Faszination Forschung 26 | 2021

Faszination **Forschung**

TUM Research Highlights
Technical University of Munich
The Science Magazine
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Hubble Constant:
Solving a Cosmic Contradiction

Ancient Adhesives – Unlocking the Secrets of Long-lasting Success
Citizen Science – Climate Change in Your Backyard
Green Carbon – Sustainable Carbon Fiber Components Made from Algae

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Dear TUM friends and associates,

We find ourselves at a turning point in history, which makes it all the more important that we shape the change we see around us. When I consider the many creative, tenacious, and academically brilliant pioneering spirits that make our TUM such a formidable powerhouse of innovation, it fills me with optimism, pride, and joy. Time and again, our scientists deliver some genuine highlights as they endeavor to understand the world through their research and shape it through their highly practical innovations.

Nanomaterials and nanotools are genuine beacons of hope, opening the door to innovative applications in all manner of different fields. But how will we get the nanorobots of the future to assemble molecules or transport things from A to B? Physicists at TUM are hunting for the interfaces between the nano and macro worlds that are crucial to success, testing out electrical control concepts for nanomolecules. In another project, scientists have managed to build an electric switch out of a single organic molecule – surely a record for the smallest switch that will never be beaten!

Our biotechnologist Thomas Brück, by contrast, is thinking big: His Green Carbon research project is turning algae and yeasts into sustainable raw materials for carbon-fiber composites, dispensing entirely with oil-based materials.

Cordt Zollfrank, meanwhile, is researching ancient adhesives such as birch tar in order to find environmentally friendly alternatives to oil-based epoxy resins. An amateur archaeologist sparked his interest in rediscovering the lost knowledge of old glues and updating this know-how for future applications.

Directing daylight exactly where you want it to go, ensuring effective insulation and ventilation, or acoustic distribution – an architecture research project has set out to combine all of these features into a single custom-made, 3D-printed facade.

If we want to counter the impact of increased global warming, we will need both environmentally sustainable technological innovations and their acceptance in society. Entirely in keeping with our guiding principle of “human-centered engineering”, the BAYSICS research partnership invites citizens to share the driving seat in studying climate change.

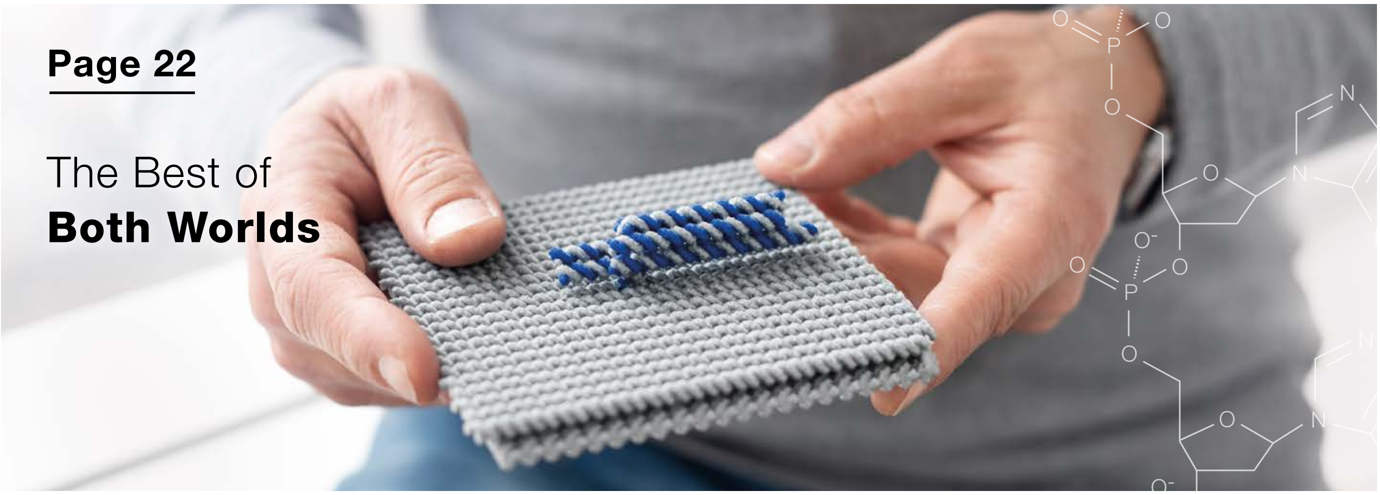
Constants provide certainty – and who wouldn’t want that, at times like these? When these constants start wavering, however, things get tricky. Just like the Hubble constant, whose precise value has been fiercely debated among astrophysicists for years. Different approaches for calculating or measuring it have produced different results. Using a new measurement method, TUM physicist Sherry Suyu has now managed to calculate the value of the Hubble constant with a very high degree of accuracy. With her outstanding scientific skills and her ability to bring people together, she may even succeed in resolving the experts’ dispute once and for all.

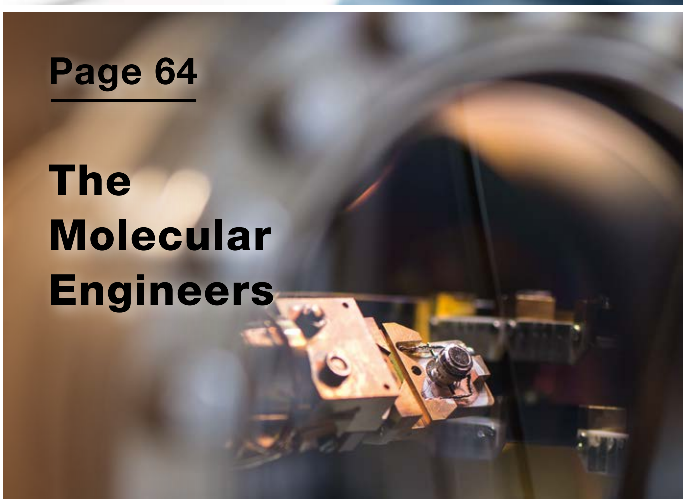
One bona fide constant at TUM is the extraordinary creative energy that distinguishes our highly talented scientists – nothing is more exciting than their high-impact discoveries, inventions, and innovations. I hope that you will also be wowed by our scientists’ enthusiasm as you read this issue of Faszination Forschung.

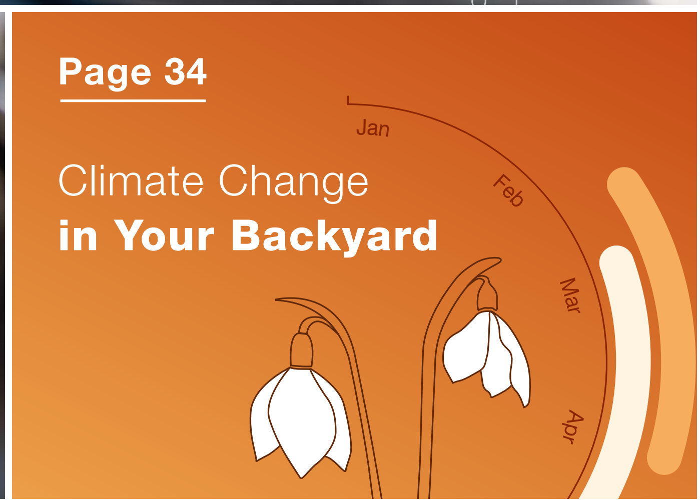
Yours,

Thomas F. Hofmann
President

Picture credit: Astrid Eckert







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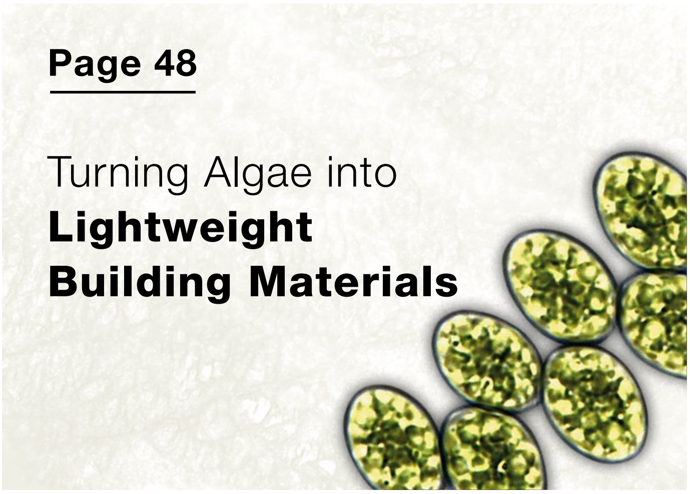

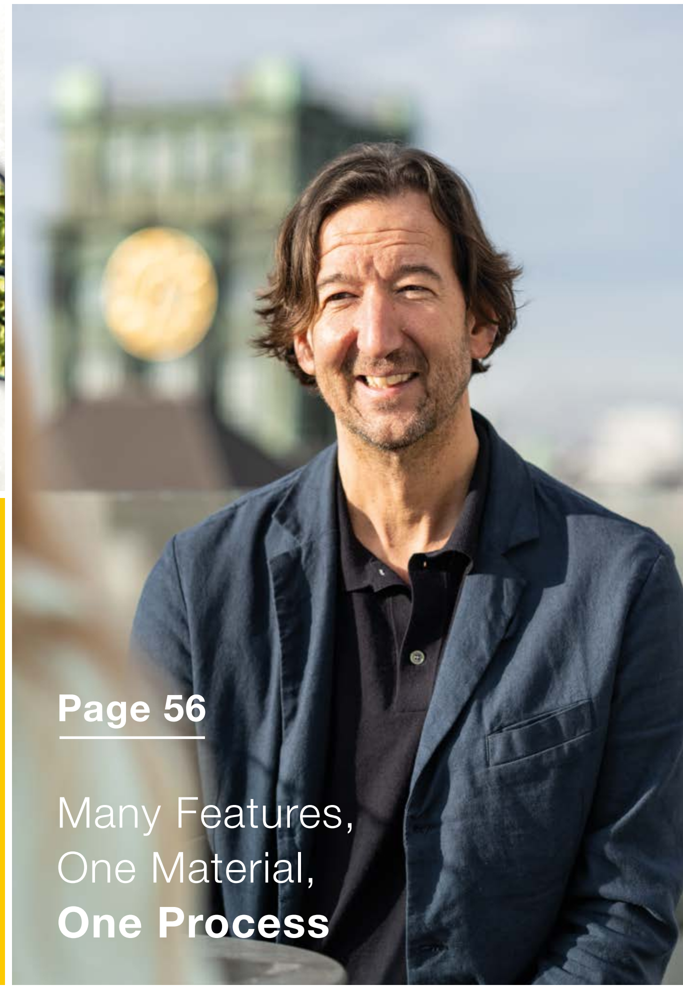

In every Issue

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German edition available as a PDF here:

www.tum.de/faszination-forschung-26

Picture credits: Stefan Woidig, Astrid Eckert/TUM, Magdalena Jooss, Peter Langenhahn; Graphics: ediundsepp (source: TUM)

An image of a lensed quasar taken by the Hubble Space Telescope. The gravitational field of a foreground galaxy acts like a lens on the incoming quasar light rays and creates four almost evenly distributed quasar images around the lens galaxy.

Picture credit: ESA/Hubble, NASA, Suyu et al.

Link

wwwmpa.mpa-garching.mpg.de/~suyu

Lenses Made from Pure Gravity Help **to Solve a Cosmic Contradiction**

Galaxies are so massive that they bend the space around them, thus creating lenses that refract light. This phenomenon is allowing physicist Sherry Suyu to measure exactly how fast the universe is expanding with the help of images from the Hubble Space Telescope. Her method could solve a heated scientific dispute.

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Linsen aus purer Schwerkraft zur Auflösung eines kosmischen Widerspruchs

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Die Geschwindigkeit, mit der sich das Universum ausdehnt, angegeben durch die Hubble-Konstante, ist eine der aktuell umstrittensten Fragen der Astrophysik. Einer Kollaboration namens H0LiCOW um die Physikerin Prof. Sherry Suyu gelang es nun, die Hubble-Konstante mit einer völlig neuen Methode zu messen. Dazu untersuchte man Quasare – besonders lichtstarke kosmische Objekte –, die sich hinter Galaxien befinden. Durch die Masse der Galaxien entstehen sogenannte Gravitationslinsen, die das Bild des jeweiligen Quasars in mehrere Bilder aufspalten, deren Licht unterschiedlich lang durch den Raum unterwegs ist. Der Unterschied beträgt bei einer Laufzeit von mehreren Milliarden Jahren mehrere Tage bis Wochen. Mithilfe des Hubble-Weltraumteleskops konnte dieses Phänomen nun so genau vermessen werden, dass Suyu und ihr Team daraus die Hubble-Konstante bestimmen konnten, was ein neues Licht auf bisher widersprüchliche Messungen der Konstante wirft. Für diese Arbeit erhält Suyu den Berkeley-Preis der Amerikanischen Astronomischen Gesellschaft für das Jahr 2021. Suyu ist Professorin für Beobachtende Kosmologie an der TUM und leitet eine Forschungsgruppe am Max-Planck-Institut für Astrophysik. □

Hubble Space Telescope observations of lensed quasars. Large galaxies in the foreground act as gravitational lenses and create multiple images. For each image, the light rays travel slightly different distances and thus take a different amount of time to reach Earth. The Hubble constant can be determined from these time delays. ▷

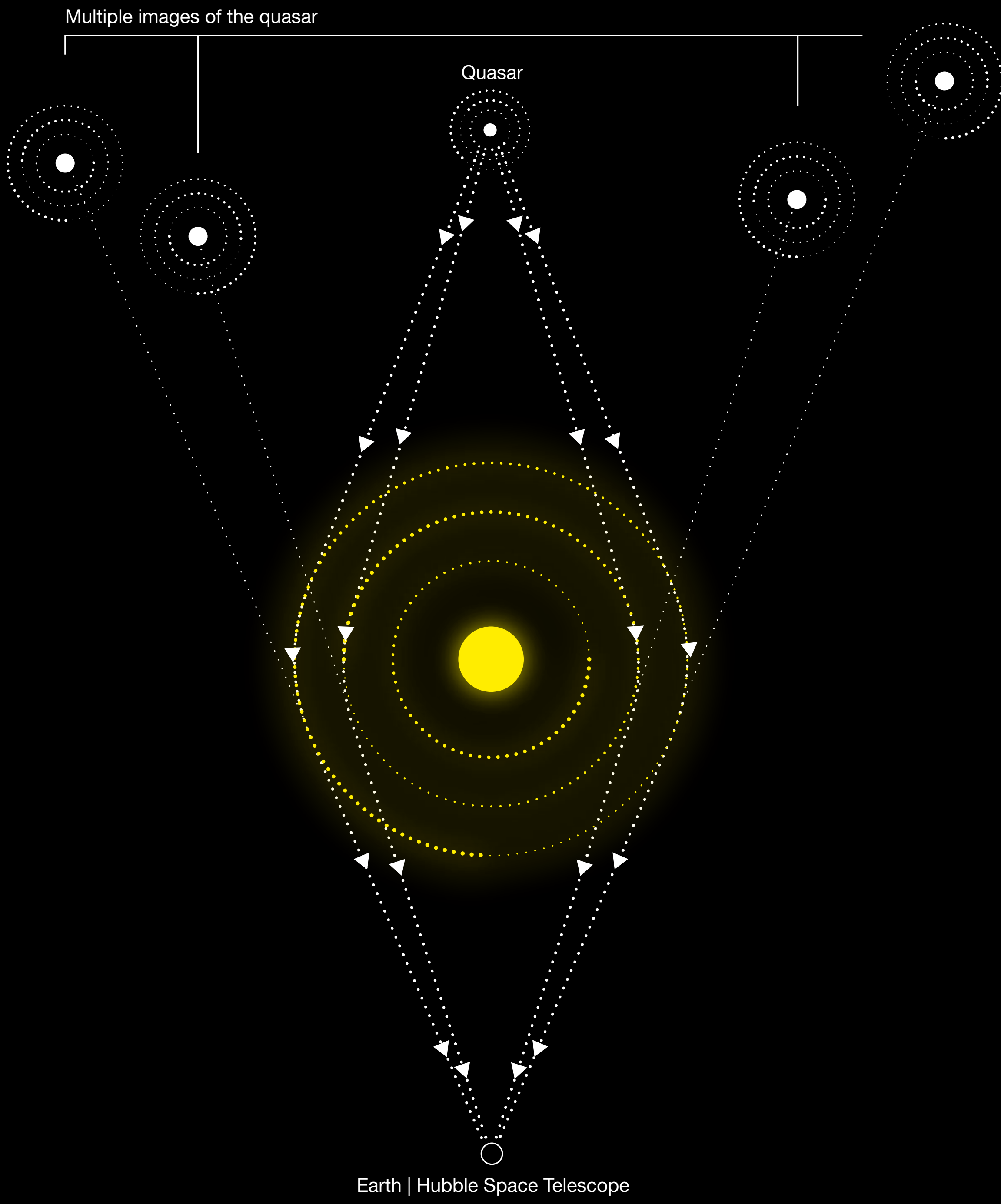
“For decades, people could only speculate about the value of the Hubble constant.”

Sherry Suyu

When Professor Sherry Suyu calls her team into an online meeting, they do not just exchange updates – they also wind up laughing a lot. “We have our fun,” admits the researcher, whose project revels in the name H0LiCOW. Behind this whimsical series of letters and numbers lies not only a fairly technical project name but also one of the most spectacular findings in astrophysics research of the past few years. If this was not widely known before Suyu – who leads the project – was named as a recipient of the American Astronomical Society’s Berkeley Prize, which she will soon be collecting, then it will be now. Suyu is Professor of Observational Cosmology at TUM and leads a research group at the Max Planck Institute for Astrophysics.

The fact that the researcher’s team is meeting online is not just down to the coronavirus pandemic. Apart from Suyu’s Munich-based colleagues, the group is spread so far across the globe that the team has only one face-to-face meeting a year – which this year had to be canceled for the first time ever. However, this bitter pill has been sweetened somewhat by the success of their work. The people in Suyu’s team do not shy away from vast distances – after all, this is what their research is all about.

Specifically, they are studying how our universe has become what it is today, and how it will develop in the future. One key measurement in this research field is the Hubble constant, which states how quickly the universe is expanding. Its precise value has far-reaching consequences that stretch beyond the boundaries of astrophysics and deep into the foundations of physics itself, because processes on an astronomical scale cannot yet be explained satisfactorily using current physical theories. Over the past few years in particular, it has become increasingly clear that there appears to be a startling gap in our understanding of how the universe is expanding. ▷



Graphics: ediundsepp (source: Suyu et al.)

Hubble observations of different quasars and foreground galaxies. The gravitational fields of the galaxies act as gravitational lenses and create multiple images (bright dots) of the quasars. These and other quasars were studied by the H0LiCOW collaboration to make an independent measurement of the Hubble constant.

How quickly is the universe expanding?
"For decades, people could only speculate about the value of the Hubble constant," Sherry Suyu explains. "In the 80s and 90s, some thought it was around 50, others about 100." Bringing an end to this debate was one of the motivations for constructing the Hubble Space Telescope, the first optical telescope capable of capturing images of galaxies and stars directly in space, without any atmospheric distortion. It enabled precise measurements of distances to faraway objects, something that was intended to help calculate the Hubble constant accurately for the first time. "The result was published in 2001," Suyu says. "Prof. Wendy Freedman and her team determined the Hubble constant to be 72, so roughly in the middle." This put the debate to bed for the time being, she explains. Around ten years later, however, it flared up again. Observations of the cosmic background radiation – a kind of echo from the Big Bang – opened the door to a new way of measuring the Hubble constant, although these measurements indicated a lower value of about 67. At the same time, however, work being done by Nobel laureate Prof. Adam Riess and his team also enabled distances to be measured even more accurately, making it increasingly unlikely that a simple solution to the conundrum would be found. "There was a discrepancy between the two results, and nobody knew where it came from," Suyu explains. The debate was fierce, she reveals, especially since the views of the rival camps had become entrenched. So groups of researchers all over the world set to devising new, independent ways to calculate the Hubble constant – and Sherry Suyu was one of them. She saw how she could use methods from her field of research to potentially resolve the dispute.

Picture credit: ESA/Hubble, NASA, Suyu et al.

Lenses in outer space

Suyu was looking into gravitational lensing, an effect that can be observed around large concentrations of mass in the universe such as galaxies and galaxy clusters. These act like lenses and literally distort the images of objects that lie behind them.

The fact that mass bends space and thus even refracts light has been known for a long time. The effect is not always as strong as around black holes, which literally swallow light. Large but less dense clusters of mass make objects behind them appear distorted or even duplicated in the sky, like mirror images. Gravitational lenses of such strength were first observed in 1979. The light from the various images of the same object can take different spans of time to travel through space and reach us, like waves in the sea that go around an island and cause a boat to rock at a certain point behind it. Suyu was aware of a Swiss collaboration called COSMOGRAIL, which was specifically studying the images of quasars influenced by gravitational lensing. Quasars are extremely luminous objects whose brightness flickers like candlelight. As the light from the various images of a quasar travels for different amounts of time in space, the flickering pattern sometimes appears after a delay of days or weeks – similar to an echo that you hear late as the sound has to travel a certain distance and back. “To be able to measure that with the necessary degree of accuracy, you need several years’ worth of observational data,” Suyu says. “Fortunately, Prof. Frédéric Courbin, Prof. Georges Meylan, and their research group began their observational program – called COSMOGRAIL – back in 2004.” Suyu knew that this effect could be used to measure the Hubble constant, because the universe has been expanding significantly during the light’s several-billion-year journey through space. This expansion exerts a measurable influence on the traveling time of the light in the individual images of the quasar. And the fact that the speed of the expansion is linked to the Hubble constant allows conclusions to be drawn about it. Suyu got in touch and launched H0LiCOW, with the “H0” being the abbreviation for the Hubble constant, the “L” signifying “lens” and the “COW” element standing for “COSMOGRAIL’s Wellspring”.

▷

Prof. Sherry Suyu

Astrophysicist Sherry Suyu is Professor of Observational Cosmology at TUM, where she is employed via the Max Planck@TUM program. Originally from Taiwan, she studied astrophysics in Canada and California and spent time researching in Bonn, Santa Barbara, Stanford, and Taipei before joining TUM in 2016. She leads a research group at the Max Planck Institute for Astrophysics. Prof. Suyu has received numerous awards and will be presented with the American Astronomical Society's Lancelot M. Berkeley Prize for her H0LiCOW project in 2021. In her free time, she enjoys playing badminton competitively and traveling.

"Although both teams, mine and COSMOGRAIL's, had the same objective, we each lacked what the other had," the physicist reveals. Even as a young researcher while studying in California, she used telescope images to measure mass distribution in galaxies. Since then, she has refined her methods further together with her Munich-based colleagues Dr. Stefan Taubenberger and Dr. Akın Yıldırım. This was key, since knowing the exact distribution of mass is crucial to calculating the strength of the lens and thus the time lag in the images. Once all these pieces of the puzzle are in place, the Hubble constant can be calculated.

Observations through the Hubble Space Telescope

That is the theory, anyway. Only one telescope would be good enough, however, to get the ultra-precise images of the lens galaxies that were needed. Sherry Suyu applied to use the Hubble Space Telescope. "It's very hard to get observation time on it," she says. But her application was accepted. Suyu got hold of the Hubble manual and began planning her next steps. "When the first pictures from Hubble arrived, it was all very exciting," she recounts. The actual analysis of the images was an extremely laborious process. "This was partly because we were conducting a blind analysis," the researcher explains. "We'd processed the data in such a way that we wouldn't know what result we were going to get until the very end." They did this to avoid any preconceptions that could potentially bias their result in this sensitive and heated debate. "We agreed to publish our findings either way, regardless of what the outcome was." Revealing the final result was thus a special moment which required all group members to concur that the analysis was complete. This was arranged at a group meeting in Copenhagen, where the whole international team met to share their thoughts. They were struck by their result: the value they had determined for the Hubble constant was a perfect match for the figure calculated by measuring the distance to faraway objects and differed from that derived from background radiation.

But the debate had not been settled for good, Suyu says: attempts continued at uncovering mistakes and inaccuracies in measurement that could explain the discrepancy in the two measurements of the Hubble constant. But the idea that new physical effects, rather than errors, are to blame now seems more plausible than ever. For instance, a new form of dark energy – that mysterious effect that is further accelerating the expansion of the universe – could have existed in the early days of the universe. That would explain the differences in the measurements and thus pave the way for research into completely new physics.

Holy smokes!

In other words, the project was a major success. Now in September, in her latest online meetings with her collaborators, Suyu has already been working on getting the next project under way. Although this also involves gravitational lensing, this time she is studying supernova explosions, rather than quasars. The name of the project? HOLISMOKES – an acronym that, besides the terms "lensing", "supernovae", and "investigations", also includes words such as "highly optimised". Once again, both spectacular astrophysics and a dash of humor go hand in hand.

■ *Reinhard Kleindl*

Picture credit: Astrid Eckert/TUM

Unlocking the **Secrets of Long-lasting Success**

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Was lange hält, ist gut

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Das Wissen über historische Klebstoffe ist zu einem Großteil verloren gegangen. Prof. Cordt Zollfrank und sein Team am TUM Campus Straubing holen es wieder ans Tageslicht. Ihr Ziel ist es, Klebstoffe zu entwickeln, die in der Herstellung und Anwendung umweltfreundlicher sind als die zurzeit am Markt dominierenden Epoxidharze auf Erdölbasis. In einem Projekt hat der Doktorand Johann Lang den wirksamen Klebstoff aus Birkenpech extrahiert. Dieser könnte als sogenannter Tackifier in modernen Heißklebstoffen eingesetzt werden. In seinen Eigenschaften ist er teils besser als bisher am Markt verfügbare Produkte.
In einem zweiten Projekt analysiert die Steinrestauratorin und Doktorandin Sophie Hoepner Klebstoffe, die vor hunderten von Jahren beim Bau von Kathedralen zum Einsatz kamen und seitdem ohne nennenswerte Alterungserscheinungen Wind und Wetter trotzen. Ihr Ziel ist es, eine Rezeptur für solch einen langlebigen Klebstoff auf Basis von Naturstoffen zu entwickeln. □

Most of what we used to know about ancient adhesives has been lost in the mists of time. Cordt Zollfrank and his colleagues at TUM's Straubing campus are shining a light on this long-forgotten knowledge once more. They are combing through old books, analyzing glue samples taken from cathedrals, and devising recipes for non-harmful adhesives made from sustainable raw materials.

Link
bgp.cs.tum.de

Picture credit: Magdalena Jooss, Unsplash/Dallas Reedy

Many materials to make ancient adhesives are harvested in nature, mostly in forests.

