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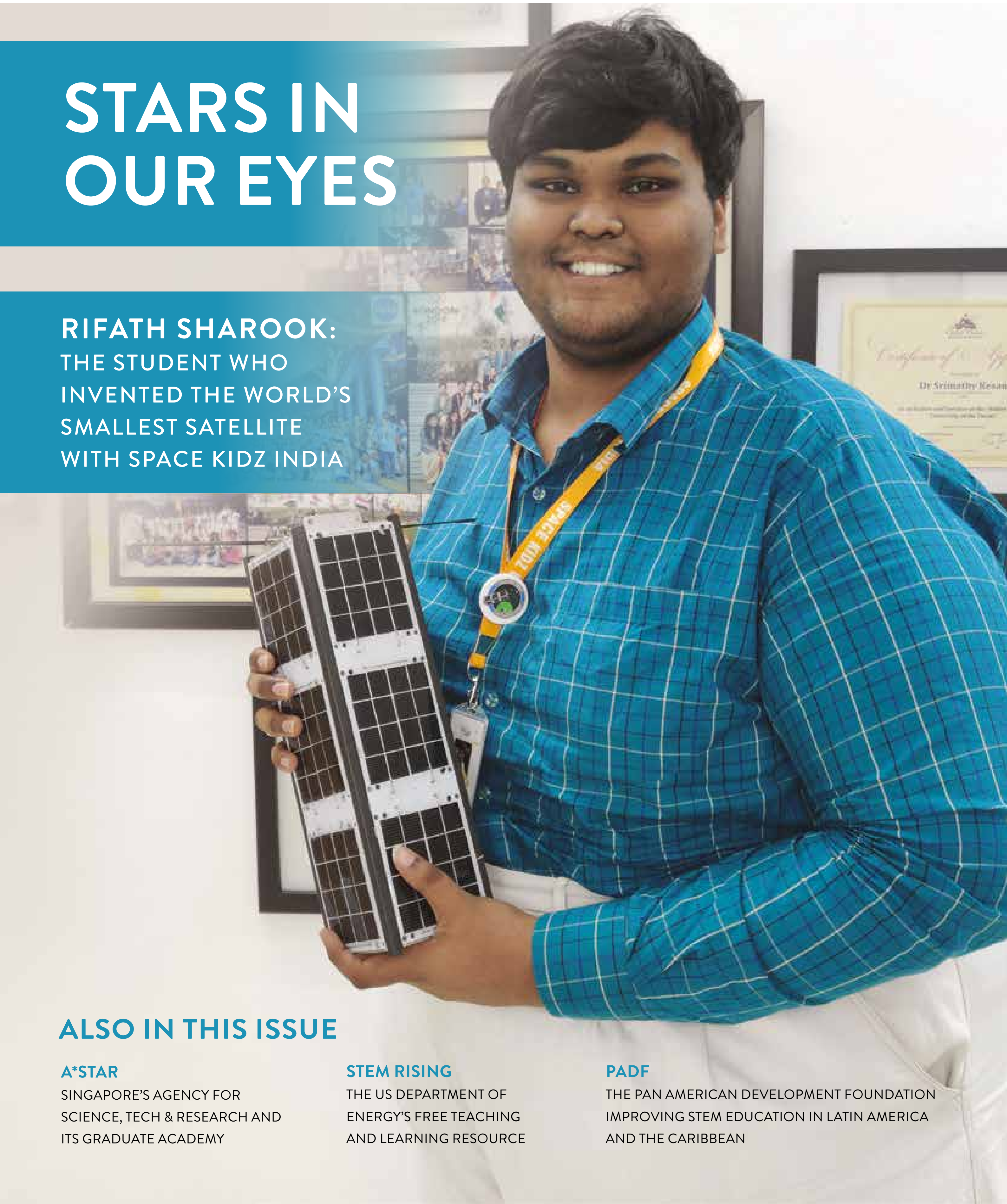
A SCIENCE, RESEARCH AND TECH MAG
FOR THE NEXT GENERATION

ISSUE 008
MAY 2021



STARS IN OUR EYES

RIFATH SHAROOK:
THE STUDENT WHO INVENTED THE WORLD'S SMALLEST SATELLITE WITH SPACE KIDZ INDIA

ALSO IN THIS ISSUE

A*STAR
SINGAPORE'S AGENCY FOR SCIENCE, TECH & RESEARCH AND ITS GRADUATE ACADEMY

STEM RISING
THE US DEPARTMENT OF ENERGY'S FREE TEACHING AND LEARNING RESOURCE

PADF
THE PAN AMERICAN DEVELOPMENT FOUNDATION IMPROVING STEM EDUCATION IN LATIN AMERICA AND THE CARIBBEAN

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STARS IN OUR EYES

Mention the word 'star' and some people will think of celebrities and influencers, while others will gaze up into the night sky and wonder at the glittering constellations. At Futurum, we believe everyone can be a star. But what would your students be thinking?

According to a survey by market research company, Morning Consult, 54% of 13-38* year-olds in the US say they would become an influencer, if they had the opportunity, and an overwhelming 86% are willing to post sponsored content for money. Given these statistics, and the huge numbers of followers that influencers have, it is highly likely that a social media star will be at the forefront of young people's minds.

Of course, there is nothing wrong with being a social media star, per se – we are all influencers to a lesser or greater degree – but we want to ensure that young people understand that being a star does not necessarily mean having the greatest number of followers. Being a star is about finding the light that shines within you – finding the subjects and a career path that will give you the most joy, and sharing that joy with others so that the world becomes a better place.

Rifath Sharook was 18 years old when he and his team members at Space Kidz India – all of whom were under the age of 21 – came up with an idea to develop the world's smallest satellite (p 6). Just like every single scientist and researcher in this issue, he started with a dream, worked hard and became a shining star.

**https://morningconsult.com/influencer-report-engaging-gen-z-and-millennials/*

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CHECK OUT OUR CAREER POWERPOINTS ONLINE …

Our PowerPoints summarise our articles and include additional 'Talking Points', making them a fantastic classroom resource: **https://futurumcareers.com/ppts**

AND TRANSLATIONS!

Some of our articles have been translated into other languages. For example:

There is a French version of Yves' article (p 16): **https://futurumcareers.com/using-nanotechnology-to-overcome-the-adhesion-of-the-bacterial-pathogen-staphylococcus-aureus**

And a Dutch version of Sander's article (p 70): **https://futurumcareers.com/greenteens-unleashing-teenagers-eco-friendly-behaviour**

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AIMING HIGH WITH A*STAR

WITH A FOCUS ON DISCOVERY, INNOVATION, DEVELOPMENT AND GROWTH, SINGAPORE'S AGENCY FOR SCIENCE, TECHNOLOGY AND RESEARCH (A*STAR) IS ON A MISSION TO NURTURE A STEM RESEARCH COMMUNITY THAT KNOWS NO BOUNDS

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This is based on an article by NIE faculty Professor Teo:* ***https://iopscience.iop.org/article/10.1088/1742-6596/1340/1/012002/pdf*

From the futuristic buildings to the beautifully biodiverse green spaces, Singapore is world-famous for being a modern, innovative and forward-thinking city state. It is a place of aspiration and attainment and now, thanks to the Singapore's Agency for Science, Technology and Research (A*STAR), is aiming to make its global mark in STEM research and development (R&D).

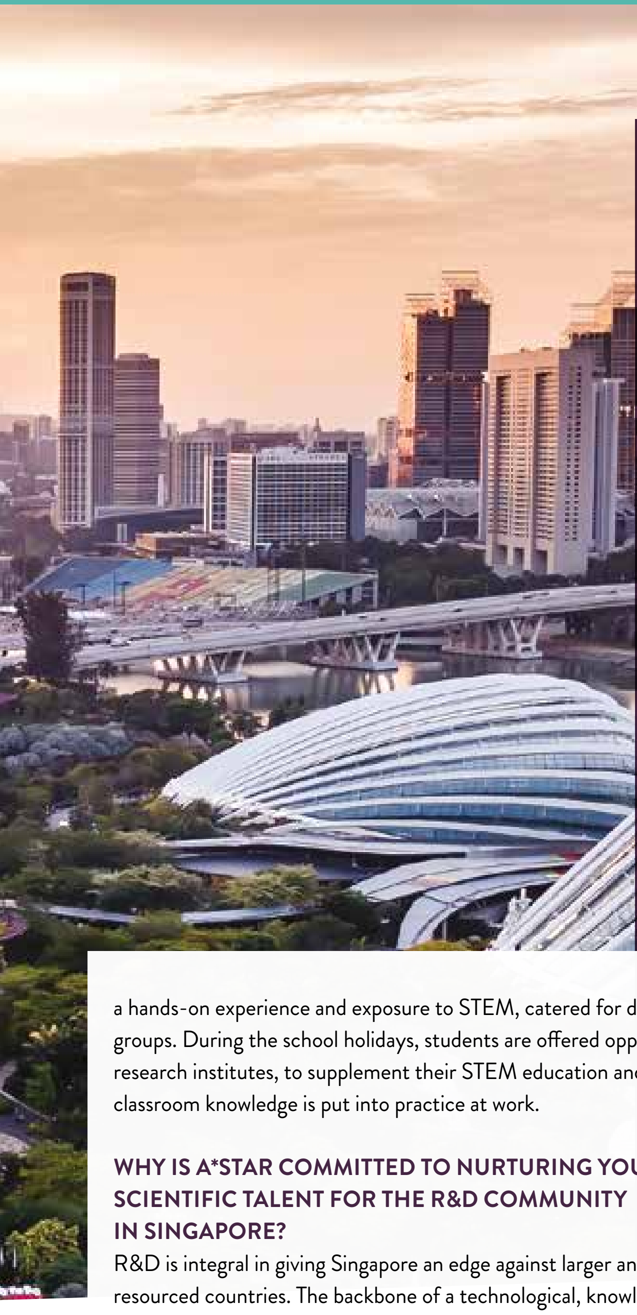
"Singapore is a knowledge-based economy which thrives on research, innovation and enterprise," explains A*STAR's Dr Shawn Hoon. To facilitate such progress, developing today's talent to be STEM leaders of tomorrow is key. This is where A*STAR, an organisation committed to STEM education and R&D, steps in. A*STAR's Dr Tan Teck Leong adds, "STEM education teaches critical thinking, problem-solving and scientific reasoning, skills that are important given the proliferation of technology in our day to day lives." A*STAR aims to nurture the potential of students, to ensure STEM innovations enhance everyone's lives.

As directors of graduate affairs for their associated councils – Dr Hoon for the BMRC and Dr Tan for the SERC – both scientists are keenly aware of the importance of ongoing education, mentoring and support for individuals to succeed and for wider communities to benefit. Here, they give us an insight into A*STAR's aspirations.

IN GENERAL, HOW WOULD YOU DESCRIBE THE STATE OF STEM EDUCATION IN SINGAPORE?

Having a strong foundation and pipeline of STEM talent enables our enterprises to remain competitive, especially in a world disrupted by COVID-19. It also drives us towards a society that harnesses relevant STEM knowledge to improve quality of life.

Internationally, Singapore students rank highly in mathematics and science, which speaks to the quality of our education system and our teachers. Increasingly, STEM education in Singapore has become more 'holistic' with the support of public and private sector organisations, and ground-up efforts to offer diverse STEM programmes catered to different groups*. For example, A*STAR conducts outreach activities such as co-organising the annual Singapore Science Festival with Science Centre Singapore, which is filled with exciting science-related experiments and exhibitions for



THE A*STAR GRADUATE ACADEMY

The Graduate Academy's vision is to make A*STAR a global nexus for scientific talent. With a comprehensive suite of undergraduate, PhD and post-doctoral scholarships, A*STAR Graduate Academy (A*GA) supports top-class education both locally and overseas to help passionate individuals realise their full potential. Youth talent is also identified through extensive outreach programmes to nurture a vibrant diverse community of young scientific talent in Singapore.

Supporting overseas students creates a diversity of talent in R&D, and life experiences that will create a vibrant landscape for R&D in Singapore. This also helps to foster future research networks and alliances internationally, which is essential for shared learning and collaboration, and research opportunities.

> *“A career in science and research also allows for an exciting journey towards making ground-breaking and important discoveries that could potentially improve the lives of people globally.”*

a hands-on experience and exposure to STEM, catered for different age groups. During the school holidays, students are offered opportunities in our research institutes, to supplement their STEM education and experience how classroom knowledge is put into practice at work.

WHY IS A*STAR COMMITTED TO NURTURING YOUNG SCIENTIFIC TALENT FOR THE R&D COMMUNITY IN SINGAPORE?

R&D is integral in giving Singapore an edge against larger and better resourced countries. The backbone of a technological, knowledge-based economy is a healthy scientific/research community.

The R&D community needs a mix of talent to take the science through from research and innovation, to high-growth enterprise. This means nurturing researchers at our public sector research institutes and universities, as well as in private sector R&D. Then there are research activities along the research, innovation and enterprise 'value chain', such as careers in intellectual property management, industry development, commercialisation, venture capital or entrepreneurship.

For example, in the area of food, some start-ups, like Shiok Meats, were spun off or set-up by A*STAR talent.
https://www.straitstimes.com/singapore/foods-of-the-future-0

A*STAR is committed to nurturing and grooming scientific talent, to catalyse innovation and raise competitiveness for the sustained economic growth of Singapore.

WHY SHOULD STUDENTS CONSIDER A CAREER IN R&D?

Almost everything in life is related to or can be explained by science. Hence, with a variety of niches and fields under the umbrella of science, there are myriad options for students interested in STEM to explore and venture into.

At A*STAR, we encourage our scholars to take ownership of their careers. Opportunities are open for PhD scholars typically after their first two years at an A*STAR research lab to develop as scientists, technologists or venture into academia, business development, industry research and beyond.

HOW DOES A*STAR SUPPORT UPPER SECONDARY, JUNIOR COLLEGE AND POLYTECHNIC STUDENTS?

Through our extensive outreach programmes and the range of awards we offer, we expose students to science and research from an early age, fuelling their interest in the sciences and encouraging them to pursue their passion in research. We measure the effectiveness of such programmes by looking at whether these students go on to pursue STEM in their next phase of education.

WHAT DO A*STAR SCHOLARSHIPS OFFER STUDENTS?

An A*STAR scholarship is not just for scholars to get a degree; it is the foundation of their career in the R&D landscape in Singapore and globally. With hands-on experience, students can be aligned to the research interests before they embark on their training. Besides the financial incentives offered through scholarships, our scholars also have mentors to turn to for career advice.

Mentorship at the junior college/polytechnic level provides insights to a scientific career, and the traits and skills that a researcher should possess. Mentors provide guidance and support and apprise students of the latest science and technology happenings in A*STAR and Singapore.

FINALLY, HOW DO YOU SEE RESEARCH DEVELOPING IN SINGAPORE?

The research landscape is becoming more inter-disciplinary, where collaboration across research fields is needed to deliver tangible and impactful outcomes that address national challenges. As such, subjects under computing, information, engineering and technology with applications across an array of disciplines, such as in artificial intelligence, analytics and informatics, health and medical technologies, manufacturing resilience (such as food production and pharmaceutical manufacturing), could see potential growth.

THE STUDENT WHO LAUNCHED THE WORLD'S SMALLEST SATELLITE

LIKE MANY YOUTHS, RIFATH SHAROOK LOVES SOLVING PROBLEMS, BUT WHAT MAKES HIM STAND OUT FROM HIS PEERS IS THE CHALLENGE HE SET HIMSELF - TO SEND A NANOSATELLITE INTO SPACE! HE TELLS US HOW AN INDIAN MILK-BASED DESSERT GAVE HIM AND HIS TEAM AT **SPACE KIDZ INDIA** THE IDEA TO CREATE KALAMSAT – THE WORLD'S SMALLEST SATELLITE

TALK LIKE SPACE KIDZ

CUBE SATELLITE – a miniaturised satellite for space research that is made up of cubic modules

IONOSPHERE – a layer of the Earth's atmosphere. It contains ions and free electrons and is able to reflect radio waves. It extends from about 80 to 1,000 km above the Earth's surface

PAYLOAD – the carrying weight of an aircraft or launch vehicle

SUB-ORBITAL – a spaceflight that reaches outer space but does not complete a full orbit of the Earth and does not escape its gravitational pull

At the age of 18, Rifath Sharook held a tiny cube in his hand, one that weighed 64 grams and had edges of just 3.6 cm. This cube carried an order of magnitude that far surpassed its tiny size. It was the world's smallest satellite, KalamSat, and it was soon to be launched into space by NASA. The team of designers and engineers that built KalamSat were all members of Space Kidz India and the oldest member of the team was just 21 years old.

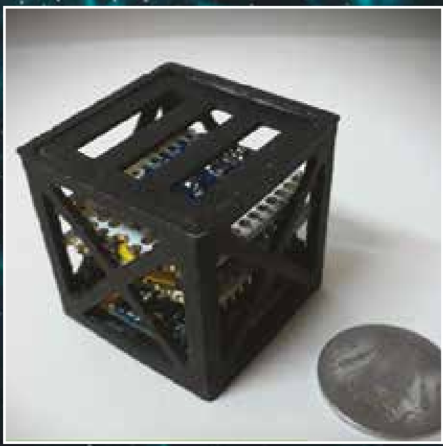
As the leader of the team that created the nanosatellite, Rifath had been working towards this project since he joined Space Kidz India: "I love satellites, but I never knew about the existence of nanosatellites. Then, I came to know about cube satellites – these 1 kg satellites – and I thought about building one. I thought it would be small and less expensive. But I found out it would cost around $100,000 just to build a 1 kg satellite – and that's not even including its launch!"

STEM is not just an acronym for an area of study for Rifath. It is a thread that has run through his life to where he is now. He became involved with Space Kidz India when he was sent to interview its Founder and CEO, Dr Srimathy Kesan, as a student journalist. This was at the age of 14 and was part of Rifaths's attempts to re-engage with science and technology after the loss of his father, an electronics professor. "My father was a scientist," he says, "and in my childhood I spent a lot of time in my Dad's lab."

An interest in STEM had been ingrained in Rifath from an early age and with a scientist for a father, looking inquisitively through a microscope or a telescope is part of who he is: "I am the kind of person who always wants to find the reason. I'm always wondering what is behind the engineering, what is behind the electronics, what is happening at the atomic, nuclear level. I went into physics so I can understand things on a much deeper level."

When Rifath interviewed Dr Kesan, they both found similar passions for research and space. And it was Rifath's desire to understand why things work and the satisfaction he gets from problem solving that led to Space Kidz India finding a solution to the expensive space problem. Dessert also played a large part! While pondering how to create an inexpensive nanosatellite, the Space Kidz team was tucking into gulab jamun, an

Shrinking a satellite from 1 kg down to the size and weight of a milk-based dessert ball is a huge-scale reduction, but Rifath and his team managed it and KalamSat weighs less than 10% of a cube satellite.



KalamSat was rocketed into a sub-orbital flight path and re-entered the Earth's atmosphere in 12 minutes.

Dr Srimathy Kesan, Founder and CEO of Space Kidz India.

Indian sweet consisting of balls of milk solids with a light syrup drizzled over the top. Each ball is between 50 and 70 grams in weight.

Rifath explains, "Abdul Kashif (the KalamSat engineer) and I thought, 'Why don't we make a satellie the size of gulab jamun? Why don't we shrink it, even?!' Computers have shrunk from the size of a room to fit in our mobile phones. Satellites are nothing but flying computers with transponders, so they can be simplified."

Shrinking a satellite from 1 kg down to the size and weight of a milk-based dessert ball is a huge-scale reduction, but the team managed it and KalamSat weighs less than 10% of a cube satellite. Rifath feels the applications for its use are endless: "Recently, sensors and micro controllers that scientists can produce are becoming very, very small. They can study the ionosphere and transmitter modulation. The possibilities are limitless."

The final piece of the puzzle for the Space Kidz team launching their own satellite came when they entered their prototype into a NASA and 'I Doodle Learning' competition called Cubes In Space. KalamSat beat 86,000 designs from 57 countries to be launched from NASA's Wallops Flight Facility in Virginia. KalamSat was rocketed into a sub-orbital flight path and re-entered the Earth's atmosphere in 12 minutes, ending with its planned descent in the Atlantic Ocean.

Now 21 years of age and studying for his MSc in Physics at the New College in Chennai, India, Rifath is still in the space game. He and his Space Kidz team have just launched their latest satellite, Satish Dhawan Sat, on a rocket created by The Indian Space Research Organisation (ISRO). Rifath is also Chief Technology Officer (CTO) at Space Kidz India, a role he has occupied since the age of 19. "As a CTO, I design the architecture for upcoming programmes. Not just satellites, but other industrial solutions, too. Once you're able to solve problems in space you can certainly work on ground-based solutions," says Rifath.

It appears that problems and a quest for knowledge are what drive Rifath. When asked about his proudest achievements, he talks less about launching things into space and more about solutions: "I find working on a future mission or how to solve a problem really satisfying. Recently, we had a computer bug and I came up with a crazy solution that made me feel proud."

What is Rifath's number one tip for budding scientists and engineers? "Explore! Explore from a young age. I have explored space and journalism. I have explored making music. And when you feel like you are getting attracted to something, go and do it!"

WHAT IS SPACE KIDZ INDIA?

Space Kidz India is an organisation aiming to inspire young scientists and create experiential learning for students in the field of science, technology, art and culture. Its 'Young Scientist Program' is designed to promote science awareness to high school students. Space Kidz India is the first organisation in the world to have launched satellites through high school and college students. It sends ambassadors around the globe and is an advocate of a 'borderless world'.

https://www.spacekidzindia.in

WHAT IF MICROBES COULD LIVE IN EXTREME ENVIRONMENTS BEYOND EARTH?

DR JAY NADEAU, BASED AT **PORTLAND STATE UNIVERSITY**, USA, IS ON A QUEST TO FIND LIFE IN EXTREME ENVIRONMENTS. HER FINDINGS COULD HELP INFORM THE SEARCH FOR BUGS IN SPACE

TALK LIKE A MICROBIOLOGIST

MICROBES – tiny living things that are found all around us and are too small to be seen by the naked eye

MICROBIOLOGY – the study of all living organisms that are too small to be visible with the naked eye

MOTILITY – the ability of an organism to move independently, using metabolic energy

ORGANELLES – subcellular structures, usually enclosed by membranes, that have one or more specific jobs to perform in the cell

PROKARYOTES – cellular organisms that lack an envelope-enclosed nucleus and membrane-enclosed organelles. Bacteria and archaea are two domains of prokaryotic life

EUKARYOTES (EUKARYA) – the third domain of life, consisting of all organisms with their DNA enclosed in nuclei. This domain includes all animals, plants and fungi

NUCLEIC ACIDS – the biopolymers, or large biomolecules, essential to encoding genetic information in all known forms of life (the overall name for DNA and RNA)

ARCHAEA – any of a group of single-celled prokaryotic organisms that have distinct molecular characteristics separating them from bacteria

ABIOTIC – relating to things in the environment that are not living

ENTROPY – a thermodynamic function that describes the randomness and disorder of molecules based on the number of different arrangements available to them in a given system or reaction

Despite the efforts of scientists and researchers, we only know of one place in the entire Universe where life has evolved – Earth. The number of things that had to happen for life to evolve – and often in a particular order – on our planet seems so unimaginably massive, that we might all reasonably be considered walking miracles. But is this actually true? Is the origin of life rare – or incredibly common? We can only start to answer questions like these by looking for life elsewhere.

We can imagine that across the entire Universe, even if life is extremely rare, the immense spaces mean that it must be inevitable that life arose somewhere. But searching the entire Universe is very difficult. The best we can do right now is build specialised telescopes to look at faraway stars for orbiting planets and signs of oxygen in their atmospheres. If there are animals, plants, or bacteria living on those planets, we have no hope of getting to see them in our lifetimes.

To actually see extraterrestrial life, we need to go to places where we can land and deploy robotic instruments. So far, this has only been Mars, where no life has been found, but lately scientists have been increasingly interested in other parts of the solar system: Venus and the moons of the giant planets such as Jupiter and Saturn. The question is, how can we look for life in these places, and what kind of life can we expect?

Until recently, we thought that life in such places was impossible. Even on Earth, there are places that were believed to be too cold, too hot, or too dry for life, until microbiologists found otherwise. By looking for Earth sites that are as similar as possible to sites on other planets, scientists hope to go to these planets better prepared to find microbes. These sites are called 'extraterrestrial analogue' sites.

Dr Jay Nadeau, a physicist based at Portland State University in the US, is on a quest to find evidence of life in analogue sites. Evidence of life in incredible places appears all the time, at extremely high or low temperatures, high pressures and sometimes with no apparent food sources. Tardigrades are a brilliant example of this – these microscopic animals have shown they can survive for years without water, in sub-zero temperatures and in space! It is not an exaggeration to say that tardigrades are the toughest animals on Earth.

WHICH EXTREME ENVIRONMENTS HAS JAY SEARCHED FOR BUGS?

Jay and her team have investigated sites in some of the most extreme environments on Earth, including sea ice in Greenland, pools in Death Valley and Ash Meadows in the California desert, mineral springs in The Cedars in the California mountains, and permafrost in Alaska. In all these places, the researchers have found a wide variety of microorganisms with incredible diversity. This is important because it shows that it is not just

DR JAY NADEAU

Associate Professor, Department of Physics, Portland State University, USA

FIELD OF RESEARCH

Physics, Microbiology and Space

RESEARCH PROJECT

Jay is looking for signs of life in some of the most extreme environments on Earth. Her studies will help inform the search for life in space and possibly revolutionise our understanding of the conditions in which life can thrive.

FUNDERS

Moore Foundation, NASA, JPL National Science Foundation

one form – or type – of life that can thrive in these environments. While some of the microorganisms that have been discovered are eukaryotes, others are prokaryotes.

WHAT EXCITING DISCOVERIES HAS JAY MADE ABOUT MICROORGANISMS?

One of the most remarkable aspects of these microorganisms is their motility, that is, the ability of organisms to be able to move by themselves. Indeed, from Jay's research it appears that there is always something moving. "When we first went to Greenland, we had no idea if we were going to see anything at all, but then, right away, something swam across the screen. The fraction of cells that swim and the speed at which they swim are highly dependent upon factors such as nutrients and temperature," explains Jay. "We have seen organisms that swim their fastest at 4°C – the same temperature as your refrigerator – and start dying when the heat reaches what we call room temperature. On the other hand, some hot spring organisms can't swim at all until they reach 85°C and are happiest just below boiling."

WHY IS MOTILITY IMPORTANT IN JAY'S RESEARCH?

Somewhat remarkably, scientists do not have a reductionist definition of what it means to be 'alive' – there is no mathematical definition or chemical formula that determines whether something is living. The only way to determine whether something is alive is by observing life-like behaviours, such as the ability to reproduce or evolve through natural selection. However, these behaviours can be very difficult to measure. Motility, on the other hand, is a much easier behaviour to measure. Technological advances have helped enormously, as the development of digital video microscopy and other types of microscopy have helped scientists peer at things much more closely, and record and analyse what they see, making observing the motility of microorganisms possible. Advances in computer technology have been just as important as developments in optics because recording motion involves generating a lot of data very quickly and often complex computational analysis.

IS JAY USING MICROSCOPES IN HER RESEARCH?

Yes! She and her team of collaborators at Caltech's Jet Propulsion Laboratory have developed a holographic microscope named SHAMU, an acronym that stands for Submersible Holographic Astrobiology Microscope with Ultraresolution. "SHAMU is a holographic microscope specifically designed to look for the smallest microorganisms, bacteria and archaea, in liquid environments. Its key feature is its high resolution, where it is able to image individual bacteria down to 700 nm in size, and its ability to be used outside in the field," says Jay. "Many other holographic microscopes exist but SHAMU uses a type of 3D microscopy, where a single image encodes for the information in the entire sample depth. Holographic microscopes tend to be delicate and require careful laboratory use in rooms without noise or vibration. Field instruments usually have lower resolution so they cannot see bacteria. SHAMU was made with these particular applications in mind so that we could see bacteria and archaea in their native environments."

HOW IS JAY SEARCHING FOR MICROORGANISMS IN SPACE?

Unfortunately, to determine whether there is life in space it is not enough to be looking in the right places – you also need the right tools, methods and approaches. If something is observed moving (a sure sign that it is alive), then it is important to actually know what this living thing is! Microscopy is essential in observing life, but a variety of chemistry instruments are also important, as they will help Jay and the team understand what components make up alien biochemistry.

"The search for biochemistry starts with building blocks, such as lipids that make up membranes, amino acids, which make up proteins, and nucleic acids which encode genetic information. We know, however, that simple building blocks can form abiotically, and have even been found in interstellar space and on asteroids," explains Jay. "Chemical studies will therefore look for more complex assemblies of building blocks, such as proteins, and attempt to classify them. Some approaches will look at the overall complexity of a sample, to find evidence of local reductions in entropy that are characteristic of life."

SEARCHING FOR LIFE IN SPACE

It is fair to say that if evidence of life can be found in space it would be one of the most remarkable discoveries that has ever occurred. In many ways, it seems staggeringly simplistic to think that across the infinity of the Universe, life only managed to find a way to exist on Earth. On the other hand, we do not know how specific the conditions and requirements for life are, or how likely each step is in the complex chain of events that leads from molecules to cells. To date, we have only looked at one place outside Earth – the planet Mars – and even that has not been fully explored. We genuinely have no idea of how rare or common life might be.

Jay's research into finding life in extreme environments has challenged many of the preconceptions we have about the conditions in which life can thrive, which opens up more possibilities in terms of the environments in which we may find evidence of life. Life on Earth is relatively fragile. Eukaryotes - from the smallest algae to large animals and plants - require oxygen, and there is a narrow band of temperatures and water availability where complex life can live. However, Jay's research is providing possible means of discovering life beyond Earth by altering our concepts of just how fragile life on Earth is.

LIFE ON OTHER PLANETS

Although current scientific knowledge shows us that complex life is impossible without oxygen, there are other forms of life – particularly bacteria and archaea – that can use chemicals in place of oxygen, including solid materials like iron! "Bacteria can withstand extremes of temperature, dryness, radiation, toxins, pressure and acceleration. They can be frozen for thousands of years and then revived. Prokaryotes have also been around on Earth for at least 4 billion years; eukaryotes did not arise until 1 to 1.5 billion years later. What this suggests is that most life elsewhere may be microbial," says Jay. "There could be entire planets, in our solar system and elsewhere, that are entirely dominated by bacteria-like organisms. If we want to find extraterrestrial life, we need to be able to see these organisms."

LOOKING FOR BUGS IN SPACE

Just think about what finding life elsewhere would do to our understanding! Many scientists like Jay are aware of the remarkable conditions in which life on Earth can be found, and if their attempts to find life in space are successful, it would perhaps be less unbelievable to them (though no less incredible) than it would to you and me. It would be front-page news around the world, it would raise so many philosophical questions, it would challenge many of the things that people hold true. It would also have exciting scientific ramifications – is life abundant in the Universe? Does all of it look more or less similar?

"We don't know if water-based life would converge to using similar sets of building blocks as those found on Earth, such as amino acids and nucleobases," explains Jay. "Finding life elsewhere would fundamentally change our understanding of what life is, how it originates, and what circumstances are necessary for it to persist and evolve. Would Martian bacteria look just like *E. coli* – or completely different?"

EUROPA

Understandably, any scientific investigations into life that require sending robots to land have to take place within our own solar system. Even that is rather large – it measures 287.46 billion km across. Within that area, some scientists think that Jupiter's moon, Europa, is most likely to harbour life. This stems from the Galileo mission which suggested the presence of a liquid water ocean underneath a layer of ice (and our understanding that life requires liquid water). We also know that minerals such as phosphorous – which are derived from rocks – are required, so a rocky core with a liquid water ocean contains all of the known requirements for life 'as we know it'.

Recently, scientists have expanded their search, however. "The Cassini mission discovered a liquid water ocean on Saturn's moon Enceladus in 2009. Several more sub-surface oceans have since been discovered on the moons Titan, Ganymede, and Callisto, and even on Pluto," says Jay. "These bodies, now collectively known as the 'Ocean Worlds', are all areas of great interest in the search for life. The Triton, Ceres and Dione moons are also candidate Ocean Worlds."

HOW TO BECOME A PHYSICIST

- The American Physical Society is a non-profit membership organisation working to advance the knowledge of physics. Have a read around the site to see what is happening in the field. **https://www.aps.org**
- Maths is of major importance to any budding physicist, as well as any physics classes you can take. Physics relates to many areas of science, so studying the fundamentals of biology and chemistry alongside it could also be beneficial.
- Salary.com claims that that average national salary in the US for a physicist is between $86,864 and $127,552. However, Jay is keen to explain that industry salaries are very different from academic salaries, and within academia, there are high- and low-paid positions.

JAY'S TOP TIPS

01 Take as many maths classes as you can, as soon as possible. Maths is useful for all sciences and any area you decide to go into will be easier to understand and get to grips with if you are well-versed in mathematical principles.

02 It's never too early to start thinking about where you want to go to college and what kind of research you might want to do. Each school has its own particular strengths and areas of research opportunity, so start thinking about this sooner rather than later!

HOW DID JAY BECOME A PHYSICIST?

WHO OR WHAT INSPIRED YOU TO STUDY PHYSICS?

I have loved Isaac Asimov's books ever since I was a kid, so I knew I wanted to study physics or chemistry. I had some terrific physics professors in college who really inspired me to pursue theoretical physics for my doctorate.

HOW DOES A PHYSICIST END UP WORKING IN MICROBIOLOGY AND SPACE SCIENCE?

That's the funny thing about astrobiology – it's not something you can study in school, really, so the people who work in the field come from a wide variety of backgrounds. All kinds of skills are needed to send a mission to another planet. First, you have the basic engineering, then there is the building and design of science instruments, then there is the design of scientific experiments which use these instruments, and finally the analysis of the data. Computer codes are also needed to control instruments and experiments, and figure out experiments on Earth that come as close as possible to what you want in space. There is truly something for everyone.

WHAT DO YOU LOVE ABOUT THE WORK YOU DO?

The best part is getting to travel to exotic locations that I would never have had the opportunity to see otherwise. There is nothing I love more than the midnight Sun.

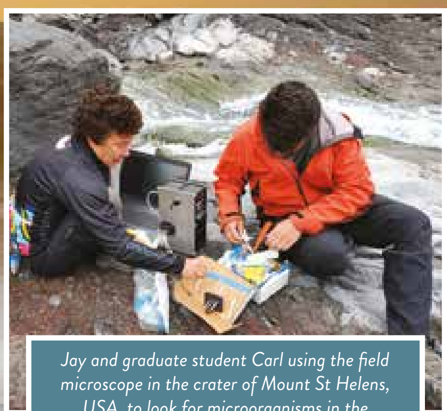
YOU ARE THE FOUNDER AND EDITOR-IN-CHIEF OF BITINGDUCK PRESS, AN INDEPENDENT PUBLISHER THAT SPECIALISES IN FICTION FOR AND ABOUT SCIENTISTS. DID YOU WANT TO BE A WRITER WHEN YOU WERE GROWING UP?

I sure did! I am a great fan of both fiction and narrative nonfiction, especially when nerdy characters are involved!

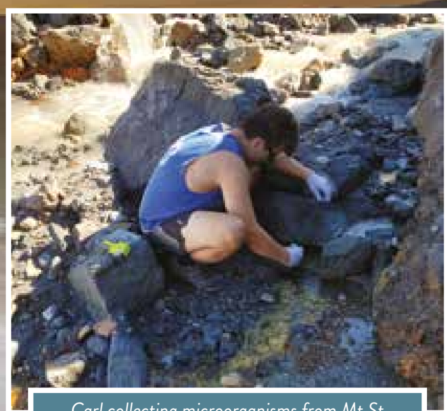
HOW DID YOU COME UP WITH THE NAME BITINGDUCK PRESS AND WHY IS THE FOCUS ON FICTION FOR AND ABOUT SCIENTISTS?

I had pet ducks and I can assure you – they do bite! I wanted to publish books that I wanted to read but couldn't find in bookstores. There are a lot of stereotypes about scientists, usually where they are either too good or too evil and I hope to redress this with the stories we publish.

The team setting up the microscope to collect sea ice brines in Greenland.



Jay and graduate student Carl using the field microscope in the crater of Mount St Helens, USA, to look for microorganisms in the glacier stream.



Carl collecting microorganisms from Mt St Helens hot springs.

Sea ice in Greenland. Even though this looks like solid land, it is actually ocean water with layers of ice and snow.

WHAT IF WE COULD CONTROL MICROBIAL COMMUNITIES?

AT HIS LAB AT THE **UNIVERSITY OF SOUTHERN CALIFORNIA** IN THE US, **PROFESSOR JAMES BOEDICKER** AND HIS TEAM FOCUS ON UNDERSTANDING THE RULES THAT MAKE COMPLEX NETWORKS OF MICROBES WORK – THE FINDINGS COULD HELP ENSURE MICROBES ARE HELPFUL TO SOCIETY

Bacteria get a bad deal! We are often encouraged to think of them as something unwanted, with many soaps and other cleaning products boasting that they kill 99.9 per cent of bacteria. However, there are many types of bacteria that live symbiotically with humans and without them we would not be able to exist. We rely on microbial communities – which are composed of thousands of types of bacteria, archaea and fungi – for many things: they live inside us and keep us healthy; they degrade pollution in the environment and clean our water; they help plants grow; and they are an essential part of cheese production!

Biophysicists have been working to expand our use of microbes to help develop new biotechnologies relating to energy production, water treatment, medicine and the reduction of CO_2 emissions. Professor James Boedicker is a biophysicist who is researching the rules that make complex networks of microbes work. He has his own laboratory based within USC Dornsife College at the University of Southern California in the US and leads a team investigating the biophysics of microbial communities – specifically, molecular exchange between bacteria.

WHY IS IT IMPORTANT TO UNDERSTAND MORE ABOUT MICROBIAL COMMUNITIES?

Microbial communities are fascinating. All cells gather information from their surroundings to determine what is happening around them and individual cells make decisions that collectively contribute to what is happening within a large population of cells. These decisions are what determines a microbial community's ability to perform important functions related to the environment, human health and biotechnologies. "Interactions between microbes in a given community have the potential to modulate whether the microbes will perform functions that we, as humans, would consider beneficial or activate functions that we dislike, such as causing an infection or not helping to clean our water," explains James. "If we better understand these interactions between microbes, we can potentially control the activity of such microbial communities to ensure that microbes will be helpful to society."

NOVEL TECHNIQUES FOR OBSERVING MICROBIAL NETWORKS

Historically, microbial research has been centred on individual species of bacteria or very large ecosystems of cells. This has resulted in scientists learning an enormous amount about what specific types of bacteria are capable of and how large groups of bacteria influence important processes, but very little about how smaller, diverse sets of microbes interact. It is only very recently that researchers have begun to understand the rules of interactions between microbes. "My research group has explored this middle ground of characterising in detail the interaction rules between different types of bacteria. For our work, we borrow approaches from physics to analyse the interactions within complex networks to explain, in a simple way, what happens in large groups of cells," says James. "We have also developed new experimental techniques to help reveal these interaction rules, such as putting cells in very tiny droplets of water to watch under the microscope how small groups of cells behave, and genetic engineering tools to monitor precisely what each cell is doing within the group."

JAMES BOEDICKER

Associate Professor of Physics, Astronomy and the Biological Sciences, USC Dornsife, University of Southern California, USA

FIELD OF RESEARCH

Biophysics

RESEARCH PROJECT

James' research is focused on understanding more about how microbial networks work. His team has developed novel methods to observe microbial networks and is looking at strategies to manipulate microbial communities.

FUNDERS

National Science Foundation, Office of Naval Research, Army Research Office

This work was supported by the NSF, under awards MCB-1818341 and PHY-1753268. The contents are solely the responsibility of the authors and do not necessarily represent the official views of the funding agency.

WHAT HAS BEEN LEARNED ABOUT MICROBIAL INTERACTIONS?

Microbes exchange chemical messages to interact and work together – and many species of microbes release special messenger molecules to announce their arrival to neighbouring cells so that they can start working together. Cells have receptor proteins that allow them to detect these messages and respond; without these signal molecules, cells would not know which bacterial species were around or if they were living in a small or large population of cells – information that helps cells decide what to do and which proteins to make.

These interactions can have a strong bearing on the overall activity of bacterial ecosystems. "Each species of microbe has many genes that enable the cells to perform a wide variety of different biochemical reactions and display many different behaviours. At any given time, each cell is only performing a fraction of the activities that are possible," explains James. "The interactions between the species, whether it be the exchange of molecular signals or cells sharing the same food source, play a role in the cell turning on and off different activities."

CHALLENGES

One of the main challenges for James is translating what is learned in the lab to molecular exchange that occurs in real microbial ecosystems in the wild. "In the lab, everything is simplified and controlled, whereas wild ecosystems are complex and unpredictable. It is simply not yet possible to study all the thousands to millions of different microbes in a given location one by one," says James. "Our hope is that by focusing on the general rules by which cells interact and using mathematical models to explore the large-scale consequences of these rules, we can eventually develop a good enough understanding of how interactions between cells influence the overall functions and activities of real communities."

EUREKA MOMENTS

"One recent success was when we were able to predict how the bacteria Bacillus subtilis was able to interpret complex mixtures of molecular signals. This result proved that even in diverse communities of microbes, it might be possible to predict how individual strains gather multiple pieces of information to determine what to do next," says James. "Another success was finding that multiple different species of bacteria could exchange molecules including DNA through vesicles. It was an eye-opening moment that made us realise how important vesicles might be to interactions within microbial ecosystems."

LOOKING AHEAD

Ultimately, James' work will help identify strategies to manipulate microbial communities in the world beyond the lab – understanding how microbes interpret and respond to complex mixtures of signals will help us control what bacteria are doing. The team's work in vesicle-mediated gene exchange could represent a major breakthrough in biotechnology. Improved treatments of genetic diseases is one possibility, but more generally, demonstrating that vesicles could help a broad range of cells take up DNA would have ramifications across a range of applications.

ABOUT BIOPHYSICS

Given that biophysics is concerned with observing what happens at incredibly small scales, it is hardly surprising that it is a relatively young branch of scientific enquiry. However, theories relating to biophysics were first posited in the 19th century when the Berlin school of physiologists presented several theories. Indeed, Adolf Fick, who was a student of the Berlin school's Carl Ludwig, published the first biophysics textbook in 1856. However, it was not until fairly recently that technology developed to a point where the tools of biophysics could help us understand microbes.

Since then, the field has expanded at a rapid rate and the potential applications of biophysics extend to addressing climate change, improving medicine and combatting food shortages. Given the relative infancy of the field, there is still much to be explored – but that should be thought of as exciting rather than hindering – and if you enter the field, you could make significant contributions to the world!

WHAT DOES JAMES FIND REWARDING ABOUT BIOPHYSICS?

James is keen to emphasise the puzzle-solving aspect of the field, where progress can be difficult to achieve, but extremely rewarding when it is achieved. "It is a whole community of different people working together, building upon the work of all the great scientists that came before us. The fun of discovering new things and trying to solve problems that haven't been solved yet is the best part," says James. "Of course, I keep in mind that research is important for society at large. There are important issues that we face as a society and we rely on science to make the world a better place in the future. Besides having fun, I do choose problems to work on that I believe will have a positive impact on society."

WHO DO BIOPHYSICISTS COLLABORATE WITH?

James and his team collaborate with scientists around the world. For example, the team regularly speaks with biologists, computer scientists, mathematicians, engineers, ecologists and physicists. One of the exciting aspects of James' research is that as it opens up into new avenues, different expertise is required, so collaboration is crucial.

WHAT ISSUES WILL FACE THE NEXT GENERATION OF BIOPHYSICISTS?

Given it is a relatively new field, there are so many different directions still to explore. As technology advances, so too do the potential areas to investigate. It is difficult to categorically state what issues the next generation of biophysicists will face, but we can be sure that it will be an area that is essential to tackling problems of the future. For James, the most important thing is to be open to new ideas and remain aware of the advances made in related fields.

EXPLORE A CAREER IN BIOPHYSICS

- *The Biophysical Society* is a brilliant website to look through and it has a section dedicated to education and careers that should prove useful to those interested in exploring further: **https://www.biophysics.org/**

- *Nature* has resources dedicated to the study of biophysics, which should give you an idea of the research taking place within the field: **https://www.nature.com/subjects/biophysics/nature**

- The average salary for a biophysicist can range between $97,000 for biophysics teachers and $105,000 for research biophysicists. However, this depends on the specific area of expertise and level of experience.

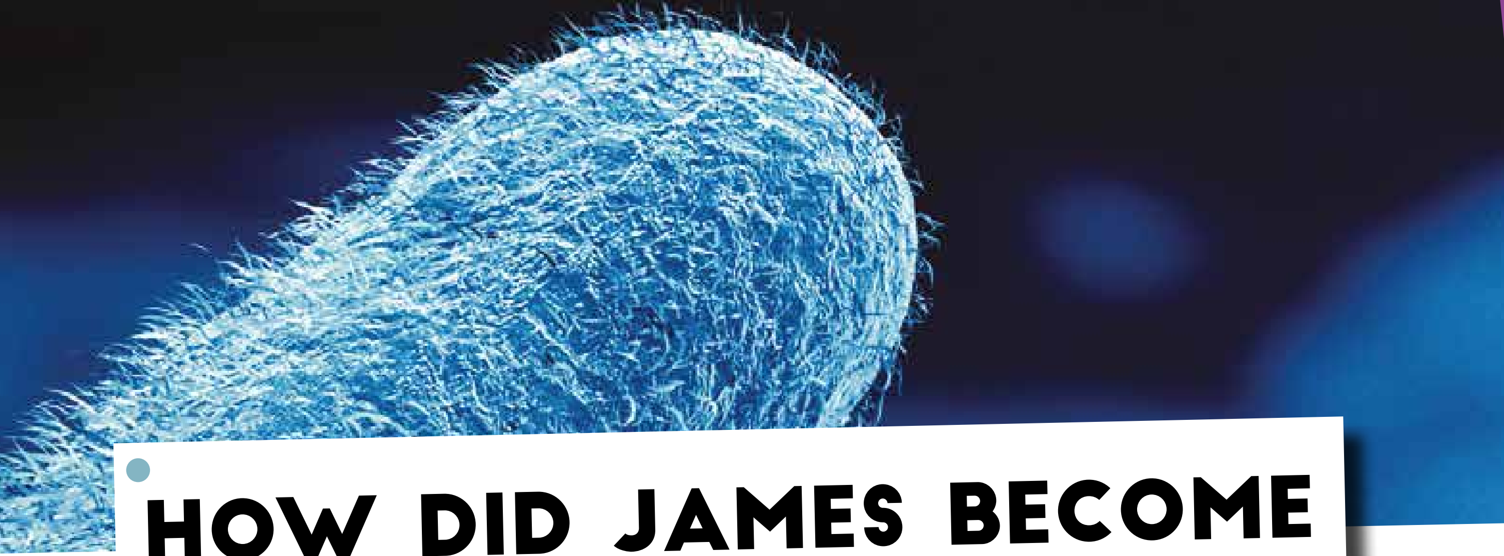
PATHWAY FROM SCHOOL TO BIOPHYSICS

James says that it is possible to approach biophysics from many different backgrounds, so there is no defined pathway. "Going through school myself, I started out as a chemical engineer, then studied chemistry, and then physics and molecular biology. Because biophysics is diverse, you could come from many disciplines including engineering, math or more traditional areas of biology," says James. "However, it is a good idea to take some physics courses. Even the intro classes of Newtonian mechanics and electricity and magnetism that non-physics majors take can give you a sense of the physics mindset."

