futurum

Inspiring the next generation

futurumcareers.com

PART I
ISSUE 18
January 2023

TSHEPISO MALEMA SPEAKS

Tshepiso introduces the motivational platform that helps young people achieve their dreams

SCIENCE AND TECHNOLOGY AUSTRALIA

Misha Schubert, CEO, tells us why education is key

THE SOCIETY OF WOMEN ENGINEERS (SWE)

Supporting girls to become part of the engineering and technology community

Be part of a STEM and SHAPE education community

Want more articles like these from researchers, students and associate organisations?

By signing up to **Futurum Careers**, you are subscribing to a community of academics, educators, employers, students – people like you – who want to show the world just how fascinating and rewarding a career in **STEM** and **SHAPE** can be.

What's in it for you?

As a member of Futurum Careers, you'll receive:

- The **latest articles** from academics and associate organisations
- **Teaching and classroom resources** relating to specific topics in STEM and SHAPE
- **Careers resources,** including PowerPoints, podcasts, animations and articles about inspirational role models
- A free, monthly **newsletter.**

Scan to sign up for free, or visit the website:

www.futurumcareers.com/sign-up

A note about your privacy

Your privacy is very important to us. We will not share, sell, reveal, publicise or market your details in any way, shape or form. Our full privacy policy can be found on the Futurum Careers website: www.futurumcareers.com/privacy

ISSUE 18
Part I

WELCOME

We are delighted to be marking the start of 2023 with a new look for Futurum magazine. This celebratory double issue showcases the impressive range of research taking place in the world today and introduces students to the wonderful researchers behind this ground-breaking work. Redesigned and looking more striking and engaging than ever, all the resources in Futurum magazine continue to be freely available online for students and teachers to use – and always will be.

As the new year dictates, we have reflected on the past year – on the fascinating educational brochures, animations and PowerPoints we have had the pleasure of creating – and are looking ahead to exciting new resources that will connect researchers with students even more. Futurum podcasts will enable researchers to 'talk to' students, sharing their personal insights, experiences and career pathways. We want students to know that everyone has a different path to take, and there is guidance and inspiration available to help them find theirs.

For this special issue, we knew we needed someone as ambitious and forward-thinking as we are for our cover star. Step forward Tshepiso Malema (p. 04), a student from South Africa who has turned his love of computer games into unique and life-changing enterprises, providing students with guidance and mentorship on their careers, and instilling a spirit of entrepreneurship.

Driven to help shape a positive future and enable young people reach their potential, Misha Schubert (p. 54) is CEO of Science & Technology Australia. She sets out its mission "to advance the public good and social and community welfare, and strengthen civil society through education, outreach and programmes".

Futurum magazine is more accessible and visually appealing than it has ever been, and we could not be prouder of Issue 18 – parts 1 and 2 – and of the inspiring articles it contains. We are excited to see what the future holds – both for us and the next generation!

THE FUTURUM TEAM

Karen Lindsay Director and Editor-in-Chief
Erica Morgan Assistant Editor
Isla Foffa Senior Editorial Assistant
Chukwudi Barrah Editorial Assistant
Brett Langenberg Director
Chris Dowell Project Manager
Kizzy Dennett Project Manager

DESIGN

Sophia Kerby Senior Graphic Designer

OUR WRITERS

Jacob Ashton, MA
Joe Aslett, MSc
Harry Carstairs, MPhys
Maureen Cohen, MPhys
Isla Foffa, PhD
Paul Redmond, MA
Lauren Shotter, PhD
Andrew Twelves, PhD
Kate Wilkinson, MA

PUBLISHED BY SCI-COMM CONSULTING

A limited company registered in England.
Company No: 10791252

futurum Inspiring the next generation

CONTACT

+44 117 9099150
info@futurumcareers.com
www.futurumcareers.com

POWERPOINTS

Our PowerPoints summarise the articles and include reflective 'Talking Points', making them a fantastic classroom resource:
futurumcareers.com/ppts

ANIMATIONS

As part of our free package of education resources, we include animations that bring many of the research stories to life:
futurumcareers.com/animations

PODCASTS

Featuring researchers talking candidly about their personal experiences, our podcasts are accessible, engaging and inspiring:
futurumcareers.com/stem-shape-podcasts

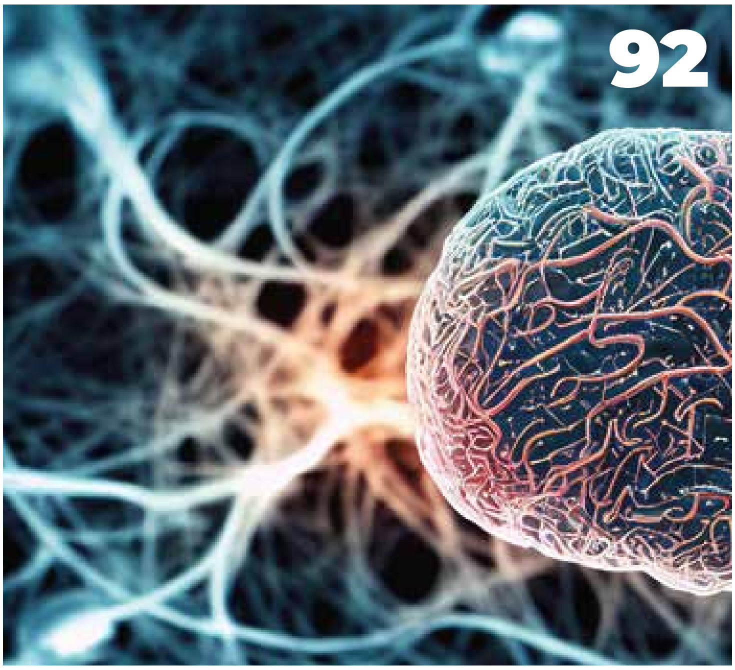
SOCIALS

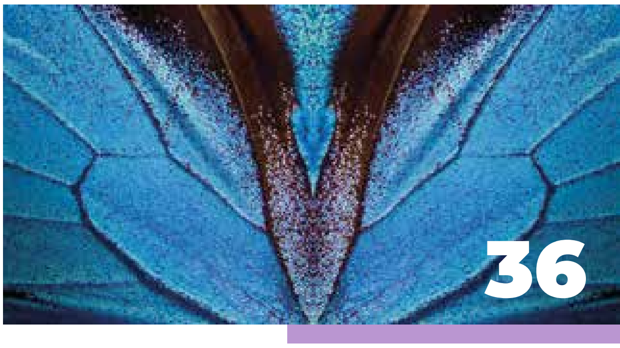
@FUTURUMCareers @Futurumcareers Futurum Careers @futurumcareers Futurum Careers

CONTENTS

Research articles

84





Research articles

INTERVIEWS

COVER STORY
Tshepiso Malema

04

© Wingman Communications

“WE WANT YOUNG PEOPLE’S DREAMS TO BE UNLOCKED THROUGH GAMING AND VIRTUAL REALITY.”

TSHEPISO MALEMA

Tshepiso Malema was 15 when he set up **Gamer’s Territory**, a place for young people to meet and play computer games, in Ivory Park, a Johannesburg township in South Africa. He then went on to set up **Tshepiso Malema Speaks**, a motivational platform to help young people achieve their dreams. He explains how his drive to support others set him on his entrepreneurial journey.

Why did you study information systems at the University of Pretoria?

At first, I wanted to study computer science, but, in South Africa, your grades determine which course you can take, and my grades weren’t good enough. So, I did some research and came across information systems at the University of Pretoria. When I read the course description and saw that it was a combination of entrepreneurship and IT, I thought, “Wow, this is what I should be doing!” At that point, the idea of studying computer science left me, and here I am, studying information systems and really enjoying it. Not having the grades I thought I needed was a blessing in disguise.

How do you stay motivated to learn?

The fear of failure keeps me motivated. My mom always tells me that I’m the one who will change our family situation. If I’m lazy and unmotivated, that means I’m ruining others’ futures.