1 Rosin clear
2 Gum mastic
3 Sugarcane wax
4 Rosin super-transparent
5 Gum sandarac
6 Bonded tensile specimens from granite
7 Rosin from pinus nigra
8 Dammar gum
9 Carnauba wax
10 Marble powder
11 Bonded tensile specimens from sandstone
12 Brick powder
13 Birch-bark pitch

When Cordt Zollfrank went to visit his close school friend Mario Pfreundner, little did he know that he would be opening a new chapter in his research work that day. Pfreundner is a keen amateur archaeologist and also teaches schoolchildren about the subject, which is very dear to his heart. So his house is strewn with the kind of home-made arrows that hunters used as long ago as the Stone Age. Following the standard method of the time, he had used birch tar that he had mixed himself to stick the stone heads and wooden shafts of his arrows together. As soon as Zollfrank saw this, he was captivated.

Though he had never heard of birch tar, it sounded highly promising. This is because hot-melt adhesives, i.e. those that are solid at room temperature but turn liquid when heated, have become such an integral part of our lives that we cannot imagine doing without them. They are used in all areas of industry, such as packaging and wood processing. Nowadays, glues are primarily made from polyamide, polyurethane, and other copolymers. Although they work quite well as adhesives, they have many drawbacks: They are produced from fossil fuels, generating a lot of CO_2 in the process, and are harmful to health and the environment.

The world's only pitch drop experiment with birch-bark pitch: The original pitch drop experiment, started in 1930 (Prof. Dr. Thomas Parnell, University of Queensland, Australia) as a long-term investigation of the liquid characteristics of pitches. Zollfrank's team started their pitch drop experiment with birch-bark pitch in October 2016.

"[Birch tar] is just as good, or even better, than the products that are currently available on the market."

Cordt Zollfrank

Using birch tar as the hot-melt element

"Birch tar, on the other hand, is a sustainable raw material," says Zollfrank, who is Head of the Department of Biogenic Polymers at TUM's Straubing campus. "And, not only that, there's an abundant supply of it in Europe and Siberia." So he immediately set about reading up on the subject. He read how people used to go into the woods, gather birch bark, and put it on the fire inside a covered pot. How it would start to smolder inside until, finally, a pitch- or tar-like substance would begin to drip out – this was birch tar. "Archaeological research has given us a wonderfully clear picture of how birch tar is made and what it contains, but there's been virtually nothing on the material properties of the substance," Zollfrank explains. This prompted him and his doctoral student Johann Lang to find out for themselves.

They carbonized birch tar under controlled conditions in a laboratory furnace to extract the powerful adhesive. "Pure birch tar stinks like an overflowing ashtray," Zollfrank says. "So you couldn't use it for anything." However, the adhesive substance that they obtained from it is virtually odorless. ▷

Picture credits: Magdalena Jooss

Prof. Cordt Zollfrank

Cordt Zollfrank studied chemistry at TUM before moving to the university's Wood Research Institute, where his studies of wood chemistry led to a doctorate in forest sciences. Between 2000 and 2002, he conducted research into biomimetic material synthesis, initially as a postdoctoral researcher at the Institute of Glass and Ceramics at Friedrich-Alexander-Universität Erlangen-Nürnberg. In 2002, he began his work developing the "Bioengineered Ceramics and Biomaterials" research group. He acquired his postdoctoral teaching qualification (habilitation) in material sciences in 2009 and was appointed Professor for Biogenic Polymers at TUM's Straubing campus on October 1, 2011. As of December 2020 he was appointed to a lighthouse professorship for Biogenic Polymers.

"These kinds of bonds have to endure wind, rain, and snow […] – often for many hundreds of years."

Sophie Hoepner

Granite tensile specimens with different hot-melt adhesive formulations prepared for the determination of tensile strength of butt joints.

Picture credits: Magdalena Jooss

Modern hot-melt adhesives consist of three elements: The first is a polymer, a macromolecule that mainly provides the mechanical strength. Then comes a “tackifier”, which improves the contact between the adhesive and the substrate – makes it “tackier”, in other words. The final piece of the puzzle is a modifier, which can alter the adhesive’s properties such as its viscosity (resistance), melting range, smell, or color. Birch tar can be made into a particularly good tackifier. “It’s just as good, or even better, than the products that are currently available on the market,” Zollfrank says.

Ever since he began his in-depth study of birch tar, he has been unable to get ancient adhesives out of his head. In a second project at his professorship, stone restorer and doctoral student Sophie Hoepner is investigating how stones used to be glued together when churches and cathedrals were built. “These kinds of bonds, particularly those outside, have to endure wind, rain, and snow and withstand continuous freeze-thaw cycles – often for many hundreds of years,” Hoepner says. If you consider that epoxy resins often begin to crumble after just 50 years, the adhesives used back then – 600 years ago! – are far superior to our modern products. ▷

Universal testing machine for the determination of tensile lap-shear strength of bonded assemblies.

1

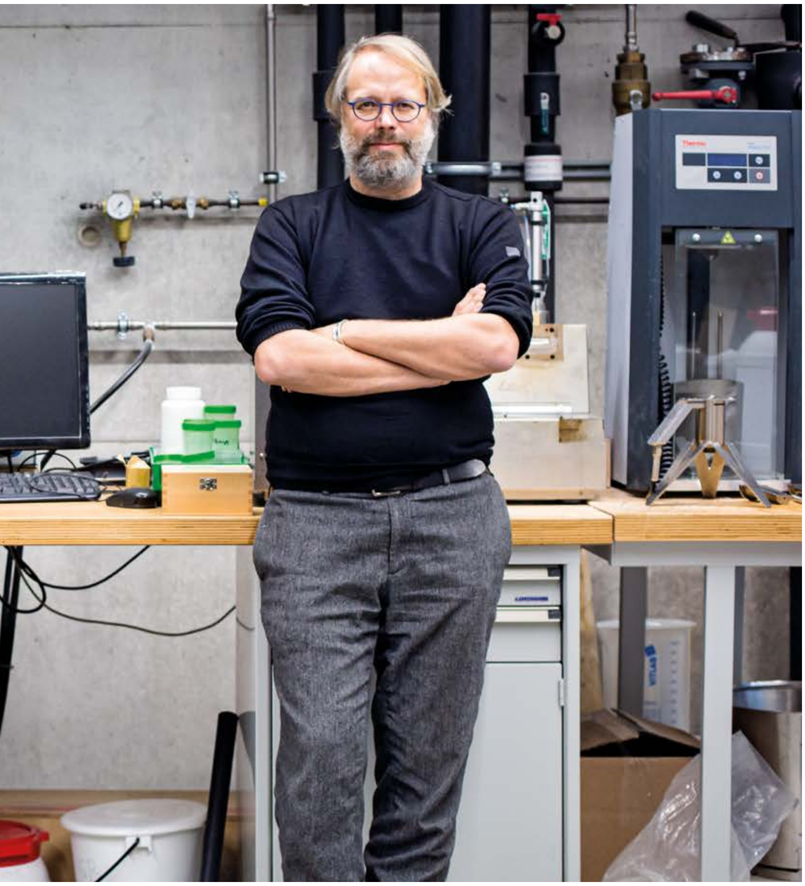
After applying hot-melt adhesive to the heated granite test specimens, glass beads of 400 µm in size are scattered on the bonding surface to achieve a constant reproducible joint thickness.

2

The adhesive-coated bonding surfaces are heated using a heat gun before joining.

3

After joining of the granite test specimens, they are loaded with 2 kg of weight until the hot-melt adhesive has cooled down.



Cordt Zollfrank and his doctoral student Sophie Hoepner share the passion for ancient adhesives.

"I can't bear the fact that this knowledge has been lost."

Cordt Zollfrank about the old adhesive recipes

Picture credits: Magdalena Jooss

Stone glues in cathedrals hold fast for centuries

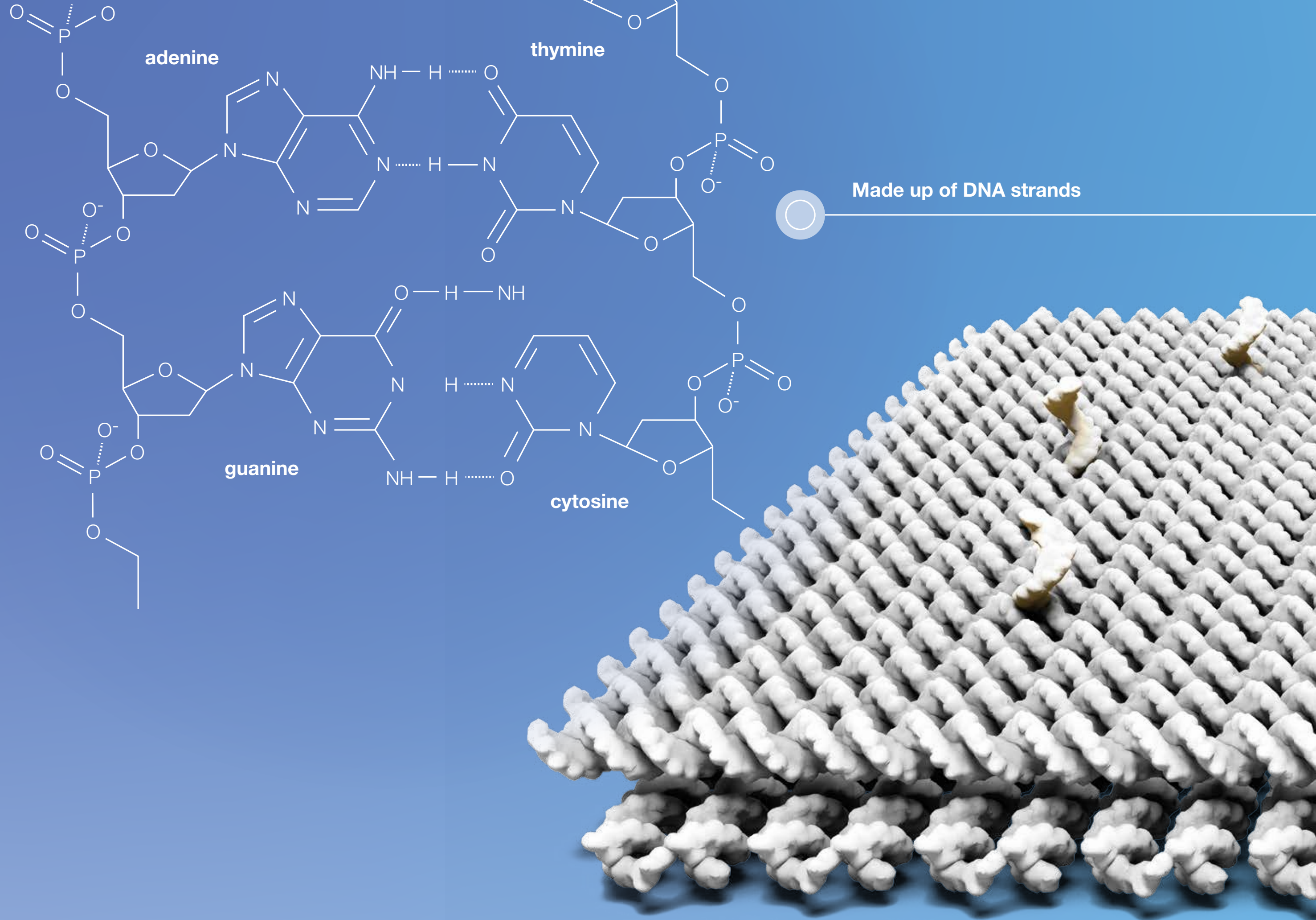
But her research into the literature did not reveal a great deal either. In the past, much was not written down at all, but rather handed down orally from the master craftsman to his apprentice. The few recipes she did find were full of fantastical weights and measures: "two handfuls" of this, a "grain" of that. The verdict: entertaining, but thoroughly useless. "I can't bear the fact that this knowledge has been lost," says Zollfrank.

Sophie Hoepner now has to tackle the matter back to front. Instead of following a recipe, she creates one herself. To do this, she uses her scalpel to remove lentil-sized samples from the glued joints between cathedral stones and analyzes their composition. She is now familiar with the fundamental materials used to make most ancient adhesives. These were based on pure wood tar from spruce or pine trees, which was distilled and mixed with mineral aggregates. Rosin, a substance left over when the pine wood resin is distilled, was also frequently used. Because it is very brittle, beeswax was added to make it elastic – but getting the right amount is crucial. "Too much beeswax makes the glue too soft, while not enough turns it brittle," Hoepner says. Rock flour, a natural byproduct of stoneworking, was also added into the mix to give the adhesive a good level of sturdiness and viscosity and a certain coloration.

An adhesive stronger than many stones

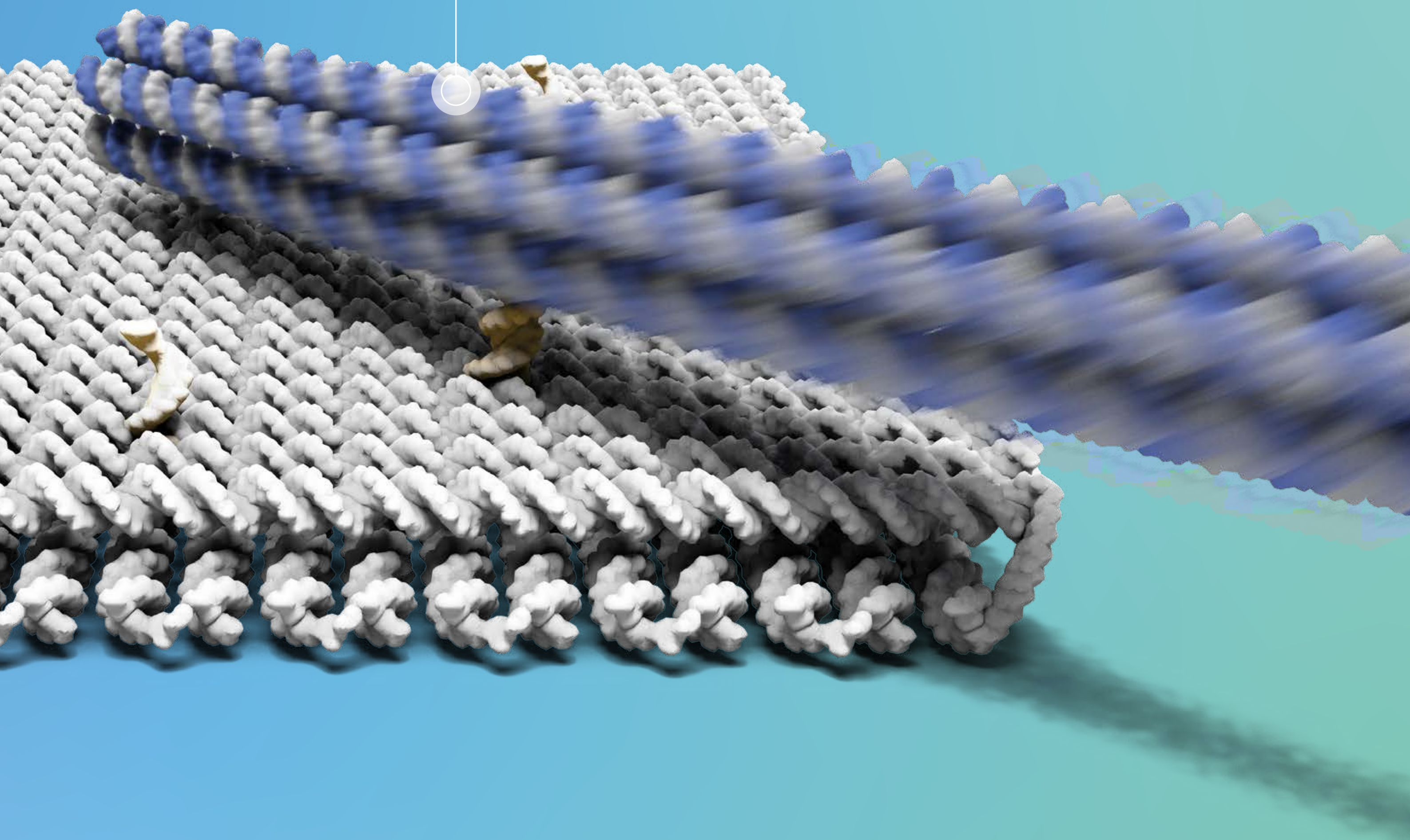
After many rounds of analysis, Hoepner mixes the first few glues of her own, whose properties she then tests in the lab. One particularly important characteristic is tensile-shear strength, which measures the force required to pull apart two bodies glued together in an overlapping arrangement. "In the tests I ran on sandstone, the stones fractured before the adhesive came unstuck," Hoepner reports. To find out exactly how tough her adhesives really were, therefore, she had to test them out on solid granite. By the end of her project, she is hoping to have come up with some detailed recipes for glues that are based on sustainable raw materials and that also last longer than the oil-based epoxy resins currently dominating the market. In the best-case scenario, we will soon see the same tried-and-tested adhesives used to restore the stonework on various historical buildings that have already been keeping one stone firmly on top of another for many hundreds of years. The construction industry will also benefit from an environmentally friendly stone adhesive that is less toxic and harmful.

■ *Claudia Doyle*



The Best of **Both Worlds**

Friedrich Simmel has made it his mission to bridge the gap between the macroscopic world and the nanoworld. His work deals with questions like "How can we utilize the benefits of molecular machines for systems adapted to the dimensions of our own macroscopic world?" and "How do we build interfaces between the two?" Three years ago, his team took a major step towards these goals when they succeeded in using electric fields to control nanostructures. The researchers are now exploring practical uses for this concept.



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Roboter im Nanomaßstab

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Am Lehrstuhl „Physik synthetischer Biosysteme“ der TUM untersuchen Prof. Friedrich Simmel und sein Team die Frage, wie man Robotik auf der Grundlage von Molekülen oder Zellen realisieren kann. Zukunftsvisionen für die Anwendung solcher Systeme gibt es im Robotik- und im Medizinbereich. Man fragt sich beispielsweise, wie man Nanoroboter dazu bringen kann, dass sie Moleküle zusammensetzen, als kleine Messgeräte arbeiten oder Transportvorgänge durchführen. Diese neuen Technologien wären Grundlage für Nanofabriken der Zukunft. Andere Beispiele sind Mikrosysteme, die sich im Körper autonom bewegen und ihre Umgebung erkunden. Sie könnten Krankheiten erkennen oder gezielt Wirkstoffe freisetzen.

Da solche robotischen Nanosysteme sowohl eine gewisse eigene Intelligenz als auch eine Steuerung von außen benötigen, befassen sich die Forscherinnen und Forscher beispielsweise mit einer elektrischen Steuerung, die eine Schnittstelle zwischen Nano- und Makrowelt ermöglicht. Andere Projekte untersuchen, wie man biologische Systeme programmieren kann und wie zellähnliche Objekte autonom reagieren können. □

Graphics: ediundsepp/E. Kopperger (TUM)

Friedrich Simmel, Professor of Physics of Synthetic Biosystems at TUM, describes the approach chosen by his team in 2017 as "a brutal solution", and actually one solely "born of desperation". They used an electric field to make a tiny molecular arm attached to a base unit consisting of DNA swing in a specific direction. Any initial doubts have long since been dispelled – their approach turned out to be a great success. It has now been patented and has given rise to an entirely new branch of nanomachine research – a branch of research in which the Munich team are now world leaders.

Nanorobot visions

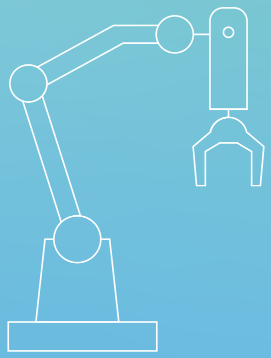
"Essentially, what we're interested in is the question of how to create molecular or cellular robots," explains the physicist. Scientists have been dreaming up applications for such robotic systems for years. Possible uses for nanorobots range from assembling molecules, to operating as tiny measuring instruments, to performing transport processes. These new technologies might one day enable the creation of nanofactories able to perform high-throughput biochemical analysis or manufacture complex drugs. The parts needed for these robots can already be manufactured inexpensively by way of DNA origami – a research field which Hendrik Dietz, a colleague of Simmel's at TUM, has played a major role in shaping. This technique enables researchers to produce large quantities of nano-objects from deoxyribonucleic acid (DNA) – the genetic material shared by all cellular organisms – using what is essentially a programming technique. (see Faszination Forschung no. 21)

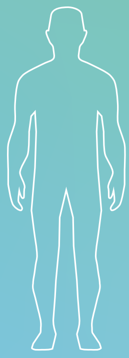
Simmel is himself a pioneer in this field. Some 20 odd years ago, as a young postdoc, he was involved in constructing the very first DNA nanomachines. "Back then, we made use of the fact that single-stranded DNA is flexible, whereas double-stranded DNA is relatively stiff. That meant that we could build mechanical elements representing either flexible connectors or rigid elements," he explains. But how do you get these nanomachines to move in a specific way? "There are a number of established techniques for achieving this. Each sequence of bases along each section of DNA represents a precise 'address'. We can use DNA control strands to target specific addresses and, for example, make one sequence move and another remain still. Alternatively, you can control this kind of process by changing the pH or changing the salt concentration." ▷

"Essentially, what we are interested in is the question of how to create molecular or cellular robots."

Friedrich Simmel

Two purposes for nanorobots





Nanofactories

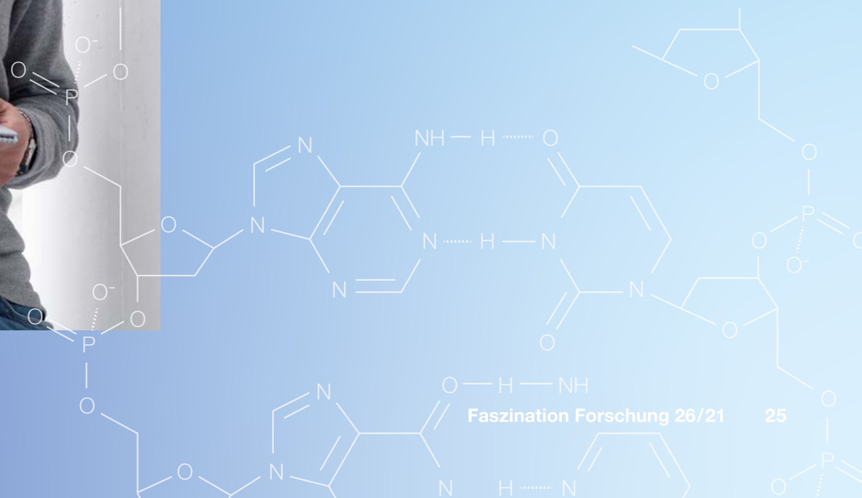
Assembly line-like production of molecules to manufacture complex drugs, for instance

Nanomedicine

Intelligent nanoparticles navigating autonomously around the body, investigating their surroundings, detecting disease or releasing a drug

Prof. Friedrich Simmel

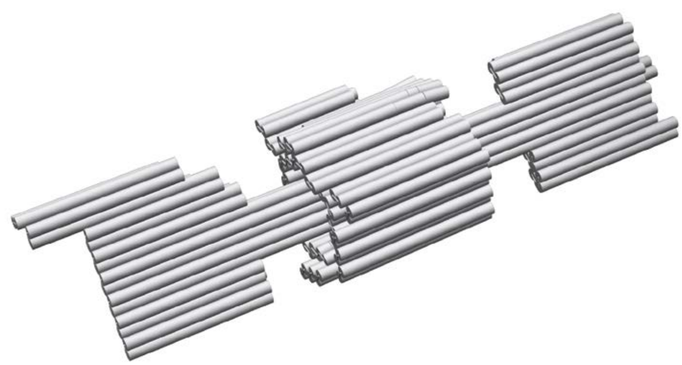
Friedrich Simmel embarked on his career as a solid-state physicist, joining the Center for Nanoscience at LMU Munich at its inception. In 2000, as a young postdoc, he worked on the project which built the first ever DNA nanomachines – long before origami entered the picture. Simmel then moved to Bell Labs in Murray Hill, NJ, USA, where he worked on biophysical systems. In 2002 he returned to LMU Munich, headed an Emmy Noether research group and completed his postdoctoral qualification period. In 2007 he took a professorship at TUM, where he has worked and taught ever since. Until October 2019, he was also co-coordinator of the Cluster of Excellence Nanosystems Initiative Munich.