Undergraduate degrees in biophysics are relatively uncommon, so most aspiring biophysicists start by studying maths, chemistry or physics and supplement these courses with biology modules.

A degree in a relevant subject will be required for postgraduate study.

https://study.com/articles/Careers_in_Biophysics_Job_Options_and_Education_Requirements.html



HOW DID JAMES BECOME A BIOPHYSICIST?

WHAT WERE YOUR INTERESTS WHEN YOU WERE YOUNGER?

As a child, I was interested in science, of course, but also classical music, cooking and building forts!

WHO OR WHAT INSPIRED YOU TO BECOME A SCIENTIST?

When I was younger, I liked my science classes in school and watched Mr. Wizard, but I didn't really know any working scientists growing up. Of course, science teachers are a type of scientist, but their job is different to being in the lab and working on an unsolved problem. It wasn't until I went to college and was surrounded by amazing scientists doing all different types of research that I finally realised what it meant to be a research scientist. I can remember being on an airplane, flying home for Thanksgiving during my first semester of college, excited about taking college calculus, and trying to derive the size of the circle traced out by the empty cup on my tray table. It was exciting to use what I was learning in college to actually solve a problem in real life.

Later that year, I emailed someone at my university to ask how to get started doing research and their first question to me was, "What do you want to work on?" – something I hadn't thought about before! I liked chemistry and polymers, so I worked in Paula Hammond's lab on polymer morphology and drug release. From that point, I was hooked and have been working in a research lab ever since.

WHAT ATTRIBUTES HAVE MADE YOU SUCCESSFUL AS A SCIENTIST?

Persistence is key to any scientist because research is typically difficult and requires many repeated attempts. Another one of my strengths is creativity. Being able to see a problem from a different perspective, drawing on different experiences from my past – that is often the key to finding a better path forward. At times, creativity is a trait associated more with artists or musicians, but it is equally important in science.

HOW DO YOU OVERCOME OBSTACLES IN YOUR WORK AND SWITCH OFF OUTSIDE THE LAB?

There are always many obstacles standing in the way of pushing science forward. When I run into one, asking others for advice can help. Sometimes, someone else will see something you are missing. Fortunately, relaxing and switching off comes naturally to me! I rarely think about work when I am home. I enjoy spending time with family and friends, cooking dinner, catching a movie or playing pinball. Then, the next day it is back to thinking about science!

WHAT ARE YOU MOST PROUD OF SO FAR?

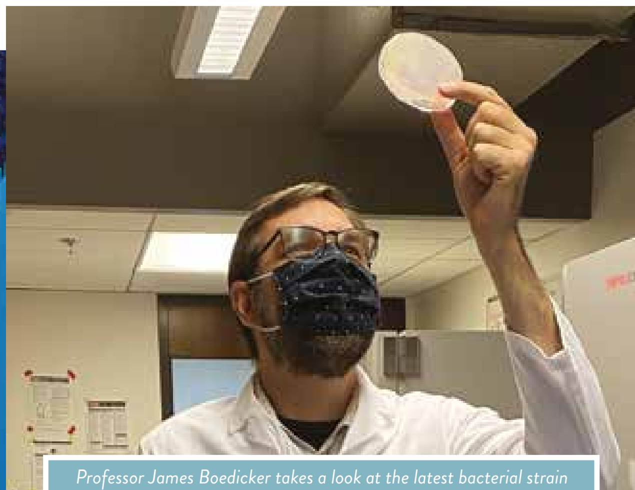
I am proud of many things I have done as a scientist. Becoming a professor and starting my very own research lab was a big day. It gave me the sense that I had really made it and would have the opportunity to continue working on exciting research problems. Also, working with my first few students and seeing them develop as scientists over the years has been a great feeling. For the future, I want to keep plugging away at my research, hopefully helping to make a few big discoveries along the way.

JAMES' TOP TIPS

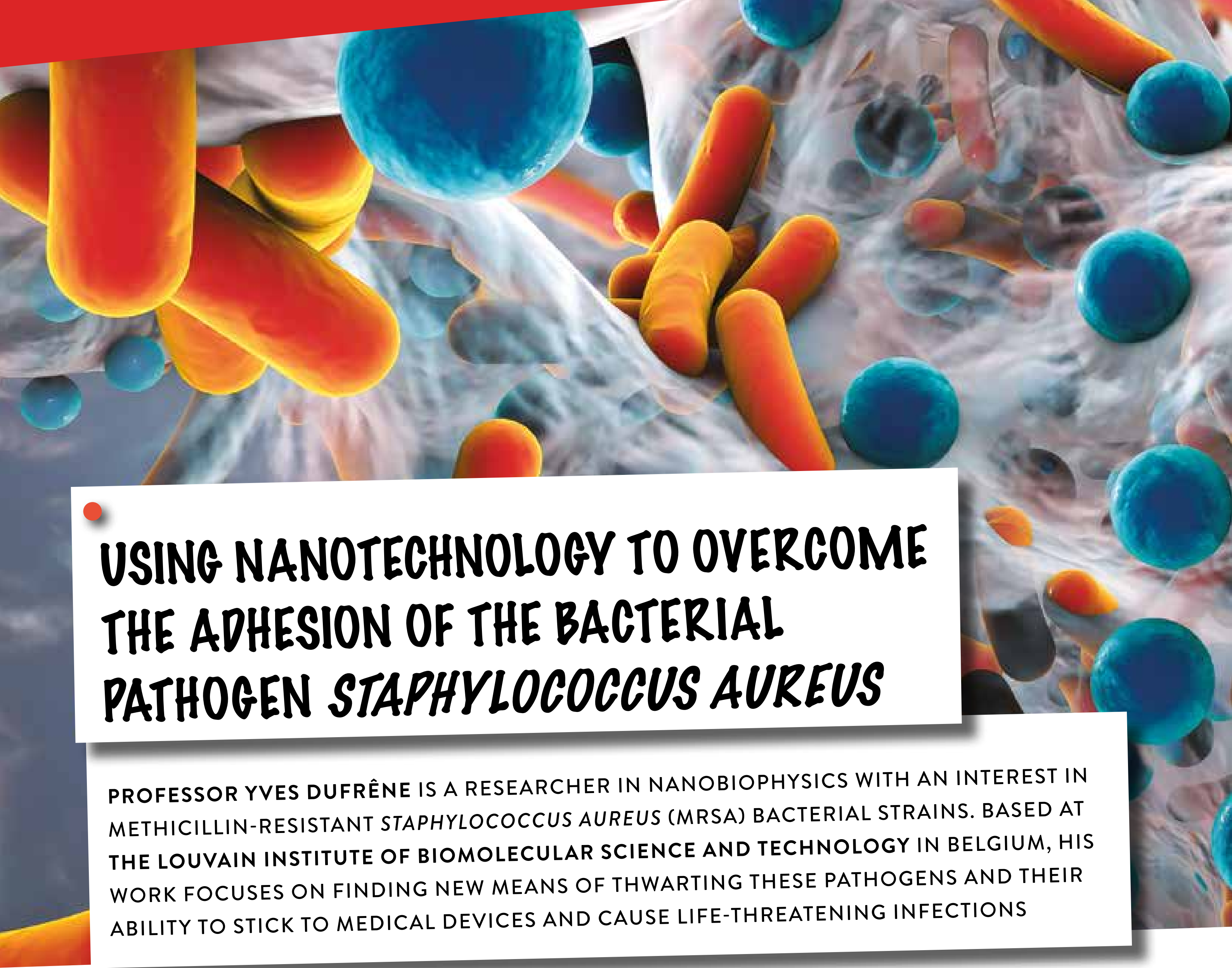
01 Follow your passion. It is so important to find what you are interested in learning more about and then pursue it – half the battle will have already been won because it is something that you want to do.

02 If you are considering becoming a scientist, try to find a scientist in your area to talk with or help arrange an opportunity to actually get started doing research. At the same time, keep in mind that everyone starts out without knowing much at first, so don't worry about not having any experience.

03 Try not to fall into the trap of sticking with what you already know or what you have done in the past. Part of the fun is embracing new things!



Professor James Boedicker takes a look at the latest bacterial strain growing in the lab.



USING NANOTECHNOLOGY TO OVERCOME THE ADHESION OF THE BACTERIAL PATHOGEN *STAPHYLOCOCCUS AUREUS*

PROFESSOR YVES DUFRÊNE IS A RESEARCHER IN NANOBIOPHYSICS WITH AN INTEREST IN METHICILLIN-RESISTANT *STAPHYLOCOCCUS AUREUS* (MRSA) BACTERIAL STRAINS. BASED AT **THE LOUVAIN INSTITUTE OF BIOMOLECULAR SCIENCE AND TECHNOLOGY** IN BELGIUM, HIS WORK FOCUSES ON FINDING NEW MEANS OF THWARTING THESE PATHOGENS AND THEIR ABILITY TO STICK TO MEDICAL DEVICES AND CAUSE LIFE-THREATENING INFECTIONS

Methicillin-resistant *Staphylococcus aureus* (MRSA) strains are pathogenic bacteria that have been shown to have a high level of antibiotic resistance. This is of enormous concern because novel antibiotics are extremely difficult to develop; the last antibiotic class that was successfully introduced as a treatment was discovered years ago. So, when bacteria are shown to be resistant to existing antibiotics, it is a huge cause of alarm, as finding a means of treating patients and saving lives becomes much more difficult.

MRSA is an important member of an emerging class of superbugs causing hospital-acquired (nosocomial) infections that clinicians around the world have expressed concern about. A major problem is that MRSA infections involve the formation of adhering multicellular communities, called biofilms, on tissues and implanted devices such as central venous catheters and prosthetic joints. Overall, bacterial biofilms are estimated to be involved in more than 65% of nosocomial infections! Biofilm related MRSA infections are very difficult to fight, because bacterial cells are protected from host defences and are resistant to many antibiotics. Ultimately, when this pathogen enters the bloodstream, it can trigger severe infections, including endocarditis and sepsis, which can rapidly lead to tissue damage, organ failure and death.

It is with all of these concerns in mind that Professor Yves Dufrêne, based at the Louvain Institute of Biomolecular Science and Technology, UCLouvain, Belgium, has established a project funded by the ERC (European Research Council) that is aiming to understand and prevent adhesion and biofilm formation by these bugs. The findings from this project may pave the way to the development of novel anti-adhesion therapies, complementing antibiotic treatments, therefore contributing to saving the lives of countless patients and creating healthier and cleaner environments inside hospitals.

WHAT ARE THE MAIN QUESTIONS THAT YVES IS TRYING TO ANSWER?

One of the starting points for Yves' research is to understand how MRSA manages to attach so strongly to medical devices and host tissues, using a variety of adhesion proteins (called adhesins) that decorate the bacterial cell surface. "We have been attempting to understand the molecular mechanisms that drive the specific adhesion of *Staphylococcus* species to human proteins, such as fibronectin and fibrinogen, which often coat implanted devices," explains Yves. "In addition, we very much want to identify new molecules (peptides, antibodies) that specifically block this adhesion."

WHAT TECHNIQUES HAS YVES' TEAM DEVELOPED?

Over the past 20 years, Yves and his research group have been working on developing atomic force microscopy (AFM) techniques to study a broad range of microbiological aspects, including the structural, adhesive and mechanical properties of the surfaces of microbes. "When it comes to bacterial adhesion, in particular, we have established two complementary approaches to study the interactions between the bacterial adhesin proteins and the human proteins that they bind to. In the first approach, we place a single living *S. aureus* bacterium on an AFM probe

PROFESSOR YVES DUFRÊNE

Louvain Institute of Biomolecular Science and Technology, UCLouvain, Belgium

FIELD OF RESEARCH

Nanosciences, Biophysics, Microbiology

RESEARCH PROJECT

Yves' research is focused on pushing the limits of nanotechniques beyond the state-of-the-art to establish them as innovative platforms to understand how pathogens such as MRSA use their surface adhesins to guide cell adhesion and trigger infections, and to develop anti-adhesion strategies for treating biofilm-infections.

FUNDER

European Research Council (ERC)

and then bring that cell probe in contact with a substrate on which we have grafted a human host protein. Retracting the cell away from the surface allows us to quantify the physical strength whereby the adhesin binds the human protein," says Yves. "In the second approach, we graft the human protein onto the AFM probe and then bring it in contact with a single *S. aureus* cell. This method allows us to study the strength and dynamics of single adhesin-ligand interactions and to map the locations of single adhesins on the bacterial cell surface."

Recently, the team has discovered that some staphylococcal adhesins have the ability to bind their human target proteins with very strong forces and that the lifetime of these bonds grows when they are subjected to increasing physical stress. These so-called catch bonds represent an unusual and counterintuitive mechanism to enhance bacterial adhesion under mechanical stresses, such as those associated with the blood flow, scraping or epithelial turnover.

ANALYSING NANOSCALE SURFACE ARCHITECTURE

AFM images are made by scanning a biological sample like a bacterial cell with an extremely sharp AFM probe (or tip) to produce images that detail the surface topography of the cell with nanometre resolution in physiological aqueous conditions. AFM is a super-resolution imaging technique meaning that the team can produce extremely detailed images of the three-dimensional surface topography of living microbial cells that show much smaller features than what is achievable by most light microscopy techniques. An exciting recent advancement is called multiparametric AFM imaging, where the researchers produce images which show the surface topography, as well as the adhesive and mechanical properties of a bacterium.

WHAT HAS YVES' RESEARCH REVEALED?

The team has made many exciting discoveries in recent years. "We were the first to find that certain staphylococcal adhesins specifically bind human proteins with extreme mechano stability: the bonds they form are as strong as the covalent bonds that keep the amino acids together in a protein's polypeptide backbone," explains Yves. "This is truly unique for a receptor-ligand interaction and critically underlies the ability of staphylococci to form mechanically stable biofilms. As for anti-adhesion therapy, they have demonstrated how special peptides and antibodies can efficiently block the specific binding of adhesins to their targets. This finding shows promise in the development of anti-adhesion agents targeting staphylococcal infections."

WHAT ARE THE NEXT STEPS?

As you might expect, the team is extremely excited about their recent discovery of the first staphylococcal adhesin that exhibits a catch-bond behaviour. The intention is to expand that knowledge and identify whether such an unusual binding mechanism is used by other staphylococcal adhesins. They are also screening for new peptides and antibodies that could prevent adhesion and biofilm formation, which, if successful, could offer exciting potential for fighting MRSA infections and improving patient outcomes around the world.

NANOTECH MEETS MICROBIOLOGY

Given that microbiology is the study of living organisms that are too small to be visible to the naked eye, it is a field that was always going to benefit from the development of new microscopy techniques enabling researchers to observe microorganisms such as bacteria, viruses and fungi. It was therefore enormously beneficial to microbiologists when the field of nanotechnology began to emerge. In the 1980s, many significant technological developments were made, beginning with the scanning tunnelling microscope (STM) which enabled scientists to observe and manipulate individual atoms (the inventors of STM were later awarded a Nobel Prize). In the mid-1980s, this was followed by the development of atomic force microscopy (AFM), in which a very sharp probe (tip) touches the sample surface with ultra-small forces while raster scanning to obtain topographic images with a resolution of only a few nanometres. AFM is also an ultrasensitive force measuring technique, an approach known as AFM force spectroscopy. Here, force-distance curves are obtained by bringing the probe against the sample and then retracting it while monitoring the force. Attaching specific bioligands to the probe makes it possible to measure the localisation, strength and dynamics of single receptor-ligand interactions, such as staphylococcal adhesin-host protein bonds.

HAVE THERE BEEN ANY EUREKA MOMENTS IN YVES' RESEARCH?

Of course! In fact, there are probably too many to mention here, but there was the discovery of the ultra-stable adhesion-host protein interactions; the finding of anti-adhesion molecules which could one day help complement antibiotics to treat multi-resistant superbugs; and the first evidence of a catch-bond between an adhesin on a living staphylococcal cell and its target protein. But the findings do not stop there! "For instance, we have done some very exciting work on yeasts, where we have unravelled the force-interaction that plays a role in mating: we now understand yeast sexuality better!" says Yves. "AFM technology is continuously improving, but recent advances in microbiology research include the improvement of imaging speeds, the possibility to do multiparametric imaging (images of topography, adhesion and stiffness generated simultaneously on live cells) and a new modality called fluidic force microscopy where microchanneled probes with micro- or nanosized apertures allow for fast manipulation and analysis of single cells."

Clearly, this is a field ripe for innovation and new discoveries, so if you are interested in making several significant contributions to a particular branch of molecular and cellular biology, this could be the one for you!

WHAT DOES YVES FIND MOST REWARDING ABOUT HIS WORK?

Yves' work is truly multidisciplinary, relying strongly on collaborations with microbiologists around the world, which provide clinical strains and bacterial mutants altered in specific adhesins, but also complement AFM data with results from traditional bioassays. It is rewarding to know his team's work will likely have positive scientific, societal and economic impacts. On a more personal level, Yves is able to work closely with early career researchers who are highly motivated, and to help them achieve their ambitions and develop their skills as scientists. In particular, his former PhD student, David Alsteens, is now a professor at UCLouvain. They share the same instruments and belong to the same nanobio group, but David's research, also funded by the ERC, mainly focuses on viruses.

WHAT ARE THE ISSUES FACING THE NEXT GENERATION OF NANOMICROBIOLOGISTS?

For those of you interested in pursuing a career in the field, you can expect to be working on problems such as how best to combine AFM with optical nanoscopy. "Optical nanoscopy is unique in that it can probe the localisation and motion of single molecules in live cells with a resolution in the range of a few tens of nanometres," says Yves. "Combining AFM and optical nanoscopy will allow researchers to probe intracellular and extracellular structures with unprecedented resolutions, thus enabling researchers to study their organisation, dynamics and interactions in individual cells, at the single-molecule level and from the inside out."

HOW TO BECOME INVOLVED IN NANOBIOPHYSICS AND MICROBIOLOGY

- UnderstandingNano includes an array of useful information relating to the wide variety of specific areas of interest within nanotechnology: **https://www.understandingnano.com/resources.html**
- Societies are a good place to start researching a field from a broad perspective.
- The American Society for Microbiology (ASM) is the oldest and largest single life science membership organisation in the world: **https://asm.org**
- The Microbiology Society provides lots of useful information, including a careers page: **https://microbiologysociety.org**

PATHWAY FROM SCHOOL TO NANOTECH, BIOPHYSICS AND MICROBIOLOGY

Yves concedes that his field is so multidisciplinary that it is virtually impossible to suggest the correct pathway to take! However, studying biology, physics and chemistry courses will be of obvious use. At university, taking a bioengineering degree could be a good way to enter the nanobioworld.

Relevant degree subjects include physics, chemistry, biophysics, microbiology and engineering.

https://targetjobs.co.uk/careers-advice/job-descriptions/454437-nanoscientist-job-description

HOW DID YVES BECOME A NANOBIOPHYSICIST?

WHAT WERE YOUR INTEREST AS A CHILD?

I was always fascinated with nature – even from a young age – and I was often dreaming and living inside my head and its thoughts. As a teenager, I found I did not really align very well with my peers in that we appeared to have very different interests. But then, at the age of 16, I went into extreme caving, meaning you spend one week in an alpine cave. We made so many exciting discoveries of new rooms and passages. It really was a brilliant experience where I made many friends excited by caving, climbing and hiking.

DID YOU HAVE A FAVOURITE BOOK AS A CHILD?

It has always been music that has been my most passionate interest outside of science. My current music interests are wide and varied, from Pink Floyd to AC/DC, through to electronic and Baroque music!

WHO OR WHAT INSPIRED YOU TO BECOME A SCIENTIST?

When I was 10, I received my first microscope (which you can see on the first page of my website). It was a life-changing experience in many ways and I came to love looking at bacteria, etc. Later, as a student, PhD and postdoc fellow, I came to be massively inspired by my mentors which led me studying many different things – but the microscope was certainly a key moment in creating that initial motivation to find out more about the world.

For as long as I can remember, I have thought of science as being an amazing way to express your imagination and creativity. One of my favourite quotes is from Albert Einstein: "Knowledge is limited. Imagination encircles the world."

WHAT ATTRIBUTES HAVE MADE YOU A SUCCESSFUL SCIENTIST?

I approach all of my studies with passion, excitement, intensity and enthusiasm, which has served me well throughout my career. Then there is the fact I am hardworking – sometimes seven days a week – and we clearly do not do that for money! It is important to have an innate love for science and enjoy what you do.

HOW DO YOU OVERCOME OBSTACLES IN YOUR WORK?

You have to be patient when researching and accept that you will fail sometimes. Indeed, failures can lead to some top discoveries! In my spare time, I like to go jogging and do yoga – it is important to find a way to switch off at times. In the summer, I very much enjoy to hike solo in the mountains, sometimes for weeks.

WHAT IS YOUR PROUDEST CAREER ACHIEVEMENT?

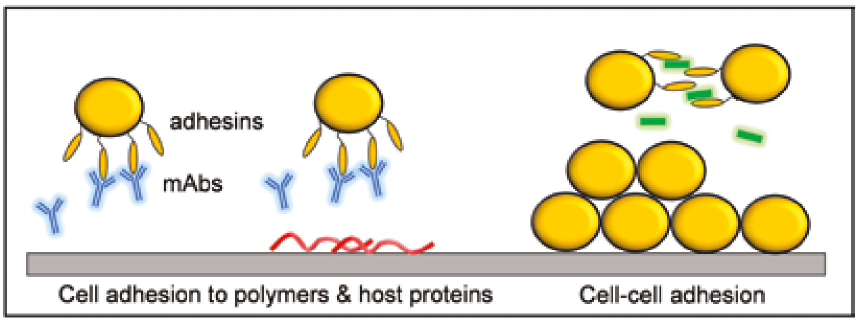
A few years ago, I was awarded a European Research Council advanced grant from the European Union. This enabled me and my team to boost our research on staphylococcal adhesion and anti-adhesion using the tools of nanotechnology. The grant has led to some exciting publications and I am extremely happy about the opportunities it has provided and will likely continue to provide in the future. I am also very grateful for the opportunities I had to work with so many highly motivated team members as well as collaborators worldwide. Finally, the AFM-based nanobiophysics community is relatively small, meaning that conferences and meetings in the field are always exciting from the intellectual and social standpoints.

YVES' TOP TIPS

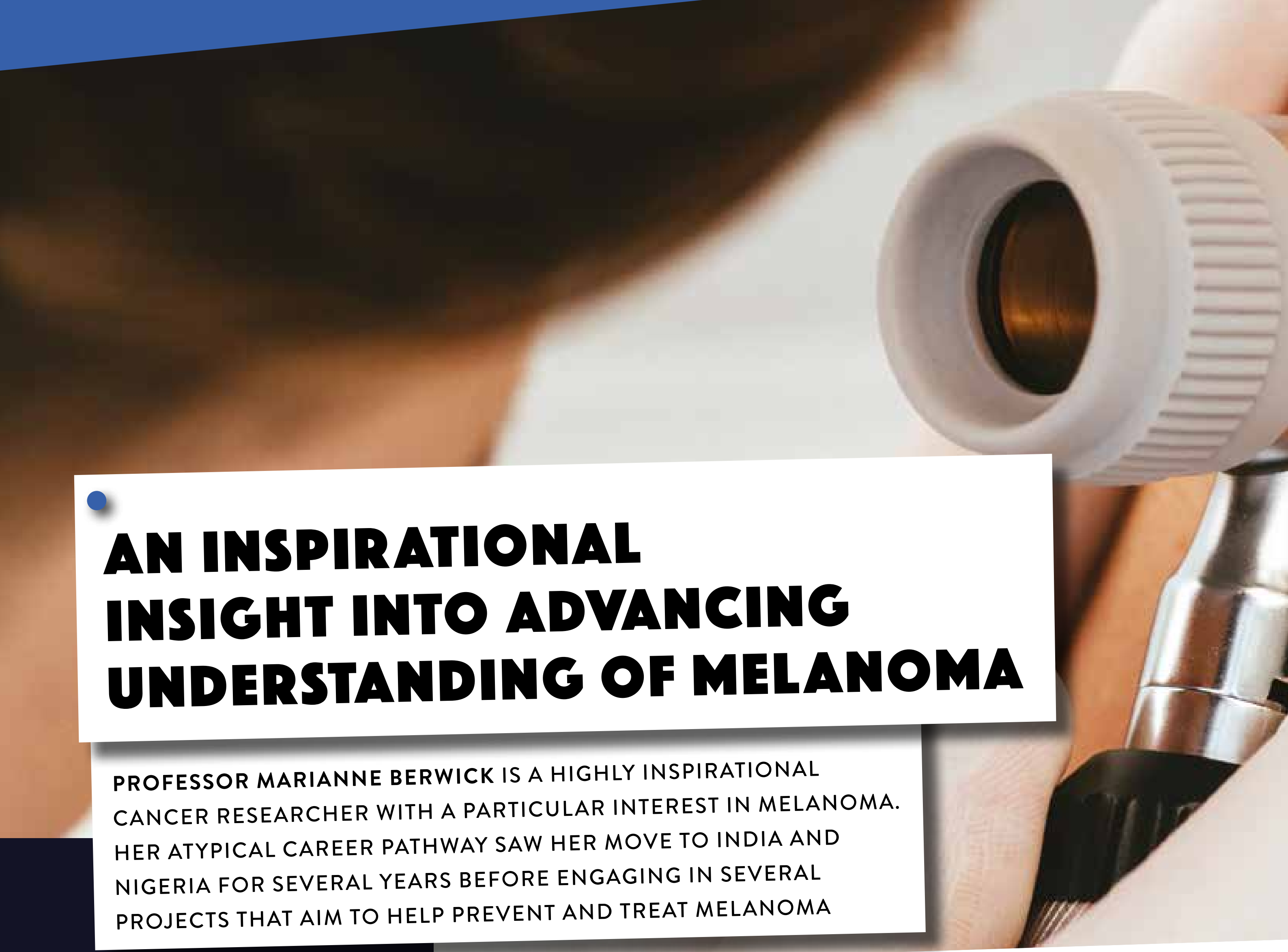
01 Approach your studies with imagination, passion, excitement and enthusiasm. There is sometimes a belief that science relies only on well-established knowledge and ultra-critical thinking but in my experience, it is a field that also enables artistic pursuits.

02 Harnessing and developing the ability to collaborate with your peers and communicate effectively with your colleagues will serve you well throughout your career. Work to improve communication for a wide range of different reasons. Good English writing and speaking skills are essential as this is the international language of scientists.

03 The work of a scientist can be difficult and sometimes frustrating, but you should always try to have fun in everything you do!



Biofilm formation and inhibition in Staphylococcus aureus. Bacterial (yellow circles) on polymer substrates coated with host proteins (red) is shown, as well as bacterial colonies (right). These steps can be inhibited by monoclonal antibodies (mAbs, blue) and peptides (green).



AN INSPIRATIONAL INSIGHT INTO ADVANCING UNDERSTANDING OF MELANOMA

PROFESSOR MARIANNE BERWICK IS A HIGHLY INSPIRATIONAL CANCER RESEARCHER WITH A PARTICULAR INTEREST IN MELANOMA. HER ATYPICAL CAREER PATHWAY SAW HER MOVE TO INDIA AND NIGERIA FOR SEVERAL YEARS BEFORE ENGAGING IN SEVERAL PROJECTS THAT AIM TO HELP PREVENT AND TREAT MELANOMA

TALK LIKE A CANCER RESEARCHER

PROGNOSIS - a medical term denoting the predicted development of a disease

POLYMORPHISM - one of two or more variants of a particular DNA sequence

CDKN2A - also known as cyclin-dependent kinase inhibitor 2A, this gene is located at chromosome 9 in humans and was first identified in 1994

MC1R - one of the genes associated with red hair

NEVUS - the medical term for a mole. Nevi is the plural of nevus

ATYPICAL - not typical, irregular

GENOTYPE - the genetic make-up of an organism

PHENOTYPE - the characteristics of a living thing, especially qualities you can see, such as hair and eye colour

Melanoma is a type of skin cancer that is said to be diagnosed in more than 9,500 people in the USA every day. Incidence of melanoma is extremely high when compared to other forms of cancer and it is estimated that at least one in five Americans will develop skin cancer by the age of 70. However, when melanoma is detected early, the five-year survival rate is 99 per cent and this encouraging statistic is in no small part thanks to researchers like Professor Marianne Berwick.

Marianne is a cancer researcher with more than 30 years' experience conducting studies and experiments on melanoma. She leads a team based at the UNM Comprehensive Cancer Center in New Mexico, USA, which is focused on preventing melanoma and helping melanoma patients survive the cancer. Her research takes the form of three main areas, which are detailed below in their own specific sections.

INTERMEL

Marianne is the principal investigator of InterMEL, an international consortium composed of 15 centres doing important work in the treatment and prevention of melanoma. The centres have come together with the goal to identify features of a tumour within its individual cells, particularly those that are associated with survival in patients with stage II and stage III melanoma.

As it stands, when a patient is diagnosed with melanoma, their prognosis is solely based on the stage of the disease. This essentially means that if the cancer has advanced to a particular stage, clinicians will automatically predict a specific outcome that the patient then has to come to terms with. However, this rigid approach is unsuitable for patients at stage II and III, not least because the mortality rate for individuals with these stages of melanoma varies wildly. Indeed, research shows that the mortality rate can be anywhere between 13 per cent and 68 per cent, so some flexibility is needed when giving a prognosis.

WHAT ARE THE ISSUES AND HOW IS INTERMEL WORKING TO OVERCOME THEM?

Part of the difficulty with prognosis of melanoma is that scientists do not fully understand why some tumours are more aggressive than others, so it is difficult to compare one tumour with another;

PROFESSOR MARIANNE BERWICK

Division of Epidemiology
Department of Internal Medicine
UNM Comprehensive Cancer Center
USA

FIELD OF RESEARCH

Melanoma

RESEARCH

Marianne has worked in the area of cancer prevention and aetiology for 30 years. Her particular focus is on melanoma prevention and survival and she has several projects on the go with that ultimate aim in mind.

FUNDERS

National Institutes of Health, National Cancer Institute. Grant numbers: NIH/NCI P01 CA206980-01A1, NIH/NCI 5R01CA233524-02, NIH/NCI P30CA11800-16

two tumours of the same size in two different patients could easily develop in completely different ways, making general prognoses unreliable.

Marianne and her team believe that looking at the different genetic features of tumour cells provides an effective indication of which melanomas are more likely to come back or grow. If enough genetic data can be gathered, then the team could develop a more reliable means of predicting outcomes in patients. This would help to identify the best treatment methods and course of action for specific patients.

GEM

The Genes, Environment & Melanoma (GEM) study is also led by Marianne. It aims to capture a range of different types of information which could help with prevention and treatment of melanoma. More than 3,500 people across various geographic regions in North America, Europe and Australia participated in the study, with the team gathering information about their DNA, lifestyle and other personal information.

Marianne and the team wanted to examine the genetic factors associated with melanoma and what people's relationship with sun exposure was.

WHAT RESULTS CAME FROM THE STUDY?

The team uncovered some unique insights relating to the influence of the genes CDKN2A and MC1R in the risk of melanoma, as well as the role that various DNA polymorphisms and exposure to the sun plays in the onset of melanoma. The next step is to examine the disease histories of the participants to see whether the history of sun exposure and genetic factors are related to the chances of surviving melanoma. The findings will influence the recommendations for preventive measures for melanoma, as well as possible treatment methods.

SONIC

Marianne contributed to a paper that was published in the *American Journal of Epidemiology* concerning nevus formation. Nevi have been identified as possible precursors of melanoma and are considered some of the most important known risk factors for the disease.

Repeated studies have shown that an important time for the formation and evolution of nevi is during adolescence. In the majority of cases, typical moles form during this time period and are almost always harmless, but there are instances where atypical moles form and these are considered the strongest indicator of melanoma risk.

WHAT IS THE PURPOSE OF THE STUDY?

The Study of Nevi in Children (SONIC) was one that attempted to understand the relationship between sun exposure and nevi – especially given the strong link between nevi and melanoma. The investigators studied nevi in a group of children in Massachusetts, with the overall objective being the documentation of the natural history of nevi.

The team used digital photography to capture images of nevi and then assessed the associations with sun exposure and sun protection behaviours. Ultimately, through conducting follow-up studies of the group, the team provided further understanding of the associations of genotype, phenotype and sun exposure with the evolution of individual moles.

Ultimately, Marianne's studies are advancing our understanding of melanoma, including the risk factors and how they relate to behaviours and the likelihood of the cancer developing. Her expertise and clear passion for the subject helps to demonstrate just how important it is to find something you love doing. Marianne's career pathway is unusual to say the least (read '*How did Marianne become a cancer researcher?*'), but this has given her a unique perspective, which has clearly aided her research.

ABOUT MELANOMA AND CANCER RESEARCH

There is a high chance that you have been affected by cancer in some way – whether that is through having had it yourself or knowing somebody who has had it. We all realise the importance of cancer research and the people who dedicate their lives to finding cures for cancers and advancing our understanding so that improved preventive measures can be developed.

Skin cancer and melanoma is one of the most prevalent cancers there is, although early detection significantly improves patient outcomes, and the mortality rate is relatively low compared with some other cancers. Marianne leads and has led several projects relating to melanoma, which aim to understand what makes some people more susceptible than others, but also why some tumours grow more aggressively than others. Her work over the past 30 years has helped significantly advance the field and all of us stand to benefit from this in some way, directly or indirectly.

WHAT ARE THE RISK FACTORS FOR DEVELOPING MELANOMA?

First, it is worth highlighting that melanoma is not common in young people, but as a person gets closer to adulthood the incidence goes up. To highlight this, the proportion of melanomas in people under the age of 20 is just 0.4 per cent, but it rises to 5.1 per cent among those aged 20-31.

There are several risk factors for developing melanoma, including having light hair, light eyes and skin that does not tan very well. "It is the intermittent sun exposure that leads to sunburn that is a major culprit in melanoma – people who tan well or who tan very gradually are less likely to develop melanoma," explains Marianne. "One of the most surprising discoveries we have made over the years is that genetic factors are really important in getting melanoma and surviving it."

Marianne and her team continue to work to understand more about these genetic factors, which have been shown to be important in the risk factors outlined above.

WOULD MARIANNE RECOMMEND A CAREER IN CANCER RESEARCH?

Of course, anybody who wishes to enter into the field of cancer research has Marianne's blessing. It goes without saying that if this is a career you want to pursue then you are clearly motivated by helping people overcome the burdens of this terrible disease. "Cancer research is highly rewarding because you can see the people you are trying to help and hopefully diminish their chances of having a severe cancer," says Marianne. "You may not be able to stop cancer, but it is possible to make it a less horrible disease through prevention and better treatments."

So, if this is an area you want to pursue, go for it!

PATHWAY FROM SCHOOL TO CANCER RESEARCH

Marianne's own experience is a little different from the normal pathway, but you should only speak from your own experience! Marianne therefore suggests that having a balance is important. "For me, a broad liberal arts education as well as a solid scientific foundation helped," says Marianne. "Although I never majored in a scientific subject until graduate school, I had a good foundation in biology, chemistry and physiology – all in high school!"

https://study.com/articles/Cancer_Researcher_Job_Description_and_Education_Requirements.html

EXPLORE A CAREER IN CANCER RESEARCH

• The National Cancer Institute is North America's leader in cancer research. Its website is a treasure trove of the latest research, as well as news and events that should be of interest to a budding cancer researcher: **https://www.cancer.gov**

• The Melanoma Research Alliance does important work in advancing understanding of melanoma: **www.curemelanoma.org**

* The average salary for a medical scientist (which includes cancer researchers) is $84,810, although this is largely dependent on the level of experience and specific job role you are performing.

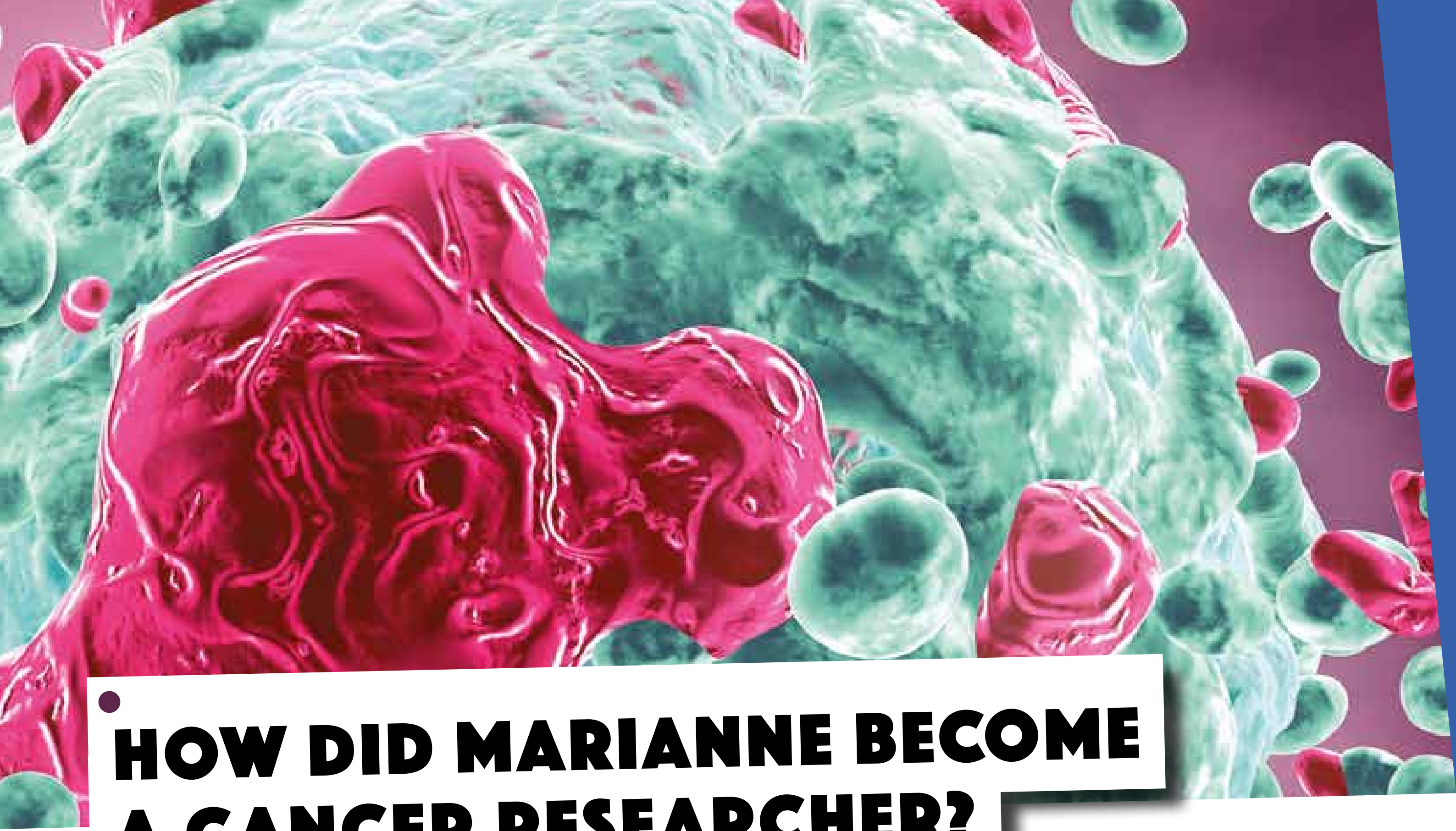
MARIANNE'S TOP TIPS

01 Find something that interests you and that you love to do and then do everything in your power to work towards that. Remember that you will be doing whatever you decide for a long time, so it is essential that it chimes with your passion!

02 There is nothing that says you absolutely have to stay on the path that you have decided to forge. There will always be opportunities to change direction, so be willing to make that change if the opportunity presents itself and if you think it is the right decision.

03 Try and ensure that your education is balanced, with consideration for arts subjects as well as the science subjects. Getting a grounding in a wide range of different areas will stand you in good stead throughout your career.

Marianne weighs a child in the Gir Forest, India, as part of her research project there.



HOW DID MARIANNE BECOME A CANCER RESEARCHER?

TELL US A LITTLE ABOUT YOUR BACKGROUND.

I grew up in a rural area and raised sheep, goats, a horse and even a baby deer. This was without the help of my family, although they were very supportive of my interest in animals. This experience set me up for what was to come. I went to the University of California, Davis (UC Davis) as I really wanted to be a veterinarian, but the industry only admitted around 5 per cent of females at the time and I was not a stellar student. I have always liked learning by doing (such as raising animals) and believe this has helped me throughout my career.

YOU HAVE AN INCREDIBLY DIVERSE CAREER. HOW DID YOU GET INTO CANCER RESEARCH?

After two years at UC Davis, I transferred to the University of California, Los Angeles and decided to become a teacher for disadvantaged children. I did this for seven years before moving to the Gir Forest in India where the only Asiatic lions still live. This is where I studied the Maldhari, semi-nomadic buffalo graziers who lived in a teak-thorn forest. I tried to gain their trust by just talking with them, drinking tea and taking them to doctors when they were sick. After a year of this, they did trust me and joked with me a lot. Because I drove a jeep and wore pants [trousers], they asked me where my moustache was!

When I went back to the US from India, I decided to go into public health to try to eliminate unhealthy living conditions. I was given the opportunity to go to Nigeria to do some research on arboviruses (viruses that are carried by mosquitoes and other arthropods). That was really difficult because the electricity was only on 50 per cent of the time, and my skin colour made me an obvious outsider so it took some people I met a while to get used to me.

When I got back to Yale University, I became a PhD student in environmental epidemiology and studied the impact of nitrogen dioxide from kerosene heaters on respiratory infections in Connecticut, USA. Then, one of my fellow student-colleagues was looking for a project director for a new melanoma study. I knew nothing about cancer, but I thought I could do it and started working on the role of screening (skin self-examination) for melanoma. One of my assistants had a 23-year-old daughter who had recently died from melanoma. Working with her gave me a strong passion to try to alleviate death from melanoma. Although only about 10 per cent of melanoma patients have illness severe enough to lead to death, those 10 per cent are very important to me.

WHERE DO YOU GET THE CONFIDENCE TO TRY NEW THINGS?

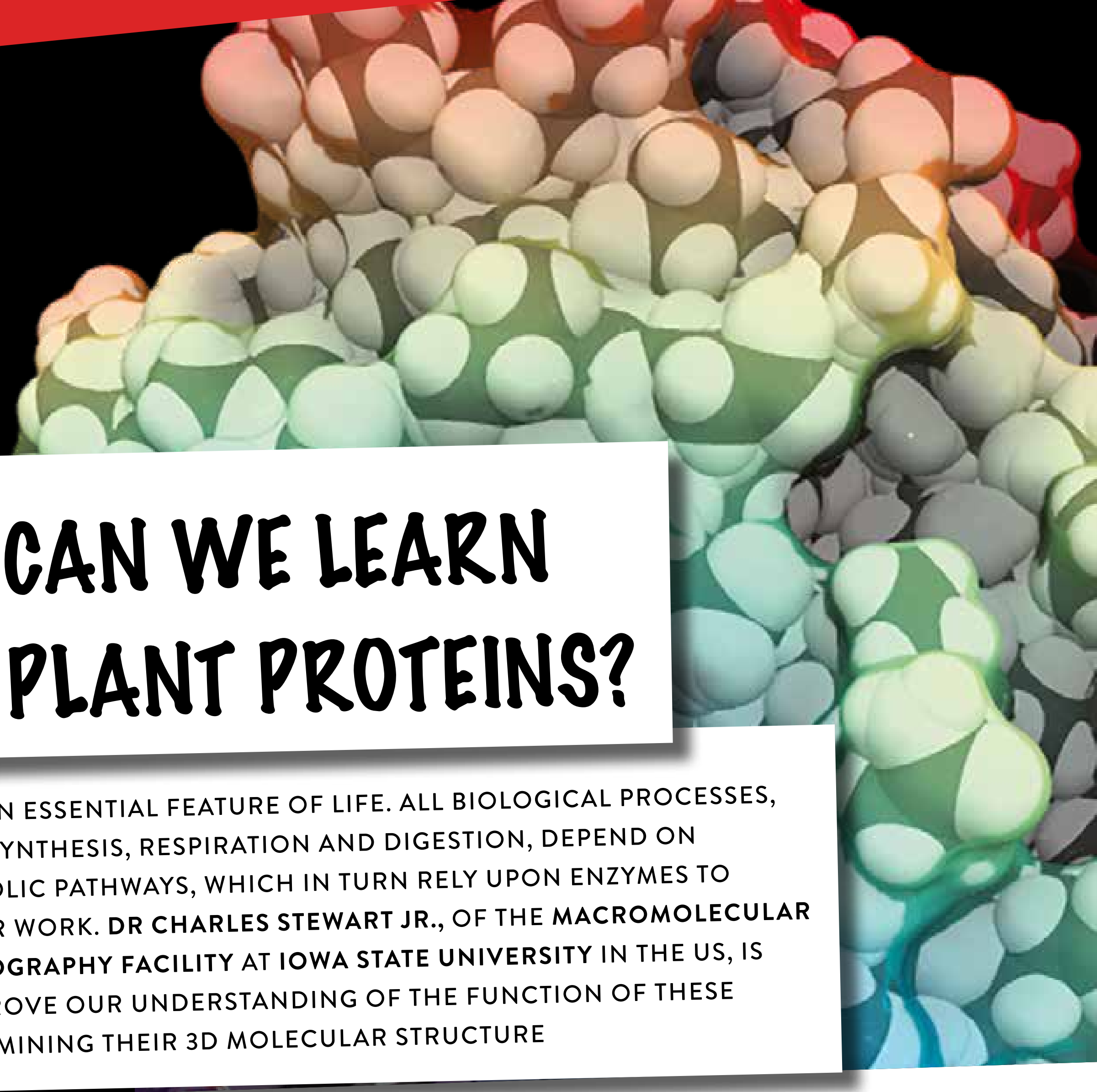
My difficult experience in Nigeria made me feel that I could do anything. Or rather, I felt that if I could isolate dengue virus in very difficult circumstances, trying something new – like molecular epidemiology, for example, even though I was not trained in biology – would be a piece of cake. So, after my PhD, I was offered a job at Memorial Sloan Kettering Cancer Center, one of the premier cancer centres in the world. I started a Molecular Epidemiology Laboratory where we worked with laboratory technicians and a few high school students, and were funded by the National Cancer Institute.

