding to approval by the German Research Foundation (DFG), cluster coordinators Professor Andreas Burkert (LMU) and Professor Stephan Paul (TUM) commented: “The experience of the Universe cluster gives us a platform for research into the new challenges we are

tackling with ORIGINS. We are delighted to continue our devotion to fundamental questions on the emergence of the universe and extending our research to the origin of molecular life.”

The research covers everything from the microscopic to the macroscopic scales. Exemplarily, the researchers are seeking to investigate the interconnection of planet formation and the emergence of the first prebiotic molecules, in order to trace the origins of life. Another key issue is the connection between the fundamental nature of dark matter and cosmic structure formation. Researchers from the fields of astrophysics, astrobiology, biophysics and particle physics will all work together in the quest for new findings.

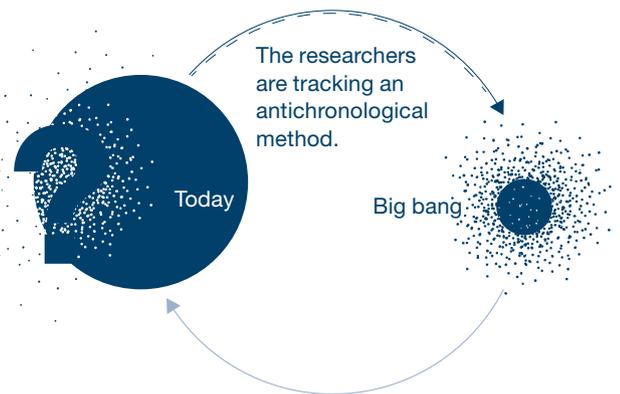
Important strands of this work will be carried out within international partnerships and involve some of the world’s most prominent research institutions, such as CERN and ESO’s Very Large Telescope in Chile. Laboratories established in the course of the Universe cluster will be flanked





This infrared image shows the Helix Nebula, 700 light-years away from Earth. The picture was taken by one of ESO's telescopes. ESO is one of the members of the ORIGINS Cluster of Excellence, which looks into the origins of both life and the universe itself.

by new facilities in Munich, such as the Origins Data Science Lab (ODSL). This will bundle existing expertise in statistical data analysis and develop the next generation of numerical and statistical methods to analyze enormous and closely interlinked data sets in the future. Meanwhile, the new Ice, Dust and Sequencing Laboratory (IDSL) will help researchers reconstruct the first cycles of Darwinian molecular development in a bid to understand how living matter emerges from inanimate substances. Alongside joint applicants TUM and LMU, the Max Planck Institutes of Astrophysics, Biochemistry, Extraterrestrial Physics, Physics, and Plasma Physics are all partners in the "ORIGINS – from the origins of the universe to the first building blocks of life" cluster – as are the European Southern Observatory (ESO), the Leibniz Supercomputing Center and the Deutsches Museum. TUM's spokesperson is Prof. Stephan Paul (physics). ■



Professor Thomas Misgeld is a neurobiologist at TUM and the TUM spokesperson for the SyNergy Cluster of Excellence. SyNergy's research focuses on the shared pathomechanisms of neurological diseases like Alzheimer's and multiple sclerosis.



Vascular diseases

# SyNergy – Holistic Research into Neurological Disease

**SyNergy – Munich Cluster for Systems Neurology studies the shared pathomechanisms of neurological diseases such as multiple sclerosis and Alzheimer's. Given the highly complex nature of the nervous system, numerous processes interact in the development of these diseases, making an interdisciplinary approach to collaboration essential.**