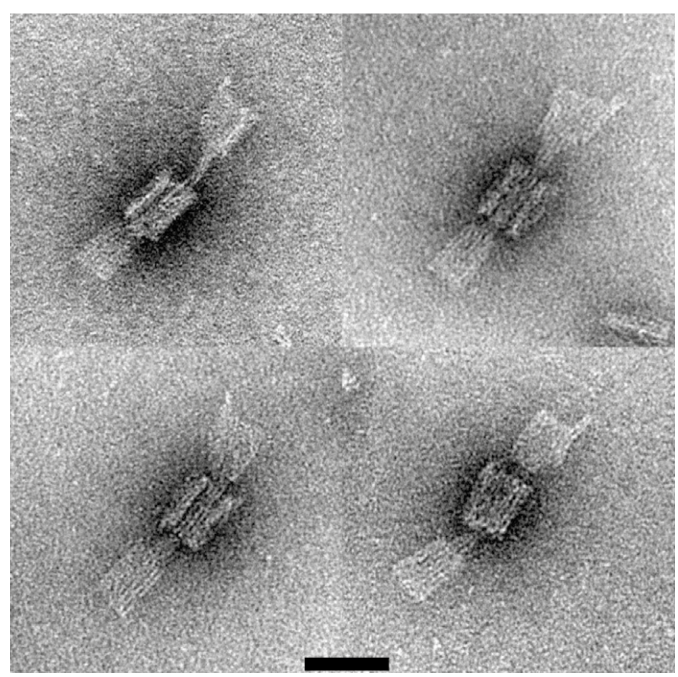


Graphics: ediundsepp (source: TUM); Picture credit: Stefan Woidig

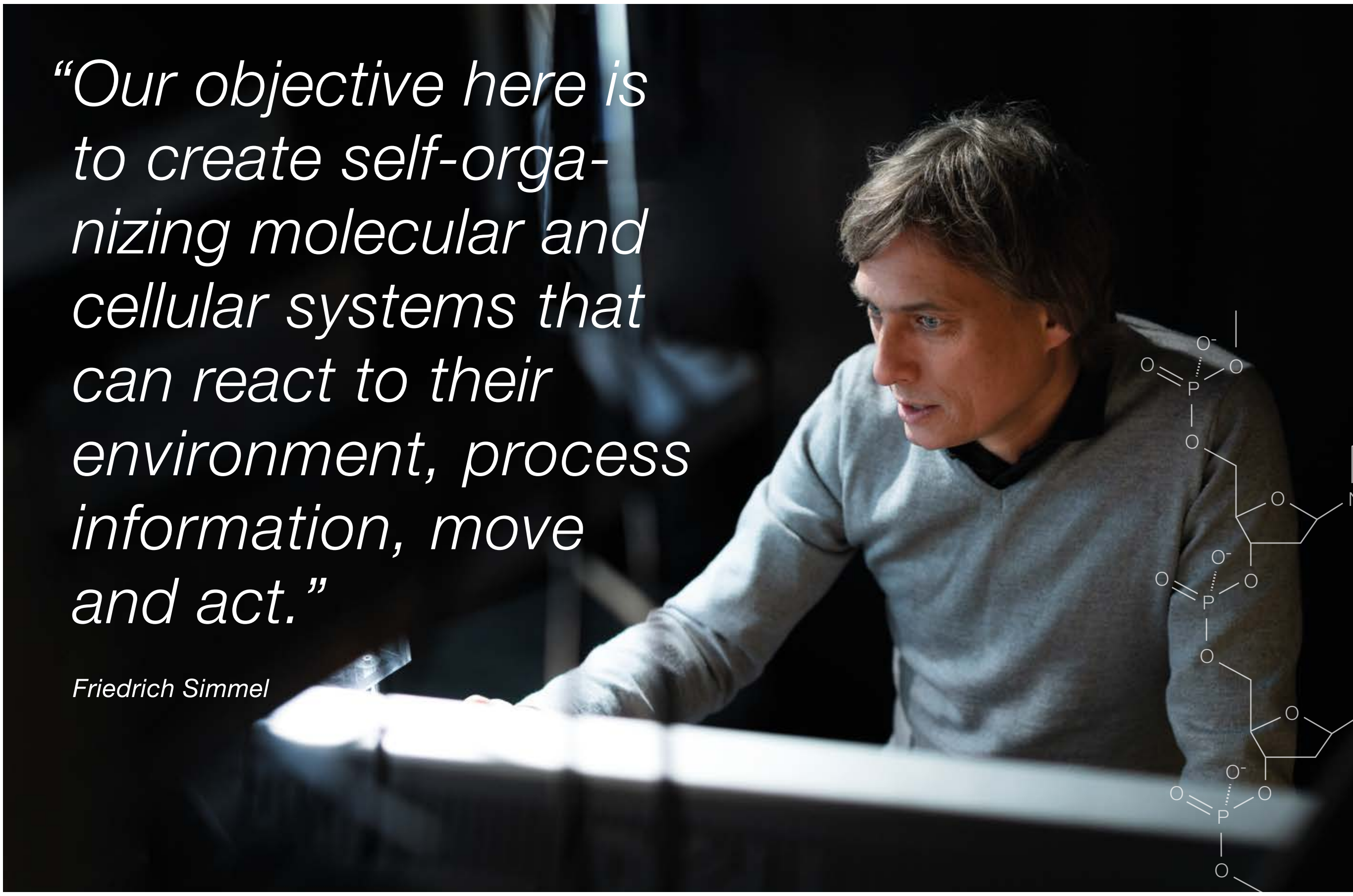
There's a fundamental problem with this type of chemical control, however – in practice it's extremely slow. It takes conventional DNA nanomachines minutes, sometimes even hours to perform these kinds of actions. "Working on these kinds of time scales, it's impossible to imagine ever being able to produce practical applications," laments Simmel. "That's why we decided to try using an electrical control. This offers the advantage of allowing rapid control from outside the system. In principle, it means you can control how a nanomachine moves using a computer." But this technique also has the disadvantage that it doesn't allow you to address specific DNA sequences – it moves all objects in the sample at the same time. "There's always a trade-off between speed and addressability, and this does of course have an effect on the possible applications," explains Simmel.

A research group in his department is now working to refine this approach and identify relevant applications. Dr. Enzo Kopperger, Dr. Martin Langecker and Dr. Jonathan List are now working to set up roboticDNA, a start-up aimed at harnessing this technology to build relatively inexpensive sensors. "We want to make use of the fact that you can attach biomolecules to the movable arm we have developed," says Kopperger. "If we then observe a large number of these devices simultaneously under a fluorescence microscope, we can see that the arm movement pattern changes when you add specific drugs. By analyzing the images automatically, we can even make quantitative measurements of the binding behavior of the individual nanorobots. This means that for each measurement we have a large volume of analyzable and usable data." This would represent one of the first applications for the team's electrical nano-drive technology. ▷

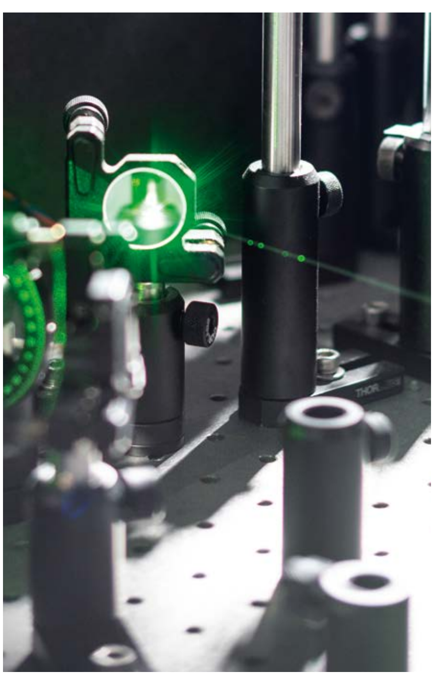


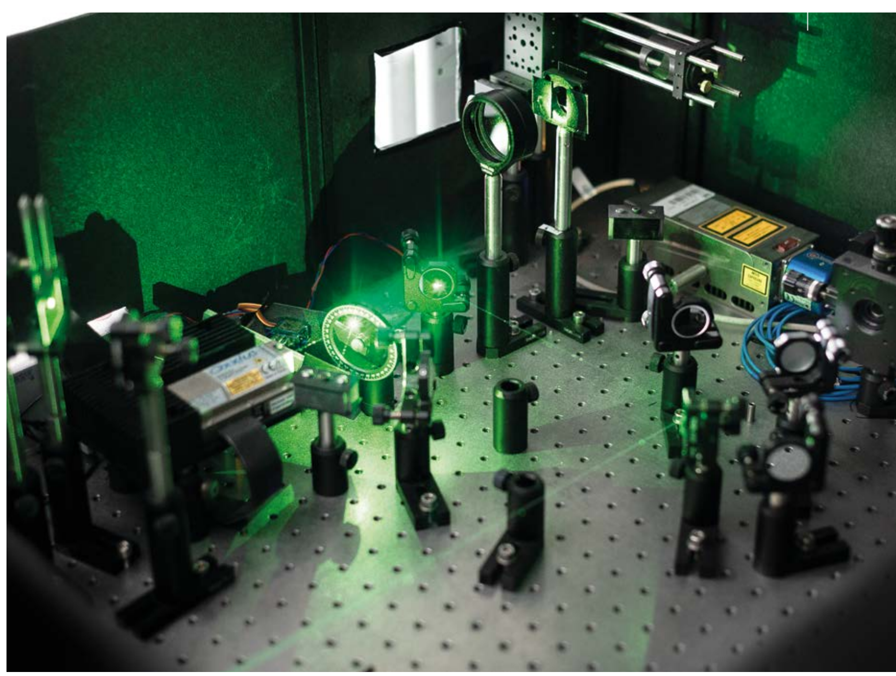


Molecular device produced via DNA origami. The rotaxane consists of an axis and a ring subunit that can glide and rotate on the axis. Top: 3D model; bottom: electron microscopy (TEM) image.



> *“Our objective here is to create self-organizing molecular and cellular systems that can react to their environment, process information, move and act.”*
>
> *Friedrich Simmel*

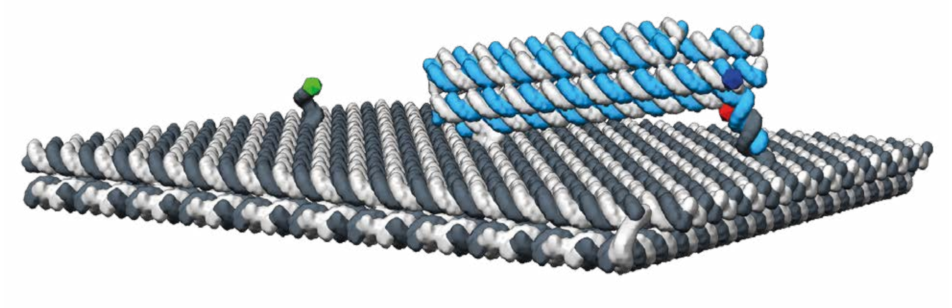




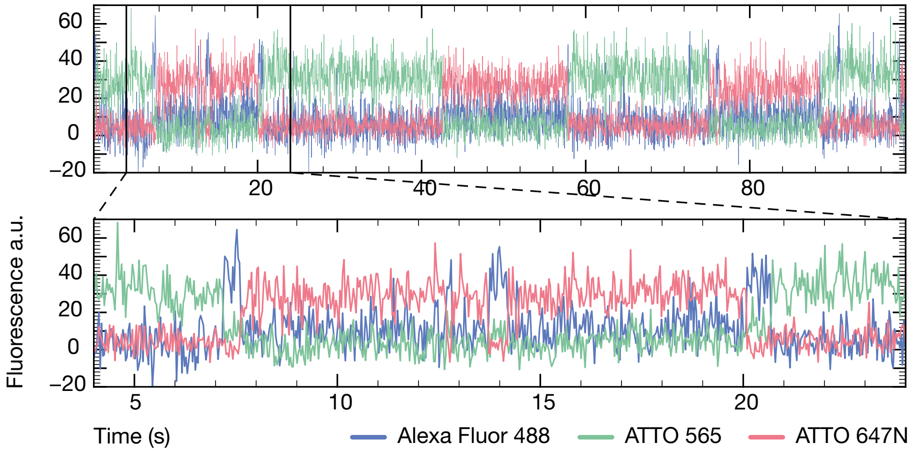
Laser-optical setup for determining the position and movement of DNA nanomachines using super-resolution microscopy and other single-molecule fluorescence methods.

Picture credit left: F. Simmel (TUM); right: Stefan Woidig

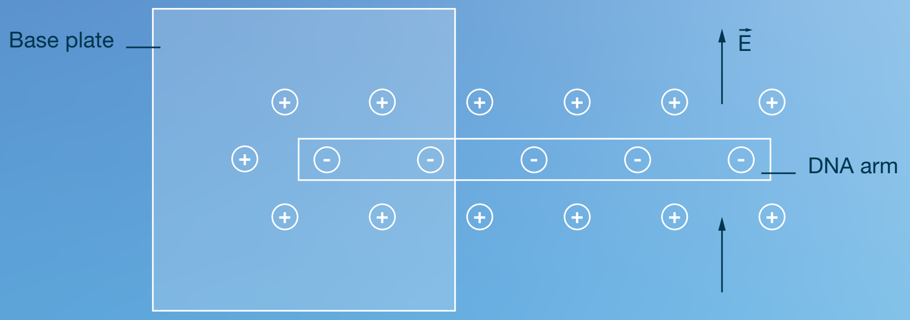
“We need to learn how to do robotics in the realm of Brownian motion.” *Friedrich Simmel*



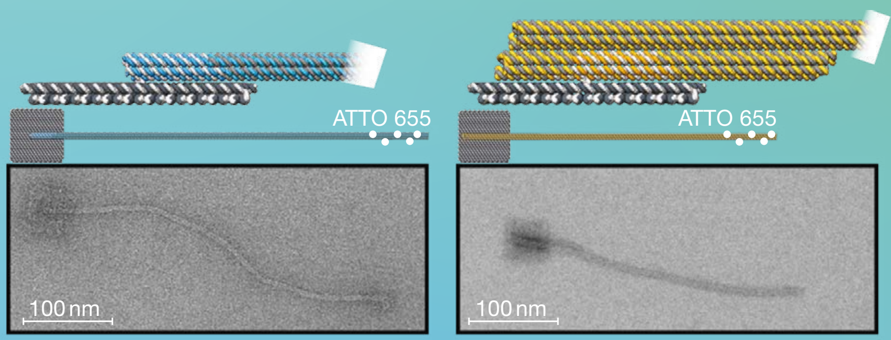
The DNA arm on the base plate can rotate and freely move between two docking sites (green and red). A fluorescent marker is attached to its free end. Like any molecular structure, the arm is always moving, just from thermal motion alone.



The fluorescence trace shows that thermal motion alone causes the arm to move back and forth between the two docking sites (green and red).

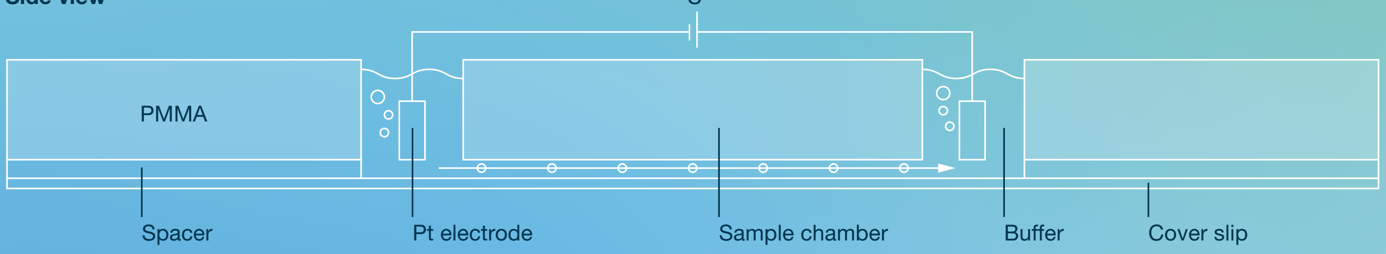


The researchers use an electric field to move the charged nanoarm in a specific direction.

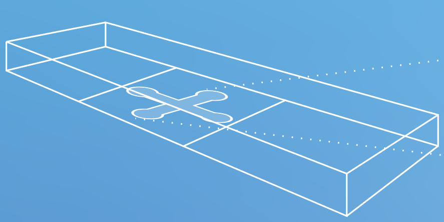


Two different nanoarms and the corresponding electron microscope images. Four electrodes connected to the sample chamber allow the researchers to controllably move the arm in a certain direction.

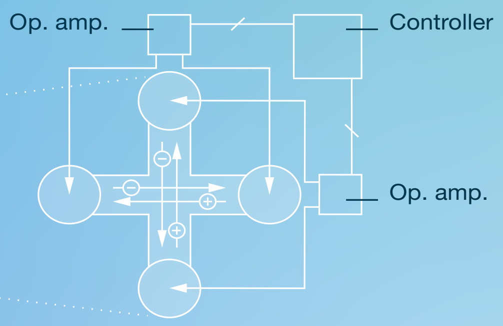
Side view

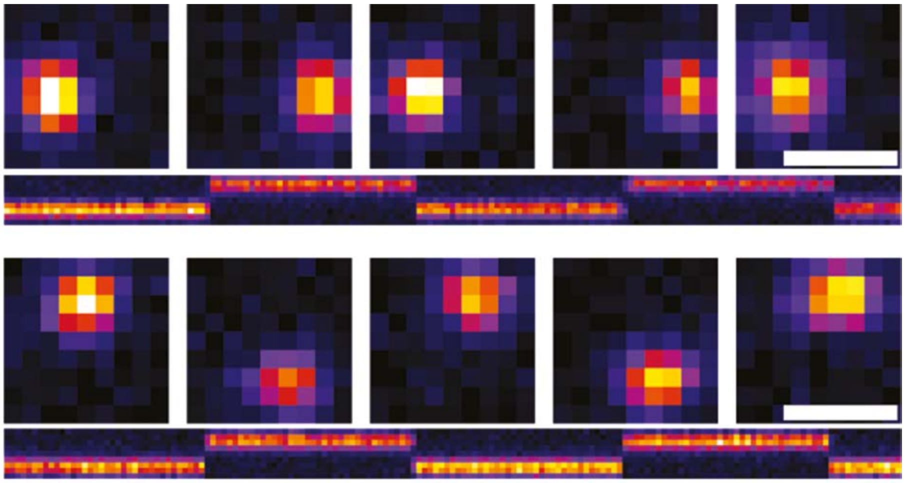


Isometric view

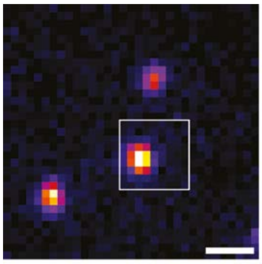


Experimental setup with four electrodes





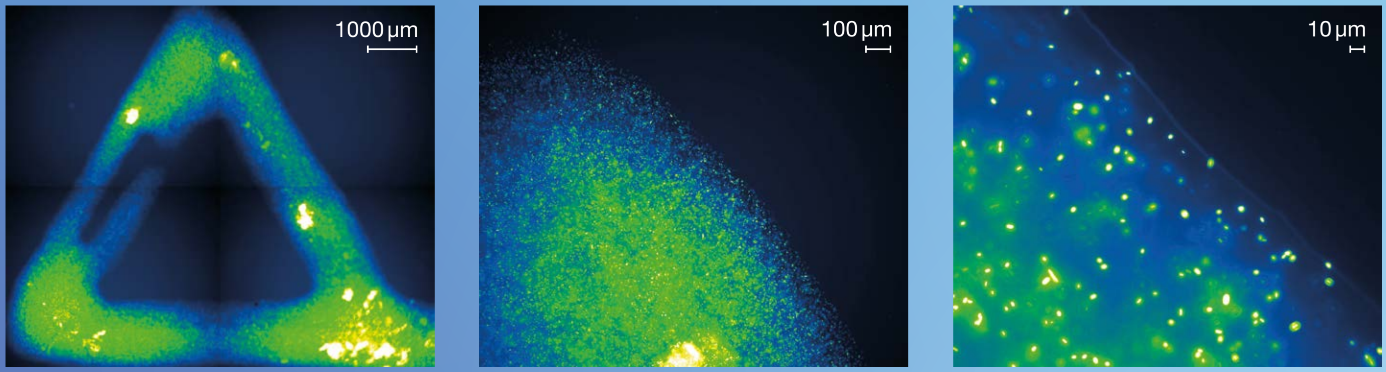
Fluorescence microscopy images of three structures that are switched in the electric field. Movements for the highlighted particle are shown left. Top row: switching the electric field left and right. Bottom row: switching up and down.



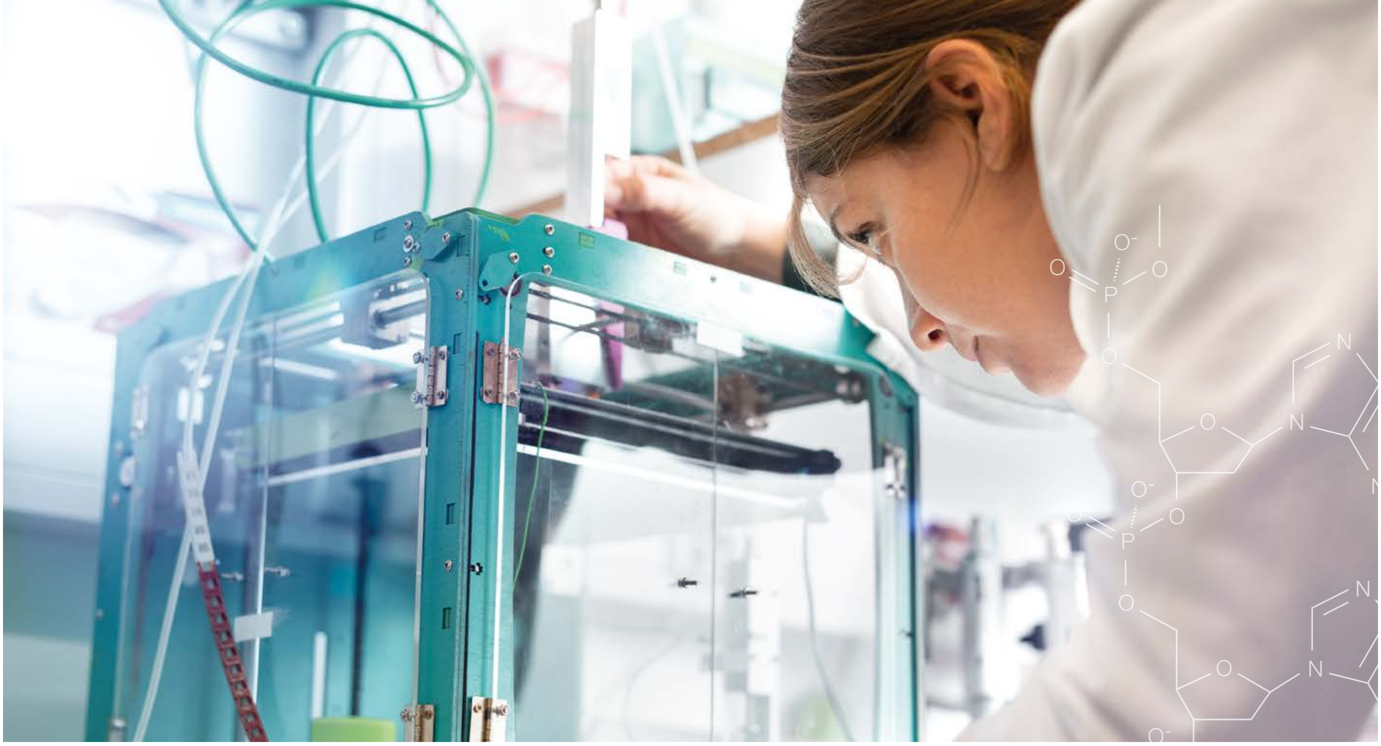
Graphics: ediundsepp (source: TUM); Picture credit: F. Simmel (TUM); left middle: F. Simmel (TUM), D. Lamb (LMU)

Julia Müller (right) employs a 3D printer to produce tiny, DNA-programmable gel droplets. A hydraulic syringe, which is controlled by the printer, dispenses the tiny samples.

The DNA bioink consists of three components: gelatin as the main component providing structural stability, alginate as a viscosity enhancer, and super low melt agarose as the DNA-functionalizable component.



Tiny gel droplets containing living bacteria are printed in a predefined structure. The encapsulated bacteria produce fluorescent proteins and make the triangular structure become visible over time.



Nanoscale robots

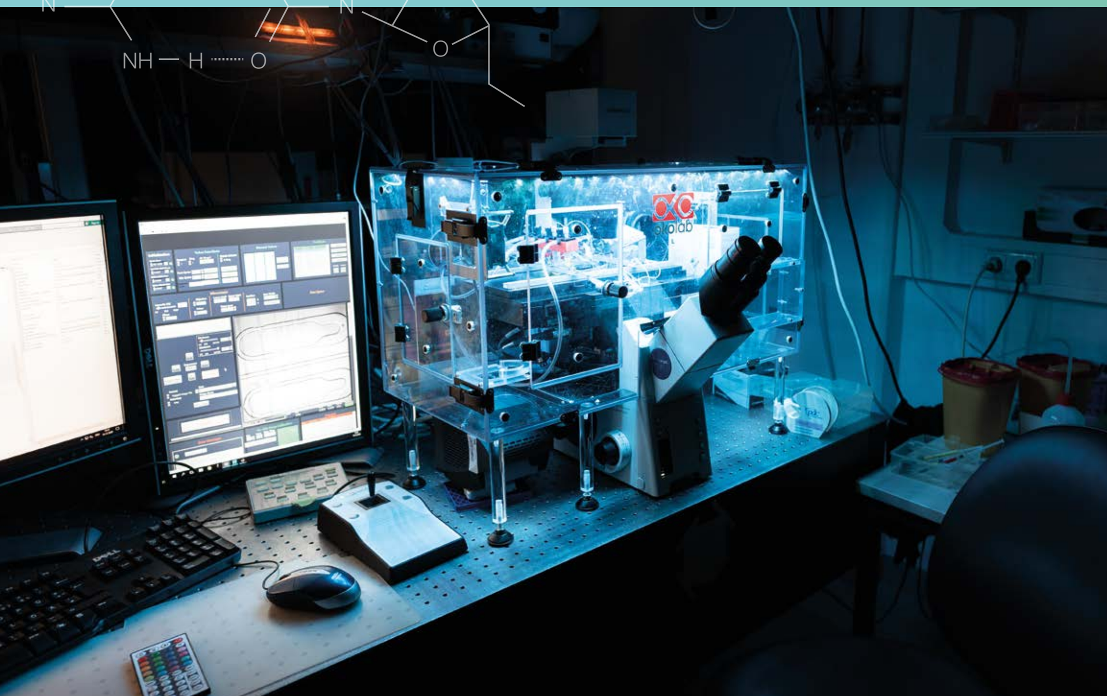
But the research being carried out by researchers in Simmel's group – who come from a range of academic backgrounds spanning physics, chemistry, biology and even electrical engineering – is in general more fundamental in nature. They might be studying how we can make tiny structures function as robots, for example. Their electrically controlled arm is a first step in this direction. "Even a classical robotics specialist would call what we have created here a robot," opines Prof. Simmel. "For our robotics specialist working on a macroscopic scale, connecting rigid elements using joints and controlling this using electrics would be entirely natural. From a robotics perspective, however, a single movable DNA arm is just an actuator. It only becomes something like a robot once it's linked up with some electrodes and a control computer. It's my hope that we will one day be able to build macroscopic robots that also contain biomolecular nano-elements."

The interfaces required for this are now under development. They might be electric, but could also operate with light or magnetic fields. Simmel takes great pleasure in aesthetic phenomena in physics and biology, and he is always on the lookout for elegant solutions. As a former solid-state physicist, in the course of his transformation into an interdisciplinary biophysicist he learned that physics and biology have quite different cultures. "Physicists are sometimes quite playful, and will do something just because they find an effect interesting or beautiful. This might give rise to a unique structure, an unusual model, something like that. In biology, by contrast, there's more of a tendency to ask, 'What's the biological question we're trying to answer?' or 'How is this biomedically relevant?' This more playful approach is probably less common among biologists than among physicists and chemists." Simmel still takes this approach, however, and applies it to the field of biomolecular computing, a field concerned with the issue of how we can use and program biological structures and processes to perform computations. In 2016 he received the Rozenberg Tulip Award in DNA Computing.

Julia Müller is another of Friedrich Simmel's co-workers. To help with such experiments, her team recently developed a method for employing a 3D printer to produce tiny gel droplets with precisely defined properties. The gel consists of a bioink containing, among other things, strands of DNA. These can be programmed and made to form patterns.

For Simmel, what makes the bionanotechnology field really interesting is that it is concerned with producing entirely novel objects. He finds this far preferable to investigating a biological process in painstaking detail. "For traditional biological scientists, DNA nanomachines might come across as pointless gimmicks." Despite this, in January 2018 the highly respected journal "Science" featured an article on electrical control of a nanorobot as its cover story. ▷

Graphics: ediundsepp (source: TUM); Picture credit left: J. Müller; right: Stefan Woidig



Fluorescence microscope with a microfluidic setup for investigating synthetic biochemical "circuits".

