hoch³ FORSCHEN
SCIENCE QUARTERLY

Winter 2020

TECHNISCHE UNIVERSITÄT DARMSTADT

Imprint

Publisher
President of TU Darmstadt,
Karolinenplatz 5,
64289 Darmstadt,
Germany

Editor
Corporate Communication
Jörg Feuck (Editor-in-chief)
Ulrike Albrecht (Graphic Design)
Patrick Bal (Images)

Conceptual design
conclouso GmbH & Co. KG, Mainz,
Germany

Title The research group around Prof. Norbert Pietralla's research includes the supra-conducting electron accelerator S-DALINAC of the Institute of Nuclear Physics on current question-positions concerning the origin of the elements and the structure of atomic nuclei; **Photography (title)** Katrin Binner

Printed by:
Druckerei Petzold, Darmstadt
on 100 g/m² PlanoScript,
FSC-zertificated

Circulation
5.000

Next issue
15th of March 2021

Service for readers
presse@pvw.tu-darmstadt.de

Newsletter subscription
www.tu-darmstadt.de/newsletter

ISSN
2196-1506

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A pocket-sized particle accelerator

A chip that can accelerate electrons in just a few millimetres to the same energy as current particle accelerators the size of a room? That is precisely what has been developed at TU Darmstadt and it could lead to inexpensive devices that can be used anywhere.

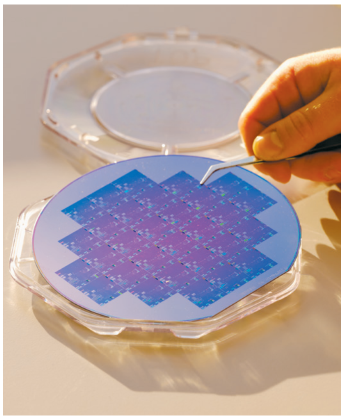

Photo: Katrin Binner

Accelerator chips could be produced in large amounts using established processes found in the semiconductor industry.

By Christian J. Meier

Let us briefly consider a scenario in the possible future of medicine: An endoscope detects a tumour. The doctor guides the instrument precisely up to the growth and presses a button. Nothing appears to happen, however fact electrons are being fired like bullets from the tip of the endoscope on the tumour cells to destroy them. This would be a very targeted cancer therapy that does not damage any of the healthy tissue around the tumour.

However, this is not possible currently because electron accelerators fill an entire room with their magnets and microwave resonators. Uwe Niedermayer from the Department of Electrical Engineering and Information Technology at TU Darmstadt would like to change this situation. In cooperation with his colleagues Thilo Egenolf and Professor Oliver Boine-Frankenheim and the members of the Accelerator on a Chip International Program (ACHIP), the engineer has presented a concept for an electron accelerator with a length of less than one millimetre. It can be fabricated in a similar way as computer chips so that large amounts could be produced at low prices. "This would mean that every university laboratory could afford their own electron accelerator", says Niedermayer.

> *"This would mean that every university laboratory could afford their own electron accelerator."*

Despite its small size, the device would be able to accelerate electrons to the same speed as a standard accelerator. In physics, the energy supplied to an electron is given in electron volts, since the electron is driven by the force of an electrical field. The mini accelerator from TU Darmstadt could be extended to any size and could therefore theoretically achieve unlimited energy. 70,000 volts have been achieved in less than a millimetre in the latest model. You would need around 50,000 standard batteries like those sold in the supermarket to reach this level of driving force.

However, a laser drives the particles here. Light also produces an electrical field but because it is a wave, this electrical field constantly changes direction. An electron would be initially accelerated but then in the next instant slowed down again by the same amount. The research team has discovered a trick that allows them to weaken the decelerating part of the field. A first design was presented in 2018. This has now been improved so that the accelerator chip can work without additional external equipment.

The principle behind it can be explained using the first, simpler design: Two parallel rows of tiny cylindrical pillars made of silicon – similar to a colonnade – are attached to the base. The channel between the cube-shaped blocks is only about 200 nanometres wide (a nanometre is one millionth of a millimetre), 25 times thinner than a human hair. The pillars themselves are also only about this size. The distance between the pillars corresponds approximately to one tenth of the wavelength of the laser. The laser beam is set up perpendicular to the channel and enters the "colonnade" from both sides. The acceleration process works roughly as follows: The silicon in the pillars interacts with the electrical field produced by the light waves and strengthens the field between the two pillars. A wave forms along the channel that oscillates more strongly between the pillars than in the free gaps. If an electron with a suitable initial velocity is sent into the channel so that it is always located between two pillars when the electrical field is pointing in its direction of travel, it will be accelerated. As the electron travels forward, it passes through the free gaps between each pair of pillars where the electrical field is weaker. This means that it is decelerated much less than it was previously accelerated. The electron travels increasingly faster as a result. The colonnade and the laser wave interact in a complex way so that the changeover from acceleration to deceleration adapts to the increasing speed of the electrons.