In 2021, during the COVID-19 lockdown, I only had three months of face-to-face contact with my teachers. The rest of the time, I was studying on my own, which was terrifying. It’s so easy to get distracted and, during that time, I read books about entrepreneurship and emailed people to ask them to mentor me. But when I went back to class, I had to start catching up. My exam results were so bad, but the thought that I may not be able to stay at university hit me and I didn’t want to lurk behind. I had always imagined myself at a university, and so I started putting in more hours.

Why did you set up Gamer’s Territory?

I come from a township, and during the holidays,

© Katlego Mphuloane

I used to visit my cousins who live in the city. Obviously, the environment in the city is very different to the environment in the township.

I remember seeing my cousins play X-Box. I didn’t know what an X-Box was. For me, it was so magical to see them control the players, and it was at that point that I knew I wanted to get into gaming. When I was in grade 10, I won a laptop in a school competition, sponsored by Nka’Thuto Edu Propeller (a non-profit STEM organisation) and became one of 30 top technopreneurs in South Africa. The first thing I did was install a game on that laptop. This set me apart from my peers in the township because no one had seen a laptop, let alone a computer game. Everyone came to my home to watch me play. That was when I thought I could make some money from this. I charged people one rand (approximately 50p or 60 cents) to watch me play, and that’s how Gamer’s Territory was formed.

What happened next?

I realised that interacting with digital devices like PlayStation is not just an entertainment, it stimulates the brain. So, I started doing some research on gaming, the technology divide and how to bridge that divide. That’s when I wanted to do more. I became passionate about bringing tech to the townships, and I reinvested the money I made into Gamer’s Territory – buying more devices, entering competitions, exploring virtual reality – and, just like that, the business grew into what it is today.

How does playing computer games bridge the divide between people living in townships and people in more affluent circumstances?

When I was in school, I took coding classes and was able to start coding my own games. This was a revelation for me. Not enough people in the townships have access to such skills. My younger brother, who’s 12 now, watched me build a computer from scratch, and the next thing I knew, he was building his own. That gave me so much hope, and I thought even if we just start teaching coding to five kids (because we have limited equipment), we would still be making a huge difference.

Introducing young people to virtual reality is also great because you can be from the most disadvantaged area and yet still visit places like Dubai, places you’ve never been or may never have to chance to see. You can see Messi or Ronaldo in the FIFA football games.

© Wingman Communications

Gamer's Territory uses the phrase 'unlocking dreams'. We want young people's dreams to be unlocked through gaming and virtual reality.

How old were you when you set up Tshepiso Malema Speaks?

I was 17. At the time, I was very shy, but I was in a space where I was surrounded by mentors and people who inspire me. Some of my peers in the township are just living for the sake of it, and I wanted to do something that would help them feel just as motivated as me.

I started a blog and wrote down my thoughts, motivational insights, how I managed to change my mindset and my life goals. A few months later, I'd had over 500 visitors from all over the country – all over the world, actually – and the feedback I was getting was so positive. I thought if I could reach people's hearts just through the blog, I could convert the blog into an organisation.

When I say organisation, I was still doing this by myself, talking to students, talking to my classmates, but there I was, acting as a motivational speaker for young people. At my school principal's request, I spoke in an assembly and, before I knew it, I was visiting other schools and talking to other students there.

Now, we're a team of 14 young people, all of whom have diverse skills. Tshepiso Malema Speaks aims to give students guidance and mentorship on their careers and instil a spirit of entrepreneurship in South Africa, which has such high levels of unemployment.

How did you find your voice when you were so shy?

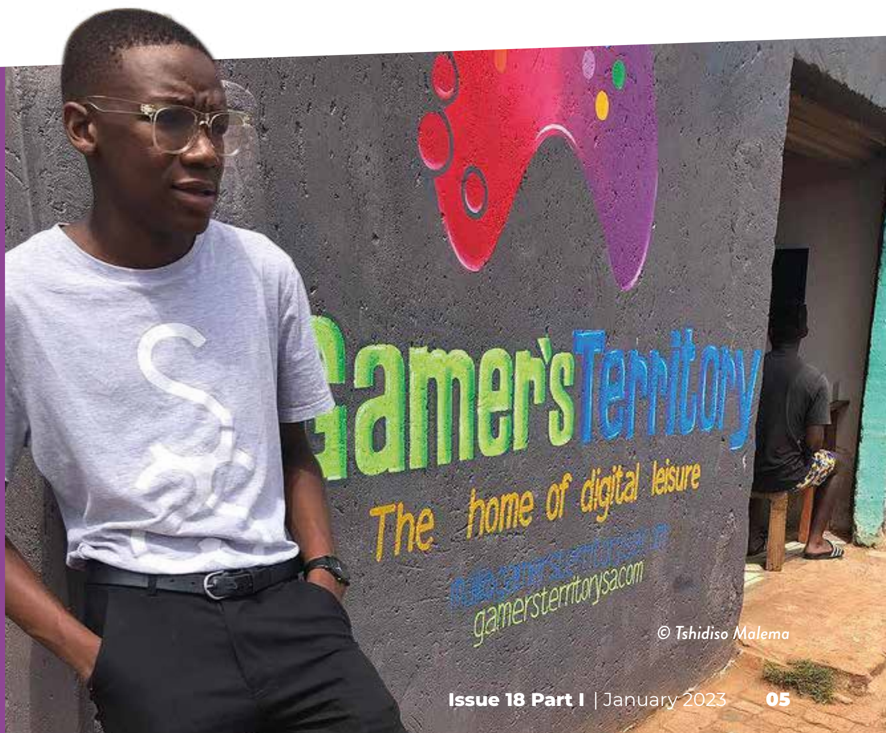
I was forced to have a voice because of the work I do and the competitions I was entering. People started inviting me to become a speaker. When you start to see positive results, it gives you power to keep going. I could see the impact I was having, and so I was forced to get out of my comfort zone.

You once said, "The entrepreneur space taught me to take risks and I cannot take risks if I still want validation." What did you mean?

I said that a long time ago, inspired by my mentor, Emmanuel Bonoko. When my entrepreneurial journey started, I was fortunate enough to have this mentor who took me by the hand and guided me on a weekly basis. Once, Emmanuel was hosting an event attended by esteemed entrepreneurs in South Africa, and he asked me to pitch my ideas to them. I'd never pitched my ideas to anyone, but his aim was to teach me the spirit of taking risks because opportunities come when you least expect them, when you're scared. If I didn't take this opportunity, it would be because I was seeking validation from other people.

I'm glad I didn't listen to people who told me to focus on school and forget about being an entrepreneur because I was too young. I didn't need validation, I had to take risks. ➔

> **"GAMER'S TERRITORY USES THE PHRASE 'UNLOCKING DREAMS'. WE WANT YOUNG PEOPLE'S DREAMS TO BE UNLOCKED THROUGH GAMES AND VIRTUAL REALITY."**



© Tshidiso Malema

© Botlhale Baily

> **THE MAIL & GUARDIAN'S TOP 200 YOUNG SOUTH AFRICANS AWARD HAS OPENED SO MANY OPPORTUNITIES FOR ME. IT'S LIKE A TAP ON THE SHOULDER TO SAY, 'KEEP GOING WITH WHAT YOU'RE DOING'.**

What are you most proud of, and why?

Being nominated for the Mail & Guardian's top 200 Young South Africans. It's an iconic list that every young person wants to be a part of, and I feel humble to be nominated alongside other young people who inspire me.

I was taught how to do 5- and 10-year plans, and the Mail & Guardian was in my 10-year plan. I thought I was going to be nominated when I was 25 or 26, but it happened much sooner. Even now, I don't know who nominated me, but I really hope they come clean one day so that I can thank them.

This award has opened so many opportunities for me and allows me to make an impact for even more people. It's like a tap on the shoulder to say, 'Keep going with what you're doing'.'

On your LinkedIn profile you say: "In a nutshell, Tshepiso Malema is what the world is waiting for'. Where does your self-belief come from?

That's a really, really a hard question! It's not really about me right now, it's about other people. Entrepreneurship is one of the hardest journeys someone can take. Most of the time, I doubt myself. I'm not always self-confident, and I'm always asking myself whether I should continue. But I wouldn't be able to get any work done if I didn't have the confidence to do it. I wouldn't be able to go to publishers, ask people to be my mentors, nor would others be able to learn and benefit from my journey. So, I always have a 'why'.