> *"In the long term, we envision autonomous systems which can also evolve."*
>
> *Friedrich Simmel*

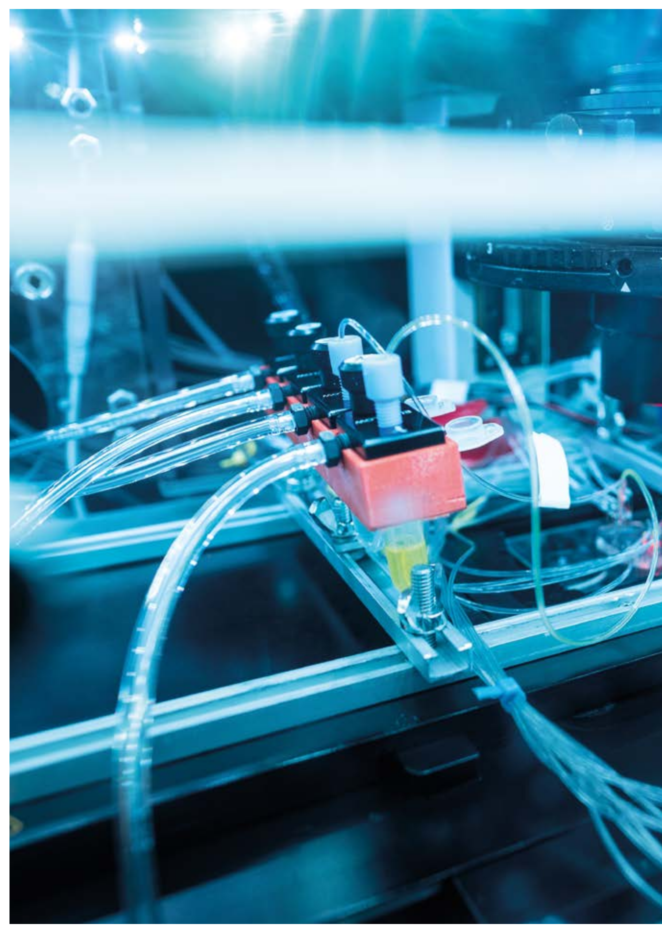
Intelligent nanoparticles

Another important pillar in Friedrich Simmel's group is synthetic biology. Although much of their work might sound like science fiction, they are in fact performing real experiments. One potential medical objective might be to develop an autonomous system able to carry out specific tasks such as navigating around the body, investigating its surroundings, detecting disease or releasing a drug. "The best option for achieving this is probably multifunctional nano or microparticles, or chemically propelled cell-like objects," reckons Simmel. "Our objective here is to create self-organizing molecular and cellular systems that can react to their environment, process information, move and act. Longer term, we envision autonomous systems which can also evolve."

In addition to cell-based synthetic biology, the last few years have also seen the rise of cell-free synthetic biology. This involves cell extracts which play host to genetic processes. "Cell-free synthetic biology involves systems that are much more complicated than DNA nanotechnology systems. They are not living systems, however, which makes them easier to engineer." Kilian Vogele, a student of Simmel's, is currently working on a new start-up project called Invitris. Invitris aims to use cell extracts to produce bacteriophages for use in phage therapy, an alternative approach to tackling antibiotic-resistant bacteria.

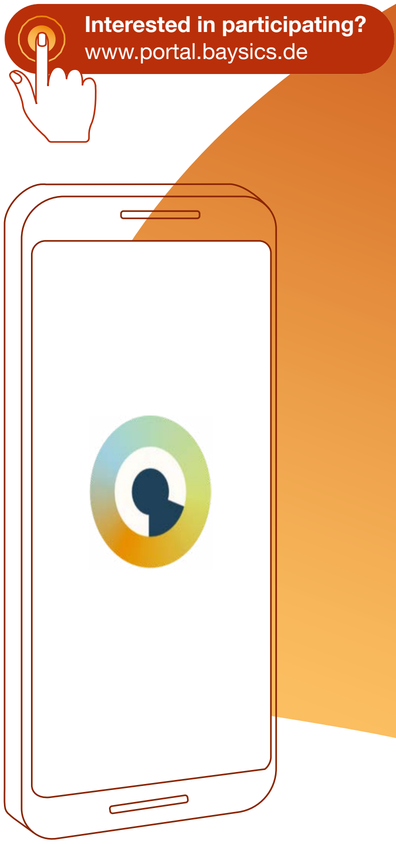
Friedrich Simmel and his team are certainly not short of ideas for new projects. Sometimes he takes his inspiration from biology, sometimes ideas just appear, for example when a lab experiment works out much better than originally expected. "Some projects develop entirely by chance," he says. "Sometimes you have something that has got completely bogged down and then you go away and think about whether you might not be able to take a great leap, whether you can do something in a completely new way. Then there are also – albeit rarely – moments of pure inspiration."

Brigitte Röthlein



The tubings (front) are used to supply cell-free reactions in a microfluidic chamber (background right) with nutrients and chemical signals.

Graphics: ediundsepp; Picture credit: Stefan Woidig



Climate Change in Your Backyard

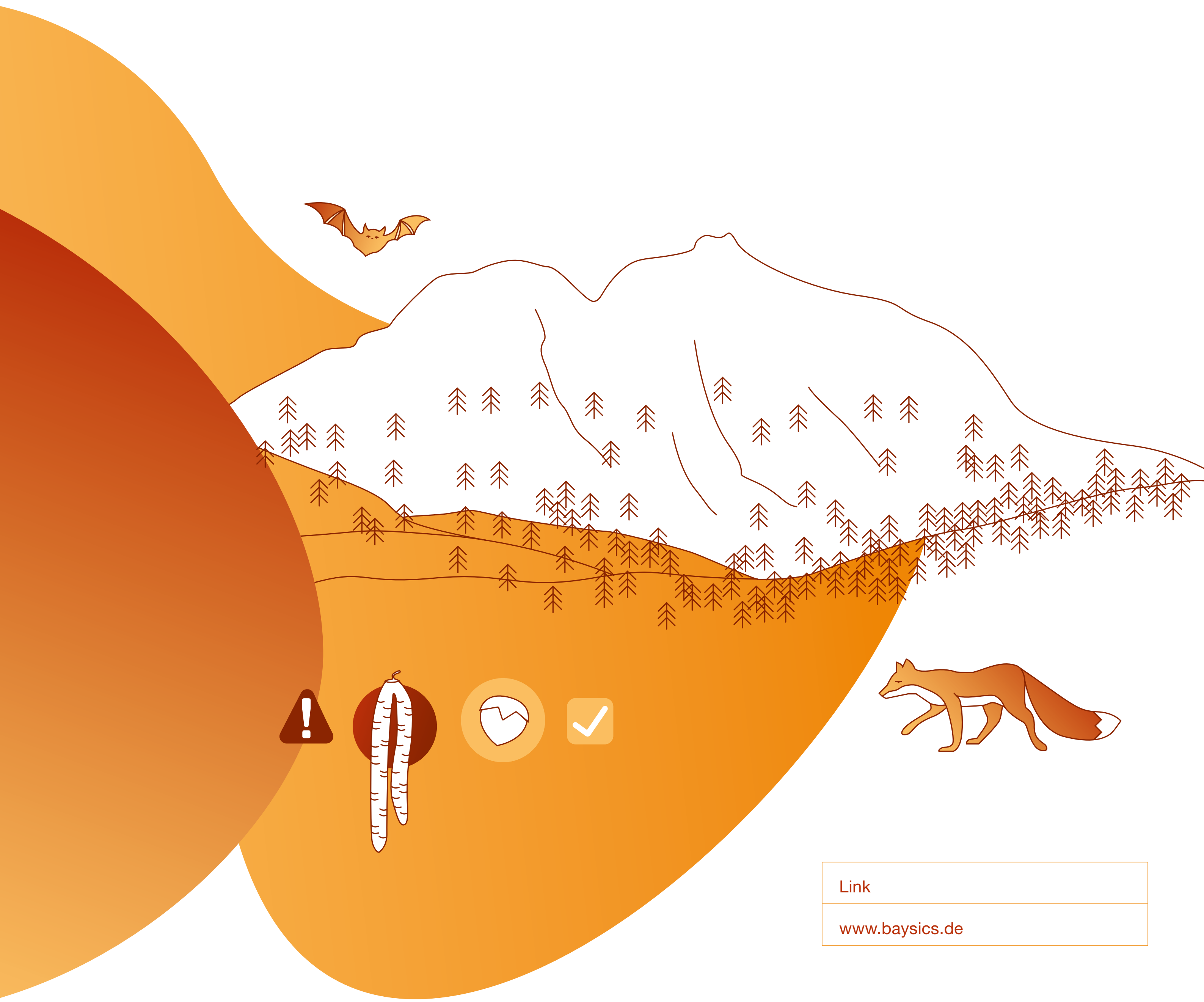
Interview with Annette Menzel about her expectations on the citizen science project.

Early Flowering Signals Global Warming

Prof. Annette Menzel
Chair of Ecoclimatology
TUM

Climate Change Impacting Mountain Forests

Prof. Jörg Ewald
Specialist Area of Botany, Vegetation Science and Mountain Ecosystems
Weihenstephan-Triesdorf University of Applied Sciences



Link

www.baysics.de

How to Avoid Hay Fever

Prof. Susanne Jochner-Oette
Physical Geography/Landscape Ecology and Sustainable Ecosystem Development
Catholic University of Eichstätt-Ingolstadt

Urban Animals

Prof. Wolfgang Weisser
Terrestrial Ecology Research Group
TUM

Graphics: ediundsepp

Climate Change **in Your Backyard**

We are all affected by global warming. Its impacts are already tangible and will require wide-ranging adaptions from humans and nature in future. Annette Menzel conducts research into these complex changes with the aim of finding a practical means of handling them – together with the citizens of Bavaria. An interactive online portal by the name of BAYSICS provides a forum for this dialog.

Kurzfassung · Langfassung: www.tum.de/faszination-forschung-26

Klimawandel vor der Haustür

D

Die Folgen der Erderwärmung sind auch in Bayern spürbar und erfordern weitreichende Änderungen des Lebensstils. Diese lassen sich in demokratischen Gesellschaften nur dann erfolgreich umsetzen, wenn sie von großen Teilen der Bevölkerung als notwendig, akzeptabel und realistisch erkannt werden. Unter dem Motto „Wissen vermitteln – Wahrnehmung fördern – Komplexität kommunizieren“ will der interdisziplinäre Forschungsverbund BAYSICS Bürgerinnen und Bürger an der Erforschung des Klimawandels teilhaben lassen. In vier Citizen-Science-Projekten haben Laien die Gelegenheit, natürliche Phänomene zu erkunden und ihre Veränderung infolge der Erderwärmung nachzuvollziehen. Inhaltliche Schwerpunkte liegen auf den klimabedingten Veränderungen des Bergwaldes, des Pollenaufkommens sowie der jahreszeitlichen Erscheinungsformen von Pflanzen und Tieren in der Stadt. Das so generierte Wissen kommt direkt den Mitwirkenden zugute. Zugleich liefert es den im Verbund Forschenden wertvolle Daten für ihre natur- und sozialwissenschaftlichen Studien. □

Picture credits: Juli Eberle; Graphics: ediundsepp

“We’re trying to address large parts of the population and gain acceptance for climate protection measures. Only then will we be able to make a change in society.”

Annette Menzel

Link
www.oekoklimatologie.wzw.tum.de

Professor Menzel, what do you hope to achieve through BAYSICS?
This new portal is part of the Bavarian Climate Research Network. In a nutshell, we want to use the portal to spread knowledge, raise awareness, and communicate complexity. Our aim is to raise awareness of the phenomenon of climate change and its consequences among as many members of society as possible and enable them to engage in research as citizen scientists.

What exactly is citizen science?
In essence, it is when ordinary citizens participate in the scientific process. We call on citizens with an interest in the topic to explore their environment and report their observations. In doing so, they generate data and create added value for science. This not only benefits professional researchers but also the citizen scientists: they have the opportunity to conduct experiments, compare their findings against existing datasets, pose their own research questions, and reflect on what they would like to know and understand. The new BAYSICS portal offers an ideal platform for this. ▷

Citizens can participate in BAYSICS via an app. Here, Annette Menzel demonstrates the app by taking a picture, which can be uploaded.

Prof. Annette Menzel

Always striving to facilitate a dialog between research and society, Annette Menzel combines her research as a forestry scientist with her role as a forest officer. After graduating from LMU Munich, she took the state examination and spent several years at the Bavarian Forestry Commission. In 1997, Menzel obtained her doctorate in the phenology of forest trees under changing climatic conditions. After obtaining her lecturer qualification, she continued to research climate change-biosphere links at the TUM Chair of Ecoclimatology; she became acting head in 2003 and was made an associate professor in 2007. Annette Menzel was lead author of the Intergovernmental Panel on Climate Change (IPCC) assessment report from 2004 to 2008 and received a European Research Council grant in 2012.

How does the BAYSICS portal work?

The centerpiece is an app specifically designed for our citizen science projects. Unlike commercial apps you can download to your phone from the App Store, we opted for a progressive web app – which can be amended or augmented as and when new questions and topics arise in future. Prof. Dieter Kranzlmüller at the Leibniz Supercomputing Centre of the Bavarian Academy of Sciences and Humanities is coordinating the programming and backend in close collaboration with Prof. Liqiu Meng from the TUM Chair of Cartography. Their teams are making sure that the entire infrastructure is easy to use and looks good, too.

Who is involved in BAYSICS?

We are a genuinely interdisciplinary network! There are four citizen science projects with different focuses in the natural sciences, plus three sub-projects in the social sciences. In collaboration with several Bavarian high schools, Prof. Ulrike Ohl from the University of Augsburg has developed an educational concept for "inquiry-based learning" with ideas for pupils and their teachers. Prof. Arne Dittmer from the University of Regensburg is developing concepts that will allow climate change to be addressed adequately at school – including its political and ethical dimensions. Meanwhile, Prof. Henrike Rau from LMU is interested in public opinion, asking: Who do different social groups consider responsible for climate change? How are measures to counter it evaluated and supported?

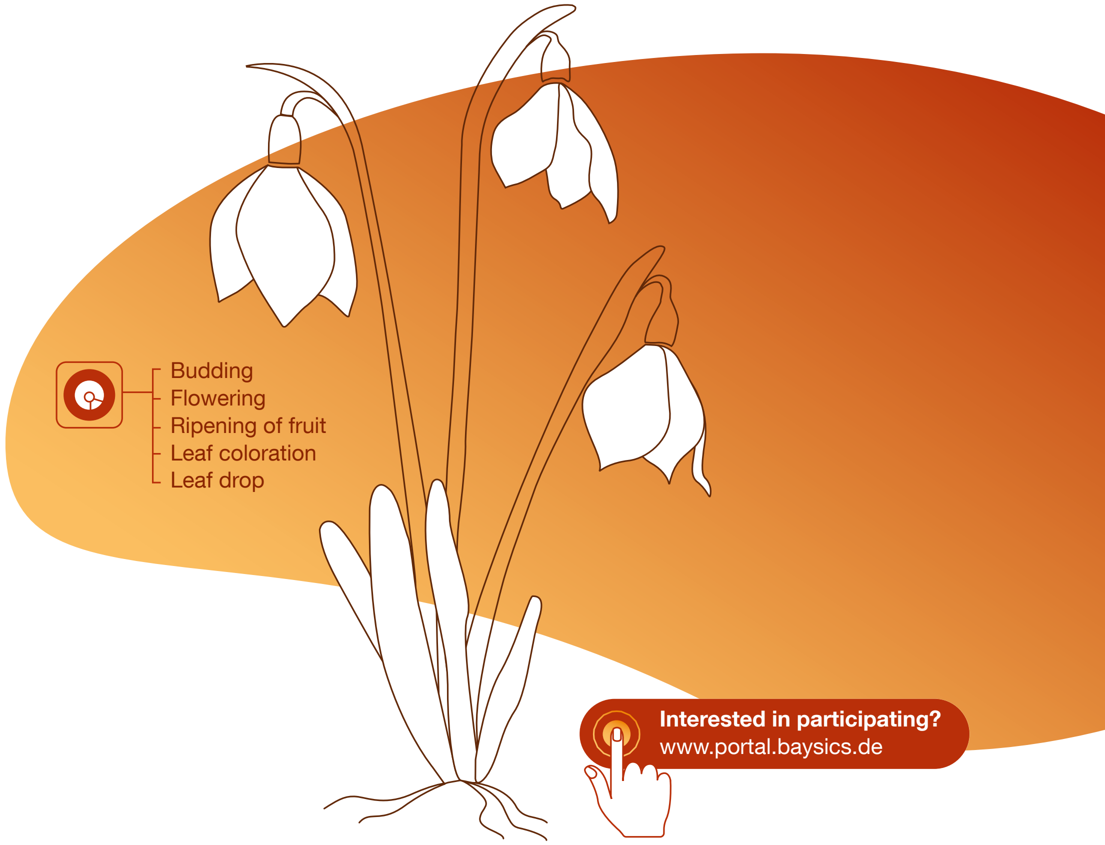
What are you hoping will come from this dialog with the citizens of Bavaria?

We want to motivate people to engage with the topic of climate change. They need to understand just how serious it is – and that our way of life must change on a fundamental level. We're trying to address large parts of the population and gain acceptance for climate protection measures. Only then will we be able to make a change in society.

■ *Monika Offenberger*

Picture credits: Juli Eberle; Graphics: ediundsepp

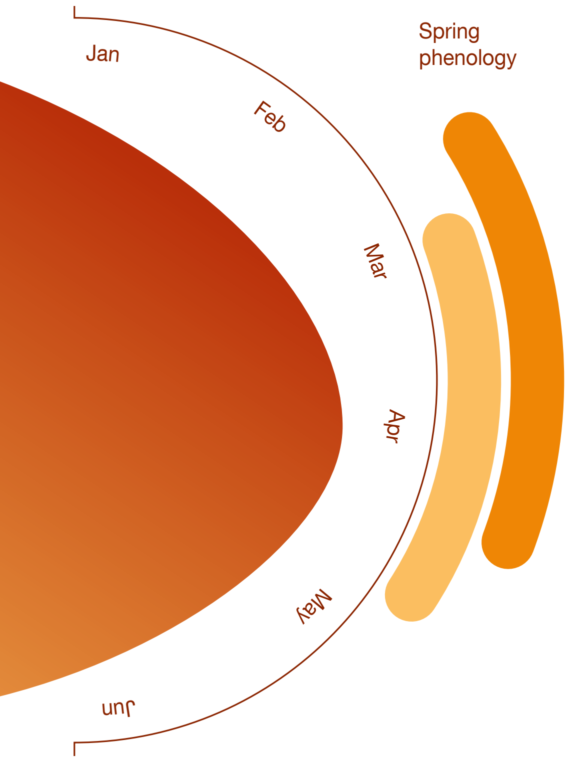
A rooftop meteorological station, high above the TUM School of Life Sciences Campus, is used for measurements and for testing measurement equipment before field use.

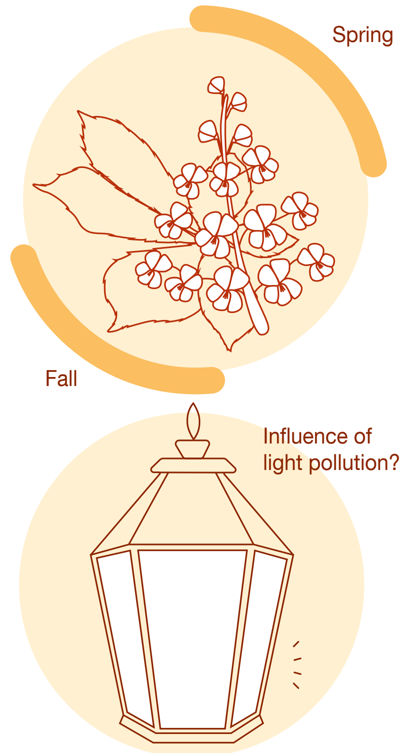


Early Flowering Signals **Global Warming**

An emaciated polar bear stranded on an ice floe in the open ocean. Images like this are often used to illustrate the dramatic consequences of global warming. When they report on climate change, media outlets tend to reach for powerful images. “But this runs the risk that many people might think it is something that doesn’t really affect them personally. The Arctic is so far removed from everyday life,” as Annette Menzel, Professor of Ecoclimatology at TUM, states. But in fact even at our latitudes, climate change has long altered the seasonal rhythms of our fauna and flora. Birds are nesting earlier. Plants are coming into leaf and flowering earlier than even just a few years ago. Fruit is ripening earlier and trees are shedding their leaves later.

The study of these seasonal events is known as phenology. Changes in the timing of such events can be clearly shown to be related to global warming. Annette Menzel has analyzed data from across Europe, which, between 1971 and 2000, recorded the phenology of 542 plant and 19 animal species. Her analysis shows that a one degree Celsius mean rise in late winter temperatures shifts spring phenology forward by an average of 2.5 to 5 days. Now, Bavarians can become citizen scientists and research these correlations for themselves. “Budding, flowering,





ripening of fruit, autumn leaf coloration and leaf drop are easy to observe and citizen scientists can record these details using the new BAYSICS app, where the observations can be linked to German Meteorological Service data going back to 1951," explains Menzel. There is also a new software package for evaluating winter twig experiments. This allows users to look back into the past, but also to get a glimpse of the future, explains the professor. "We can use statistical models to simulate the effects of rising temperatures on the natural world."

The ability to run simulation experiments like this sets the BAYSICS app apart from commercial software. "People can play with real datasets and try out different climate change scenarios. We aim to make science fun, while still managing to showcase complex interrelationships," explains Menzel. She hopes the app will also benefit her research. Little is known, for example, about why horse chestnuts produce new flowers in autumn, or whether street lights affect autumn leaf coloration. Similarly, it's not clear whether fruit tree blossoms are being destroyed by late frosts more often than in the past. "If enough people join in, we will be able to collect data for the first time on a wide range of poorly researched phenomena."

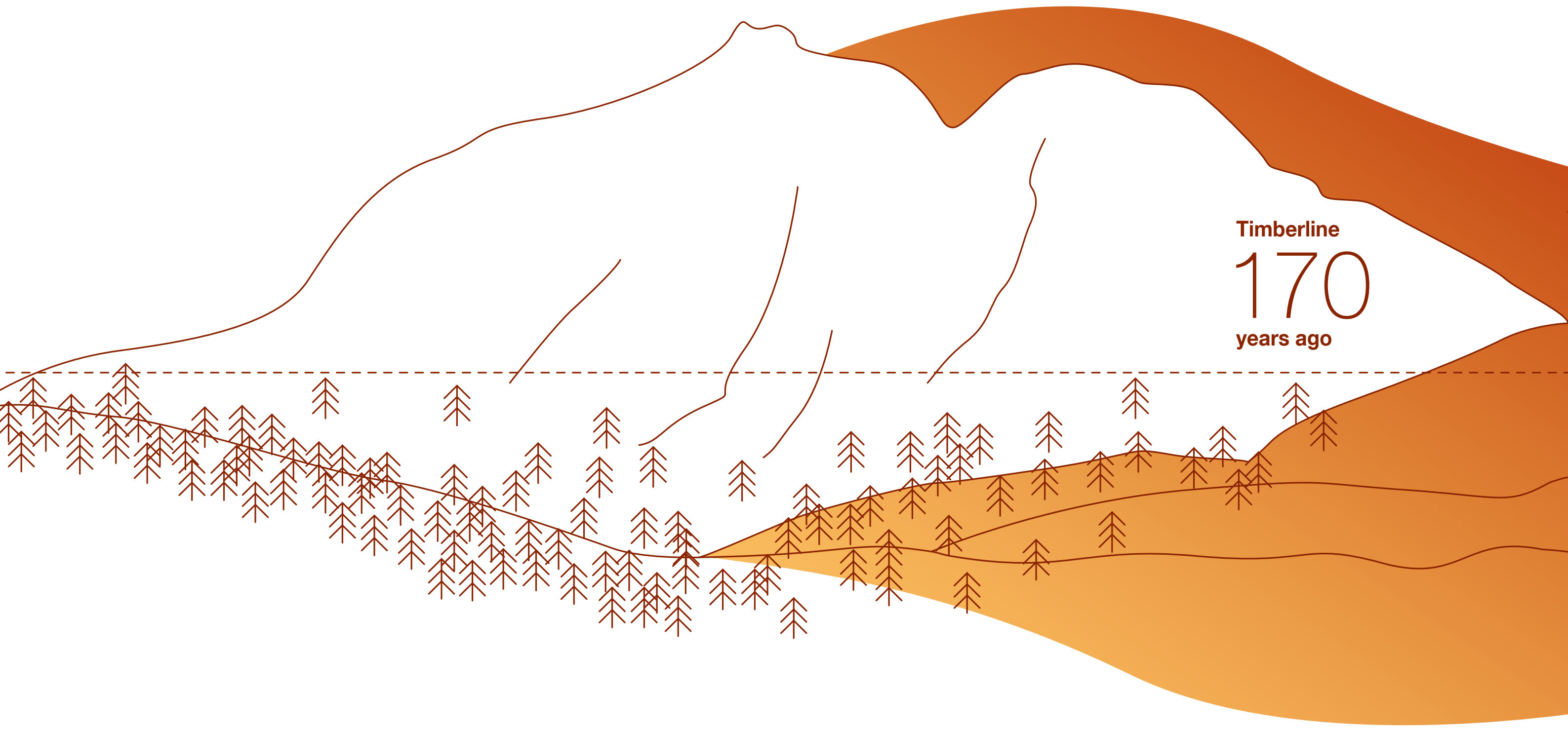
■ *Monika Offenberger*

"If enough people join in, we will be able to collect data for the first time on a wide range of poorly researched phenomena."

