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This special was created by the editors of *New Scientist* on behalf of Centrum Wiskunde & Informatica (CWI), on the occasion of its 75th anniversary.

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75 years of dynamic research

It is CWI's anniversary, and we are celebrating it with a look behind the scenes of the institute. Over the past 75 years, this has been the birthplace of numerous breakthroughs in mathematics and computer science. As early as 1952, six years after its foundation, researchers developed the first computer in the Netherlands, right here at this institute. Many more successes would follow.

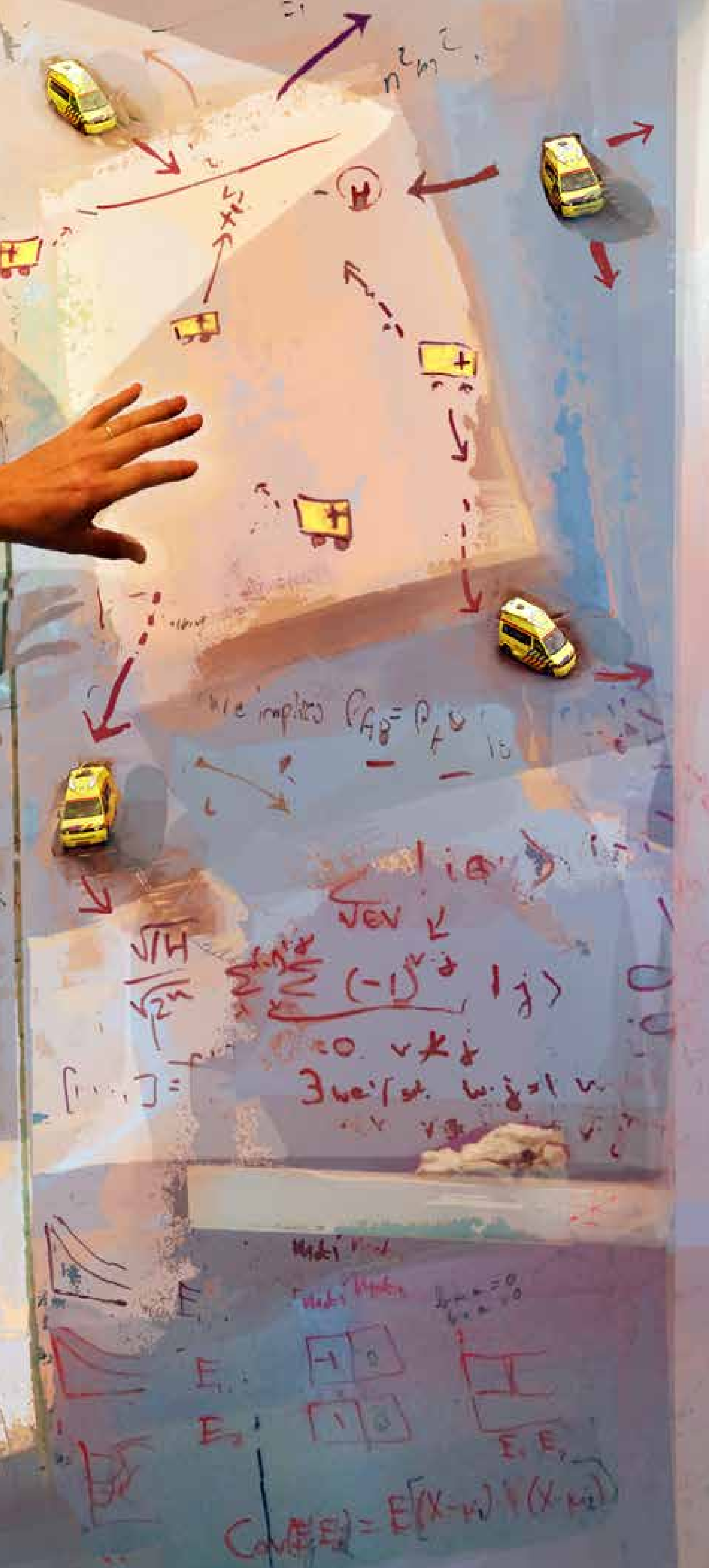
In this magazine, however, we will not so much reflect on the past, but rather look to the future. What are CWI researchers working on now, and what are the greatest challenges? This forward-looking view is characteristic of science, and CWI is no exception. As a national institute, this is *the* place where mathematics and computer science meet, and where scientists explore bold research paths.

CWI is not alone in this. Together with eight other institutes, CWI falls under the NWO-I umbrella organization, i.e., the institute organization of the Dutch Research Council (NWO). The institutes collectively cover a multicoloured palette of research fields, each from their own expertise, from particle physics and astronomy to marine research and criminology. Like the other institutes, CWI fulfils the role of a national research centre. It always looks for connections with other organizations at home and abroad, with both academic partners as well as companies and social institutions. This leads to wonderful breakthroughs, which not only increase fundamental knowledge, but also have an impact on society.

I am, therefore, proud of the achievements of CWI, and congratulate all CWI employees on this jubilee. I hope you, as the recipient of the magazine, will enjoy reading about it as much as I do.

Miriam Luizink
Director of NWO-I

COVER DESIGN: PASCAL TIEMAN
IMAGE: ROBERT VAN LIERE AND JOHANNES ABELING



MAAIKE PUTMAN

Saving lives with mathematics

Rob van der Mei, professor of applied mathematics: 'When I obtained my PhD in the mid-1990s, I was focussing on post offices. Customers come in at random moments, needing a different amount of time per person. So, the question is: how many counters are needed to get the average waiting time per customer under ten minutes, for example? Later, the Internet and mobile networks emerged, with similar issues. When and how long people call is purely coincidental. How many masts do you have to install in which locations to make sure that the chance of someone not being able to make a call or surf the Internet at any given time is sufficiently small? More recently, we looked at ambulances. In a life-threatening situation, they must be on site within fifteen minutes. So, how do you make sure that as many ambulances as possible actually succeed? It is important to be able to predict to a certain extent where and when accidents will occur. In general, we do not have ambulances drive back to their fixed location but send them to a location where the number of ambulances is low at that time. That way, they are already in the neighbourhood, in case of an accident. And that approach really works. During a pilot project, there were 30 per cent fewer cases where the ambulance was en route for longer than the prescribed 15 minutes. So, you could say that maths saves lives. The fire brigade, the police, and ProRail, among others, can also benefit from similar models. We are also working on a project to improve acute care for the elderly. These are all great examples of applied mathematics that are of enormous societal importance.' – JPK

‘Fundamental research is not a luxury’

The mathematicians and computer scientists working at CWI should be treated like top football players, according to director **Ton de Kok**: give them room to let their talent flourish, so they can provide the best solutions to society's needs.

Text: Joris Janssen and Jim Jansen
Photography: Bob Bronshoff

When you think of science, universities readily come to mind. Extensive knowledge strongholds that explore many different corners of science and educate a stream of students. The Centrum Wiskunde & Informatica (CWI) does things differently. At this research institute, mathematics and computer science are the order of the day. And, although young researchers take their first steps in science here, you will not find any undergraduates in the CWI building at the Science Park in Amsterdam.
CWI has had a new director since 1 October 2020: Ton de Kok. He previously worked at Philips, where he focused on the mathematical optimization of business processes. He then switched to Eindhoven University of Technology, where he is now professor of quantitative analysis of operational processes one day a week. We talked to him about the unique position CWI is in and what we can expect from CWI in the next five years – the period of his appointment.

You were a little surprised that CWI came to you as a possible new director. How so?
'I once called myself a mathematician adrift. Here at CWI, they really do have the Lionel Messis of mathematics and computer science. I wouldn't dare to compare myself with their talent. I have quite an international reputation in my profession, but I know my place. When I recently read a scientific article by one of our researchers about software for future quantum computers, I thought: I know my stuff, but this is pretty difficult.

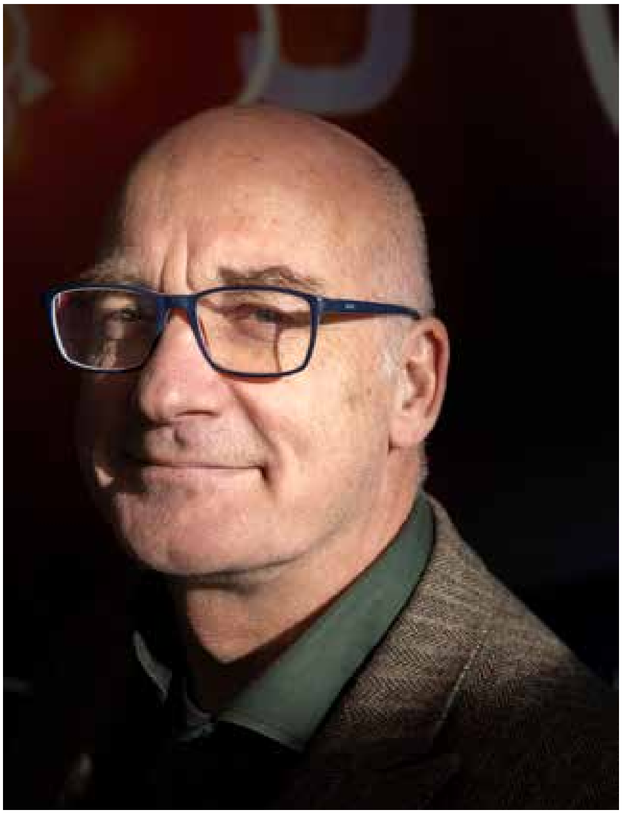
Fortunately, it is my job to focus on more overarching developments, such as the positioning of CWI in the major field of issues where mathematics and computer science are relevant. There, you don't talk about professional matters, but about how to organize yourself together with others in such a way that you achieve maximum results. And that is something I know all about.'

One of the unique aspects of CWI is that it combines mathematics and computer science. What does that mean?
'Math can exist without reality. You can do mathematics in a purely abstract world. But from the beginning, when CWI was still called the Mathematisch Centrum, it has focused on applying mathematics to social applications. For example, calculations of the safe height of dikes in the fifties and the development of the first computers in the Netherlands. A good example of the interplay between mathematics and computer science is the "shortest path algorithm" developed by Edsger Dijkstra in 1959. That algorithm is at the heart of today's navigation systems.'

> 'At CWI, we have the Lionel Messis of mathematics and computer science'

What are the advantages of combining mathematics and computer science within one institute?
'In the mid-1980s, it became clear that computer science is the field par excellence for the broad application of mathematics in society. Computers and information systems began to play an increasingly important role. All kinds of algorithms were created with the aim of making processes run optimally. Mathematics plays an important role in this. Again and again, mathematicians try to prove the effectiveness and efficiency of the algorithms that computer scientists come up with. As soon as you understand how and why an algorithm works, you can implement it in a smarter way. Because mathematicians and computer scientists at CWI work within one location, you speed up this process.'

How do you view the position of CWI in these developments? What kind of focus do you envisage?
'If you ask me what we should be good at, my answer is: those things that we have been good at for a very long time. As far as I am concerned, we should not widen our



'People can delve deeply in their research'

Ton de Kok has been director of CWI since October 2020.

focus now. You cannot focus on everything at once, because you have to invest a lot to be able to take the next step in an area. On the basis of the foundations of mathematics and computer science, we can respond to the needs of society, together with knowledge partners, in areas such as energy transition, mobility, sustainable food production, and communication. For example, we are now investing a great deal in things like quantum computing and cryptography.'

What role does CWI have in the development of the quantum computer?
'In the 1990s Paul Vitanyi, one of our researchers, first researched algorithms that could be used in future quantum computers. Another computer scientist of ours, Harry Buhrman, dedicated himself to the complexity of these algorithms and gained world fame in doing so. His research is a good example of how mathematicians can provide insight into the workings of quantum algorithms before a quantum computer is even available to test them.

At CWI, we are researching which problems quantum computers could solve much faster than current computers. Quantum computers can have an enormous impact on, for example, the generation, storage, and distribution of energy. But also, on the smart use of data from the *Internet of things*, on self-driving cars, on the development of better medicines, and so on. If we continue to focus on the fundamental aspects of computer systems and algorithms, CWI can make a contribution across the full breadth of these application areas.'