I'm writing a book called *What is Your Why?* I believe it's my 'why' that keeps me going. My initial 'why' was to change my family situation, but now it's more about helping people improve their lives so that they can improve their families'

© Gordon Harris Photographic CC

lives and then maybe even more people will be inspired by them.

It's not about self-confidence or how I feel. One of the biggest responsibilities we have as leaders, or as people who are destined to do more, is to do certain things no matter how we're feeling. We just have to fight.

Can everyone learn this ethos?

Yes, because I've witnessed it. To give an example, one of my team members at Tshepiso Malema Speaks used to be very shy. But when she saw the change I was making just by telling my story – because everyone has a unique story that might change someone's life – she started telling us, the team, her story, and it was so inspiring.

One day, I put her in the spotlight. I said, "Just talk to these kids, I'm sure they really want to hear your story." Today she's getting gigs just for telling her story.

I think if you can get away from the idea that you're doing this for yourself and stop thinking about the masses of people you're going to impact, this makes things a lot easier. When you start to think about the potential outcomes of what you're doing, it can be daunting, and you can lose confidence. You just need to do it without over-thinking!

> **"ENTREPRENEURSHIP IS ONE OF THE HARDEST JOURNEYS SOMEONE CAN TAKE. MOST OF THE TIME, I DOUBT MYSELF."**

> **"IT'S NOT REALLY ABOUT ME RIGHT NOW, IT'S ABOUT OTHER PEOPLE."**

About Tshepiso Malema

© Wingman Communications

Tshepiso is in his second year studying information systems at the University of Pretoria in South Africa. He is also the founder of Gamer's Territory, which provides young people in townships access to computer games, and Tshepiso Malema Speaks, which aims to help people overcome challenges and fulfil their dreams. Tshepiso has been named one of the Mail & Guardian 200 Young South Africans and has been awarded a FOYA Award for Most Promising Founder of the Year 2022.

tshepisomalema.home.blog

ABOUT

Left: Tshepiso at the Gordon's Institute of Business Science. © Wingman Communications
Top right: Tshepiso mentoring boys © Mpumelelo Buthelezi
Bottom right: Tshepiso with his team at Tshepiso Malema Speaks. © Fernando Nando

PLUGGING IN: DIRECTLY LINKING THE BRAIN TO A COMPUTER

Brain-computer interfaces (BCIs) link the brain directly to external computers, allowing users to do something just by thinking it. In recent years, BCIs have moved from science fiction to something that could have real potential. At the **University of Technology,** Sydney, Australia, **Professor Chin-Teng Lin** is on the frontline of pioneering the development of such systems.

Professor Chin-Teng Lin

Co-Director, Australian AI Institute (AAII),
Distinguished Professor,
School of Computer Science,
University of Technology Sydney (UTS),
New South Wales, Australia

Fields of research
Computer Science, Artificial Intelligence (AI), Brain Computer Interfaces (BCIs)

Research project
Developing sophisticated direct-sense BCIs based on natural cognition to progress BCI technology towards real-world applications

Funder
This work was supported in part by the Australian Research Council (ARC) under discovery grant DP210101093 and DP220100803. Research was also sponsored in part by the Australian Defence Innovation Hub (DIH) under Contract No. P18-650825. The contents are solely the responsibility of the authors and do not necessarily represent the official views of ARC and DIH.

TALK LIKE A ...

COMPUTER SCIENTIST

Artificial intelligence (AI) — computer systems able to perform tasks normally requiring human intelligence

Augmented reality (AR) — technology that superimposes computer-generated images onto a user's view of the real world

Brain-computer interface (BCI) — a direct communication pathway between the brain's activity and an external device

Direct-sense BCI (DS-BCI) — BCI methods that operate directly and seamlessly from human cognition, rather than relying on external stimuli

Electroencephalography (EEG) — recording of brain activity through non-invasive sensors attached to the scalp that pick up the brain's electrical signals

Machine learning — computer systems able to learn and adapt without following explicit instructions, through recognising and inferring patterns in data

Virtual reality (VR) — computer-generated simulations of environments that users can interact with in a way similar to real life

Brains and computers share lots of similarities. Both use electrical signals transmitted through complex networks to trigger a particular event. The human brain remains far more sophisticated than even the most advanced computer, but the gap is narrowing, and, with the help of other innovative technologies, the potential of linking up brains with computers becomes closer to a practical reality. The combination of human and machine intelligence has a staggering array of potential real-world applications, from the detection of cognitive illnesses or emotional states, to precise control of sophisticated machines, to the intuitive navigation of immersive virtual worlds.

Professor Chin-Teng (CT) Lin works at the University of Technology Sydney. He has several decades of experience at the forefront of human-machine collaboration and sees a bright future for brain-computer interfaces. "Recent advances in AI, material sensor technologies and attention to user-friendliness in computer hardware have spurred BCI research, taking it from pure academia into the world of industry," he explains.

How do BCIs work?

"BCIs provide a channel for humans to interact with external artificial devices through their brain activity," says CT. "Usually, a machine learning algorithm decodes electrical signals in the brain to work out the user's intentions and then transmits a 'mental command' to the device." There are a variety of different sensor systems to pick up and interpret brain activity, each with their own pros and cons. Some measure the brain's electrical

© Who is Danny/stock.adobe.com

signals, some measure its magnetic activity and others measure changes in blood oxygen.

"While some measurement techniques are non-invasive, others are invasive, meaning the sensors must be placed under the scalp," says CT. "While invasive methods usually provide more precise measurements, they also have obvious disadvantages for the user." Understandably, lots of people do not want electrical devices under their skin, and there are risks involved with prolonged or repeated use, which makes invasive methods unlikely to be widely taken up in society. "Research on invasive methods is mostly limited to animals at the moment and, although latest findings indicate they might be safe for human use, it's unlikely that human implants will be approved any time soon," says CT. "For the foreseeable future, non-invasive sensors are the only practical solution for investigating cognitive processes in the human brain."

Limitations of BCIs

While BCIs have crossed the threshold from fiction to fact, uptake in the world outside the lab is slow. "Interacting with the real world via a computer is unnatural to humans," says CT. "Furthermore, the response feedback produced by the computer is far slower than our brains, creating a delay." The accuracy of machine learning provides another limitation, though this is a rapidly advancing field. "Recent progress in deep learning provides substantial potential benefits for neural networks, computer vision and BCI techniques," says CT.

There are other practical drawbacks too. "The sensors that pick up signals from the brain still need improvement," explains CT. "Most BCIs only work when the user is stationary, limiting their use in many real-world applications." Because non-invasive methods, in particular, rely upon detecting quite subtle stimuli, any interference – such as the noise created by movement or physically interacting with an object – can affect their functioning. Staying motionless while 'interacting' with the world is unnatural to us and means such methods can only be used in controlled environments.

> ***"BUILDING A SYSTEM THAT TRANSLATES USER INTENTIONS INTO BCI INSTRUCTIONS HAS SHIFTED FROM A DISTANT GOAL TO A FEASIBLE POSSIBILITY."***

Wearable computers

We are already familiar with the concept of wearable computers, through VR headsets, AR glasses and other trendy tech. As well as their entertainment value, wearable computers also have many promising practical applications. "Wearable computers can offer highly immersive experiences for entertainment, health monitoring and research purposes, among many others," says CT. "Their research applications are most exciting for us at present."

Wearable computers have revolutionised the practicalities of BCI research. Until recently, BCI research has relied upon static and simple stimuli – presenting an object to a subject in a lab environment, for instance – which does not bear much relation to everyday life. "By using wearable computers, researchers can design, simulate and finely control experiments to examine human brain dynamics inside and outside the laboratory," says CT. VR and AR can now create sophisticated scenarios similar to real life; by monitoring a subject's brain activity when encountering these scenarios, results are far more meaningful in terms of relating findings to the real world.

Direct-sense BCIs

Based on such technological advancements and their own innovations, CT and his team are working on a next-generation solution called direct-sense BCI (DS-BCI). "We are developing two systems within DS-BCI, based on speech and vision, to seamlessly decode the brain signals linked to our natural senses without additional stimulus," he says. Such techniques are far closer aligned to our experiences of the real world than most BCI research. To make its measurements, the team is principally using non-invasive sensors that monitor electrical signals in the brain, the signal known as electroencephalography (EEG).