WITH ALL THESE EXPERIENCES UNDER YOUR BELT, WHAT HAS BEEN THE HIGHLIGHT?

Personally, I have been blessed with three wonderful children (now grown) and five grandchildren and a very supportive husband. Professionally, my work in India was life-changing and our studies on melanoma have been extremely satisfying.

WHAT DO YOU KNOW NOW THAT YOU WISH YOU'D KNOWN WHEN YOU WERE YOUNGER?

That is a really tough question. I might have studied more, but, on the other hand, it is really important to follow your passions – they may change over time. Mine changed from loving working with animals to loving working with people, and then focusing on a relatively small group of people – those who might die from melanoma – to hopefully make a difference. Serendipity must be followed!



WHAT CAN WE LEARN FROM PLANT PROTEINS?

METABOLISM IS AN ESSENTIAL FEATURE OF LIFE. ALL BIOLOGICAL PROCESSES, SUCH AS PHOTOSYNTHESIS, RESPIRATION AND DIGESTION, DEPEND ON VARIOUS METABOLIC PATHWAYS, WHICH IN TURN RELY UPON ENZYMES TO CARRY OUT THEIR WORK. **DR CHARLES STEWART JR.**, OF THE **MACROMOLECULAR X-RAY CRYSTALLOGRAPHY FACILITY** AT **IOWA STATE UNIVERSITY** IN THE US, IS SEEKING TO IMPROVE OUR UNDERSTANDING OF THE FUNCTION OF THESE ENZYMES BY EXAMINING THEIR 3D MOLECULAR STRUCTURE

TALK LIKE A STRUCTURAL BIOLOGIST

CATALYSE – to cause or accelerate a chemical reaction

ENZYMES – the proteins responsible for catalysing all chemical reactions in cells

METABOLIC PATHWAY – a series of linked chemical reactions within a cell

METABOLISM – all chemical reactions within a cell that are required to keep it alive

PROTEINS – biological molecules that contribute to almost all activities in an organism

STRUCTURAL BIOLOGY – the study of the 3D structure of biological molecules

X-RAY CRYSTALLOGRAPHY – the use of X-ray radiation to examine the structure and arrangement of molecules inside a crystal

Proteins are the biological molecules that contribute to almost all activities in an organism. From antibodies which fight viruses, to hormones which coordinate biological processes, and to haemoglobin which carries oxygen in the blood, we could not function without proteins. Dr Charles Stewart Jr. of Iowa State University studies the proteins found in plants, specifically the enzymes responsible for plant metabolism.
Protein molecules are far too small to be examined by eye under a microscope as most are less than 10 nanometres in diameter (equivalent to 0.00001 mm). In comparison, the average human hair has a diameter of 0.1 mm. This means that you could fit 10,000 protein molecules across the width of a single strand of hair!

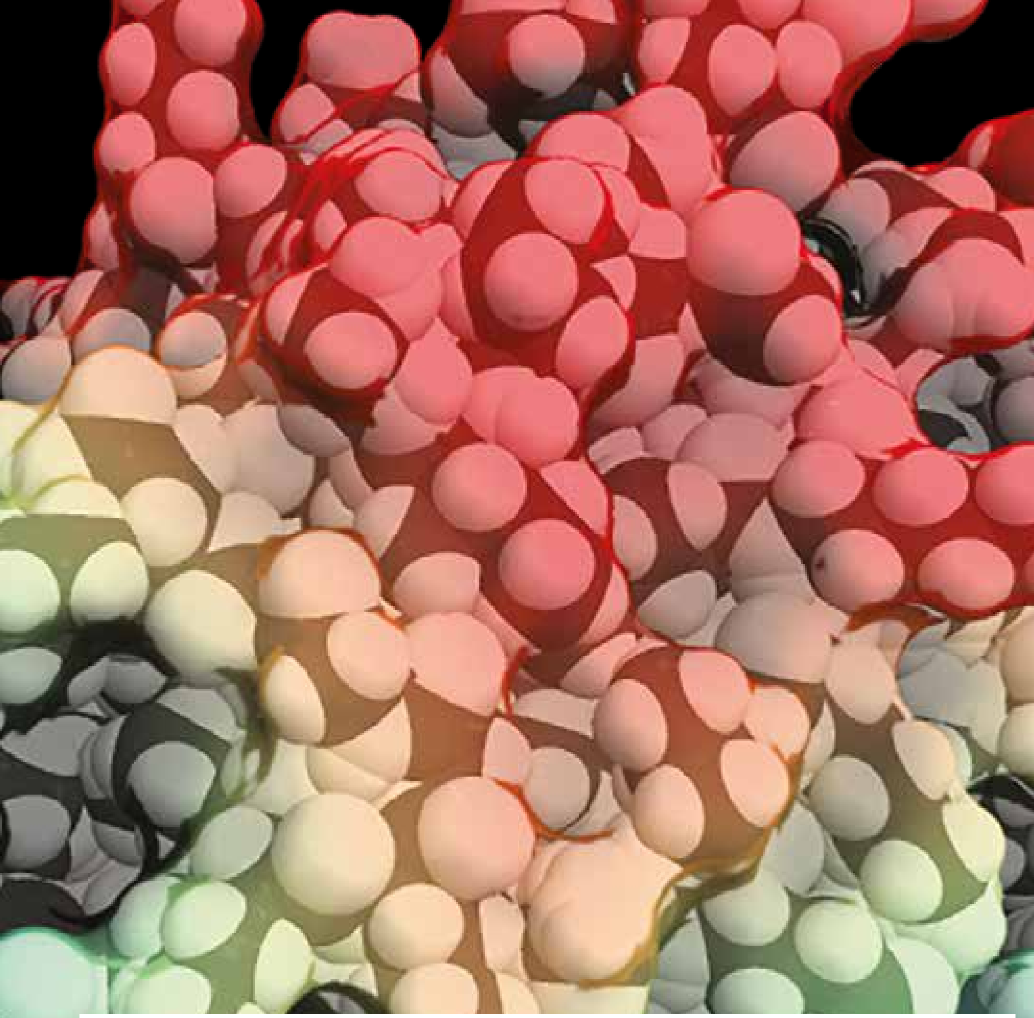
HOW DO YOU STUDY SOMETHING SO SMALL?

Charles studies protein molecules using a technique called X-ray crystallography. A beam of X-rays is fired at a rotating protein crystal, and these rays are diffracted (bent) by the protein molecules within it. The intensity and degree of diffraction of the rays are recorded by a detector, which, when combined with the laws of physics underlying X-ray diffraction, enables scientists to build a 3D model of the protein's molecular structure.

To start the process, Charles must first grow the protein crystal in the laboratory. Unfortunately, protein crystallisation has a high rate of failure, so this is often the most labour-intensive part of the whole procedure. "Although there are general scientific principles to follow, the growing of protein crystals is mostly based on trial-and-error," explains Charles. It can be hard to predict how the crystallisation experiment will run, so Charles must overcome any technical hurdles as they arise. However, technological advances are helping to address these issues, and robots can now greatly improve the speed of screening different crystallisation parameters.

FINDING BEAUTY IN SMALL THINGS

Charles describes his research as a mix of science and art. He says, "I think that there is an intrinsic beauty to protein crystals and the resultant protein structures, which is often under-appreciated in the scientific literature." Once he has solved the scientific challenges associated with growing his protein crystals, he has the excitement of discovering the incredible structural details that become visible



DR CHARLES STEWART JR.

Manager of the Macromolecular X-ray Crystallography Facility at Iowa State University, USA

FIELD OF RESEARCH

Structural Biology

RESEARCH PROJECT

Investigating the 3D structure of proteins to understand their function

FUNDERS

National Science Foundation (Award 1714148) and National Institutes of Health

only with X-ray crystallography. For many of these molecules, Charles is the first person to ever observe what they look like.

One memorable example of this was during his postdoctoral training. After successfully growing new protein crystals, Charles prepared to spend a long night examining them. “Around 2am, my computer monitor started displaying the most beautiful diffraction patterns I had ever seen,” he says. The data he generated that night allowed Charles to view the fine molecular details of a protein, as they had never been seen before, and enabled him to uncover the protein’s 3D structure. Some of his work today is still based on the hypotheses he developed from his results of that night.

THE MANY BENEFITS OF MEDICINAL PLANTS

Charles’ current research is focusing on two enzymes which catalyse a diverse array of chemical reactions in plants. He is studying polyketide synthases, which are responsible for making defensive molecules, and a methyltransferase, which is thought to transfer a methyl group (a functional group from organic chemistry) onto a nitrogen atom.

The metabolic pathways catalysed by these two enzymes produce tropane alkaloids, a group of molecules made by various plant species that are commonly used in medicines due to their pharmacological properties. Examples include atropine, used to treat pesticide poisoning, hyoscyamine, used to control symptoms of Parkinson’s disease, and scopolamine, used to treat motion sickness, all of which are produced by toxic plants.

However, there are several enzymatic steps of the metabolic pathway that generates tropane alkaloids that are still not understood. It also appears that these enzymes result in different products in different plants, but no one yet knows why this is the case. “I aim to clarify the biosynthetic pathway of tropane alkaloids by focusing on the polyketide synthase and methyltransferase that initiate the process,” explains Charles. “I would like to know not only how these enzymes work, but just as important, what the molecular changes of each enzyme are that determine which products are made in different plants.”

To achieve this, Charles is using X-ray crystallography to discover the molecular structure of multiple enzymes from multiple plant species. Once resolved, he must then establish what role each enzyme is performing in the plant, which is dependent upon its 3D structure. Charles and his collaborators deliberately alter the known structures of these enzymes, generating mutations they think will alter their biochemical activities. By testing whether the mutated enzymes still perform the same functions, they can ascertain exactly which mutations are responsible for causing each enzyme function.

Due to their medicinal value, there is a huge amount of interest in creating tropane alkaloids for pharmaceuticals. The work undertaken by Charles and his colleagues will lay the foundation for bioengineering these molecules, as well as potentially developing new, custom-made proteins that are specifically designed to target medicinal issues.

HAS HE DISCOVERED ANYTHING SO FAR?

Yes! Charles has confirmed that a polyketide synthase is involved in the production of tropane alkaloids, however this particular enzyme uses a different reaction mechanism than common polyketide synthases. He has also discovered that the methyltransferase he has been studying catalyses a biochemical reaction that was previously unknown. In this way, Charles’ research is expanding our understanding of the potential of these enzymes, as well as improving our fundamental knowledge of chemistry itself. “These findings indicate that there are novel enzymes and biochemical pathways still waiting to be discovered,” he explains.

ABOUT STRUCTURAL BIOLOGY

WHY DO WE NEED STRUCTURAL BIOLOGISTS?

A human body is composed of trillions of cells. Each cell contains millions of molecules, and our health depends upon every molecule fulfilling its correct function. Sometimes, molecules within our cells become misshapen, preventing them from interacting as they should, and resulting in diseases.

Structural biology is the study of the 3D structure of biological molecules. Knowledge of how biological molecules are built allows scientists to understand how they act within an organism, and how alterations to their structure cause them to mis-function. Proteins are of special interest to structural biologists, as they are responsible for almost every activity in our body, and each protein has a unique shape related to its specific function. For example, antibodies are Y-shaped to bind to viruses, while enzymes contain pockets that allow them to connect with other molecules. But as soon as the protein's shape becomes altered, it can no longer perform its job correctly. Cystic fibrosis, Alzheimer's disease and Parkinson's disease are all caused by misshapen protein molecules. If structural biologists can determine the structure of these misshapen molecules, then this will improve our understanding of diseases and hopefully help scientists to develop cures.

WHAT OTHER AREAS OF SCIENCE DEPEND UPON STRUCTURAL BIOLOGY?

Structural biology is necessary for any discipline which involves understanding how proteins function at a molecular level. This includes biochemistry, immunology, plant sciences, evolution, microbiology and bioengineering. Many researchers working with Charles are using the Macromolecular X-ray Crystallography Facility to better understand human diseases. For example, Charles is collaborating with Professor Julien Roche who is focused on finding the structure of a protein that predisposes people to mental illness.

Another group is studying the structure of an enzyme from the parasite that causes malaria, which could lead to the basis of antimalarial treatment. Lastly, a group is studying enzymes that are critical for sending signals within cells, which can cause a range of illnesses if they are disrupted. By examining their molecular structure using crystallography, scientists will learn how the enzymes function, which may hopefully lead to the development of cures.

AN INTERESTING CAREER

As structural biology is a multidisciplinary field, Charles works on a wide variety of projects with colleagues from around the world. "Some projects are geared towards fundamental advances in science," he says, "while others are directly tied to an output that has immediate and obvious benefits to society."

Charles began his research career studying agricultural biochemistry at Iowa State University. This was followed by a doctorate in plant biology at Cornell University where he investigated how chili peppers make capsaicin, the molecule responsible for their heat, earning him the nickname 'Dr Pepper'. Alongside his research, he also participated in an agricultural development project, spending two months working with farming communities in northern Ghana. Although this project was unrelated to any research that he had previously performed, Charles was able to apply his scientific knowledge to a new project in a new environment. "It was a great experience and gave me the confidence to go into research areas that were outside my comfort zone."

Following postdoctoral research positions in California, which saw him develop his skills as a protein crystallographer and begin his studies of polyketide synthases, Charles came full circle to return to Iowa State University as manager of the Macromolecular X-ray Crystallography Facility. "One thing I enjoy about this position is that I am constantly learning," says Charles. "I work with researchers from different fields, on projects that range from antibodies and human diseases, to proteins underlying agriculturally-important traits, to enzymes being explored to gain fundamental knowledge of chemistry."

WHAT CHANGES WILL THE FUTURE BRING?

Charles predicts that advances in machine learning and artificial intelligence will transform all science disciplines. He explains, "As machine learning software becomes more user-friendly, scientists from all fields are going to make new discoveries."

For structural biology, this revolution has already begun. In 2020, a project led by Google, using its artificial intelligence initiative DeepMind, paved the way to overcoming one of the greatest challenges in the field – how to accurately determine the structure of a protein from its amino acid sequence. Future structural biologists will be able to take advantage of these technological innovations to further enhance our understanding of the building blocks of life.

EXPLORE A CAREER IN STRUCTURAL BIOLOGY

- Charles runs tours of the Macromolecular X-ray Crystallography Facility at Iowa State University for people interested in learning more about the work his team does. If you want to discover what is involved in structural biology, find out if there is a facility near you that you can visit.
- According to PayScale, in the USA a structural biologist can expect an average salary of $105k.

PATHWAY FROM SCHOOL TO STRUCTURAL BIOLOGIST

Charles recommends studying the basic science courses such as biology, chemistry, genetics and physics. "But also look for courses that pique your curiosity," says Charles. "It is hard to predict what courses and experiences are going to fuel your creative flair."

- A degree in biology or a related subdiscipline is a common route into structural biology. As an interdisciplinary field, other degrees including biochemistry and biophysics can also lead into a career in structural biology.
- To become a structural biologist, you will have to complete a master's degree or PhD after your initial university studies.

HOW DID CHARLES BECOME A STRUCTURAL BIOLOGIST?

WHAT WERE YOUR INTERESTS AS A CHILD?
I was a curious child. I liked music (singing), math, history and science. I enjoyed the outdoors and re-modelling houses with my father.

WHO OR WHAT INSPIRED YOU TO BECOME A SCIENTIST?
My father, who worked in a factory, stressed the importance of science as a career option. He knew that manufacturing jobs were on the decline in America and foresaw that STEM careers would be growing.

Equally important was my participation in a high school program called Science Bound, operated by Iowa State University, which opened my eyes to the various careers that a major in STEM could provide. I was in the initial class of Science Bound students and had the honor of being the first Science Bound student to graduate from Iowa State University.

WHAT CHARACTERISTICS HAVE MADE YOU A SUCCESSFUL SCIENTIST?
I think having an intrinsic level of curiosity is necessary for success in science. The ability to pay attention to detail and a determination to work through problems are also important.

HOW DO YOU OVERCOME OBSTACLES IN YOUR WORK?
I step back and take a break. When I return to the problem, I will try to break down the obstacle into pieces and figure out which piece is causing the problem. Or I will try to understand if I am making incorrect assumptions. Of course, I will ask others for advice if I feel that they can help me.

WHAT HAVE BEEN YOUR PROUDEST CAREER ACHIEVEMENTS SO FAR?
All the places that I've studied or worked have provided invaluable knowledge, wisdom, friendships and memories. I am proud of my work launching the Macromolecular X-ray Crystallography Facility here at Iowa State University. It pushed me out of my comfort zone and allowed me to develop, not only as a scientist, but also as a leader.

WHAT ARE YOUR AMBITIONS FOR THE FUTURE?
As a scientist, I want to keep doing research that furthers our understanding of how nature works. I also want to expand the reach of scientific research to countries and communities that have historically lacked the resources.

As the manager of the Macromolecular X-ray Crystallography Facility, I would like to attract scientists to the facility who may not be experts in crystallography, but who want to use this method to solve their own research problems. Additionally, I would like to develop outreach projects to help young students learn about STEM, not only as a career option, but also as a way to better understand the world we live in.

CHARLES' TOP TIPS

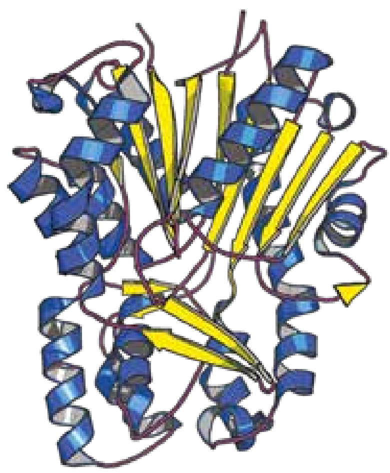
01 Develop a strong foundation in science.

02 Be willing to learn new things.

03 Find a mentor – someone who you can ask questions of and get feedback from.

A CHALLENGE FROM CHARLES

Can you identify the secondary structures shown in this image? The secondary structure of a protein consists of regular, recurring shapes formed by amino acids near each other. The three most common secondary structure elements are helices, beta sheets and loops. The image provided is of a polyketide synthase (pdb code 5wc4). Hint: look at the shapes associated with each colour.



MAKING X-RAYS SAFER - AND MORE EFFICIENT

ALTHOUGH INCREDIBLY USEFUL TO DETECT A WIDE RANGE OF CONDITIONS, FROM BROKEN BONES TO DECAYING TEETH, AN X-RAY OR A CT SCAN CARRIES A CERTAIN AMOUNT OF RISK. WORRIED ABOUT THE HIGH LEVELS OF RADIATION EXPOSURE DURING X-RAYS, **PROFESSOR LÁSZLÓ FORRÓ** OF THE **ÉCOLE POLYTHECHNIQUE FÉDÉRALE DE LAUSANNE**, IN SWITZERLAND, HAS DEVELOPED THE BASIS OF A NEW DEVICE THAT NOT ONLY USES SIGNIFICANTLY LOWER LEVELS OF RADIATION, BUT IS ALSO MORE EFFICIENT AND CHEAPER TO BUILD

X-rays are an essential medical imaging tool used by doctors all around the world. However, despite the obvious benefits for patients, this procedure is also associated with an increased risk of cancer. Professor László Forró, Head of the Laboratory of Physics of Complex Matter based at the École Polythechnique Fédérale de Lausanne, in Switzerland, wants to use the latest technology to develop a new device that requires significantly lower levels of radiation for the same image quality and, therefore, reduces health risks.

We may not think about it, but the simple act of getting an X-ray or a CT scan in a hospital or at the dentist's surgery has the potential to be risky for our health. You cannot see them or feel them, but X-rays are like beams of invisible light with the ability to pass through your body. As they do this, the energy from these beams is absorbed differently in different tissues. An X-ray photodetector picks up the remaining X-rays on the other side of the body and creates a black and white image. Soft parts, like the heart and lungs, appear darker as the X-rays cross easily, whereas dense parts, like bone, appear white because the X-rays find it harder to cross.

TALK LIKE A NANOSCALE SCIENTIST

CT SCAN (OR COMPUTED TOMOGRAPHY SCAN) – involves multiple X-ray measurements taken from different angles to generate a tomographic image of the body

MICRO – a prefix meaning one millionth (1/1,000,000)

MICROMETRE (μM) – a distance unit representing one-millionth of a metre or one-thousandth of a millimetre. Also known as micron

NANO – a prefix meaning one billionth (1/1,000,000,000)

NANOMANIPULATOR – a device, based on an atomic force microscope and a joystick, for controlling and manipulating individual molecules or nanoscale objects

NANOMETRE (NM) – a distance unit representing one-billionth of a metre or one-millionth of a millimetre

NANOSCIENCE – science conducted at the nanoscale, which is between 1 and 100 nanometres

SURFACE AREA – a measure of the total area that the surface of the object occupies

X-RAY (X-RADIATION) – a type of radiation, known as electromagnetic waves, which is very energetic and can penetrate skin and internal organs

X-RAY PHOTODETECTOR (OR, SIMPLY, DETECTORS) – devices that can measure X-ray radiation. In a medical setting, these machines are usually imaging detectors. For many years, doctors used photographic plates and X-ray film, but now most have been replaced by computerised devices like flat panel detectors

PROFESSOR LÁSZLÓ FORRÓ

Laboratory of Physics of Complex Matter, École Polytechnique Fédérale de Lausanne, Switzerland

FIELD OF RESEARCH

Physics, Nanoscale Science and Novel Electronic Materials

RESEARCH PROJECT

Developing an 3D aerosol-jet-printed perovskite X-ray photodetector.

FUNDER

ERC Advanced Grant and ERC Proof of Concept

This makes X-rays incredibly powerful tools to spot many diseases, like cancers, cardiovascular diseases and osteoporosis. The problem is that the radiation crossing our body can cause small changes in our DNA, which may produce mutations and cause cancer later in life.

HOW CAN WE LIMIT RADIATION EXPOSURE?

“The current imaging technique needs lots of very complex electronics. Making it simpler, easier and more user-friendly would be an advantage”, says László.

With this in mind, László’s team has been working on a new method to produce X-ray images using a significantly lower amount of radiation, all thanks to an inspiring new material: lead halide perovskites.

In the name of this synthetic material, ‘perovskite’ denotes the structure, which was first identified by Lev Perovski for a mineral originally discovered in Russia. Typically, this compound includes several chemical elements with both positive and negative charges, such as lead, bromine or iodine, arranged in a complex octahedron.

Researchers have known about the curious properties of these perovskites at the nanoscale for a while, but only recently started using it in different devices, including lasers, light-emitting diodes, gas sensors and photodetectors. Most of these are still in the development stage in the lab, but have perovskite-based solar panels - the first product to be created - are already on their way to commercialisation either as a standalone product or in combination with other types of solar panels.

Forging a new use for this material, László developed the element of an X-ray photodetector with a thin layer of perovskite, which turned out to be several times more sensitive than conventional detectors. It is still in its early stages, but this new device seems to be able to catch more X-rays - which would be lost in conventional detectors - due to the presence of heavy elements such as lead and iodine in perovskite. As a result, László’s perovskite-based detector easily outperforms silicon-based traditional X-ray detectors. The researchers believe this high sensitivity will allow medical and dental images to be obtained with only a fraction of the radiation compared to normal X-ray imaging. This is good news as lower levels of exposure reduce the risk of cancer for both patients and health care professionals. Other uses, which may also benefit from a more efficient X-ray detector, include revealing counterfeit art and scanning luggage in airports.

HOW IS PEROVSKITE PRINTED?

László and his team have discovered that to achieve this extraordinary sensitivity to X-rays, perovskite needs to be deposited in a very thin layer of carbon material called graphene, which strongly amplifies the signal generated by the X-rays. A further improvement for having highly detailed images with low doses of X-rays is to print this perovskite onto graphene in the form of pillars (imagine a bed of nails), using a method called 3D aerosol jet printing. This is a radically new approach, and where going down to the nanoscale is useful, as this method allows the layer to be printed with μm (micrometre) precision.

The new perovskite photodetector is also cheaper and faster to produce. The conventional approach involves a cumbersome and time-consuming method to grow a large silicon crystal, amorphous selenium or very expensive cadmium telluride, all of which need to be conducted with complex procedures – for example, silicon at high temperatures and under vacuum conditions.

In contrast, 3D aerosol jet printing is quick and easy. Perovskite is simply mixed with ink, but not standard liquid ink used in pens. In this case, the ink is a liquid that can dissolve perovskite and evaporate it almost immediately, keeping the material in place with incredible accuracy. “Using a rapid and cheap printing technique, we have structured and tested an X-ray detector unit, which shows a record sensitivity four orders of magnitude higher than the up-to-date perovskite devices,” says László.

Given the promising results so far, László and the team are looking for investors to continue developing and testing their prototype. They are very confident that this new X-ray detector could be a potential game changer for medical imaging. Not only is it cheaper to produce, but more importantly, it needs lower radiation levels, resulting in safer imaging systems.

As nanoscale science and technology become more embedded in our lives, new opportunities for a career in this field arise daily. There are many different sectors which would welcome a nanoscale scientist, including aerospace, medicine, forensics, the military and biotechnology. Nanoscience and nanotechnology are in high demand and offer good prospects for the future. According to Salary Expert, the estimated salary for a nanotechnology engineer will increase 8% over the next five years.

If you want to find out more, the École Polytechnique Fédérale de Lausanne offers regular outreach programmes. At one of these events, László’s laboratory demonstrated a nanomanipulator hooked to a joystick like the ones used in computer games. With this special device, students could feel the force needed to push an atom on a surface, or the force needed to cut a carbon nanotube. “The kids were amazed by the experience. I am sure that many of them will want to study with us”, enthuses László.

ABOUT NANOSCALE SCIENCE

WHAT IS SO SPECIAL ABOUT NANOSCALE SCIENCE?

Nanoscale science – or nanoscience – is the study of materials on a truly small scale. This field of science may be relatively new, but it has a huge potential to change our world. From developing new materials, to energy related topics (photovoltaics, fuel cells, thermoelectrics), environmental challenges (water purification, protective and sterilising air filters), to breakthroughs in medicine (vectors for drug delivery, contrast agents in MRI, cancer treatment), the possibilities are endless. Such achievements are only possible with a cross-disciplinary approach, where scientists from a wide range of fields come together. All around the world, chemists, physicists, biologists, medical doctors, computer engineers and many others are studying nanoscience and using it to better understand and change our world.

JUST HOW SMALL IS NANOSCALE?

Nanoscale is the scale used to measure atoms and molecules, which means it is really tiny. You would need 10 hydrogen atoms stacked up on top of each other to reach 1 nanometre height, and a strand of DNA is only about 2.5 nanometres in diameter. If you imagine that everybody on Earth was only one nanometre tall, you could fit the entire population in a matchbox! That is how small nanoscale really is. Think small, then think smaller.

HOW CAN NANOSCIENCE CHANGE OUR VIEWS OF THE WORLD?

Thinking about how small we can go is fun, but the real value of nanoscale science is how chemical and physical properties of different materials change in the nanoworld. For example, we all know that gold is yellow, but break it down into nanosize nuggets and it can be orange, purple or green depending on the size and shape of each piece.

Scientists have learnt how to change properties such as colour, conductivity or even strength by controlling how these nanosize particles are formed. This is incredible, because they are not changing the chemical composition, they are changing the size of each particle. This happens because as more of the material's surface area is exposed, these tiny particles become incredibly reactive. This phenomenon opens so many doors to improve virtually all manufacturing processes and make them more energy efficient. The 3D aerosol-jet-printed perovskite X-ray photodetector is just one example of this.

ARE NANOSCIENCE AND NANOTECHNOLOGY THE SAME THING?

These two terms are often used interchangeably. They are not exactly the same thing but are interlinked. Nanoscience is the study of the very small, whereas nanotechnology involves building devices and structures at the nanoscale. Essentially, nanoscience studies materials and their properties at the nanoscale and then nanotechnology uses them to create something new.

HOW TO BECOME A NANOSCALE SCIENTIST

- This is an incredibly varied field. For some positions, you may need experience working in a laboratory environment, while others may prefer a background in industry.
- Nanowerk (**https://www.nanowerk.com/nanocareer/homepage.php**) in Europe and Nano4me (**http://nano4me.org/**) in the USA are good starting points to look for positions in nanotechnology and nanoscience.
- According to Salary Expert, an experienced nanoscientist or nanotechnologist may earn up to CHF 91'811 (about £76K) per year:

  https://www.salaryexpert.com/salary/job/nanotechnology-engineering-technologist/switzerland

PATHWAY FROM SCHOOL TO NANOSCIENCE AND NANOTECHNOLOGY

- To start a career in nanoscale science, you need a degree in one or more of the fundamental sciences, such as physics, chemistry or even biology. Other relevant courses include electronics, engineering and materials science.
- Most colleges and universities offer specialised courses in nanoscience and nanotechnology: **https://nanotech.law.asu.edu/Documents/2009/09/Education%20Catalogue%200305_251_4633.pdf**
- Postgrad.com lists establishments that offer postgraduate courses in nanotechnology: **https://www.postgrad.com/courses/nanotechnology/europe/**
- If you are interested in finding out more about the nano world, the National Nanotechnology Initiative offers a wide range of educational resources from secondary school to postgrad level: **https://www.nano.gov/education-training**

Graduate student, Edoardo Martino, performing an optical measurement at the SOLEIL research center in Paris.

HOW DID LÁSZLÓ BECOME A NANOSCALE SCIENTIST?

WHAT WERE YOUR INTERESTS AS A CHILD?

Many! I used to read a lot, but I was also fond of art and natural sciences. Although I grew up in a modest family, I had many positive influences in my environment. I received all the support I needed from my parents to study.

WHO OR WHAT INSPIRED YOU TO BECOME A SCIENTIST?

In secondary school, I regularly attended competitions in maths and physics, and met interesting people, who became friends and forged my interest and motivation in science. And, of course, reading the biographies of scientists helped me a lot.

WHAT ATTRIBUTES HAVE MADE YOU A SUCCESSFUL SCIENTIST?

Imagination and creativity are essential for being a successful scientist. But the prerequisite is very good technical knowledge, so university studies are very important. In physics, what we learn, what we are trained for, is problem solving. We have analytical minds. This is very important.

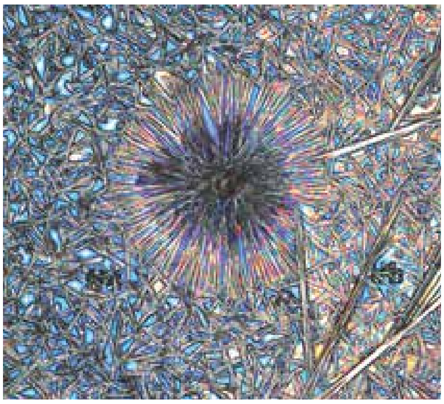
HOW DO YOU OVERCOME OBSTACLES IN YOUR WORK?

We can have many kinds of problems: human, technical, conceptual. The most difficult ones are human obstacles. But with a positive attitude, you can solve most of them.

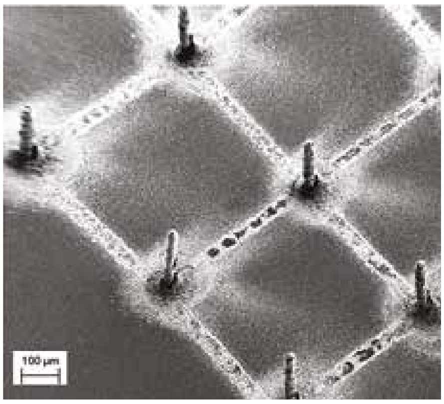
WHAT ARE YOUR PROUDEST CAREER ACHIEVEMENTS?

I have several achievements, which start with the sentence, "for the first time, we have managed to...".

I can give you one example: Cells maintain their form with the help of protein polymers called microtubules. These are also the 'wires' which pull apart the chromosomes during cell division. Their diameter is only 24 nanometres; one cannot see them. Nobody has measured how mechanically strong they are, but it is an important quantity to describe how the cell functions. One of my post-docs managed to extract just a few grams of these microtubules from a cow's brain and elaborated a method to measure its mechanical strength. Since then, many scientists have applied our method to measure nanoscale biological structures. I can say that I am proud of this path to discovery, because it needed imagination and conviction to do it.



It was a great surprise to László and his team that these perovskites can form beautiful assemblies of nanowires.



A great discovery – pillars can be printed from the perovskite for X-ray detection purposes.

LÁSZLÓ'S TOP TIPS

01 Take your science subjects seriously!

02 Do not be afraid to dream, to have a vivid imagination, and to have the courage to go to unexplored fields.

03 It is important to read, to be fond of art, to be a colourful person. Beyond the fact that it is a great intellectual pleasure to enjoy art, it will help you to develop your imagination and communication skills.

04 Forging a network of supportive people, including colleagues and friends, is also very important to be successful.

A LEAP FORWARD IN THE APPLICATION OF ULTRAFAST LASERS

DR XIAOMING YU IS BASED WITHIN **CREOL, THE COLLEGE OF OPTICS AND PHOTONICS** AT THE **UNIVERSITY OF CENTRAL FLORIDA** IN THE US. HE IS WORKING ON A NOVEL NANOMANUFACTURING PROCESS THAT WILL LEAD TO THE CREATION OF NEW AND IMPROVED MEDICAL DEVICES WITH A RANGE OF BENEFITS

On 22 March 1960, American physicists Charles H. Townes and Arthur L. Schawlow were granted a patent for something called an optical maser. While this term might be unfamiliar to some of our readers, the majority will have heard of what it has become known as in the years after: lasers. Lasers are used in a wide range of different applications, from CD players, to medical applications and even self-driving cars!

However, the invention of lasers would not have been possible were it not for Max Planck's discovery of elementary energy quanta (for which he received the 1918 Nobel Prize in physics). Later, Einstein suggested that it might be possible to stimulate electrons and make them emit light of a particular wavelength. As usual, Einstein was way ahead of his time and it was more than four decades after this that his theory was demonstrated in practice. So, what is a laser? Well, put simply, a laser is something that can make billions of atoms generate trillions of light particles (protons) that line up to produce a concentrated beam of light. So concentrated is this beam of light, that it makes lasers extremely precise and powerful.

Now that we are firmly within the 21st century, technological advancements are enabling more developed lasers to be used in a range of applications, with enormous benefits across a range of fields. Dr Xiaoming Yu, who is based within CREOL, The College of Optics and Photonics at the University of Central Florida in the US, is working on using ultrafast lasers as a potential manufacturing tool – one that could lead to the development of new and improved medical devices (as well as many other possible applications).

WHAT ARE THE BENEFITS OF USING ULTRAFAST LASERS?

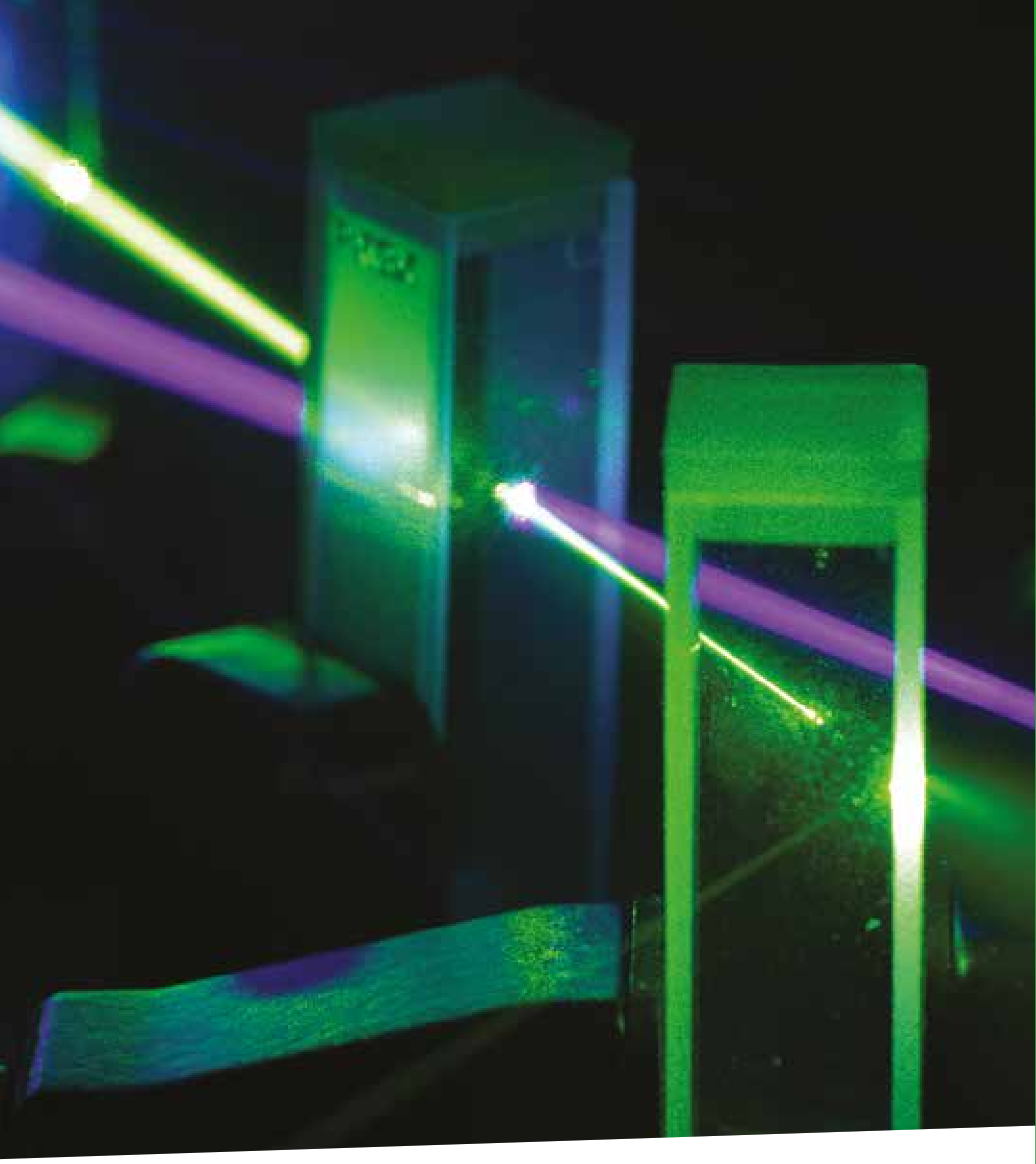
Firstly, lasers have the ability to modify materials from the inside! For instance, there are bubblegrams, which are solid blocks of glass that have been exposed to laser beams to produce 3D designs inside. The precision that enables these artworks to be created also has exciting applications in 3D printing to produce medical devices and even artificial tissues.

The second benefit is the high resolution that ultrafast lasers boast, which means they have extremely small features – smaller than a red blood cell – which is where Xiaoming's research comes in. They can do this because, unlike other types of laser, ultrafast lasers (also known as ultrashort-pulsed lasers) emit bursts of light that are unbelievably short. So short in fact that the light they emit travels a shorter distance than a fraction of the width of a human hair!

These ultrashort pulses are 100 trillion times brighter than sunlight. "When shining onto a material, these bursts create extremely high temperatures and pressure that can only be found at an explosion of thousands of tons of TNT or a small nuclear bomb, turning the material to a plasma (the fourth state of matter)," explains Xiaoming. "What is more important is that these bursts are so short that the high temperature does not have enough time to spread, so the plasma only affects a small area. This is called 'nonthermal ablation' and is unique to ultrafast lasers and the reason that small features can be made."

HOW HAVE XIAOMING AND HIS TEAM WORKED TO DEVELOP THESE LASERS?

Xiaoming has developed a new process to fabricate large-area nanostructures on



DR XIAOMING YU

Assistant Professor of Optics & Photonics, CREOL
The College of Optics and Photonics
University of Central Florida, USA

FIELD OF RESEARCH

Optics and Photonics

RESEARCH PROJECT

Developing a new nanomanufacturing process that can be used in the fabrication of medical devices and display panels. The findings will improve various aspects of our lives.

FUNDER

National Science Foundation

dielectric materials, that is, materials that do not conduct electricity. The new process is called Laser Etching by Avalanche-assisted Photoabsorption (LEAP), which uses the ultrashort laser pulses mentioned earlier. "LEAP uses multiphoton absorption and another photo-physical process called avalanche ionisation, which means an ultrafast laser beam creates a cascade of energised electrons similar to an avalanche – one electron turns into two, then four, then eight, etc. This process repeats itself as long as there are new pulses coming in," says Xiaoming. "In LEAP, such a process is controlled so precisely that the last pulse creates just enough energised electrons to form a nano-plasma, which is smaller than using multiphoton absorption only, so the resolution is enhanced."

HAVE THERE BEEN ANY CHALLENGES IN THE RESEARCH?

Yes! When working with these ultrashort pulses, it becomes extremely challenging to control them. Given that the pulse travels such an incredibly short distance, the slightest thing – like a slight misalignment of the beam or even movement in the air – can change the characteristics of the pulse.

To overcome this, Xiaoming and the team designed their instrument in such a way that potential disturbances could be minimised and compensated for. "The entire instrument was built on a single piece of metal so each component would move in the same way if there was any vibration. We mounted the mirrors on motors so the timing of the pulses could be tuned precisely," explains Xiaoming. "Since the pulses were so strong, we looked at and blocked every possible way the beam could escape and cause damage."

Of course, alongside these experimental challenges there is the overall challenge regarding the big question the team want to answer: how to make ultrafast lasers a more versatile and useful manufacturing tool. Xiaoming is therefore spending time working to improve the concentration of the laser energy and deposit energy more efficiently.

WHAT ARE THE NEXT STEPS FOR THE RESEARCH?

Xiaoming and the team have focused on building the instrument for the experiment to prove that it can work. This has enabled them to develop a model that unifies the results from other researchers and acts as the basis of other findings on the ultimate resolution limit of ultrafast lasers. Over the course of their studies, they came across an unexpected result when two laser pulses were slightly misaligned, and the overlapped region created a feature that was smaller than that from each individual pulse. Discovered purely by chance, this helped demonstrate a way of enhancing the resolution.

The next steps are to use the instrument to produce pulses with characteristics in favour of the aforementioned avalanche process. "We will make the laser beam go into a small focus and use it to fabricate nanostructures on the surface and in the bulk of glass samples," says Xiaoming. "Ultimately, my work can be used in the fabrication of medical devices, such as stents and scaffolds, laser surgery and the processing of display panels. In addition, smartphone panels are processed by lasers and my work will make the manufacturing of these materials more precise and error-free."

ABOUT OPTICS AND PHOTONICS

The word photonics comes from the Greek word 'phos' meaning light (and is also the reason we call particles of light photons). The invention of the laser in 1960 gave rise to the field of photonics, which is closely related to optics. However, optics was established far before photonics, with the development of lenses for microscopes, the refracting lens and the reflecting mirror. Of course, with the advent of significant technological developments, researchers have been able to advance the field of photonics in considerable ways, particularly those related to fields like quantum optics and quantum electronics.

WHAT DOES XIAOMING FIND MOST REWARDING ABOUT HIS RESEARCH?

Xiaoming is a pioneer in the fields of optics and photonics; he has developed many techniques that have since been used by other researchers to solve real-world problems. "A technique I developed when I was a graduate student – 'polarisation-sensitive chemical etching' – has been used to fabricate microfluidic chips used in large chemical plants," explains Xiaoming. "I am collaborating with a US manufacturer of fabric-processing machines which will be using ultrafast lasers as the main processing tool. I hope the LEAP method, once fully developed in the current project, will help laser processing companies reduce cost and increase throughput."

WHAT TYPES OF COLLABORATION HIS XIAOMING ENGAGED IN?

Since lasers were invented more than 60 years ago, the field has been interdisciplinary by nature and that continues to the present day. Xiaoming is currently working with a chemist to develop a new material suitable for 3D printing and a mechanical engineer to develop a multi-physics model that will help scientists understand different types of laser-induced phenomena. And then, of course, there is the team he collaborates with at his college at CREOL.

WHAT WILL THE NEXT GENERATION OF SCIENTISTS ENGAGED IN OPTICS AND PHOTONICS BE FOCUSING ON?

Even though this field has been studied for more than half a century and a lot has been learned about the interaction between ultrashort laser pulses and solid materials, Xiaoming is confident that this complex and fascinating topic has only had its surface scratched. "On the theory side, many models dealing with steady-state phenomena would not work under the extreme temperature and pressure environment induced by the ultrafast laser, so new theories need to be developed. Practically, ultrafast lasers are still difficult to use because of the stringent requirement on the environment," says Xiaoming. "We need engineers to make ultrafast lasers 'smarter', so that they can sense any change in the environment and make adjustment by themselves. The physicist, Richard Feynman, once imagined a future when atoms can be manipulated individually to build things like nano-robots. We are far from this, but we are moving toward this goal with the new generation of scientists and engineers."

HOW TO GET INVOLVED IN OPTICS AND PHOTONICS

- Optics.org is dedicated to providing daily coverage of the optics and photonics industry and the markets that it serves: **https://optics.org/**
- Photonics.com has a heady list of societies and associations to explore: **https://www.photonics.com/EDU/EducationalInstitutions.aspx?TID=1**
- The average salary for a photonics engineer in the US is approximately $99,000, although that figure can rise significantly for more experienced engineers.

PATHWAY FROM SCHOOL TO OPTICS AND PHOTONICS

Optics is a sub-field of physics, so basic physics courses are helpful, as well as mathematics courses that you will likely encounter in high school. "It is worth taking more advanced courses in subjects such as static and dynamic electromagnetics, solid state physics, linear algebra, matrices, linear systems, quantum mechanics and thermodynamics," explains Xiaoming. "I also recommend taking as many chemistry and biology modules as possible because optics and photonics is a highly interdisciplinary field."