As a research institute, how can you keep up with these rapid developments?
'As a scientist, you should not want to keep up with these developments at all. You have to look for the scientific challenges that lie behind these developments. We must continue to work on fundamental issues. It often takes a while to find solutions. Sometimes you succeed with a stroke of luck. But often it requires perseverance together with other people in the world who have the ability to structure, abstract, formulate, and gather results from problems. With this perseverance, we at CWI can optimally dedicate ourselves to welfare and prosperity in the Netherlands and the rest of the world.'

Is this focus on fundamental science another characteristic that gives CWI a unique position within the Dutch world of research?
'The unique thing about CWI is that there are many extremely smart people here, who are very good at their jobs. And the great thing is that they can fully concentrate on their research here. People can delve deeply in their research. And that is necessary, too. The outside world sometimes sees it as quite a luxury. But I do not think that term is quite appropriate. You can compare it a bit with the "position of luxury" that professional footballers have. It is entirely due to their talent.'

Where do you hope CWI will be in five years?
'In the end, success is measured by what others say about you. I hope they are still happy with CWI in five years' time. That goes for Dutch universities, but also for NWO, for example. You cannot earn a good reputation by shouting very loudly that you are good. You want others to say: I want to work with *you*.

Besides, I think we should remain realistic. Not just us at CWI, but the people around CWI as well. Together with 17 million Dutch people, we determine how much money we spend on science. In the light of the history of mathematics and computer science in the Netherlands, I think we should have high ambitions. We have to get rid of the idea that this kind of fundamental research is a luxury.' ■

SPOTLIGHT

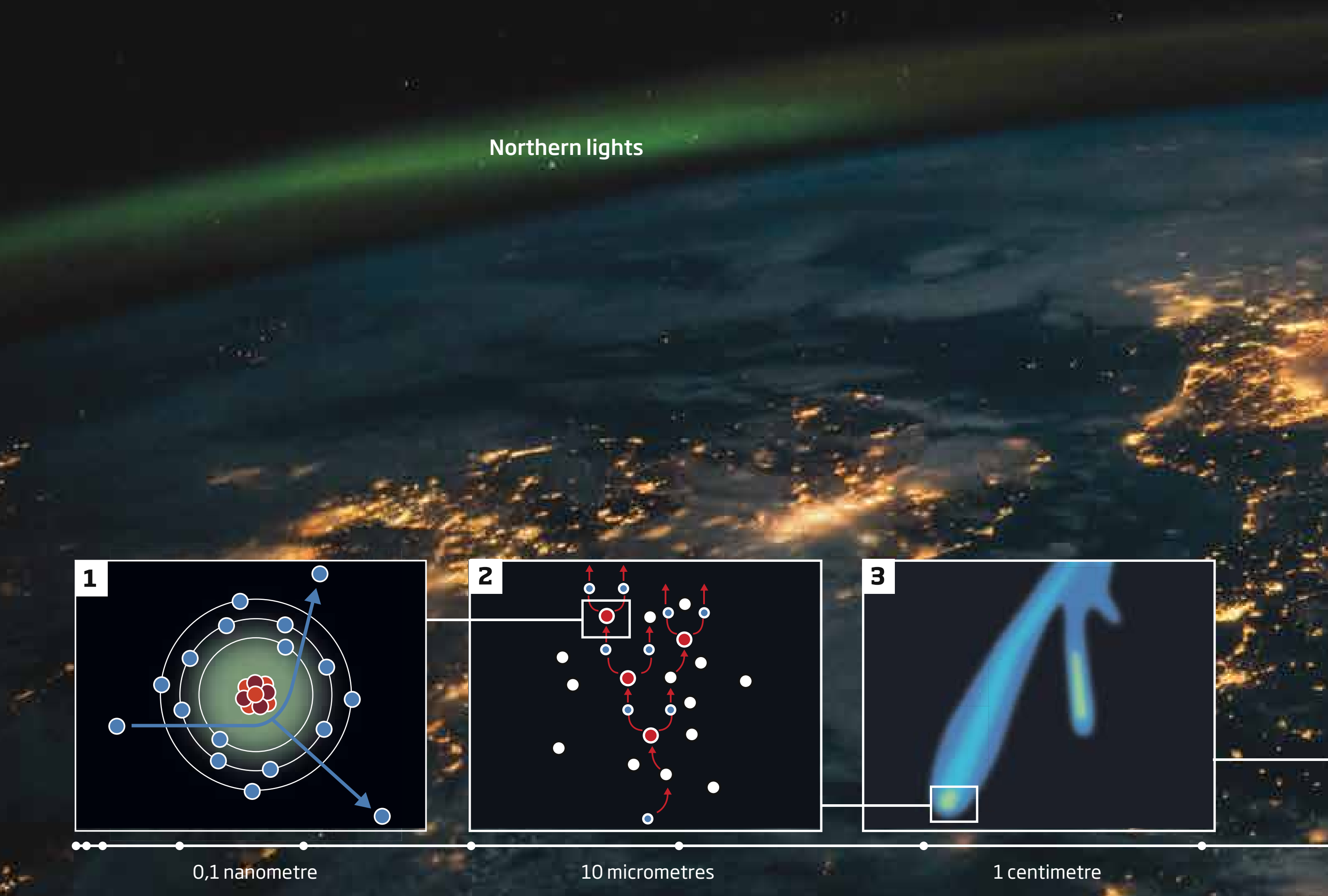
'We want to teach AI to deal with different perspectives'

'Jan Punt's 1739 etching *Allegory of the VOC* shows a woman receiving gifts. She is the personification of the Dutch East India Company, officially the United East India Company. In the background, Batavia is depicted, which was the centre of the Dutch colonial territories at that time,' says CWI researcher Laura Hollink. 'The etching shows how proud the Dutch were of their wealth and trading spirit. This perspective is the artist's choice. There is also the perspective of inhabitants of the colonial territories. They did not live in luxury but were exploited. Our current digital infrastructure is not built to deal with multiple perspectives. At the new Cultural AI Lab, we want to use cultural heritage such as this etching to teach artificially intelligent (AI) computer systems to deal with different perspectives.' To this end, computer scientists from CWI, among others, are working with humanities scholars and cultural heritage institutions with a great deal of experience and knowledge in this field. Hollink: 'The aim is ultimately to develop AI that can, for example, search through large heritage collections to compare perspectives or analyse how perspectives change over time.' The Cultural AI Lab, of which the Rijksmuseum is also part, wants to be able to place collections in a new context and provide a more complete picture. Hollink: 'AI could help with this in the future by, for example, making implicit perspectives explicit, so that you know from which perspective a work has been described. AI may also be able to find new links between heritage objects, for example between this etching and an object belonging to someone who lived in Batavia at the time.' –DS

BRAM BELLONI

Lightning under the mathematical microscope

Every second, 45 bolts of lightning hit the earth. Lightning seems to be a familiar phenomenon, but it is one that always has new surprises for us. For example, it has not been known for very long that gigantic bolts of lightning can also shoot up above the clouds, and that lightning can make the air radioactive and can even launch antimatter into space.
To understand the kilometres of lightning (see 5 and 6), we have to zoom in on the free electrons in a thundercloud, which collide with an air molecule roughly every millionth of a metre (see 1). These microscopic processes are too small and too fast to observe, but CWI researchers can now simulate them with computer models and calculate discharges at ever-increasing length scales (see 2 to 4).



INFOGRAPHIC: PEPIJN BARNARD, TEXT: LAURA BERGSHOEF
SOURCE: UTE EBERT, CWI
IMAGE: NASA, BART VAN OVERBEEKE

Mini lightning in technology

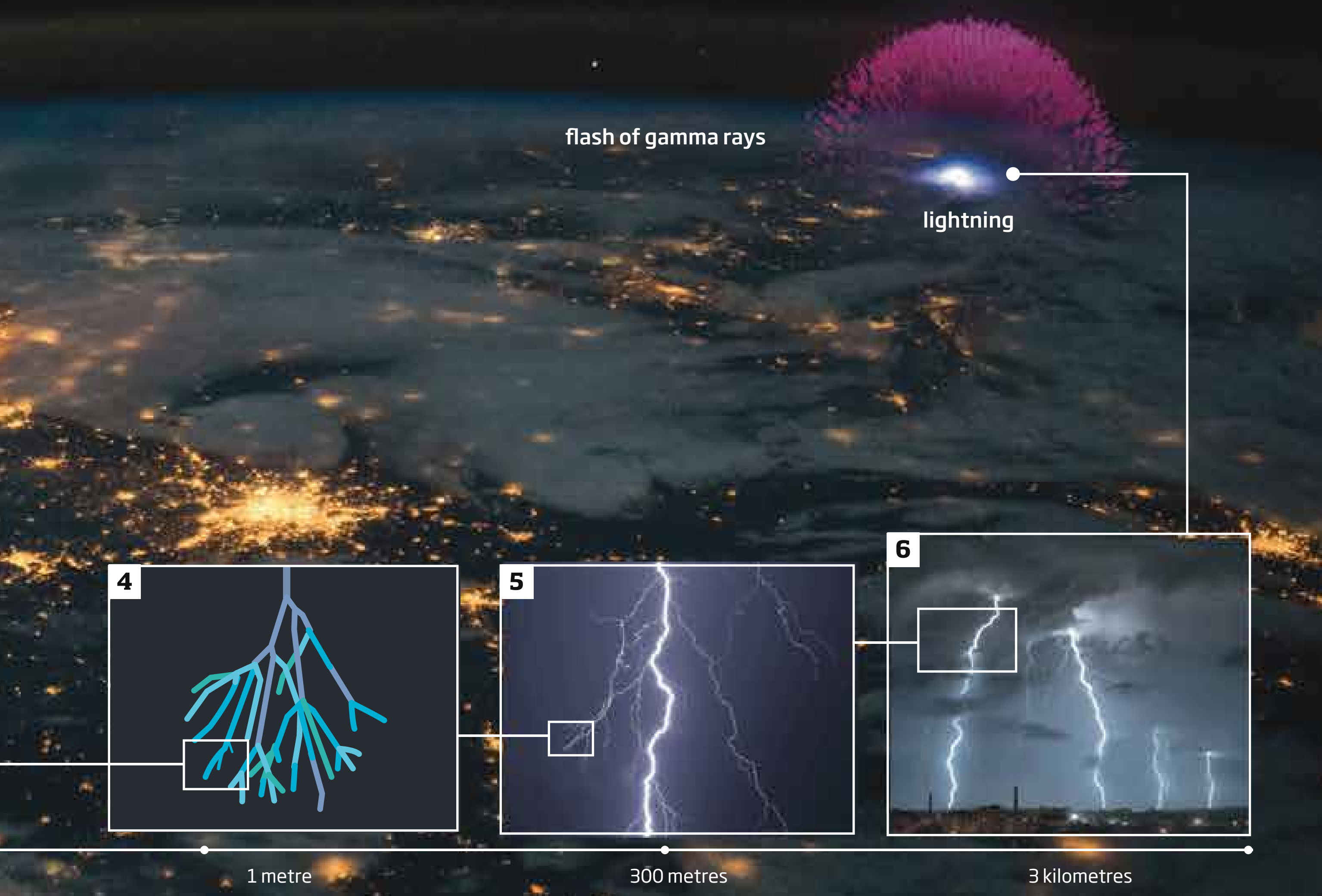
The CWI models are also applied in the development of new technologies, such as *plasma medicine*. A miniature bolt of lightning can produce aggressive nitrogen and oxygen compounds and UV radiation. This can be used to kill bacteria while leaving human cells intact.

1 Electron-molecule collisions In a thundercloud, high electrical fields are created that accelerate free electrons. When an energetic electron collides with an air molecule, the molecule can split into a positive ion and a second free electron. The collisions also result in chemical conversions of the molecules, which is why thunderstorms produce greenhouse gases. Chemical conversions also underlie many technical applications (see text box). If the electron energy is high enough, gamma radiation, radioactivity, and antimatter are produced.