Direct-speech BCI aims to translate 'silent speech' from neural signals into system commands. "Currently, our EEG sensors can decode the intention conveyed when participants imagine themselves speaking," explains CT. "This approach provides a novel channel of interaction with BCIs for any user and could be an important assistive tool for people not able to speak naturally."

Direct-sight BCI detects what object is in a person's mind based on their EEG signals as they look around an environment. "This is more innovative than current BCI methods, which rely mostly on stimulus onset – in other words, displaying a specific series of objects to the subject – while ours takes a more natural approach to interacting with one's environment," says CT. "The ability to actively recognise objects is an essential skill in daily lives, which is why this is an active research field."

The possibilities for the future of BCIs are exciting to CT and his team. "Building a system that translates user intentions into BCI instructions has shifted from a distant goal to a feasible possibility," says CT. "From our progress so far, we foresee a wearable system that can directly decode a user's sensory data. The speed and capacity for natural interaction of these BCIs will bring this technology closer to real-life application."

ABOUT *COMPUTER SCIENCE AND BRAIN-COMPUTER INTERFACES (BCIs)*

Distinguished Professor Chin-Teng Lin is a leading researcher in BCIs. He explains more about his research and how it combines understanding of the human brain with the latest technological developments.

"I study the human brain and the physiological changes that take place when cognition and behaviour is happening. In particular, I'm interested in ways to combine this physiological information with AI to develop monitoring and feedback systems.

"I want to improve the flow of information from humans to robots. This will help humans make better decisions and enable them to respond to complex, stressful situations with the assistance of machines. I believe such human-machine cooperation can deliver a common good for humanity.

"In 1992, I invented fuzzy neural networks (FNNs). A 'fuzzy' system is something that doesn't always follow hard rules, such as human cognition. I introduced neural-network learning into these systems, allowing machines to learn and predict the approximate functions of such a system, essentially incorporating human-like reasoning into computers. Since then, I've developed a series of FNN models for different learning environments, with applications including cybersecurity and coordinating multiple drones at once.

"I founded the Computational Intelligence and Brain-Computer Interface Lab at UTS. The lab is developing mobile sensing technology to measure brain activity using non-invasive methods, to help assess human cognitive states.

"From 2010-2020, I led a large project with the US Army Research Lab. The project explored how to integrate a BCI when the user is in a moving vehicle or suffering cognitive fatigue, leading to the development of wearable EEG devices. In more recent years, I've worked with Australia's Department of Defence to examine how to use brainwaves to command and control autonomous vehicles."

"I WANT TO IMPROVE THE FLOW OF INFORMATION FROM HUMANS TO ROBOTS. THIS WILL HELP HUMANS MAKE BETTER DECISIONS AND ENABLE THEM TO RESPOND TO COMPLEX, STRESSFUL SITUATIONS WITH THE ASSISTANCE OF MACHINES."

Pathway from school to *computer science*

- For a career in computer science, commonly desirable subjects to study at school and post-16 include mathematics, computer science, statistics and physics. If you are interested in BCIs and similar technologies, biology or psychology may also prove useful.
- At university, CT suggests seeking courses or modules in areas such as linear algebra, algorithms and data science, signal processing, optimisation, neural networks, fuzzy logic and AI.

Explore careers in *computer science*

- The IEEE Computational Intelligence Society runs educational outreach programmes for high schools (**www.cis.ieee.org/activities/professional-development/high-school-outreach-subcommittee**), competitions and webinars, and has a repository for educational materials (**www.resourcecenter.cis.ieee.org**).
- The UTS Faculty of Engineering and Information Technology runs innovative outreach programmes (**www.uts.edu.au/about/faculty-engineering-and-information-technology/what-we-do/outreach-and-community/schools-outreach**) for schools.
- CT says the UTS Australian AI Institute (**www.uts.edu.au/research/australian-artificial-intelligence-institute**) and the Computational Intelligence and Brain-Computer Interface Lab (**www.uts.edu.au/research-and-teaching/our-research/centre-artificial-intelligence/research/cai-research-labs/computational-intelligence-and-brain-computer-interface-centre**) both offer opportunities for students to get involved practically.
- Computer scientists are in high demand, and there are many opportunities available in academia, industry and the public sector. According to **www.au.talent.com/salary**, the average annual salary for a computer scientist in Australia is AUS$103,000.

CT's *top tips*

1. When you're working on ways to integrate computer science into society, interdisciplinary knowledge – such as having an understanding of life sciences and biomedical engineering – is useful.

2. Look into new research and the latest industry developments to keep abreast of progress and stay excited about the field. Think especially about real-life applications of such technologies.

Meet CT

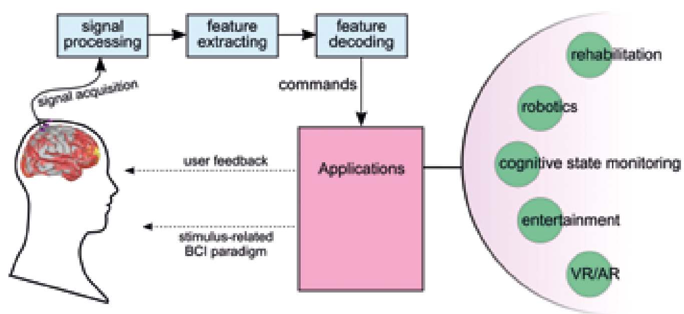
As a child, I was fascinated by movies and toys featuring robots. This sowed the seeds for pursuing a career in finding ways for humans and machines to team up and work together to solve real-world issues.

After university, I became specifically interested in 'augmented human intelligence'. This led to me inventing the fuzzy neural network (FNN) models, which integrate high-level human-like thinking with low-level machine learning. This has since led to hundreds of thousands of scientific publications on FNNs from researchers around the world.

Later on in my career, I realised that BCI advancement would rely on a deeper understanding of the human brain. I began researching brain science about 20 years ago, focusing on 'natural' cognition — how brains behave when people are performing ordinary tasks in real-life situations. This included developing non-invasive BCI headsets that subjects can wear.

Now, I think it's the right time to pursue my ultimate career goal: to augment human intelligence through BCI and AI. My dream is to develop the next-generation human-machine interface, allowing human brains and computers to truly work together and enhance one another in decision-making.

Brainwave (EEG) dry sensors and headsets for BCI developed by CT Lin and his team



A typical BCI system configuration (copyright (2021) IEEE. Reprinted, with permission from C. T. Lin and T. T. Nguyen Do, "Direct-Sense Brain-Computer Interfaces and Wearable Computers," IEEE Transactions on Systems, Man, and Cybernetics - Systems, 50th Anniversary Issue, Vol. 51, No. 1, pp. 298-312, January 2021

ONLINE BATTLES: COMBATTING FALSE INFORMATION AND REDUCING ONLINE RISKS

These days, we are all online, but it is difficult to have a full understanding of the risks this entails. **Professor Shujun Li** and his colleagues, **Sarah Turner, Dr Rahime Belen-Saglam** and **Dr Virginia N.L. Franqueira** at the **Institute of Cyber Security for Society (iCSS),** University of Kent in the UK, are working on enhancing people's awareness of the risks of online false information and sharing personal data online.