Annette Menzel, TUM

Graphics: ediundsepp

Climate Change Impacting **Mountain Forests**

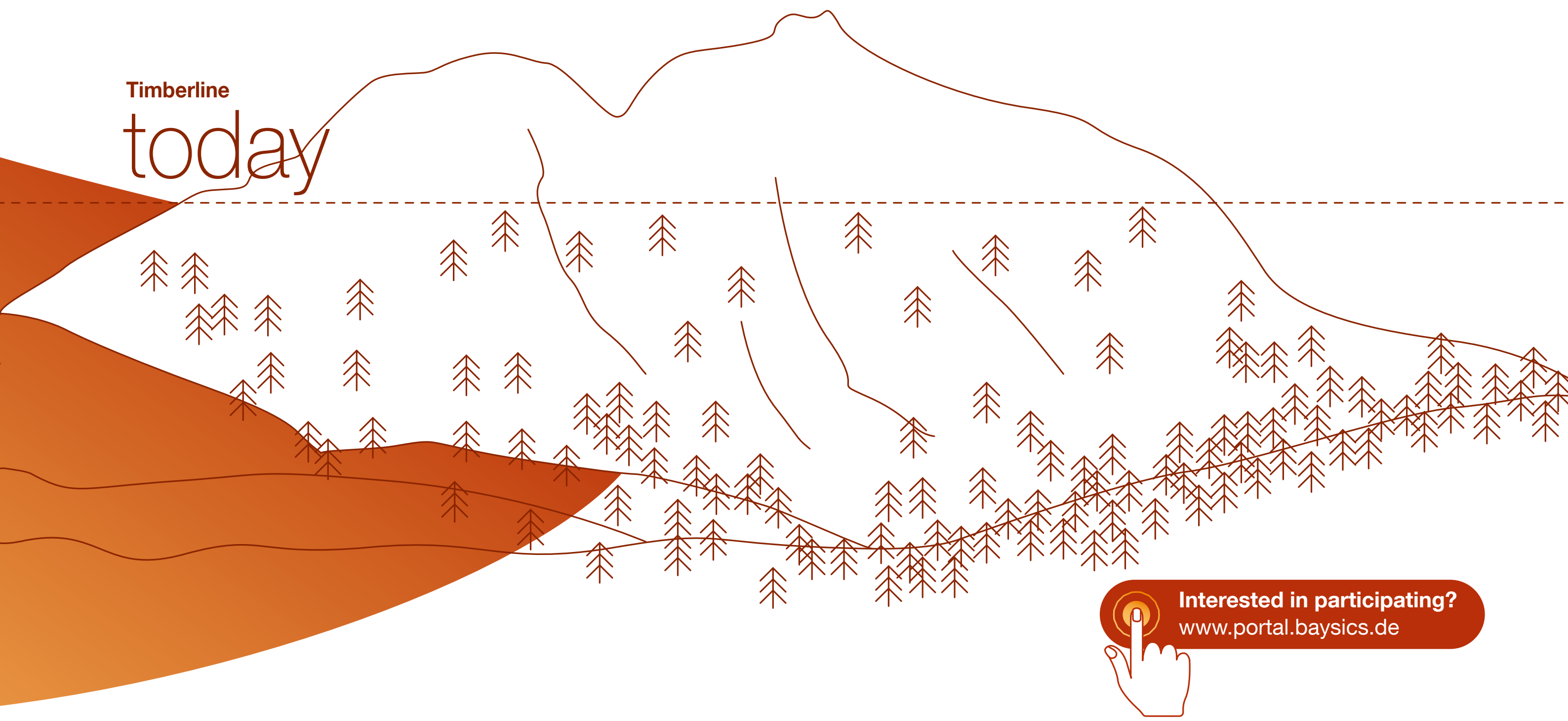


“What we need now is as much current data as we can get hold of.”

Jörg Ewald,
Weihenstephan-Triesdorf University of Applied Sciences

People hiking in the Alps enjoy not only the exercise, but above all the experience of being surrounded by nature. “It’s the transition between forest and rock that makes mountain landscapes so aesthetically pleasing,” says Jörg Ewald, Professor of Forest and Forestry at Weihenstephan-Triesdorf University of Applied Sciences. At which altitude trees and bushes are still able to grow and at which altitude they stop is determined by climatic conditions. With these conditions being transformed by climate change, more and more plant species globally are moving up from lower altitudes towards higher mountain regions.

So are mountain forests in the Bavarian Alps also experiencing this kind of change? Are beech, spruce, mountain pine and arolla pine growing at higher altitudes than before? In the middle of the 19th century, long before climate change, Munich botanist Otto Sendtner was com-



Interested in participating?
www.portal.baysics.de

missioned by King Maximilian II of Bavaria to record the precise altitudes at which our native trees were able to survive. “At that time, the highest arolla pine in the Berchtesgaden Alps stood at an altitude at 2,041 meters and the highest spruce at 1,860 meters. We looked at and digitized a total of 441 of these old records. We use them as reference data for making comparisons with today’s trees. What we need now is as much current data as we can get hold of,” explains Jörg Ewald. That’s how Ewald, a passionate mountaineer, came up with the idea for a citizen science project aimed at measuring the altitudinal boundaries for a total of 22 tree species.

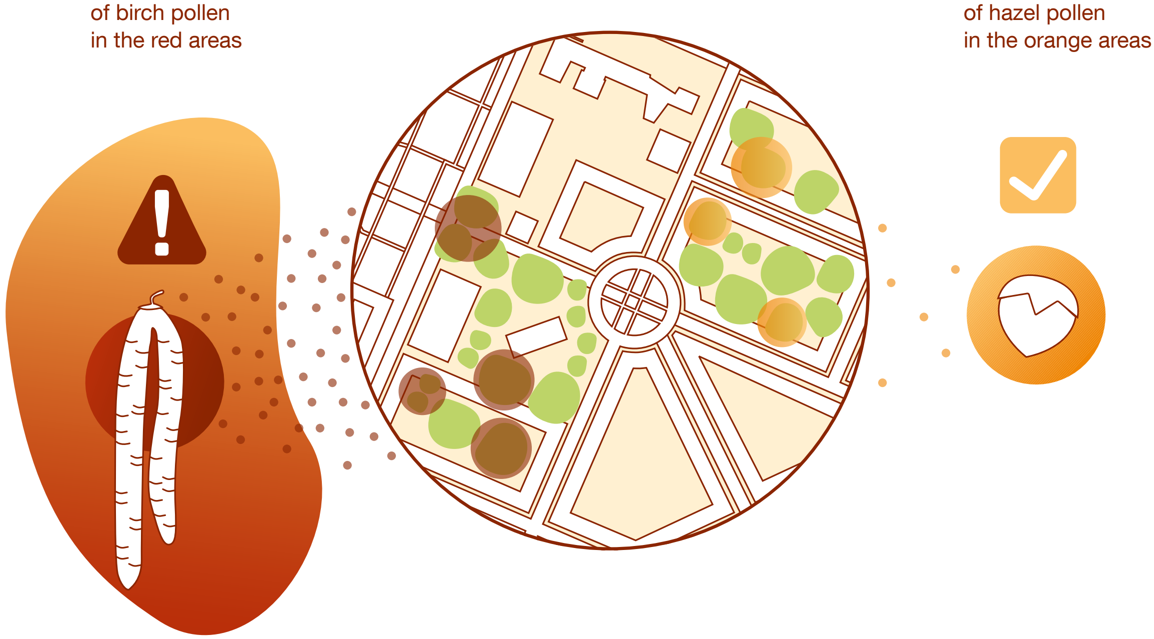
The project will particularly appeal to lovers of mountain hikes, many of whom take an interest in the surrounding flora and, with a little practice, are usually able to correctly identify trees and shrubs. Jörg Ewald explains what they need to do: “On the way up you tend to be focused on the exercise aspect of your hike, and on getting to the summit. On your way down, however, there’s plenty of time to record the highest mountain pine, green alder or rowan and GPS data for its location.” Ideally, the BAYSICS researcher would like his citizen scientists to record separately the highest seedling, shrub and tree for each species and take photos. “That way we can estimate age and time of colonization.”

Over the summer, numerous alpinists and students have entered their observations on the BAYSICS portal. The data so far suggests that treelines for most species are today about 150 meters higher than in Sendtner’s era. Ewald hopes that the new data will also help to answer other interesting research questions. “Nobody knows how the montane forest as a whole changes when individual tree species are subject to competition from species moving up from lower altitudes.” ■ *Monika Offenberger*

Graphics: ediundsepp

"Beyond simply asking our citizen scientists to provide data, we are providing them with useful feedback and scientific insights."

Susanne Jochner-Oette,
Catholic University of Eichstätt-Ingolstadt



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How to **Avoid Hay Fever**

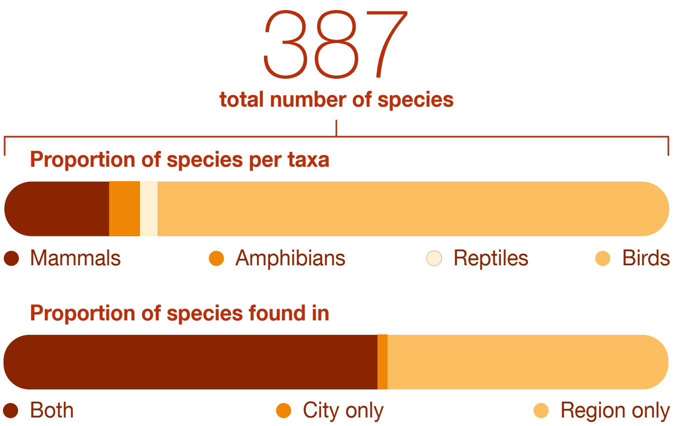
For people with a pollen allergy, springtime often begins as early as January, when hazel trees and shrubs release their pollen. Other tree species follow suit and, as from April, grasses and herbs make spending time outdoors even harder for allergy sufferers. The number of people with such allergies continues to rise and currently accounts for around 15% of the population. Climate change is a contributing factor to this trend – as Susanne Jochner-Oette, Professor of Physical Geography, Landscape Ecology and Sustainable Ecosystem Development at the Catholic University of Eichstätt-Ingolstadt, explains: "Higher temperatures result in pollen grains being produced in greater quantities and released earlier. They also tend to contain more allergens and therefore trigger more severe reactions."

A citizen science project has been launched to investigate these interrelationships and help those affected to understand them better. "We want to make people aware of why pollen is present in the air earlier and in greater quantities nowadays – as well as how they can protect themselves more effectively," the geographer explains, inviting anyone with an interest to share their observations with like-minded people via the BAYSICS app. Where and when do birch, hazel, dock, ribwort and grasses flower in your town? Do you experience any allergic symptoms as a result? If so, what symptoms? Making connections between certain plants and physical symptoms can help allergy sufferers to avoid specific locations. In addition, the app allows users to compare their findings with existing data, such as when certain plants flower across Bavaria and pollen count data from previous years.

"Beyond simply asking our citizen scientists to provide data, we are providing them with useful feedback and scientific insights. That's what separates our projects from other research offerings," emphasizes Jochner-Oette. She also decries the media's habit of announcing blanket time windows in which allergy sufferers should air their homes – without any scientific basis. "We hope that BAYSICS will provide us with more precise data, thereby closing gaps in our understanding and allowing us to issue well-founded recommendations in future," she says. Her doctoral student Johanna Jetschni, who has been collecting and analyzing pollen samples in and around Ingolstadt for the past two years, has made a significant contribution. Initial analyses indicate that the air in rural areas contains significantly more grass pollen than the city center and residential areas. Pollen counts, however, follow the same pattern in all areas over the course of the day, reaching their peak between 12pm and 2pm.

■ *Monika Offenberger*

Graphics: ediundsepp



Observations of animals in Nuremberg and surroundings (50 km around center). More than 50 percent of all species live in both the city and its surroundings (data: Global Biodiversity Information Facility).

Urban Animals

“Anyone who enters their own findings […] can also compare them against existing datasets.”

Wolfgang Weisser, TUM

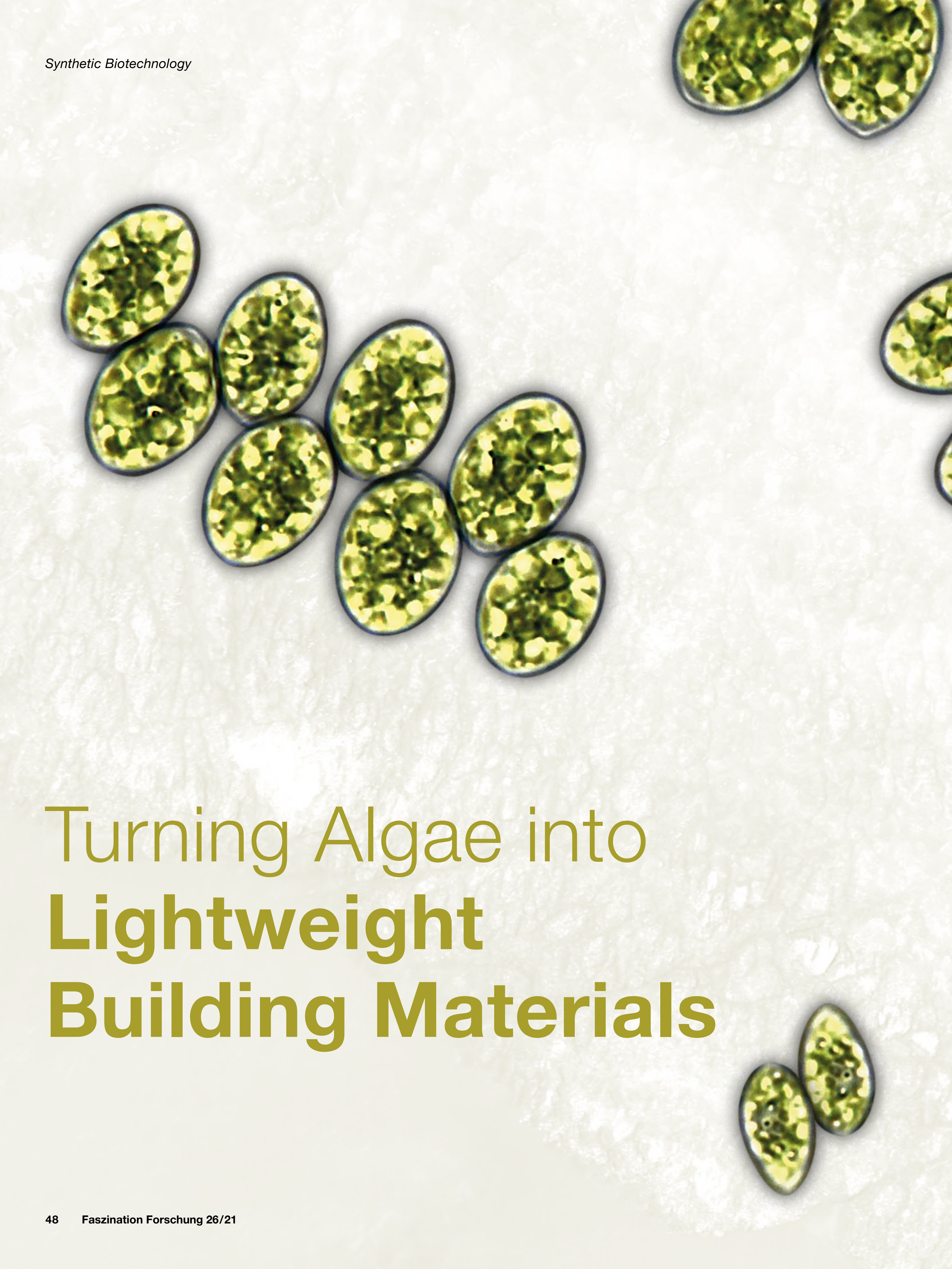
Humans are not the only ones for whom cities make an attractive home. More than one hundred species of birds breed in the Munich municipal area alone; foxes and beavers have established territories in the city, while eight species of bat hunt for prey in Munich’s parks and urban courtyards. “Many animals live in the city. For a lot of people, urban nature is the only form of nature they come into contact with during their day-to-day life,” says Wolfgang Weisser, Professor of Terrestrial Ecology at TUM. Despite this, urban planning remains poorly attuned to the realities of human-animal coexistence. “The city is becoming increasingly compacted and green spaces are disappearing,” the biodiversity researcher says. “Many buildings are being refurbished – also in response to climate change – to the extent that sparrows and swifts can no longer find places to nest. As a result, more and more potential habitats for animals are disappearing.”

Graphics: ediundsepp (data: TUM)

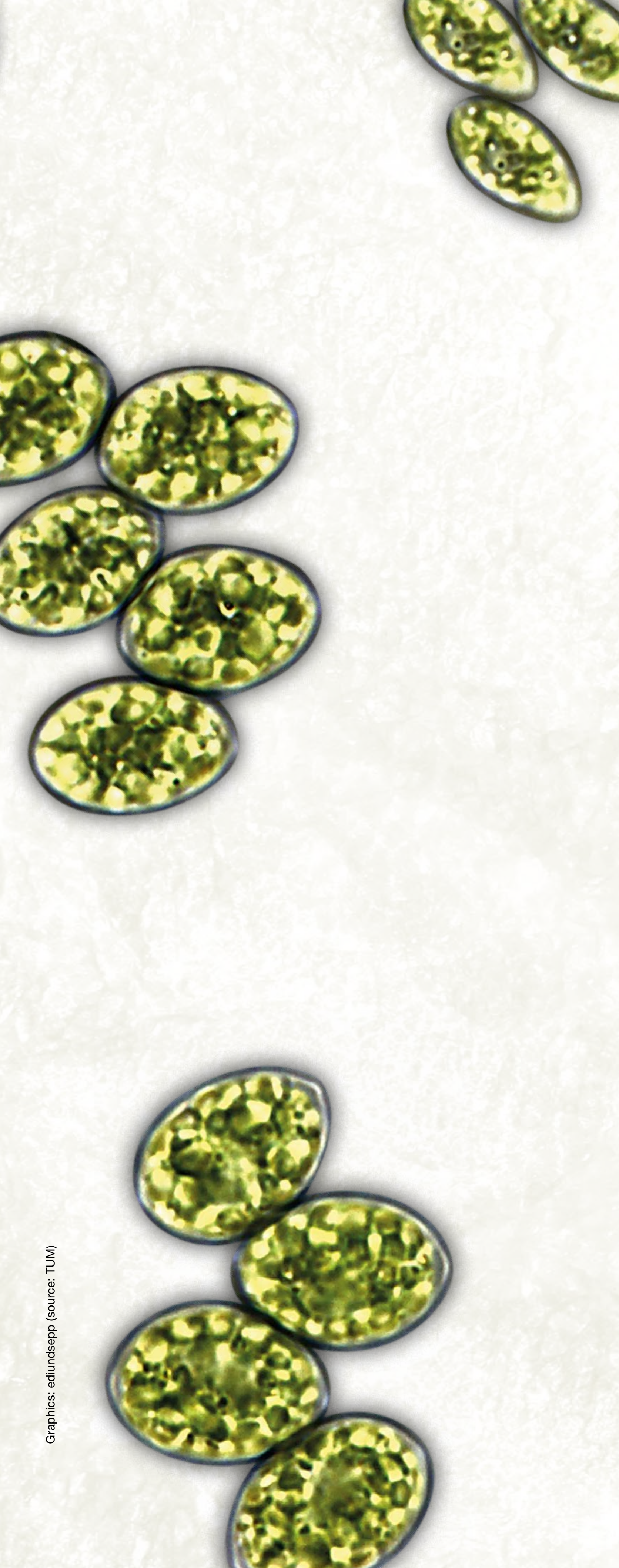
People in positions of responsibility in housing associations and planning offices are often unaware of the consequences of their actions – as shown by a national survey to which Weisser's team contributed. "Many said they would pay greater attention to animals' needs if only they knew how. And if residents welcome the animals," the Munich-based biologist explains. It is the attitudes of these residents that Weisser now hopes to explore. "We want to know which animals people like in their area and which they do not – and whether they would support measures to support certain species in their neighborhood," he says. A test study with around a thousand students showed that preferences for and aversions to certain animals also depended on the respondents' gender and background.

A citizen science project has now been established to drill down into the different motivations at play. It also aims to encourage citizens to engage with the world around them. "We are purposefully asking about specific animals such as hedgehogs, squirrels and hummingbird hawk moths. Where and when have they been sighted? Anyone who enters their own findings into the BAYSICS portal can also compare them against existing datasets. This means that ordinary citizens can learn to understand how climate change and urban densification influences the lives of animals," explains Prof. Weisser. The initiative is also intended to benefit the citizens who submit reports. As Weisser explains, their efforts should help urban planning processes give greater consideration to the needs of humans and animals in future: "In the interests of environmental justice, everyone must have the opportunity to experience nature where they live and work – including in cities."

■ *Monika Offenberger*



Turning Algae into **Lightweight Building Materials**



Graphics: ediundsepp (source: TUM)

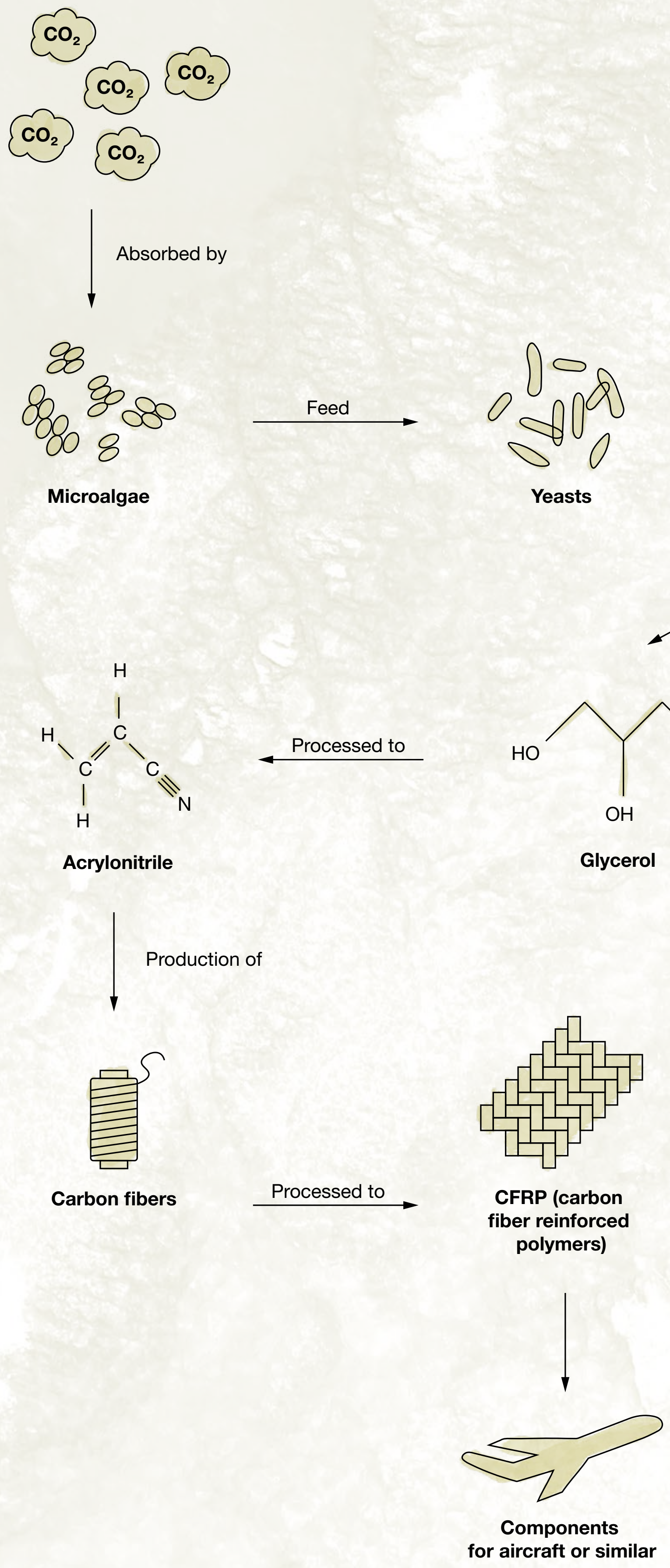
Carbon-fiber components are very light and extremely strong. At present they are manufactured from oil. In a project by the name of Green Carbon, the Werner Siemens Chair of Synthetic Biotechnology at TUM is now working with partner businesses to manufacture sustainable carbon fiber drawing on algae and yeast. A key focus is on scaling up the technology for industrial use.

Kurzfassung · Langfassung: www.tum.de/faszination-forschung-26

Freunde zu Verbündeten gemacht D

Leichte Bauteile aus Carbonfaser-Verbundwerkstoffen werden normalerweise aus Erdöl hergestellt. Der TUM Biotechnologe Prof. Thomas Brück arbeitet im Projekt Green Carbon jetzt daran, die benötigten Rohstoffe erstmals gänzlich aus Algen und Hefen zu gewinnen. In einem an der TUM entwickelten Prozess werden Algen gezüchtet, deren Biomasse anschließend an spezielle Hefen verfüttert wird, die Öl produzieren. Das Öl wird dann in seine Bestandteile aufgespalten – in Glycerin und lange Fettsäureketten. Das Projekt Green Carbon nutzt beide für die Herstellung von grünen Carbonfaserverbunden. Das Glycerin wird in den Werkstoff Acrylnitril gewandelt, aus dem Carbonfasern hergestellt werden. Die Fettsäuren werden zu Kunststoffharzen verarbeitet, mit denen die Carbonfasern zu einem Bauteil verklebt werden. Ferner werden im Projekt Green Carbon erstmals dünne Schichten aus Carbonfaserverbunden mit dünnen Lagen aus Stein kombiniert. Diese leichten und sehr stabilen Carbonfasersteinkomposite eignen sich insbesondere für den Hausbau. Sie können beispielsweise schwere Stahlträger ersetzen. □

Link
www.department.ch.tum.de/wssb



CO_2
Absorbed by
Microalgae
Feed
Yeasts
Convert
Oil
Byproduct
Conversion process
H
H
C
C
C
N
H
Processed to
HO
OH
OH
Acrylonitrile
Glycerol
Free fatty acid chains
Production of
Production of
Carbon fibers
Processed to
CFRP (carbon fiber reinforced polymers)
Processed to
Synthetic resins
Components for aircraft or similar

Sometimes research projects take surprising turns. Especially when you're not afraid to strike out in new, sometimes speculative directions. When Prof. Thomas Brück started cultivating algae seven years ago, his aim was to use them to produce high-quality aviation biofuel. His plan was based on an audacious-sounding idea. The idea was to cultivate algae and use the algal biomass as food for special oil-producing (oleaginous) yeast. The oil produced by the yeast would then be processed into aviation biofuel. So, over the next few years, on TUM's Ottobrunn campus he built what amounted to a high-tech greenhouse for growing algae in large tanks. The greenhouse was lit by a unique lighting system that mimicked sunlight in different geographical regions and climate zones. His experiments proved highly successful. After a lengthy series of tests, Brück and his team succeeded in determining the ideal growing conditions for both algae and yeast. "We developed a process in which the oleaginous yeast convert algal biomass into oil in four to five days," explains Brück. "We were then able to process the oil to produce high-quality aviation fuel."