You will need a degree in a relevant subject for postgraduate study.

https://www.careerexplorer.com/careers/photonics-engineer/

XIAOMING'S TOP TIPS

01 Have confidence in everything that you do. Always keep in mind that every piece of technology you are using in the present moment was invented by people just like you.

02 Keep an open mind and consider every opinion, particularly criticisms, which are often the best advice you can have to improve yourself.

03 Never be afraid of making mistakes – the important thing is to learn from your mistakes. Do not let the fear of failure stop you from dreaming big but remember to always examine your ideas carefully.

HOW DID XIAOMING BECOME AN EXPERT IN OPTICS AND PHOTONICS?

WHAT WERE YOUR INTERESTS AS A CHILD?

I liked astronomy when I was young, which was an interest that was partly influenced by Stephen Hawking's book 'A Brief History of Time' and partly because a night sky always triggered my imagination about the many unknown worlds beyond our reach. I liked reading magazines about science and technology and enjoyed tinkering with (often destroying) things that had moving parts in them. I guess it was because I wanted to know how stuff worked – that's how I explained it anyway!

WHO INSPIRED YOU TO BECOME A SCIENTIST?

Famous scientists like Stephen Hawking and Richard Feynman, mainly through their books. I was inspired by my high school physics teacher, who taught me the power of science. Using nothing but imagination, logic and perhaps a piece of paper and a pencil, Newton was able to declare a law that every object in the universe must obey. I became fascinated by science after learning about this in high school.

WHAT ATTRIBUTES HAVE MADE YOU SUCCESSFUL AS A SCIENTIST?

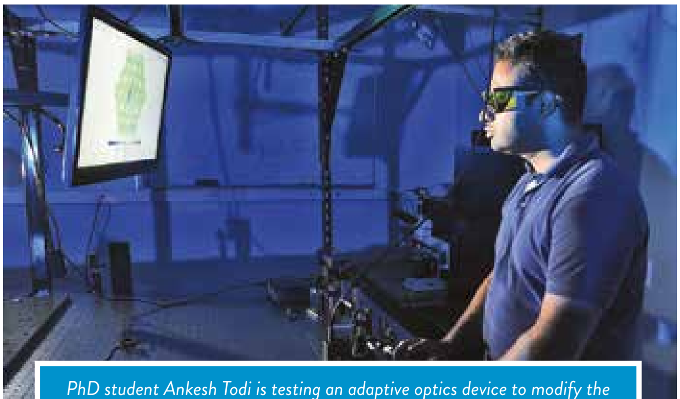
I wouldn't call myself successful! There are so many things to learn which, I guess, counts as an attribute – the acknowledgement that there is always something new to learn. Another key attribute is critical thinking, which is the ability to provide independent assessment of facts and opinions. The third attribute is persistence. There will be challenges in research and many of them have not been solved or even encountered before. It is in such moments that scientists and researchers need to hold on to their beliefs and try everything they can. Every problem has a solution.

HOW DO YOU OVERCOME OBSTACLES IN YOUR WORK?

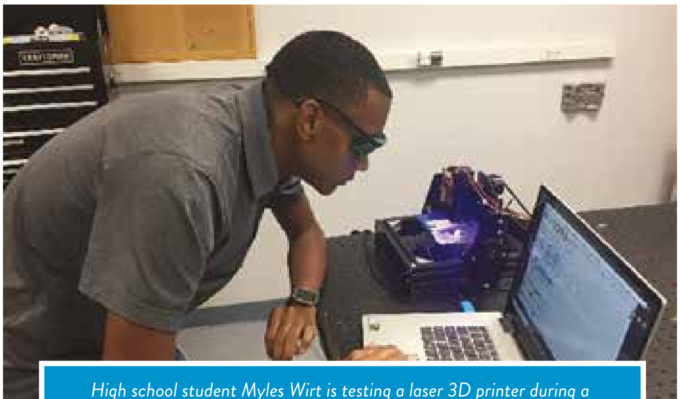
Learning from others. The majority of problems can be solved using my own knowledge and experience, but once in a while there are problems that exceed my ability. Instead of trying to force myself to work on the problem, I seek help from others – and not always those who have the exact expertise, but anybody who has an open mind and is willing to share their opinions from a different perspective. I find this often broadens my views and helps me solve problems using a new approach.

WHAT AMBITIONS HAVE YOU SET YOURSELF FOR THE FUTURE?

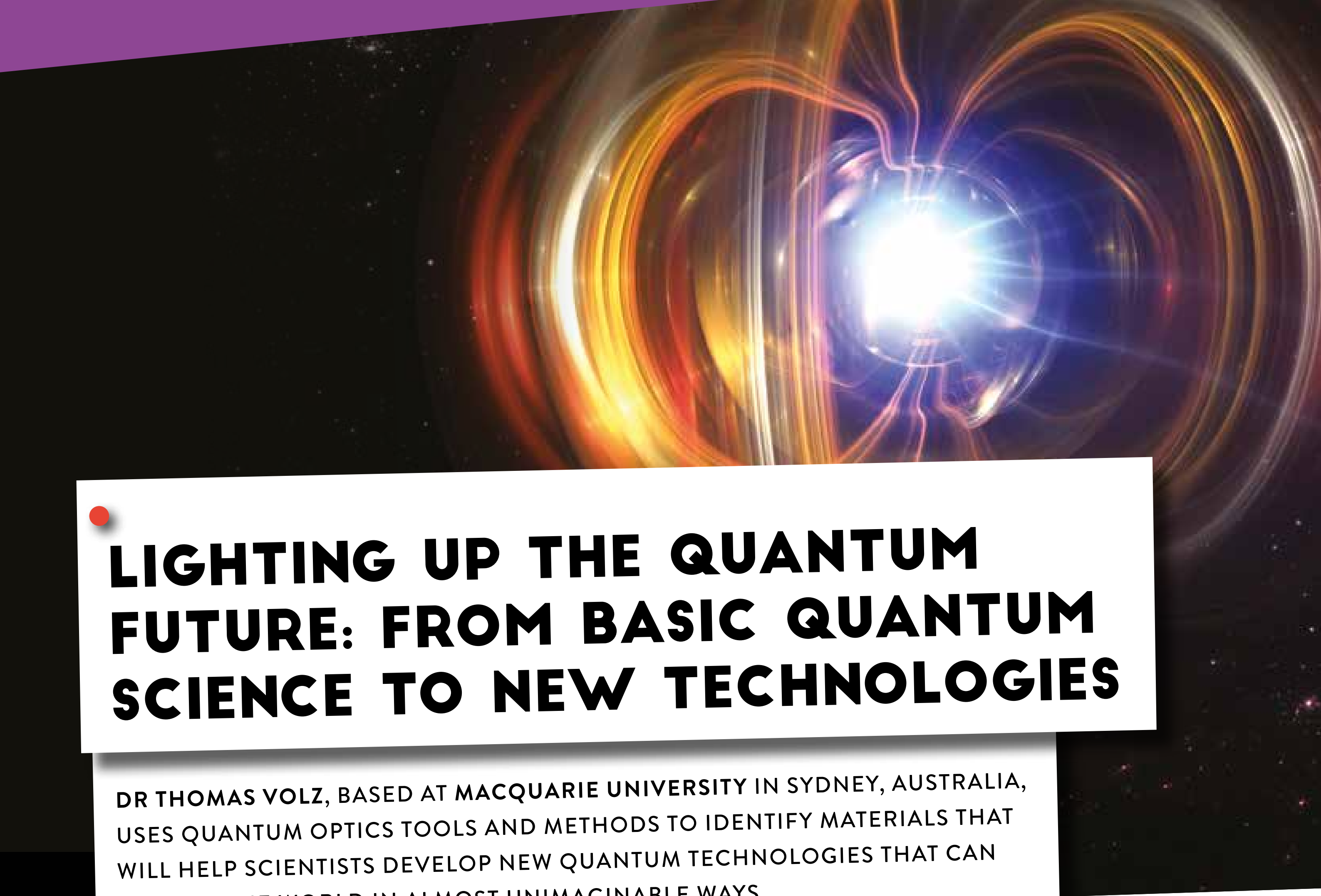
I would like to see laser materials processing, in general, and ultrafast laser processing, in particular, become more widely used manufacturing tools. Lasers are versatile in that they can be tailored to suit different types of applications, like a swiss army knife. I would like to continue my contribution in this field and my biggest ambition is to build a 'universal laser machine' that can do different jobs and is accessible to the public. I like to think of this as a personal workshop which ordinary people could use to build the parts they need in a way as simple as clicking a few buttons.



PhD student Ankesh Todi is testing an adaptive optics device to modify the spatial shape of a laser beam.



High school student Myles Wirt is testing a laser 3D printer during a summer internship in Xiaoming's lab.



LIGHTING UP THE QUANTUM FUTURE: FROM BASIC QUANTUM SCIENCE TO NEW TECHNOLOGIES

DR THOMAS VOLZ, BASED AT **MACQUARIE UNIVERSITY** IN SYDNEY, AUSTRALIA, USES QUANTUM OPTICS TOOLS AND METHODS TO IDENTIFY MATERIALS THAT WILL HELP SCIENTISTS DEVELOP NEW QUANTUM TECHNOLOGIES THAT CAN CHANGE THE WORLD IN ALMOST UNIMAGINABLE WAYS

TALK LIKE A QUANTUM SCIENTIST

PHOTONS – the fundamental particles or quanta of light. They have unique properties in that they behave both as a particle and as a wave

NANODIAMONDS – diamonds that are below 1,000 nanometres (=1 micrometre) in size. They can be produced quickly by impact events such as explosions, or slowly in a microwave oven using a process that grows them atom by atom. These nanodiamonds possess fascinating mechanical, chemical, optical and biological properties

POLARITONS – hybrid particles made up of a photon strongly coupled to an electric dipole, e.g. of an atom or an excitation in a solid. A hallmark signature of polaritons is the occurrence of the phenomenon known as level repulsion or avoided crossing

SPIN – Classically, spin denotes a self-rotating object (think of a gyroscope). In quantum physics, spin is an intrinsic form of angular momentum carried by elementary particles, composite particles and atomic nuclei

SPECTROMETER – a device for detecting and analysing wavelengths of light over a wide range of the electromagnetic spectrum. It is a tool commonly used not only by quantum physicists but also by astronomers, for example, to gather information about the chemical composition, temperature, density, mass, distance, luminosity and motion of planets and stars

Quantum physics is the science of the small. The *very* small. Essentially, it revolves around a fundamental theory in physics that investigates properties of matter at the atomic scale and even below. A key finding of quantum physics is that atoms and photons (and all other 'particles') behave both as particles and as waves. And, in the same way that a wave does not have a specific location, atoms and photons are not localised until they are measured by a detector. In fact, atoms and photons can be in different positions at the same time and can travel different paths at the same time. This phenomenon is at the heart of quantum physics and is called 'superposition'. Superposition is not restricted to position. It also extends to 'internal' states, e.g. the spin of an atom or an electron pointing up and down at the same time.

Imagine a coin showing heads and tails at the same time, or a cat that is dead but also alive. Quantum physics says that these phenomena happen all the time at the atomic scale, and even up to the micron scale. Another remarkable feat that comes with the phenomenon of superposition is that whenever a measurement of the actual state is made, the outcome is entirely random, each time. This has resulted in quantum scientists using different methods to classical physicists, such

as using predictions that are a probability of possible outcomes rather than something more definitive.

Still, despite or rather because of the bizarre nature of the quantum scale, the field of quantum science boasts huge potential for changing the world in a range of ways. For example, the concept of superposition is at the heart of a quantum computer. It is with this in mind that Dr Thomas Volz, based at Macquarie University in Australia, is conducting various quantum experiments involving quantum emitter systems and laser light.

WHAT ARE QUANTUM EMITTER SYSTEMS?

Quantum emitters emit single photons (the basic unit of all light) one by one. The simplest quantum emitter is a single isolated atom with two distinct energy levels. When the atom is 'excited' with a laser pulse, it can absorb a photon, go to an excited state and then spontaneously re-emit a single photon. "As well as isolated atoms in free space, solid-state materials can be host to so-called artificial atoms," explains Thomas. "These typically consist of either electron-hole pairs in semiconductors or molecular complexes made of foreign atoms and empty lattice sites within a solid crystal, as is the case for colour centres in diamond." [See Lachlan Rogers' article on pages 40-43].

Many quantum emitters have a complicated level structure corresponding to different spin states. It is these different spin states that are of particular interest to researchers who want to build quantum sensors and quantum computers.

WHY IS THOMAS STUDYING THE BEHAVIOUR OF QUANTUM EMITTERS IN MATERIALS?

If our future world is going to make use of various quantum technologies, it is essential that the right materials are used to perform specific functions. Nanodiamonds are an example. Somewhat ironically, to gain a greater understanding of nanodiamonds' or other solid materials' usefulness in a given application, researchers need to use quantum technologies to study them. Understanding the behaviour of quantum emitters in solids can provide insight into the material and its fundamental behaviour. "It is worth noting that we are in the midst of what we call the Second Quantum Revolution and still need to learn a lot about the different quantum materials out there," says Thomas. "Studying quantum emitters in solid materials can provide us with new material platforms for implementing a range of new quantum technologies."

WHAT ARE THE POTENTIAL APPLICATIONS OF QUANTUM LIGHT?

In its most extreme form, quantum light consists of single identical photons that arrive in time, one after the other, like the pearls on a string. Not all light is like this – sunlight, for instance, consists of photons that tend to come in pairs, while laser light exists somewhere between the two extremes. Laser photons come at completely random times and have no correlation with each other. Even so, lasers are one of the most powerful technologies in the world today.

To generate quantum light, a quantum emitter is needed, which is where Thomas' studies come in. Quantum light is a key resource for a variety of potential quantum information applications, such as building a quantum internet and performing quantum computations with light.

WHAT OTHER ACTIVITIES IS THOMAS ENGAGED IN?

In addition to his work on quantum emitter systems, Thomas has co-founded a start-up company called Redback Systems. The team at Redback Systems is building advanced optical spectrometers that have their origin in astronomy (two of Thomas' co-founders are astronomers with experience in building some of the best and most expensive spectrometers in the world). "With many visitors coming through our lab and asking where one can buy these spectrometers, we realised there was a commercial opportunity and decided to go for it," says Thomas. "We were greatly supported by the ARC Centre of Excellence for Engineered Quantum Systems (EQUS) and Australia's national science organisation CSIRO through its ON programme. This enabled us to form a viable company and we shipped our first product in January 2021."

If all that was not enough, Thomas is also the Principal Investigator of QMAPP, more details of which can be found in the following pages. It is fair to say that regardless of how small the focus of quantum science is, Thomas is involved in a very large number of different projects!

DR THOMAS VOLZ

Associate Professor, Department of Physics and Astronomy, Macquarie University, Australia

FIELD OF RESEARCH

Quantum Optics, Quantum Engineering, Quantum Materials

RESEARCH PROJECT

Thomas is engaged in a variety of quantum research projects, typically involving quantum emitters and light. His studies will help understand various materials, their fundamental behaviours and suitability for a range of technological applications that will change the world.

FUNDER

Australian Research Council Centre of Excellence for Engineered Quantum Systems (EQUS)

ABOUT QMAPP

Thomas is Principal Investigator of the Quantum Materials and Applications Group (QMAPP), a group focused on research activities in quantum physics, nanotechnology and materials science. QMAPP is part of the Physics and Astronomy Department at Macquarie University and is composed of a small team of seasoned researchers, as well as early career researchers and students who are just starting out on their pathway.

WHAT FACILITIES DOES QMAPP HAVE ACCESS TO?

Given the nature of its scientific enquiries, it is vital that the team has access to state-of-the-art facilities. "We have a number of high-power, widely tunable, narrow-line width lasers for manipulating the quantum systems we are dealing with, as well as state-of-the-art single-photon detectors that are able to detect single photons with very high efficiency and with a few tens of picoseconds (1/1,000,000,000,000 seconds) time resolution," explains Thomas. "We also have special, optically accessible fridges for carrying out experiments at helium temperatures, which are four degrees above absolute zero."

HAVE THE TEAM AT QMAPP HAD ANY MAJOR ACHIEVEMENTS?

Yes! In 2019, they were able to report on a key scientific breakthrough, which was centred on the 'emergence of quantum correlations from interacting fibre cavity polaritons' and was published in Nature Materials. "The observation we reported on was predicted in 2006 and was (and still is) one of the key goals in the field of exciton polaritons. Essentially, we report on a way to create quantum light from semiconductor electron-hole pairs that does not require the presence of single quantum emitters in the material," says Thomas. "I was personally thrilled by the outcome since this was a project I started working on when I was a postdoctoral researcher at ETH Zurich in Switzerland, back in 2009!"

The findings took ten years from inception to publication, but Thomas considers it to be one of the key achievements of his career so far. This highlights the hard work that goes into a scientific career and how perseverance leads to great things. That said, scientific discoveries are not the only significant achievement. Thomas alludes to the fact that the group dynamics at QMAPP are really good – collaboration and working alongside like-minded scientists is a perk of the job that you too could enjoy one day.

HOW TO BECOME A QUANTUM SCIENTIST

- STEM Learning has a wealth of resources for those interested in quantum technology. Although many of the papers, on topics such as diffraction, cryptography and laser cooling, are designed for teachers to use, they can be accessed by anybody: **https://www.stem.org.uk**
- Forbes has put together six things we should all know about quantum physics. It is a fascinating read and should enable you to read around specific areas within the field: **https://tinyurl.com/2sryvvu4**
- There are so many different roles within quantum science that an estimated salary is difficult to provide. However, for a research scientist in quantum information science, the average salary is the equivalent of around AUS $100,000. It is worth noting that quantum physics is such a niche field, and one that will revolutionise the world before long, meaning that people with expertise and knowledge in this field will be highly sought after.

THOMAS' TOP TIPS

01 There are a few key traits that are important for a career in science, such as curiosity and an ability to think logically. If you can develop those skills as soon as possible, it will stand you in good stead throughout your career.

02 Quantum science requires very good maths skills, particularly as physics is a quantitative science. Do everything you can to hone your understanding of maths and pay attention in class!

03 The ability to present in front of others and defend key arguments when questioned are important to succeed in science. In addition, excellent writing skills will enable successful grant and publication writing.

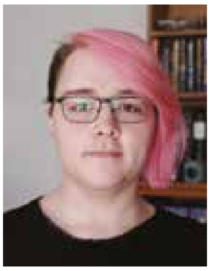
PATHWAY FROM SCHOOL TO QUANTUM SCIENCE

Thomas recommends students think about developing a broader range of skills other than simply focusing on maths and physics (which are essential to quantum science). It might be worth considering studying IT/programming and English, which will be useful for writing up your findings for publication.

You will need a degree in a relevant subject for postgraduate study such as mathematics and/or physics.

https://study.com/articles/quantum_physics_degree_programs_requirements.html

MEET LYRA



Lyra Cronin has just completed her Master of Research (MRes) degree, which means she was able to undertake her studies in quantum optics as part of the QMAPP team.

I loved English and physics during high school. This was mainly because of the wonderful teachers I had. In my first year at university, I did both linguistics and physics subjects, and because of the experience studying physics, it made me more certain that this is the path I wanted to follow.

A large part of my motivation for working in this field is to make the world a better place. If by working steadily at research I can help further our understanding of the universe we live in, then there is no other way I would prefer to spend my time.

My current work is focused on the development and exploration of a maser system. This is a laser that operates at microwave frequencies and is realised by using diamond. While masers have been around for decades, and are used commonly in deep space communication, GPS satellites and high accuracy timekeeping, the existing systems are inaccessible for most other fields due to their cost and operating requirements.

I finished my MRes programme at the end of 2020. I started the maser project during my MRes thesis and will continue working on the same project over the next few years as part of my PhD. This has been my goal for some time, and I am still not sure where I will go afterwards – but, whatever I do, I will want to continue doing research.

I would certainly encourage others to study physics and quantum optics. Little in my life has been as rewarding as conducting research and even though it can be difficult at times, I have never doubted that this is the right path for me. Even outside of academia and research, a background in quantum physics means you are incredibly well positioned to be at the forefront of a new industry.

I would also encourage women and people from underrepresented backgrounds to consider studying physics. In the past, physics has not been especially welcoming for many people, but this is changing rapidly thanks to the efforts of many within the field. Macquarie University, in particular, has been wonderful, and has come so far so quickly. There is an idea that quantum physics is particularly difficult, but it is not inherently more difficult than any other field of science. Anybody can pursue a career in quantum science if they want to.

If I could speak to my younger self, I would say that getting a PhD is possible. Throughout the early years of university, I struggled with severe depression – I had to stop studying for a year and try to recover. Even then I had to study part time for most of my undergraduate degree. During that time, I also came out as trans and began transitioning, which was not easy. Ultimately, even with these struggles, I have been able to get to where I wanted, and it has been one of the best periods of my life.

FIND OUT MORE ABOUT THOMAS

My fascination with light and the use of light for doing experiments really came at university when I was able to work in a real lab and experience lasers first-hand. I was always fascinated by logic and rational argument as a kid – this then turned into a strong interest in both maths and physics. I almost ended up in theoretical physics but eventually settled on experimental quantum optics due to the close link between theory and experiment.

During my third year at university, I took a subject on 'modern laser physics and its applications' with my later PhD advisor Professor Gerhard Rempe. He ran an experimental group at the University of Konstanz in Germany and later became a Director at the Max-Planck Institute for Quantum Optics. He was one of the key figures in the emerging field of experimental quantum optics. In my experience, it is always the people you come in contact and work with who can have an enormous influence on your career.

The path to getting an academic job at a university or research institute is a long and hard one – there are not many jobs in academia and, so, securing such a job is a huge achievement. But I should also highlight that a lot of that achievement boils down to luck and meeting the right people along the way, i.e. simply being at the right place at the right time.

An academic career is full of failures and, with an experimental PhD, one experiences failures almost daily. In fact, during my studies and later in my PhD, I was told that it is all about building 'frustration tolerance'! It takes the right mindset and a strong will to try again and again – a bit like Sisyphus in Greek mythology (or a steady batsman in a five-day test). But when ideas turn out to be correct, the challenging experiment finally works, the big grant application is accepted, and the paper gets printed in a top journal – these moments more than compensate for the many failed attempts.

GLOWING DIAMONDS ARE A QUANTUM SCIENTIST'S BEST FRIEND

DR LACHLAN ROGERS, BASED AT THE **UNIVERSITY OF NEWCASTLE** IN AUSTRALIA, IS INVESTIGATING DIAMOND COLOUR CENTRES. THE ULTIMATE AIM IS TO ENABLE THE DEVELOPMENT OF NEW QUANTUM TECHNOLOGIES THAT WILL REVOLUTIONISE MANY ASPECTS OF LIFE

Diamonds are precious stones that were formed on Earth more than one billion years ago. They are the hardest natural substance on our planet and are made of only one element: carbon. When we think of diamonds, we probably imagine a white, silvery shining jewel (like those pictured above), but the truth is that diamonds can come in pretty much any colour. They are formed deep within the Earth's crust when intense pressure and heat cause carbon atoms to crystallise. It is believed that because of similar conditions deep within Neptune and Uranus, it rains diamonds – imagine the umbrella you would need if you ever found yourself walking around on either planet!

As scientific research continues to discover new and improved ways of doing things, technological developments enable scientists to perform tasks and experiments that would have been unimaginable just a few decades ago. For instance, it is now possible to grow diamonds in a laboratory, simply by reproducing the geological conditions needed (heat, pressure and carbon).

But, you might ask, why are scientists interested in growing diamonds? Well, it is not because they want to become exceedingly rich – the diamonds that are grown for Lachlan's lab are only about four nanometres in size (about 100 times smaller than the wavelength of visible light) even though it is possible to grow larger diamond samples. These diamonds are of interest to researchers because they enable experiments relating to quantum physics.

Dr Lachlan Rogers, based at the University of Newcastle in Australia, is investigating diamond colour centres. Colour centres are defects where a non-carbon atom interrupts the regular array of atoms within the diamond, and they absorb some visible and ultraviolet light. "They are what give some diamonds 'colour' and the 'centre' refers to the fact they are just an atom or two in size – about as small as it gets in a crystal!" says Lachlan. He and his team are using diamonds grown in a lab rather than naturally occurring diamonds. This is because even the best naturally occurring diamonds have too many atomic defects. Lab-grown diamonds have an extremely high chemical purity, allowing control of the colour centres that form. It is these colour centres that open up an exciting world of quantum technology applications.

WHY ARE COLOUR CENTRES IMPORTANT TO LACHLAN'S RESEARCH?

It is worth noting that it is only the colour centres of diamonds that interact with and absorb/emit visible photons – bundles of electromagnetic energy that makes up all light. The pure diamond crystal surrounding these centres is transparent to visible light and is essentially useless when it comes to experiments in quantum physics. "A single colour centre can emit a clearly detectable amount of light, so we can 'talk' to just one at a time," says Lachlan. "However, there is a limit on how small you can focus light, so even with the best lenses, there are tens of thousands of atoms in the optical 'detection spot'. To be able to talk to just one colour centre we need to know that the typical distance between colour centres in the diamond is much more than this focus size."

DR LACHLAN ROGERS

Lecturer, School of Mathematical and Physical Sciences, The University of Newcastle, Australia

FIELD OF RESEARCH

Quantum Optics

RESEARCH PROJECT

Lachlan works on a project that focuses on diamond colour centres. They are one of the most promising means of enabling the development of various quantum technologies that will change the world.

FUNDER

Australian Research Council Centre of Excellence for Engineered Quantum Systems (EQUS)

LACHLAN'S TOP TIPS

01 If you want to get into quantum optics you can never do too much maths! It is very much the language of physics, so improving your mathematical fluency will always serve you well throughout your studies and later career.

02 Being able to write software has turned out to be a bit of a 'superpower' in my research career! I am lucky that it was an amateur interest of mine throughout school. If you have the opportunity to study some coding or software design, you should take it – I am sure it will benefit your interest in quantum physics.

03 The field of quantum optics (and quantum physics, in general) is developing at an increasingly fast rate. It is important to try and keep on top of the latest developments, so do your best to read science magazines and trawl through science websites. There are also loads of high-quality YouTube videos explaining scientific concepts, which can help.

Lachlan's aim is to have just a few colour centres per billion carbon atoms in the diamond crystal.

HOW DOES THE TEAM HARNESS COLOUR CENTRES TO BUILD QUANTUM COMPUTERS?

Lachlan and the team are looking at the light that comes from a single colour centre, which essentially means they are 'talking' to a single electron. Diamonds are a vehicle, providing a convenient way to hold that single electron in place. "Electrons have physical properties like mass and energy, but they also have a quantum property known as 'spin'," says Lachlan. "This 'spin' can be used to store and process quantum information."

WHAT IS QUANTUM METROLOGY?

In addition to shining a light on the possibilities surrounding quantum computing and a quantum internet, the team's investigations consider how colour centres feed into quantum metrology – which makes use of quantum details to improve measurement precision and sensitivity. Two notable examples of this at work are the atomic clock, which is the most accurate means of determining the time and is based on the interaction of electromagnetic radiation with the excited states of atoms; and Magnetic Resonance Imaging (MRI), which is used in hospitals to look inside a patient's body.

Recently, it has become possible for Lachlan and other researchers to control and interact with single quantum objects at a time. "A single colour centre in diamond can do the same measurements as an MRI machine, but on a single molecule in a biological cell," explains Lachlan. "By giving us access to single quantum objects, diamond colour centres are enabling quantum measurement of magnetic fields, electric fields and temperature."

WHAT IS LACHLAN'S ULTIMATE GOAL?

As you might already know, quantum physics appears to have magic capabilities that cannot be explained by classical physics (hence the rise of a sister branch of physics). Lachlan's work is focused on harnessing capabilities that could give rise to a quantum internet which, in theory, would be able to perform tasks that are simply not possible using the internet of today. Then there is the field of quantum sensors, which would revolutionise molecular bioscience and improve treatments, therapies and the lives of people around the world. Experiments in these fields are extremely difficult, but diamond colour centres provide a means of helping such technologies work at room temperature instead of inside massive super-fridges. Lachlan's aim is to discover and engineer diamond colour centres that have better quantum properties and could help to revolutionise our world.

ABOUT QUANTUM OPTICS

Put simply, quantum optics is the study of how photons interact with atoms and molecules. Scientists like Lachlan are working on accurately controlling these interactions and creating quantum states of matter and light that can facilitate the development of a wide range of quantum technological applications. The research and experiments that Lachlan is conducting could help us create a quantum computer and develop sensors made from individual atoms. It is difficult to overstate how much this would change the world as we know it.

Dr Thomas Volz's concerns are very similar to those of Lachlan (see pages 36-39). But, interestingly, Lachlan actually worked in Thomas' lab in the past and is a co-founder of Redback Systems, a company created by Thomas and Lachlan. Clearly, quantum optics is an exciting and emerging field of science that will afford any student a range of opportunities and directions in which to move forward in their career.

WOULD LACHLAN RECOMMEND A CAREER IN QUANTUM OPTICS?

Absolutely! One of the most exciting aspects of quantum physics is that it is weird and magical, and flies in the face of many things we consider intuitive. That keeps it interesting and will always throw up fascinating surprises. "It is a fantastic time to consider a career in quantum science, because so many new options are opening up. Once upon a time electromagnetism was a fundamental research field in university laboratories, but it is now normal to study electrical engineering because so many commercial and industrial tools rely on electronics," says Lachlan. "The same is happening right now for quantum technologies – we are on the cusp of the first-ever generation of quantum engineers."

HOW BIG IS THE FIELD OF QUANTUM OPTICS IN AUSTRALIA?

As Lachlan and Thomas have shown, there is clearly loads of interest in quantum physics and quantum optics down under. It is a large and active field in Australia and, like many countries, researchers have developed a strong research focus on quantum science and its wide range of applications. "Not all quantum technologies are optical (others use electronic control and readout), but optical control has some advantages because it does not require physical contact," explains Lachlan. "At a meeting two years ago of just the people in Australia working on quantum technologies in diamond, there were at least 100 people – and many more work on other related quantum optical systems."

WHAT DOES THE FUTURE HOLD FOR QUANTUM OPTICS?

As mentioned, we should perhaps think about what the future holds for humanity with the development of quantum optics! We are all familiar with computers and digital communications, which are electronic devices that enable us to perform an enormous range of tasks. But all of these technologies are based on the principles of classical physics – quantum optical technologies will run much faster. If you have broadband in your home, ask your parents if you have optical fibre internet – that has significantly sped up the speed at which you can connect to the internet; there is a similar potential for optical computers, even if they are not quantum computers.

HOW TO BECOME A QUANTUM SCIENTIST

- Nature Research has an entire section of its website dedicated to quantum optics, featuring loads of open access research papers. Some of them will be very challenging to understand, but the abstracts should give you an idea of what is happening in the field.

- The Optical Society is a brilliant resource for those interested in understanding more about optics and photonics.

- The world of physics is changing and becoming more inclusive than it has historically been. Lachlan's position at the University of Newcastle is part of generational handover, where many professors have recently retired and been replaced by younger academics. The physics department there is 50% male and 50% female, which shows that the field is heading in the right direction. Work hard and you have a great chance of success!

PATHWAY FROM SCHOOL TO QUANTUM OPTICS

An understanding of maths and physics is a basic requirement for studying quantum optics, but do try and focus on other subjects that may come in handy, such as English (for writing theses, papers and presentations), and IT, which will help give you a greater understanding of computing.

You will need a degree in a relevant subject for postgraduate study.

https://www.prospects.ac.uk/careers-advice/what-can-i-do-with-my-degree/physics

HOW DID LACHLAN BECOME INVOLVED IN QUANTUM OPTICS?

DID YOU ALWAYS KNOW YOU WANTED TO BE A SCIENTIST?

I don't remember specifically wanting to be a scientist, but I have always found science and mathematics very interesting. When I was young, my dad would play games with me when slicing apples: "Would you like ONE third or TWO eighths?" and I had to work out which one gave me more apple!

WHO OR WHAT INSPIRED YOU TO STUDY MATHS AND PHYSICS?

My dad and (maternal) grandfather both have science PhDs, so an interest in maths and physics certainly seemed 'normal' to me as a child. At various times I visited universities for holiday programmes and public lectures, and I was enthralled by all the amazing instruments and lab devices. I think part of my interest in physics is just that I like playing with cool toys!

HOW DID YOU END UP GETTING INTO QUANTUM OPTICS AND THE INVESTIGATION OF COLOUR CENTRES IN DIAMONDS?

When I was an undergraduate student, I applied for a student travel scholarship to attend the Australian Institute of Physics Congress. The form had a field for areas of interest and I wrote quantum computing because it sounded cool to me. A professor saw this form and offered me a tour of their research lab, and I was so excited by the things I saw that I ended up doing my PhD under that professor!

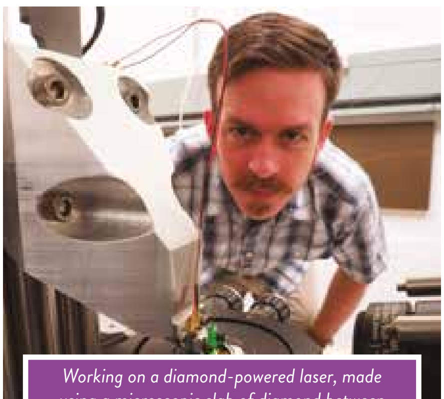
EARLIER ON IN YOUR CAREER YOU WERE SUPERVISED BY DR THOMAS VOLZ. HOW DID YOU COME TO WORK WITH THOMAS AND WHAT DID YOU LEARN?

After my PhD I moved to Germany to do postdoctoral research for a few years. I was successful in applying for an early-career research fellowship in Australia and came back to work with Thomas. I learned loads of things – but the main scientific tasks I worked on were temperature sensing and optical cavities (light bouncing back and forward between two mirrors). We were trying to make a diamond-powered laser to measure tiny magnetic fields.

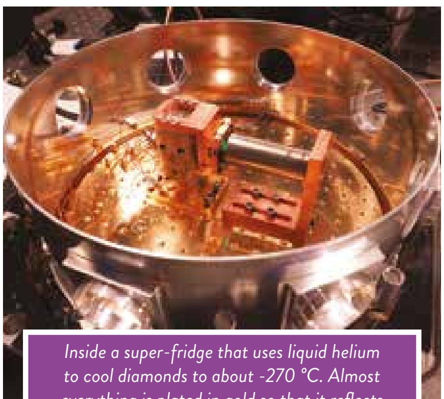
YOU HAVE SINCE COME TO HAVE YOUR OWN RESEARCH GROUP. WHY DID YOU SET THIS UP AND IS IT A TYPICAL CAREER PATH FOR RESEARCHERS?

The research fellowship that I had working in Thomas' lab was a fixed-term, not ongoing. This is very normal for early-career academic research. I applied for numerous positions over a few years and was delighted to be offered an ongoing job at the University of Newcastle. This is geographically close enough to keep close collaborations with Thomas and other colleagues in the Sydney area.

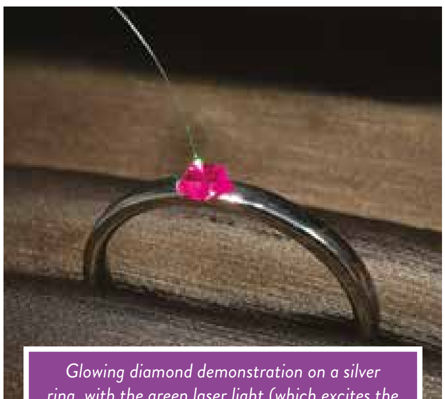
Getting an ongoing position (a 'proper job' as I often joke with friends) is a huge step on the career path for researchers. It means my research is interrupted more by having to teach (luckily, I enjoy teaching), but it also means that I can make longer-term research plans and really work towards big goals and projects



Working on a diamond-powered laser, made using a microscopic slab of diamond between two mirrors.



Inside a super-fridge that uses liquid helium to cool diamonds to about -270 °C. Almost everything is plated in gold so that it reflects (instead of absorbs) radiative heat.



Glowing diamond demonstration on a silver ring, with the green laser light (which excites the colour centres) delivered through an optical fibre.

"BUILDING A HIGH-QUALITY STEM WORKFORCE IS CRITICAL TO THE US DEPARTMENT OF ENERGY'S MISSION SUCCESS, AS WELL AS TO THE NATION"

THE US DEPARTMENT OF ENERGY IS ON A MISSION TO INSPIRE YOUNG PEOPLE INTO STEM CAREERS AND TO SOLVE CHALLENGES RELATING TO ENERGY AND THE ENVIRONMENT. **ANNEMARIE HOROWITZ**, DIRECTOR OF **STEM RISING** TELLS US ABOUT THE EXTENSIVE RESOURCES THE AGENCY HAS TO OFFER

As Director of the STEM Rising initiative in the Department of Energy's (DOE) Office of Public Affairs, I get to spend my time broadcasting all the impressive and important work our agency is doing to get students of all ages interested in STEM learning and energy careers. There are literally hundreds of ways the DOE supports STEM learning and professions, from kindergarten to the workforce. I also run a website, blog and newsletter, as well as develop social media content and other creative ways to help generate conversations about STEM fields.

Following an eighth-grade civics class, I was drawn to studying politics and citizen engagement in the government. I decided I wanted to be in a career where I helped people learn about what the government is doing and how they are impacted by it – by blending a communications and political science background. I was Editor in Chief of my collegiate weekly paper and got to take advantage of an internship on Capitol Hill and with a few senators' district offices during college. After working on a presidential campaign and a nonprofit, I earned a master's degree in government and started working in federal communications with the DOE.

We have a limited amount of time to address the climate crisis head-on, and we need all hands on deck to do it. Some of the biggest ways people can make an impact on our nation's energy and environmental challenges is by pursing STEM careers, and learning about STEM fundamentals in school regardless of what profession they end up choosing. It's exciting to work in a field to support this outreach.

I wish I started studying environmental and climate causes sooner. I love reading, being outdoors and learning, but it didn't occur to me I could combine all my passions into a career or a degree. But it's never too late to jump in and make an impact where we can, and I'm happy I get to work on encouraging people to make a difference through energy careers.

HOW WOULD YOU DESCRIBE STEM RISING?

STEM Rising is an outreach effort to showcase the DOE's extensive programmes, events, competitions and resources for science, technology, engineering and mathematics (STEM) learning. You can find us online (energy.gov/STEM), on social media (#STEMRising), your inbox (subscribe to the newsletter), and at STEM events in the US.

YOU LAUNCHED STEM RISING IN AUGUST 2017 IN THE OFFICE OF PUBLIC AFFAIRS. WHAT WAS YOUR REASON FOR DOING THIS?

I created STEM Rising in an effort to cohesively message the investment in STEM by the DOE and make it easier to learn about the wide variety of STEM offerings across our National Laboratories, National Nuclear Security Administration (NNSA), site offices and programme offices. Previously, to know what the DOE does in the STEM space, from kindergarten all the way up through the energy workforce, you had to visit, one place at a time, the websites or offices of all 17 National Laboratories, field sites, programme offices and the NNSA to explore what is offered. With STEM Rising, this information is brought together in a digital format and printed materials for the public, educators and educational organisations.

AnneMarie Horowitz, Director of STEM Rising, with the Department of Energy's STEM Rising exhibit at G.I.R.L. in October 2019. Photo by Jenn Rivers, DOE

WHAT IS THE DOE ULTIMATELY HOPING TO ACHIEVE THROUGH STEM RISING?

Building a high-quality STEM workforce is critical to the agency's mission success as well as to the nation. The DOE is striving to accomplish this not just in the government sector, but the entire energy sector at large. STEM Rising's goal is to package and share what the DOE is doing to address the climate crisis and solve big problems in this arena. Nearly 40 percent of the federal staff of the DOE are in STEM positions, and the percentage is even higher amongst the contractors in the National Laboratory workforce.

HOW HAS STEM RISING ADAPTED ITS RESOURCES FOR HOME AND VIRTUAL LEARNING?

A large majority of programmes are pivoted to meet people where they are. There are virtual tours of all 17 national labs, the contests shifted to virtual participation, and even some internship experiences at the labs are virtual. STEM Rising revamped the K-12 page to make searching for virtual resources easy, and a new page is in development to showcase all of lab's virtual tours.

WHAT DOES SUCCESS LOOK LIKE FOR STEM RISING?

Every time a student, teacher or young person connects with the DOE, and thinks a little longer or a little harder about learning about our agency's work, it's a huge success. We hope you're considering it right now!

STEM RISING IS YOUR GO-TO RESOURCE FOR ALL-THINGS-STEM AT THE DOE

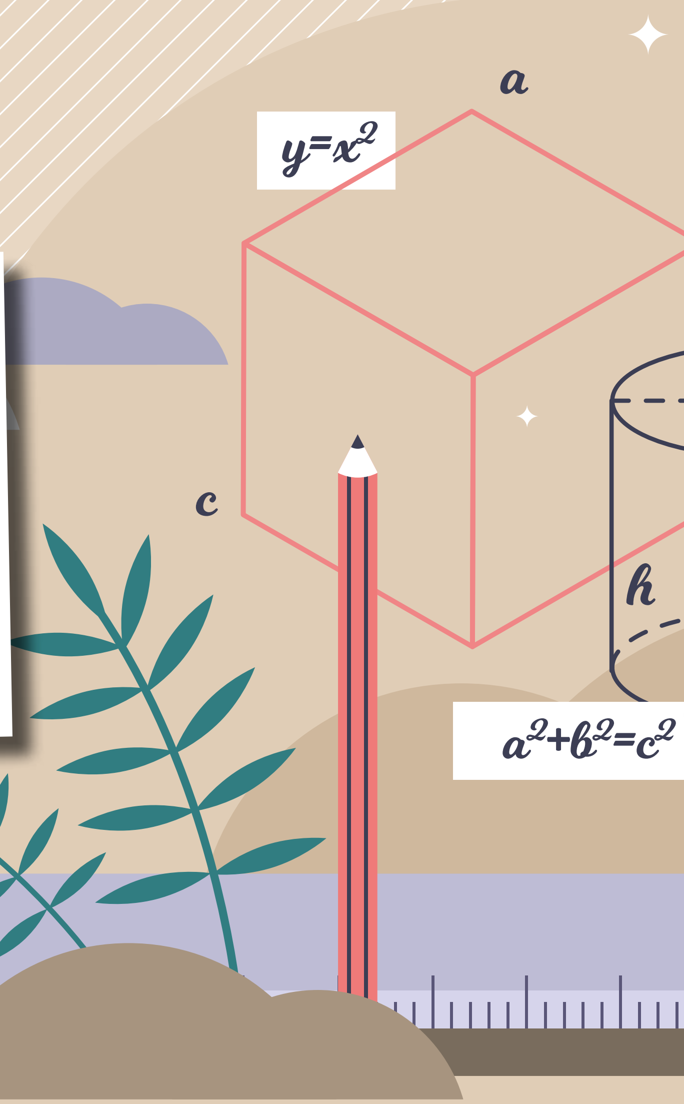
STUDENTS – You will find competitions, learning resources, events, internship opportunities and a whole lot more. Check out resources on the K-12 page or the Undergrad & Continued Learning page, which is a great launch pad. Starting in high school, students can join the DOE team as an intern, fellow or researcher.

"It's an amazing way to gain exposure to energy careers and what we do," says AnneMarie. "It's also a huge boost to any resume. If students don't have the time or ability yet to come work with us, they can get experience by jumping into one of our national competitions, like the National Science Bowl or Solar Decathlon." Look at the STEM Rising pages in the "Contests and Competitions" section to find more information on these programmes and a host of others.

TEACHERS – You will find STEM lesson activities, virtual learning resources and research opportunities. The resource library pages are a great place to start, and both the Idaho National Laboratory and Fermilab have robust offerings. Their pages provide an overview of available materials, from videos to podcasts to downloadable lessons to virtual tours.

www.energy.gov/STEM

SPREADING THE JOY OF MATHEMATICS



DR JAMES TANTON IS THE FOUNDER OF THE **GLOBAL MATH PROJECT**, A WORLDWIDE MOVEMENT OF TEACHERS COMMITTED TO INSPIRING A LOVE OF MATHEMATICS IN STUDENTS AND SPREADING THE JOY OF THIS AMAZING SUBJECT TO ALL CORNERS OF THE GLOBE!

Following tried and tested methods can be the right course of action for some people, but not Dr James Tanton. James is the founder of the Global Math Project, an exciting worldwide movement of teachers and educators taking a new and innovative approach to inspiring a love of mathematics in students.

WHAT WAS JAMES' PERSONAL MOTIVATION FOR THE PROJECT?

James grew up in Australia where he enjoyed school very much. However, when it came to learning maths, he found that the process was extremely rigid and traditional; from an early age, he came to see that his purpose in a maths class was to memorise what he was told, then repeat it.

However, he had (and continues to have) a natural curiosity and a desire to ask questions, rather than parrot answers he has been given. One formative moment occurred when he was 13. "Our teacher began by asking the class to take out our rulers and protractors, draw three examples of right-angled triangles, measure each of their three side lengths, and compute $a^2 + b^2$ and compare it with c^2 to see they have the same value," recalls James. "I had two problems with the exercise. The first was that I did not believe anyone was seeing $a^2 + b^2$ equalling c^2: no human can measure exactly enough to see them be absolutely equal. I let this issue slide. Everyone thought it turned out to be close enough to be believed. But I could not let my second issue slide."

James decided to ask the teacher a question: was it possible to know why the value of c^2 being the same as $a^2 + b^2$ was not just a coincidence? The teacher told James to repeat the task, expecting that seeing another three examples would turn it from coincidence to mathematical fact. James was being asked to tread the same path that had gone before without questioning it. He came to realise that his teacher was not in the position to help his pupils understand why something was the case – it was enough for them to simply know that it was.

This experience stirred something within James that continued to grow over the years: the desire to ensure no one is denied the opportunity to see the awe, wonder and profound joy that mathematics can offer.

HOW DID JAMES BUILD A WORLDWIDE MATHS COMMUNITY?

It began with an idea that relied on the kindness of people and volunteers to make it a reality. "Teachers are the most wonderful advocates of mathematics and they have come through in spades to get this grass-roots effort off the ground," says James. "The fact that we have reached over 6.4 million students from across 170 countries and territories solely by word-of-mouth and basic social media is truly remarkable. Astounding, in fact! And this is mathematics – classroom mathematics!"