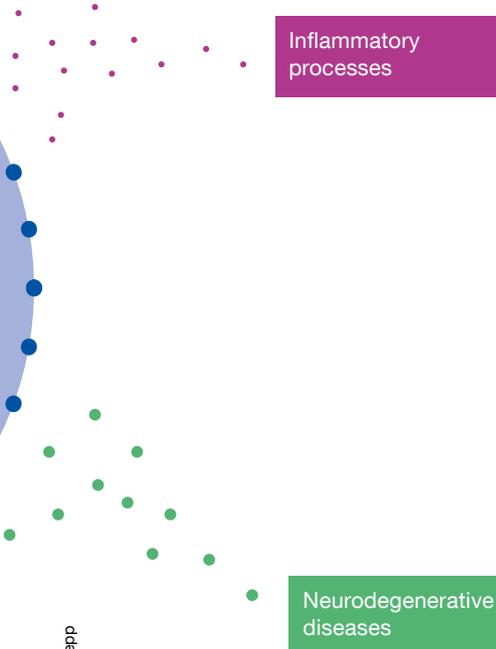
**A**t the heart of this Cluster of Excellence lies a whole new field of science: systems neurology. This interdisciplinary concept fosters collaboration between experts in diverse fields of medical research. Their shared aim is to investigate the closely interlinked mechanisms that occur during the onset of neurological diseases. The norm to date has been separate specialists in inflammation (inflammatory processes), in the destruction of nerve cells (neurodegenerative diseases) and in blood vessels (vascular changes). In systems neurology, these experts all now work closely together, crossing the lines between their disciplines – for instance, to investigate how inflammatory responses influence neurodegenerative processes, how microvascular and degenerative damage mechanisms affect each other and how immune cells interact with the blood-brain barrier.

The SyNergy Cluster creates a scientific and structural framework to establish Munich as the European center for systems neurology. It builds a collaborative network between basic researchers, clinical scientists and leading experts in the field of systems analysis. This also involves pursuing new, interdisciplinary approaches to the analysis, modeling and modification of disease processes. To this end, tandem projects are funded, which entail two or more scientists working together. These tandems have a two-way bridging function: both horizontally, between different disease mechanisms, and vertically, between basic research and clinical application.

Additionally, a number of new SyNergy professorships have been created to bring in outstanding scientists with special expertise at the interfaces between the various fields. A new program has also been set up to train and promote young clinical scientists.

This cluster has been funded by the Excellence Initiative since 2012. The close collaboration between teams from different scientific disciplines has already yielded highly impressive results, including the discovery that catabolic products of lipid metabolism aggravate inflammation in damaged nerve fibers and prevent healing in multiple sclerosis.

Alongside TUM and LMU as joint applicants, the German Center for Neurodegenerative Diseases (federal initiative), Helmholtz Zentrum München and the Max Planck Institutes of Biochemistry, Neurobiology and Psychiatry are collaborating in SyNergy. The spokesperson for TUM is Prof. Thomas Misgeld (medicine), whose counterpart from LMU is Prof. Christian Haass. ■



Lower Band (// links)

$\alpha^0$

$A_0$  (resources)

$P_1$  (players)

$A_1$

$P$

$A$



$\max_{i \in I} f_i(b_{i-1}) \geq f_i(b_{i-2}) = f_i(b)$

$\bar{S}^k$ : players

$$w_i(\bar{S}^k) = \sum_{e \in \bar{S}^k} \dots = \left( \frac{\alpha^{i-1}}{\phi_d} \right)^{|\bar{S}^k|}$$

$$\left[ \left( \frac{\alpha^{i-1}}{\phi_d} \right)^{r-i} \right] \left( \frac{i \cdot k}{\sum} \right)$$

# Operations Research – One of Math’s Greatest Secret Weapons

Computer algorithms in the field of Operations Research have the potential to streamline a vast range of processes – from optimizing inventory costs and traffic flows to staff scheduling and project management. Prof. Andreas S. Schulz refines the procedures, develops new ones, and often gains astonishing insights along the way.

Link

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## Operations Research – eine mathematische Wunderwaffe

D

Es handelt sich um einen Zweig der Mathematik, der sich vor allem mit der Modellierung und Optimierung wirtschaftlicher Abläufe befasst. Aus einer Vielzahl von Möglichkeiten können Algorithmen die jeweils beste auswählen und zur Entscheidungsfindung in Unternehmen vorschlagen. Andreas S. Schulz, Alexander von Humboldt-Professor für Operations Research an der TUM, entwickelt die dafür nötigen Verfahren weiter, erfindet neue und entdeckt bei der dahinter liegenden Theorie

manchmal verblüffende Ergebnisse. So konnte er zum Beispiel nachweisen, dass ein Problem aus der Lagerhaltung mindestens so schwer zu lösen ist wie die Faktorisierung ganzer Zahlen. Oder dass ein vernetztes System, in dem jeder nur seinem eigenen Nutzen folgt, nur wenig schlechter funktioniert als eines, in dem alle dem allgemeinen Wohl folgen. Schulz engagiert sich nicht nur für ökonomische Fragen, sondern wendet seine Verfahren auch auf soziale und humanitäre Projekte an. □