> *"The result [of this process] is 100% biologically produced carbon fiber composites entirely from CO_2."*
>
> *Thomas Brück*

Graphics: ediundsepp

Glycerol as feedstock

Algae absorb carbon dioxide from the atmosphere and process it to produce a biomass rich in energy-dense sugars. The yeast converts this biomass into oil. It's an extremely sustainable process. Brück could have left it at that, but there was one thing that bothered him. The process of turning the oil into aviation fuel produced a byproduct – glycerol. If the oil industry really were to one day start producing aviation biofuel at scale, Brück realized that this would result in the production of huge amounts of glycerol. Every ton of biofuel produced also yields around 100 kg of glycerol. "But there just isn't any demand for that much glycerol," he says. "Glycerol is used in the cosmetics and pharmaceutical industries, but by no means in the kind of quantities that would be produced by large-scale aviation biofuel production." So what to do with all that excess glycerol? Thomas Brück, who holds the Werner Siemens Chair of Synthetic Biotechnology, came up with a brilliant idea. Via a short series of chemical reactions, glycerol can be transformed into acrylonitrile – an extremely useful chemical compound that happens to be utilized in making carbon fibers. They are a material with a very bright future. Processing these fibers with synthetic resins produces very durable, very lightweight carbon fiber reinforced polymers (CFRP) – more commonly known simply as carbon fiber. The process has been around for some years. CFRPs are used in particular for manufacturing wind turbine blades and in aviation – the Airbus A350, for example, is more than 50 percent CFRP. Thanks to lightweight CFRP, aircraft fuel consumption is significantly reduced. It would take 9.7 tons of glycerol to make one ton of carbon fibers. ▷

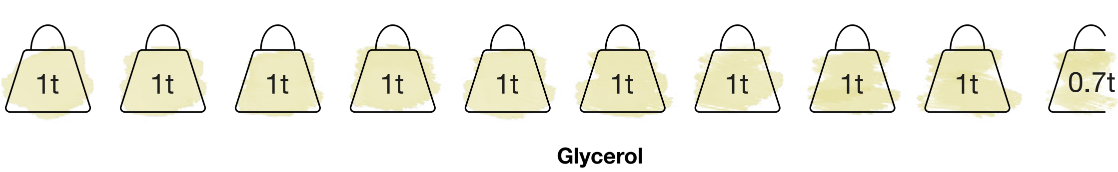
100% green components

Brück has since largely moved on from his original idea of producing aviation fuel to focus almost completely on CFRP. That's because it's not just the glycerol that can be used for this purpose – it's all of the oil produced by the yeast. This oil consists of fatty acid chains attached to a glycerol molecule like long pieces of string. The fatty acids can be separated from the glycerol chemically. Thomas Brück's original plan was to use these fatty acids to produce aviation fuel. "But fatty acids can also be chemically modified and made into plastics," he says. "For example, the synthetic resins involved in manufacturing carbon fiber reinforced polymers." So Brück's algae can, via the medium of oleaginous yeasts, not only be used to produce carbon fibers, but also the resins needed to produce CFRP. "The result is 100% biologically produced carbon fiber composites entirely from CO_2." To be able to produce green, and in particular economically viable CFRP on an industrial scale, generously dimensioned algae farms would be required. Such farms would be best built in sunny Mediterranean regions. Brück estimates that these algae farms would need to cover an area of at least four square kilometers.

EUR 12 million grant for the industrial-scale Green Carbon project

The Green Carbon project is paving the way to industrial-scale production. Working with industry partners, Brück will further develop the process for producing carbon fiber components from algae until it is ready for mature industrial processes. The project has received a EUR 12 million

Laboratory scaling of algae cultivation in closed photobioreactors. The technical data generated here are the basis for the next process scale-up steps at the TUM AlgaeTech Center in Ottobrunn.

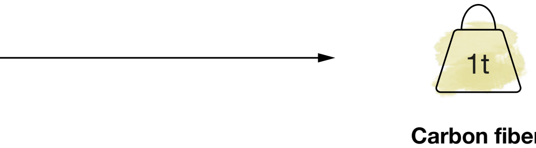


Picture credit: Andreas Heddergott; Graphics: ediundsepp

grant from the German Federal Ministry of Education and Research. The carbon fiber manufacturer SGL Carbon is also on board and will contribute its CFRP expertise. “The acrylonitrile we make from glycerol is the same molecule that’s normally produced from oil – which means it’s the same quality,” explains Brück.

For the process to make the leap from university project to real-life application, from pilot project size to industrial scale, the facilities have to be bigger and process higher volumes of biomass – at least 50,000 to 100,000 times bigger. Consequently, one of the companies partnering in the Green Carbon project is consulting firm AHP. Their experts use computer models to analyze mass flow rates in industrial plants, as well as energy and space requirements. Their calculations are important when it comes to seeking finance for any future system. ▷

The next step in algae biotechnology developments. Accelerating selection of the best oil-producing algae strains using a robotic screening platform at the Werner Siemens Chair for Synthetic Biotechnology.



Prof. Thomas Brück

The practical relevance of his research is very important to Thomas Brück. That’s why he works on interdisciplinary projects involving industrial partners. Born in Cologne in 1972, he took his degree in chemistry, biochemistry and business administration in the UK. He then studied for a masters in molecular medicine at Keele University in Stoke-on-Trent. In 2002 he obtained a PhD from the University of Greenwich for his work on biochemical reactions of important enzymes. In 2006 he returned to Germany, where he moved into industry. In 2010 he was appointed head of the industrial biocatalysis research group at TUM. He has headed the Werner Siemens Chair of Synthetic Biotechnology since 2018.

Building new products from carbon fiber stone

In acknowledgement of his work, Brück has now been honored with the TUM's inaugural Sustainability Award. A while ago, Brück was also contacted by a company called TechnoCarbon Technologies (TCT). They had the surprising idea of combining carbon fiber composites with wafer-thin layers of hard rock such as granite. Initial experiments had demonstrated that the concept works in principle. Working with experts from TCT, Thomas Brück's team used resins produced from algae to bond thin slices of granite just a few millimeters thick with carbon fiber composite strips. This produced an extremely flexible and strong building material. The results were sufficiently promising that TCT has been signed up as a further partner in the Green Carbon project. The company has now manufactured a T-beam made of carbon fibers and Bavarian granite, which is half the weight of a standard steel beam. In house construction such beams are used to support floors. Depending on the applications and the load, carbon fiber stone can reduce the consumption of steel or cement by between one-half and three-quarters. After having the beams evaluated by experts, Brück has now, together with TCT, showcased the technology in a number of international journals. In one report, no less an authority than the Intergovernmental Panel on Climate Change describes carbon fiber stone composites as holding out great promise for reducing industrial CO_2 emissions. "The steel and cement industries are two of the biggest sources of industrial carbon emissions," explains Thomas Brück. "If we can succeed in establishing carbon fiber stone composites as an alternative material, we could not just neutralize annual carbon emissions from the steel and cement industry, we could actually reverse them."

Long-term carbon sequestration

The Green Carbon project's key goal is to remove carbon dioxide from the atmosphere, store it permanently in carbon fiber, and in doing so help to arrest climate change. The carbon will be stored in carbon fiber reinforced polymers for cars, aviation or wind turbines, or even in carbon fiber stone composites for buildings. The combustion of coal, natural gas and oil releases around 37 billion tons of carbon dioxide annually. Industrial CFRP production from algae could absorb between one and two billion tons a year – a far from negligible figure. "For me it's about long-term sequestration of atmospheric carbon dioxide. Only then does our process make a genuine contribution to climate protection," says Thomas Brück. Carbon fiber stone composites could be used in buildings lasting 100 years or indeed far longer.

The lifespan of CFRPs in aircraft and similar applications is shorter, as aircraft and other vehicles are taken out of service much sooner. However, when an aircraft is scrapped after some 25 years, the carbon fibers can be recycled. The fibers can, however, only be recycled two to three times, as the recycling process breaks them and they end up being too short. Brück also has some ideas for solving this issue, adding, "Green carbon fiber components are an extremely sustainable, climate-friendly alternative. It's high time to get them out there in the real world."

■ *Tim Schröder*

> *"Carbon fiber stone composites as an alternative material to steel and cement could more than neutralize the carbon emissions of that industry."* Thomas Brück

Graphics: ediundsepp

Removing CO_2 from the atmosphere to store it permanently in carbon fiber is the idea behind green carbon. Green CFRP can be used for aircraft, automobiles or wind turbines, for instance. It can also be further processed into carbon fiber stone, offering a climate-friendly alternative to steel and cement.

Picture credit: Andreas Heddergott

Link

www.ar.tum.de/en/hk/associate-professorship
www.3fstudio.de

Many Features, One Material, One Process

Moritz Mungenast designs recyclable facades. For his research doctorate, the architect studied how 3D-printed facades can simplify and improve the traditional method used to construct them.

Kurzfassung · Langfassung: www.tum.de/faszination-forschung-26

Viele Funktionen, ein Material, ein Prozess

D

Digitalisierung in der Architektur wirkte sich bislang auf den Entwurfsprozess aus. Mit der Entwicklung immer besserer 3D-Drucker, die immer größere Bauteile im Maßstab 1:1 herstellen können, ergibt sich ein neues Potenzial. Dies systematisch zu erforschen, ist Thema der Promotion „3D Printed Future Facade“ von Dr. Moritz Mungenast. Als wissenschaftlicher Mitarbeiter an der Professur für Entwerfen und Gebäudehülle der TUM untersuchte er Möglichkeiten der Additiven Fertigung, wie sie sich mit dem 3D-Druck erstmals bieten. Konkret entwarf er Funktionsgeometrien und erprobte die Funktionsintegration von 3D-gedruckten Fassadenelementen. Ein prototypisch realisiertes Element wurde auf seine optischen, thermischen und statischen Eigenschaften hin untersucht und einem Langzeittest auf der Solarstation der TUM unterzogen. Dabei zeigten sich die Möglichkeiten, wie man mit nur einem Material und in nur einem Prozess komplexe Anforderungen technischer und gestalterischer Art individuell erfüllen kann. □

Dr. Moritz Mungenast

Born in 1974, Moritz Mungenast studied architecture in Kaiserslautern, Lausanne, and Barcelona, before completing his Diploma (equivalent to a Master's degree) at TUM in 2003. His career has included roles at Auer + Weber in Munich and Shigeru Ban in Paris. He was a research fellow at the Professorship of Building Design and Product Development at TUM in 2009 and has been based at the Associate Professorship of Architectural Design and Building Envelope and the Guest Professorship of Emerging Technologies since 2010. In 2014, he launched and led the "3d-printed envelopes" research initiative while continuing to work on his doctorate, which he completed in 2019. He co-founded the spin-off 3F Studio in 2018.

Dr. Mungenast, what's the basic idea behind your research project?

What I first asked myself was this: Can you use 3D printing to create a strong, functionally integrated facade that also happens to be recyclable? Taking the facade as an example, I demonstrate some of the advanced possibilities that 3D printing offers for 1:1 application in architecture. One priority is how to integrate various functions and features into the printed facade. This prompts more questions, such as: How should you design moving parts? For instance, what would a 3D-printed door look like if it could adapt to a free-form surface? As this is about architecture, design considerations also play a key role alongside technical ones.

What specific aspects did you have to deal with?

My thought process was: If you had a facade that was the perfect combination of computational design and 3D printing, what could it look like? The aim is to simplify the construction process and fill the gap in the digital chain between design and production without sacrificing performance. This requires devising completely new geometries for the structure to fulfill its functions – known as functional geometries. Faced with a raft of new possibilities, I had to pick out those that were suited to being part of a facade element. First of all, I used 3D-printed prototypes to investigate individual aspects such as insulation, sun protection, ventilation, acoustic distribution, and ease of movement – of a door, for example. After I'd analyzed my results, these features were combined into a single, functionally integrated component, which was then itself reviewed and optimized.

What did "functional integration" mean?

Facades are usually made up of several elements. There's the window, a sealed panel providing insulation, another element protecting against the sun, a further component ensuring ventilation, and so on. These individual components interact and, in so doing, perform various functions. Hence the idea to integrate these functions with the help of efficient geometry. The desired degree of comfort and convenience – such as you get from a building's insulation, lighting, ventilation, and the shadow it casts – is achieved using a single element made from a single material, which is manufactured in a single process step and is completely recyclable.

What can a 3D-printed facade do that conventional ones can't?

First and foremost, they need to do everything conventional facades can. But it's easier to tailor them to different locations and tweak their unique features. Plus they form part of a closed-loop material cycle. In other words, the facade is turned back into a facade, something that's still some way off being achieved in conventional construction. They also offer a wide range of design possibilities.

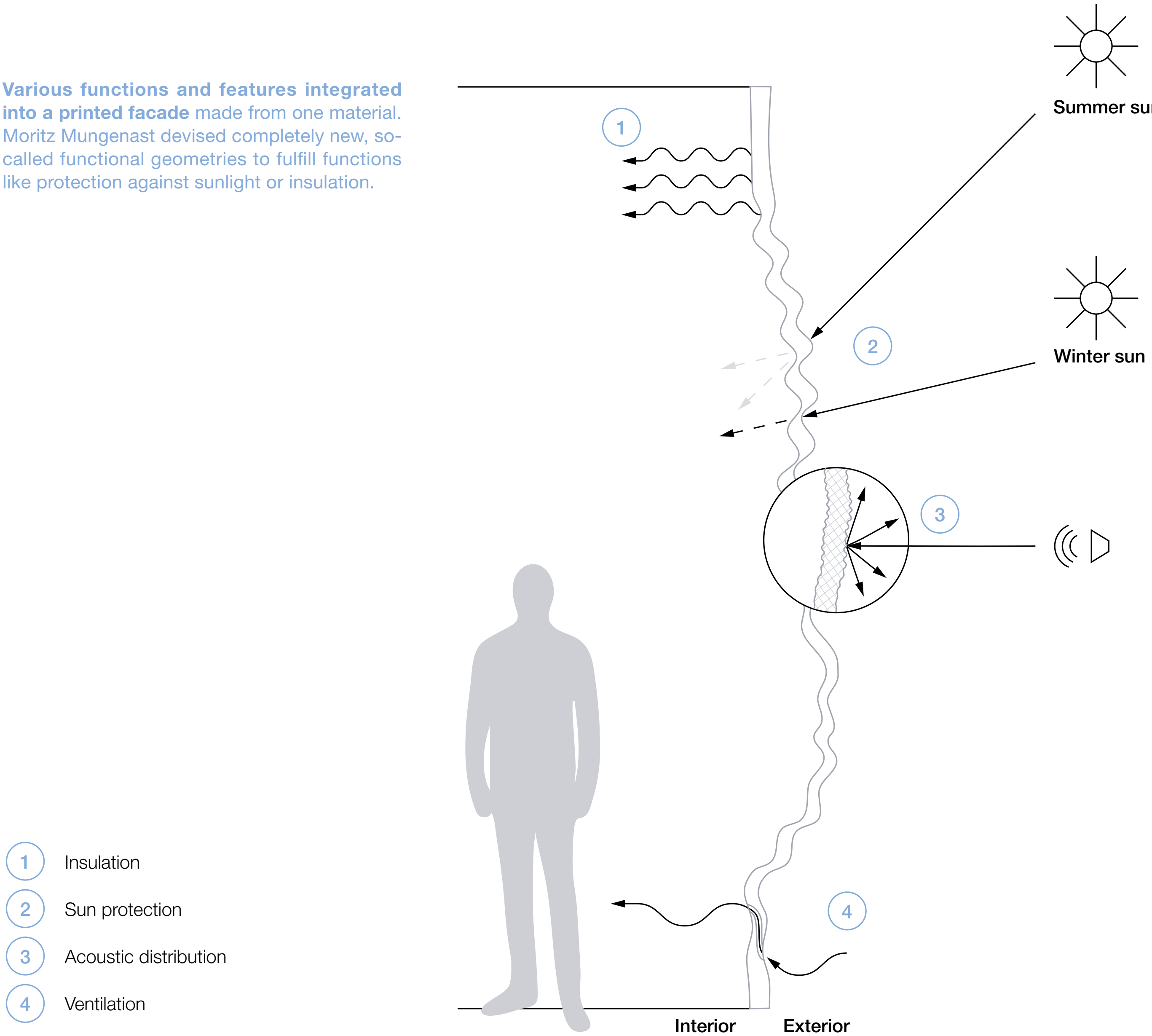
What problems did you have to solve to get where you wanted to be?

First of all, I had to decide what features I could reasonably achieve using a 3D printer, what parameters determine functional geometry, and how they can be combined in a single component. All of this I investigated as part of what I was teaching my students. After that, the biggest challenge remains the implementation – reproducing the geometries in plastic on a scale of 1:1. This process is just getting under way. 3D printers don't yet have the level of process reliability that would mean you only needed to press the button to achieve a consistent result. Melting the material, printing the design, and leaving it to cool down – these are all highly sensitive parameters that you need to monitor. And then there's the time element: Printing is still a very long-winded process. Even in the follow-on projects, however, tolerance ranges have been significantly improved and printing takes much less time. The technology is progressing extremely rapidly. ▷

3D printing of a facade element (ca. 80 x 90 cm) at the technical center of the TUM Department of Architecture. The printer is a large area delta printer.

Picture credit: Peter Langenhahn

Various functions and features integrated into a printed facade made from one material. Moritz Mungenast devised completely new, so-called functional geometries to fulfill functions like protection against sunlight or insulation.



How did you settle on specific geometries?

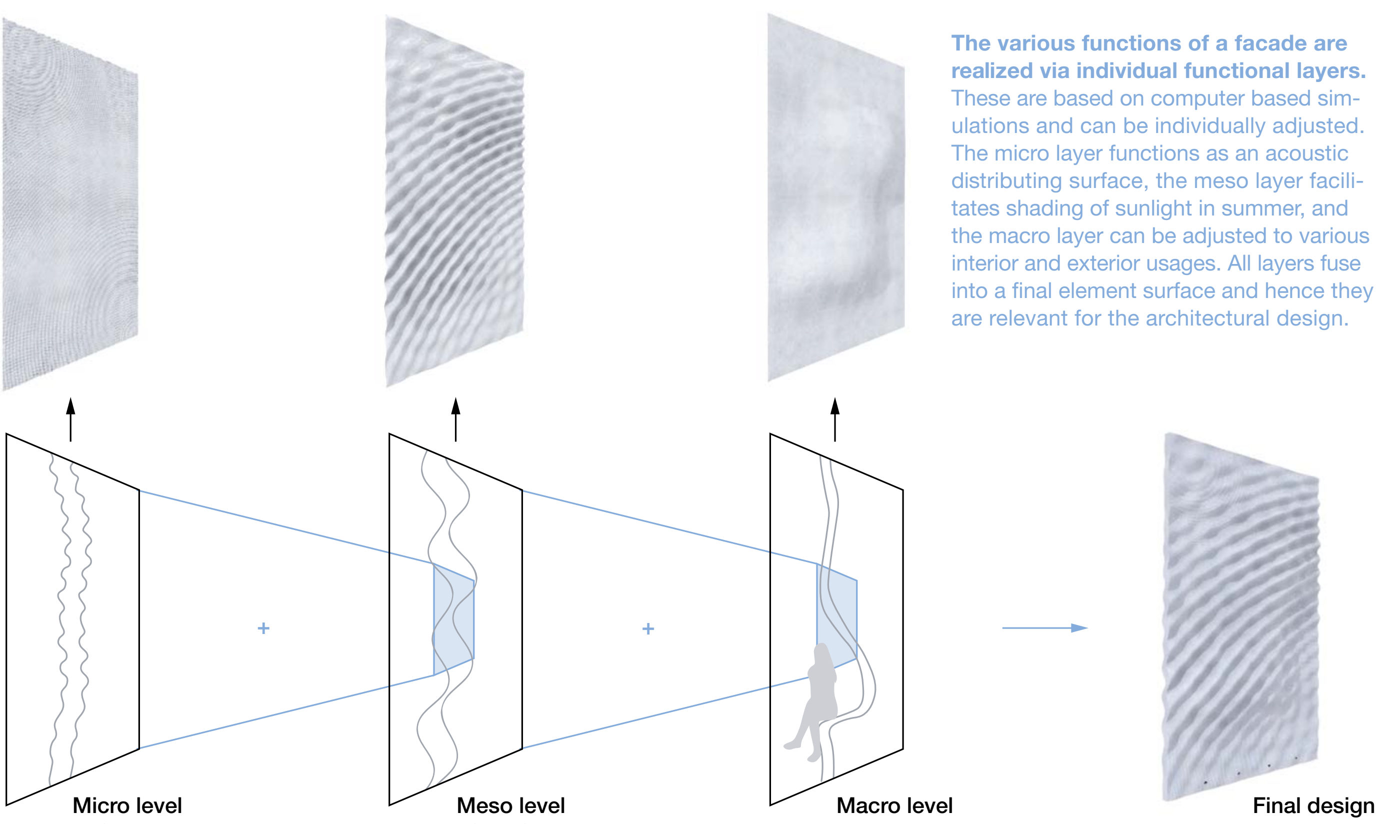
There are various selection criteria: Can a geometry be printed? Does a suitable material exist? It's an iterative process: Several versions were printed, tested, and fine-tuned. With this kind of architecture, it's a case of research by design. The only way to make progress is to try things out. You get valid results when you make everything full-scale. Finally, the course of the sun is simulated with regard to the orientation of the facade. This has a decisive impact on the geometries, in terms of the shadow it casts, for instance.

What implications does this have for architecture?

Up until now, we've been in working architecture with more or less rigid systems, which we use for a range of construction tasks and sites. This means that you often have to make do with solutions that are a bit of a compromise. You use systems and modules that fit more or less OK wherever you are. Computational design allows us to devise tailored, sophisticated solutions for specific requirements and a specific location and to implement them effectively using additive manufacturing. ▷

“There’s a lot of potential in developing new materials and a closed-loop material cycle for a transparent or translucent building envelope.”

Moritz Mungenast



The various functions of a facade are realized via individual functional layers. These are based on computer based simulations and can be individually adjusted. The micro layer functions as an acoustic distributing surface, the meso layer facilitates shading of sunlight in summer, and the macro layer can be adjusted to various interior and exterior usages. All layers fuse into a final element surface and hence they are relevant for the architectural design.

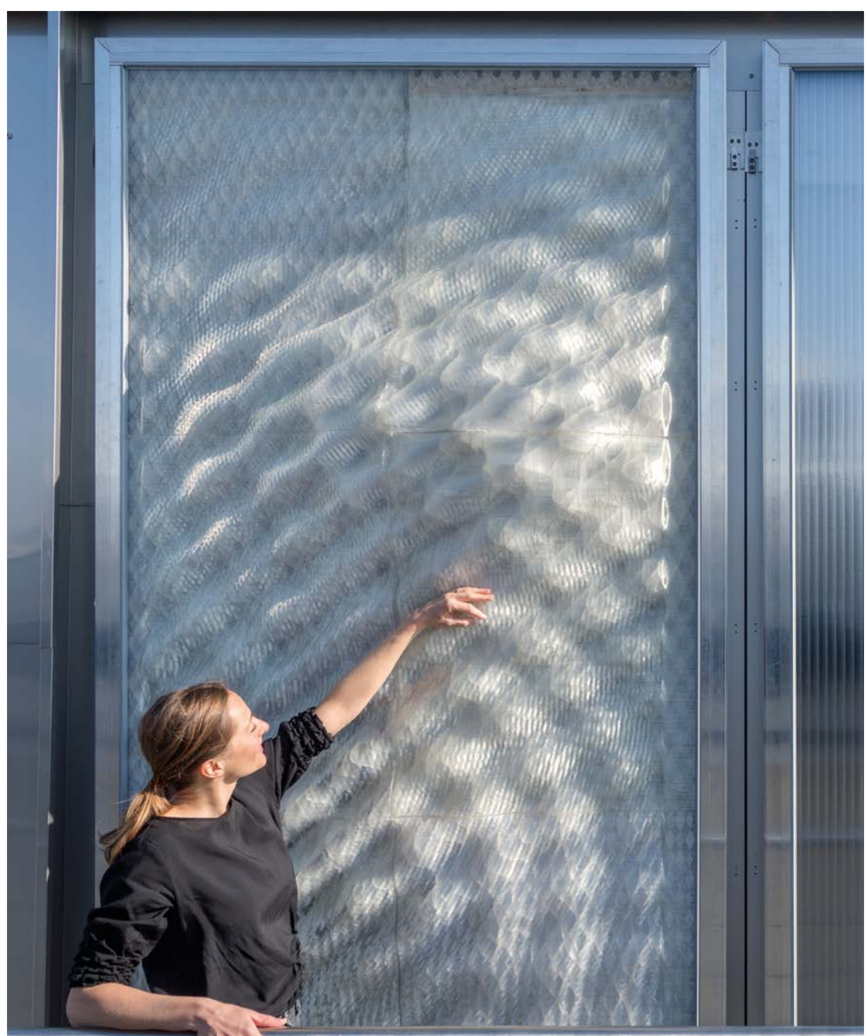
Graphics: ediundsepp (source: M. Mungenast); Picture credit: Peter Langenhahn

What will you be moving on to next?
My overriding motivation is to make a contribution to the global construction tasks of the future. Although there are already solutions made from sustainable materials like wood for building designs, we're only just beginning when it comes to translucent facades. There's a lot of potential in developing new materials and a closed-loop material cycle for a transparent or translucent building envelope. To take the idea further, we set up the company 3F Studio. We just finished an application study for a 3D-printed, functionally integrated 250-square-meter facade to be produced on an industrial scale.

What material are you using?
The aim is to move away from conventional plastics. We definitely want to be working with biobased, sustainable raw materials in the future. PET, an oil-based plastic, was the starting point. We're currently using recycled plastic, made from old water bottles, for instance. In the future, we'd like to integrate algae or even chitin into our 3D printing and into the construction industry. Both these materials are translucent and lighter than glass. We're looking for suitable ways of producing transparent bioplastics. We'll be developing this further together with our partners for materials.

Thomas Edelmann

First-ever prototype of a 3D-printed, multifunctional, translucent facade. Test installation at the solar station of TUM in order to perform experiments for comparative tests and investigation of long-term behavior under various weather conditions.