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Photo: Katrin Binner

Dr. Uwe Niedermayer performs research on design and simulation of accelerator-microchips at the Accelerator Physics Group at TU Darmstadt

One huge challenge that faced Niedermayer and his team was how to ensure that the electrons travel in a straight line through the channel. This is a problem because the strength of the electrical field changes at the edge of the channel, meaning that the electrons are driven away from their straight path.

In a standard electron accelerator, special magnets force the particles to travel in a straight line. The force that these quadrupole magnets apply to an electron can be described by comparing the electron with a ball on a saddle. The saddle is curved along its long side so that the ball will roll from the edge to the middle of the saddle where it should remain. However, the saddle curves downwards from the middle on its short sides so that the ball rolls away and falls from the saddle. But if the saddle is rotated quickly, after initially starting to roll away the ball would then be caught again quickly by the rotating, upwardly curved surface of the saddle. As a result, the ball remains in the middle of the saddle. This principle is recreated in particle accelerators by switching the field alignment of the quadrupole magnets along the path travelled by the electrons.

The scientists have designed their colonnade analogue to this principle. There are a series of large gaps between the otherwise regularly ordered columns. These create a similar effect to the rotation of a quadrupole magnet. If the electrons have been pulled away before a gap, the electrical field behind the gap changes so that the electrons are steered back into the middle.

The first version of their design still suffered from the drawback that the electrons were still diverging vertically. This focussing problem has now also been solved in the current design by making the lower section of each pillar out of glass and the upper section out of silicon. The refractive index contrast of these materials produces a similar focussing effect to that in the horizontal direction.

Niedermayer, who received the “Young Scientist Award for Accelerator Physics 2020” from the German Physical Society, is delighted with the simple design. “Our design has shortened the path to commercial application”, says Niedermayer. This is because there are already low-cost chip wafers available on the market that provide a double layer of glass and silicon. The Darmstadt design could be produced from these wafers using established processes in the semiconductor industry. Moreover, the team has now had a new idea that will reduce the technical complexity and costs even further, for which it has just submitted a patent application. This will take the researchers a step closer to achieving one goal of the ACHIP project: A particle accelerator, including its electron source and laser optics, which fits into a shoe box and could in the far future even be integrated into an endoscope.

The author is a scientific journalist and holds a PhD in physics.

Publication:
Uwe Niedermayer et al.: Physical Review Letters, 125, 164801 (2020);
DOI: 10.1103/PhysRevLett.125.164801

The Accelerator on a Chip International Program (ACHIP) is funded by the American Gordon and Betty Moore Foundation: **https://achip.stanford.edu/**

Prediction made by Noble Prize laureates confirmed

Physicists headed by Professor Norbert Pietralla from the Institute of Nuclear Physics at the Technical University of Darmstadt have developed a method to very precisely differentiate between the states of atomic nuclei. This has led them to make a spectacular discovery.

By Christian J. Meier

In the world of science, predictions sometimes precede the discovery by several decades. The physicists in Darmstadt are thus especially excited that they have been able to prove the existence of atomic nuclei with unusual symmetries, as was predicted 45 years ago by the Nobel Prize laureates Aage Bohr and Ben Mottelson. "These types of atomic nuclei are extremely difficult to observe", says Tobias Beck from the Institute of Nuclear Physics at the Technical University of Darmstadt. The team headed by Norbert Pietralla has now achieved this using new analysis and measurement methods that can very precisely map the decay of excited nuclei. The researcher's work was supported by an experiment carried out under the guidance of Dr. Volker Werner, who is also a researcher in Pietralla's work group. The State of Hesse provided support for the project as part of the "Nuclear Photonics" research cluster funded by the LOEWE programme. Support was also provided by teams in the USA, Russia, Great Britain and Romania, while the project received additional financial assistance from the German Federal Ministry for Education and Research. Yet the researchers also had some luck.