2 Ionization avalanche If the electric field is high enough, an avalanche of free electrons and ions is created. In this way, a plasma can be created: a soup of many positively charged ions and negatively charged electrons between the air molecules.

3 Joining forces The plasma joins the electrical forces at the tip of an elongated plasma channel. This allows the plasma to grow further than the tip and branch out from time to time. This joining of forces allows lightning to grow outside the cloud.

4 'Lightning trees' CWI models the growth of lightning over distances of more than one metre as a branching tree. Through good mathematical approximations, the researchers also include all relevant processes on a smaller scale.



A plunge into
THE HEART OF THINGS

Fairy tales warn us about the desire for hidden knowledge. Those who are too eager to know how the most beautiful things are structured from the inside, end up with a pile of shards. At least, that used to be the case, before the FleX-ray Lab existed. In this special space at CWI, nature and art reveal their hidden interiors. In two, three, and four dimensions.

Text: Sebastiaan van de Water

'Have you seen the series *Chernobyl*? Then this might look familiar to you.' Sophia Bethany Coban waves a device along the metal walls of a large machine. A soft clicking sound can be heard. Thousands of kilometres separate us from the radioactive ghost town of Prypjat, but here at Science Park in Amsterdam the universal radiation logo, soldered on the big machine, also commands respect. Click. But the rhythm of the Geiger counter remains slow. 'We're doing this just to be sure. These walls are very thick and weighted with lead,' says Coban, who is a postdoctoral researcher with CWI's Computational Imaging Group (CI group). With pride she taps the solid machine that she has come to know better than anyone in recent years. The FleX-ray scanner. It does not look very elegant. A strip of red LED lights serves as the only adornment. It is somewhat reminiscent of a time machine from a comic book. For those who know the abilities of the FleX-ray, that comparison is not even that far-fetched.

Three years ago, this room at CWI was still a glorified broom closet. The FleX-ray has done remarkably little to change that. The wall cabinets are still filled with yellow sponges, granular pieces of polystyrene foam, spilled silicone sealant guns, old smartphones with keyboards, packages of oatmeal bran, a homemade clock, a 4x4x4 Rubik's Cube, and an almost empty box of Kinder Surprise Eggs. All these objects have one thing in common. 'I cannot help it,' Coban says with a laugh. 'The thought keeps going through my head: hey, what would I discover if I put this or that object in the FleX-ray?' According to her CV, Coban is a mathematician and not an explorer, but in this lab these two vocations appear to overlap. Any random object is a bit of *terra incognita*. Only one

Francien Bossema: 'Sometimes art historians are sceptical about what a mathematical institute can do for them. But soon enough they are staring at the results on the screen with wide eyes.'

restriction limits Coban's drive for discovery. Living vertebrates are forbidden research material. 'I've seen a snail crawl around inside its shell. And I've seen a seed germinate. And a lava lamp bubbling.' In the name of science, of course.

'I'll show you how it works,' says Coban as she walks towards the box of Kinder Surprise Eggs. She has given this demonstration before. To children, mathematicians, politicians, and art historians. She enjoys the reactions at least as much as

Sophia Bethany Coban explains the research into Chinese puzzle balls.


Disappointing: the layer of chocolate around a Kinder Surprise Egg turns out to be wafer-thin.

BRAM BELLONI

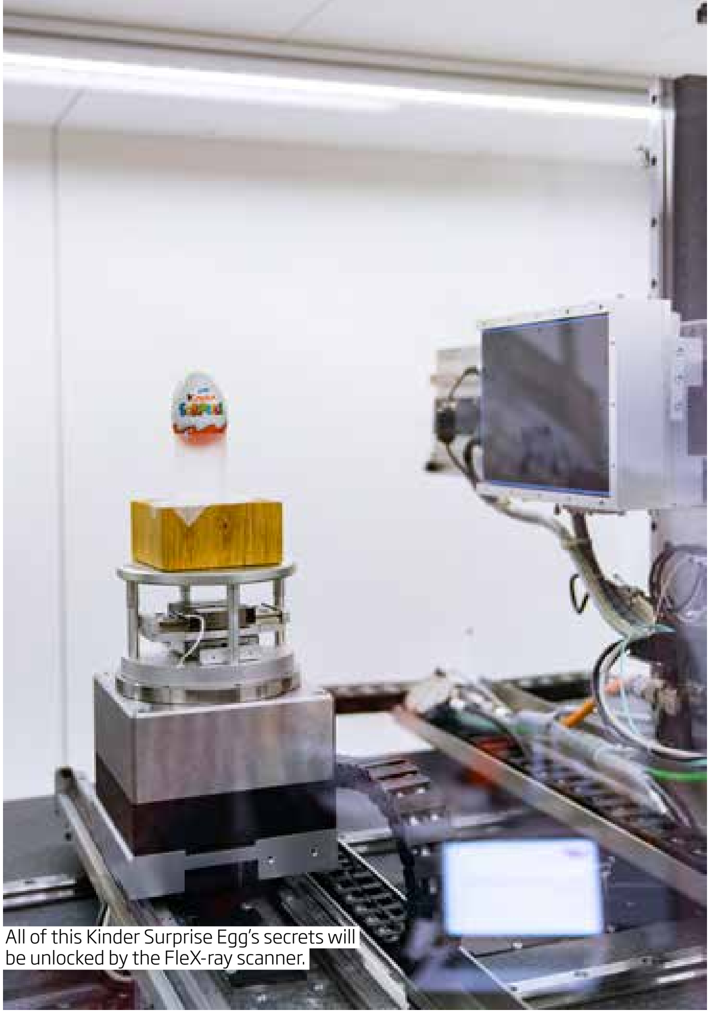
she enjoys the brilliant mathematics that make all this possible. She opens the compartment of the FleX-ray and climbs on a stool. ‘Unfortunately, they didn’t take my height into account during construction.’ Stretching herself out, she places the red-and-white egg in the compartment. She closes the door and types some instructions into a computer. Invisible to human eyes, a panel on the left side of the FleX-ray launches a dose of X-rays that travel through the egg and collide with a black plate on the right side. A 2D scan of a transparent oval object appears on the computer screen. ‘Children are always disappointed when I point out the thin outer edge. That’s the layer of chocolate. “So little?!” they say. Then I let them guess what the shape in the middle is. Sometimes it’s a smurf… but now?’

Bad chocolate

So far, the FleX-ray does little more than an X-ray scanner at an airport, checking your hand luggage for illegal bottles of water. Coban presses some more buttons. The egg begins to rotate. Within minutes, the machine takes twelve hundred different X-rays. At the same time, a powerful computer analyses the raw data. Algorithms, developed by the Computational Imaging group, integrate the increasingly fine scans into a detailed three-dimensional rendering. ‘This is the most advanced way of *real-time CT scanning* in the world,’ says Coban, as she rotates the virtual egg on the screen. ‘We can make any cross-section now.’ One click and part of the egg disappears. We are now looking from above into the bottom half and then diving into the layer of chocolate. Coban’s shaking her head. ‘See all those empty spots? Those are air bubbles. Typical for poor quality chocolate. This brand is deteriorating.’ She shifts the perspective to the centre of the egg. It is like we are a little beetle, trapped inside the egg together with the plastic doll. ‘Ah… too bad, no smurf this time. You’re not going to believe this, but during a previous demonstration, there was a radiologist smurf in the egg.’

> ‘The impact of these kinds of scans will soon be experienced in everyday life’

The extent to which you can gain insight into hidden layers of reality with the FleX-ray is demonstrated by numerous fascinating experiments. Like the time CWI got its hands on a seventeenth-century manuscript where, years later, someone had scratched through all mentions of the author’s name. Coban scanned the manuscript and tried to virtually dive beneath the top layer of ink. In some places this proved impossible: the scratcher had damaged the paper itself. But in other places original letters came to light. By combining all the pieces, the centuries-



BRAM BELLONI

All of this Kinder Surprise Egg's secrets will be unlocked by the FleX-ray scanner.

By diving virtually into the core of a Chinese puzzle ball, CWI researchers made a surprising discovery.
ROBERT VAN LIERE

old censorship was undone. Leendert Cornelisse Romeijn was the author's name.

Amazing research objects were also the Rijksmuseum's Chinese puzzle balls. These ivory works of art once served as show-pieces in Chinese palace halls. The balls give the illusion of a hollow ball floating in a hollow ball in a hollow ball, with each ball containing its own geometrically cut patterns. Analysis in the FleX-ray revealed that some of the puzzle balls contain twelve or more layers, and that they end in a hidden solid ivory core. By diving into the core virtually, experts came up with a surprising discovery: the balls are not made of ivory from Asian elephants, but from African elephants. Therefore, ivory trade must have flourished between China and sub-Saharan Africa a long time ago.

Hidden fingerprint

Researchers of the Rijksmuseum knock on the door of the FleX-ray Lab with increasing regularity, hoping to make more discoveries of this kind. Wearing special gloves, they bring in precious robes, statuettes or paintings, under the supervision of PhD student Francien Bossema. 'Sometimes art historians are sceptical about what a mathematical institute can do for them,' says Bossema. 'But soon enough they are staring at the results on the screen with wide eyes.' In the middle of a terracotta statue of an angel, the CI group found a hidden fingerprint. 'Super interesting, because in the past people thought this statue was made by Michelangelo and many millions were paid for it,' Bossema says. When doubts later arose, its value plummeted. Exactly who made it is unknown. 'A colleague is now formulating algorithms to translate the 3D fingerprints into the 2D form of fingerprints in databases. Then perhaps we can settle this matter once and for all.'

'I am constantly thinking: hey, what would I discover if I put this object in the FleX-ray?'

The possibilities of real-time 3D CT scanning extend far beyond the world of statuettes and puzzle balls. Surgeons – and their patients – will benefit enormously from more precise identification of the location and shape of a tumour. Companies see potential in another area: quality control. Coban has already scanned a shipment of apples and found fly eggs in them. 'We also compared the inner structure of chicken with that of vegetarian meat,' says Tristan van Leeuwen, future leader of the CI group. 'The impact of these kinds of scans will soon be experienced in everyday life. Especially if we manage to create a self-learning system. Now, each scan requires manual fine-tuning. I want the system to recognize for itself: "This is a walnut; I have seen it before and then settings x and y were best. I will do that again." If we manage to do that, we will soon have products in stores that have been taken to a higher level thanks to real-time 3D CT scanning.' Starting with, if it is up to Sophia Coban, apples without fly eggs and chocolate eggs without air bubbles. ■

SPOTLIGHT

Virtual conferences and cake designs

What do you do if your workshop on social virtual reality that was supposed take place on Hawaii was cancelled because of Covid-19? You put on your VR glasses and seize the opportunity to explore how to use an online VR platform for an international workshop. 'For example, we organized a five-hour online workshop in VR with 25 researchers from all over the world,' says Jie Li, postdoctoral researcher at CWI.

Li designs VR environments where people – wearing VR glasses – can come together virtually for, for example, a conference, a consultation with a doctor (if a hospital visit is difficult or painful) or to virtually discuss a cake design with a pastry chef. 'I am not only a researcher, I am also a cake designer with my own café,' Li says. 'In this work, two of my interests come together.'

In addition, Li is researching the user experience of these VR applications. 'After the VR workshop, we talked to participants. They told us, for example, that recognizing and addressing others was difficult.' People were represented by cartoonish avatars, which made social signals, such as eye contact or smiling, impossible. 'We try to make VR experiences more realistic, with new technological developments. In the lab, we have a prototype that can show a 3D representation of someone in VR, as a kind of hologram. It takes four cameras. That's not something you can do at home. That is why we are working on a way to make this possible with just one camera. Privacy must also be taken into account. A lot of development is still needed, but I think that realistic VR experiences will become possible in the future.' –DS

BRAM BELLONI

'The diversity problem is not a women's problem'

The time that mathematics and computer science were exclusively male-dominated are long gone. But there's still a great deal of diversity work to be done, says CWI management team member **Monique Laurent** and PhD researcher **Sophie Huiberts**.