1

production step required for a 3D-printed facade

>8

production steps required for a bespoke unitized facade

Picture credit: Andreas Heddergott; M. Mungenast

1

material needed for a
3D-printed facade

>6

individual materials needed
for a bespoke unitized facade

Application study for a 3D-printed, functionally integrated facade to be produced on an industrial scale

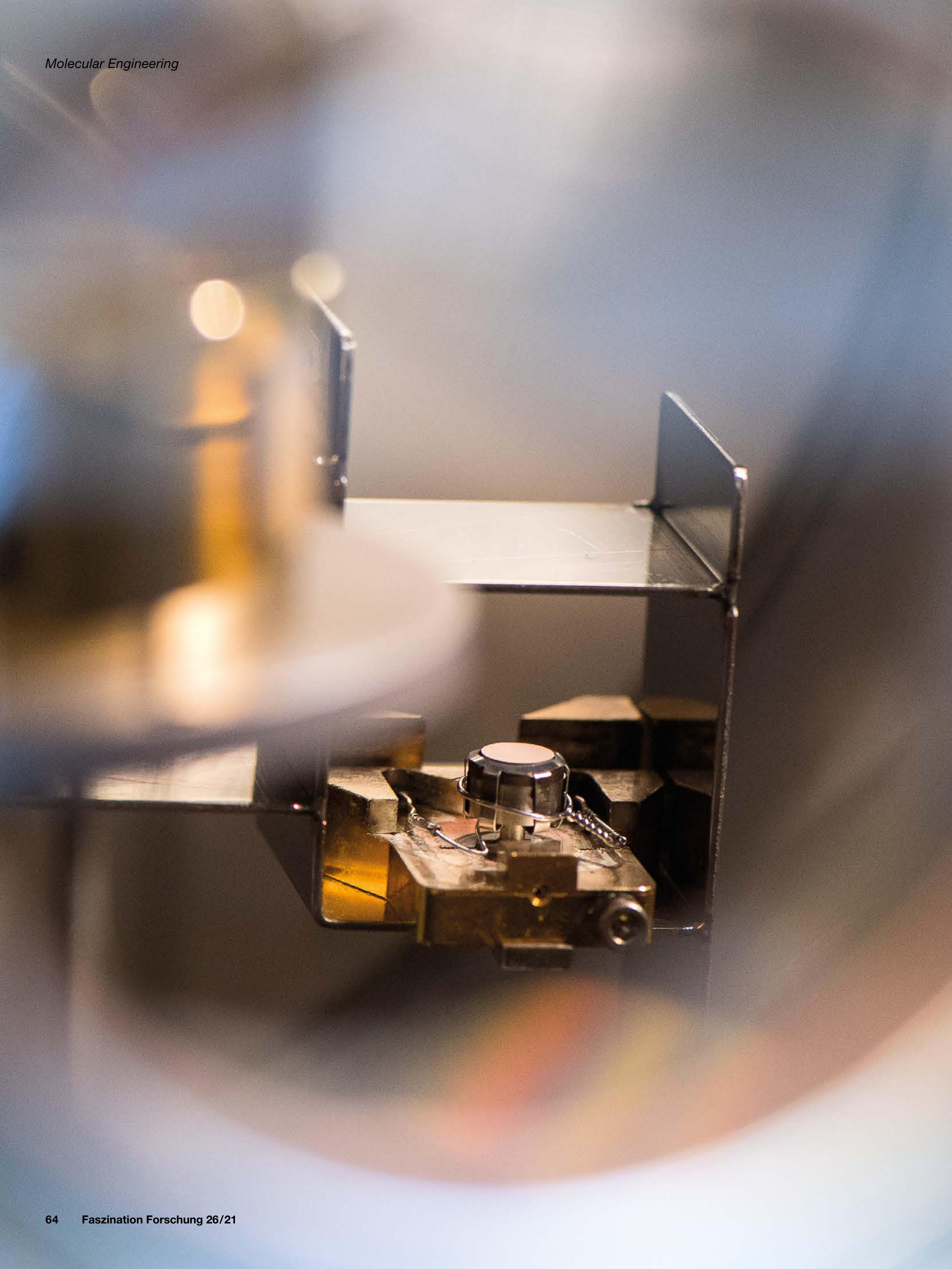
At 750 square meters large, this first-ever 3D printed facade was designed for a temporary entrance at the Deutsches Museum, which is currently undergoing complete renovation. The design was produced by the TUM spin-off 3F Studio based on research conducted by Moritz Mungenast. It is a multifunctional, translucent facade made from recyclable material. The cellular structure of the facade elements produced from the 3D-printed cells ensures stability, while their air-filled cavities provide optimum insulation. Waves cast welcome shadows in summer. 3F Studio was founded by Moritz Mungenast, Oliver Tessin, and Luc Morroni and specializes in 3D-printed architecture and design.

15 kg

weight of 1 m²
3D-printed facade

45 kg

weight of 1 m²
bespoke unitized facade



The **Molecular** Engineers

Time and again, individual molecules and atomically structured materials have been found to exhibit amazing properties. With elaborate ideas and sophisticated analytical methods, researchers around Willi Auwärter and Johannes Barth are currently exploring novel avenues towards future nanoelectronics, photonics, sensing, catalysis and quantum materials.

Kurzfassung · Langfassung: www.tum.de/faszination-forschung-26

Die Molekül-Ingenieure

D

Aus Groß mach Klein: Heute werden Computerchips mit winzigen Schaltkreisen in greifbar großen Scheiben aus Silizium strukturiert. Aber auch umgekehrt lassen sich filigrane, elektrische Schalter auch aus einzelnen Molekülen zusammensetzen. Dieses Bottom-Up-Prinzip nutzen die drei Molekül-Ingenieure Prof. Johannes Barth, Dr. Joachim Reichert und Prof. Willi Auwärter, um mit ihren Arbeitsgruppen am Physik-Department der TUM neue Wege für funktionelle Einheiten zu gehen. Viele Anwendungen locken: Von Molekül-Schaltern und winzigen Sensoren über effizientere Lichtquellen und Energiespeicher bis hin zu reaktionsschnellen Materialien für Katalysatoren, Nanomotoren und sogar zu Funktionseinheiten zukünftiger Quantencomputer. „Mit unseren Experimenten betreten wir wissenschaftliches Neuland", sagt Lehrstuhlinhaber Barth. So besteht ein erster Schalter-Prototyp nur aus einem einzigen Molekül aus der Gruppe der Oligophenyle. Parallel zum Bau neuer funktioneller Einheiten nutzen die Nanoforscher von Rastertunnelmikroskopen bis zu selbst entwickelten optischen Methoden einen ganzen Strauß an Analyseverfahren. Damit messen sie die Eigenschaften einzelner Moleküle oder komplexer metallorganischer Strukturen. Die Forscher legen so die Grundlagen für konkrete Anwendungen von der Nanoelektronik über die Photonik bis zur Katalyse – im Einklang mit den ambitionierten Forschungsprogrammen des Münchner Exzellenzclusters e-conversion und dem Munich Quantum Center sowie dem TUM Institute of Advanced Study. □

Picture credit: Astrid Eckert/TUM

An atomically well-defined sample serves as the construction platform for custom-designed molecular nano-architectures investigated by high-resolution scanning probe microscopy.

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"We are exploring innovative ways of preparing a paradigm shift."
Johannes Barth


Picture credit: Astrid Eckert/TUM

Three scientists with a passion to build nanostructures using bottom-up construction principles. Biographies below from left to right.

Prof. Willi Auwärter

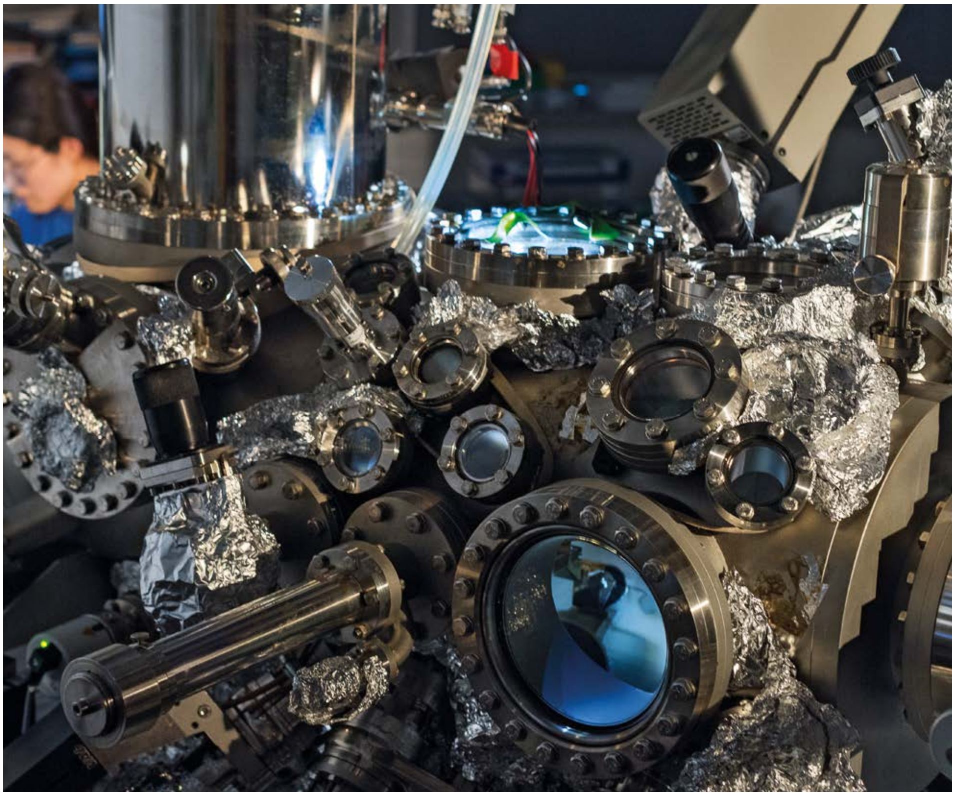
After being awarded his doctorate in physics by the University of Zurich in 2003, Willi Auwärter undertook research at the University of British Columbia in Vancouver and at the École Polytechnique Fédérale de Lausanne. He joined TUM in 2007, initially as a Fellow at the TUM Institute for Advanced Study and since 2015 as professor. His research was supported with an ERC Consolidator Grant and an Heisenberg professorship. His research group researches atomically precise molecular nanostructures and low-dimensional materials.

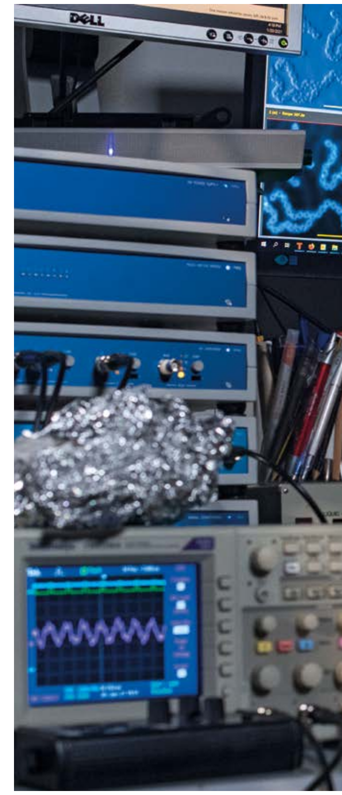
Prof. Johannes Barth

Physicist Johannes Barth was awarded his doctorate in physical chemistry in 1992 for work with Nobel Laureate Gerhard Ertl at the Fritz Haber Institute of the Max Planck Society in Berlin. After research visits at the IBM Almaden Research Center in San Jose and receiving the venia legendi at the École Polytechnique Fédérale de Lausanne, he was appointed professor of physics and chemistry at the University of British Columbia in Vancouver. Since 2007, he has been researching and teaching at TUM as chaired Professor of Surface and Interface Physics and has been Dean of the Physics Department for a number of years. He has received multiple awards and his work – supported in part by the renowned ERC Advanced Investigator Grant – deals with functional interfaces, surface chemical physics and molecular nanoscience.

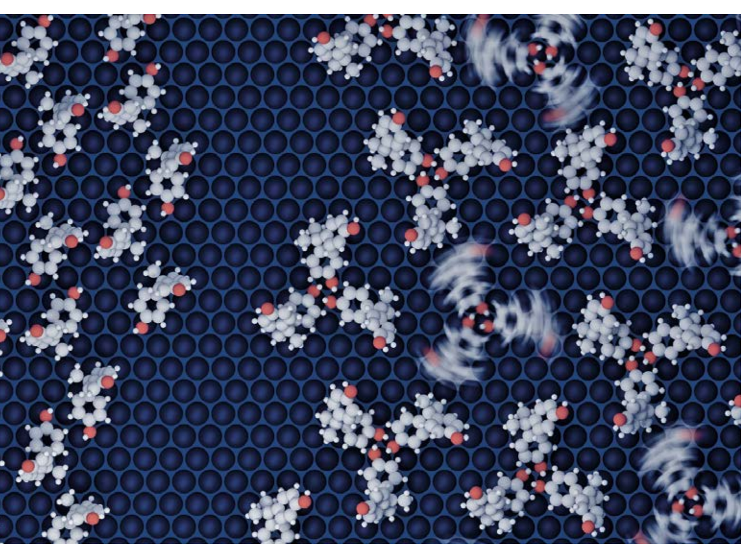
Dr. Joachim Reichert

Joachim Reichert earned his doctorate in physics from Karlsruhe Institute of Technology in 2003. He then undertook further research at the University of Münster and the University of British Columbia in Vancouver. Since 2007 he has headed a research group at TUM involved in analyzing and developing functional nanostructures and searching for potential components for the molecular electronics of the future.



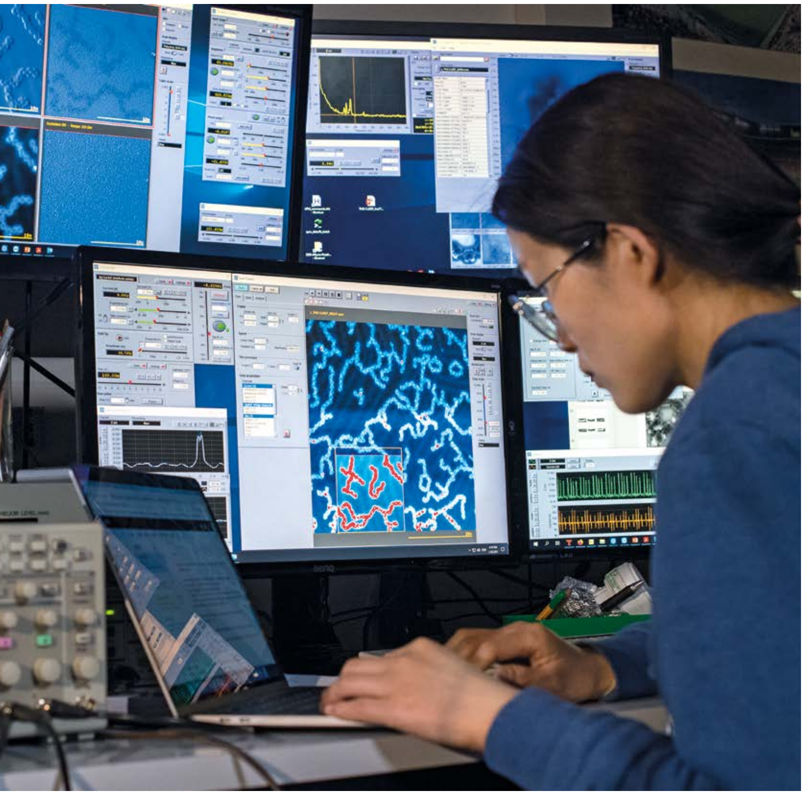


△ **To study individual molecules,** the team uses the atomic force microscope shown above and the scanning tunneling microscope.



△ **Computer generated image of a structure formed by bisphenol A molecules.** On extremely smooth surfaces (here: silver), three BPA molecules form trimers. Individual molecular trimers can be found rotating within a matrix of the same molecules, which remain static.

An electrical switch can hardly get smaller than this, consisting of just a single molecule from a group of chemicals called oligophenyls. Apply an electric charge, and the molecular backbone undergoes a controlled structural change. This modification is accompanied by a transition in the molecule's optoelectronic properties – the basis for jumping from 0 to 1 in digital switches. If a current with a voltage of a little more than a volt flows through this organic molecule, the three spatially rotated phenyl rings, each consisting of six carbon atoms, adopt a coplanar orientation – they all line up in the same plane. "Transiently, non-permanently charging the molecule transforms it from being an insulator to an electrical conductor and bestows a strikingly different optical response," explains Dr. Joachim Reichert, nanoresearcher in the Physics Department at TUM. In other words, the molecule suddenly acquires the ability to strongly scatter incident light, thereby providing an infallible means of determining whether the switching process has been successful.
Of course, there's a very long road ahead before we will be using legions of these molecules to produce extremely



△ **PhD candidate Nan Cao** works at the scanning tunneling microscope. The screens show STM images featuring chain-like covalently bonded molecular structures (white/light blue) grown on a gold surface (dark blue). Selected molecular chains are highlighted in red.

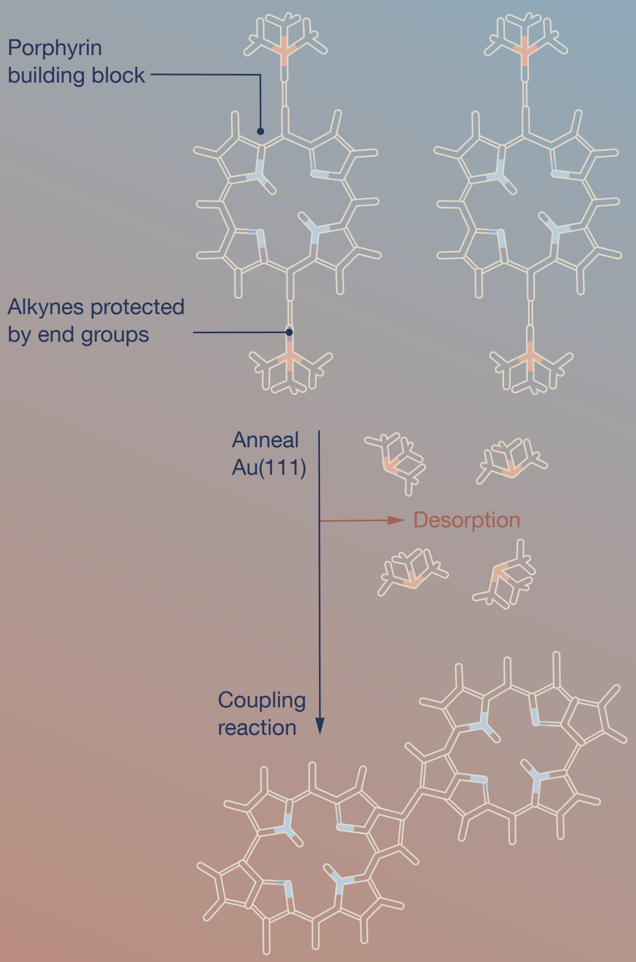
Picture credit: TUM/Julian Lloyd, Astrid Eckert/TUM, TUM/Nan Cao; Graphics: ediundsepp (source: TUM)

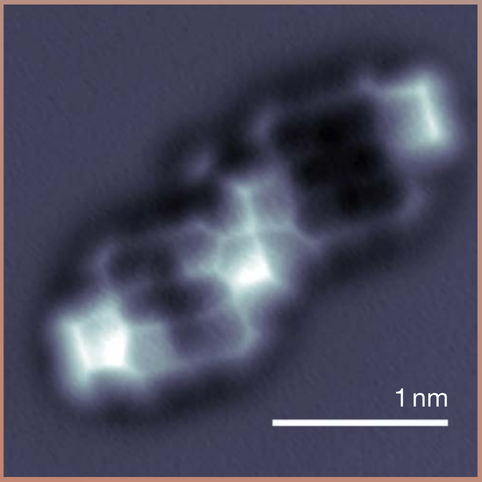
powerful processors. “At present, the switching process is still much more primitive than in a transistor,” says Reichert. But the foundations for molecular nanoelectronics have been laid, and chip manufacturers carefully follow this striking evolution. Conventional silicon circuits make use of structures just five to seven nanometers in size, but this technology is already butting up against its limits. Switches made of individual molecules – spanning just a fraction of a nanometer and many times smaller than current switches – could enable processors to continue their rapid miniaturization, or provide distinct useful features and response characteristics.

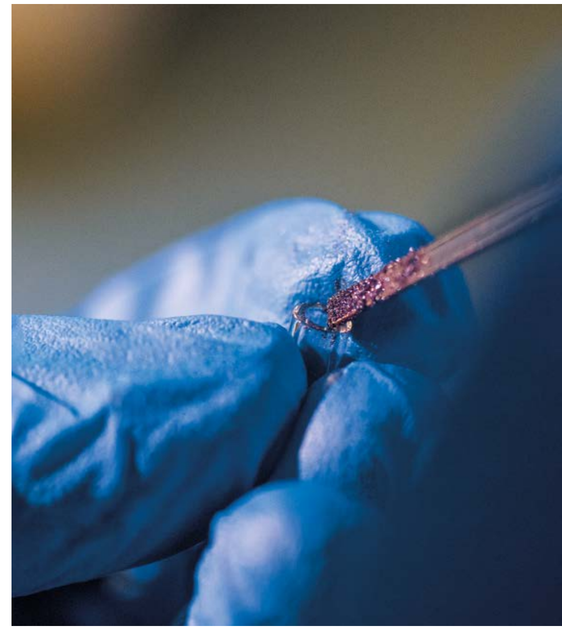
Bottom-up, not top-down: From molecule to material

“Our experiments take us into scientifically uncharted territory,” says Prof. Johannes Barth, who established the research unit. “We are exploring innovative ways of preparing a paradigm shift.” Barth and his colleagues are reversing the conventional process for developing new, versatile materials. Instead of forming smaller and smaller structures from large material blanks, they are ▷

▽ **Porphyrin building blocks form chain-like molecular structures** when they are deployed on a gold surface and tempered (thermal annealing). The protecting end groups separate and the remaining porphyrene structures form nanowires. The atomic force microscope image resolves the bonds between the individual “rings” and the newly established carbon-carbon linkage between them.





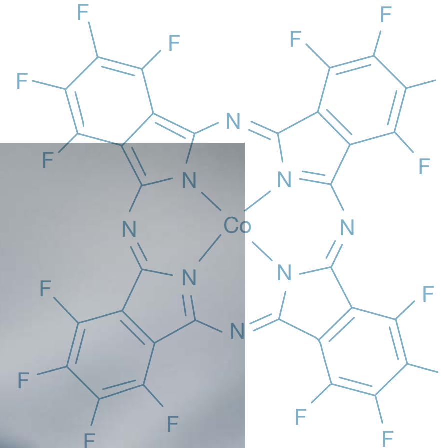


Preparatory steps to evaporate molecules onto the surface: Cobalt-phthalocyanine molecules are transferred from the container into a quartz crucible.

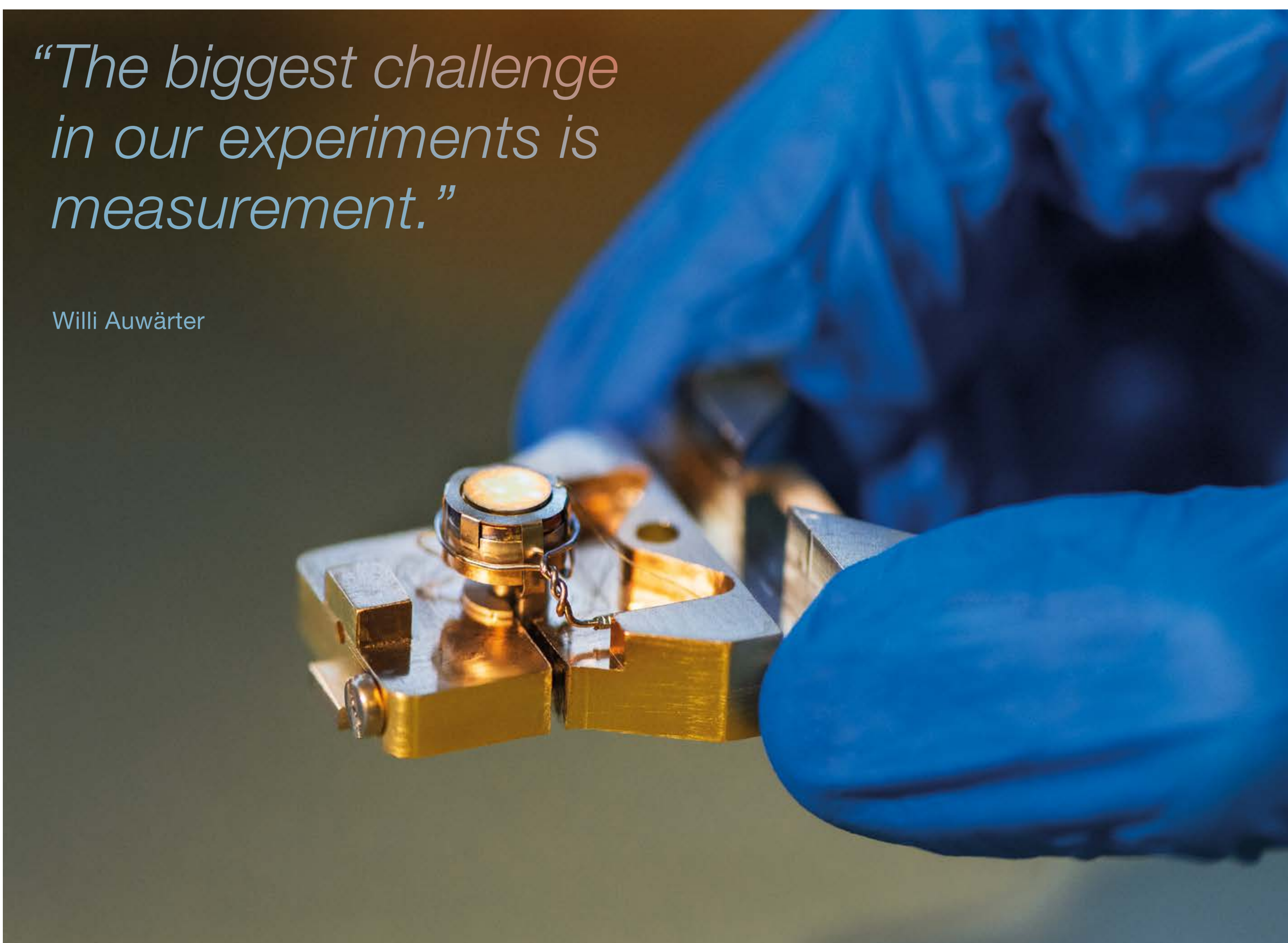
assembling functional units at interfaces molecule by molecule to produce hybrid systems with entirely novel properties. The technical jargon for this approach to nanotechnology is ‘bottom up’, in contrast to conventional ‘top down’ procedures. Nanoelectronics is just one of many potential applications for molecular engineering. These range from tiny sensors, more efficient light sources, solar cells and energy storage, to responsive, fast-reacting materials for catalysts, nanomotors and even the processing units for future quantum computers.