"This explains why such a quantum state had never been previously observed."

Atomic nuclei are extremely useful, for example in medical imaging technology such as nuclear magnetic resonance imaging. A great deal is already known about them in nuclear physics but these tiny particles are still shrouded in some mystery. One mystery is the question of what spatial form atomic nuclei can take. Laymen often imagine them as being spherical but most nuclei take on a different form. For example, the sphere can be distorted along one axis to form a sort of cigar shape and thus has a much less symmetrical structure.

Symmetry changes the behaviour of nuclei. As atomic components, they are subject to the laws of quantum mechanics – which state that a spherical object cannot rotate because no new, distinguishable state would exist as a result. A cigar-shaped nucleus cannot rotate around its longitudinal axis because this would not change its state. However, the "cigar" can certainly rotate around an axis which is perpendicular to the longitudinal axis. Yet in this case, it is also possible to observe both higher and lower symmetry. Quantum mechanics describes objects using a mathematical function – the so-called wave function. This can be positive or also negative at different locations. If you imagine the signs of the wave function of a nucleus to be red (positive) and blue (negative), it can occur that the "cigar" changes its "signs" as it rotates around 180 degrees. The red and blue colours will thus swap sides. It is only after further rotation around a full 360 degrees that the initial state is restored. It is also possible for both sides to be blue (or red) and a 180 degree rotation is then sufficient to achieve congruency. The specialist jargon for these two cases is R-symmetry. They are described using the values +1 (identical to the initial state after a 180 degree rotation) and -1 (a 360 degree rotation is required).

An atomic nucleus cannot only be symmetrical with respect to its axial rotation but also its reflection about its centre point. Roughly speaking, a point lying on the bottom left is reflected in the top right or vice versa. This type of symmetry is called parity in physics. There are also two types of parity defined as +1 and -1.

States of atomic nuclei in which R-symmetry and parity have the same sign have been well studied. "However, there is a lack of information on states with different signs", says Tobias Beck. Although these states had been predicted by the Nobel Prize laureates Bohr and Mottelson, they are extremely difficult to observe directly. To detect the rotating state of a nucleus, the nuclei have to be given energy, for instance in the form of gamma radiation. Different states can then be excited energetically. As the nuclei return to their ground states, each one emits a characteristic gamma ray signature with different energy. Special forms of nuclei are difficult to detect because they are only rarely excited in comparison to other forms.

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"While investigating atomic nuclei of dysprosium, we were lucky enough to find unusually favourable conditions in the isotope ^{164}Dy", says Beck. In this isotope, there is a mix of states with different values for the R-symmetry. It would be like having a cigar with a red and a blue half but where the red half also has a blue tip. In this type of situation, the high probability of being excited by gamma radiation is inherited from the symmetrical configuration (two blue tips). "This makes them easier to observe", says Beck.

The team from Darmstadt achieved this thanks to a very precise measurement method that was developed using the High Intensity Gamma Ray Source at Duke University in Durham, North Carolina, USA. It produces gamma radiation that can target individual excited states of the atomic nuclei. he research cluster "Nuclear Photonics" is dedicated to this kind of precise manipulation of nuclear states and Darmstadt is a world leader in the further development of this field of research. The scientists at TU Darmstadt were thus able to excite mixed states that should contain the desired quantum state of positive parity and negative R-symmetry.

Their model predicted that this previously unobserved state would emit its excitation energy in the form of gamma radiation with two different energies, whereby one would be twice as intensive as the other. In the more familiar state with the same signs for parity and R-symmetry, the relationship between the two intensities is reversed. The researchers were able to determine the different intensities of the two types of radiation in an experiment. They discovered that there was a mix of two intensity ratios. The contributions made by the investigated state with different signs for parity and R-symmetry proved to be 125 times weaker than for the known state. "This explains why such a quantum state had never been previously observed", says Beck.

"In the future, we want to specifically investigate other atomic nuclei in which we expect to find deviations in the decay behaviour", adds the physicist. He hopes that this work will be helped above all by the planned commissioning of the "Variable Energy Gamma-ray System" at the European research facility "Extreme Light Infrastructure – Nuclear Physics" in Bucharest, Romania, in 2022. The nuclear physicists in Darmstadt have made decisive contributions to the design of this facility and it will allow the energy to be focussed even more precisely into a narrow frequency band. It is something that Tobias Beck is looking forward to: "It will take our research into nuclear photonics and its scientific and technical applications to a whole new level."