Professor Shujun Li

Professor of Cyber Security of School of Computing and Director of the Institute of Cyber Security for Society (iCSS), University of Kent, UK

Research
Investigating online false information, cyber fraud, online privacy risks, data protection, cyber security and online safety education

Funders
Engineering and Physical Sciences Research Council (EPSRC)/UK Research and Innovation (UKRI), National Cyber Security Centre (NCSC)/Government Communications Headquarters (GCHQ), Defence Science and Technology Laboratory (Dstl)/Ministry of Defence (MoD), Global Forum on Cyber Expertise (GFCE), Turkish government (Ministry of National Education), and others

PROFILE

TALK LIKE A ...
CYBER SECURITY EXPERT

Artificial Intelligence (AI) — computer algorithms and systems able to perform tasks that would typically require human intelligence

Crowdsourcing — getting input or information by enlisting a large number of people to contribute

Deepfake — manipulation of existing digital media (image, video and/ or audio) – e.g., by swapping faces and changing voices – or creation of new media, typically using machine learning-based techniques such as deep learning

Deep learning — technology able to automatically learn from a large set of digital media and apply what has been learnt to manipulate or create sophisticated media

Machine learning — AI algorithms and systems able to automatically learn from data to perform a specific task

Metadata — a (large) set of data giving information about other data

Misinformation — false or inaccurate information created and spread without an intention to harm others

Disinformation — false or inaccurate information created and spread maliciously, often used for deceptive purposes

Personal data — information relating to an identifiable individual

Online false information

Online false information, including misinformation and disinformation, has become rife, shaping social groups and political opinions, and leading to dangerous beliefs and conspiracy theories. The age of the internet allows false information, such as 'fake news', to spread like wildfire. It is now incredibly easy for claimed factual information, even if entirely false, to reach millions of people very quickly. Educating people about the harms caused by online false information, and how to detect and avoid it, is becoming a growing priority for many.

"Young people may be more likely to fall for false information, especially misinformation or conspiracy theories, because of their lack of life experience, sufficient technical knowledge and tendency to believe in others more easily," says Professor Shujun Li. Shujun is Professor of Cyber Security and Director of the Institute of Cyber Security for Society (iCSS) at the University of Kent, where many researchers are actively researching on understanding, detection and prevention of online false information and digital data deception. "Young people can be super-spreaders of online false information," he says. "This is because of their active use of social media, and they may read and share posts rapidly, without proper fact-checking."

Fact-checking

As more of our daily activity takes place online, the boundaries between the online and physical worlds are becoming increasingly blurred. Fact-checking has become an important tool to help distinguish what is true and what is false. Fact-checkers can be humans or machines. "Crowdsourcing methods have been developed so that fact-checking professionals or willing citizens can work together to identify and debunk false information online more efficiently," says Shujun. "This includes human-in-the-loop AI systems that allow humans and machines to work in tandem to fight against false information." Humans and AI algorithms are proficient at different things,


© shintartanya/stock.adobe.com

so combining their powers is often a more effective way of identifying false information.

It is not only words that can be misleading, but also non-textual data such as digital images and videos. The rise of powerful image- and video-editing software means that it is easier than ever to construct digital images and videos that look real but are fake or misleading. While some are easy to spot, the advent of more advanced fake-making technologies, such as those behind 'deepfakes', is making it harder to tell fact from fiction. However, advances in technology are combatting this. "Many methods using AI have been developed to automatically detect fake images and videos, and can help human fact-checkers do their job more easily," says Shujun.

Trustworthy experts

To differentiate fact from fiction, Shujun advocates the 'STOP, THINK, CHECK' technique from the Irish *Be Media Start* campaign (**www.bemediasmart.ie**). "Stop to take time to think, and then think about if and what you need to check," he says. 'Stop' involves taking time to read beyond a headline and not believing in what you read immediately. 'Think' involves considering what the purpose of the information is – e.g., to inform or persuade – and how our own biases might affect our likelihood of believing something. 'Check' involves looking at the source and investigating whether this information appears on a range of reliable platforms elsewhere online.

This final stage, identifying whether information comes from a reliable source, is not always straightforward. "Check if the information comes from experts," says Shujun. "This can include scientific papers at reputable scientific journals and conferences, statements from reputable research organisations and professional bodies for expertise in the subject they're talking about." Endorsements from other trustworthy sources can help build confidence. "Find out if the information has been endorsed by, for example, a public body, a reputable international body such as the World Health Organization (WHO), a charity with a good reputation on the subject matter, or a media platform with a long-term reputation for accurate reporting," he says.

Personal data sharing

"Sharing some personal information online with some online users is necessary for being part of cyber space," says Shujun. The cyber world offers lots of positives, but many of us are quite lax with our personal data, which is a valuable commodity that can be dangerous if it falls into the wrong hands. "Digital services suck up data about us in different ways," says Sarah Turner, Research Student at the iCSS. "Often, sharing data is an important part of getting full use of a digital platform, helping us connect with friends and contacts, for instance. Additionally, many apps and other digital platforms require access to your data to work correctly."

Threat modelling

Data can seem abstract, and it is all too easy to click the 'Accept' button without thinking too much about the consequences. Sarah suggests thinking about how you share your data in a more structured way. "Threat modelling is often used in software creation but can also be applied to your own personal data," she says. "It involves thinking about a threat and then considering the steps needed to overcome this threat and whether these steps are proportional to the risks." The Electronic Frontier Foundation's *Personal Threat Modelling* questions are as follows:
What do I want to protect?
Who do I want to protect it from?
How bad are the consequences if I fail?
How likely is it that I will need to protect it?
How much trouble am I willing to go through to try to prevent potential consequences?

Sarah also suggests adding in the following, final question: *What do I need to know or do to make that happen?*

Sarah points out that 'threats' are not just the anonymous malicious hackers of our mind's eye. "There are often other people who, intentionally or not, might cause you problems if they access certain bits of your personal information," says Sarah. "What if a possible employer finds questionable tweets you wrote five years ago? What if a mischievous sibling deleted your coursework because they knew your password?"

Games and data

While games can be a great way to relax and escape, they are not excluded from the online data-gathering world. "Most games want to hook you with the gameplay, which can be enriched by using your personal information," says Sarah. "For example, *Animal Crossing: New Horizons* uses your birthday to celebrate your big day and personalise the experience." Games can go further and encourage engagement with other online players, exposing your data more broadly. "Games also collect metadata," she says. "For instance, they can recognise what device you're playing on, and at what times, and details about your internet connection."

Names and birthdays may seem like harmless information to share widely, but Sarah points out it can be problematic. "Data can be stolen and sold to the highest bidder," she says. "They can do whatever they like with this – for example, a name and date of birth can be sufficient to carry out identity theft." More insidiously, advertising agencies use our data to suggest specific things for us to support or buy tailored to our interests. This may seem helpful rather than malicious, but it can contribute to the profiling of particular groups, such as by pigeonholing people into particular 'bubbles' where they only see information or products that reinforce or narrow their own worldview.

All that glitters

"Data is like glitter: once it's out, it's everywhere!" says Sarah. Once something is online, it often remains there for years and years, even if you think you have deleted it. "Try to get into the mindset of threat modelling before using a new service or buying a new device," says Sarah. "This will help you investigate how the service or device works and what it does with your data, which may influence your decision about using it."

ABOUT *CYBER SECURITY*

Cyber security focuses on making the world safer through preventing or mitigating online threats. This can involve technical careers in computing and software but, given the significant human aspect involved in cyber security, also involves social sciences and humanities.

The interdisciplinary nature of cyber security means different skills, knowledge and attributes are needed depending on what sort of cyber security career you might be interested in. From academic research to government policy to teaching young children how to be safe online, cyber security is a vast and vital field.

Pathway from school to *cyber security*

For technical degrees and careers, subjects like computer science and mathematics can be useful. For those more focused on social sciences or humanities, subjects like psychology, business studies, economics, criminology, politics and international relations, media and communications may be important.

Virginia and Shujun recommend extending what you learn at school through, for example:

- finding a relevant club
- doing an extended project, such as one leading to a Cyber EPQ, CIISec's Cyber Extended Project Qualification worth half an A-level and up to an extra 28 UCAS points (**cyberepq.org.uk**)
- participating in an experience week or an internship at a university (e.g., iCSS at the University of Kent), either within your curriculum, if it allows, or elsewhere.