**T**he many influences of mathematics on our everyday lives are exemplified by the work carried out at the Chair of Operations Research in a building on Karlstrasse in Munich. While the shop on the building's ground floor sells shiny helium balloons floating in the air, up on the 6th floor, researchers are thinking about ways of getting their mathematical ideas off the ground. Specifically, the researchers focus on developing and improving algorithms that optimize complex processes inherent to a wide range of businesses and industries. The number of possible executions for a complex process can be extremely large, so the objective is often to efficiently find the best one in terms of time and resources. "We seek methods that can deal with both huge volumes of data and with uncertainty," explains the Alexander von Humboldt Professor Andreas S. Schulz, who has been head of this chair and an interdisciplinary research center between the Department of Mathematics and the School of Management since 2015. "We also take challenging circumstances into consideration, such as dynamically changing environments, with privately held information and multiple – sometimes conflicting – objectives."

### The optimal route

The traveling salesperson problem (TSP) is regarded as a classic problem in Operations Research (OR). The objective is to determine the order in which a salesperson should visit their customers so as to minimize the distance traveled. "The beauty of this problem is that it relates to the real world, can be easily grasped, and everyone is quick in proposing ideas for solving it," says Schulz. "The fascinating aspect for me, though, is that this problem is mathematically so difficult that decades of research have so far failed to come up with a general solution method that finds optimal solutions to all instances efficiently. It is also a prototype for similar tasks where you have to choose a best alternative from a multitude of possibilities."

When the number of customers is small, all routes can be explicitly listed and easily compared. However, the number of potential routes increases rapidly as the customer base expands: with five customers, there are 24 possible options. With six, there are 120. If the traveling salesperson has 13 customers, the number of possible routes already exceeds the odds of getting six numbers out of ▶



**5**

**24**

**6**

**120**

**25**

**620 448 401  
733 239 439  
360 000**

customers

number of possible routes

The traveling salesperson problem (TSP) has the objective of determining the order in which a salesperson should visit their customers so as to minimize the distance traveled. The picture shows two possible routes (blue and red). The TSP is a challenging mathematical problem, not only because the number of potential routes increases rapidly as the customer base expands (see left).

49 in the lottery. With 25 customers, there are sextillions of potential routes. The most powerful supercomputers would take months to calculate all of these possible combinations. Clearly, with several hundred customers the problem cannot be solved simply by listing and comparing the efficiency of individual routes, and a more strategic approach is needed.

The traveling salesperson problem occurs in many different contexts, such as the logistics of parcel deliveries, organization of flight plans, and emergency room scheduling, as well as the planning of inventory picking from high-bay warehouses, and even sequencing drill holes in circuit boards. Nowadays, there are mathematical algorithms capable of finding good or optimal solutions for many of these practical problems – for example, the branch-and-cut method. However, there is no known method that can always find an optimum efficiently.

“The question of why we have not yet managed to discover an efficient exact algorithm to the traveling salesman problem is central to OR and theoretical computer science,” explains Schulz. “It is no surprise that in the year 2000, the Clay Mathematics Institute in Massachusetts announced one million dollars in prize money to anyone who could develop what is called a polynomial-time algorithm for solving the TSP, or else prove that no such algorithm exists.”

### Military origins

The origins of OR can be traced back to methods used by the British and Americans in World War II and subsequently in the Korean War to improve military strategies and weapons deployment. It was not until the 1950s that non-military companies started to use these optimization methods for their own purposes. Soon after that, an academic community began to develop around the subject. Since then, several Nobel Prizes in Economic Sciences have been awarded to researchers for their discoveries in the field of OR (see box).



### Nobel Prizes in Economic Sciences for OR problems

**1969 Jan Tinbergen jointly with Ragnar Frisch** “for having developed and applied dynamic models for the analysis of economic processes”.

**1975 Leonid V. Kantorovich and Tjalling C. Koopmans** “for their contributions to the theory of optimum allocation of resources”.

**1990 Harry M. Markowitz jointly with William F. Sharpe and Merton H. Miller** “for the application of mathematical or computer techniques to practical problems, particularly problems of business decisions under uncertainty”.