The author is a scientific journalist and holds a PhD in physics.

Publications:

T. Beck et al.: ΔK =0 M1 Excitation Strength of the Well-Deformed Nucleus ^{164}Dy from K Mixing, Physical Review Letters 125, 092501 (2020).
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.125.092501

State Offensive for the Development of Scientific and Economic Excellence (LOEWE): "Nuclear Photonics" research cluster at TU Darmstadt:
www.ikp.tu-darmstadt.de/nuclearphotonics/nuclear_photonics/index.en.jsp

Photo: Katrin Binner

Tobias Beck (left) and Dr. Volker Werner (right) next to the superconducting electron accelerator S-DALINAC in the Institute of Nuclear Physics

The world as a data community

A team of computer scientists headed by Professor Carsten Binnig is developing a trustable platform for data sharing called TrustDBle. The aim is to open up completely new possibilities for cooperation in the area of big data and AI.

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A team of computer scientists headed by Professor Carsten Binnig is developing a trustable platform for data sharing. The aim is to open up completely new possibilities for cooperation in the area of big data and AI.

__ By Boris Hänßler

When a patient goes to see the doctor, he doesn't necessarily want to share the data that is collected by the doctor with any third parties. If the patient is suffering from a serious illness, however, they might be happy to share their data for medical research purposes but this is not easy to do due to data protection regulations. The conflict between data protection and data sharing does not only affect the medical sector: Shared data could help to make the production process in the industrial sector more efficient, cheaper, quicker and environmentally friendly. Data could help politicians make better decisions, while it is also essential for uncovering credit card fraud and money laundering in the financial sector. However, data protection regulations make data sharing a daunting task not to speak of the lack of a echnical infrastructure that would make it possible to share data in compliance with these regulations.

And there is a huge amount of data available: It is anticipated that the amount of data produced worldwide will increase to 175 zettabytes by 2025. Although this data could be useful for the larger community, much of it is often lost because companies keep it for themselves. The EU wants to make data sharing easier but the technologies required do not yet exist. And this is the problem that the researchers headed by Professor Carsten Binnig from the Data Management Lab at TU Darmstadt are working on. They are developing TrustDBle (pronounced "'trustable") – a new platform that will enable trustworthy and uncomplicated data sharing. The research is being conducted as part of the National Research Center for Applied Cybersecurity ATHENE, an alliance between TU Darmstadt, the Darmstadt University of Applied Sciences and the Fraunhofer Institutes SIT and IGD. It is the largest alliance between research institutes in the area of cybersecurity in Europe.

Photo: Katrin Binner

There is a huge need for technology such as TrustDBle. "We are currently experiencing a paradigm shift in the economy", says Binnig. Companies have focussed up to now on using their data just for themselves. In the automotive sector, for example, manufacturers and suppliers have developed their own information systems. Although the individual information systems are often connected via interfaces, this only allows very limited data sharing capabilities and requires huge efforts to connect the individual systems. Today, more or less each company still manages only their own data in silos and does not yet leverage the potential of sharing data between companies.

"However, industry recently realised that it is beneficial to share data across organizational boundaries", says Binnig.. "It allows them to optimise business processes and make them more transparent, as well as to better push forward many applications in the area of AI where there is simply a lack of data, or even to make such applications possible at all." But why is it so difficult to share data? "There are a whole series of challenges when sharing data", says the researcher from TU Darmstadt. "On the one hand, there are a multitude of laws such as the EU General Data Protection Regulation that stipulate how the data has to be handled. In addition, there are internal company policies that also regulate which data can be shared with whom and where."

A good example is in a hospital: Although the hospital is permitted to collect data about patients, the volumes of data are very small overall and insufficient for training AI models. AI usually requires lots of example data to reliably learn patterns. For instance, in order to detect skin cancer on images, the AI ideally has to be provided with hundreds of thousands or preferably millions of images of skin cancer and also of healthy skin – it is only in this way that the AI will reliably be able to differentiate between the two on its own.

"I am convinced that data sharing will have huge benefits for the economy and society."