“There is no shortage of promising substances,” notes Barth, who is at home both in chemical physics and molecular engineering. In addition to oligophenyls, for example, his group has also explored using the aromatic molecule bisphenol A for molecular switching. On extremely smooth silver surfaces, this molecule can be made to undergo controlled rotation about its axis like a radial rotor. Porous two-dimensional structures – in which atoms organize themselves into honeycomb lattices occupying a single plane, rather than a three-dimensional lattice – can be used as cages for holding individual atoms and molecules. “We have, for example, developed metal-organic networks with variable pore sizes in which we can incorporate and control either individual guest molecules or metal atoms,” says Barth. Using their modular molecular system, the researchers can also create complex sandwich structures that promise to yield further novel properties. “For custom-designed molecules, we love to work closely with other expert research groups,” says Barth, noting fruitful collaborations with chemists at the University of Basel, Karlsruhe Institute of Technology or Trinity College Dublin.

“Nonetheless, in building our molecular structures we receive comprehensive assistance from nature itself,” says Barth. That’s because almost all biological structures – from DNA strands to mitochondria to cell membranes – are produced through a process of self-assembly. The blueprint for these fundamental units of life lies in the molecules themselves. Our understanding of the spontaneous self-organization processes involved is constantly improving. It is this understanding that Barth and his colleagues are exploiting. By cleverly selecting the base chemicals, substrates and symmetries, they are able to induce molecules to arrange themselves into specific patterns. ▷



In a later step, the filled crucible is mounted in an evaporator, which will be attached to the ultra-high vacuum chamber. Even a small amount of molecules is sufficient to coat large surface areas.



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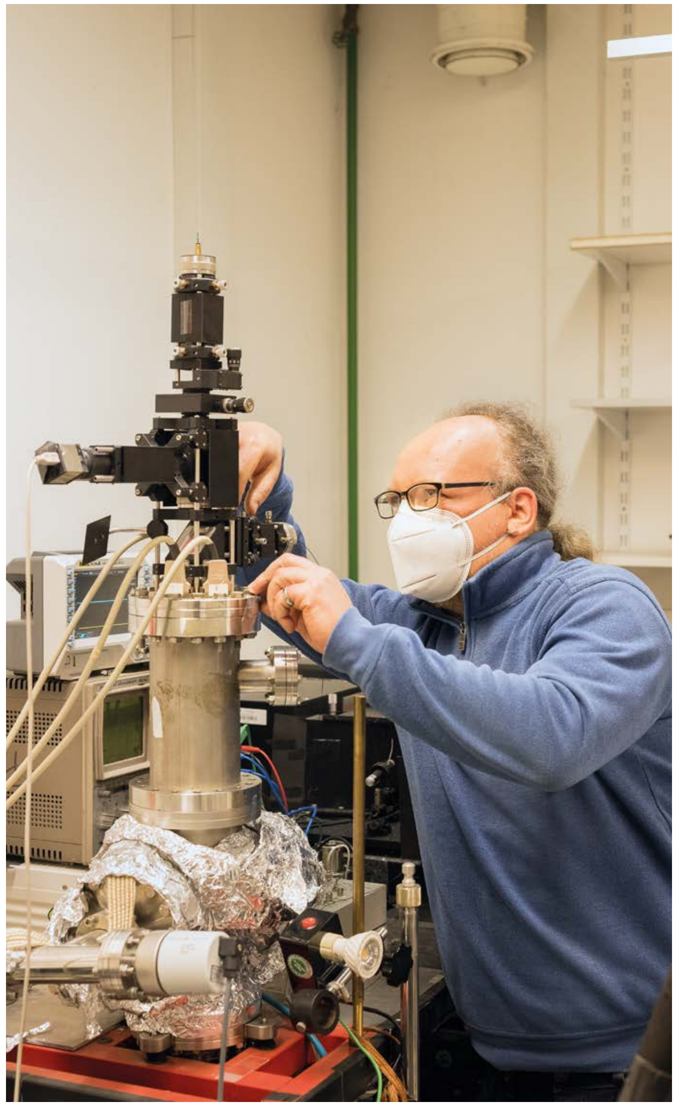
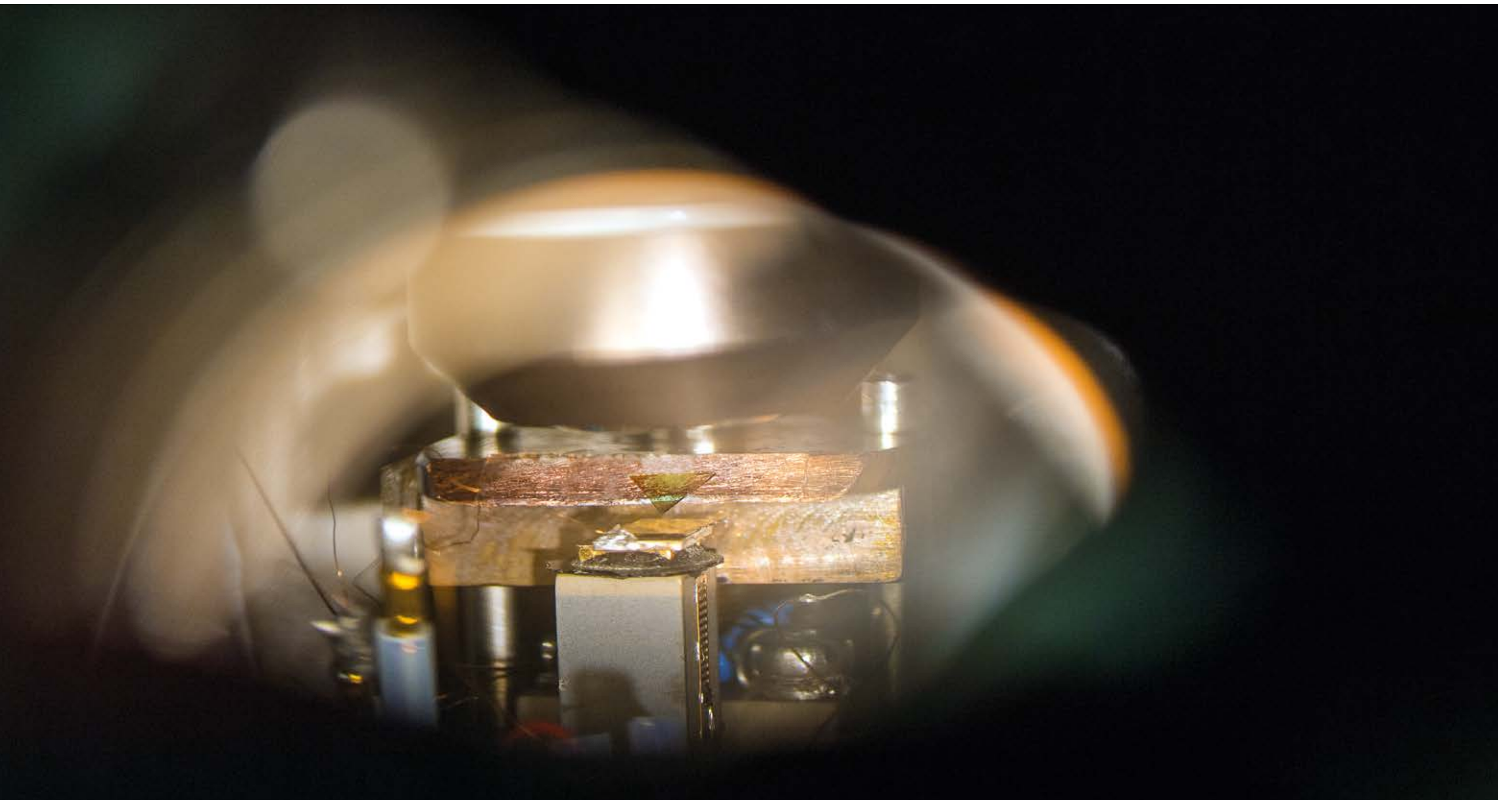


Joachim Reichert prepares a Raman scattering experiment to investigate the switching process of a single molecule contacted in a nanojunction between two electrodes.

New analytical methods

But synthesizing new functional units is just the beginning. To analyze the chemical and physical properties of individual molecules or complex metal-organic structures, molecular engineers need a whole host of analytical methods. Some are well established, some still need painstaking optimization and some haven't even been developed yet. "The biggest challenge in our experiments is measurement," says Willi Auwärter, Professor of Molecular Engineering at Functional Interfaces at TUM. In contrast to conventional analytical methods in chemistry, which typically deliver data averaged across ensembles comprising billions of molecules, "We are inspecting the properties of and the bonds formed by a single molecule," he explains. Auwärter therefore uses extremely powerful imaging and atomic manipulation tools – the scanning tunneling microscope (STM) and the atomic force microscope (AFM). Both techniques utilize an atomically sharp microscope tip to address individual molecules. To minimize interference, experiments are carried out under vacuum conditions and at temperatures of around minus 268°C. By controling the tunneling current between the surface and the tip of the microscope, it is possible to visualize individual atoms and the structure of individual molecules.



"It was only by using this Raman sensor that we were finally able to demonstrate the molecular switching process."

Joachim Reichert

A look inside the measurement chamber: A gold-coated glass prism is used to electrically connect an oligophenyl molecular switch.

Picture credits: Astrid Eckert/TUM

Atomic force microscopes probe samples physically. The forces exerted on the tip alter the frequency of oscillation of a tiny cantilever in the microscope. By measuring these changes in frequency, it is possible to produce images with atomic resolution. "We can also use this technique to stimulate and modify the molecule," says Auwärter. In addition, by combining the two methods, he has been able to characterize chemical bonds and even determine the charge distribution in a metal-organic complex made up of cobalt and a phthalocyanine scaffold. This is an important step in understanding the electronic properties of this compound.

These measurements are made easier by using a special substrate for the molecular probes. Auwärter did not use pure monocrystalline gold or iridium substrates. Instead, he used a copper substrate, which he coated with an atomically thin layer of boron nitride. Because boron nitride acts as an electrical insulator, his sample was electrically decoupled from the substrate. Using this method, Auwärter and his team were able to measure the electronic properties of molecules and molecular aggregates in the absence of distorting interactions with the metal substrate.

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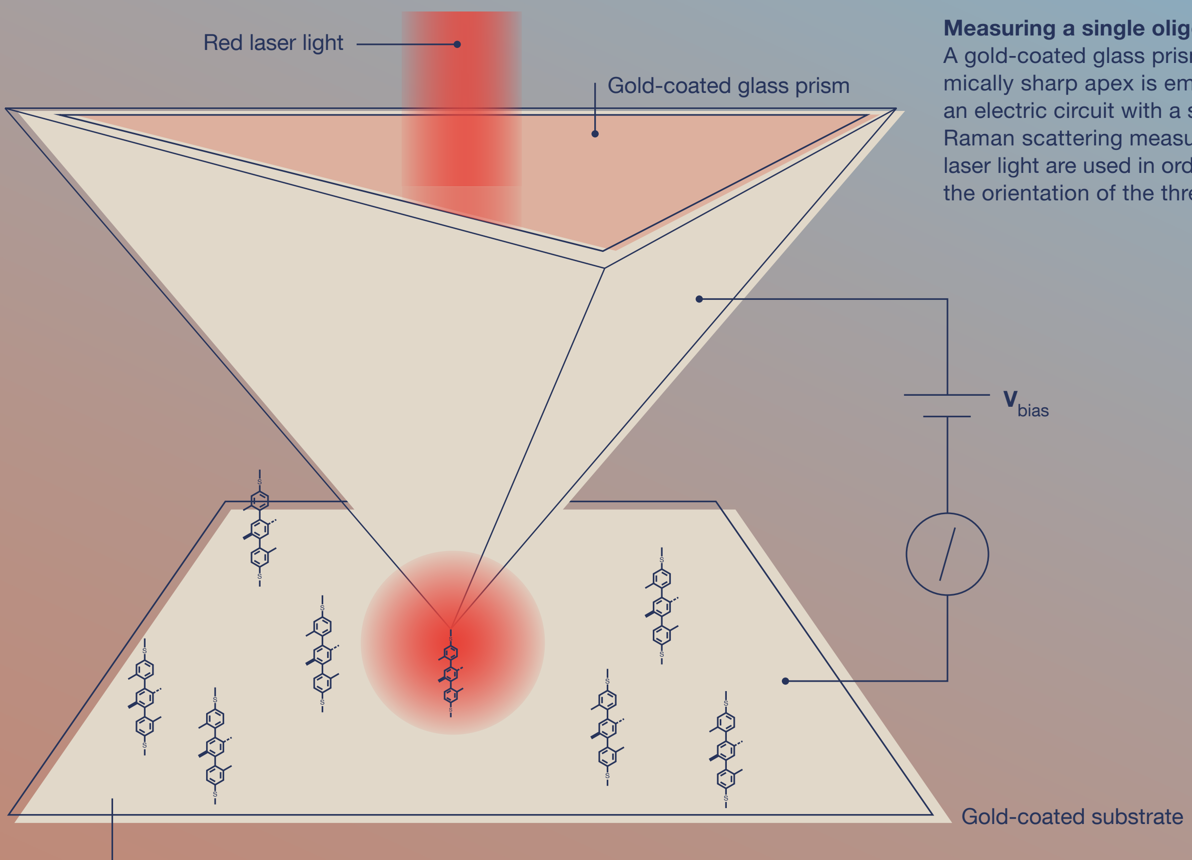
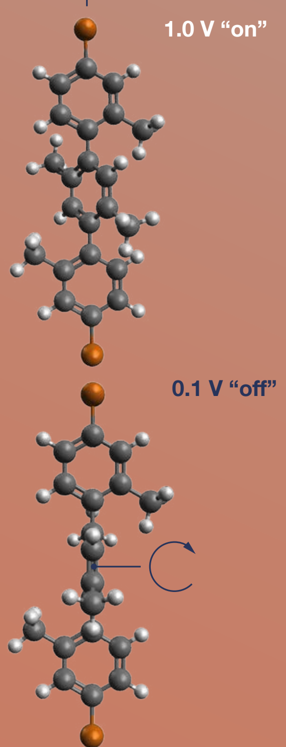
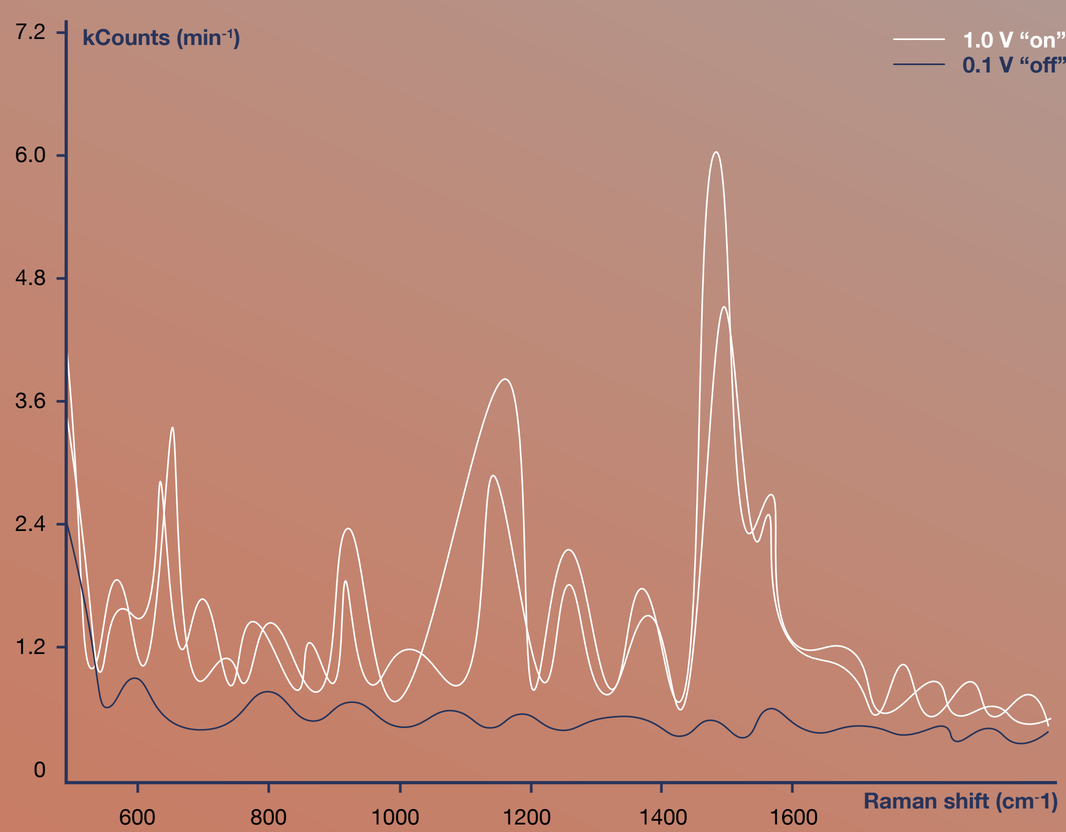
Measuring a single oligophenyl switch. A gold-coated glass prism with an atomically sharp apex is employed to create an electric circuit with a single molecule. Raman scattering measurements with red laser light are used in order to determine the orientation of the three phenyl rings.







The olygophenyl molecule switches when all three phenyl rings adopt a coplanar orientation.

A controlled fragmentation process produces glass prisms with an atomically sharp apex.

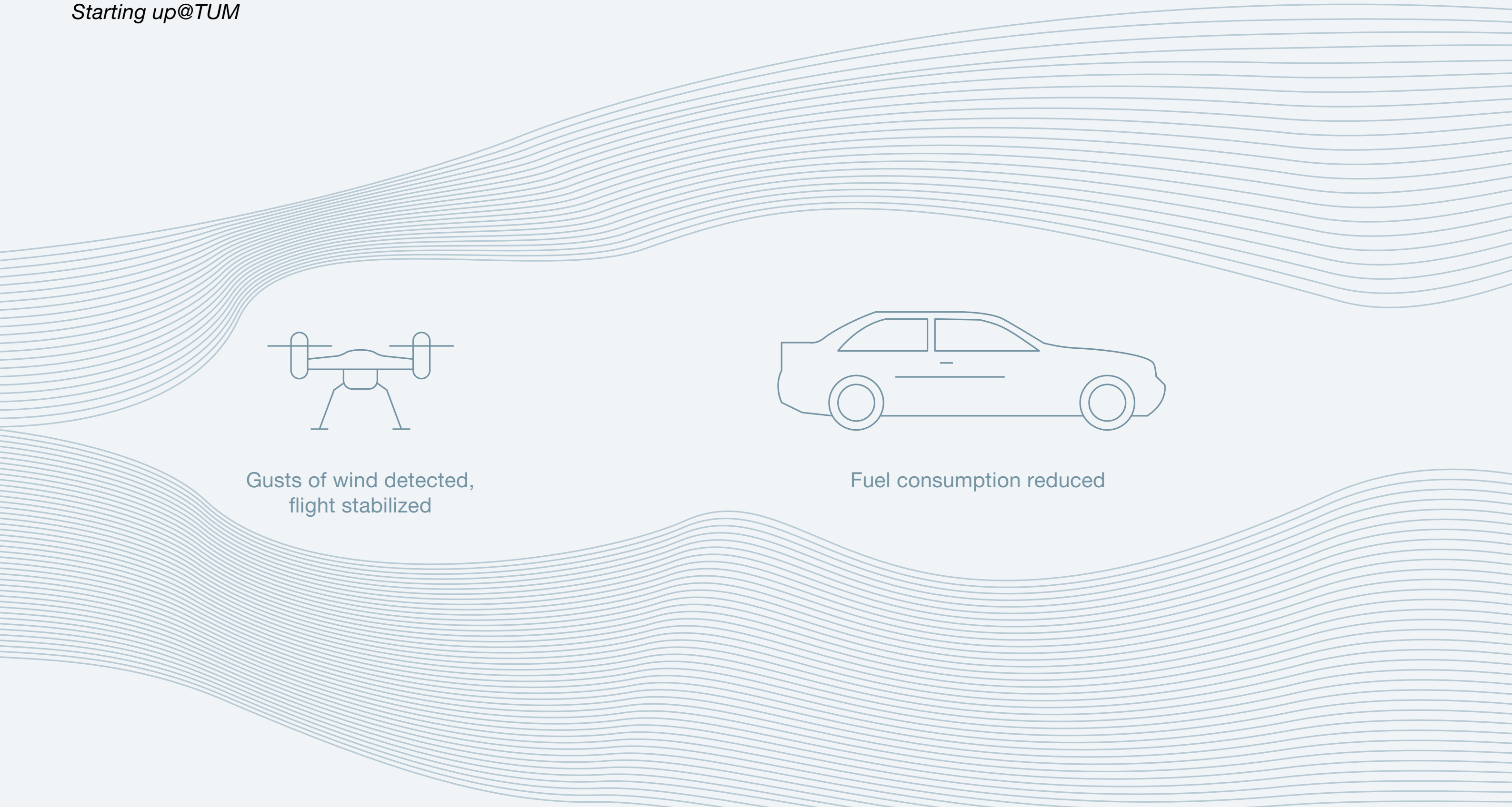
Picture credits: Astrid Eckert/TUM; Graphics: ediundsepp (source: TUM/Joachim Reichert)

Electrodes for individual molecules

Auwärter is gradually refining his scanning probe microscopy techniques to enable analysis of individual functional molecules. In parallel with this, Joachim Reichert is expanding the palette of molecular engineering techniques available to the Munich team by developing a clever new tool. With this new approach it became possible to scrutinize an individual oligophenyl switch. The challenge was to create an electrical circuit using a single molecule. Reichert used glass that had been subjected to a controlled fragmentation process to produce an atomically sharp apex. Coating the glass with a ultra-thin layer of gold produces an extremely sharp electrode tip, using which the oligophenyl molecule can be connected to a counter electrode. And it gets better: through the glass, Reichert shone red laser light, which was scattered by the switchable molecular species. This is known as Raman scattering, and by measuring it the researchers were able to obtain data on the chemical structure of the molecule at different applied voltages. “It was only by using this Raman sensor that we were finally able to demonstrate the molecular switching process,” explains Reichert.

“Our research unit brings together the ability to prepare functional elements at the molecular level with the methods needed to analyze them,” explains Johannes Barth. The spectrum ranges from molecular switches and photoactive molecules to tiny carbon nanowires and magnetically active systems. Each new approach, each new material, each experiment gives Barth and his 30 or so colleagues a further insight into the versatility of and exciting opportunities offered by molecular engineering. “We are laying foundations that could lead to real applications in areas ranging from nanoelectronics to photonics to catalysis.”

■ *Jan Oliver Löfken*



Getting Everything **Flowing Nicely**

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Wenn es einfach gut strömt

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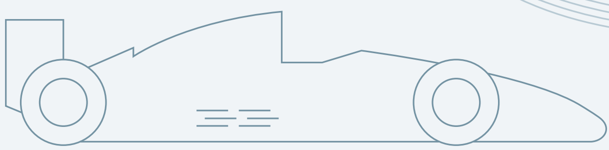
Im Windkanal bei BMW überlegte TUM Studentin Katharina Kreitz, wie viel besser man mit Sonden messen könnte, die perfekt auf die jeweilige Anwendung in punkto Form, Material und Dimension zugeschnitten wären. Warum also nicht selbst Sonden herstellen? Mit einem Partner gründete sie die Vectoflow GmbH, die überall da tätig ist, wo etwas strömt – ob Turbomaschinen, Flugzeuge oder Drohnen. □

Link
www.vectoflow.de

Whether you need to make a racing car faster, get a family car to consume less fuel or stabilize a drone in flight, knowing the flow behavior of your product will allow you to improve it. With its 3D-printed probes, Vectoflow has shaken up the niche market for pressure-based measurement technology.

All theory is gray, according to Goethe. Katharina Kreitz was a Mechanical Engineering student at TUM specializing in aviation, gas dynamics and astronautics. Wanting more than just to sit in lectures acquiring knowledge, she juggled her degree with jobs at several companies, where she mainly worked on the test bench. In the process, she realized that the niche market for pressure-based measurement technology was dominated by one company located in the United States. And, as often happens when a single player is virtually monopolizing a market, good service and custom-made products were hard to come by. Sitting in the wind tunnel at BMW while working on her Master's dissertation with her then supervisor Dr. Christian Haigermoser, the two found themselves thinking how much better you could measure if you had probes whose size, shape and material were tailored perfectly to their respective application. So why not manufacture probes themselves?



Speed improved: better balance between lift and downforce

No sooner said than done. The pair approached a world-leading provider of industrial 3D printing technology and designed a probe for metal 3D printing – a product that they felt many companies would definitely be interested in. So why not found their own company to produce these probes?
No sooner said than done. They decided to apply for an EXIST Business Start-up Grant. Awarded by the German Federal Ministry of Economic Affairs and Energy, this year-long grant covers the salaries of people looking to set up a business as well as their material expenses and coaching costs. The idea was very well received. According to the award criteria, however, one of the members of the start-up team needed qualifications in business administration. Although a job advert posted online attracted a lot of interest, none of the applicants seemed suitable. “Starting a business is like a marriage,” says Katharina Kreitz. “It all has to fit perfectly.” So why not acquire the business administration skills herself?
No sooner said than done. Without further ado, Katharina Kreitz launched herself into a ten-month international MBA at the Collège des Ingénieurs, attending lectures in Paris, Munich, St. Gallen and Turin. The grant was secured, and a 3D printing company came on board as an investor. And so Vectoflow was launched in 2015. The start-up’s website attracted the attention of people involved in Formula 1. Always working to improve their racing cars, they invited the team in for a discussion. This resulted in their first-ever order: to design a probe with three heads, a small-scale “measuring computer” for wind tunnels.

Customized, precise, integrated

Five years down the line, Vectoflow is on hand wherever anything is flowing – be that in wind turbines, turbomachinery, planes, drones, cooker hoods or hairdryers. In a nutshell: “Whenever something’s moving, we’ll measure it,” Katharina Kreitz says. This is because, the more manufacturers know about flow behavior, the better they can design their aerodynamics to be. As for the F1 engineers, they can improve the speed, the balance between lift and downforce and the resistance of a racing car. Family cars can be optimized to consume less fuel, while drones can be stabilized in flight, as the probes detect gusts of wind in advance before making sure that the drone’s components are perfectly aligned.
Thanks to 3D printing, the probes are tailored specifically to the customer’s requirements, meaning that they also deliver more precise measurements than their predecessors. The algorithms they use are more accurate, while interfaces enable the software to be integrated into the customer’s IT system. No competitor product can do all of this. In other words, Vectoflow has really shaken up this niche market.
Vectoflow currently employs 15 members of staff and serves customers in some 70 countries via an international network of distributors. The team have retained close links with TUM, where they have made use of many services available to start-up entrepreneurs. In MakerSpace, for instance, they still use the laser cutter to apply serial numbers to their probes. TUM provides a lot of student trainees, some of whom have already been taken on permanently. The company is planning to set up its first subsidiary in the USA in the coming year. In the future, Vectoflow wants to be the go-to provider for measurement technology for customers all over the world.
■ *Gitta Rohling*

Graphics: ediundsepp (source: Vectoflow)

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