CV

MONIQUE LAURENT
Laurent is a researcher and member of the management team at CWI. She is a member of the Royal Netherlands Academy of Arts and Sciences (KNAW) and professor at Tilburg University. As a mathematician, she develops methods to solve optimization problems. These can be used for all kinds of applications, from economic systems to logistics.

Text: Ans Hekkenberg
Photography: Bram Belloni

If you look at the percentage of female researchers at CWI, the institute has not yet achieved its objectives. Why is that?
ML: 'In our fields of expertise, diversity is not only a difficult issue at CWI, but worldwide. The number of female students is large, but higher up the ladder, from PhD researchers to professors, the number becomes smaller. It is a challenge to get women into those positions. We are doing our best, but sometimes we are unlucky. We recruit talented women, but they leave.'

Why does that happen?
ML: 'What sometimes plays a role is the so-called two-body problem, which arises when two scientists have a relationship. One of them may be able to find a good position, but the other should also be able to get a job nearby. If that doesn't work, it leads to departure. At CWI, we have witnessed the loss of many talented women in this way. Fortunately, we have recently managed to attract a number of talented women.'

In what ways is CWI trying to increase diversity?
ML: 'The pool of female scientists is smaller. That is why we actively look for female candidates for positions, for example by emailing promising scientists about them. And we participate in initiatives of funding agency NWO (the Dutch Research Council – ed.) to recruit female researchers with extra grants. In addition, we try to have an impact in the long term by showing young girls role models. If girls only see men in science, then a career like that does not seem attractive. But when they see researchers who look like them, they tend to think: "That is a job I can do when I grow up!"'

Are role models also important for young researchers?
SH: 'I think so. Theoretical computer science has a number of very impressive women. Virginia Vassilevska Williams, for example (famous for her work in rapidly multiplying number collections called matrices – ed.). Someone like that inspires people. As a woman in computer science, you do not see many women around you. That makes it all the more important to see that there are women who are so incredibly successful – to see it's possible to achieve this.'

What should change in the field to improve the gender balance?

ML: 'A career in science requires a lot from young researchers. You often have to go abroad for years. This can conflict with your private life, for example if you have a wish to start a family. Of course, that does not only apply to women. Requirements like that cause people to leave science. It is a shame, because that is how we miss out on talent. That is why I think we need to be more flexible. We should not judge people if they make choices other than following the usual path. There needs to be more diversity in how you can structure your career.'

SH: 'I do not think a desire to have children is the only bottleneck. I recognize the problem Monique described. I know a lot of postdoctoral researchers who are in a different country every year and very few who are happy because of it. I like living in the Netherlands. I do not know if I would want to live in the United States for a year, for example. That could be a reason not to continue in the field.'

Have you experienced any obstacles during your career because of being a woman?

SH: 'I tried to talk to a researcher at a conference who was very curt. Later, I saw that same scientist having a long chat with another junior researcher. Strange, I thought, until I heard through the grapevine that this person hates women. As a young researcher, you do not even realize things like that. You have to hear it from others.'

ML: 'I myself have not encountered any obstacles. However, as a female scientist, it is sometimes difficult to cope with the extra tasks assigned to you. It is important that boards that award prizes or research positions do not consist exclusively of men. But that does mean that the few women in the field are always asked for such boards. That increases the workload. What I think is important is that we realize that the diversity problem is not a women's problem. Men need to work on it as well; or even more so than women.'

Many diversity strategies are aimed at cisgender women. Sophie Huiberts, as a transgender woman, do you think that science has too narrow a focus when it comes to diversity?

SH: 'I definitely think a lot of diversity efforts are too limited. Whether that applies specifically to the cis/trans dynamic is difficult to judge. Of course, there are fewer of us, so I do not know if we are underrepresented. What strikes me more is that our institute consists mainly of white scientists. That is not okay. The Netherlands has many people with a migration background, but that is not reflected at CWI.'

ML: 'I endorse that. The same applies to other knowledge institutions. I think the problem starts in elementary schools. People have preconceptions about children with a migration background, just as they have preconceptions about girls. That pushes these kids in a certain direction, even if it is done mostly subconsciously.'

Will it ever change?

ML: 'I hope so. Fortunately, there are currently many opportunities for talented women. And the great thing about mathematics is, it knows no boundaries, no colour, no gender.'

SH: 'I don't quite agree. As an abstract thing, apart from human context, mathematics indeed knows no colour and gender. But mathematics is done by people. We decide what research is important and how it should be done. And because of these decisions, mathematics is coloured and shaped in practice. Think, for example, of algorithms that determine who is profiled by the police. Because we base these algorithms on databases created by humans, human prejudices are reflected in them. An algorithm can still disadvantage certain groups. If you say that mathematics is gender and colourblind, you are ignoring that.'

ML: 'You are right about that. You can do little harm with pure algebraic geometry or combinatorics. But when it comes to applications, things become different.' ■

'As a female scientist, it is sometimes difficult to cope with the extra tasks assigned to you'

CV

SOPHIE HUIBERTS

Huiberts is a PhD student at CWI and a member of the works council. In 2019, she was invited as one of the *200 most qualified young researchers worldwide* to the Heidelberg Laureate Forum, where young talents network with the absolute top of mathematics and computer science. She is the Dutch contact of the European Women in Mathematics network. Huiberts also works on optimization. Factories and companies use optimization software to determine their schedules. Huiberts aims to find out why this software works so well, even with complex problems.

Putting a SPIN on quantum computing

For decades, CWI has been conducting leading research in the field of quantum computing. Five years ago, it was time to broaden the horizon and QuSoft was founded. This institute now has a prominent role in science, business, and society.

Text: Yannick Fritschy
Photography: Bob Bronshoff and Ivar Pel

Google, IBM, Microsoft, and other tech giants are working on it: the quantum computer. This computer uses strange quantum mechanics phenomena in its calculations; for example, that particles can be in two places at the same time and influence each other at a distance. Thanks to this different method of calculation, a quantum computer promises to be much faster in some respects than a classic computer, so that you can calculate things that were previously impossible.

But mind you: it *promises* to be faster. Because, although the tech giants are developing one prototype after another, there is no real quantum computer yet.

Five years ago, it sounded crazy to outsiders that an institute was being set up for the development of software for the quantum computer. What good is software without hardware? But you really should start with software, says QuSoft director Harry Buhrman, professor at the University of Amsterdam (UvA) and leader of the CWI Algorithms & Complexity research group. 'You have to develop algorithms that show that a quantum computer can solve certain problems more efficiently before you start building that computer,' he says.

It is a misunderstanding that a quantum computer can solve any problem faster than a classic computer. In fact, it is unclear exactly what a quantum computer can and cannot do. Buhrman: 'We know of some things that the quantum computer can calculate faster, and some things we have proved it cannot. But in between, there is a very large grey area of research questions.'

The researchers at QuSoft, a joint venture between the UvA and CWI, deal with these kinds of issues. One of them is Stacey Jeffery, researcher in the Algorithms & Complexity group. 'I came here in 2017 because this was one of the first groups in the world to do theoretical research on the quantum computer,' she says.

Drunkard's walk

Jeffery is helping to develop algorithms that can later be used in quantum software. These are, for example, so-called quantum-walk algorithms. They focus on the quantum variation of the 'drunkard's walk,' the term that scientists use for random movement.

Because a quantum computer works on quantum particles, you would expect it to be able to simulate the random movement of such quantum particles faster than a classic computer. Jeffery is researching for specific problems whether this is indeed the case, and if so, how much faster. 'We have recently demonstrated that a quantum computer with such a quantum-walk algorithm can solve certain search problems quadratically faster. In the time in which a classic computer calculates a certain number of steps, a quantum computer can calculate the square of that number of steps. In the case of a problem with many steps, that is a huge time gain.'

The tricky thing about developing software without hardware is that you cannot test the software properly. But according to Jeffery, that is not necessary right now. 'We assume that one day we will have a functioning quantum computer, and we are developing algorithms for that. We will fine-tune it later,' she says.

Harry Buhrman

Stacey Jeffery

More urgent and relevant

However, Jeffery does expect to focus more on the quantum computers that are actually forthcoming. Because there is a lot going on in the field of hardware. 'Things are happening faster than I had dared hope for,' says Buhrman. 'So much money is being invested internationally that I expect growth to continue. This makes the question of what we can do with a quantum computer even more urgent and relevant.'

The quantum computer has many possible applications. Within science, for example, it could be used to simulate the movement of molecules in chemical reactions. But it can also be used outside of science, for example in logistics. If you want to determine the optimal route for parcel delivery, you have to simulate a lot of possible routes. If a quantum computer can do that faster, it saves a lot of time and money.

That is why more and more companies are knocking on QuSoft's door. 'We have, for example, ongoing projects with Bosch and ABN to see if the quantum computer can do something for them,' says Buhrman. The stormy developments surrounding the quantum computer have led to QuSoft's enormous growth over the past five years. 'We started with about twenty people, now we have seventy,' says Buhrman. 'We have regular researchers, research students, and PhD students. The research varies from theoretical to applied.'

Beyond the country's borders

What's more, there are a lot of non-investigators out there right now. Because QuSoft has not only grown, but above all broadened out. Buhrman: 'In addition to CWI and the University of Amsterdam, we are now also working with the Amsterdam University of Applied Sciences. And in 2017, we received a large grant to set up the Quantum Software Consortium together with the universities of Delft, Leiden, Eindhoven, and Twente. This has now resulted in an even larger national agenda, Quantum Delta NL.' And QuSoft is now also looking beyond the borders of the Netherlands. 'We are trying to bring quantum software to the attention of companies all over Europe. And with the recently established Turing Chair, we are bringing international high-profile professors to Amsterdam,' says Buhrman.

'QuSoft is a real community, a nice place for everyone who works here'

In addition, an education programme has been set up for both university and secondary school students. And a surprising new addition is the legal and ethical board, set up together with the law faculty of the University of Amsterdam, which deals with ethical issues that might play a role in future. Buhrman: 'Imagine, for example, that one company has a monopoly on the quantum computer and is appropriating chemical patents. Do we have to take action against that?'

Women's association

In addition to her research, Jeffery also focuses on society. Together with researcher Julia Cramer of Leiden University, she started an association called Women in Quantum Development. 'There are few women in quantum research and computer science, and the research groups are small. So, there is a good chance that you are the only woman in your group. This can be an obstacle for women to enter this field. Even though anyone who wants to, should just do it,' she says. 'We set up WIQD mainly to make it possible for women to meet each other. Our first event, which was to take place in March 2020, was unfortunately cancelled due to the COVID outbreak. Now we are trying to set up an online community.'

In addition, Jeffery can often be found at the social events organized by QuSoft. 'It is a real community, a nice place for everyone who works here,' she says.

For the near future, Buhrman expects QuSoft to continue expanding and broadening out. 'In five years, I hope we have 150 people. And that, with Quantum Amsterdam, we will have created a hub that acquires new knowledge about the quantum computer and brings it to companies and society.' And Buhrman's personal role in this? 'I especially want to continue to do fundamental research; that is what I like best. I am very happy to be able to work with young people to take this research a step further. I am grateful to CWI and the UvA that they have always stood behind us and helped us. It is not a matter of course that so many people in different departments are all on the same page. But everyone sees the added value of our research. That is pretty special.' ■

CUTTING EDGE RESEARCH

75 years of CWI

1946

Creation of the Mathematisch Centrum (MC) to help rebuild the Netherlands after WWII.

1952

The MC develops the first Dutch computer, the Automatic Relay Calculator Amsterdam (ARRA) and its successors.

JAREN '50

The MC performs calculations and models for the Delta Works, which protect the Netherlands against flooding after the great North Sea flood of 1953.

1954

The MC performs calculations for the design of the wings of passenger aircraft Fokker F27 Friendship.

photo: Stichting Electrologica

1956

Creation of Electrologica, computer producer and the first spin-off of the institute.

1959

Edsger Dijkstra, the later Turing Award winner, develops the shortest path algorithm, which is now used for route navigation, traffic models, and telecommunication.