The Global Math Ambassadors involved are people with a range of backgrounds and experiences who have discovered the Global Math Project and have pledged to help spread the wonder of mathematics.

WHAT IS GLOBAL MATH WEEK?

James, and his six cofounders, felt it was a good idea to pick some dates that could serve as Global Math Week. Somewhat ironically, given the thinking behind the project, they decided on 10 – 17 October, which is eight days! Whether you write the date in DD/MM format or MM/DD format, the start date will always be 10/10, so everyone around the world can remember it.

The first Global Math Week took place in 2017 – "We simply asked teachers across the planet to conduct just one Exploding Dots lesson sometime during the week and let the world know by making

DR JAMES TANTON

Mathematician-at-Large for the Mathematical Association of America
Founder of the Global Math Project
educator and author.

FIELD OF INTEREST

Mathematics Education and Outreach

RESEARCH PROJECT

James is the founder of the Global Math Project which is an exciting initiative designed to inspire a love for mathematics in students. The flagship programme within the project is Exploding Dots, a visual means of understanding maths that speaks a universal language.

SUPPORTER

The American Institute of Mathematics

a comment about it on social media," explains James. "By the end of that week, we had 1.7 million students and teachers try out Exploding Dots on the web app, and we know that many others conducted lessons in their classrooms without technology."

Of course, the pandemic that continues to wreak havoc around the world impacted on Global Math Week 2020, but the team collaborated with the National Museum of Mathematics to offer a series of lessons to people around the world. In addition, they worked with the Mathematical Association of America to offer an open series of activities entitled 'Puzzles that can be Explained with Exploding Dots'.

WHAT IS EXPLODING DOTS?

Put simply, Exploding Dots is an exciting and successful technique that teachers can use in the classroom to encourage and inspire maths students. It is a story that comes in 12 short-and-swift explorations that act as a purely visual way to cut through the clutter and literally see the meaning and operations of place-value and arithmetic. "It overcomes barriers of language and even choice of base," explains James. "Humans have a predilection for the number 10 when we count and do arithmetic because of how many fingers we have, but there may well be people around the world who want to use a different base to 10. We cater for that!"

The idea behind Exploding Dots is to provide students with an intuitive understanding of place value, which then ensures that more maths, such as polynomial algebra and infinite series, falls into place. Students readily go from the basic maths of how we write and think about numbers, through all the arithmetic one learns in primary school, to high-school algebra and pre-calculus, all the way up to some unsolved problems that still baffle mathematicians to this day.

HAS JAMES FACED ANY CHALLENGES WITH THE PROJECT?

Yes. Unfortunately, there will always be those who are sceptical of something new. Several maths teachers have told James that they have had to conduct Exploding Dots with their students semi-secretly. "There is a lot of pressure on teachers to only teach endorsed curriculum content that is immediately tied to current curriculum standards. Since the story of Exploding Dots starts with mathematics from the early grades and moves its way through the entire K-12 curriculum, we can give the full story of the subject and not be pigeon-holed into just doing content relevant to year 5 or year 10," says James. "Initially, we were at odds with many school administrators' views that classroom maths should always – and only ever – be connected to the maths of that grade level. The idea of putting that mathematics in full context did not seem to be a priority."

However, times are changing. Increasingly, James and the team are invited to give live online sessions to students in schools across the US and curriculum writers are asking for permission to use Exploding Dots in their materials. As with many grassroot efforts, a major challenge is funding. The project relies on volunteer effort, but it is important to try and compensate people for their time and effort. James explains, "We would like to translate all our materials into as many languages as possible, for instance, and develop more curriculum materials."

WHERE DOES JAMES SEE THE PROJECT HEADING?

While Global Math Week is an extremely important part of what James and the team are trying to achieve, the truth is that the maths they offer is year-long. Thus, there is an emphasis on live classroom lessons and the materials that are used to teach them. "We are becoming a classroom presence in North America and I can only see that strengthening and expanding around the globe in the future," says James. "We also offer other topics and hope to see them gain increased awareness and popularity in the future. In fact – we would love to offer versions of all the maths presented in K-12 schools in joyous ways. There is nothing wrong with thinking big!"

HOW TO BECOME A MATHEMATICIAN

- The American Institute of Mathematics, a supporter of James's project, is a brilliant resource for those interested in all things maths: **https://aimath.org**
- The Mathematical Association of America provides maths-related news, programmes and communities to help you get involved: **https://www.maa.org/**
- According to www.salary.com, the salary for a mathematician in the US typically falls into the range of $64,000 to $98,000, although it depends massively on the level of experience, whether you are an academic or professional, and what your specific area of maths is.

JAMES' TOP TIPS FOR TEACHERS

01 Try de-emphasising the focus on getting answers and focus more on the processes involved. Perhaps, try giving tests with all the numerical answers given in the margin but with blank spaces for students to write out their work.

02 Tell the stories of mathematics. Hunt the internet for the history of the mathematics at hand. Why are quadratic equations called 'quadratic' when the prefix quad means four? Who chose the number 360 for the count of degrees in a circle? Why isn't December the tenth month of the year when deca means ten? Look up the quirky names of the common math symbols we use: obelus, vinculum, radix, virgul, and so on. Better yet – have students look things up and tell you!

03 Talk about the nature of problem-solving with your students. Reacting in human ways is perfectly normal, so when your class is stuck on a tough problem, make their homework something like, "Go for a 20-minute walk and do not think about this maths problem." Someone always comes back the next day with new insight!

PATHWAY FROM SCHOOL TO MATHEMATICS

It goes without saying that you will need to study maths at GCSE and A level (or equivalent). However, physics is also useful, while there are those students who choose to take other subjects as well, including IT and computing, chemistry and business studies.

You will need a degree in a relevant subject for postgraduate study.

www.theuniguide.co.uk/advice/a-level-choices/what-a-levels-do-you-need-to-study-maths

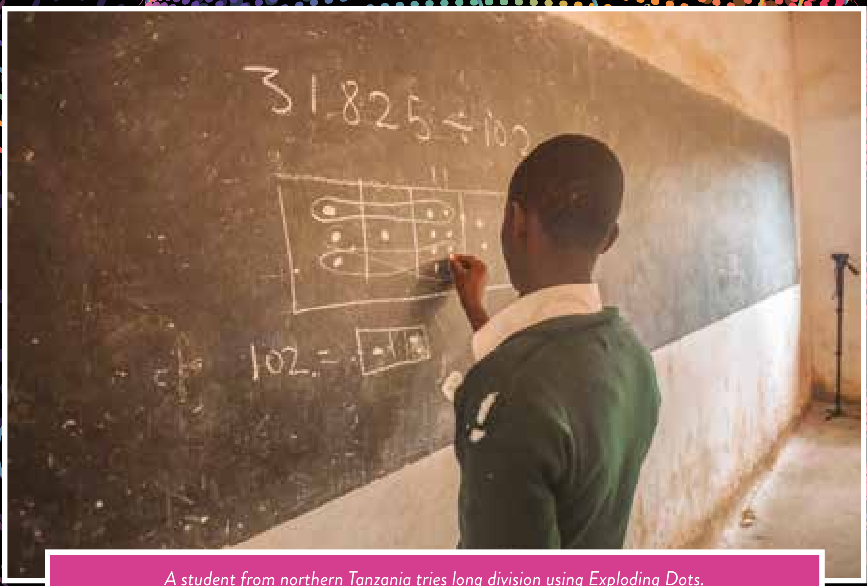
JAMES' TOP TIPS FOR STUDENTS

01 If you are struggling to find the joy in maths, then do your best to work through the clutter in your mind and try to understand the process. Many students will merely memorise stuff they have learned, but the joy comes from developing genuine understanding.

02 The internet is a truly wonderful source for finding out about the stories behind mathematics. It is easy to find yourself down some fun rabbit holes and encounter some amazing maths along the way!

03 Reflect on the parts of maths that are hazy in your mind and consider what it is that is proving difficult. It sometimes helps to take a step back and ask questions. Can you truly explain why negative multiplied by negative is positive? Why did mathematicians switch from degrees to radians for advanced maths? Maths is as much about asking questions than it is providing answers.

Students play with the Exploding Dots web app.



A student from northern Tanzania tries long division using Exploding Dots.

HOW DID JAMES BECOME A MATHEMATICIAN?

"**I was a bit of a lonely child.** I remember spending long periods of time staring at my bedroom ceiling and thinking about maths puzzles. I have actually produced an essay detailing my favourite maths puzzle which came about because my childhood bedroom had a particularly geometric pattern. I began inventing puzzles and games based on that grid.

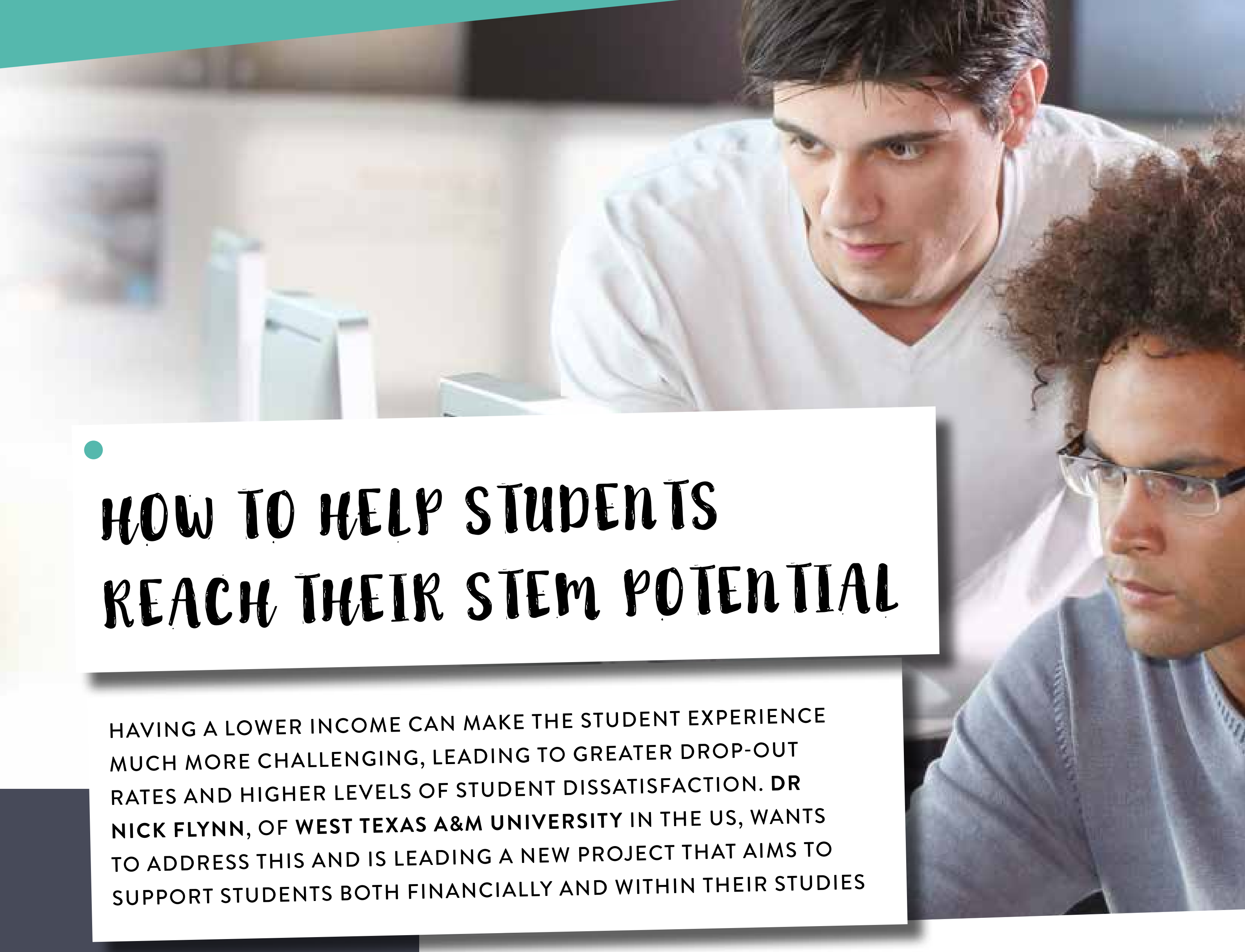
I also liked to imagine what it would take to talk with aliens (again, I have produced an essay that explains this in more detail). As you can see, my main interest as a child was maths – it has been in my mind for as long as I can remember and I am as passionate about it now as I was then, if not more.

I think my curiosity has been a great asset, as has my confidence to always think of the why, what else and what if questions. Behind that is a willingness to tinker and play with ideas, which is key to being a mathematician. My schoolwork was always about getting numerical answers to questions and then stopping. In my opinion, the answers are the boring part! How to get an answer is far more interesting, and then changing the path one took to get to an answer to see what new insights doing so could offer is the extra fun.

I am willing to 'walk into the haze'. We all know when studying a subject that there are hazy parts where you secretly know you don't quite get what is going on, or you sense something hasn't quite clicked, but you can still do the work and push on. These parts can be a bit scary and most people tend to push them out of their mind. My schooling encouraged this, but I have since learned not to be afraid of the haze and instead recognise it as the place to go to find deep understanding and meaning. The haze is a signal that something is amiss, so explore this. Find all those fabulous lightbulbs in your mind and switch them on!

My proudest career achievement was at 11am on day two of our first Global Math Week when I was sitting at my laptop and saw the counter on our Exploding Dots site turn to one million! This made me cry. I had no idea that our hare-brained attempt to bring a piece of joyous school-connected mathematics to the world would be noticed and accepted.

My ambition is to change the entire world's perception of what mathematics can and should be. I am not hoping for everyone to love mathematics, but I do want everyone to see that there is something to love about it, to understand why others love it, and to know that mathematics is within their reach if they wanted to pursue it. I want it to be their choice!"



HOW TO HELP STUDENTS REACH THEIR STEM POTENTIAL

HAVING A LOWER INCOME CAN MAKE THE STUDENT EXPERIENCE MUCH MORE CHALLENGING, LEADING TO GREATER DROP-OUT RATES AND HIGHER LEVELS OF STUDENT DISSATISFACTION. **DR NICK FLYNN**, OF **WEST TEXAS A&M UNIVERSITY** IN THE US, WANTS TO ADDRESS THIS AND IS LEADING A NEW PROJECT THAT AIMS TO SUPPORT STUDENTS BOTH FINANCIALLY AND WITHIN THEIR STUDIES

GLOSSARY

FACULTY – a group of related university departments and the members of staff within them

GATEWAY COURSE – an introductory course to a particular subject area that means the student can go on to study other courses within the subject area

HIGH-IMPACT PRACTICES – core activities that lead to greater student success in college, such as internships, research projects and learning communities

MENTORING – advising or training someone, usually one-on-one

PEER – a person at a similar stage in life to another, such as a friend or classmate

"While I was serving as department head, I realised that some students were working 30 hours or more every week just to survive and pay all of their educational expenses," says Dr Nick Flynn. "I also realised that our students needed additional help in developing leadership and career soft skills." Nick, a professor of biochemistry at West Texas A&M University in the US, witnessed first-hand the challenges that students faced. This motivated him to take the lead on a new programme aimed to help low-income students reach success in STEM careers, through financial support, developing their leadership skills, and updating the science courses that the college provides.

THE PROJECT

Nick's project is not just about helping students financially, though it does do this through providing scholarships for high-achieving students between 2019 and 2023. It also includes mentoring, career skill development and leadership training, all of which are known to aid students' chances of success both within their course and later in their career. The project also involves a redesign of six first-year science courses, to make them more accessible and relevant. These redesigns were carried out by three co-principal investigators on the project: Dr Greg McGovern redesigned the two chemistry labs, Dr Christopher Baird redesigned the two physics labs and Dr Donna Byers revised the two biology lectures. These redesigns were based on discipline-specific initiatives and guidance from national discipline organisations.

Nick secured funding for this project through the National Science Foundation's Scholarships in STEM (S-STEM) programme, which awarded his college a grant of almost $1 million (Award #1833499). The project aims to increase retention and graduation rates of low-income, academically-talented students, increase student success in gateway courses, and increase student engagement and participation in high-impact practices.

MENTORING

"We provide peer mentoring, faculty mentoring and college success mentoring for this programme," says Nick. "Mentoring activities include goal setting, the peer review process and personalised career guidance." Mentors can come from various sources and all have their own role to play in improving students' experience and chances of success.

DR NICK FLYNN

Professor of Biochemistry
Department of Chemistry and Physics
West Texas A&M University, Texas, USA

FIELD OF RESEARCH

Chemistry, Biochemistry
and STEM Education

RESEARCH PROJECT

Supporting low-income students for
success in STEM careers.

FUNDERS

National Science Foundation (S-STEM)
Welch Foundation
West Texas A&M University

The work was supported by the National Science Foundation (Award # 1833499) and the Welch Foundation (Grant # AE-025).

Peer mentors are other students who help new recruits with their transition to college life and the introduction to STEM courses. This includes helping new students form study strategies, investigate student organisations and begin thinking about graduate school and future employment. Faculty mentors are members of staff that supplement students' mentoring efforts through discussing career paths and providing advice on academic goals. Nick mentors biochemistry majors, while Chris mentors physics majors and Donna mentors biology majors. Both peer and faculty mentors benefit from the experience too. "Peer mentors can learn from each other and be a part of somebody else's professional development," says Nick. "Faculty mentors gain the satisfaction of knowing that they are helping students become successful."

LEADERSHIP SKILLS

As well as knowing about science and how to undertake scientific research, leadership also forms an essential part of a successful scientific career, but development of this quality is often neglected in STEM courses. "To remedy this, we are providing about eight hours of leadership workshops to help students lead any organisation or professional team they are involved with currently and/or to prepare them for leadership roles in the future," says Nick. "Young scientists need to learn how to work in groups, manage conflict and meet deadlines."

Science does not just take a breadth of knowledge but also requires discipline. "Key lessons we want our students to learn are how to stay organised, build and maintain professional relationships, and focus on their short-term and long-term goals," says Nick. This more holistic approach to science, rather than focusing solely on the academic content side, is key to creating well-rounded scientists – which is why the workshops make sure these aspects are covered.

COURSE REDESIGNS

"We have redesigned four lab courses and two lecture courses for this project," says Nick. "We wanted to make sure courses are more engaging and inclusive." Thankfully, Nick's team did not have to start from scratch, because a number of national reviews had already identified an array of key factors for improving the learning experience of courses in chemistry, biology and physics. The team drew on these authoritative publications during the redesign, to ensure that the new principles they introduced were supported by a strong pool of evidence. In addition, the redesign is a result of interdisciplinary collaboration – such planning is unique and a particular strength of Nick's innovative programme.

So, what changes have the courses undergone? "The primary changes were updating experiments, generating lab modules with more practical applications, and ensuring that lab and lecture components of each course were closely aligned," says Nick. "While many of our results are still being analysed, we do feel that students are gaining a better appreciation for each discipline. We have an amazing group of people who worked together very well and remain focused on helping students succeed in these six courses."

SUCCESSES

"We have had quite a bit of success with the programme," says Nick. "Students are enjoying the redesigns and several of our S-STEM participants have been elected to officer positions within student organisations." Now, Nick is looking forward to improving the programme even further. "Next, we need to get the word out about our leadership and career skills workshops," he says. "We are considering expanding these efforts to include arts and humanities in a follow-up proposal."

ABOUT BIOCHEMISTRY

Nick is now a professor of biochemistry, though his work has taken him across many disciplines. He explains more about his career:

WHAT COLLABORATIONS HAS YOUR CAREER INVOLVED?

I've collaborated with a variety of sectors, such as the brewing industry, agricultural management, government laboratories, food producers, the chemical industry and industrial safety managers. Biochemistry offers a wealth of career opportunities due to the interdisciplinary nature of the field.

WHAT INTERDISCIPLINARY WORK HAS YOUR WORK INVOLVED?

Lots! I led the Department of Mathematics, Chemistry & Physics, which is about as interdisciplinary as you can get! As other examples, the chemistry and physics departments share some facilities; we have run outreach Science Days incorporating biology, physics, chemistry and biochemistry; and visits to a local honey farm show how closely chemistry and agriculture are linked. These are just a few examples – in this modern age, an interdisciplinary approach is always a good thing, since it allows you to draw from the strengths of each discipline.

WHAT DO YOU FIND REWARDING AND CHALLENGING ABOUT CHEMISTRY?

Chemistry allows you to come up with explanations for things that we do not currently understand. On the other hand, teaching chemistry can sometimes be a challenge, since some students do not understand why it is required for their degree! My greatest reward as a teacher is some of my student evaluation comments where they recognise my passion for chemistry and my willingness to go to great lengths to get them to appreciate how much chemistry can affect and improve the quality of their life. My greatest challenge has been helping a student realise that the tools they learn in chemistry can be applied in their everyday life. For example, I use doubling or tripling a cookie recipe to help students see how dimensional analysis can be used to identify how much of each particular ingredient they need.

WHAT IS THE ROLE OF STORYTELLING IN SCIENTIFIC EDUCATION?

Storytelling is an excellent way to engage students in all types of subject matter. Some of the material we teach in science can be quite dry, so adding a personal touch can make it much more enjoyable. I've worked with the history department to give a talk on science through the ages with two physics colleagues – to tell the narratives behind the scientific achievements. That's another great example of different disciplines being intrinsically linked. Storytelling can also help students gain appreciation for concepts we teach such as the fact that even weak acids, such as hydrofluoric acid, need to be treated with respect. In fact, I use an old episode of the TV series ER regarding this very acid to explain the concepts of electronegativity and acid strength to my students. I have had senior level students tell me that they still remember that particular discussion in class.

HOW DOES YOUR PASSION FOR BIOCHEMISTRY EXTEND INTO YOUR FREE TIME?

I love homebrewing, particularly the community it forms. We have the opportunity to learn so much from each other and to share our knowledge and passion. From a chemistry perspective, I am fascinated by the ageing process of beer – sometimes it is a good thing, and sometimes it is not! Recently, I gave a webinar to the American Chemical Society entitled: 'Chemists Make the Best Homebrewers', where we discussed methods of homebrewing and how chemical educators can use brewing concepts in their courses.

WHAT WILL BE THE KEY ISSUES FOR THE NEXT GENERATION OF BIOCHEMISTS?

Water purity and industrial safety are set to become major challenges. Food production, as well as environmental protection and clean-up, will also be ever-more important issues into the future. The wonderful thing about being a scientist is having the opportunity to make things better for the entire world.

DOES THE WEST TEXAS A&M UNIVERSITY OFFER ANY PUBLIC OUTREACH SCHEMES FOR YOUNG PEOPLE?

We collaborate with the Don Harrington Discovery Center, a local science museum, to provide activities for the ACS National Chemistry Week and Chemists Celebrate Earth Week. We also invite speakers from many walks of life, such as industry, weather and environmental sciences.

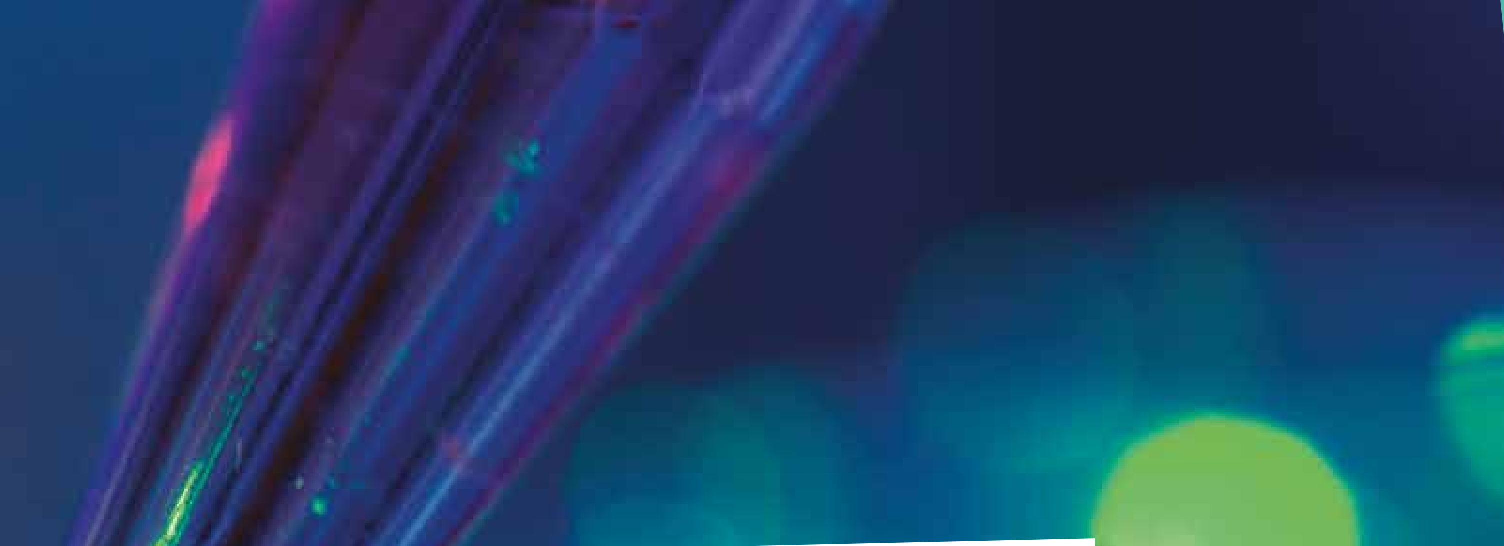
EXPLORE A CAREER IN BIOCHEMISTRY

- The American Chemical Society (ACS) offers educational resources and careers advice: **www.acs.org**
- According to PayScale, the average salary for a biochemist in the US is around $62k. Like most STEM careers, industry will tend to pay higher than academia.

PATHWAY FROM SCHOOL TO BIOCHEMIST

Many courses require qualifications in two or more sciences, especially chemistry and mathematics. Nick says a strong mathematical foundation is essential and also advocates taking English or public speaking to learn how to express your ideas clearly.

- Biochemistry can be an undergraduate qualification in itself but, more often, degrees in chemistry or biology will allow specialisation in biochemistry after two or three years. Other degrees, such as natural sciences or medicine, can also lead to a career in biochemistry.



HOW DID NICK BECOME A BIOCHEMIST?

WHAT WERE YOUR INTERESTS AS A CHILD?

I loved playing sports, particularly soccer and rugby. Additionally, I always had a fascination with how 'things' in the world worked. My parents got me started in science by telling me to look things up if I had a question about something. My first encyclopaedia set kept me occupied for hours on end.

WHO INSPIRED YOU TO BECOME A SCIENTIST?

My high school science teachers. They accepted me for who I was and were always willing to answer my questions in class, or work with me outside of class to understand something better.

WHAT ATTRIBUTES HAVE MADE YOU SUCCESSFUL AS A SCIENTIST?

Curiosity and a willingness to work hard, even when things do not go the way I want them to. I like to tell my students that there is a reason that they call it REsearch - you have to do things over and over again, sometimes, and that's okay. I also have a strong passion for getting other people interested and involved in science.

HOW DO YOU SWITCH OFF FROM WORK?

I enjoy working out and learning about how our bodies process food. Physical activity has always been an important stress reliever for me.

WHAT ARE YOUR PROUDEST CAREER ACHIEVEMENTS SO FAR?

Getting the National Science Foundation S-STEM grant was a personal highlight for me. I have had many grants funded, but this one was definitely the largest one. Additionally, I was very proud when one of my undergraduate research students was selected to lead a government lab, and another student became a professor of chemistry.

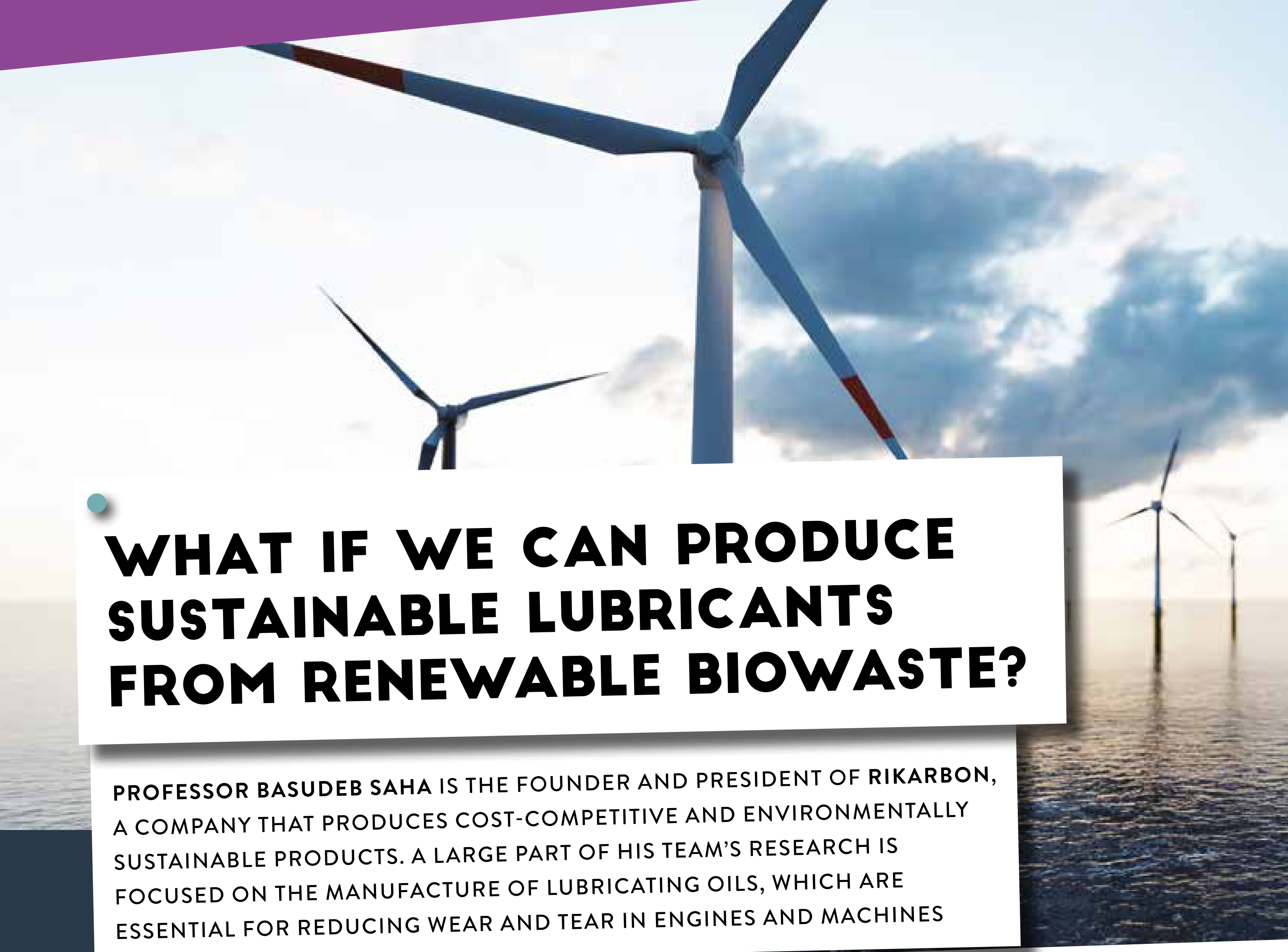
NICKS' TOP TIPS

01 Always be open to new opportunities and experiences.

02 If you find yourself dissatisfied, think about what is actually important to you and what would get you excited about work or study. This will help you identify where you should focus to reach your goals.

03 Learn how to express yourself, both when writing and when speaking. Many times, I have seen a great, well-designed study compromised by a poor presentation.

Dr Nick Flynn conducting sensory analysis on hop samples.



WHAT IF WE CAN PRODUCE SUSTAINABLE LUBRICANTS FROM RENEWABLE BIOWASTE?

PROFESSOR BASUDEB SAHA IS THE FOUNDER AND PRESIDENT OF **RIKARBON**, A COMPANY THAT PRODUCES COST-COMPETITIVE AND ENVIRONMENTALLY SUSTAINABLE PRODUCTS. A LARGE PART OF HIS TEAM'S RESEARCH IS FOCUSED ON THE MANUFACTURE OF LUBRICATING OILS, WHICH ARE ESSENTIAL FOR REDUCING WEAR AND TEAR IN ENGINES AND MACHINES

TALK LIKE A GREEN CHEMIST

LUBRICANT – any substance that reduces the amount of friction between two surfaces in contact with each other

BIOMASS – materials derived from trees, plants or animals that can be used as fuels or as raw materials for other products

BIOPRODUCTS – materials or chemicals that have been manufactured from renewable biomass

ENVIRONMENTAL SUSTAINABILITY – when actions cause little to no damage to the natural environment

ORGANIC MOLECULE – any chemical compound containing bonds between carbon and hydrogen atoms

BIOPOLYMERS – naturally occurring materials made up of long chains of organic molecules

FUNCTIONAL GROUP – groups of atoms attached to larger molecules, which alter their chemical properties

PETROLEUM – a dark liquid found deep beneath the Earth's surface, which can be refined into many different types of carbon-emitting fuel

Without lubricating oils, many of the technologies we rely on in our everyday lives would literally grind to a halt. By allowing machine parts to smoothly glide over each other without generating too much friction, lubricants are crucial for running components like engines, turbines and compressors. When applied, they allow technologies as wide-ranging as airplanes, refrigerators and hydroelectric dams to operate reliably over decades-long lifespans. Yet, as companies worldwide begin to make serious efforts to reduce their carbon footprints, a lack of innovation in lubricant manufacturing techniques means that the whole industry risks falling behind in this crucial goal.

In 2018, Professor Basudeb Saha founded RiKarbon, a company based in Delaware, USA, which aims to provide ground-breaking solutions for industries that manufacture lubricating oils with high-carbon numbers. An important part of Basu's work is based around the use of agricultural waste materials, including corn cobs, grasses and wood, to provide purely renewable and sustainable carbon for industrial lubricants. By developing new ways to process the natural ingredients present in these renewable materials, RiKarbon has already made significant strides towards providing greener futures for many different industries.

WHY IS LUBRICANT MANUFACTURING SO UNSUSTAINABLE?

The friction-reducing properties of lubricating oils are made possible by organic molecules that have a structure based on long chains of carbon atoms. These molecules can be found in a wide variety of sources including methane and butane. Currently, the most popular lubricant is petroleum or crude oil, which is petroleum without the gas component. Petroleum is made up of decomposed organisms that have been buried deep underground for many millions of years. It is a complex mixture of hydrocarbons, carbon atoms that are joined together in chains

and rings, and therefore a rich source of organic molecules. Petroleum is cheap and easy to refine to produce different products like gasoline, diesel and lubricants, which is why it is a popular choice for manufacturers of lubricating oils.

Unfortunately, when these lubricating oils reach the end of their operating lifetimes, the carbon they contain is released into the environment, causing pollution and contributing to climate change. To be more sustainable, lubricant manufacturing companies need to move away from their current practices. Renewable agricultural waste is one promising alternative.

Like petroleum, organic molecules can also be found in agricultural waste, often in the form of biopolymers named cellulose and lignin. Cellulose and lignin are found in plant cell walls and contain long chains of molecules, which can be broken down into a variety of organic molecule building blocks. Until recently, the chemical processes required to transform these polymers into useful products were too expensive. Not only that but once these biopolymers are broken down, their building blocks usually contain only short, simple chains of carbon atoms, making them an unsuitable alternative for petroleum-based lubricants with long carbon chains.

WHAT DOES RIKARBON DO DIFFERENTLY?

Basu and his team at RiKarbon have developed innovative chemical processes that can convert biopolymers into far larger and more complex molecules. So far, the scientists have been able to synthesise molecules with a wide variety of carbon chain lengths, and even chains which branch in certain places. They can also attach particular functional groups to the molecules, altering their chemical properties.

In turn, the friction-reducing properties of RiKarbon's oils can be precisely tailored to suit the specific needs of lubricant manufacturers, who require different types of lubricant in their formulating processes. Crucially, the structures of these molecules are similar to those found in lubricants made from petroleum, meaning the manufacturers who use them do not need to alter their usual practices. Reaching this point has been a key step in bringing RiKarbon's lubricating oils into the real world.

CAN RIKARBON'S PRODUCTS COMPETE WITH PETROLEUM?

In the past, lubricant manufacturers could only bring about the properties they wanted in their products by mixing in large amounts of petroleum-based additives. This was a costly and time-consuming process. Through Basu's approach, the need for additives can potentially be done away with entirely, since the properties of their sustainably-produced oils can be finely tuned during the manufacturing process itself.

This comes with a whole host of advantages over petroleum-based products. In car engines and hydroelectric turbines, for example, temperatures can become extremely high, which risks breaking down the chemical structures of lubricants if the molecules are unstable. RiKarbon is producing highly stable molecules that offer long, operational lifetimes for lubricating oils, even when they are regularly exposed to extreme temperatures.

Similarly, the branching structures of RiKarbon's lubricating oils mean that they do not freeze easily and remain in their liquid form even in extreme cold conditions. This is critical for aeroplanes flying through the cold stratosphere, and machines that operate in harsh winter conditions.

PROF BASUDEB SAHA

Founder, RiKarbon, Newark, Delaware USA

FIELD OF RESEARCH

Green Chemistry, Sustainable Products, Catalysis

RESEARCH PROJECT

Basu is leading his company in developing new ways to manufacture lubricating oils from biomass waste. The resultant innovations are helping large manufacturing companies meet their sustainability targets.

FUNDER

US Department of Energy
(Grant number: DE-SC0018789)

WHAT DOES THE FUTURE HOLD FOR RIKARBON?

By inventing new ways to produce sustainable lubricants with desirable, highly tuneable properties, i.e. they can be adapted to manufacturers' specific needs, Basu and his team are offering products with significant advantages over petroleum-based alternatives, even in a highly competitive market. Excitingly, the researchers are collaborating with several large companies to expand the reach of their products on the global marketplace. As part of these collaborations, they are aiming to help manufacturers reach new sustainability goals and, ultimately, achieve net-zero carbon emissions in the coming decades.

Through these efforts, Basu and his team hope to expand the scope of their manufacturing processes even further, extending into cosmetic moisturisers and advancing ways to recycle plastic. Ultimately, their innovations could pave the way for a more sustainable future, where industrial manufacturing does not come at the cost of damaging our planet's atmosphere and ecosystems.

ABOUT GREEN CHEMISTRY

Green chemistry is a branch of chemistry that aims to develop products that are safer for human health and less damaging to the environment. The reactions and processes studied by green chemists are not any different from those used in other fields of chemistry, except that these researchers always aim towards sustainability as an end goal.

WHY IS GREEN CHEMISTRY SO IMPORTANT?

No one knows how many chemicals are in use today, but the Environmental Protection Agency in the US has more than 85,000 chemicals listed on its inventory of substances that fall under the Toxic Substances Control Act. Green chemistry is fast becoming crucial to the global fight against environmental degradation. Across the world, many large companies and academic institutions are adapting their policies to reduce their environmental impact, as well as reach net zero carbon emissions. Because of this, Basu says that there are more opportunities than ever for aspiring green chemists, and the number of jobs in this area is growing by the day.

WHERE COULD GREEN CHEMISTRY RESEARCH LEAD IN THE FUTURE?

Besides lubricants, there are still many products that rely on carbon-intensive manufacturing processes, including steel and concrete. Discoveries made by researchers like Basu, as well as a new generation of green chemists, will provide ingenious solutions to these problems. As they combine innovations with stronger relationships with manufacturers and the busines sector, green chemists could become key players in the world's efforts to solve environmental challenges, including climate change.

PATHWAY FROM SCHOOL TO GREEN CHEMIST

Basu recommends following a regular curriculum in science at school: "When it comes to choosing a university, pay attention to professors who are interested in green chemistry methodologies."

HOW TO BECOME A GREEN CHEMIST

- RiKarbon welcomes high school students to their labs on request. If you are not based in Delaware, reach out to similar green chemistry companies in your area. Showing an interest in green chemistry in this way will enable you to gain an insight into the work involved and extend your network of people working in this field. You may even end up with an apprenticeship or mentor!
- The American Chemical Society has a lot of information on how to start a career in chemistry and branch out to become a green chemist: **https://www.acs.org/content/acs/en/education/students.html**
- Many universities worldwide are now offering degrees in green chemistry, including the universities of Massachusetts-Boston, Michigan and Oregon in the US; and York, Leicester and Imperial College London in the UK.
- The average salary for a green chemist with an undergraduate degree in the US is between $53,324 and $67,840.

The RiKarbon team in the R&D lab. From left: Sudip Majumdar, Bryan Feyock, Chinmay Pawar, Basudeb Saha

BASU'S TOP TIPS

01 If you care about the environment and are passionate about environmental sustainability, you will enjoy a career in green chemistry.

02 All of us have certain in-born qualities. Nurture these qualities and use these strengths, not weaknesses, to promote your passion.

03 If you are planning to start your own environmentally-friendly venture, start by identifying one or more products that you suspect or know are problematic for the environment. Interview your friends, family and peers to find out whether they have the same environmental concerns. Expand your research: How many people share these same concerns? And do they belong to a particular socio-economic or age group? This will give you an idea how big or small the problem is. Now, look for solutions and find out whether people would be willing to pay for these solutions. Identifying a problem, finding out how big the problem is and working out who would buy your solution/product are key steps for launching a business. Most people fail in business because they have not considered all of these factors. It needs time and patience, but passion will drive you and keep you on track.

HOW DID BASU BECOME A GREEN CHEMIST?

TELL US ABOUT YOUR BACKGROUND.

I was brought up in a business family in India. I completed my PhD in chemistry from a reputed institute in India – the Indian Association of Cultivation of Science. This was where Professor C.V. Raman discovered the Raman spectrometer, for which he received a Nobel prize. Afterwards, I worked with chemical engineers and chemists at Iowa State University and Dow Chemicals in the US, and taught chemistry courses to BSc, MSc and PhD students at the Universities of Delhi and Delaware. These positions gave me opportunities to learn green chemistry methodologies, practise chemistry with a green-mindset and produce products where safety and society come first.

OUTSIDE OF RIKARBON, WHAT ARE YOUR RESEARCH INTERESTS?

Since 2009, after moving back to academic research, my work has primarily focused on developing new technologies, including taking waste products, such as non-food biomass and carbon monoxide, and converting them into a variety of renewable products and fuels. These products help meet growing consumer demands, promote the environment and reduce carbon footprints. I have invented 21 granted and submitted patents, overall, and authored over 115 peer-reviewed journal articles. I also edited the book *Sustainable Catalytic Processes*, which was published by Elsevier.

Alongside this work, I founded and co-founded two start-ups to commercialise sustainable products for cosmetics, lubricants, food flavourings and bio-plastics.

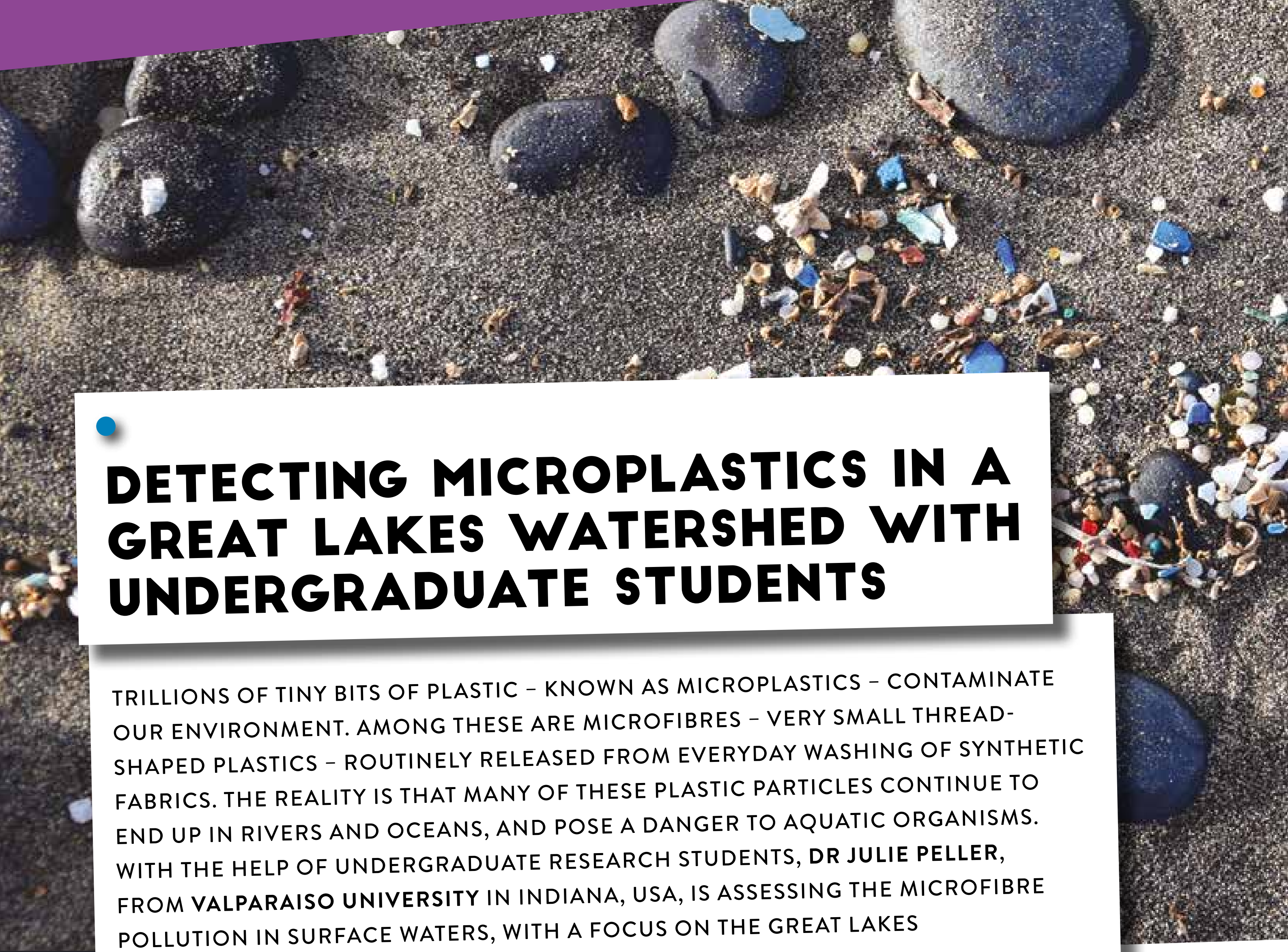
WHAT LED TO THE EARLY SUCCESS OF RIKARBON?