Explore careers in *cyber security*

- The UK Cyber Security Council provides a careers route map for the profession, providing details on the 16 specialisms within cyber security and pathways to get there: **www.ukcybersecuritycouncil.org.uk/careers-learning/careers-route-map**
- To get a fuller understanding of what cyber security entails, Virginia and Shujun recommend getting involved in relevant activities, such as Safer Internet Day (**www.saferinternetday.org**), Cyber Security Challenge UK (**www.cybersecuritychallenge.org.uk**), and TryHackme (**tryhackme.com**).
- The National Cyber Security Centre (NCSC) runs CyberFirst, a programme of activities intended to encourage students to consider careers in the sector and apply for a related bursary: **www.ncsc.gov.uk/cyberfirst/overview**
- Read more about Shujun's career path: **futurumcareers.com/how-to-beat-the-cybercriminals-and-stay-safe-online**

© Thaut Images/stock.adobe.com

Meet *the iCSS team*

Virginia N. L. Franqueira
Lecturer in Cyber Security, Deputy Director (Education) of the iCSS

I started my career working in industry, involved with software testing, maintenance and development projects. My specialisation in cyber security was triggered, quite by chance, when I decided to leave industry to pursue a PhD in The Netherlands.

I never assume I know everything I should know, which leads to the need for continuous learning. This is essential in the field of cyber security, since it develops at such a fast pace.

I was drawn to digital forensics and cybercrime investigations through my first lectureship post. I became passionate about these subjects, not only from a law enforcement perspective but also from the perspective of improving methods and processes that can ultimately make a positive difference for victims of interpersonal cybercrime (such as domestic abuse and exploitation of children).

Digital forensics is fascinating. It involves technical skills to understand how things work (such as devices, operating systems and applications), as well as where to collect data and how to interpret it to help answer important questions about past activities. It also involves investigative skills to approach the work in a systematic way, with attention to details and to documentation. Finally, digital forensics requires awareness of human behaviour and motivations since there is always a human directly or indirectly involved in a wrong-doing.

Machine learning has the potential of assisting digital forensic investigators in many ways. For example, in identifying previously unseen illegal images based on images already known to be illegal, or estimating the age of people appearing on an image/video of interest, or helping to speed up examination and analysis of digital evidence.

Virginia's *top tip*

Be curious about technology. Follow technology news, and take an interest in learning beyond what is taught at school and college.

Rahime Belen-Saglam

Research Associate, iCSS

I specialised in cyber security quite by chance! I was working in other research areas, including information retrieval and data quality. While working with a PhD student on his thesis, we needed guidance on cyber security, and this is how I met and started working with Professor Shujun Li.

I've always enjoyed reading and learning new things. As cyber security is a very dynamic field, those attributes help me to catch up well with the new research areas. I am also interested in analysing information and finding solutions to problems.

Currently, I am working on data privacy and security issues of blockchains, the technology behind cryptocurrencies such as Bitcoin. I am conducting a literature review study, where I read scientific articles published in a specific research area and generate knowledge from those studies in a systematic way. I've identified some research gaps in the literature regarding the algorithms proposed to protect personal data on blockchain systems.

I would like to conduct studies that aim to use technology for good. This includes projects that try to prevent the misuse of technologies. Improving the cyber security skills of younger people is another area I would like to keep studying.

Rahime's *top tip*

Keep in mind that there are several ways to getinto cyber security. It is an interdisciplinary area – technical, legal, business, economic, psychological and societal perspectives are very important. Discover what excites you the most, and follow your own footsteps.

Sarah Turner

Research Student, iCSS

I came back to academia after spending 10 years working with regulation and technology in financial services. I started looking at how public policy needs to deal with technology, which led to the realisation that people need support to make sure the devices they use are as secure as possible.

People love the novelty of Internet of Things devices and will bring them into their homes with little to no understanding of how or why they work – or what that could mean for them if things go wrong.

Digital technologies and their place in society are in flux at the moment. I hope I can do something to make people less of an afterthought as these technologies become part of our daily lives!

Sarah's *top tip*

Be sure of yourself, but always listen to others – having multiple viewpoints almost always makes for a much better final result!

A teacher's *viewpoint*

Samantha Barnes

Head of Junior School ICT and Computer Science, St Edmund's Junior School, Canterbury, UK

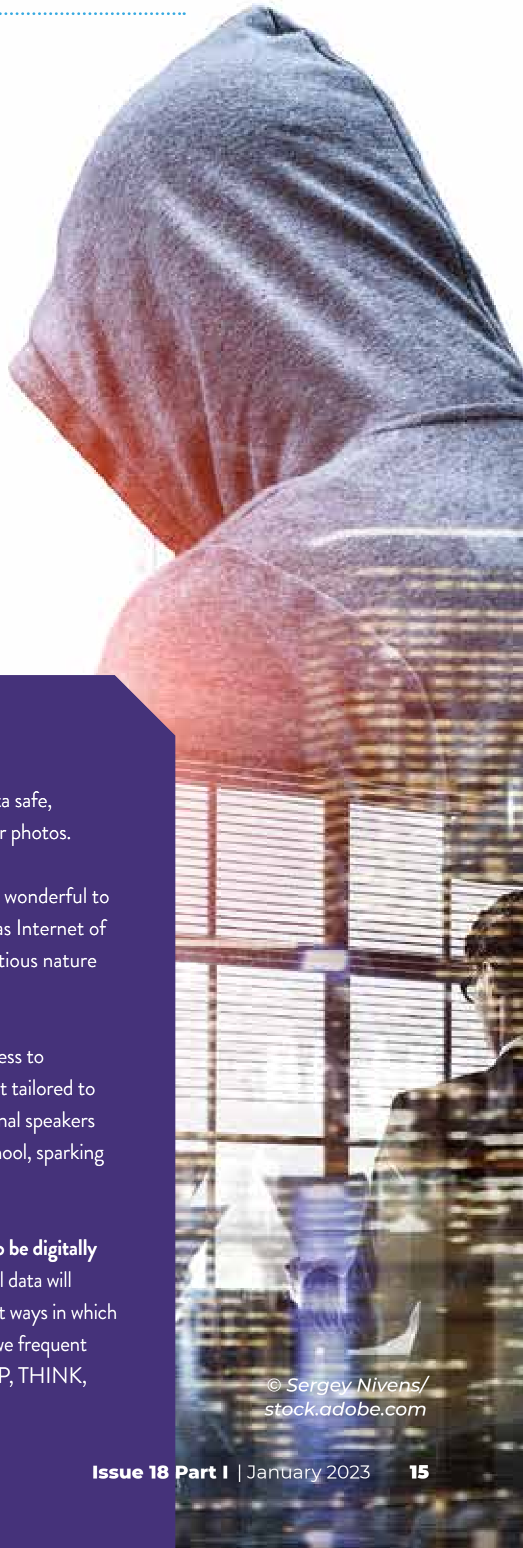
Currently, there is no specific or dedicated curriculum on cyber security across all key stages, and where there is a requirement for eSafety, historically the terminology used leads to a narrow view and misunderstandings of how vast cyber security is.

Younger students are taught that what we do offline should reflect what we do online in terms of our human behaviour, ensuring adults in our lives are aware of the activities of our cyber lives. Children are taught to fact check with various sources, with both adults and websites. Some already understand how to keep their data safe, including metadata that can be found within our photos.

Collaborating with the iCSS team, it has been wonderful to adjust our lens to more pressing matters such as Internet of Things awareness in the home and the surreptitious nature of misinformation.

We ran a Safer Internet Day where we had access to academic staff from the iCSS team and content tailored to our school. The children very much enjoy external speakers who come from the world of work beyond a school, sparking their curiosity to dig deeper.

Next, we'll be exploring further what it means to be digitally literate in a world where protecting your personal data will become ever more important. We will also look at ways in which we validate what we learn from the cyber space we frequent and inhabit, such as fact-checkers and the 'STOP, THINK, CHECK' technique.



© Sergey Nivens/ stock.adobe.com

TAKING FICTION FROM BROADSHEET TO BROADBAND

Professor Katherine Bode at the **Australian National University** in Australia is rediscovering – and shaping – literary history by curating fiction from 19th and 20th century newspapers for 21st century reading.

Professor Katherine Bode

Professor of Literary and Textual Studies,
College of Arts and Social Sciences,
Australian National University, Canberra, Australia

Field of research
Computational Literary Studies

Research project
Curating digital platforms for people to interact with 19th and 20th century Australian newspaper fiction

Funder
Australian Research Council (ARC)

PROFILE

TALK LIKE A ...