1960

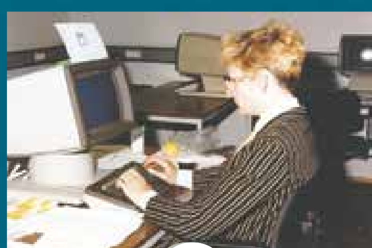
Dijkstra and others create the first compiler for programming language ALGOL 60.

1968

MC director Aad van Wijngaarden develops the ALGOL 68 programming language with others.

1982

Launch of the first UNIX network in Europe, the forerunner of the Internet. The centre of this network was at the MC.



1983

In view of the growing importance of computer science, the institute is renamed Centrum Wiskunde & Informatica (CWI).

1986

CWI registers '.nl' on 25 April, as one of the first country domains worldwide. The first domain name follows on 1 May: cwi.nl.

INFOGRAPHIC: PEPIJN BARNARD
TEXT: ANS HEKKENBERG
SOURCE: CWI

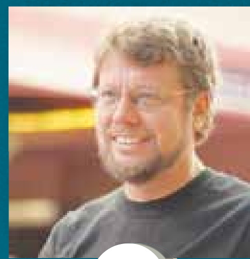
From left to right: internet pioneers Jaap Akkerhuis, Daniel Karrenberg, Teus Hagen, and Piet Beertema.

1988

On 17 November, CWI connects the Netherlands to the open Internet. The Netherlands is the first country in Europe to be connected.

1989

CWI founds ERCIM, the European research consortium for informatics and mathematics, together with the German GMD and French Inria.



1989

Guido van Rossum develops and designs programming language Python.

JAREN '90

CWI participates in the development of web standards CSS, HTML4, XHTML, XForms, and SMIL, as well as RDF, RDFa, and more.

1993

www.cwi.nl was one of the first 500 websites worldwide in 1993. Now there are over a billion.

1999

CWI coordinates the breaking of the RSA-512 security standard used on the Internet, which is achieved by resolving large numbers into prime factors.

2004

Launch of open-source database system MonetDB, which uses columns.

2007

Spinoza winner Lex Schrijver and others create an algorithm that optimizes the timetable of the Dutch Railways.

2008

CWI breaks security standard MD5 used on the Internet: the so-called 'https crunch'.

2015

QuSoft

Launch of QuSoft, the research centre for quantum software.

2017

CWI breaks security standard SHA-1 used on the Internet, which is used for credit card transactions and digital signatures, among other things.

2017

Opening of the FleX-ray Lab, an unrivalled 3D X-ray scanner that creates real-time images.

2020

Development of AI based on evolutionary algorithms to design better internal radiation treatment plans for cancer.

Unavoidable UNCERTAINTY

Predicting is difficult, especially when reality is too complex to capture exactly in rules. CWI's research group Scientific Computing is trying to minimize the uncertainty that is, therefore, often found in models.

Text: Fenna van der Grient

It is a familiar scenario: you keep eyeing Buienrader hopefully to determine when it is best to get on your bike, but you end up getting drenched anyway. Maybe you curse the app, but that is not entirely justified. There is always a degree of uncertainty in a weather forecast. Predictions about all kinds of other things also involve uncertainty: whether this is the course of the COVID pandemic, the probability of a power failure or how well a wind turbine can withstand changing conditions.

Predicting all these things is such a complex matter that the situation has to be simplified. For that, mathematicians use models. And no matter how good those models are, they are never as precise as reality itself. This means that there is always a certain degree of uncertainty in the predictions a model makes.

You can, of course, strive to make this uncertainty as small as possible. And, equally important, to calculate exactly how great this uncertainty is. CWI's research group Scientific Computing, led by Daan Crommelin, focusses on these kinds of issues.

Sources of uncertainty

To make a model, for example to predict the weather, you need several things. First of all, you have to enter various elements into it that are relevant to the system that you are trying to describe. In the case of a weather or climate model, this could include the viscosity of the water in the ocean, or the friction of the atmosphere along the earth's surface. 'The elements that you enter into the model are not always very well known or measured,' says Crommelin. This already introduces a degree of uncertainty.

Then you need initial values. To be able to predict the weather a week ahead, you first have to tell the model exactly what today's situation is: what is the current temperature, pressure, humidity, etc.? Again, these initial values can never be measured with infinite precision, which leads to even more uncertainty.

Limited number of pixels

Finally, you are faced with the fact that you always have to choose what you do and do not include in your model. 'You cannot include all the processes that play a role in your model, because that would be far too expensive and time-consuming,' Crommelin explains. 'Computers are nowhere near powerful enough to handle so many details.' That is why we always make a simplification. If you do not know what the contribution of the omitted factors is, that adds a third form of uncertainty.

'You cannot include all the processes that play a role in a model'

This form of uncertainty plays an important role in creating computer simulations of the atmosphere. To make a simplification like that, researchers divide the atmosphere into manageable sections. These are, for example, rectangular blocks, stacked vertically in columns that reach all the way from the bottom to the top of the atmosphere, and are, for example, 50 by 50 kilometres. For each block, you only describe the average temperature, humidity, pressure, etcetera. You enter this into the model and watch how it develops. This may seem like a reliable method, but because you take the average of all variables, you overlook all kinds of small-scale processes that take place within one of these blocks. You can compare it to a photo taken with a primitive digital camera, with a limited number of pixels. A camera like that is perfectly suited to give

'You do not need to know all the exact details of the fluctuations, as long as you take into account that it fluctuates'

you a general picture of a beautiful beach or forest. But you will not see the details that are smaller than the dimensions of an individual pixel.

Important fluctuations

With a picture it might not be so bad if you are missing some details, but with a simulation of the atmosphere those details are very important. 'You cannot just take the average of the whole column,' Crommelin says. 'Take, for example, rainfall in the atmosphere. Taking an average would mean that it is always a bit drizzly in every column. Of course, that is not the case, because sometimes it is dry for a long time, and at other times you have enormous downpours.'

Downpours are annoying if you are about to get on your bike and Buienradar says it is drizzling. But even more important is that they also affect the weather in the long term. Moreover, they affect the weather not only inside the column, but also outside it. So, somehow you have to include the details within the column to simulate the atmosphere for a large area in the long term, for example as part of a climate simulation.

Because actually simulating all cloud formation and rain within a column takes far too much computing power, researchers solve this in a different way: by introducing noise. You do not need to know all the exact details of the fluctuations, as long as you take into account that it fluctuates. And this approach appears to work very well in practice. You only need to take one very precise measurement of what is happening within such a column. This information can then be used to simulate the fluctuations in the entire model.

Degree of uncertainty

In this way, you take the uncertainty that comes from simplifications you do at the beginning into account. Next, it is important to know how much uncertainty remains in the final predictions. Crommelin and colleagues are, therefore, developing techniques to determine this efficiently. They look at how uncertainties develop in a model: which uncertainties in the input create a large uncertainty in the outcome? Are there uncertainties that reinforce each other?

Crommelin and colleagues use their techniques in various fields. For example, the COVID pandemic. If you want to predict the effect of new measures, the uncertainty in the input is very high, partly because the unpredictable human factor plays a major role. And so, the uncertainty in the outcome can also be great.

When designing windmills, it is also important to determine how uncertainties develop in a model. Windmills have to be able to function optimally under all kinds of changing conditions. One of the challenges in this application is that the standard methods for determining the development of uncertainty assume that these conditions do not affect each other. In practice, however, they often do; when the wind is strong, a wind turbine at sea will also be affected by a heavy sea.

Uncertainty also plays an increasing role in the electricity grid, because more and more fluctuating sources such as wind turbines and solar cells are being connected to it. Crommelin: 'One question we are looking into is what the chances are that, due to a very unfortunate combination of energy injection in certain places and consumption in others, higher currents will occur than the network can handle.' This information allows you to adjust the network to minimize the chance of a power failure.

In all these situations, one hundred percent certainty will probably never be achieved. In the future, you will on occasion get drenched and there is always a small chance of a power failure. But by increasingly knowing where the uncertainty lies, you can become more and more sure of your ground. ■

From **research** to **business**

Since its founding, CWI has not only focused on science itself, but also on the transfer of knowledge to society. Many research projects grow into companies: spin-offs. Here are a few examples.

Text: Marleen Hoebe

MonetDB Solutions
Established: 2013

Martin Kersten

Almost every company has a database, a system in which all essential company data is stored. A system like that must be reliable, fast, and flexible – preferably including professional support. Computer scientist Martin Kersten also realized this.

He has been working on database technology since the 1970s. In 1993, together with colleagues from CWI, he set up a database system: MonetDB. 'MonetDB was the first fully-fledged database system with column-based data storage, which is essential for data analysis, among other things.'

'This system is open source. So, it is free, and anyone can use it. The reason for this is that we built it at a research institute, with public money. It was a by-product of scientific research. I think everyone should be able to use it.'

In 2013, Kersten and colleagues founded spin-off MonetDB Solutions, to support companies in using MonetDB. 'We take care of maintenance and improvements,' says Kersten. 'We do this not only for companies in the Netherlands, but also from Chile to Catalonia, and from California to China. Anything we improve in the software – no matter for which company – we incorporate back into the MonetDB system. It still remains open source. No one can claim the system legally.'

MonetDB is trail-blazing and popular, according to SIGMOD, the Special Interest Group on Management of Data. Each year, this group hands out an award to a researcher whose technical contribution has had a significant impact on data management systems. Kersten received such an award in 2016.

How will MonetDB Solutions continue in the coming years? 'We have to keep innovating for the customer. There is still a lot of work to be done, both in terms of maintenance and scientific challenges.'

> 'Anything we improve in the software, we incorporate back into the MonetDB system'

Seita
Established: 2016

Nicolas Höning

Sometimes, it is smarter to charge an electric car at a different time or to have a big clean-up with lots of water. Because it can be more sustainable to wait for the most favourable availability and it can be cheaper. But how does an energy cooperative or water supplier know when the time is right to consume lots of energy or water?

Machine learning engineer Nicolas Höning knows the answer: with the help of algorithms. Together with co-founder Felix Claessen, he uses them in spin-off Seita, to look ahead in time as it were. Using these algorithms, Seita can set up a software platform that, for example, advises a charging service for electric cars when it is best for their customers to charge cars, says Höning. 'Our software also takes into account all kinds of predictions, such as weather or price forecasts, in its advice.'

'Large-volume users can save thousands of euros a year with the help of the software. In the case of households with an electric car and solar panels, this can mean savings of almost three hundred euros per year. The software developed by Seita also helps prevent consumption peaks. This type of software will, therefore, eventually be able to play an important role in achieving the CO_2 savings targets that the Netherlands is striving for.'

Höning and Claessen want to continue working with meta data analyses. Seita receives a lot of consumption data and can, based on analyses, not only identify when a lot of energy is consumed at the same time, but also when a water supplier loses a lot of water somewhere, for example due to an unnoticed leak. 'Without data analysis, it is possible that a supplier will only notice a leak very late, because the water runs directly into the sewer somewhere, for example,' Höning explains. 'With our software, we can improve leak detection and prevent water loss.'

The software developed by Seita helps prevent peaks in, for example, water consumption.
ISTOCK

swat.engineering
Established: 2017

Davy Landman

There are many programming languages that can be used to write down, for example, how an online shop or bank account works. They often contain long descriptions for putting a computer to work. Usually, you are unable to understand this explanation yourself, because it can be quite complex. This is not always convenient, for example, if you want to modify software.

In 2009, Jurgen Vinju, Paul Klint, and Tijs van der Storm designed metaprogramming language Rascal at CWI. 'A metaprogramming language can be used to develop programming languages, among other things, enabling you to generate domain-specific language, or DSL, more quickly,' explains software engineer Davy Landman. He was a PhD student in the same research group of Rascal designers.

DSL is a clearer language; it is represented in the vocabulary that the people for whom the language is designed are familiar with. It is specially made to express their concepts easily. Not everyone at a company can write DSL themselves, but at least they can read it, which is handy when you have to work with it. It is like a lot of people can read a recipe, but not everyone can write one.'