In 2014, I co-founded my first venture to commercialise fragrance and food flavouring ingredients. This provided me with my first experience in entrepreneurship and helped to flush out the key business components and challenges for RiKarbon's current technology. I founded RiKarbon in 2018 to transform my other lab-scale research invention into commercial products. From the start, the RiKarbon team was fortunate in three particular areas. Firstly, we were able to collaborate with the Horn Entrepreneurship Centre at the University of Delaware and Delaware Small Business Development Centre. Secondly, we secured funds from Blue Hen, after developing a prototype of our methods. Finally, we received support from the National Science Foundation for the I-Corps cohort programme.

The I-corps programme allowed us to carry out over 160 in-person interviews and to attend trade shows and workshops to gain knowledge about current products, gaps and market needs. This market research enabled us to lay out a realistic plan for the business and to create new relationships with customers, partners, advisors and contract research companies. Finally, I secured funding resources from the US Government SBIR/STTR programme, making RiKarbon a reality. This allowed us to hire employees, develop the company infrastructure and the technology required for the process, and send products to potential customers for testing.

WHAT ARE THE NEXT STEPS FOR YOUR BUSINESS?

I see tremendous enthusiasm for our products among our potential customers, partners and investors as they seek to achieve their sustainability goals. In turn, this gives me enormous enthusiasm to continue transforming RiKarbon into a large company. The next steps include identifying partners to manufacture products on commercial scales, selling our products to lubricant and cosmetics manufacturing companies, hiring more employees and developing an even more diverse range of products!



DETECTING MICROPLASTICS IN A GREAT LAKES WATERSHED WITH UNDERGRADUATE STUDENTS

TRILLIONS OF TINY BITS OF PLASTIC – KNOWN AS MICROPLASTICS – CONTAMINATE OUR ENVIRONMENT. AMONG THESE ARE MICROFIBRES – VERY SMALL THREAD-SHAPED PLASTICS – ROUTINELY RELEASED FROM EVERYDAY WASHING OF SYNTHETIC FABRICS. THE REALITY IS THAT MANY OF THESE PLASTIC PARTICLES CONTINUE TO END UP IN RIVERS AND OCEANS, AND POSE A DANGER TO AQUATIC ORGANISMS. WITH THE HELP OF UNDERGRADUATE RESEARCH STUDENTS, DR JULIE PELLER, FROM VALPARAISO UNIVERSITY IN INDIANA, USA, IS ASSESSING THE MICROFIBRE POLLUTION IN SURFACE WATERS, WITH A FOCUS ON THE GREAT LAKES

TALK LIKE A CHEMIST

MICROPLASTICS – very small pieces of plastic that pollute the environment. These include all types of plastic that are smaller than 5 mm

MICROFIBRES – fibres made of either natural or synthetic materials that are less than 5 mm in length. Synthetic microfibres are a category of microplastics

BIODEGRADABLE – refers to the breakdown of matter, typically done by microorganisms, such as bacteria and fungi, present in the soil or water

WASTEWATER TREATMENT PLANT – a facility that uses various processes, including physical, chemical and biological, to treat wastewater and remove pollutants

CHEMICAL OXIDATION – a type of chemical reaction involving oxygen or an oxygen-containing substance that increases the amount of oxygen or oxidation state of another substance

FENTON'S REAGENT – a solution used to break down many organic compounds via chemical oxidation

HYDROGEN PEROXIDE – a chemical compound with the formula H_2O_2

ORGANIC MATTER – refers to carbon-based living or dead animal and plant material. This includes living plants and animals, remains at various stages of decomposition, as well as microorganisms and their excretions

POLLUTANT – any substance, including certain chemicals and waste products, that is detrimental to the environment. It can be anything that causes pollution, from toxic gases in the air to microplastics in the water

We are surrounded by plastic: plastic bags, water bottles, takeaway containers, chocolate wrappers, the list is endless. Unfortunately, many people ignore the massive waste problems associated with plastic, especially single-use plastic, and much of our plastic waste breaks down into microplastics. Now, microplastic pollutants seem to be present everywhere, even in remote areas of our planet like the Arctic and Antarctic.

Knowing they pose a serious threat to many aquatic species, Dr Julie Peller, from Valparaiso University in Indiana in the US, has been assessing the levels of microplastics, in particular microfibres, in a Lake Michigan watershed and other Great Lakes ecosystems. Undergraduate research students also contribute to this project, not only to increase awareness about the importance of scientific research but also to contribute to the pool of knowledge as the magnitude of the problem grows daily. As Julie warns, "The negative effects will be exasperated if we do not address the problem."

WHY IS PLASTIC SUCH A BIG ISSUE?

Plastic is not biodegradable. Unfortunately, instead of being recycled, most of it ends up in a landfill or in the environment, where

DR JULIE PELLER

Professor of Chemistry, Department of Chemistry, Valparaiso University, Indiana USA

FIELD OF RESEARCH

Environmental Chemistry

RESEARCH PROJECT

Tracking the distribution of microfibre pollution in a southern Lake Michigan watershed through the analysis of water, sediment and air.

FUNDER

US National Science Foundation

This work was supported by the US National Science Foundation (EAGER: PAPER 1744004). Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

sunlight and other weathering processes break it down into tiny particles called microplastics. Scientists know that these particles can be extremely dangerous, with studies showing how they stunt growth, disrupt reproduction and alter feeding habits of fish and other aquatic species.

Microplastics are also shed from clothes made from synthetic fabrics, such as polyester, when they are washed. Standard washing machines were never manufactured to remove all these microfibres and they end up in our wastewater. Most of these microfibres can be removed in wastewater treatment plants, but a small percentage remains in the water and flows to natural surface waters, including the oceans.

Previous studies looking at the microplastic content in Lake Michigan (part of the Great Lakes in the USA) motivated Julie to test for the presence of microplastics and microfibres in surface waters flowing into Lake Michigan. "The water in local streams and creeks flows into Lake Michigan, and we were interested in determining the extent of microplastics contamination in both the water and sediment," says Julie.

AN EXPERIMENT AIMED AT UNDERGRADUATE STUDENTS

The twist in the research was that it was adjusted to be part of first-year undergraduate students' chemistry curriculum. Julie and her colleagues wanted to engage these students in active scientific research by exploring the current worldwide problem of microplastics contamination. Over the course of a three-week experiment, students collect soil samples from two locations, one near a local wastewater treatment plant. Using different lab techniques, they remove particles larger than 5 microns. The next step involves chemical oxidation to reduce the natural organic matter, leaving the plastics and some inorganics behind. This is done by exposing the samples to the Fenton reagent, a solution of hydrogen peroxide (H_2O_2) and iron (II) chloride. The mixture is heated until it stops foaming, which is an indication that most of the reactive organic matter is chemically broken down. After this mixture is filtered, students count microfibres present in each sample using a microscope.

From the research project, the amount of microfibres found in the samples collected closer to the wastewater treatment plant, and the samples collected further away (and presumably not affected by household sewage) were similar. For Julie, this indicates that the water from the wastewater treatment plant is not the only source for the high amount of microfibres in this area of the Lake Michigan watershed. "The data showed that a significant amount of synthetic microfibres are discharged daily to Lake Michigan," says Julie. "We analysed just one main tributary and expect that it is somewhat representative of others".

The big question now is how to reduce these pollutants and minimise their adverse effects. Scientists are still learning about the consequences of these contaminants in our environment, but this research needs to be done with a great deal of urgency. Our world is drowning in plastic with more and more being added every day.

GOOD NEWS FOR FUTURE RESEARCH

Julie believes that recent studies of Lake Michigan green algae with microfibres may offer insight into ways to battle against this type of plastic. Certain aquatic plants are able to trap and cling to microplastics. If researchers learn more about these natural mechanisms, they may be able to develop ways to reduce the discharge of microplastics into aquatic environments.

In addition to the valuable data collected from microplastics research, Julie's project also helps undergraduate students become more aware of how scientific research is used to solve every-day problems. As a bonus, this work made most participants more conscious about the dangers of plastic pollution and consider reducing the amount of plastic they use in their life. This is ideal preparation to enable these students to lead citizen science projects in the future.

Julie and her team at Valparaiso University are keen to offer public outreach programmes for schools and young people, which may be a good way to find out more about becoming a chemist. Choosing a career in chemistry can be extremely rewarding. Many chemists work in a lab, but there is so much more they can do. Chemists can develop new textiles for the latest fashion trends or even play a key role in criminal investigations. It is fascinating to think where chemistry could take you!

ABOUT CHEMISTRY

WHAT IS CHEMISTRY?

Chemistry is everywhere. Everything you eat, smell and touch involves chemicals. It is the makeup of materials, including all the complex chemical reactions that happen in your body. In everyday life, you can find chemistry when you cook, make a cup of tea or even when you pick new trainers to go running.

In academic terms, chemistry is the science that deals with the properties and structure of different substances, as well as the transformations they can have.

HOW CAN CHEMISTRY HELP FIGHT POLLUTION?

Chemistry can be very useful in the fight against pollution. It can help scientists understand how pollutants interact with animals and plants and how they can be harmful. Chemistry is also key to creating new ways to reduce pollution, including developing cleaner fuels or fitting vehicles and industries with pollution control devices.

WHY IS WATER QUALITY SO IMPORTANT?

Monitoring and investigating aspects of water quality and environmental health are incredibly important. After all, living organisms rely on healthy fresh water for survival. It is very rewarding to contribute knowledge on water quality and environmental issues that impact people around the globe.

WHY INVOLVE STUDENTS IN THIS PROJECT?

Integrating research projects in science courses challenges students to go beyond textbooks and think about the key questions that we need to answer. Students get a better idea of how research is conducted, learn beyond the surface level and often find greater interest in topics. Many of these topics should be part of science curriculum since they impact our lives in critical ways.

HOW TO BECOME A CHEMIST

- A good place to discover the wide range of career options in the chemical sciences is the American Chemical Society: **https://www.acs.org/content/acs/en/careers/college-to-career/chemistry-careers.html**
- Typical employers include health services, research institutes, military and law enforcement, industry and schools.
- In the UK, you could work towards chartered status, including Chartered Chemist (CChem) and Chartered Scientist (CSci).
- According to the American Chemistry Council, the average annual salary of a US chemical industry employee is $87,000.

PATHWAY FROM SCHOOL TO CHEMISTRY

To become a chemist, you usually need a degree in either pure chemistry or in a specific field, such as analytical chemistry or biochemistry. Some employers may favour a relevant postgraduate qualification.

You may also be able to get into this career through a laboratory scientist higher apprenticeship or start as a laboratory technician and train while working by doing a relevant qualification.

The education website for the Royal Society of Chemistry is a good resource if you are considering a future as a chemist: **https://edu.rsc.org/future-in-chemistry/**

JULIE'S TOP TIPS

01 Follow your interests.

02 Work with integrity.

03 Take advantage of opportunities.

04 Always take pride in your pursuits!

Undergraduate research student, Eddie Kostelnik, collecting algae from Lake Michigan near the shoreline in Portage, Indiana, USA.

HOW DID JULIE BECOME A CHEMIST?

WHAT WERE YOUR INTERESTS AS A CHILD?

I mainly pursued my interest in music and took piano lessons throughout my younger years. I was admitted to one of the top music schools in the US when I was 18 but began to recognise my interest in science and in the chemistry courses I took during my freshman year. Obviously, I transitioned to science, but still play piano almost daily.

WHO OR WHAT INSPIRED YOU TO BECOME A SCIENTIST?

I cannot pinpoint any one single person who inspired me to become a scientist but attribute my path to teachers and professors who taught and encouraged me.

WHAT ATTRIBUTES HAVE MADE YOU A SUCCESSFUL SCIENTIST?

I love to learn, to investigate and to solve problems. I also enjoy sharing these experiences with friends, collaborators, students, colleagues and community. I believe that when you enjoy getting up in the morning and pursuing your interests, you can accomplish a great deal.

HOW DO YOU OVERCOME OBSTACLES IN YOUR WORK?

Science requires supplies and equipment, which can be costly and challenging. It is not always possible to have the resources that you want to carry out research, and this is often a large obstacle. Also, as a university professor, much of my time is devoted to teaching and service, in addition to research. These challenges are met with resourcefulness and effective time management, especially when you are interested in making progress in your work.

WHAT ARE YOUR PROUDEST CAREER ACHIEVEMENTS?

I would say that I feel most proud when my students offer sincere gratitude for the experiences and education that I have provided for them. I also feel that I have contributed to science when I publish new findings with my collaborators.

WHAT WOULD BE YOUR ‘DREAM’ RESEARCH PROJECT TO WORK ON?

I am grateful that I am able to pursue my research interests thanks to many great institutions, collaborators, colleagues and students. I aspire to create greater awareness of critical environmental problems, such as plastic waste. I find that once people are aware of the problems, they are more inclined to participate in the solutions.

WHAT IF RAINDROPS COULD HELP US UNDERSTAND CLIMATE CHANGE?

A RAINDROP FALLING ONTO THE OCEAN SEEMS LIKE A SIMPLE EVENT, BUT BEHIND THIS, THERE IS AN INCREDIBLY COMPLEX SEQUENCE OF PHYSICAL PROCESSES. **DR XINAN LIU** OF THE **UNIVERSITY OF MARYLAND**, USA, USES ADVANCED TECHNIQUES TO FILM RAINDROPS. HIS AIM IS TO UNDERSTAND THE PHYSICS AND HOW THE SMALL ACT OF RAIN FALLING ONTO WATER CONTRIBUTES TO OUR GLOBAL CLIMATE

TALK LIKE A PHYSICAL OCEANOGRAPHER

PHYSICAL OCEANOGRAPHY – the study of physical processes and conditions in the ocean

AIR-SEA BOUNDARY LAYER – the area where the air and ocean meet; between the two, water and air exchanges occur

EVAPORATION – when a liquid becomes a gas

DROPLETS – small drops of water that are present in the air

SURFACE TENSION – The property of the surface of a liquid that allows it to resist an external force, due to the cohesive nature of its molecules. This is why a paper clip made of steel can float. See: **https://www.usgs.gov/special-topic/water-science-school/science/surface-tension-and-water?qt-science_center_objects=0#qt-science_center_objects**

MODELLING – using physics equations to predict and understand the behaviour of systems such as rainstorms

The ocean covers 70 per cent of the world's surface and holds 97 per cent of the world's water. This vast expanse of water plays a key role in our planet's climate and local weather conditions. Indeed, water evaporating from the ocean surface, and ending up as rainfall on land or back on the ocean, is part of an endless process of change known as the water cycle. Ocean currents – continuous, directed movements of sea water around the globe – are also vital for distributing heat energy, regulating weather and climate, and cycling nutrients and gases.

Dr Xinan Liu is fascinated by the ocean and understanding how it interacts with rain. He researches the air-sea boundary layer, which is where the rain meets the ocean. The air-sea boundary layer is one of the ways the ocean plays an important role in our climate, but we know surprisingly little about the physics behind the raindrops that fall in it.

Understanding how raindrops fall and splash on the ocean surface is important for predicting how much moisture will be in the air at the air-sea boundary layer. It is also important for working out how weather conditions, like wind, can change the evaporation processes happening at sea.

RAINDROPS

When raindrops fall on the surface of the ocean, they make splashes and ripples, just as you would see if you watched the rain falling on a puddle. The challenge for Xinan is to find the right equations and physics to describe these events, including the processes we cannot see.

Xinan uses high-speed cameras to capture the movements of water on the ocean surface that are too fast for the naked eye. By studying these images, Xinan has shown that when a raindrop hits the ocean, a thin sheet of water is thrown up in all directions. This water sheet is unstable, meaning that thin jets of water form on the top surface and the resulting splash looks like a crown.

The crown then breaks up and ejects droplets of various sizes. While these droplets are forming, a central water column or 'stalk'

DR XINAN LIU

Research Professor
University of Maryland, USA

FIELD OF RESEARCH

Physical Oceanography and Fluid Mechanics

RESEARCH PROJECT

Understanding the air-sea boundary layer and its effects on our climate

FUNDER

National Science Foundation

rises from the point at which the raindrop hits the surface of the ocean and ripples start to take shape.

Given that so many different events happen when a raindrop falls on the water surface, Xinan uses varying photographic techniques. For some experiments in the lab, he adds fluorescent dyes to water tanks to track the movement of the water surface. At sea, he uses radar systems to map the shapes formed by the stalks. And, at an even larger scale, Xinan and his team make use of satellite-based radar imagery. “With sophisticated radar instruments employed in satellites, we can look at rain cells – the area within which it is raining – and storms in three-dimensions and observe how rain and snow vary with time over both land and oceans around the world,” says Xinan.

Interestingly, how the rain behaves when it hits the ocean surface varies considerably. Xinan wants to understand the physics behind these events and how they are affected by environmental conditions like windspeed and temperature.

WARMING EFFECTS

When air becomes warmer, it can hold more water. This means the atmosphere becomes moister, particularly over the ocean. Higher temperatures lead to more water evaporation and, combined with greater moisture levels, this means more rain, snow and intense rainstorms.

Xinan has discovered that the surface tension and wind speed across the ocean surface affect how raindrops fall and their contribution to the air-sea boundary layer. Being able to describe the physics involved will enable scientists to monitor ocean weather more effectively and predict how our planet’s climate is changing.

The data Xinan collects are used to improve modelling and therefore our understanding of how water is transferred between the air and the sea.

“I develop and test techniques to measure micro-scale phenomena generated by the impact of raindrops on the ocean,” explains Xinan. “This research is important because large scale motions in the atmosphere and ocean are determined by these micro-scale phenomena”.

A white-light image of secondary droplets observed near the water surface. The vertical bars are raindrops but are shown in this way due to a long exposure time in the high-speed camera.

ABOUT PHYSICAL OCEANOGRAPHY

Physical oceanography is about understanding the patterns of how oceans move. It is closely related to fluid dynamics, which is an area of physics and engineering that seeks to understand how liquids and other fluids move and flow. Oceanography can cover everything from monitoring the effect of polar sea ice on ocean currents to looking at how and why big waves form during storms.

Work in physical oceanography involves a mixture of theory, observation and simulation. For example, some oceanographers go out to sea to take measurements of ocean temperatures in a given region and monitor how they change with time. This data can then be incorporated into models and simulations. When combined with the physics of the ocean's behaviour, these models and simulations can be used to predict events and monitor changes.

Research in physical oceanography is very important because the ocean plays a critical role in the Earth's climate as well as sustaining life. Ocean acidification and rising sea levels are two areas of change related to our oceans that many scientists are concerned about and therefore working to better understand.

CAREER OPPORTUNITIES IN PHYSICAL OCEANOGRAPHY

"Careers in physical oceanography are not as popular as mechanical engineering, but far from impossible to find," says Xinan. "If you prepare well, and with a bit of luck, your dream of working in this field can come true. Many other career opportunities related to physical oceanography are also on the rise. For instance, as more satellites are launched into orbit, scientific programmers will be required to analyse and manage satellite data."

All in all, studying physical oceanography opens up many exciting routes to either working in a laboratory setting or out in the field, on boats, exploring the oceans. Given how important our oceans are to all life on Earth, physical oceanographers are vital to helping us understand how oceans behave and move. And, as climate change increasingly impacts our seas, physical oceanographers will be key to helping us understand how the changes in the ocean will affect all our lives.

HOW TO BECOME A PHYSICAL OCEANOGRAPHER

- Contact local universities or research centres to see if you are able to get relevant work experience. For example, under normal circumstances, when there are no lockdowns and a global pandemic, the Hydrodynamics Lab at the University of Maryland welcomes high school students. "We can provide a half-hour tour for individuals or a group of high-school students, demonstrating our rain and wave facilities and answering their questions," says Xinan. "In the summer, we offer several internships and work experience opportunities for high school and college students, including financial support. The students can conduct their own experiments using the facilities in our lab or work with our graduate students on ongoing research projects."

- The National Oceanography Centre has many resources on their website about what it is like to be an oceanographer and news about jobs and research: **https://www.noc.ac.uk/careers**

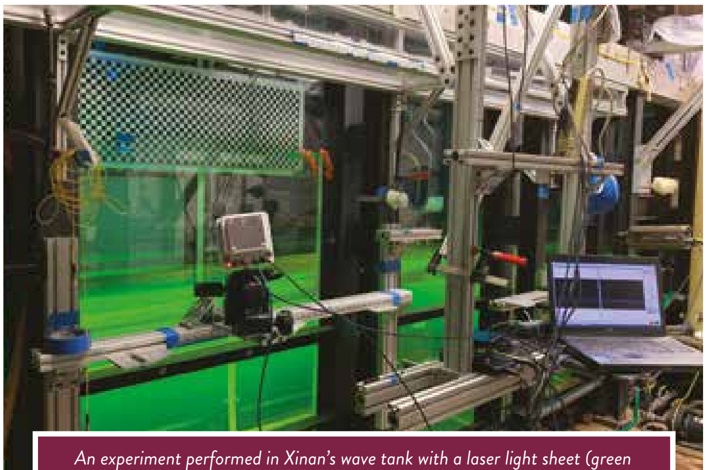
- The average salary in the US for an oceanographer is $70.251

PATHWAY FROM SCHOOL TO PHYSICAL OCEANOGRAPHER

There are a number of routes into oceanography. Most people have at least a bachelor's degree in either oceanography or a related subject.

For physical oceanography, related subjects would include mathematics, physics, engineering or ocean science.

As many oceanography jobs involve research, a relevant master's and PhD may be useful. Strong mathematical and data analysis skills are also beneficial, as well as any research experience.



An experiment performed in Xinan's wave tank with a laser light sheet (green colour) at the centre of the tank and two cameras and a computer outside the tank.

HOW DID XINAN BECOME A PHYSICAL OCEANOGRAPHER?

WHAT DID YOU WANT TO BE WHEN YOU WERE YOUNGER?

Once, I was interested in becoming a middle or high school teacher because I believe education can improve people's lives and teaching was one of my favourite jobs. However, while I was learning, I decided to follow my interests and prepare myself for whatever lay ahead, instead of a particular career path. I did well in maths and science but also spent a lot of time reading books about different subjects, doing things outside the classroom and practising all kinds of technical and social skills. I followed my curiosity and developed my education through serendipity, which is how I became a physical oceanographer.

WHAT DREW YOU TO STUDYING RAINFALL?

A number of years after I finished my PhD, one of my colleagues, who is a scientist in the field of physical oceanography and remote sensing, started a conversation about seeing the phenomena of rainfall over the ocean in satellite images. Fascinated by those images, I wanted to find out more about rainfall over the ocean. So, I started to design laboratory experiments to simulate the impact of raindrops on the ocean surface and explore the physics of the interaction between raindrops and water surface.

YOU WORK IN THE DEPARTMENT OF MECHANICAL ENGINEERING. IS YOUR BACKGROUND IN MECHANICAL ENGINEERING OR OCEANOGRAPHY?

My educational background is interdisciplinary. I have a BS degree in mathematics, an MS degree in physical oceanography and my PhD is in mechanical engineering, with a major in fluid mechanics.

WHAT DO YOU LOVE MOST ABOUT THE WORK YOU DO?

My work has provided me with the opportunity to explore things no one has ever seen before. I have made new friends around the world from different cultures and multiple research fields. Nowadays, observations of many interesting phenomena in nature heavily depend on instruments and techniques, which people in mechanical engineering develop and make. I love to learn about and apply the latest technologies in my research, and I especially enjoy working in the lab.

HOW OFTEN DO YOU GET TO TRAVEL IN A BOAT OUT TO SEA? OR DO YOU WORK MAINLY IN A LAB?

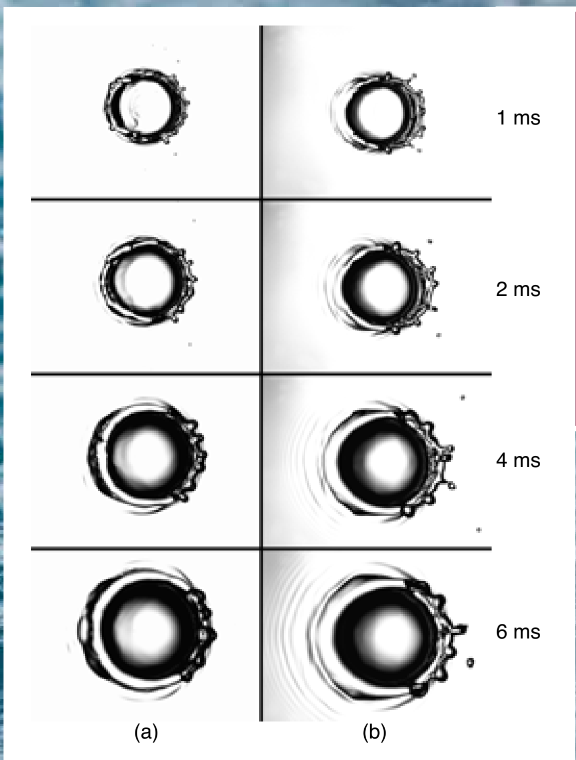
I travelled in various vessels out to sea many years ago when I worked in an institute of oceanography. Now, I mainly work in lab.

XINAN'S TOP TIPS

01 Prepare for your professional career. Being better prepared means having more practice. The more practice you have, the better the jobs you will have in the future. I am a strong believer in luck coming with hard work.

02 Be persistent in your learning. Maths and science courses can sometimes be challenging, but they are well worth the effort to set you on a path of success.

03 Be proactive in identifying potential problems when you talk and listen to people from different disciplines and backgrounds. You may contribute to solutions to the challenges they face.



The crowns generated in different wind fields after a raindrop hits the water surface. The camera, set above the water's surface, looked downward, while the light source came from underneath the water (the bottom of the tank). The numbers on the right indicate the time in milliseconds after the drop hits the surface of the water.

HOW DO SEA LEVEL OSCILLATIONS CONTRIBUTE TO SEA LEVEL EXTREMES?

DR JADRANKA ŠEPIĆ FORMS PART OF A GEOPHYSICS TEAM BASED AT THE **UNIVERSITY OF SPLIT** IN CROATIA. HER WORK IS PRIMARILY FOCUSED ON UNDERSTANDING WHICH AREAS ARE AT THE GREATEST RISK OF SEA LEVEL OSCILLATIONS – A RISK WHICH WILL BECOME HEIGHTENED IN THE FUTURE AS SEA LEVELS RISE

TALK LIKE A GEOPHYSICIST

ATMOSPHERIC GRAVITY WAVE – a wave caused when gravity force acts on atmospheric particles displaced from their equilibrium position

EXTREME SEA LEVELS – sea level that is higher than 99.95% of sea levels measured at a specific location. This can be 1 metre at some stations to more than 16 metres at others

MEAN SEA LEVEL (MSL) – the average level of the surface of one or more of Earth's seas

MELTWATER – water formed by melted snow and ice

METEOROLOGICAL – relating to the science of the atmosphere and weather

SEA LEVEL OSCILLATIONS – variations to the average level of a sea's surface

SEISMIC – related to earthquakes and other movements of the Earth's crust

STORM SURGE – rising of the sea level as a result of the atmospheric pressure changes and strong on-shore winds within a storm (hurricane/cyclone/typhoon)

SUB-HOURLY SEA LEVEL OSCILLATIONS – variations to the sea level that occur at shorter periods than an hour

Since 1880, the global mean sea level has risen by between 21 and 24 centimetres, with approximately one-third of that happening in the last 25 years. The rising water level around the world is largely a result of meltwater, which is produced as glaciers and ice sheets melt – something which is happening more and more as temperatures rise due to global warming and climate change.

Alarmingly, the rate at which sea levels are rising is accelerating and the issue is becoming worse; it is estimated that by the year 2100, mean sea level will rise between 40 and 60 centimetres worldwide. And the problems do not stop there. Higher mean sea levels will likely lead to an increase in flood risks that are associated with extreme sea levels. ESLs are sporadic, short-lasting episodes of sea level rises due to passing hurricanes, cyclones, smaller atmospheric disturbances or submarine earthquakes (which, in turn, generate tsunamis). Hurricane Katrina, which occurred in August 2005, caused catastrophic damage, particularly to New Orleans, as the storm surge reached more than 9 metres. That disaster occurred at present-day sea levels, so consider how much worse it would have been if it had occurred at future-day mean sea levels. In addition, it is estimated that for the coasts of Europe, the types of floods that currently occur once a century will occur once every one to three years – and this is all because of the

expected mean sea level rise.

It is with these issues in mind that Dr Jadranka Šepić is conducting research focused on improving our understanding of contributors to ESLs. Based at the University of Split in Croatia, Jadranka forms part of a team that is studying the contribution of sub-hourly sea level oscillations to ESLs along the European coast.

WHY IS IT NECESSARY TO STUDY THESE ASPECTS OF ESLS?

Jadranka's project is entitled 'Estimating contribution of sub-hourly sea level oscillations to overall sea level extremes in changing climate' (SHExtreme) and is expected to fill in some important knowledge gaps in our understanding of this area. "When we are talking about flooding, contribution of hourly (or longer) sea level changes to ESLs has been extensively researched so far. However, due to previously insufficient measurement time steps of sea level instruments (tide gauges), contribution of sub-hourly sea-level oscillations has been investigated only sporadically," explains Jadranka. "Recently, these sub-hourly sea-level oscillations have started to attract a lot of scientific interest – mostly due to the strongest of these events, so called meteorological tsunamis, which can reach hazardous levels, generate significant material damage, and even endanger human lives, much like seismic tsunamis."

Up until now, the majority of studies have looked at sporadic episodes of extreme sub-hourly sea-level oscillations; what the scientific community is lacking are detailed statistical studies of contributions of these oscillations to overall sea level extremes. Jadranka and her colleagues hope to provide this information through their research.

WHAT TYPES OF DATA WILL JADRANKA BE COLLECTING AND HOW?

In order to collect the vast amounts of data relating to the sea level changes which occur at minute time scale, Jadranka's first challenge is to establish collaborations with scientists from a host of European countries. With collaborators, Jadranka will be able to tackle the second challenge: to carefully check the data and remove the unreliable measurements (of which there are bound to be some in a study this comprehensive). "We will collect sea level data measured with a one-minute time step, where possible. These data are partly available online but the remaining data will be acquired through collaboration with the European research institutions and scientists," says Jadranka. "We will also use atmospheric pressure and wind measurements which can be obtained through collaboration with national weather services. Further on in our investigations, we will use atmospheric and ocean reanalysis data (numerical weather and ocean predictions of past conditions), as well as climate simulations of future atmospheric and ocean conditions."

The overall aim is to analyse the data, look for patterns, try to understand the underlying mechanisms of ESL episodes and, finally, present the findings to the public and wider scientific community.

WHAT DOES THE TEAM ALREADY KNOW ABOUT SUB-HOURLY ESLS?

In some parts of Europe, such as in the Mediterranean, sub-hourly ESLs are related to atmospheric gravity waves. These gravity waves are waves in the atmosphere that resemble the waves in the sea, but because they are in the air we cannot see them. However, it is possible to measure them, so we know that they are there. "Atmospheric gravity waves happen when a strong wind in a moist air mass. blows over a calmer, drier air mass below it, thus generating waves in the lower air mass. These waves can propagate all the way to the sea and generate long tsunami-like waves there," explains Jadranka. "This is similar to wind in the atmosphere blowing over the sea and generating ocean waves."

WHAT IMPACT WILL JADRANKA'S RESEARCH HAVE?

While Jadranka's research will not ensure that sea levels do not rise at the rate that is expected (we have to rely on other scientific fields for that), there is real hope that the outputs from her studies will result in increased awareness that these sea level oscillations do, indeed, present a substantial danger and can cause great material damage and endanger human lives. It is Jadranka's hope that tools will be developed that will allow for timely warnings which will save untold lives and restrict the devastating impact these events could have in the future

DR JADRANKA ŠEPIĆ

Department of Physics, Faculty of Science, University of Split, Croatia

FIELD OF RESEARCH

Geophysics and Physical Oceanography

RESEARCH PROJECT

Jadranka's project aims to discover which parts of the European coast are especially endangered by sub-hourly sea level oscillations. In addition, she wants to understand what processes in the atmosphere generate these dangerous oscillations.

FUNDER

European Research Council

JADRANKA'S TOP TIPS

01 Follow your own path and try to discover what interests you. Once you have done that, start to pursue it one step at a time and accept that your interests might change over time.

02 When conducting research, ensure that you focus on the process and not the goal – enjoy what you are doing and try to retain your curiosity; working to find the next answer will stand you in good stead throughout your career.

03 Never be afraid of getting it wrong! Be mindful of the possibility that you could come to a conclusion that will challenge previous conclusions – that is all part of the process.

ABOUT GEOPHYSICS

Geophysics is a field of science that is concerned with the physical aspects of our planet. Geophysicists use a range of tools and methods to aid their work and rely on distinct (though related) scientific areas, including magnetic, electrical and seismic studies. Many geophysicists work for oil and gas companies, with concerted efforts worldwide looking for petroleum, but you are not obliged to work for such industries – there are a wealth of opportunities in environmental agencies if that is more aligned to your interests.

As Jadranka's research shows, it is possible for geophysicists to dedicate their academic lives to finding a means of helping humanity overcome some of the challenges related to global warming and the resultant climate change. Ultimately, you can expect to be working on creating a geophysical picture of our planet, of what is happening below the surface of the Earth, or even what is happening to sea levels (as is the case with Jadranka's studies).

WHAT DOES JADRANKA FIND REWARDING ABOUT HER RESEARCH?

For Jadranka, the most rewarding aspects of her studies revolve around working on discovering something new. Of course, being alongside colleagues throughout her investigations enables her to discuss these discoveries at length, conversations with like-minded people who share her passions and enthusiasms. "The thing I like most about the process of discovery is that through the involvement of different people, the research broadens and becomes better," explains Jadranka. "I love how everyone contributes, even if only a tiny bit, and as a result we can gather something that is new and interesting."

Researchers tend to be motivated by a love of their field and a desire to solve problems, but recognition of their hard work is always appreciated. Jadranka was granted such an accolade in 2019 when she received the NH Division Outstanding Early Career Scientist Award for 'fundamental contributions to the research on meteorological tsunamis and high-frequency sea level oscillations'. The award meant a lot to her, both personally and professionally, and is clearly a recognition for the important work that she continues to conduct to this day.

WHAT ISSUES CAN I EXPECT TO FACE AS A GEOPHYSICIST IN THE FUTURE?

It will hardly come as a surprise that one of the main issues facing all of us – climate change – is something that will have to be addressed by the next generation of geophysicists. We all recognise that global warming is impacting on oceans, weather processes and systems, and the work of geophysicists will become increasingly important as we work to understand the impacts of human activity. "Rising sea levels will obviously attract a lot of scientific interest in the future," says Jadranka. "There are so many questions that will need answering: how much will sea levels rise? What will happen with the Antarctica and Greenland ice sheets? Will they melt? If so, how fast will they melt? Is there a way of stopping this? How extreme will the new extremes be?"

HOW TO BECOME A GEOPHYSICIST

- The Geological Society is a brilliant resource for those interested in pursuing a career in the field: **https://www.geolsoc.org.uk/**
- The British Geographical Association contains a plethora of information regarding geophysics. Take a look through the site to get a real feel for what is happening in the field: **https://geophysics.org.uk/**
- Starting salaries for geophysicists typically range from £28,000 to £35,000, depending on your level of qualifications and experience. Those at a more senior level range from £40,000 to £75,000 per year.

PATHWAY FROM SCHOOL TO GEOPHYSICS

Jadranka suggests that you begin by taking a lot of courses in general physics and mathematics and try to incorporate some geography if you can. "Later, taking more specialised courses in physical oceanography and meteorology will help," explains Jadranka. "Seismology is also part of the geophysics study area, so make sure you check out those courses as well."

Relevant degree subjects include physics, mathematics, applied sciences and engineering. A postgraduate qualification in a relevant course, such as a master's degree in geophysics or geoscience (or a PhD), may improve your employment prospects and enhance your salary.

https://www.prospects.ac.uk/job-profiles/geophysicist

HOW DID JADRANKA BECOME A GEOPHYSICIST?

WHAT WERE YOUR INTERESTS AS A CHILD?

My main interests were drawing, reading, writing and daydreaming. I could spend hours doing any of these. I enjoyed imagining new worlds, be it in my head or on paper.

WHO OR WHAT INSPIRED YOU TO BECOME A SCIENTIST?

When I was a high-school senior, my dilemma was whether to study literature or physics. In the end, I decided to study physics because I watched a lot of Star Trek! I wanted to work for NASA and explore the Universe. But then, during the second year of my studies, I realised that I could specialise in geophysics and, in particular, physical oceanography. Having grown up near the sea, I fell in love with this science area – everything was so interesting, clear and easy to understand. When we talked about waves, circulation patterns, wind, upwelling, downwelling, etc., I could visualise these processes and understand what each equation related to (something I found difficult in other areas of physics). Also, I had excellent professors who encouraged me and inspired me to pursue this career.

WHAT ATTRIBUTES HAVE MADE YOU SUCCESSFUL?

I would say curiosity – the desire to understand what is happening and why. To me, doing science is like solving puzzles, getting a right detail here and a right detail there, doing a lot of unconnected work, then suddenly seeing a bigger picture. I also love to tell the story behind my research – so I put a lot of effort into writing papers and creating images. I want my readers to understand the physics of the process easily.

WHAT ARE SOME OF YOUR FAVOURITE BOOKS?

I had a lot of favourite books as a child. There are a few, though, which I read numerous times: The Little Prince by Antoine de Saint-Exupéry, Jonathan Livingston Seagull by Richard Bach and Sylvius by Henry Bosco. The last one I find the most charming and still read it from time to time. To me, all these books tell a story about those who dared to be different and to follow their heart's desires, despite their families, friends and societies being against it. Especially this old chap, Silvius – he did all of those things, in a nice and gentle way.

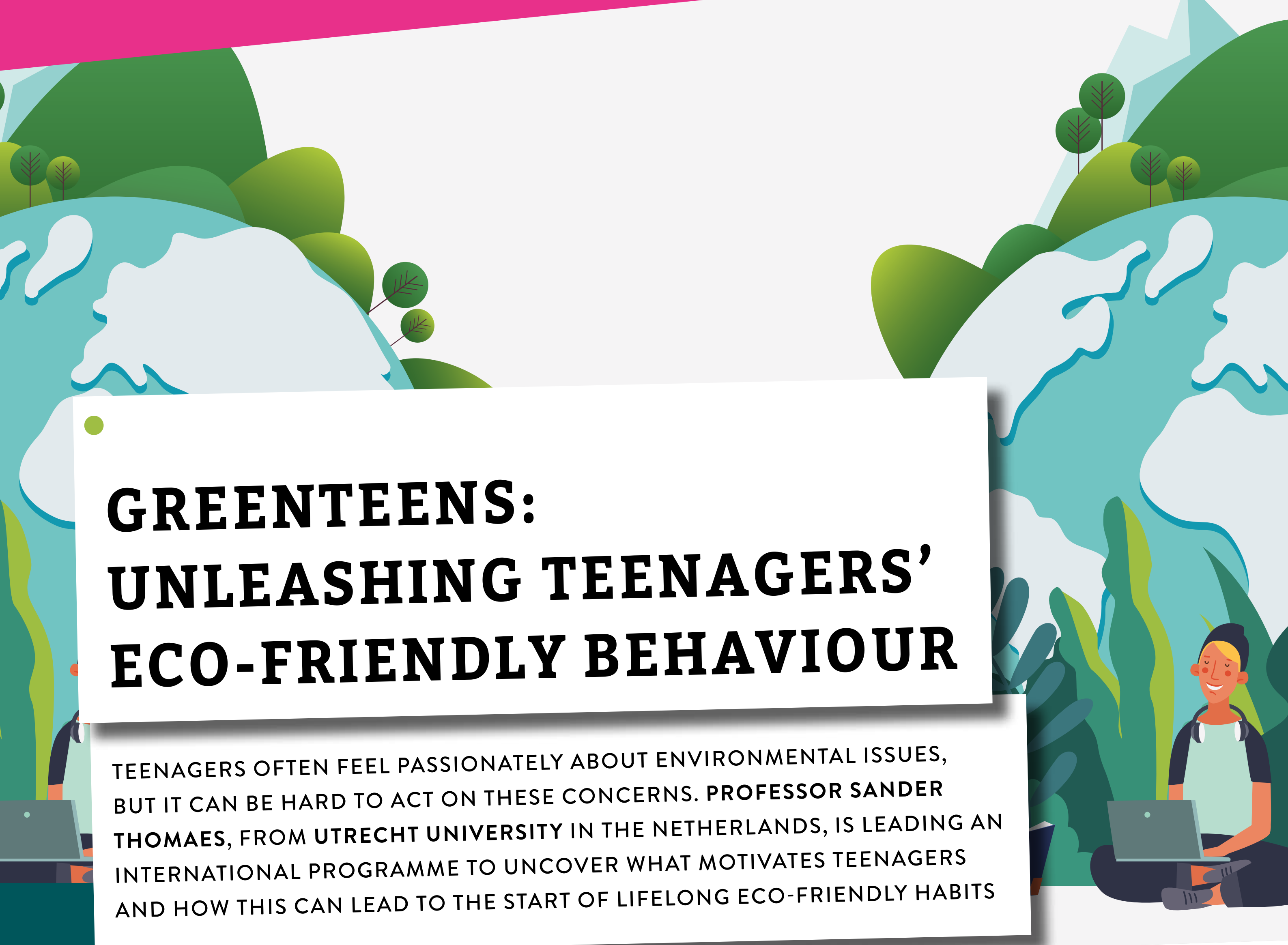
Now, I also have a lot of books which are very dear to me. My most favourite ones are Combray by Marcel Proust and Housekeeping by Marilynne Robinson. I like books that are gentle and slow, and in which most of things occur not outside of the main characters, but within their souls. It is the inner life of the characters I find most inspiring.

WHAT ARE YOUR PROUDEST CAREER ACHIEVEMENTS SO FAR?

I am happiest when I discover something unexpected. For instance, when I conduct research about a particular flooding event, then realise that it happened because of a very small disturbance in the atmosphere and that disturbance was linked to a particular cloud, and that cloud to a wind blowing over a mountain range 200km away. It is these little discoveries that I am most proud of. My main goals for the future would not be to achieve something specific, but rather to keep learning, keep doing research and to stay curious and thrilled by science!

Jadranka receiving the award for Young Meteorologist from The Croatian Meteorological Society in 2017.

Jadranka conducting atmospheric measurements with students at the University of Split.



GREENTEENS: UNLEASHING TEENAGERS' ECO-FRIENDLY BEHAVIOUR

TEENAGERS OFTEN FEEL PASSIONATELY ABOUT ENVIRONMENTAL ISSUES, BUT IT CAN BE HARD TO ACT ON THESE CONCERNS. **PROFESSOR SANDER THOMAES**, FROM **UTRECHT UNIVERSITY** IN THE NETHERLANDS, IS LEADING AN INTERNATIONAL PROGRAMME TO UNCOVER WHAT MOTIVATES TEENAGERS AND HOW THIS CAN LEAD TO THE START OF LIFELONG ECO-FRIENDLY HABITS

TALK LIKE A PSYCHOLOGIST

ATTITUDE-BEHAVIOUR GAP – the space between someone's values (attitudes) and their actions (behaviour)

EXPERIMENTAL STUDY – a study where researchers change a particular variable and measure the effects of this change

LONGITUDINAL STUDY – a study that observes the same participants at various stages over a long period of time

MOTIVE-MATCH HYPOTHESIS – the idea that values are more likely to lead to behavioural change if they are relevant to one's personal life

PSYCHOLOGY – the study of how the human mind works and influences behaviour

"Some people think that teenagers do not care about societal problems. This belief is a myth." So states Sander Thomaes, a Professor of Developmental Psychology at Utrecht University in the Netherlands. He is leading the 'GREENTEENS' programme, an international collaborative effort that is examining what influences teenagers to take up eco-friendly behaviours.

"Many adolescents really care about the environment. For example, a recent survey from the United Nations and University of Oxford found that two out of three teenagers consider climate change a global emergency," says Sander. "However, it can be hard to act on these concerns, and this can be especially true for adolescents."

Sander is talking about what psychologists call the 'attitude-behaviour gap' – the difference between our values and how we act in real life. This is especially evident for environmental matters; think about how we might set our eco-friendly values aside when we take a flight abroad or eat a steak. For teenagers, there are many factors that make following through on their eco-friendly values particularly difficult. "Many adolescents are grappling with pressing questions, especially about finding their own sense of identity and their place in the world," says Sander. "It is hard to make societal concerns a priority when there are so many important things happening in your personal life."

ADOLESCENTS EXPLAINED

How to encourage people to adopt eco-friendly lifestyles is a question that has plagued scientists for decades. For a long time, it was assumed that if people possessed the facts – about the effects of climate change, for instance – they would change their behaviour accordingly. But this has not been the case. Sander's team conducted a meta-analysis as a preliminary to their research to find out why this is so. "Many adolescents do not like being told what to think or do," says Sander. "If they are taught information, they are already familiar with then efforts can even backfire, if they feel they are being patronised. The meta-analysis confirmed this and highlighted there is much room for improvement in education programmes."

While teenagers remain a mystery for many adults, psychologists know of a few key adolescent traits to bear in mind. "Most teenagers want to be autonomous," says Sander. "They want to make their own decisions on issues that matter to them. This is partly rooted in hormonal changes, in particular testosterone increases (in both boys and girls), as well as a growing sense of identity." Teenagers are also particularly driven by status – they find it important to be valued or respected by their peers. This is true of almost all people, of course, but it is especially relevant during one's teenage years when one's place in the world is being established.

THE MOTIVE-MATCH HYPOTHESIS

"Our research, as well as that of others, has found that adolescents are especially motivated to act on their concerns about societal issues if these actions are directly relevant to their personal lives," says Sander. "For instance, concern for the environment can materialise through protests, which can be especially appealing to those who feel it ties into their identity – being an independent-minded person who stands up to irresponsible authority figures."

Sander calls this effect the Motive-Match Hypothesis. "Adolescents will be more likely to engage in sustainable behaviour if it supports their sense of identity or is respected by their peers," says Sander. "Otherwise, even if they believe that sustainable behaviour is important, it becomes a chore." This has big implications for the design of educational programmes and publicity campaigns. "Current educational programmes do not always tap into that dedication to protecting the planet that many teenagers naturally have," says Sander.