**1994 John C. Harsanyi jointly with John F. Nash Jr. and Reinhard Selten** “for their pioneering analysis of equilibria in the theory of non-cooperative games”.

**2012 Alvin E. Roth and Lloyd S. Shapley** “for the theory of stable allocations and the practice of market design”.



The search for an optimal warehousing strategy is deceptively difficult. If you have two or more different products that may be ordered together at a discount but do not have to be, nobody knows of an efficient algorithm to identify an optimal solution.



“Sometimes I hear about a new method and consider whether it would work for one of my own mathematical problems,” says Professor Schulz.

Nowadays, you can buy software programs for warehousing, business processes and logistics. Schools and railway companies use this kind of software to compile their timetables. The success of industry giants like Amazon and Google is closely tied to the use of mathematical methods. In contrast, however, small and medium-sized enterprises still tend to be unaware of the huge potential for improvement that OR can bring. Another factor for the untapped use of OR in smaller enterprises could be that OR requires a certain level of background knowledge. “Standard software is available,” the professor points out, “but I have found that every situation has its own particular set of circumstances and one size does not fit all. You often have to start by developing a suitable model that captures the specifics of the case in question.”

Schulz is one of the world’s leading academics in the field of Operations Research. He completed his Master’s degree and PhD at the Technical University of Berlin, and captured the attention of the academic community early on with his doctoral thesis. At the young age of 29, he was appointed Professor of Mathematics of Operations Research at the Massachusetts Institute of Technology (MIT) in Cambridge, USA, where he later took up the Patrick J. McGovern Chair of Management Science. ▶

He remained at MIT for 17 years with occasional visiting positions at other universities before accepting an offer from TUM in 2015. He has received prizes and awards for his scientific work almost on a yearly basis, and his discoveries have not only solved problems that mathematicians have grappled with for a long time, but they have also had significant practical implications.

### Ideas in the shower

Many of his best ideas come to him through discussions with colleagues: “A large number of proposals and problems are aired at symposiums for example. Sometimes you encounter a problem and think: Aha, I can think of a technique that might work for that. Or else I hear about a new method and consider whether it would work for one of my own mathematical problems. I was once in a meeting where all three speakers were talking about their individual topic, yet at the end I felt that they had all said the same thing without even noticing. The following year, I developed a common theory for all of these contributions.” The flow of ideas then continues at home: “Guests sometimes come to the institute to give a talk. I latch on to something that fascinates me and it sticks in my memory,” says Schulz. “Another idea then comes to me, perhaps while walking or having a shower. In mathematics, the subconscious plays a very important role.” At this stage, he uses the computer only to test a conjecture or idea.

This is also the methodology Schulz recommends to his students and doctoral candidates: “I often say to my group: You need to have a deep understanding of the subject because the solutions will then eventually present themselves. You cannot consciously work towards it. We can set out to tackle major unresolved problems, but the solution is unlikely to come within a year or two. In the meantime, we will come across other interesting questions, and will be able to present partial solutions, at the very least.”



Many of his best ideas come to Andreas S. Schulz through discussions with colleagues.

This has happened, for example, in the search for an optimal warehousing strategy – another problem that seems straightforward at first glance, but is deceptively difficult. If you look at the ordering costs and compare them with the warehousing costs, it is easy to calculate the delivery intervals required to keep the overall costs as low as possible for a single product. But if you have two different products that may be ordered together at a discount but do not have to be, nobody knows of an efficient algorithm to identify an optimal solution. This is precisely the type of challenge that absorbs a mathematician like Schulz. He and one of his PhD students succeeded in showing that the problem is at least as difficult to solve as the factorization of integers. Integer factorization involves decomposing an integer into a product of smaller integers, for example  $39 = 3 \times 13$ . Calculating the product of two large prime numbers is unproblematic. However, if the product has hundreds of digits, then the reverse procedure of finding two factors is extremely difficult.



Methods of OR are also suitable for the planning and optimization of new traffic routes.

The computing effort required quickly exceeds the realistic realm of possibility. Because of this, the factorization of very large numbers is a security component in the RSA encryption processes frequently used today.