After the development of Rascal, Landman worked with others to improve its implementation. He, Vinju, and Klint saw that companies wanted to use Rascal – an open-source programming language available to everyone – to maintain DSL. However, these companies needed support. The three reseachers wanted to share their knowledge and founded swat.engineering. Landman was appointed CEO.

The spin-off helped the Netherlands Forensic Institute to find evidence more easily in the data of phones, tablets, laptops, etcetera. 'All these devices have different apps that all store data in their own way,' says Landman. 'It does not all come together nicely in one database. You can easily have several terabytes of data when you take possession of someone's devices. So, it is kind of like fighting a losing battle. We created a DSL that makes it easier to extract all that data.'

Landman wants to help companies to develop DSL in a direct way, but also to support companies that already use Rascal, so that they can develop DSL themselves.


With a 3D printer that prints on a very small scale, researchers can easily test their ideas.

Photosynthetic
Established: 2018

Alexander Kostenko

Minuscule prototypes, objects of less than a millimetre, cannot be created just like that. However, biomedical scientists and chemists can very well use prototypes of less than a millimetre for their research, for example, to manufacture objects for the analysis of small amounts of liquid.

Physicist Alexander Kostenko realized how important it is for these scientists in microfluidics to have an instrument that can quickly help them design very small prototypes. He was a research student at CWI making three-dimensional models for museums when he saw that the algorithms that he was using for this could also be used in a 3D printer. 'With a 3D printer that prints on a very small scale, researchers can directly and easily test their ideas and view them in 3D instead of having to make complex prototypes.'

The idea for Photosynthetic, a spin-off that develops technology for making micro prototypes, was born. Kostenko applied for a patent. 'Actually, Photosynthetic is different from other CWI spin-offs. They are mostly concerned with algorithms and software. You do not need a patent and lab setup for that. We have to make an end product that we want to bring to the market at some point – hopefully by the end of 2021. Its development is taking quite some time.'

> 'Printing at a resolution of one micrometre can be done faster thanks to our algorithms'

Photosynthetic already has interesting research results. 'The results show that printing objects with a resolution of one micrometre, one thousandth of a millimetre, is possible at higher speeds than other technologies operating at microscale. If our instrument is fast enough, there is a chance that both researchers and the industry will start using it.' ■

SPOTLIGHT

Digging through data in a higher gear

More efficient parcel delivery, improved traffic flow, and monitoring the spread of COVID-19. Society is constantly being optimized by learning from data. Data scientists use data storage and analysis systems for this purpose. 'These are complex and important systems,' says Peter Boncz, affiliated with the Database Architectures research group at CWI. 'Our research group is looking at how we can make these systems faster and more efficient.'

The group developed fundamental database technologies, such as the 'column-store' storage method, which can be found in many modern data systems. For example, they developed open-source database system MonetDB and spin-off VectorWise. Both are optimized to perform complex (search) tasks in large databases by storing and searching through the data in a smart way.

Boncz: 'CWI researchers Hannes Muehleisen and Mark Raasveldt, for example, are currently working on DuckDB, which is a database system that supports scientists when preparing data for machine learning.'

The importance of databases and the international leading role of the CWI group is demonstrated, among other things, by the successful spin-off companies that the group produces. Recently, cloud database company Snowflake, co-founded by Marcin Zukowski who obtained his PhD under Boncz, was launched on the American stock exchange with a value of 70 billion dollars.

The group also plays an important role in linking researchers and companies. This is reflected in the settlement of leading American data company Databricks to Amsterdam. Boncz: 'I am proud that a lot of my alumni work there. I hope that Amsterdam will become a high-tech city in the field of data, where even more talented people want to work.' –DS

BRAM BELLONI

'Have a computer negotiate your salary'

In complex negotiations – from the sale of a house to the formation of a cabinet – it is often impossible for people to oversee all aspects. **Tim Baarslag** is developing algorithms that can do this and can help people achieve better negotiation results.

Text: Wim de Jong
Photography: Bram Belloni

During the time-consuming formation of the Rutte III cabinet, you suggested using a computer to speed up negotiations. Maybe an idea for upcoming formations?
'I still believe that. A coalition agreement can be seen as a collection of agreements on all kinds of social issues. The "space" for all possible solutions is enormous. The human way of looking through this is to go through them one by one. "Let's agree on one topic first, then move on to the next." But it leads to better results if you discuss several subjects at the same time, so that you can make trade-offs. This "multitasking" is very difficult for people.

The complexity increases enormously as soon as you discuss even a few subjects at the same time. All facets of the different subjects interact, and so you end up with an explosion of possibilities. A computer could calculate these combinations of possible solutions and come up with proposals for outcomes that would be of interest to everyone. Of course, sometimes these are fundamental social and ethical issues, for which the computer can be no more than an advisor and the human dimension must be the deciding factor.'

So, the next formations should be a piece of cake?
'No, unfortunately, it is not possible to use a computer for this at the moment. One of the problems here is that most of the theories about negotiations on which the algorithms are based are about one-to-one negotiations. For example, it is quite possible to apply an algorithm to bidding on a house (see text box). But Dutch politics almost always involves more than two parties forging a coalition. That is much more difficult, the current algorithms cannot handle that yet. They are working on it, though. That is what I like about my field: it is so new, there is so much work to be done.

Apart from the negotiation theory, a negotiation computer must, of course, know what you want. With my Veni grant, I am researching how a computer can find that out. A computer must have data to understand what we find important in negotiations. In the example of the cabinet formation: do you care more about defence or about education? And what are the ratios between those different issues for you? We have developed a method with which you can get an incredibly good idea of what is important to the user to achieve a good result, even with a limited number of questions, sometimes fewer than twenty.

Algorithms can help people better and better with negotiations and eventually even handle them for you autonomously. Suppose you are talking about a new job. You could put the computer to work with your wishes for salary, days off, and other conditions of employment. The computer could then negotiate with your potential new employer and come back with the best possible result for you, without you having to do anything yourself. And there are countless areas where negotiation algorithms can play a role, from the distribution of inheritances to self-driving cars that have to give each other right-of-way.'

In 2020, you joined the Young Academy, a platform for young scientific talents. What are you going to do?
'I want to change the way we scientists communicate about the social impact of innovations, especially in my field of AI. Take, for example, all the worries about social media bubbles, discrimination by algorithms, loss

'Scientists often have insufficient answers to questions about the negative impact of their work'

of jobs due to automation, fake news, impact on politics – that's quite something. But the same applies to other disciplines, such as biology with designer babies and physics with nuclear energy. These really are innovations with great societal impact.

Scientists often paint a very rosy picture of what a new technology means. This makes sense, because they want to highlight the positive aspects of their work. But when critical questions about negative impact come from the media, citizens or the government, they often have insufficient answers.

That is what I want to think about: how we can make it normal for us scientists to think proactively about potential negative impact and contribute solutions.

For example, did you create a new negotiation algorithm? Great, but also think about what it means for people who do not have access to this negotiation algorithm. Or what happens when everyone uses it?'

In 2019, newspaper *Het Financieele Dagblad* selected you as one of fifty entrepreneurial talents under 35. I read in the accompanying special that you would like to become a professor.

'Haha, when I was four years old, I said that it was indeed my dream to become a mathematics professor, although, at that time I did not know what that meant, of course. I have been studying mathematics according to plan, but if I ever become a professor, it will be in AI.

I would very much like to have my own research group. Fortunately, this subject is fresh, and there is a lot to be done in it. Finding new ideas to explore is not the problem. It is mainly a matter of finding the manpower to work out the ideas I have and the possibilities I see. In addition to my four-day position at CWI, I work at Utrecht University one day a week as an assistant professor, so who knows what the future will bring.'

Someone with your knowledge and skills is also very interesting for the business community. Do they know where to find you?

'I am currently working with Acumex, a Danish company that wants to use negotiation algorithms when trading in products. If, for example, a construction company wins a large tender to build a residential area, negotiations take place with all sorts of suppliers to purchase stone, cement, steel, right down to the sinks. That is currently done by people behind a desk, over the phone, and with Excel sheets. I am helping this company to see if this can be done online using negotiation algorithms.

They use my expertise and together we do research to take it to the next level. So, it is not so much that the business community attracts me as a potential employer – I like science far too much for that – but I do enjoy seeing applications in business. As a scientist, you want to lay the foundation on which others can build.' ■

Tim's housing algorithm

Are you about to make an offer on a house and are you curious how an algorithm can help you with that? Tim Baarslag has designed one that you can try out at www.ntr.nl/html/focus/huizenbodalgoritme.

ISTOCK

Getting ready for the post-quantum era

The more our lives take place in the digital world, the greater the importance of digital security becomes. At CWI, **Marten van Dijk** and **Ronald Cramer** are working hard with their research groups to ensure that our bank accounts are not plundered, we can work safely on virtual desktops, and state secrets do not end up in public.

Text: Fenna van der Grient

All sensitive digital communication is encrypted before it is transferred. This prevents malicious parties from intercepting or modifying information, so we can safely do our banking online and citizens, businesses, and intelligence services can communicate securely over the Internet. Today's encryption methods are uncrackable even for the fastest supercomputers. However, the development of the quantum computer poses a major threat to these encryption methods. A quantum computer calculates in a completely different way, which allows it to crack the encryptions. So, if there were to be a quantum computer with sufficient computing power, suddenly all current encryption methods would be insecure.

That is why Ronald Cramer, head of the Cryptology research group, is preparing us for this so-called post-quantum era. Opinions are rather divided as to when this will become a threat. According to some, there will be a quantum computer in two years that can crack our current encryption methods; according to others, this will play out in a hundred years' time.

State secrets

Whatever the case may be, it is important to tackle this in time. Firstly, because it takes a lot of time to fully develop new encryption methods so that you can be sure that they are secure in all situations. Then you have to implement them as well. But there is another factor. Most communications require short-term security: for example, you need to be able to establish a secure connection with your bank to transfer money at this moment in time. If it turns out that that connection will no longer be secure in a few years, you can switch to another system at that time. From that moment on, new bank transfers will be encrypted in a different way. A possible assailant cannot do anything with a banking connection that was set up a year ago.

For matters that have to remain secret for a longer period of time, such as state secrets or health data, it is a different story. Cramer: 'Even if you think that there will not be a quantum computer for another fifty or a hundred years, it is a good thing that you ae working on it now. Anything you encrypt in the next few decades must be safe for a long time after that.' If a malicious person currently has an encrypted state secret on his hard drive, he can keep it and in fifty years' time, when quantum computers exist, decrypt it with ease. If that information is still sensitive at the time, we have a problem. Information that remains sensitive for a longer period of time should, therefore, already be encrypted in such a way that it will not be possible to crack it even in decades to come.

That is why Cramer and his research group are developing new standard methods for encryption that are resistant to attacks from quantum computers.

Virtual environments

If you are able to encrypt all your data properly and, therefore, communicate securely, you are on your way, but you are not there yet. Usually, you also want to do something with the data: perform calculations or process the data with a program, for example. Nowadays, this does not always happen on a computer or server that is located in your office or company premises. Calculations, programs, and applications are increasingly run in the cloud. There are advantages to this: instead of every company having to have many servers, we share all the servers in data centres. Very efficient, but a calculation that takes place in a virtual environment is a great deal more susceptible to attacks than a calculation that takes place on your own isolated computer.

> 'A calculation that takes place in a virtual environment is a lot more susceptible to attacks'

Islands of security

The Computer Security research group led by Marten van Dijk focusses on the question of how to perform calculations securely in such a virtual environment. 'There is a good chance that, in future, everyone will have a virtual desktop,' says Van Dijk. 'If it has privacy-sensitive information or competition-sensitive software on it, you do not want it to leak.' What makes it complicated is that when you start calculating in such an environment, you are given lots of intermediate results. They have to be stored within that virtual environment, which makes them vulnerable to external attacks. Van Dijk: 'We are looking, for example, at how we can carry out small parts of the calculations isolated from all the others within such an environment. So, you create islands of security, as it were. Even if an attacker gains access to your entire virtual environment, those islands are still safe. With a smart combination of hardware and software, it can be achieved.'