THE GREENTEENS PROGRAMME

Understanding the Motive-Match Hypothesis is therefore crucial for designing education and outreach programmes that inspire teenagers to action. Sander's team will tackle this through coordinating a range of different studies under the GREENTEENS umbrella, all of which aim to provide a piece of the puzzle. The research will take place in three geographically and culturally diverse countries: China, Colombia and the Netherlands. "This will allow us to detect differences and similarities in what motivates adolescents of different countries towards eco-friendly behaviour," says Sander.

The studies they plan to carry out have a range of methodologies. One is a longitudinal study, which sees how participants' eco-friendly behaviour changes over the course of two years, as they grow older and their sense of identity becomes more defined. They will also carry out a number of experimental studies, seeing what conditions lead to instances of more sustainable behaviour. They will also investigate why some adolescents think climate change is not real or not important, analysing the roles of personal values, lack of knowledge, or parental influence in environmental scepticism.

"Regardless of where adolescents live, they care about developing autonomy and being respected by their peers," says Sander. "However, we cannot assume the Motive-Match Hypothesis will apply the same around the world, which is why we are testing it with participants from three continents."

DEPLOYING THE PROJECT

This GREENTEENS project is only just beginning, so there is much for Sander to look forward to as a researcher. "In particular, I am excited about working with the team," he says. "The other scientists involved – Astrid Poorthuis, Judith van de Wetering, and Stathis Grapsas – all bring their own expertise and skills. It is sometimes thought that scientists work by themselves, but the opposite is true. Science almost always requires teamwork and that is often what makes it so rewarding."

PROFESSOR SANDER THOMAES

Professor of Developmental Psychology
Utrecht University, The Netherlands

FIELD OF RESEARCH

Psychology

RESEARCH PROJECT

GREENTEENS, an international programme investigating how to motivate adolescents to adopt sustainable behaviours.

FUNDER

European Research Council (ERC)

This article covers a research project that has received funding from the European Research Council (ERC) under the Horizon 2020 research and innovation programme (Grant agreement No. 864137).

The emphasis on collaboration and teamwork does not stop there. Sander explains, "We are also asking teenagers to give feedback on our research design before we roll it out, so I am looking forward to seeing their comments about how to make sure the project really resonates with participants."

The hope is that the GREENTEENS project should provide critical insights to help educators and policymakers design education programmes and publicity campaigns that motivate adolescents. "Recent decades have shown that people find it difficult to treat the planet in a sustainable way," says Sander. "And yet, most of us – perhaps, especially young people – have good intentions at heart. I hope that GREENTEENS will show us how to fill the 'missing link' between good intentions and collective behaviour change. Given their capacity for rapid learning and adaptation, teenagers have the potential to spearhead this movement – and we must harness this potential as much as we can."

ABOUT PSYCHOLOGY

Sander explains more about his subject and his career:

WHAT IS PSYCHOLOGY?

Psychology is the study of how people think, feel, and act. A major challenge and interest point for psychology is that no two individuals are the same. Psychologists study the surprising ways that people are different or similar to one another.

WHAT DO YOU FIND REWARDING ABOUT YOUR WORK?

It is commonly thought that the main aim of psychology is to find cures for mental illnesses, but while this is certainly an important aspect, psychology is much more than that. I enjoy studying the psychological aspects that help people thrive. For instance, adolescents are exceptionally quick and flexible learners and are highly committed to causes they find important.

WHAT TYPES OF COLLABORATION DOES YOUR WORK REQUIRE?

No individual scientist can excel at every aspect of their work. Therefore, it is often a good – and rewarding – idea to work in a team, where each member has their own skillset. For instance, one team member might handle grant writing and getting funding, another data collection, another analysing data and another communicating the team's findings to the public.

WHAT ISSUES WILL FACE THE NEXT GENERATION OF PSYCHOLOGISTS?

One key flaw of traditional psychological research is that it has been mainly conducted in Western countries. This means we have an incomplete and potentially biased understanding of what it means to be human. I hope that the next generation of psychologists can address this and undertake studies in a wide range of cultures, to make our scientific knowledge more representative of the world population.

HOW TO BECOME A PSYCHOLOGIST

- Psychology can be studied at most universities. It is an accessible and popular subject worldwide.
- According to QS World University Rankings, the best universities for psychology are Harvard, Stanford, Cambridge, Oxford and California Berkeley.
- Many universities and scientific institutions offer outreach events. For instance, Utrecht University, where Sander works, hosts an annual 'Meet the Professor' event where professors cycle to schools throughout the city to answer questions from students.
- According to Glassdoor, the average annual salary for a psychologist in the Netherlands is around €45k.

PATHWAY FROM SCHOOL TO PSYCHOLOGY

At school, studying subjects like biology, chemistry, maths and physics provides a good foundation for any scientific career, psychology included. Given psychology often involves a strong social aspect, other subjects such as English and history can also be useful.

SANDER'S TOP TIPS

01 Find out what makes your heart thump! This is not easy, so take the time you need. Try out many different subjects and extracurricular activities if you get the chance. Read books on topics you find interesting and listen carefully to people whose opinions you value.

02 Realise that setbacks are essential to every learning process. Try to learn from them and move on.

03 One misconception about scientists is that they were always extremely smart, but this is often not necessarily the case. A scientific career is not about how clever you are, but how much you enjoy finding creative ways to learn new things.

Judith van de Wetering editing the videos she uses in her experiments.

HOW DID SANDER BECOME A PSYCHOLOGIST?

WHAT WERE YOUR INTERESTS AS A CHILD?

I had quite typical childhood interests. As a kid, I loved playing football with friends after school and by the time I was a teenager, I played guitar in a band. I think my mom still has nightmares about my funky haircuts! Although I struggled in some subjects, especially physics and maths, I enjoyed learning, which set me on the path to science.

DO YOU HAVE A FAVOURITE BOOK?

As a teenager I loved Goethe's 'The Sorrows of Young Werther' – even though it's over 200 years old, I was drawn in by its big emotions, big struggles and big love!

WHAT INSPIRED YOU TO BECOME A SCIENTIST?

I'm inspired by the everyday behaviour of everyday people. I've always liked observing people and trying to understand their behaviour – I remember as a child, watching how long it would take my teacher's smiling face to return to a neutral expression, for instance. Now, as a psychologist, the same applies: asking questions about people and behaviour, trying to learn from it and sharing any discoveries with others.

WHAT ATTRIBUTES HAVE MADE YOU SUCCESSFUL AS A SCIENTIST?

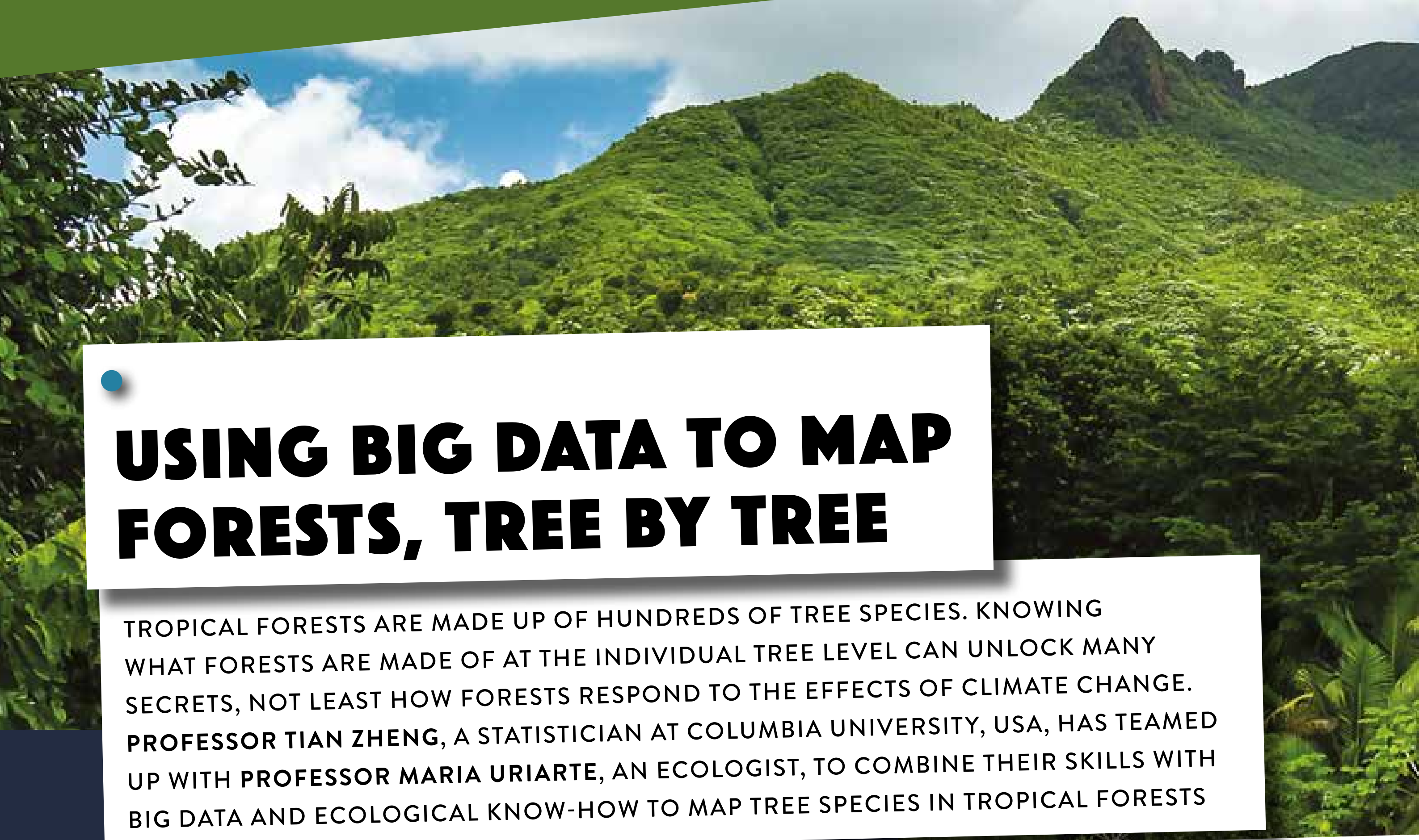
Most scientists, myself included, share three attributes. They are curious, persistent and eager to learn. Not many scientists consider themselves successful – I think because you soon realise how much there is that you don't know, which is quite humbling.

HOW DO YOU OVERCOME OBSTACLES AT WORK?

I try to think of obstacles in terms of what I can learn from them. In science, difficult problems can be motivating – they offer a rare chance to learn something new or unexpected.

WHAT ARE YOUR PROUDEST ACHIEVEMENTS SO FAR?

The day we got the GREENTEENs research grant was one of the best of my life. It can be quite a struggle to get funding and several previous proposals had been rejected, so I am very thankful it worked out. I now have the chance to do my dream research, which would not have been possible without the support of the grant.



USING BIG DATA TO MAP FORESTS, TREE BY TREE

TROPICAL FORESTS ARE MADE UP OF HUNDREDS OF TREE SPECIES. KNOWING WHAT FORESTS ARE MADE OF AT THE INDIVIDUAL TREE LEVEL CAN UNLOCK MANY SECRETS, NOT LEAST HOW FORESTS RESPOND TO THE EFFECTS OF CLIMATE CHANGE. **PROFESSOR TIAN ZHENG**, A STATISTICIAN AT COLUMBIA UNIVERSITY, USA, HAS TEAMED UP WITH **PROFESSOR MARIA URIARTE**, AN ECOLOGIST, TO COMBINE THEIR SKILLS WITH BIG DATA AND ECOLOGICAL KNOW-HOW TO MAP TREE SPECIES IN TROPICAL FORESTS

GLOSSARY

ARTIFICIAL INTELLIGENCE – the science of developing computer systems that can perform tasks usually reserved for humans, such as visual perception and decision-making

BIG DATA – extremely large datasets, within which computer programs may be able to recognise patterns or trends

LIDAR (LIGHT DETECTION AND RANGING) – a remote sensing method that uses a pulsed laser to measure distances between things

MACHINE LEARNING – a field of artificial intelligence, specifically concerning the development of computer programs that can learn and adapt without human intervention

REMOTE SENSING – using satellites or aircraft to capture data about the Earth's surface

AERIAL IMAGING – a remote sensing method whereby drones, or manned aircraft, equipped with a high-resolution camera and LiDAR take images of the forest, which can then be processed and analysed

Climate change is already having a profound effect on the world, not least through the rising frequency and intensity of cyclonic storms. Scientists know that powerful storms such as hurricanes can cause a lot of damage to forests, but how forests recover from these impacts is less well understood. There are winners and losers, with some species benefiting from storms at the expense of others. This has big implications for mitigating climate change, too: forests absorb a fifth of the carbon that we emit, but storms can release stored carbon and change the dominance of different species.

Understanding how hurricanes affect forests is a task that cannot be tackled by one scientific discipline alone. In Columbia University in New York City, this recognition has led to a unique collaboration. Professor Tian Zheng works in the Department of Statistics at Columbia and is also a member of Columbia's Data Science Institute, while her colleague Professor Maria Uriarte is a tropical ecologist within the Department of Ecology, Evolution and Environmental Biology. By combining their skillsets and working with others, they have taken strides in understanding what happens to forests after storms.

SEEING THE TREES FROM THE FOREST

Mapping a forest by traditional methods is no easy task. Documenting the trees that make up a forest from the ground level involves time-consuming treks over difficult terrain and usually only results in a small proportion of a forest being sampled. Given that forests are highly complex environments, and the diversity of trees within any one forested area, there is no guarantee that the sample area even represents the rest of the forest. Nevertheless, many intrepid ecologists have undertaken extensive mapping surveys, but now they have a helping hand – in the form of modern technology.

"We are interested in using big data produced by remote sensing technology to study the spatial distribution of species," says Tian. Aerial imaging is one kind of remote sensing technology that gives researchers access to images of massive areas of forest, but there is another method that can be even more revealing. LiDAR (Light Detection and Ranging) offers something different: this remote sensing technology uses lasers, emitted by apparatus on an aeroplane, for instance, which 'bounce' when they hit something below them and are then picked up again by the apparatus. By emitting thousands upon thousands of these lasers, a three-dimensional image of the world beneath is produced as a cloud of points. This is the same technology used by self-driving cars to detect the distance between themselves and

objects around them, so they do not bump into things.

BIG DATA, BIG POSSIBILITIES

These days, scientists can generate massive datasets using new technology. The trick to scientific discovery, however, is drawing insights from these data – which, when you have masses of the stuff, is not so straightforward. This is where machine learning comes in. Once a computer program has been 'taught' how to interpret a certain sort of data, it can then do the same process for massive datasets.

Take the case of remote sensing data. After data collection, the researchers will have a massive two-dimensional image and three-dimensional 'map' of a forest's canopy, which can be detailed enough to be able to pick out the individual leaves of some tree species. Researchers know that certain patterns in the map indicate that the lasers have bounced off a certain sort of tree but picking these out by hand would take years. Instead, they teach a computer program which patterns correspond to which species, and then let the machine run through the rest of the dataset. "The process mimics how human infants learn, through cognitive development," says Tian. The end product is a highly detailed map of the forest, right down to the individual species of the trees within it.

BEFORE (AND AFTER) THE STORM

In 2017, Hurricane Maria devastated the island of Puerto Rico, including its forests. Ecologist Maria Uriarte had been mapping trees in Puerto Rico's forests for fifteen years prior, which, together with remote sensing data, meant that a solid map existed for some of the island's forests. Using LiDAR and aerial imaging from the weeks and months following the hurricane, Tian and Maria are planning on building a second map – together, creating 'before' and 'after' datasets that can then be compared.

Initially, Tian and Maria focused on two species: *Prestoea acuminata*, a species of palm, and the distinctive tree *Cecropia schreberiana*. "The distributions of these species can act as signatures of hurricane damage," says Tian. For instance, *Cecropia schreberiana* is a pioneer species – this means that after a hurricane or some other event has caused devastation, it is one of the first species to 'colonise' the area due to its rapid growth conditions. Both species have visual features that are easy to identify by humans and the algorithms analysing the datasets.

The difference is that a well-trained computer algorithm will be able to identify these species 50 times faster than a human and with the same accuracy. This means that scientists are freed up from what could be a long and laborious task, giving them more time to focus on important questions such as how climate change is impacting forests.

NEXT STEPS

Indeed, now that Maria and Tian are equipped with an initial set of machine learning and imaging tools, they will be looking to answer specific questions. For instance, they are interested in discovering how landscape characteristics, such as a forest's underlying topography and geology, influence storm damage. They will be able to compare datasets to find out how hurricane damage influences species composition, and even whether human activity has an effect on forests' recovery. Beyond this study, there are potential applications for this fusion of technologies in all sorts of other fields. "We are evaluating how this sort of machine learning could be applicable to other areas, such as medical imaging," says Tian. As artificial intelligence becomes increasingly powerful, there will be increasing potential for discovering things about our world that have not been in our grasp before.

PROFESSOR TIAN ZHENG

Department of Statistics, Data Science Institute, Columbia University, New York USA

PROFESSOR MARIA URIARTE

Department of Ecology, Evolution and Environmental Biology, Columbia University, New York, USA

FIELD OF RESEARCH

Big Data and Machine Learning

RESEARCH PROJECT

Using artificial intelligence to map forests' species composition to understand the effects of powerful storms on rainforests.

FUNDER

Microsoft

ABOUT BIG DATA AND AI

Tian explains more about her career and opportunities within her discipline:

HOW MUCH MULTIDISCIPLINARY COLLABORATION DOES YOUR ROLE INVOLVE?

I started my career collaborating with computational biologists and geneticists. Over the years, I have collaborated with sociologists, political scientists, psychologists, climate scientists and, now, ecologists. Like John Tukey (a renowned mathematician) once said, "The best thing about being a statistician is that you get to play in everyone's backyard." I have played in many backyards!

WHAT EXCITES YOU ABOUT BIG DATA?

I am excited to be able to unleash the insights hidden within all the data we are collecting today, and how that will lead to new solutions. Machine learning offers new ways of extracting valuable information from large amounts of data.

COULD ADVANCES IN MACHINE LEARNING LEAD TO FEWER JOBS IN THE FUTURE?

I think it is unlikely. Some repetitive tasks (e.g. labelling trees from images of a forest) might be replaced by machines, but this opens the door for new creative careers to emerge. Within the development of machine learning, numerous career opportunities have already been created because every algorithm requires humans to design and optimise them. Data are not perfect, and algorithms need continuous fine-tuning to make sure they give valid conclusions. This calls for a lot of people who are talented in statistics, computer science, optimisation and data ethics.

ARE THERE MANY OPPORTUNITIES FOR STUDYING AND WORKING WITH BIG DATA, ARTIFICIAL INTELLIGENCE AND STATISTICS?

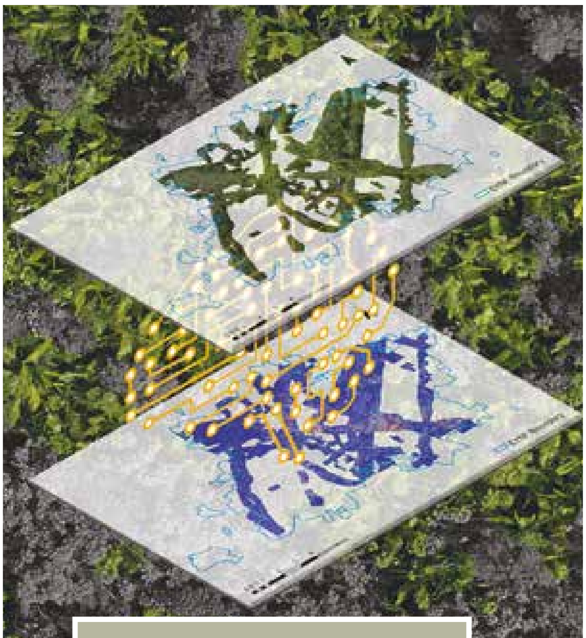
Yes, there is a great need for talent in these areas across all sectors in the USA. Finding real-world, data-driven solutions to problems often requires mathematical and statistical modelling, computational technologies and expert knowledge. In particular, statistical thinking has become ever more important to understanding the potential for bias or uncertainty. These are critical factors that need to be considered if big data is to realise its potential.

HOW TO BECOME A STATISTICIAN

- Some universities offer undergraduate degrees specifically in statistics, whereas others will incorporate it within mathematics, often with the option to specialise further during your degree.
- According to QS World University Rankings, the best universities for statistics are MIT, ETH Zurich, Stanford, Harvard, Oxford and Cambridge.
- Columbia University is among the top 15 in the QS World University Rankings and offers undergraduate and graduate programmes in statistics, AI, machine learning and data science.
- According to PayScale, the average annual salary for a statistician in the US is around $74k.

PATHWAY FROM SCHOOL TO STATISTICIAN

Tian recommends taking courses in mathematics, statistics and coding at school/college. Other subjects, especially the sciences, can also be useful.



A survey of a forest in Puerto Rico using AI

TIAN'S TOP TIPS

01 If you enjoyed or continue to enjoy playing with LEGO or reading detective stories and solving crimes, then you are already prepared for a career in data science (and science, overall). The same curiosity and problem-solving skills apply to careers in data science.

02 There are a lot of similarities between a data scientist and a detective. You are using all the available tools to piece together clues. You may not succeed at first, some experiments may fail, but the joy in finally making something work and finding an answer to a problem is one of the most rewarding aspects of being a scientist.

HOW DID TIAN BECOME A STATISTICIAN?

WHAT DID YOU WANT TO BE WHEN YOU WERE YOUNGER?
Originally, I wanted to be an architect, but this didn't work out. Instead, I discovered a fantastic career in mathematics!

WHAT CAREER OPTIONS WERE OPEN TO YOU AFTER COMPLETING YOUR UNDERGRADUATE DEGREE?
Some of my classmates went to work for banks and research labs directly after graduation. Others, like me, continued on to graduate school.

WHAT INSPIRED YOU TO TAKE A MASTER'S AND PHD IN STATISTICS?
I have always liked solving problems. Statistics is a field that uses data to solve problems, which was a very strong draw for me.

WHAT DO YOU LOVE MOST ABOUT YOUR WORK?
I love creating statistical models and machine learning algorithms that reveal interesting patterns in data.

YOUR TWITTER PROFILE SAYS YOU ARE A 'UNICORN TRAINER'! WHAT DOES THIS INVOLVE?
When data science first became established as a discipline, certain news articles referred to data scientists as 'unicorns'. Since I designed courses to teach students data science skills, I dubbed myself a 'unicorn trainer'!

MEET CHENGLIANG TANG

Chengliang Tang is a PhD student at Columbia University who works with Tian and Maria on the tree species mapping project.

WHY DID YOU CHOOSE TO STUDY MATHEMATICS AS AN UNDERGRADUATE?
I have been interested in mathematics since high school. People say that mathematics makes up the foundation of all sciences, which I believe without a doubt.

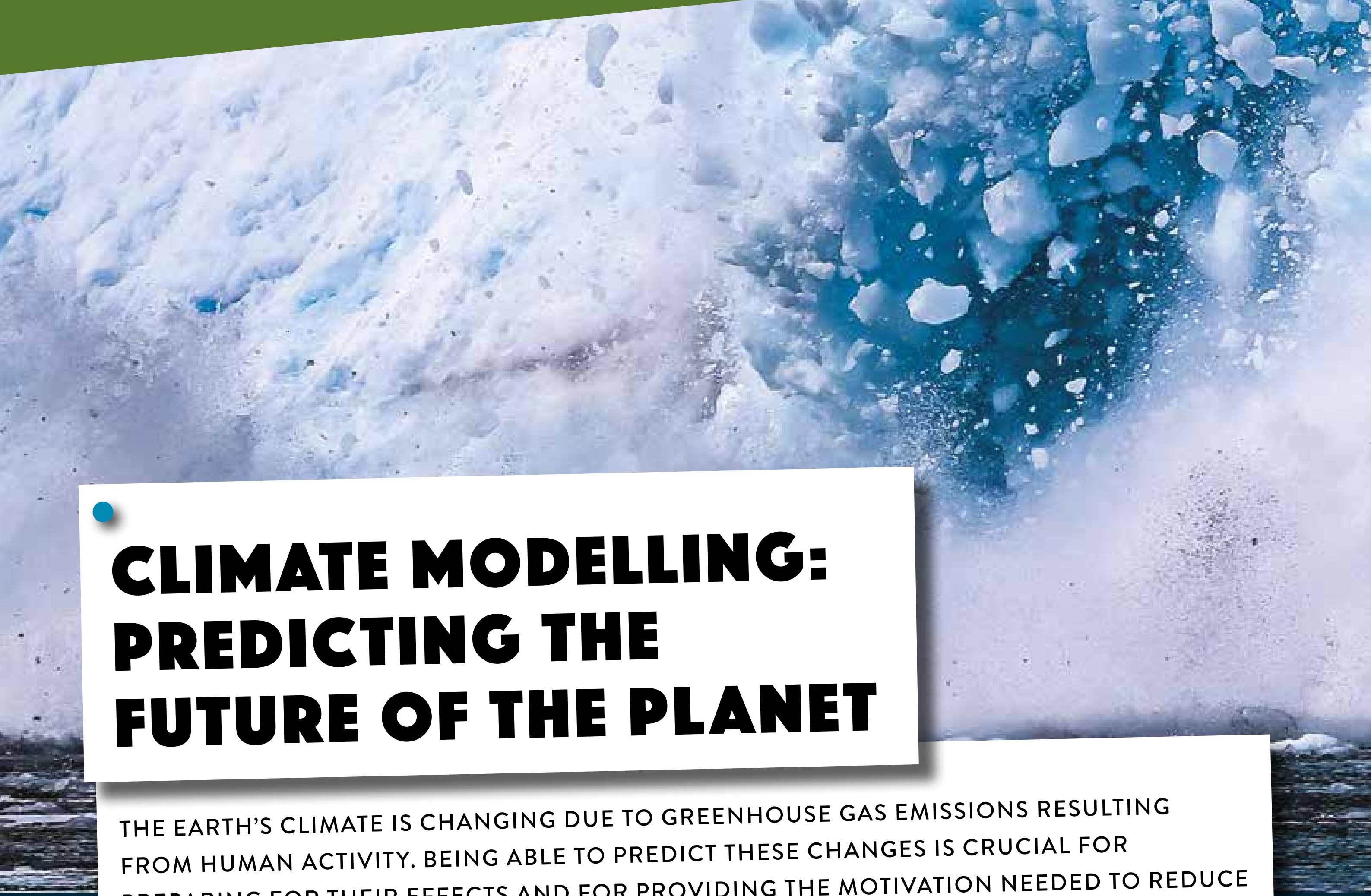
WHAT DREW YOU TO STUDY STATISTICS?
I took courses in many different fields besides pure maths. I found statistics to be a field that revealed the beauty of mathematical theories and led to them having an impact in the real world. As we enter the era of big data, there are more and more opportunities emerging within statistics.

WHAT DO YOU FIND ENJOYABLE ABOUT THE TREE SPECIES MAPPING PROJECT?
Tian and Maria are experts in their domains, so during our weekly meetings I learn a lot from them. The project is motivated by important questions about climate change and forests, involving data collected by ecologists and meaningful outputs that help answer these questions. The significance of this project really motivates me.

WHERE DO YOU SEE YOURSELF GOING NEXT?
The world is changing rapidly, so it is difficult to predict, but I do hope to continue working in statistics. It is an exciting subject with new ideas and challenges emerging every day. I am eager to learn more, do more and contribute to our growing knowledge base.

WOULD YOU ENCOURAGE OTHERS TO STUDY MATHEMATICS?
Yes, absolutely! As well as everything I mention above, mathematics has also fundamentally shaped my way of thinking. Everyday life is full of meaningless noise, but statistics teaches you how to extract the valuable signals from within it. These changes are so gradual and imperceptible that I didn't realise they were happening until recently.

WHAT ADVICE WOULD YOU GIVE TO YOUR YOUNGER SELF?
Take more exercise! I used to undervalue physical activity, but I now realise how crucial it is for physical and mental health. Research projects are long journeys full of ups and downs. Exercise helps us keep a positive attitude and enjoy what we are doing.



CLIMATE MODELLING: PREDICTING THE FUTURE OF THE PLANET

THE EARTH'S CLIMATE IS CHANGING DUE TO GREENHOUSE GAS EMISSIONS RESULTING FROM HUMAN ACTIVITY. BEING ABLE TO PREDICT THESE CHANGES IS CRUCIAL FOR PREPARING FOR THEIR EFFECTS AND FOR PROVIDING THE MOTIVATION NEEDED TO REDUCE EMISSIONS. **DR ALAN CONDRON** OF THE **WOODS HOLE OCEANOGRAPHIC INSTITUTION** IS DEVELOPING SOME KEY CLIMATE MODELS TO BRING THESE PREDICTIONS INTO EXISTENCE

TALK LIKE A CLIMATE MODELLER

CLIMATE CHANGE – a change in regional or global climate patterns, generally caused by changes in the planet's atmospheric or ocean circulation. Many of the changes we predict will occur in the future are a result of increased greenhouse gases caused by humans burning fossils

ICE CORE – a cylinder of ice obtained by drilling down into an ice sheet or glacier. The layers of ice towards the bottom of the cylinder are older than those at the top and so their characteristics provide a record of the climate in the past

LATITUDE – the distance of a place from the equator, with 0° beginning at the equator and 90° the north or south pole

NUMERICAL MODEL – a type of mathematical simulation capable of performing complex predictions

OCEAN CIRCULATION – the movement of water in the ocean basins and a key regulator of climate

PALAEOCLIMATOLOGY – the study of the Earth's past climate, used to understand modern climate change

PARIS AGREEMENT – a landmark international treaty, effective from 2016, that sets out a global framework for avoiding dangerous climate change

RUNOFF – the draining of water from land into a larger water body (e.g. the ocean)

"The ultimate goal of my research is to determine what causes the Earth's climate to change abruptly," says climate modeller Dr Alan Condron. "To do this, I use numerical models to determine what factors drove changes in climate, tens to hundreds of thousands of years ago." Extreme and rapid climatic changes have happened in the past, with profound impacts for life on Earth, and it is very possible these could happen again – and are potentially already happening. "Dramatic shifts in global temperatures or rainfall patterns would directly affect human society," says Alan.

The Earth's climate is a dazzlingly complex system and predicting how it will change is no easy task. There is a huge array of factors to consider: not only greenhouse gas emissions, but many other variables such as deforestation, ocean chemistry and melting ice, to name a few. Alan is currently focusing on one particular factor. "A key part of my research focuses on determining whether changes in freshwater runoff from melting ice sheets near the Earth's poles could trigger abrupt shifts in climate," he says.

FROM ONE POLE...

At present, Europe benefits from the Gulf Stream, a flow of warm water from the tropics of the Americas, across the North Atlantic and to the shores of western Europe. The current warms the air above it, which is why parts of Europe

are generally much warmer than places of the same latitude in Canada. However, the Gulf Stream (and consequently Europe's mild climate) would rapidly change if this supply of heat was to suddenly shut down.

"The Arctic is basically a vast reservoir of relatively fresh ocean water, covered by entirely fresh floating sea ice," explains Alan. "Changes in the atmosphere can cause this stored freshwater and sea ice to be released into the North Atlantic and disrupt existing ocean currents." A lot of this frozen freshwater is also stored on land, especially within Greenland's massive ice sheet. When this ice melts, it not only affects ocean currents but also contributes to sea level rise.

As the Gulf Stream flows towards Europe, the warm waters within it gradually cool and sink, ultimately returning south as cold and deep waters, before rising again in the warmer tropics and continuing the cycle. However, the introduction of freshwater from the Arctic would make surface waters less dense and, therefore, more difficult for them to sink. This would slow the entire cycle, meaning less heat would get transported to Europe, and so Europe would experience a much colder climate. "Much of my research is spent investigating whether such a scenario will occur in the future," says Alan.

...TO ANOTHER

Alan's research also investigates the other end of the Earth: the Antarctic. "This is a new avenue for my group but it is turning out to be extremely fascinating and exciting," he says. Antarctica releases five times more freshwater into the ocean than the Greenland ice sheet, so is of great significance.

The west Antarctic ice sheet also has the potential to undergo a rapid runaway ice collapse, that once begun could become unstoppable, even if greenhouse gas emissions were cut to zero. "As the ice sheet starts to collapse it releases enormous volumes of cold freshwater into the ocean which, since this water is much less dense than the salty oceanic waters, would remain on the ocean's surface where it could allow a thick layer of floating sea ice to grow," Alan explains. "The white ice would reflect the sun's warmth, rather than absorbing it as sea water does, which could cause a worldwide cooling effect."

Some may think this sounds like good news, considering greenhouse gases are otherwise heating up the atmosphere, but Alan offers a word of caution. "This should not be regarded as a 'global cooling' scenario, or a solution to combat global warming" he says. "According to our model, even with this cooling effect, average global temperatures would still be 3°C warmer than today."

KNOWLEDGE GAPS

"My research has highlighted many uncertainties in how ocean circulation and climate respond to freshwater input from ice sheets," says Alan. "For instance, I have found that our climate system is especially sensitive to freshwater coming from high latitudes."

Alan's explorations of historical climate change have also thrown up some perplexing results. "Since the last major ice age, there have been times when huge volumes of freshwater entered the ocean," he says. "However, rather than seeing a weakening in ocean circulation and climate cooling, we see the opposite response. It is important to unravel this mystery to understand the effects of human activities on the global climate."

TIPPING POINTS

Forty years ago, it was thought that historical changes to Earth's climate had been a gradual process, largely driven by variations in the Earth's orbit around the Sun. This idea changed in the 1980s, when researchers investigating ice cores found there had been many periods in the past when the North Atlantic climate had warmed dramatically in just a few decades. "These dramatic changes are now known as

DR ALAN CONDRON

Assistant Scientist, Woods Hole Oceanographic Institution, USA

FIELD OF RESEARCH

Climate Change

RESEARCH PROJECT

Investigating past incidences of climate change to model future changes to the climate, especially with regards to the introduction of freshwater from high latitudes into the ocean.

FUNDERS

National Science Foundation, US Department of Energy

Dansgaard-Oescher events and are considered classic examples of how rapidly Earth's climate can change," says Alan. "They are very relevant to my research because they are thought to have been caused by changes to the circulation of the North Atlantic Ocean."

Dansgaard-Oescher events are a major example of a tipping point: when climate change leads to a runaway effect that cannot be stopped, but instead gathers momentum as changes become more and more drastic. It is thought that the North Atlantic system could act as a major tipping point, as could Antarctic melting on a longer timescale. Predicting when these might occur, and doing everything we can to prevent them, is a major priority.

"It seems we have reached a point where human activities are playing the dominant role in steering climate change, compared to other factors," says Alan. "This is very different from past climatic changes. Historically, freshwater runoff has been a main driver of abrupt climate change, but this time its role is quite uncertain. Clearing up this uncertainty is what my research hopes to achieve."

ABOUT CLIMATE MODELLING

Alan's work has a significant role to play in anticipating, and responding to, possible future scenarios for the world's climate. He explains how he makes these predictions and why they are important for society.

WHAT ARE CLIMATE MODELS?

A climate model can be as simple as a one-line equation that calculates average temperature on Earth by incorporating estimates of how much energy from the Sun is absorbed or reflected into space. However, more precise models are far more complex, going so far as three-dimensional 'Earth systems' that comprise countless lines of computer code and incorporate many different climatic processes. The level of complexity needed depends on what questions need to be answered.

HOW LONG DOES IT TAKE TO CREATE A CLIMATE MODEL?

It depends on its complexity. Simple models can be created in a few hours, but complex models can take several years. These models are so complex and contain so many different components of the climate system, that they are usually developed at dedicated modelling centres by a full team of programmers and climatologists.

WHAT ARE THE BENEFITS OF CLIMATE MODELS?

Climate models are the only way we can predict future climate change. For instance, they are used by the UN and governments around the world to calculate how much we need to reduce greenhouse gas emissions to achieve the Paris Agreement's goal of limiting temperature rise to 2°C.

WHAT ARE THE LIMITATIONS OF CLIMATE MODELS?

All models are simplifications of the real world. In the real climate system, there are many processes that are either too complex or not understood well enough to fully simulate. If the model does not accurately describe a component of the climate system, predictions may deviate from what the real outcome would be. Right now, we are working to make models as accurate and close to reality as possible.

WHO USES CLIMATE MODELS?

Historically, climate modelling was the realm of just a few specialists. These days, they are run by glaciologists, geologists, palaeoclimatologists and biologists – to name just a few. With the advent of the internet and easily accessible high-powered computers, anyone with a laptop can download and run many useful and informative climate models.

HOW TO BECOME A CLIMATE MODELLER

- There are many pathways towards climate modelling, but Alan recommends getting a degree in mathematics, physics or computer science, "although an interest in computer programming and Earth Sciences (geography, geology) would also get you a long way. There is no magic formula!"
- According to QS World University Rankings, the best universities for mathematics or physics are MIT, Harvard, Stanford, Cambridge and Oxford. Alan says, "There are also many other great universities out there, where you can get the same education but that don't require you to have 'top grades'. In fact, if you've got commitment all you need is to join a local library and read books on these subjects."
- A number of institutes specialise in climate modelling and often offer internships for students or postgraduate positions. In the UK, Alan suggests looking into research institutes such as ECMWF at Reading University, the Met Office and National Oceanography Centre, Southampton. In the US, he recommends the Los Alamos National Lab, National Center for Atmospheric Research (NCAR), Princeton and MIT. If you are also interested in studying 'past climate change', the universities of Leeds, Bristol and Sheffield (UK) and the University of Massachusetts Amherst, Brown University and Columbia/Lamont (USA) are great places to look.
- According to Glassdoor, the average salary for a climate scientist in the US is around $77k.

ALAN'S TOP TIPS

01 If you're considering climate modelling, make sure you enjoy coding! Start by learning to write code for something you're interested in – maybe a simple computer game you can test on your friends. And there are lots of programming languages that are free to use.

02 There are many pathways to become a climate modeller – from backgrounds in computer science, physics or Earth sciences, to name a few.

PATHWAY FROM SCHOOL TO CLIMATE MODELLER

Alan recommends getting a solid background in mathematics, physics, and/or computer sciences at school. He adds that his Earth science degree was invaluable in opening his eyes to the applications of numerical modelling. "If you pursue your work to the master's and/or PhD level then I'd also encourage you to explore a range of research options. When I began my career, I was working in a lab processing soil samples. Turns out I was pretty rubbish at it and much better at computer modelling!"

HOW DID ALAN BECOME A CLIMATE MODELLER?

WHAT DID YOU WANT TO BE WHEN YOU WERE YOUNGER?

I had no idea I wanted to be a scientist when I was a child. My dad worked in manufacturing, and even the idea of going to university seemed ambitious to me! I always enjoyed science at school, but I had no idea it was possible to do it as a career. I actually wanted to be either a medical doctor, computer games programmer, or outdoor instructor – quite the range!

WHAT DREW YOU TO GEOLOGY AND GEOPHYSICS?

My parents would take me and my brother on long walks in the UK's National Parks. I remember standing on mountains thinking how cool it would be to study a degree that led to me being outside most of the time. As a result, I took up Earth Sciences at the University of Wales, Aberystwyth.

HOW DID YOU GET INTO CLIMATE MODELLING?

I don't come from either a computer science or physics background, so I differ from many of my peers. I was interested in programming from a fairly young age, ever since my Dad bought an Atari computer in the mid-1980s and my brother and I had a go at coding. We didn't have much success at the time, but it laid the groundwork for my future career.

It was during my undergraduate degree that I first learned about climate change. Whilst studying, I stumbled across a book on palaeoclimatology and was so struck by it that I applied to do a master's degree with the author, Ray Bradley. I was very surprised to be accepted and it was during my master's that I took my first computer modelling class. It came naturally to me – all those years of Atari paid off, it seemed! I found it amazing that these models could simulate Earth's climate, help us understand its past and even predict its future.

WHAT DO YOU LOVE MOST ABOUT YOUR WORK?

There is a lot of freedom in being a scientist. I can work on projects and ideas that interest and excite me, and day-to-day I am pretty much my own boss. I can also set my own hours, which means that I can stop work when I need a break or to get some exercise, and then return to the computer again later on.

DO YOU THINK WE WILL SOLVE THE CLIMATE CRISIS?

In many ways the solutions already exist, such as renewable energy technology. The hardest part is making the necessary changes at the national and international level, and there is much to be done. Small changes in our individual lives all add up too, especially if they influence others to make climate-conscious decisions.

Alan working on climate modelling in his lab.
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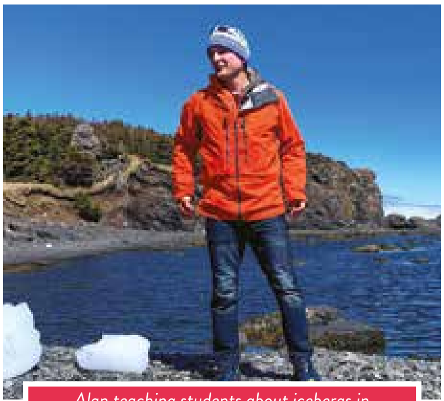
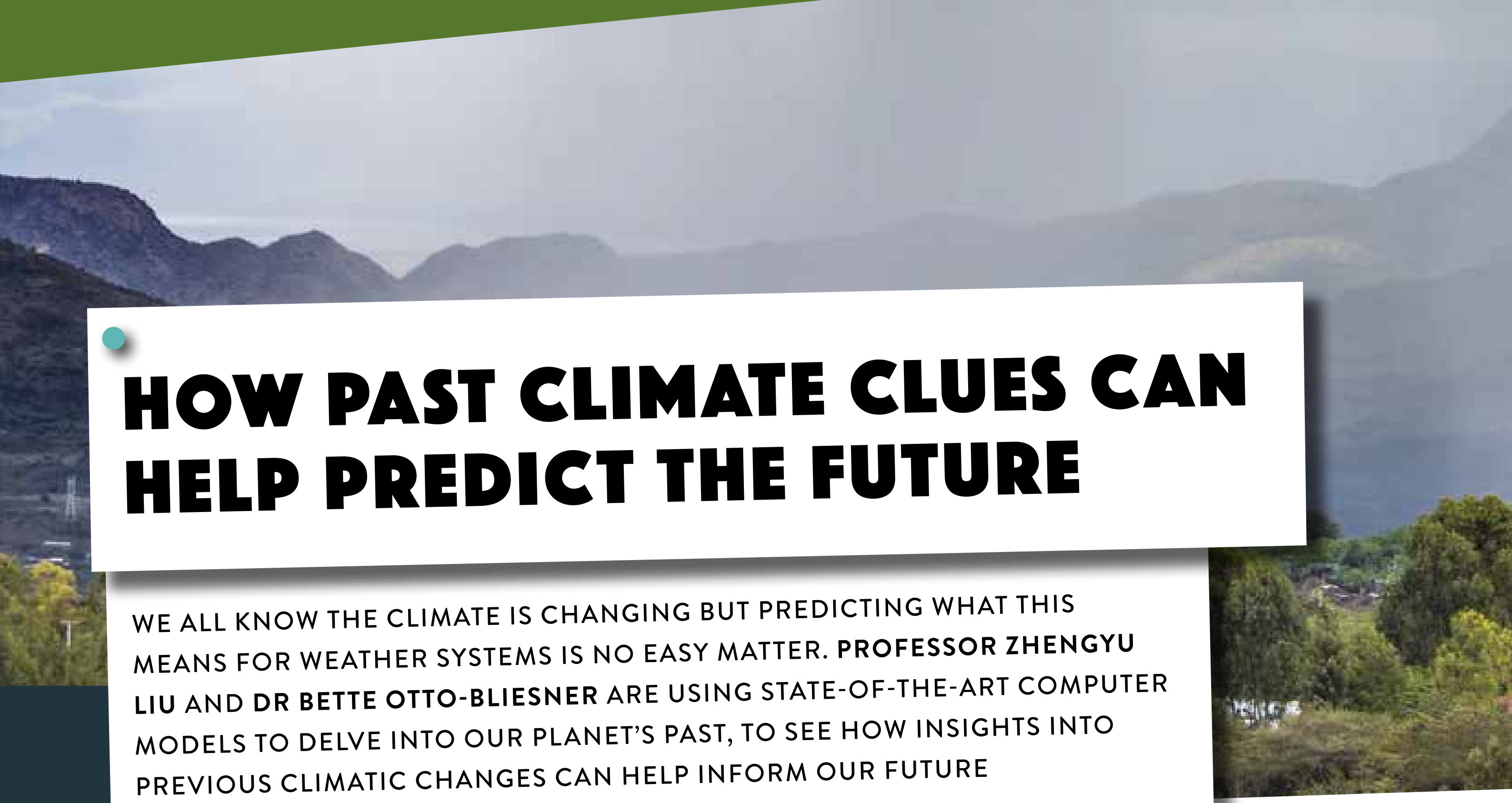


Alan teaching students about icebergs in Newfoundland, Canada.

Looking for icebergs in Newfoundland.



HOW PAST CLIMATE CLUES CAN HELP PREDICT THE FUTURE

WE ALL KNOW THE CLIMATE IS CHANGING BUT PREDICTING WHAT THIS MEANS FOR WEATHER SYSTEMS IS NO EASY MATTER. **PROFESSOR ZHENGYU LIU** AND **DR BETTE OTTO-BLIESNER** ARE USING STATE-OF-THE-ART COMPUTER MODELS TO DELVE INTO OUR PLANET'S PAST, TO SEE HOW INSIGHTS INTO PREVIOUS CLIMATIC CHANGES CAN HELP INFORM OUR FUTURE

TALK LIKE A CLIMATE SCIENTIST

CLIMATE CHANGE – a change in the global climate, leading to changes in temperatures, weather and other factors

CLIMATE MODEL – a computer simulation of the world's past, present or possible future climate

MELTWATER – water formed from melting ice sheet

MONSOON – a seasonal influx of rain brought in by prevailing winds

OCEAN CURRENTS – the motion of the ocean, driven by wind, water density differences and tides

PALEODATA – data that give information about ancient times

SOLAR RADIATION – sunlight, including the electromagnetic radiation that results in heat

Climate change does not just mean the world is getting hotter; it signals a whole range of effects on planetary systems, affecting everything from weather patterns to ocean currents. Getting to grips with what climate change means for the world – and for humanity – is essential for two reasons. Firstly, it strengthens the case for action to mitigate climate change as soon as possible. Secondly, it helps us prepare for the changes that might be inevitable, helping to build resilience into human society.