### Braess Paradox

The Braess Paradox is an unexpected result from network theory. It states that adding capacity could actually slow down the speed of the network. Applied to highways, the Braess Paradox means that the addition of one road can make the average journey time longer, or that closing some roads could speed up traffic. This effect was observed in New York City, for example, on the occasion when 42nd Street near Times Square was closed to traffic for Earth Day on April 22, 1990. Everybody had predicted that traffic chaos would ensue, but they were mistaken – the traffic distributed itself evenly onto the other streets.

### The price of anarchy

Another problem, which is highly relevant in everyday life and whose solution sometimes defies common sense, was initially studied over 20 years ago. The question goes: If you have a networked system where everyone does what is best for them personally, how much more unfavorably does the overall system function in comparison to a situation where everyone does what is best for the common interest? Or in other words: What is the price of anarchy?

For example, in traffic flows it is naturally assumed that all drivers are taking the route which they believe is the quickest, and this often leads to traffic jams on many major roadways. However, it could be possible to avoid congestion if traffic was directed so that not all cars take their assumed quickest route, thus improving the total travel time. ▶

*“You need to have a deep understanding of the subject because the solutions will then eventually present themselves.”*

Andreas S. Schulz

By modeling these systems mathematically, the surprising insight was found that the addition of one road can make the journey time longer. This effect is known as the Braess Paradox, and was discovered in 1968 by the German mathematician Dietrich Braess (see box). That this effect can be observed in real life was proven in New York City, for example, on the occasion when 42nd Street was closed to traffic for Earth Day on April 22, 1990. Everybody had predicted that traffic chaos would ensue, but they were mistaken – the traffic distributed itself evenly onto the other streets.

Schulz attempted to analyze this question, and for the price of anarchy he found a “very nice geometric proof which is now included in standard textbooks.” He was able to demonstrate that with a particular type of driving behavior, the worst possible solution is only 33 percent worse than the best possible one. “Those are idealized assumptions, however,” he admits. “You can make a few refinements for real-life road networks. Then you determine that you lose 36 percent in the worst-case scenario.” It is possible to significantly reduce costs with OR. An example comes from Jannik Matuschke, a former member of Schulz’s group, who was appointed as an Assistant Professor at the Catholic University of Leuven in January. His doctoral thesis shows that a parcel delivery service in Germany was able to achieve a 14 percent reduction in costs over a year, corresponding to EUR 1.6 million, with an OR method specifically developed for this company. Schulz is keen, however, for his methodologies to be used for more than just maximizing the profits of businesses. He wants to use them to give something back to society and to support non-profit organizations.

For example, they could significantly improve distribution of aid in disaster zones or revolutionize the allocation of donor kidneys.

Many people are willing to donate a kidney to a relative, but discover that they are biologically incompatible. Sometimes there are also altruistic donors who are willing to donate one of their kidneys to a complete stranger. OR makes it possible to build chains of the following type: if a patient receives an altruistic donation, that patient’s incompatible donor donates to another patient, and so on. With OR optimization methods it is possible to arrive at a situation where many more people than before receive a compatible kidney. “This has already been put into practice in the USA,” says Schulz. “In Germany, donations to strangers are virtually banned, so we are not able to realize such a scheme here just yet. There is of course always a chance that the law will be amended slightly to make this possible.”

Looking at the bigger picture, Schulz sees a new era dawning for OR: “Due to the ever-increasing overlap of computer science, mathematics and economics, new opportunities and applications naturally arise. We can continue to develop our methods by incorporating intangible factors such as incentives and uncertainties. This will put us in an even better position to tackle some of the critical challenges that society is facing today.” ■

Brigitte Röthlein




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**Prof. Andreas S. Schulz**

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## A mathematician reaching out to economics

Prof. Andreas S. Schulz, born in 1969, studied applied mathematics at the Technical University of Berlin, where he completed his PhD in 1996. He spent two years there as a research assistant before accepting an appointment at the Massachusetts Institute of Technology (MIT) in Cambridge, USA. After starting as an assistant professor, he went on to become Patrick J. McGovern Professor of Management Science and Professor of Mathematics of Operations Research. Having received a Humboldt Research Award, he accepted a visiting position at TUM in 2011, and returned to his alma mater in Berlin for a research stay in 2013. He has been a visiting professor at several universities, including the University of British Columbia, the Swiss Federal Institute of Technology (ETH) Zurich, and the University of Maastricht. He is also a founding member of the Junge Akademie (Young Academy) in Berlin, Germany.

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