Simulated Zeus

Another challenge is a situation in which you want to carry out a calculation together with several parties. For example, you want to process sensitive information with various parties who do not trust each other, without the other parties seeing that information. A digital election, for example. Each party votes, providing a small chunk of information. All these votes together must somehow be processed into a joint result: who has the most votes, and how many do they have?

Cramer and colleagues are developing systems to enable this type of calculation between multiple parties. In doing so, they are pursuing a fictitious ideal: 'Ideally, all parties involved would give their information to a mediator who can be trusted completely, let's call him Zeus,' says Cramer. 'Well, the Greek gods were not always to be trusted either, but let's assume for a moment that they were,' he laughs. Zeus runs a calculation with the numbers and shares the outcome with all parties: the result of the elections.'

In practice, you do not have a mediator like that, so you have to simulate Zeus. You can do this by creating a network between all parties that, as a whole, functions as a kind of Zeus. Each party does part of the calculations, communicates with the other parties, and carries out tests.

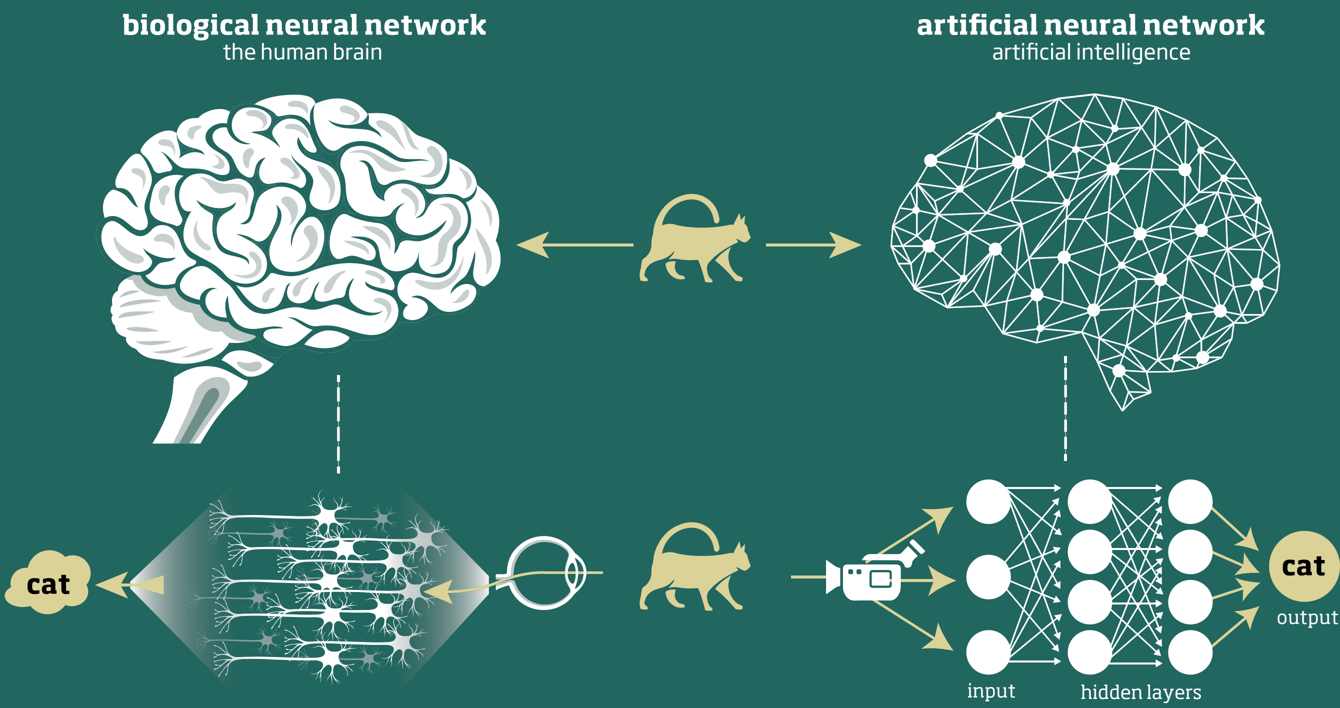
All this together ensures the requested outcome, without the parties seeing confidential information from the other parties. 'There is a lot of maths behind it, but it is actually a little magical, that it can be done this way,' Cramer laughs. 'The great thing is that with a network of at least three parties, even an infinitely powerful computer cannot break this system.' ■

Physical systems

The importance of digital security also plays a major role in physical systems. For example, the Delta Works and the electricity grid are controlled using digital systems. If malicious parties can break into those systems, the consequences would be disastrous. In addition, we are all bringing in more and more intelligent systems into our home, which we do not want anyone to be able to hack. Van Dijk and his research group are developing methods to secure these types of systems as effectively as possible.

Neural networks

Our brain consists of a very extensive network of tens of billions of interconnected neurons. Each neuron is a linchpin in the larger whole: it is able to process signals and pass on this information to other neurons. This creates circuits of neurons that jointly regulate all sorts of bodily functions, such as our faculty of thought. Artificial neural networks are inspired by the workings of our brain. Among other things, they are applied in artificial intelligence (AI), which can mimic elements of independent thought processes.



Nerve cells	What are the neurons?	Processors (or sometimes simulated by software)
Via electrical pulses, which are transmitted when a threshold value in the neuron is exceeded. The cells are connected via synapses.	How do neurons communicate with each other?	Via simple, numerical messages.
In each area of the brain, sensory nerve cells receive impulses from the sensory cells throughout the body. These are passed on to the relay neurons, which are not directly connected to areas outside the brain but take care of the local processing of the signals. The motor nerve cells form the end station where the processed information is fed back to the body, for example, by sending a signal to a muscle.	How is the network structured?	For each different type of information that has to be processed by the system, there is an input neuron. The number of output neurons depends on the desired outcome. In between are a number of intermediate layers of neurons, which further process the information. The neurons are connected on a large scale. By 'training' the network, interconnections can be strengthened or weakened so that, just as in the brain, certain circuits are created.
Storage of knowledge and information, thought processes, regulation of bodily functions, coordination of senses, (day)dreaming, movement control, etc.	What can the network be used for?	Self-driving cars, image recognition, predicting stock market prices, and much more.

INFOGRAPHIC: PEPIJN BARNARD
TEXT: DENNIS VAENDEL
SOURCE: SANDER BOHTÉ, CWI

How brains and artificial neural networks inspire each other

The human brain still works much more efficiently than AI. Inspired by the workings of our brains, researchers can optimize artificial neural networks. By the same token, the functioning of artificial networks can also teach us a lot about misunderstood processes in the brain.

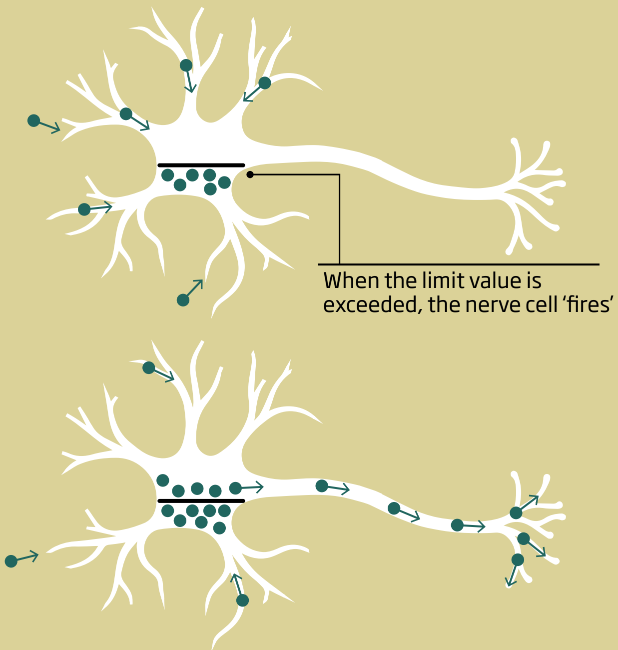
CWI researchers are working on this interface. For example, Sander Bohté and his team recently succeeded in developing more energy-efficient and privacy-friendly AI systems by better imitating the functioning of our brain (see 'Firing neurons' text box).

Firing neurons

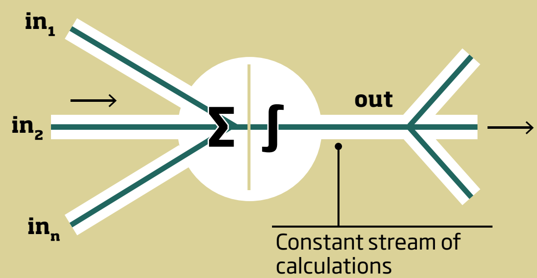
Nerve cells in the brain build up a potential, and only 'fire' when they have reached a certain limit. However, most normal artificial neural networks are continuously connected to each other, which is less efficient and consumes a great deal of energy. The brain is at least a million times more energy efficient.

AI applications could, therefore, work more efficiently by also 'firing' their neurons. However, this makes the network more mathematically complex, making it difficult to work with and difficult to train. Through smart mathematics, however, CWI researchers have developed a new algorithm for spiking (firing) neural networks that is as powerful as commonly used neural networks, but much more energy efficient.

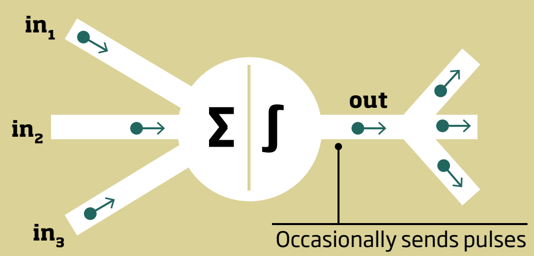
Nerve cells



Normal neural network



Spiking neuraal netwerk



Local applications

The spiking neural networks are one hundred to one thousand times more energy efficient than normal neural networks. Because of the low energy costs, they can also be put into a chip, allowing them to run locally (e.g., in your phone). This eliminates the need to transfer the data to a powerful data centre for processing, making AI applications more privacy friendly.


Voice recognition


Classification of ECG signals


Recognition of gestures

'Python is half my life'

Just over 25 years ago, CWI computer scientist **Guido van Rossum** laid the foundation for Python, which is still one of the most important programming languages in the world today.

Text: Ans Hekkenberg and Ed Croonenberg
Photography: Inge Hoogland

The Python programming language is in the top three most widely used computer languages worldwide. Millions of software writers use it, for the creation of games to the programming of artificial intelligence. Now that Python is so popular, it is hard to imagine how small the language began: as a hobby project with which Guido van Rossum, then working at CWI, filled his Christmas holidays.

You started Python in 1989. Why did you think it was time for a new programming language?
'I started at CWI in a group that wanted to develop an accessible programming language so that people without programming experience – like scientists – could use a computer fairly quickly. It was at that time that programming language Basic was on the rise. Someone like Lambert Meertens (former CWI researcher, ed.) was disappointed with the advance of this not-at-all powerful language. *"Stamp out Basic!"* was his motto. In the end, ABC, as our language was called, did not catch on.

I was disappointed that ABC was not a success. And I had some ideas about why this was the case. For example, I thought the grammar of programming languages should be made easier – by using more common words and fewer cryptic symbols. I spent two weeks at the computer during my Christmas holidays. After that, I worked weekends and evenings. After three months, I had a working prototype.'

To what extent was CWI a stimulating environment?
'The colleagues were stimulating, of course, but also the enormous freedom to learn anything and everything. This learning was often done by undertaking projects without knowing exactly what the outcome would be. The freedom to do that was great.'

What made Python successful?
'It is easy to use. And besides that, I had the times on my side. In the ABC days, if you wanted to send a piece of code to America, you had to take a plane to deliver a tape somewhere in person. Now there was the beginnings of the Internet. So, Python could spread much faster. Moreover, I was lucky that Python was used by influential people in science and industry. Google's first prototype was written in Python.'