We are witnessing our climate change at an unprecedented pace and, so, it is not easy to say what will happen next. Our best way of predicting the future is by using computer models that simulate the Earth's systems and make projections about what lies in store. However, to ensure that these models are accurate and not making misleading predictions, we have to make sure they match up to the real world – in other words, we must compare them to past incidents of climate change. Professor Zhengyu Liu, of Ohio State University, and Dr Bette Otto-Bliesner, of the National Center for Atmospheric Research in Colorado, have joined forces to do just this, building models that simulate what the planet's climate has been through over the last 21,000 years. They call their project Transient Climate Evolution, or TraCE for short.

LOOKING BACK TO LOOK FORWARD

"To predict the future, we need to know the past," says Liu. "Climate models used to project future impacts need to be tested against past climate records." TraCE compares two distinct lines of scientific enquiry, looking for similarities and differences between the two. The first is the computer model: Liu and Bette use the Community Earth System Model (CESM), which incorporates the latest scientific understanding and technological capabilities to build a computer model that is as true to the real world as possible. The second is paleodata: this is prehistorical evidence left behind on the Earth that we can use to infer what past climates would have been like.

Examining how closely the simulation and real-world data match up helps scientists ascertain both the quality of the computer models and the conclusions drawn from the paleodata. If they 'predict' past consequences of climate change that we know did happen, then they are good models. "Studying past climates provides a natural 'laboratory' to fully understand the Earth system beyond what people have measured directly in the last couple of centuries," says Bette. "The Earth's climate has fluctuated a lot in the past – it has gone through periods of much warmer and colder climates, and rapid transitions between the two."

THE COMMUNITY EARTH SYSTEM MODEL

Climate models are becoming ever-more sophisticated and much of this is down to the increasing capabilities of computers. "Enhanced supercomputers have made it possible to run state-of-the-art climate models for ultra-long simulations, which is what TraCE is based on," says Liu. CESM's simulation accounts for atmospheric greenhouse gases, solar radiation entering our atmosphere, the role of ice sheets, ocean currents and meltwater, among many other factors. It also models how these all interact with one another.

CESM can also account for how things have physically changed over the last 21,000 years: the distance between the Earth and the Sun, which affect sunlight reaching the earth; the

PROFESSOR ZHENGYU LIU

Max Thomas Professor of Climate Dynamics, Department of Geography Ohio State University, USA

FIELD OF RESEARCH

Climate Dynamics

RESEARCH PROJECT

Using climate models and historical data to predict the relationship between the Atlantic Meridional Overturning Circulation and abrupt climate change.

FUNDERS

US National Science Foundation
US Department of Energy
Natural Science Foundation of China

DR BETTE OTTO-BLIESNER

Senior Scientist, National Center for Atmospheric Research (NCAR) Boulder, Colorado, USA

FIELD OF RESEARCH

Meteorology and Climatology

RESEARCH PROJECT

Using climate models and historical data to predict the relationship between regional climate change and monsoon patterns in Africa and Asia.

FUNDERS

US National Science Foundation
US Department of Energy

shape of continents and oceans; ice sheets and mountains; and the composition of the atmosphere, including greenhouse gases. The model is regularly supplemented with an ever-growing depth of scientific understanding. "By incorporating our new knowledge of planetary processes and how they interact into the models, we can make them ever-more accurate," says Bette.

CLIMATE CLUES FROM THE PAST

It is all very well building all these factors into computer models, but there must be a way to check that they are making accurate predictions. This can be done by 'calibrating' the model with data gleaned from the prehistorical record. Scientists are finding increasingly insightful ways of making inferences from the clues left behind on Earth.

Ice cores and sediment cores form the backbone of climate paleodata. A core is a vertical sample of ice or sediment extracted from an area of interest. The core effectively acts as a 'timeline' – the ice or sediment nearer the top of the core will have been laid down recently, whilst that nearer the bottom will have been laid down a long time ago. By studying the characteristics of the ice or sediment at different points on the core that correspond to different points in the past, we can find clues about what the world used to look like. For ice cores, these clues include things like bubbles of greenhouse gases, particles of dust or ash, and oxygen isotopes that act as a proxy for past temperatures. Sediment cores can include pollen, which give an indication of the sort of vegetation that used to grow in an area which, by comparing to modern-day knowledge about plants' living conditions, can help us infer what that area's climate used to be like.

Neither of these methods give us a perfectly accurate window into the past, but by comparing results with each other and with other sources of paleodata, we can build a good picture. Being able to compare these deductions with computer models such as the CESM means there is even more room for taking a critical look and fine-tuning our knowledge of our planet's history ever further.

THE AFRICA PUZZLE

Although they collaborate on the TraCE project, Liu and Bette's specialisms lead to them focusing on different areas. Bette's work covers the interaction between climate change and the monsoon season in Africa and Asia. One peculiar finding from delving into the planet's past was a period known as the 'African Humid Period'. This time, from 14,700 to 5,000 years ago, saw an abrupt increase in rainfall in Africa, so much so that deserts turned into grasslands and savannahs.

Scientists found an explanation for why this might have happened for those areas north of the equator: the Earth's orbit had a 'wobble' at the time, due to its gravitational interactions with other celestial bodies such as Jupiter and Saturn. This meant that the northern hemisphere was closer to the Sun in summer, leading to stronger summer temperatures that strengthened monsoon winds and led to more rainfall.

However, large swathes of Africa south of the equator also experienced more rain, which cannot be explained by this wobble, since the southern hemisphere would be further from the Sun during its summer. "Our CESM simulation revealed the role of two other factors," says Bette. "A change in Atlantic Ocean currents, coupled with a rise in greenhouse gases, rapidly boosted rainfall in the region." The role of greenhouse gases in this phenomenon can help us predict more accurately what the effects of climate change may look like this time around, which will have major consequences for Africa's agriculture industry and other sectors.

ATLANTIC CURRENT EVENTS

These findings also link to Liu's specialism, which is the interaction between climate change and ocean currents. Ocean currents act like a 'conveyor belt', ensuring that oceanic waters are continuously in circulation. This has big implications for life on Earth: for instance, the Gulf Stream ensures that Europe has relatively mild weather, while the El Niño current ensures that nutrients that have sunk to the seafloor are periodically brought back into surface waters off the coast of Peru.

A major current system, that feeds into all ocean currents around the world, is the Atlantic Meridional Overturning Circulation (AMOC). There is some evidence that this circulation has weakened in recent years. Historical evidence and climate models suggest that this could lead to a feedback loop – meltwater from the polar regions weakens the AMOC, which accelerates the rate of climate change. This raises the possibility of a 'tipping point' in the Earth's near future where an abrupt change to the climate takes place.

TRACE IN ACTION

Through these findings and many others, TraCE has led to significant steps forward in our understanding of global climate since the Last Glacial Maximum (LGM). The LGM was about 21,000 years ago, when the planet was around 6°C colder, and glaciers were at their furthest extent. For this time period, TraCE has found that the CESM simulation overall matches up well with inferred climate changes from paleodata, particularly in areas such as Greenland, Antarctica, Africa, the tropical Pacific and the Southern and Deep Oceans.

However, findings do not always match up – for instance, Liu and Bette found that historical data showed a weak global cooling trend over the last 10,000 years, whereas the model indicated a weak global warming trend for the same period. Having dug into it further, the researchers believe this is due to shortcomings both in the data and the model. "The inconsistencies are likely partly due to a data bias towards the summer season and inadequate representation of feedback processes in the model," says Liu. Now they know this, they can go back and work on making our understanding of the historical record more accurate and the computer model truer to life.

Key to these processes is collaboration. Although Liu specialises in climate dynamics and Bette in atmospheric sciences, by combining their different strands of knowledge they can accelerate the rate of scientific knowledge. This is enriched by collaboration with many others – entire teams of scientists, computer modellers, engineers, geologists and more, all work together to ensure we have as comprehensive a picture of our planet's past and future as possible.

HOW TO BECOME A CLIMATOLOGIST

- Liu specialises in climate dynamics. This field involves studying the processes behind the global climate system and how they change over time. This includes the interactions of the atmosphere, oceans and ice, bodies of land and biological organisms.
- There are some undergraduate degrees in climatology. A number of other undergraduate degrees, including physics, applied mathematics, Earth sciences, and chemistry, can also lead to a career in climate dynamics.
- According to QS World University Rankings, the best universities in the world for physics (as an example) are MIT, Stanford, Harvard, Cambridge, and Oxford.
- According to PayScale, the average climatologist salary in the US is $70k.

HOW TO BECOME AN ATMOSPHERIC SCIENTIST

- Bette specialises in atmospheric science. This involves understanding the processes within the atmosphere and how they link to weather and climate patterns, including interactions with longer climatic changes.
- There are meteorology undergraduate degrees available, but a career in meteorology can also be secured following a degree in physics, atmospheric sciences, maths or computer science.
- According to QS World University Rankings, the best universities in the world for meteorology and atmospheric sciences are the University of Colorado at Boulder, University of Washington, Colorado State University, University of Reading (UK) and California Institute of Technology.
- According to PayScale, the average meteorologist salary in the US is around $57.6k. Pay scales really depend on degree (B.S., M.S. or Ph.D), employer (academic, government or business) and seniority.

PATHWAY FROM SCHOOL TO CLIMATOLOGIST

Liu recommends taking mathematics at school, as well as the sciences, especially physics and chemistry. Other subjects such as computer science could also be useful.

PATHWAY FROM SCHOOL TO ATMOSPHERIC SCIENCE

Bette recommends subjects such as maths, physics, chemistry, statistics and computer programming.

HOW DID LIU AND BETTE BECOME CLIMATE SCIENTISTS?

WHAT WERE YOUR INTERESTS AS A CHILD?

L: When I was younger I was more interested in painting and literature than science. Nature always drew my curiosity, which is perhaps where my scientific interests arose.

B: I loved watching the weather! I was always curious about understanding what led to the weather patterns I could see.

WHAT INSPIRED YOU TO BECOME A SCIENTIST?

L: I don't remember any particular reason, other than my interest in the natural world, which likely drew me to science.

B: Maths and science were my favourite subjects in school and university. In many classes I was one of only a few females, but I always had the support of my teachers and my parents.

WHAT ATTRIBUTES MAKE A SUCCESSFUL SCIENTIST?

L: Keeping your curiosity is a key factor.

B: Collaborating with those who have different areas of expertise is essential. The Earth is a complex and interconnected system, after all.

WHAT DO YOU FIND MOST REWARDING ABOUT YOUR WORK?

L: I love being able to uncover some of the secrets of the natural world that are hidden within the climate system.

B: Communicating about the importance of understanding past climates to prepare us for the future brings me the most satisfaction.

WHAT ARE YOUR PROUDEST CAREER ACHIEVEMENTS?

L: Developing TraCE is definitely one of my best accomplishments. I am also proud of some fundamental theories on climate variability that I developed.

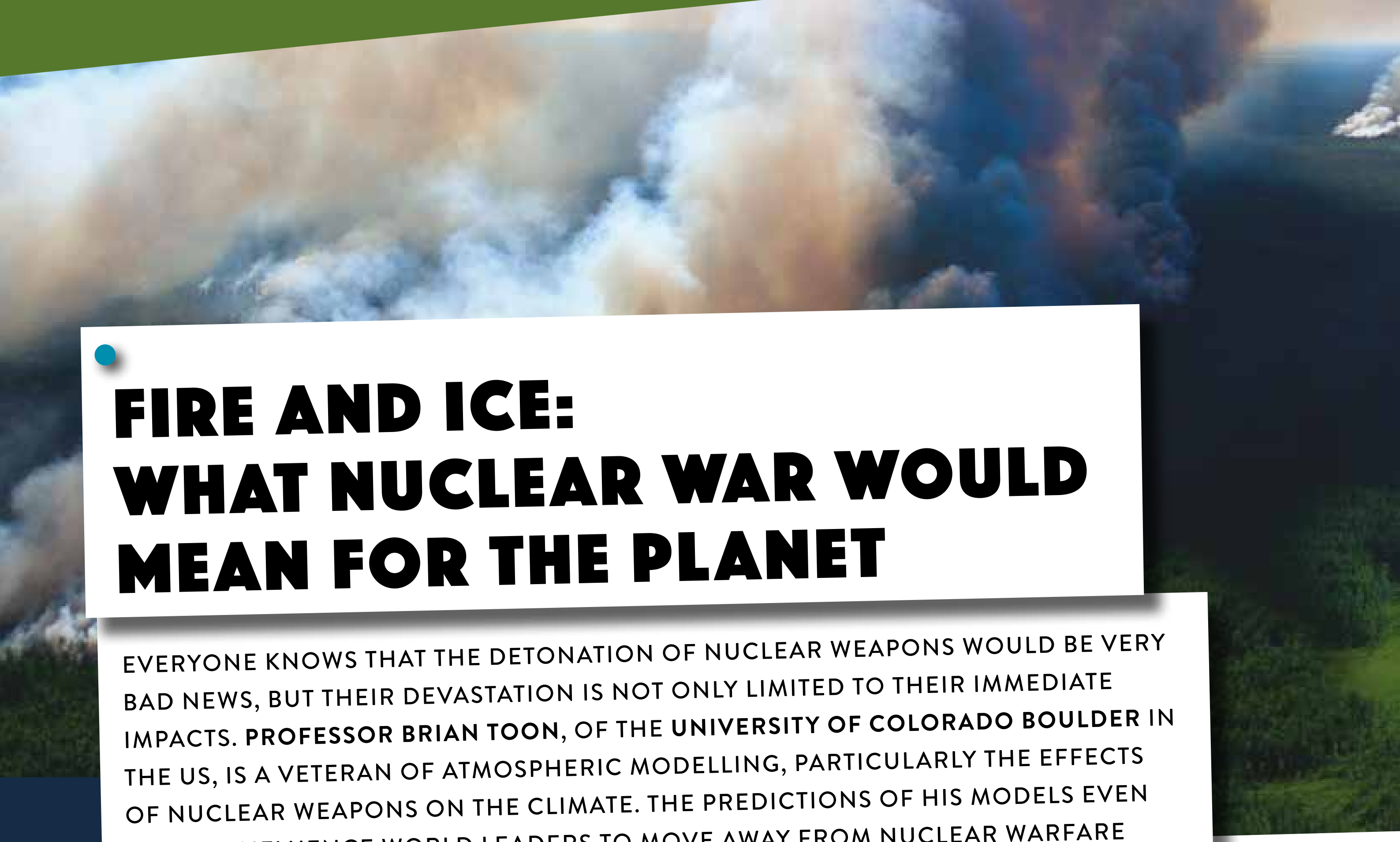
B: Of course, TraCE is one of my proudest achievements and has been many decades in the works. I have also served as a lead author on two IPCC (Intergovernmental Panel on Climate Change) reports, which was an honour. This led to me being a co-recipient of the Nobel Peace Prize in 2007.

LIU AND BETTE'S' TOP TIPS

01 Keep your curiosity about the world around you – always ask yourself, why does this work the way it does?

02 Always be persistent. The answer to a scientific challenge could be just around the corner.

03 Maths and the sciences are essential components of a lot of research, so it is worth getting a solid grounding in them.



FIRE AND ICE: WHAT NUCLEAR WAR WOULD MEAN FOR THE PLANET

EVERYONE KNOWS THAT THE DETONATION OF NUCLEAR WEAPONS WOULD BE VERY BAD NEWS, BUT THEIR DEVASTATION IS NOT ONLY LIMITED TO THEIR IMMEDIATE IMPACTS. **PROFESSOR BRIAN TOON**, OF THE **UNIVERSITY OF COLORADO BOULDER** IN THE US, IS A VETERAN OF ATMOSPHERIC MODELLING, PARTICULARLY THE EFFECTS OF NUCLEAR WEAPONS ON THE CLIMATE. THE PREDICTIONS OF HIS MODELS EVEN HELPED INFLUENCE WORLD LEADERS TO MOVE AWAY FROM NUCLEAR WARFARE

TALK LIKE AN ATMOSPHERIC SCIENTIST

CLIMATE MODELLING – computer models that simulate the Earth's climate and can be used to project past and future climates.

COLD WAR – a long period of political tension between the USA and Russia, from the late 1940s and ending in 1991 with the dissolution of the Soviet Union. It was characterised by threats of nuclear attacks from both sides – although none happened, mainly for fear of mutual annihilation.

NUCLEAR WEAPON – a bomb or missile that creates an explosion through nuclear fission and/or fusion. Also known as an atomic bomb.

NUCLEAR WINTER – a period of prolonged cold and darkness following a nuclear war, due to smoke and dust in the atmosphere blocking the sun's rays.

STRATOSPHERE – the layer of atmosphere that begins about 7 miles from the Earth's surface, directly above the layer where clouds and rain form (troposphere). We live at the bottom of the troposphere, while airliners typically cruise in the lower stratosphere.

The history of nuclear weapons is not pleasant. Nuclear warheads were first developed and deployed by the US during World War II, with the devastating bombings of Hiroshima and Nagasaki. Though they have not been used aggressively since then, the tensions of the Cold War led to well-justified fears that a nuclear war between the US and Russia could be imminent. The nations' leaders eventually backed down when scientists shared their discoveries that such a war could lead to a global nuclear winter and mass starvation due to the inability to grow food.

Although the quantity of nuclear weapons in the world has decreased by a factor of 5 since the mid-1980s, the 14,000 that remain could do immense harm. Despite nations' claims that the weapons' existence is simply a deterrent, global tensions mean nuclear war remains a distinct possibility.

Professor Brian Toon, of the University of Colorado at Boulder in the US, has spent decades predicting what effects nuclear war would have on society. He and his research group use sophisticated computer programs to model the world's atmosphere and to see how it could change in different nuclear scenarios. His findings have informed global leaders, making sure they are aware about the dire consequences of nuclear conflict.

CLIMATE MODELLING

Most science relies on experimentation, but this is simply not possible when predicting the effects of nuclear wars. Instead, scientists turn to computer modelling, which takes certain inputs, for example the amount of smoke injected into the atmosphere by fires started by nuclear explosions, and calculates a projected outcome for a scenario, such as the changes in climate and impacts on agriculture and fisheries. Modelling the future of the Earth's climate is especially important in today's world, as we need to understand the effects of a rapidly changing climate. The same climate models can be used to predict the effect of other global scenarios, such as nuclear wars.

As computers have become increasingly sophisticated, so have computer models. They better capture the complexities of the real world and their predictions are more accurate. More recent models for predicting the effects of a nuclear war have resulted in a worrying conclusion: even a relatively modest nuclear war, such as between India and Pakistan, could have a profound global impact. Localised conflicts could have devastating worldwide effects; the decisions of Pakistani and Indian

PROFESSOR BRIAN TOON

Professor of Atmospheric and Oceanic Sciences, Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, USA

FIELD OF RESEARCH

Atmospheric and Planetary Sciences

RESEARCH PROJECT

Using computer models to predict the outcomes of nuclear war, in particular its implications for the global atmosphere.

FUNDER

Open Philanthropy Foundation

politicians and generals could lead to starvation throughout the rest of the world.

GOING NUCLEAR

Any good model uses evidence from past events to inform predictions. "We know a lot about the immediate, local effects of nuclear detonations because over 500 nuclear bombs were detonated in the atmosphere before testing was banned in 1963," says Brian. "However, these tests were conducted in deserts or on small islands, to prevent the outbreak of huge fires." It is fires that most concern Brian – if nuclear weapons were to target cities, they are expected to alight massive blazes. Cities contain a lot of fuel to burn through, much more than forests. The fires and explosions would kill tens or hundreds of millions of people. The single, small nuclear weapon dropped on Hiroshima, Japan, in World War II is thought to have killed around 100,000 people. However, these local effects of nuclear explosions are not the greatest danger to the world.

Where there is fire, there is smoke – and the smoke generated could have world-changing effects. "A lot of the smoke produced would enter the stratosphere," says Brian. "This smoke would spread across the globe within a few weeks, cooling the planet's surface by a few degrees on average, even from a war between India and Pakistan, with less than 1% of the world's nuclear weapons." The world would turn cold, dark and dry, leading to a range of serious consequences, most notably huge damage to agriculture. "High-latitude countries, such as Russia, would be most impacted given the already cold conditions there," says Brian. "The world would face widespread starvation."

LOOKING DEEP INTO THE PAST

While evidence from past nuclear tests can reveal the immediate impacts of nuclear detonation, it is not sufficient to extrapolate the effects of a nuclear winter using models. Because the Earth has never experienced a nuclear winter, we have to look for analogous events deep in the planet's past. One planet-shaking event that shaped the course of life on Earth stands out.

66 million years ago, an asteroid the size of Everest struck the Earth, in what is now Mexico, at a speed 10 times that of a bullet from a rifle. Ultimately, the impact killed off about three-quarters of all species, including all the dinosaurs, except those avian dinosaurs that remain with us today as birds. "The asteroid impact had the energy of 100 million of the largest nuclear weapons," says Brian. "The asteroid impact started fires that burned practically everything on Earth's surface. After the initial catastrophic effects, a huge volume of soot remained in the atmosphere for about 10 years. Remnants of the smoke are still found in the geologic layers marking the extinction. This smoke absorbed all the sunlight, freezing the Earth's surface and heating the stratosphere to such high temperatures that it destroyed the ozone layer." For those creatures that survived the initial event, the next few years were desperately challenging. Starvation and exposure led to the demise of entire species.

Although there are still many unknowns about the effects of the asteroid, smaller events within relatively recent human history lend crucial insights. "The huge eruption of the Tambora volcano in Indonesia in 1815 impacted the entire world," says Brian. "It was followed by the 'year without a summer', as the cooling effect of the particles in the stratosphere, in this case made of sulfuric acid instead of smoke, caused crop losses across the globe." Because of the massive fires caused by nuclear weapons, especially when targeting urban areas, it is likely that nuclear war would result in a similar scenario – or even worse, depending on the scale of the conflict.

INFLUENCING POLITICS

The de-escalation of the Cold War provides a shining example of how science can influence policy for humanity's benefit. It was during this period that scientists developed the models that predicted a nuclear winter and were quick to convey the consequences to world leaders, influencing them to step away from the red button. However, nuclear weapons have not gone away. "We are currently teetering on a precipice where the nuclear arms race might get worse, or peace might prevail," says Brian. "Young people today will live with the consequences of the course of action chosen in the next few years."

Brian is passionate about the need to avoid nuclear war at all costs. "Nuclear weapons are a sign of power, control and defence," he says. "At the moment, several treaties need to be rewritten to limit the runaway construction of ever more nuclear weapons. In addition, the UN has voted to ban nuclear weapons." Despite this crucial necessity of new treaties, Brian's group is one of very few investigating the issue. "Hardly any scientists are working on predicting the impacts of nuclear war," he says. "This lack of scientific input is very unusual for an important scientific and societal issue. Government leaders need unbiased information to make intelligent decisions."

ABOUT ATMOSPHERIC SCIENCE

Brian's work is very varied and leads him across many scientific disciplines.

WHAT DO YOU FIND MOST REWARDING ABOUT YOUR FIELD OF RESEARCH?
I enjoy working with students and other colleagues. However, it can be challenging to find the funds needed to support students – it can cost half a million dollars to take one graduate student to a PhD.

IS THERE A LOT OF RANGE IN YOUR WORK?
Currently, in addition to the nuclear winter studies, I work with students and colleagues to investigate volcanic clouds, rivers on ancient Mars, the climates of exoplanets, the distant past and future climates of Earth, the extinction of the dinosaurs, Asian air pollution during the monsoon season, loss of ozone in the polar regions as in the ozone hole, and simulation of clouds in climate models. I also teach. As well as all of these, I am involved with several satellite projects, and other projects using NSF and NASA high-altitude aircraft.

WHAT COLLABORATIONS DOES YOUR WORK INVOLVE?
I work with hundreds of people, mostly on large field studies involving NASA aircraft studying atmospheric clouds, chemistry and climate. These projects take huge numbers of people to carry out and many years to work on the data. Even computer modelling takes a lot of students and researchers to tackle the various aspects of the problems at hand.

WHAT WILL BE THE MAIN CHALLENGES FOR TOMORROW'S ATMOSPHERIC SCIENTISTS?
Climate change is going to have a major impact in coming decades. We will be forced to adapt to rising sea levels and extreme temperatures, among many other effects. Hopefully, we can find ways to mitigate this problem, but to do this we need a complete overhaul of our energy production systems, which is a major technical and political challenge. Climate change will also lead to increases in conflict and immigration, which could make nuclear war more likely – something that it is crucial to avoid.

HOW TO BECOME AN ATMOSPHERIC SCIENTIST

- A career in atmospheric science can be approached from many backgrounds. While many undergraduates study meteorology or atmospheric science, one can also study any of the major science fields such as physics, chemistry, biology or engineering. According to QS World University Rankings, the best universities for Natural Sciences (as an example subject) are MIT, Harvard, Stanford, Cambridge and Oxford. The University of Colorado at Boulder is one of the leading Geosciences universities in the world, along with the California Institute of Technology.

- Many institutions offer internships covering atmospheric science: **https://www.pathwaystoscience.org/Discipline.aspx?sort=EAR-AtmosphericSci_Atmospheric%20Sciences**

- According to CareerExplorer, the average annual salary for an atmospheric scientist in the US is around $95k.

HOW DID BRIAN BECOME AN ATMOSPHERIC SCIENTIST?

My family moved every few years because my father was a naval aviator, so I had to make new friends constantly. We had many pets, and I also spent a lot of time swimming, fishing and being outdoors whenever possible. I enjoyed reading, especially books by famous scientists, as an effort to try and understand the world around me.

I grew up in an age when many young people were being encouraged to pursue science, through efforts in the media and breakthroughs around the world such as the Sputnik satellite. My mother bought me many science books which I devoured, and from that point on I have spent my life trying to understand scientific mysteries.

Successful scientists are driven to understand the issues that interest them. There is a bit of luck needed sometimes, but mostly it comes down to determination and hard work. I find that the students who do best are not necessarily those recognised as the smartest, but rather those most determined to pursue their dreams.

I encounter obstacles on a daily basis! I try not to let myself get side-tracked on minor issues, and I also diversify my work so if one area reaches a barrier, I can move forward with another. I am also tenacious; I have been working on some problems for nearly fifty years and there is still disagreement about the solutions. Nevertheless, great progress has been made.

As well as my scientific discoveries, many of my proudest moments relate to the interaction of science with world affairs. I am proud to have helped influence the US and Russian leaders during the Cold War to sign a treaty to limit intermediate range nuclear weapons through the development of the nuclear winter theory. Since then, I am proud to have been recognised for contributing to the Nobel Peace Prize awarded to the UN and Al Gore for research on climate change. I am also proud of my work on understanding the ozone hole including predicting the occurrence of nitric acid clouds in the polar night. Finally, I am also very proud of the many students who have worked with me and gone on to have great careers of their own.

BRIAN'S TOP TIPS

01 Figure out what you are passionate about and pursue it – but don't be afraid to change direction if your interests change.

02 Take the opportunities that are available to you. You may not be asked twice!

03 Never give up. Science can take a long time and suffer many setbacks, but the resultant breakthroughs make it worth it.

PATHWAY FROM SCHOOL TO ATMOSPHERIC SCIENTIST

Brian says that people can get into atmospheric science from almost any background but recommends getting a solid background in the fundamental sciences – physics, chemistry and biology. He emphasises that atmospheric science is a multidisciplinary field and needs people from a wide range of backgrounds, such as engineering and computer science.

Brian enjoys being outside, no matter the weather brings. He enjoys kayaking, snorkeling and hiking, when possible

CHANGING THE POLITICS OF TOMORROW BY QUESTIONING TODAY

DR JONAS PONTUSSON LEADS THE UNEQUAL DEMOCRACIES PROGRAMME BASED AT THE **UNIVERSITY OF GENEVA** IN SWITZERLAND. THE PROJECT EXPLORES RISING INCOME INEQUALITY AND THE WAYS IT AFFECTS POLITICAL PROCESSES IN LIBERAL DEMOCRACIES

It is one of the great shames of the 21st century that income equality has continued to rise, with the gap between the rich and the poor becoming an ever-widening chasm. How can it be that there are those with literally billions of pounds, while others do not have enough to eat? The coronavirus pandemic has brought rising inequality into sharp focus, with several recent studies showing that the rich have got even richer as Covid-19 continues to wreak havoc around the world – Jeff Bezos, the founder of Amazon, saw his wealth swell by $74 billion in 2020 alone.

Research from Oxfam shows the world's richest 1 per cent has more than twice as much wealth as 6.9 billion people, with almost 50 per cent of humanity living on less than $5.50 per day. Despite these shocking and appalling facts, there is a distinct lack of acknowledgement from governments around the world. We might ask if this would be the case if more members of the public voiced their displeasure concerning the situation and there was a clamour for change.

To understand more about citizens' perceptions of income inequality and the role that government might play in combatting it, a team led by Dr Jonas Pontusson, a political scientist based at the University of Geneva in Switzerland, has embarked on a project that is composed of a survey designed to shed some light on what members of the public think about of income inequality, and what the varying opinions regarding what inequality means are.

WHAT WERE THE THEORETICAL MOTIVATIONS BEHIND THE SURVEY?

Jonas has a long-standing interest in the comparative politics of inequality and redistribution. With this survey, he hoped to understand more about how citizens view inequality and why there is not more demand for change. "Income inequality, especially top-end income inequality, has risen in most West European countries (as well as the US) over the last two or three decades. Assuming that they are well-informed and self-interested, we would expect low- and middle-income citizens to respond to this development by demanding compensatory policies from government, shifting the tax burden onto the rich and/or increasing income transfers to low- and middle-income households," explains Jonas. "The conventional view is that democracy would lead us to expect governments to respond to the demands of these citizens, since they constitute a majority of citizens. But we see very little by way of compensatory redistribution in these countries."

Of course, there could be many reasons for this, such as governments being more responsive to the needs of the rich, but it could also be because low- and middle-income citizens do not behave in a way we might expect. For instance, they might not be aware of what is happening with income inequality, or they might think of inequality in terms of fair rewards for effort and talent. There is the possibility they do not see how government can change the situation, or they have different priorities, such as climate change or immigration. Jonas determined to answer these questions through the survey.

HOW WAS THE SURVEY DEVISED?

The questionnaire was created by Jonas and three of his collaborators. Many of the questions they asked were taken from previous surveys, which enabled them to compare samples of

DR JONAS PONTUSSON

Professor of Comparative Politics
Geneva School of Social Sciences
University of Geneva, Switzerland

FIELD OF RESEARCH

Comparative Politics

RESEARCH PROJECT

Jonas' research is composed of a survey that forms part of a project entitled Unequal Democracies. The survey is designed to understand citizens' perceptions of income equality and the role that governments can play in combatting it.

FUNDER

European Research Council

their respondents with those of other surveys. Trying to ensure that the questions were unbiased was an important consideration for the team. "In formulating survey questions, it is important to avoid giving respondents the impression that there is a right answer and to let them know that they have the option not to answer questions they consider to be sensitive," says Jonas. "Equally important, the questions and response options have to be as clear as possible. Before finalising the survey, we had a workshop in which researchers with extensive experience with surveys gave us feedback on our draft questionnaire."

HOW WAS THE SURVEY IMPLEMENTED AND WHAT WAS THE PROCESS FOR ANALYSING THE DATA?

The team used a commercial survey-research company called Ipsos, which carried out the survey in 14 countries selected by Jonas and his collaborators. There were at least 2,000 respondents in each country, with a focus on long-standing liberal democracies in Western Europe, as well as the US and other Western European countries with different inequality trajectories over the last 20 years.

Ipsos provided Jonas and his team with the data from the survey around a year ago. Researchers involved in the project are currently analysing the findings and addressing different questions – one is writing a PhD thesis on what shapes people's perceptions of whether inequality is fair and how fairness matters for policy preferences, while others are working on how union members' views of inequality differ from those of other survey respondents.

WHAT HAS THE SURVEY REVEALED SO FAR?

Generally speaking, the findings show that people are well aware that inequality has risen in their respective countries over the past 20 years or so. Interestingly, it appears as though respondents tend to overestimate the extent of inequality, although they consider other societal problems, such as unemployment and climate change, as being more important than income inequality. "In all 14 countries, large majorities of survey respondents agree with the proposition that politicians are particularly attentive to the policy demands of affluent citizens and corporations. Large majorities also agree that their own views are not very well represented by elected officials," explains Jonas. "Whether or not people are dissatisfied with the way that democracy works, they clearly do not believe that democracy is a 'level playing field'."

Another striking finding is that support for higher taxes on the rich has increased in most countries and so has support for a flat-rate pension and unemployment compensation, as opposed to earnings-differentiated benefits. From this, it appears as if public opinion has moved to the left since the economic crisis of 2008-09.

So far, the team's analyses have focused on differences of perception across income groups, but the survey also enables them to explore differences across educational levels and occupational groups. One of the researchers is writing a paper on whether social class is more relevant than relative income for people's attitudes towards inequality. One of the most critical questions is how different forms of income inequality affect political attitudes and behaviour. Currently, it looks as if low-income respondents who perceive politics as biased in favour of the rich are more likely to abstain from voting.

WHAT ARE THE NEXT STEPS FOR THE RESEARCH?

The team wants to link the survey data on individual attitudes and behaviour to data on country differences in inequality trends and policy outputs. "We want to understand whether the shift to the left has been more pronounced in countries where top income shares have risen most dramatically," says Jonas. "We also want to determine the extent to which policy makers have responded to this shift in public opinion – if at all."

ABOUT COMPARATIVE POLITICS

Politics affects every one of us in some way, shape or form. The pandemic has shown us how government policy can affect the citizens of any given country in myriad ways; the UK has recently suffered its 100,000th death from Covid-19, while countries such as New Zealand have all but eradicated the virus. That is not down to pure chance – it is heavily related to the measures that have been put in place by the governing party (although it is worth acknowledging that it is more complex than this and is also clearly related to citizens' behaviour – although this can also be linked to the government within a given country).

Comparative politics is a branch of political science that seeks to use varying methods to explore and understand politics within different countries around the world. In many ways it is a huge undertaking, if only because there are so many complex reasons for people thinking and acting in the way that they do that accessing a definitive answer to related questions is very challenging.

As Jonas' survey has shown, there are parallels and distinctions that can be made across countries, ones that serve to shed some light on specific situations. By engaging with comparative politics, Jonas is attempting to understand what people think about inequality and – perhaps more importantly – why they think what they do.

WHAT DOES JONAS FIND REWARDING ABOUT HIS FIELD?

Jonas really enjoys the breadth of activities within his work. "I love the combination of research, training researchers and teaching undergraduate students," explains Jonas. "Research focuses on very specific questions and often becomes quite technical – it is an interesting challenge to explain to students aged 18 or 19 why these questions are important and how they relate to the pressing questions of our times."

HOW DOES JONAS STAY MOTIVATED?

The project's focus on income inequality and the statistics that are highlighted at the beginning of the article are disheartening. Reading and researching some of the findings highlights some of what is unfair about the world that we live in. However, the fact that Jonas and other researchers are conducting such research is heartening and encouraging – bringing about change can only be achieved by questioning today's realities and understanding people's opinions is a huge part of that.

It is always worth keeping in mind that there is plenty that is beautiful and brilliant about our world too. "My own children, their friends and most of the students that I meet at the university are kind, tolerant people," says Jonas. "They are committed to progressive solutions to the social and environmental challenges that we face today, which certainly bodes well for the future."

WHAT DOES JONAS SEE FOR THE FUTURE OF DEMOCRACY?

Clearly, there are many problems around the world, but Jonas believes that identifying solutions is not the difficult part – the issue is finding politicians who are committed to implementing solutions. "Over the last 20 or 30 years, mainstream political parties have increasingly competed for the support of relatively affluent middle-class voters and have tended to ignore the uneducated, the poor and immigrants – citizens and non-citizens who often do not vote and who lack other ways to make themselves heard in politics," says Jonas. "Political elites have tended to assume that the 'low-educated' constitute a rapidly diminishing minority of citizens. In the context of rising inequality, economic stagnation and populist backlash, political elites have, belatedly, come to recognise that neglecting the people in the bottom half of the income distribution is not politically viable. I worry about the authoritarian nature of some populist politicians – Trump in particular – but, on the whole, I see the 'populist challenge' as a much-needed wake-up call for mainstream political parties."

HOW TO BECOME A POLITICAL SCIENTIST

- YouthPolitics UK is an award-winning, non-profit organisation that is dedicated to giving young people a voice:

  https://youthpolitics.org.uk/

- Teen Power Politics is a large collection of different resources related to various political organisations and causes in the US and beyond:

  http://www.teenpowerpolitics.com/tpp_ref.html

- The average salary for a political scientist in the UK is around £41,000, with a minimum of around £27,000 and maximum of £90,000, depending on the level of experience.

PATHWAY FROM SCHOOL TO COMPARATIVE POLITICS

Comparative politics is a sub-field of political science, which is a field you can expect to encounter at university but not at school. However, history, sociology and economics are related subjects and will provide a good foundation for doing research in comparative politics at a later stage in your studies. Statistical skills can also be very useful.

2 or 3 A levels, or equivalent, although you do not necessarily need one in politics to study it at university.

You will need a degree in a relevant subject for postgraduate study.

https://www.theuniguide.co.uk/advice/a-level-choices/what-a-levels-do-you-need-to-study-politics

HOW DID JONAS BECOME A POLITICAL SCIENTIST?

"**When I was a kid I was interested in history and wanted to become a diplomat.** However, my encounter with the anti-war movement in the early 1970s set me off in a different direction and I have never looked back.

Having grown up in Sweden, I moved to the US in 1972, at the age of 16. I was shocked by the inequality I saw there. At the same time, I was fortunate to attend a really good liberal arts college in the US, with several truly inspiring teachers. These experiences have informed all my subsequent thinking about politics and society.

I am curious, but also stubborn. I look to challenge what other researchers have said about topics that interest me, digging deeper, and pursuing alternative lines of inquiry. I also tend to stick to my guns and keep looking for evidence in support of arguments that I believe in.

Collaboration with other researchers – often younger and better trained than me – has served as a way for me to accomplish things that I could not do by myself. More generally, critical feedback from colleagues and collaborators can be very helpful when you get stuck (and perhaps need to abandon some idea you have come to believe in).

I am proud of having trained a dozen PhD students who have gone on to do really important research in the domain of comparative politics. I am also proud that I have tackled similar questions using a wide range of different methods over my career."

JONAS' TOP TIPS

01 The key to being a successful academic researcher, especially a social scientist, is to critically examine conventional wisdoms among people who work on the questions that interest you.

02 Real-world problems should guide the questions that you tackle in your research, so pay attention to what is happening in countries around the world and see what sparks your interest.

03 Inform yourself through mainstream news media, preferably several different media outlets. Mainstream media outlets have biases, but the news they report is not fake. Read the opinion pages and discuss politics with friends and family.

"WE BELIEVE IN GIVING OUR CHILDREN THE SKILLS THEY NEED FOR THE 21ST CENTURY."

LUISA VILLEGAS IS THE SENIOR DIRECTOR OF PROGRAM INNOVATION, AND EDUCATION THEMATIC LEADER, AT THE **PAN AMERICAN DEVELOPMENT FOUNDATION.** SHE EXPLAINS WHY PADF IS ON A MISSION TO IMPROVE STEM EDUCATION IN LATIN AMERICA AND THE CARIBBEAN

Born and raised in Colombia, Luisa worked in radio and TV before pursuing an undergraduate degree in journalism and communications in Medellin, her hometown. She won a Rotary Club scholarship, which enabled her to pursue a master's degree in Political Science in the US. Luisa started working at the Pan American Development Foundation (PADF) 15 years ago.

As Senior Director for Program Innovation, Luisa looks for ways to improve the management of PADF's programmes and is currently leading the implementation of a PMO (Project Management Office). As the thematic leader for education, Luisa is also responsible for setting up and expanding PADF's flagship STEM Americas programme. In addition, she leads internal and external communities of practice around the topic of education.

The First Lady of Panama Yazmín Colón de Cortizo has been named PADF Goodwill Ambassador for STEM Education.

IN ITS MISSION STATEMENT, PADF SAYS, "WE BELIEVE IN GIVING OUR CHILDREN THE SKILLS THEY NEED FOR THE 21ST CENTURY." WHAT SKILLS DOES PADF BELIEVE CHILDREN NEED AND WHY?

21st century competencies are those that allow students to thrive in today's world. These competencies are leadership, teamwork, critical thinking, creativity and the ability to use interdisciplinary skills for problem solving. These skills will help children to be successful, regardless of the type of job they choose.

HOW WOULD YOU DESCRIBE THE CURRENT STATE OF STEM EDUCATION IN LATIN AMERICA? HOW DOES IT COMPARE WITH THE REST OF THE WORLD?

It is hard to generalise such a large and diverse region. Countries like Colombia and Chile understand the power of STEM education and have embraced this methodology and incorporated it into their public policies at the national, state or local levels. Other countries still need to understand that STEM is not simply something you bring to privileged schools, or to schools that are already focusing on maths or science, or have the best computer labs. On the contrary, STEM needs to be invested in areas where children are being left behind, to give them a fair chance of succeeding.

The global pandemic is a perfect example for governments to understand the need to invest in better education and preparing future scientists and innovators who are going to be able to solve humanity's greatest challenges. We can no longer rely on other countries to provide those solutions – all these challenges need to be solved globally and locally.

WHAT IS PADF ULTIMATELY HOPING TO ACHIEVE THROUGH ITS STEM AMERICAS INITIATIVE?

We believe that STEM education needs to become public policy in all countries in this region. We cannot do that alone, but we can build a critical mass of successful projects so that governments take note of the positive impact that STEM education has on students.

A great example of a country where we are achieving this is Panama. Here, the work of our local partner has been so successful that it is now receiving support from the President and First Lady of Panama, and there is a collaboration in place to

provide STEM training to thousands of schoolteachers. This is exactly the type of impact we want to achieve throughout Latin America and the Caribbean.

Through the STEM Americas initiative, PADF also wants to promote the participation of women and girls in STEM. STEM education can promote girls' confidence in their maths and science abilities, and break gender stereotypes that claim that girls are not very good at these subjects. If girls gain more interest and confidence in maths and science, they are more likely to pursue STEM careers, have better career options and help close the gender gap.

THE FIRST LADY OF PANAMA YAZMÍN COLÓN DE CORTIZO HAS BEEN NAMED PADF GOODWILL AMBASSADOR FOR STEM EDUCATION. WHAT DOES THIS MEAN FOR STEM TEACHERS AND STUDENTS IN THE REGION?

The First Lady of Panama is committed to promoting STEM education not just in her country but also with her counterparts (other first ladies of the region), and in other international fora. She will help provide visibility to STEM education as an innovative and effective way to improve educational outcomes for the children and youth of our region. Ultimately, her job is to help realise PADF's vision of every child having the opportunity to experience STEM education as a way to ignite their creativity and acquire much needed skills.

PADF WORKS WITH PARTNER ORGANISATIONS IN ARGENTINA, BOLIVIA, CHILE, COLOMBIA, ECUADOR, PANAMA AND PERU. HOW DOES IT SUPPORT THESE ORGANISATIONS?

PADF provides funding for our partners' activities, training, technical assistance and a community to share, exchange and collaborate on best practices.

WHAT TRAINING PROGRAMMES DOES PADF OFFER TEACHERS IN LATIN AMERICA?

We are affiliated with the Organization of American States (OAS), the international body of governments of the western hemisphere. In partnership with OAS, we offer a STEM MOOC that provides a basic understanding of what STEM education should look like and the methodologies and strategies used to incorporate STEM into classrooms. We also offer scholarships to a 19-week graduate certificate that provides teachers with all the necessary skills to design STEM education programmes, learning environments and curricular content. In addition, our local partners offer their own training programmes adapted to their local needs.

PADF ALSO DEVELOPS LESSON PLANS INTENDED TO IGNITE CURIOSITY AND ENGAGE STUDENTS IN CREATIVE WAYS. HOW DO TEACHERS ACCESS THESE LESSON PLANS?

As mentioned, one of the strengths of our STEM Americas programme is the ability to support local partners and their work. They have various types of content and materials for different levels of accessibility, which are currently available in Spanish.

We are also working on an exciting initiative that will provide content relating to STEM and aerospace for teachers, parents or just about any person who is interested in learning about this topic. Stay tuned!

ON A PERSONAL LEVEL, WHY ARE YOU PASSIONATE ABOUT STEM EDUCATION?

I see STEM education as a vehicle for closing several gaps: educational, digital and gender gaps, in particular. STEM education is as an opportunity for countries to make significant gains, not just on their education performance but also on the creation of competitive jobs and improving the quality of life of its citizens.

FINALLY, WHAT DO YOU KNOW NOW THAT YOU WISH YOU KNEW WHEN YOU WERE YOUNGER?

The subject you choose to pursue in college is not as important as the soft skills you will acquire. We put so much pressure on our children to choose a career path even before they finish high school but, in my experience, life will put opportunities in front of you that will allow you to change course or even continue to explore new paths that never occurred to you when you were younger.

HOW TO USE OUR EDUCATION AND CAREER RESOURCES

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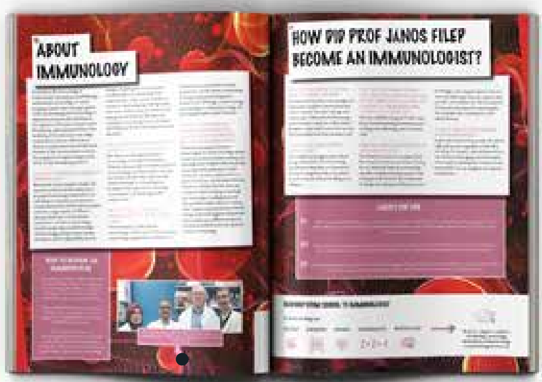

Find out how the researchers got to be where they are today

For example, János wasn't massively interested in biology when he was younger. He is now an immunologist!

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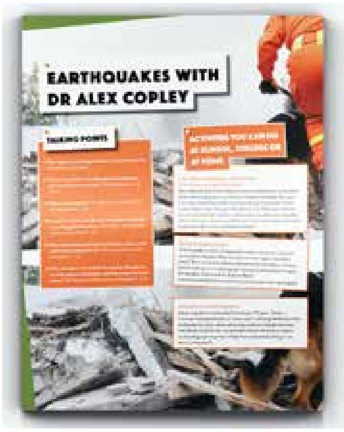

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We'll get back to you!

The work presented in this document has received funding from the European Union's H2020 research and innovation programme – project Scientix 4 (Grant agreement N. 101000063), coordinated by European Schoolnet (EUN). The content of the document is the sole responsibility of the organizer and it does not represent the opinion of the European Commission (EC), and the EC is not responsible for any use that might be made of information contained.