COMPUTATIONAL LITERARY RESEARCHER

Colonial — relating to colonisation: the act of a foreign government claiming control over an area of land and its people

First Nations peoples — culturally-distinct groups who descend from the earliest inhabitants of a place

Oral tradition — communication of culture and ideas through speech and song

Computational — using computers, usually for quantitative, statistical, or algorithmic tasks, or for curating and investigating large amounts of data

Collaborative digital editing (CDE) — process in which multiple people work together creating and editing literary works on computers

Optical character recognition (OCR) — computerised way of turning printed or handwritten material into digital text

Think of the last time you delved into a story: how did you interact with it? Maybe you turned the pages of a paperback, scrolled through an ebook, or plugged in your headphones to listen to an audiobook. If you were living in 19th century Australia, the chances are that the last chapter you read would have been in a newspaper.

Exploring the history of Australian literature, therefore, means digging through a lot of old newspapers. Thankfully, for literary researchers like Professor Katherine Bode at the Australian National University, computational tools are transforming our ability to collect, organise, analyse and even re-publish such stories. By creating new digital archives, Katherine is not only shedding light on her country's cultural history, but also allowing the public to engage with thousands of unrecorded novels in new and surprising ways.

Why were newspapers so important in Australia?

Before the British colonised Australia in 1788, the continent was home to many different and distinct groups, with diverse cultures and languages. First Nations languages were passed on orally, and stories were not written but told with rich repertoires of signs, sand-drawings, songs and dance. It was, therefore, the English-speaking colonisers who were the first to demand written publications.

In the 19th and early 20th century, newspapers were the main source of reading material because they were economical and accessible. By combining news, advice, opinion, advertising and fiction into a single publication, they appealed to a wide audience in a country that did not have many book publishers. Newspapers provided a connection to Europe and Western culture, for example, through reporting on overseas wars, articles on international scientific developments, or stories about snowy Christmas celebrations published to coincide with Australian summer Christmases. Alongside this, they included local information and community discussion, making them important for day-to-day communication. Katherine says that this interplay between global

© alphaspirit/stock.adobe.com

and local can also be found in the fiction that was included in almost all newspapers at the time. “It was often the case that stories written by overseas authors were adapted to seem local, or that stories advertised as being written especially for that newspaper were published in scores of far-flung newspapers at the same time! Fiction participated in this mapping out of the world,” she explains.

Were newspaper stories dominated by British authors?

The popular understanding of Australian literature in the colonial era is that almost all fiction initially came from Britain, because that is what readers demanded. Katherine has discovered otherwise. The authors she has identified in newspaper fiction came from all over the world, including the US, Canada, Europe, Japan, Russia and South Africa. British authors accounted for only half of publications.

Furthermore, about a quarter of the stories came from local – though not Indigenous – writers, and ‘Australian’ was one of the most common words in story titles. There is still uncertainty, as many stories were published anonymously, but the evidence suggests that locally-authored fiction played a big part in developing Australian identity and culture. Katherine stresses that this new identity “cannot – and should not – be separated from the dispossession of Australia’s First Nations People: an issue commonly explored in local fiction in both horribly racist and surprisingly critical ways”.

How are digital platforms transforming literary studies?

Digital technology allows researchers to store large amounts of data, for example the text of millions of books, and to search quickly for interesting patterns, such as the frequency of different words and phrases over time. This is just the start, though. Katherine goes as far to say that “data and computation are reforming what literature, literacy and literate practices are and can be”.

> **“THE DIGITAL AGE HOLDS OUT THE POSSIBILITY OF MORE DISTRIBUTED AND DEMOCRATIC PARTICIPATION IN LITERATURE.”**

Katherine’s vision is to move on from seeing texts as data points to be computed. Instead, she is setting up platforms that allow a wide range of people to interact with fiction and with the institutions that curate our cultural archive. This means enabling scholars and the public not just to view stories, but also to edit existing ones, combine historical stories with their own writing, or download data for their own analysis. An example of such a platform is the “To be Continued” database of Australian newspaper fiction.

At “To be Continued”, users can search for stories by title, author, newspaper and date. Each record has a scanned image of the newspaper story as well as a digital text generated by a machine learning technique called optical character recognition (OCR). Because old newspapers are often missing parts or are damaged, and because OCR guesses at the letters on the page, the digital text often contains many errors, which users can correct themselves on the database.

One of Katherine’s proudest achievements is that over 2,000 titles and many more thousands of corrections in “To be Continued” were added by members of the public and have been saved by the National Library of Australia. In some cases, people have even rediscovered fiction that was unknown to literary researchers. This collective approach is something she hopes to build on.

What are the next steps?

Katherine plans to add a collaborative digital editing (CDE) tool to the online database. The CDE will let readers create their own collections and even publish them as new ebooks. “We’re calling this participatory literary history, and we are interested in what types of works readers will engage with,” she explains. She expects some readers will even choose to rewrite some texts, perhaps to remove the racism and sexism that was common in writing at the time.

Tools such as the CDE will allow anybody with an internet connection to get involved. This could turn literary history from a private discussion between professional writers and academics into an open forum where a wide range of people have a voice. Katherine hopes this is how her research will have a positive impact on today’s society. For example, by allowing the public to look back at – and write back to – the racist and sexist themes of 19th century fiction, digital archives provide a chance to reflect on the past and reimagine the present and future.

“The digital age holds out the possibility of more distributed and democratic participation in literature,” says Katherine. “If we think of archives as our cultural memory, then participation in them gives us an opportunity to challenge past and ongoing discriminations and oppressions. Enabling people to curate, write, rewrite and remix texts provides the potential for humanities research to make a difference to the way we understand the world.”

© alphaspirit/stock.adobe.com

ABOUT *COMPUTATIONAL LITERARY STUDIES*

What words are most commonly used to describe women in 20th century American fiction? Can an algorithm predict the outcome of an Agatha Christie murder-mystery? Could a computer write a new novel in the style of Charles Dickens? These are just some questions that researchers in computational literary studies might be interested in. The field encompasses the study of written prose, poetry and drama, through digitisation and the application of techniques from computer science.

What does a typical day look like?

Researchers in computational literary studies spend time reading literature and writing about it, while also creating datasets and exploring them by writing code or using specialist programs. As university workers, their job also includes meetings with students and colleagues to discuss common interests and plan research programmes.

For Katherine, the combination of literature and computing is an exciting challenge. "I love combining the critical, conceptual, technological, and infrastructural questions raised by literature and computation. It's fascinating to me to think about how these supposedly very different systems work together and the characteristics they share, as well as the ways each is transforming the other".

What will the next generation study?

The potential of computational literary studies is huge because it combines a relatively new discipline with a much older one. On the one hand, literary studies is a discipline with centuries of history and a deep expertise in language and its infrastructures (for instance, how class relates to print publishing). On the other hand, developments such as the internet and machine learning have transformed computing in just the last few decades and even years.

Computation used to be mostly relevant to science, but now can be applied across the humanities. So far, though, very few researchers have bridged the gap between the disciplines of computing and literature. The next generation of researchers will have the chance to apply the latest algorithms to learn more than ever before and will likely have a skills advantage having grown up in the digital age. Katherine highlights that the relationship between literature and computing goes both ways: "Critical understandings of language and culture also have the potential to transform computation".

Explore careers in *computational literary studies*

- A good way to start exploring a field is by seeing what support and guidance professional societies offer. The main society for digital humanities, which includes Katherine's field of computational literary studies, is the Alliance of Digital Humanities Organizations (ADHO): **www.adho.org**
- The Journal of Cultural Inquiry is an open-access journal where lots of work in computational literary studies is being published. Visit the website to discover the range of research being carried out: **culturalanalytics.org**
- Katherine says, "I have been involved in curating a series of workshops on the ethics of data curation and data ontologies with Professor Lauren Goodlad at the University of Rutgers, through the Critical AI (artificial intelligence) initiative. Copies of the readings, videos and blogs are all freely available and make a good introduction to someone interested in how AI relates to humanities." Find out more: **sites.rutgers.edu/critical-ai/event-details**
- Katherine is an academic who conducts research projects, but expertise in her field also leads to careers in industry. She explains, "You could study computational literary studies and use the capabilities gained there for multiple careers at the intersection of language-rhetoric and computation-technology, from media communications to policy analysis."