An extraordinary community has emerged around Python: hundreds of volunteers are working together to develop the language. How did that community come about?
'In the beginning, there was a small group of people who were enthusiastic about Python and wanted to talk about it. That led to a mailing list. The first Python workshop followed in 1994, in Maryland in the United States. About twenty people came together there. The institute that organized the workshop invited me to stay for two months. Then I was offered a job. In April 1995, I left for America with four suitcases and a cat. I have been living there ever since. I have worked for small start-ups – none of which has been a success. Then I joined Google, and later Dropbox. I recently started a new part-time job at Microsoft.'

For years, you headed the Python volunteer group. You held the title *benevolent dictator for life*.
'Yes. Anyone can make suggestions for Python, but not all contributions will be accepted. If someone suggested something that I thought was a bad idea, it would not be added. It was not a democracy.'

You monitored which new features would be introduced in the language until July 2018, when you washed your hands of it.
'I was getting very unpleasant reactions to a decision I had made about a new feature in the language. It was a so-called operator – but actually it is not even that important what it was. I had thought long and hard about my decision and finally implemented the feature. Then I got blasted on Twitter. I felt like I did not deserve that. If they really thought they knew so much better, they could figure it out for themselves, I decided. In retrospect, a burn-out was lurking just around the corner. This was the straw that broke the camel's back.

'Google's first prototype was written in Python'

If I had not been on the verge of a burn-out, I might have done things differently.'

Who is the benevolent dictator now?
'Nobody. There is now a board of five people, elected each year by 150 Python developers at the heart of the community. I was on the first board, but I haven't been since. Now I am working on the design of new features.'

It sounds like you are having a hard time letting go of Python.
'Well... Yes. I cannot let it go so easily. Occasionally, my wife and son would want me to spend less time on it. They are worried that I take it so seriously. But I have been emotionally involved in this project for thirty years. Python is half my life.'

On 21 November 2019, CWI awarded you with a Dijkstra Fellowship for your work - a title for those who have done exceptional work in the field of mathematics and computer science. What did you think of that?
'Of course, I am very proud; I think it is wonderful that I got that recognition from CWI. And I thought, deep down in my heart: justice at last. When I developed Python, management was not as enthusiastic as I had hoped. Several programming language projects had taken place recently and none had been successful. So, they were not eager for a new programming language. It was only afterwards that the importance of Python became clear.' ■

Faster **smarter** more sustainable

When you think about mathematics and computer science, the things that come to mind at first instance are probably not cancer treatments, railway management, waste in the city, and sustainable housing. Yet these are things for which mathematics and computer science can be used very successfully. CWI research has been applied in practice for decades.

Text: Marleen Hoebe

Better treatment plans

Computer scientist Peter Bosman

One of the examples of CWI research in practice is the research of computer scientist Peter Bosman. Doctors at Amsterdam University Medical Centre now use the results of his research for a particular treatment of prostate cancer.

Known therapies for cancer are chemo or surgery, but radiotherapy is also an important treatment. For prostate cancer, for example, you can apply brachytherapy, an internal form of radiotherapy. Doctors insert hollow needles – catheters – into the patient's prostate. From those catheters, doctors irradiate the tumour using a radioactive source.

The challenge with radiotherapy is to have the tumour receive sufficient radiation, while other areas are affected as little as possible. However, the therapy should not compromise too much on the amount of radiation, because there must be sufficient coverage of the tumour. Doctors normally make their own irradiation plans. 'But it is difficult to determine for yourself how much radiation is needed,' says Bosman.

That is why he and his team developed intelligent algorithms that learn how to combine the best features of different plans without the need for a whole stack of data. 'You could see it as a form of natural evolution in the computer. For this, we use a rather mathematical approach in which you always estimate the chance a part of a plan is good.' With feedback from the end users – tirhe doctors, 'because if they do not want to use the technology, it will not work' – Bosman and his colleagues created algorithms that they researched in a blind study.

'In 98 per cent of the tests in which doctors had to choose a radiation plan, they chose our algorithm's plans instead of a plan they had drawn up themselves. We then created software for clinical use. I am very proud that this worked out. There is an enormous collection of literature on what we can do with intelligent algorithms in the medical world, but in the past little of that really ended up in a hospital.'

'Building on this success, I will also be preparing this technology for cervical cancer treatment, together with colleagues from Amsterdam and Leiden University Medical Centres. Its use will also be tested nationwide.'

Fewer delays for rail passengers

PhD student Dylan Huizing

Delays caused by incidents on the railways should be reduced with the help of new mathematical algorithms developed by PhD student Dylan Huizing. He is assisting ProRail in making a plan in which incident responders – employees who respond to calamities and try to solve them – are optimally spread out across different regions and can be at a certain location as quickly as possible, if necessary.

'A large part of the day, there are no incidents at ProRail. But it's not like incident responders are sitting around waiting. They carry out preventive inspections; among other things, they walk along the railway tracks to see if there are no people walking too close to the tracks, picking berries or walking their dogs. And they are checking to make sure that nothing is broken. They also carry out weekly inspections at goods locations. In my research, I am looking at whether we can plan these preventive tasks in such a way that everyone is always spread out evenly across the regions. In the event of an incident, the incident responders must be on site as soon as possible. At the moment, ProRail plans this as it sees fit. This is feasible, but there is a lot to be gained by using mathematical optimization.'

'ProRail has a lot to gain through mathematical optimization when planning incident management'

In the event of an incident, incident responders must be on site quickly. At the moment, ProRail plans this as they see fit.
PRORAIL

From a scientific point of view, creating this plan is an interesting problem, according to Huizing. 'It lies between two known mathematical problems: the vehicle routing problem and the facility location problem. The vehicle routing problem is, for example, Albert Heijn supermarket's home delivery service. The delivery vehicles must always take the routes with the shortest distances. The facility location problem is about having the best possible coverage across a network. For example, where can distribution centres best be built to achieve that.'

Huizing and other researchers incorporated the elements of these two mathematical problems into an algorithm. When that was shown to work, they talked to ProRail employees. Huizing: 'As a result, we discovered that there are more things we need to take into account, such as that incident responders always have to carry out some tasks in groups, need qualifications for certain tasks, and have to do a number of things around rush hour, for example.'

Huizing thinks they are now at a point where almost all the things you can think of for this plan are in the algorithm. 'ProRail then took steps to integrate the algorithm. In collaboration with software builders, we have built a good application that incident responders can use on their smartphones, among other things. This enables planners to draw up a plan within seconds that is no more than 3 or 4 percent off from the optimal solution.' The application is now entering the test phase, which Huizing finds quite exciting. 'I hope our mathematics can help reduce delays for rail passengers.'

More efficient waste processing

Mathematician Nanda Piersma

What is the best way to set up a dynamic route forf waste collection vehicles? Mathematician Nanda Piersma is researching this problem. 'Waste collection vehicles, for example, cannot all be out in rush hour at the same time.

The municipality can work much more efficiently in terms of waste collection.
ISTOCK

In addition, the vehicles are no longer allowed to cross all Amsterdam bridges and not all Amsterdam streets are accessible. And then you have to take into account the wishes of the waste collectors; they want a coffee break at some point. Determining the best route is, therefore, a complex puzzle. I am working with colleagues to see how we can use mathematical models for this purpose.'

The municipality of Amsterdam provides them with all manner of data on waste. In the mathematical models, they also have to take into account how much waste the city produces, where that waste occurs, and at what times there is more waste. Piersma: 'We are now seeing a huge shift in that, because everyone is working from home. As a collector of household waste, the municipality is now much busier.'

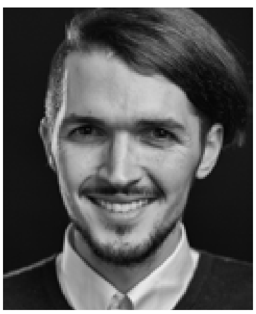
These mathematical models – so-called digital twins – also make further calculations. They outline future scenarios. 'On the basis of this, we will examine whether the city's waste can be reused,' explains Piersma.

However, it is important that these mathematical models take into account citizens as much as possible and keep in line with reality. 'Some systems may seem neutral at first glance, but they disadvantage some people. 'If you program a system incorrectly, it can make harsh choices.'

An example of such a harsh choice was Piersma's model for smarter charging stations that only charge electric cars at certain times, when more power is available. 'We found out that not all cars were able to handle this, especially the less expensive ones. We are looking at how to prevent situations like this in mathematical models.'

Fair distribution of energy

Computer scientist Michael Kaisers



Neighbours who jointly generate green energy via solar panels want to share that energy with each other. But how do you do this fairly? A system that automatically distributes energy intelligently can offer a solution.

Michael Kaisers focusses on such systems that represent users. This is useful for cooperatives such as Schoonschip in Amsterdam-Noord: a community of 46 households that get their energy from solar panels on their roofs. Often these households are not able to use their solar energy immediately and want to store it for later or share it with another household in the community that does not have enough energy at that time.

'You have to coordinate energy distribution,' says Kaisers, 'but people do not want to spend all their time on it, so it has to be automated. Together with other scientists, I am trying to find algorithms that can make all these decisions, that learn, and that plan by themselves. These algorithms realize at a certain point that it is not useful, for example, if all households start charging at the same time; they learn through the effects of their previous decisions. We no longer have to give instructions.'

The system must keep in mind what the users' wishes are. 'People can choose only green energy, but that is not always the cheapest option. Now we ask them what

'People do not want to spend all their time on energy distribution, so it has to be automated'

they think is more important: green energy or money. Ultimately, algorithms are supposed to ask this themselves, a bit like Siri does with Apple products. That way, the algorithms also learn from interaction with users.'

Kaisers does think that perhaps not everyone in such communities benefits equally from renewable energy. 'There is competition. In reality, some people have a larger roof with more solar panels than others. And some have a greater focus on sustainability than others. But if you do not use intelligent systems to coordinate the storage and distribution of energy, the difference between households would be even greater. These systems really try to find the best solution.' ■

Neighbours who generate energy together using solar panels, like the Schoonschip cooperative in Amsterdam-Noord, want to share that energy with each other. But how can this be done fairly? SHUTTERSTOCK

Jurgen Vinju

Tijs van der Storm

column

Software as language

Many successful software products last for years. Over the course of their lives, they are gradually updated and expanded. As a result, these software programs (from smart software for a small start-up, to products for online banks, and even the Tax and Customs Administration) often grow into unfathomable and unaffordable monstrosities. How do we prevent this? And how do we fix it? These are the questions that characterize the research field of software engineering: the what, the why, and the how of software.

At CWI, the perspective of 'software is language' has traditionally been a leitmotiv. In other words: software is a means of communication between the designer and the computer, but also between designers themselves. This perspective has two sides. Better languages can lead to better communication (i.e., better software). In addition, we can study existing software as a kind of text.

On the one hand, this means that you could view the design of a programming language as the software engineering version of the motto 'form follows function', often heard in industrial design. Domain-specific programming languages – small languages with which you cannot do everything, but what you can do with them is very efficient – are the logical interpretation of this train of thought. From the very beginning, CWI has contributed to the what, the how, and the why of these 'small languages'. For example, CWI designed the Rascal programming language, a meta programming language that can read, understand, and modify these types of languages for the user. Those who have mastered the 'basic' Rascal language can effectively and inexpensively design tools for many small programming languages.

On the other hand, there are billions of source code lines supporting applications all around the world. The reality is that there is a lot of software; how do we keep it manageable? While science searches for the answer to this question, we also have to answer other pressing questions. For example: how well is my privacy guaranteed by existing software systems? How can we replace a part of a major program without the system failing? Answering such questions requires automated tools. Software programs are often too large and complex to go through by hand. By viewing software as a language, source code can automatically be analysed, unravelled, and queried. We also designed Rascal for this purpose. In this way, the computer can help us better understand and maintain software.

Software is indispensable in today's society. As a result, software engineering has also become a crucial discipline. The major difficulty is that in this field short and long-term challenges fight for priority: the quantity of unbridled growth versus the reflection on quality. In order to face challenges *and* to choose which challenges have the highest priority, different disciplines have to work together. Software is language, and more than ever scientists, industry, and policy makers have to learn to speak each other's languages to ensure the quality of software.

Jurgen Vinju and Tijs van der Storm


75 YEARS
1946 - 2021
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