However, data protection regulations often make it difficult to share data. The hospital cannot simply add data it has collected to a pool of other data even if it would have a medical benefit. A doctor or a hospital manager must always ask themselves: What am I permitted to do? What are the legal regulations? Most people then make the decision not to share the data. "We have to develop a system that can flexibly implement different legal or internal company regulations for the sharing of data", says Binnig. The researchers are basing their work on blockchain technology. It is suitable for this purpose because it offers important advantages for the sharing of data. On the one hand, the data is saved in tamper-resistant blockchains. This is important in order to prevent commonly used data from being changed unnoticed by an individual participant. This is especially relevant when critical decisions are made based on this commonly used data, as is the case with medical data from patient files.

The tamper-resistant blockchain technology is secured with the aid of cryptographic processes that summarise change operations in blocks. Every block in a chain is linked to previous element via a unique ID (so-called cryptographic hashes). The ID is generated from the contents of a block so that any change to the contents of one block requires a change to all subsequent blocks – otherwise the chain of IDs is no longer valid. Blockchains can also use smart contracts to conclude digital contracts between parties that define how the data can be accessed. However, the agreement processes that must be carried out to implement smart contracts in blockchains require time and resources which makes everything slow and expensive. This effect is intensified as the number of participants grows, which is why blockchains are difficult to scale up.

The team of researchers at TU Darmstadt have now had the idea to add an additional layer on top of the blockchain that forms an abstraction layer over existing blockchains. The new layer works like a database that partitions the managed data and parallelises read and also change operations on the data across multiple blockchains. In addition, the layer makes it possible to partially replicate data so that not every participant receives a copy of all of the data but only a configurable part. Furthermore, the data is temporarily saved on an ongoing basis in a cache so that quick access is possible without having to burden the blockchain itself every time. The participants can also agree that a majority is not needed to approve any changes to non-sensitive data. Basically, the system combines the advantages of a traditional distributed database with those of blockchain technology. On the one hand, this makes TrustDBle as efficient as a database and means it can enable the common use of data for many applications, while on the other hand, TrustDBle offers the tamper-resistant features of blockchain technology. In the event of any legal disputes, all changes to the data are transparently logged in the blockchains at all times.

"Another advantage of our method is its flexibility", says Muhammad El-Hindi, who developed the system together with Binnig and Simon Karrer. "Due to the fact that the most important activities take place at the layer above the blockchain, the technology still works even when the blockchain technology itself is enhanced." El-Hindi and Karrer are thus planning to launch a start-up to make the technology behind TrustDBle marketable and then sell it commercially. The chances of success are good. The range of potential applications is extremely diverse. The researchers are also planning, for example, to cooperate with Merck and Fraunhofer IWKS to network data from the recycling industry and thus make recycling processes more efficient.

"This is a particularly good example of how data sharing in industry can also have implications for society", says Karrer. "In the chemical industry, a waste product for one company is often a raw material for another." Nevertheless, companies dispose of this waste, which is not only bad for the environmental footprint but also results in economic burdens due to the high cost of disposing of the waste or purchasing raw materials. In future, companies will be able to operate a joint platform using the technology developed in Darmstadt that will allow them to share production data and avoid waste products. The trustable sharing of data is a basic requirement for these types of application that involve competitors. "I am convinced that data sharing will have huge benefits for the economy and society", says Binnig. "The technical infrastructure required to achieve this has now finally been realised with TrustDBle."

The author is a technical journalist.

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El-Hindi, Muhammad; Karrer, Simon; Doci, Gloria; Binnig, Carsten: TrustDBle: Towards Trustable Shared Databases. In: FAB 2020.

El-Hindi, Muhammad; Heyden, Martin; Binnig, Carsten; Ramamurthy, Ravi; Arasu, Arvind; Kossmann: BlockchainDB – Towards a Shared Database on Blockchains. In: SIGMOD 2019.

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Background:

The TU Professors Casten Binnig and Sebastian Faust head the ATHENE mission TRUDATA. The aim is to develop new technologies that will enable the trustable, reliable and autonomous sharing of data, which is relevant for many different applications in the health, manufacturing and financial sectors.

Artificial intelligence is becoming more versatile

Neural networks are good at solving specific tasks but unlike humans they struggle to transfer a strategy they have just learned to other tasks. Researchers at TU Darmstadt are making this possible.

By Boris Hänßler

When a child is asked to sort out and tidy up his toys, he finds it an easy task because he knows how to tidy up and also where everything belongs. After all, he has done the same thing hundreds of times. The child's parents now ask him to help them with a new task in future – to tidy up the kitchen and sort out the rubbish. Despite this being a new task, the child learns quickly because he already understands the concept of sorting things out. He only has to work out where everything should go. A robot whose "brain" is a neural network can also learn to tidy up toys. If you then ask the robot to sort the rubbish, however, it has to start all over again from scratch.

Neural networks are designed to behave like the brain. They learn like a human, who learns by training so-called synapses – in the network these are actually parameters – and these synapses are reinforced every time a training session is completed successfully. The stronger the synapses become, the more reliably the network functions. Yet these learnt skills are forgotten again when faced with a new task. "Although deep learning networks are particularly good at learning to complete specific tasks, managing to extract the underlying structures used to find the solution and transfer them to other tasks has remained an open area of research until now", explains Daniel Tanneberg, a doctoral candidate in the Intelligent Autonomous Systems (IAS) Group at TU Darmstadt. He and his colleagues have now developed a neural computer architecture that is designed to do exactly this. They describe their system – the Neural Harvard Computer (NHC) – in a paper published in the journal Nature Machine Intelligence.

"We know from learning research that the ability to transfer strategies used for one problem to another is a key feature of intelligent behaviour", says Tanneberg. Therefore, a neural network must be designed to be as generalised as possible so that it can handle not only different data but also different tasks. It is only then that it actually behaves intelligently.

The NHC has a memory-augmented, network-based architecture. The researchers have augmented a traditional neural network with multiple modules, such as external memory, and this makes it possible to introduce another level of abstraction. The information flows are split and the algorithmic operations are decoupled from the data manipulations. The network separates what it has learnt about specific data from the general strategies it has learnt. For a robot, one level would be differentiating between the toys and another sorting them. Until now, both of these levels were encoded into the synaptic weightings in neural networks and were thus not separated.

Using a set of eleven tasks, the researchers have shown that the NHC can reliably learn algorithmic solutions with strong generalisation and transfer them to any task configuration. "This has the huge advantage that the network is able to master new tasks more quickly because only the data-specific operations need to be adapted", says Tanneberg. This saves resources because neural networks often require a large amount of computing power and a lot of days of training. Another advantage is that it is easier to understand these types of networks because they offer greater insights into the learning process and their behaviour after learning. The new architecture opens up the possibility to discover new and unexpected strategies that the network adapts. Ultimately, it wouldn't do us humans any harm to learn to behave even more intelligently.

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Publication

Tanneberg, D., Rueckert, E. & Peters, J. Evolutionary training and abstraction yields algorithmic generalization of neural computers. Nature Machine Intelligence (2020).
In Nature Machine Intelligence: **https://rdcu.be/caXgk**

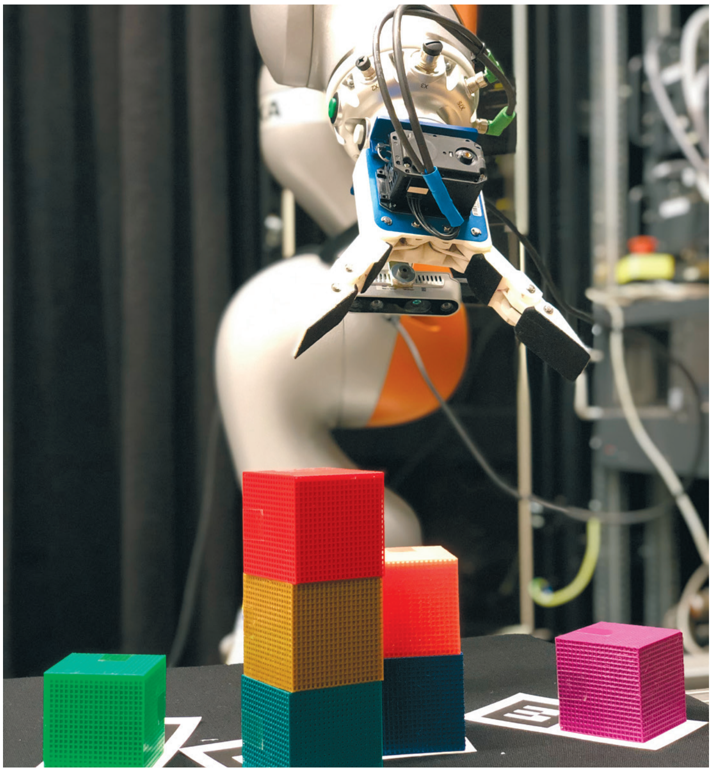

Photo: Daniel Tanneberg

The robot cleans up objects using a strategy learned from a computer game.