Pathway from school to *computational literary studies*

- At school and post-16, studying English/literature, maths and history, philosophy or computer science will provide a good foundation.
- Although computer science and literature are traditionally separate subjects, it is possible to study both after school; look for universities that offer joint degrees or courses in computational literary studies or digital humanities.
- To become a university researcher, you will need to study for a PhD after your undergraduate degree.

Q&A

Meet Katherine

What were your interests when you were growing up?
I liked reading, movies and solitary sports (like ice skating and swimming).

Who or what inspired you to become a literary researcher?
When I finished my undergraduate degree, I realised that I'd enjoyed university and wanted to study more. At the time (it is less so now) the scholarship for a PhD was only a bit less than what I would have been paid for an entry level job, so I thought it would be a good way to keep studying.

> "MY PROUDEST ACHIEVEMENT IS CLOSING THE LOOP IN THE DIGITAL HUMANITIES DATA CYCLE."

I didn't explore computational approaches to literature (or literary approaches to computation) in my PhD, which was on how contemporary Australian women writers represent men's bodies. But when I finished that work, I was frustrated that I had spent a lot of time learning so much about a handful of texts and authors, yet knew little about how they fitted in with other literary trends.

My brother was doing his PhD in mathematical ecology, and I wondered if the dynamics he was exploring and the way he was studying them would be relevant to literary 'ecosystems'. I would now say that the analogy is too scientific, but I proposed a project that went in this direction and was awarded funding for a postdoctoral research project. As I was finishing my postdoc, jobs were becoming available in this area that was being called digital humanities, so I was able to get a job as a literary researcher and continue pursuing those questions with my own students and colleagues, for which I count myself very lucky.

You have travelled and worked in Europe and Asia. How have these experiences impacted you?
I value the opportunity to experience new cultures and take a break from routine, and both are combined in travel. It has helped me appreciate that things I thought of as normal or natural growing up, can be and often are done differently in different places. That knowledge has enabled me to ask myself, on various occasions, if I'm doing things on autopilot or because I think that's the way they should be done, and that's helped me in both my professional and personal life.

What are your proudest career achievements, so far?
My proudest achievement is closing the loop in the digital humanities data cycle. Too often, data is drawn out of cultural institutions and other collections and improved by researchers without there being mechanisms for returning the improved data.

Working with the National Library of Australia to set up a process whereby the work we do with their digitised newspapers – to find, index and edit fiction – is returned to their collection, in the form of unique records linked to the "To be continued" database, ensures that this knowledge is re-embedded in the collections that enable it. This allows others – academic researchers and members of the public – to benefit from (to enjoy, learn from, engage with, experience and, of course, add to and expand) the work we've done.

Illustration for a story in 19th century newspapers: "The Story of a Royal Pendulum". Illustrated Sydney News, Saturday 28 February, 1891, p. 5

Illustration on the cover of a 19th century newspaper: Illustrated Sydney News, Saturday March 15, 1884, p. 1

Katherine's *top tip*

Don't silo your interests into separate disciplines – or believe in the division of science and humanities, or social science and creative arts – but, instead, follow them where they go. The disciplines and organisations of knowledge that emerged in the 19th century are inadequate for how the world works today.

HOW MACHINE LEARNING IS REVOLUTIONISING MATERIALS SCIENCE

Research in materials science and engineering is crucial for developing materials that can help solve some of society's biggest challenges. In recent years, the field has begun to harness the potential of machine learning, which is massively increasing our understanding of materials' properties, and how we can discover and design new materials. **Professor Dane Morgan** and **Dr Ryan Jacobs** from the **University of Wisconsin-Madison** in the US are investigating the opportunities and challenges this advancement poses.

Professor Dane Morgan

Harvey D. Spangler Professor of Engineering

Dr Ryan Jacobs

Research Staff Scientist

Computational Materials,
Department of Materials Science and Engineering,
College of Engineering,
University of Wisconsin-Madison, USA

Field of research
Materials Science and Engineering (MS&E)

Research project
Investigating the opportunities and challenges for machine learning in the field of MS&E

Funders
Dane and Ryan gratefully acknowledge financial support from the United States National Science Foundation (NSF) Cyberinfrastructure for Sustained Scientific Innovation (CSSI) award # 1931298.

TALK LIKE A ...

MATERIALS SCIENTIST AND ENGINEER

Artificial intelligence (AI) — computer systems able to perform tasks normally requiring human intelligence

Compound — a mixture of two or more elements

Machine learning (ML) — computer systems able to learn and adapt without following specific instruction

Materials science and engineering (MS&E) — the study of materials' compositions and properties, and developing materials to fulfil specific functions

Natural language processing (NLP) — computational techniques that can analyse and synthesise natural human language

Qualitative data — data that describe the attributes or properties of something

Quantitative data — data expressing a measurable property of something

Machine learning (ML) is a powerful emerging field involving programming computers that 'learn' as they go. A part of artificial intelligence, ML looks for patterns in existing datasets and uses the patterns it finds to make its own decisions or predictions. "Machine learning has undergone astonishing growth in its capabilities in the last couple of decades," says Professor Dane Morgan, of the University of Wisconsin-Madison's College of Engineering. "These new capabilities are impacting almost all aspects of life and the study of materials is no exception. Now, the challenge is for the field to figure out how to use it most effectively."

Dane and his colleague Dr Ryan Jacobs are focusing on understanding ML's capabilities and exploring how they can be harnessed within materials science and engineering (MS&E). MS&E involves the study of materials' properties and the creation of new materials for specific purposes based on these relationships. "The use of ML in MS&E is in its early stages but evolving rapidly," says Ryan. "We've seen its power in other fields – for instance, beating the world's best professional chess or poker players, and enabling potentially transformative technologies such as autonomous vehicles – and it's clear that ML is driving advancements in science and technology."

A digital abundance

All areas of science have benefited from the rise of computation and the internet. "We now have easy access to papers and data, including massive digital databases that compile the structure and properties of countless compounds," says Dane. "This


© James Thew/stock.adobe.com

is coupled with powerful computing and modelling capabilities that make it far easier to explore and predict complex relationships between materials' structure, composition and their properties."

The majority of today's computational tools come from open-source software. "The fundamental ML algorithms are almost all available to everyone for free," says Dane. "This includes tools made by large corporations such as Facebook and Google, as well as packages made by other MS&E researchers." This accessibility removes barriers and promotes exploration and development of further tools and discoveries.

Hidden correlations

ML is especially adept at finding patterns in huge datasets that would be impossible for humans to notice. "ML can identify incredibly complex relationships between materials' structure, properties and performance," says Ryan. "It extracts information from data to form links between a material's composition (the types and quantities of elements it contains) and structure (positions of atoms in space) to particular properties or functions (e.g., its melting temperature or ability to store charge in a battery)." Dane gives the example of how the brittleness of steel, when exposed to certain conditions, is affected by the type and distribution of atoms within its structure. ML can be used to quantify these relationships, which is extremely useful for selecting a type of steel that will perform properly in important roles – within a nuclear reactor, for instance.

As well as testing existing materials, these relationships can also be extended by using ML to predict structure-property-performance relationships in currently non-existent materials. "Molecular-scale simulations are routinely used to understand predicted properties prior to real-world experiments and are a key part of the discovery and design process," says Ryan. "ML can learn how atoms in a material interact with one another based on existing data and uses this knowledge to calculate the properties of novel materials." For example, ML is being used to discover which materials can be used to make solar panels as efficiently as possible, by predicting how structural changes affect its ability to convert sunlight into electricity.

Natural language processing

Though much existing MS&E data is quantitative – based on numbers that can be relatively easily compared – a lot of data is qualitative, which is more challenging to compare or even extract in the first place, given the vast number of existing MS&E research papers in existence. "ML is emerging as an effective means of data collection through natural language processing (NLP)," says Ryan. "Manually searching existing papers for relevant knowledge is massively time consuming, but NLP methods can extract information far more rapidly." NLP involves using ML techniques to enable computers to learn the different ways that qualitative data might be presented in scientific papers – for instance, a preparation technique might say "the mixture is rapidly stirred" – and bring this data together into a format that can be used by scientists.

As such technologies become increasingly powerful, there is a growing need for MS&E researchers to adapt to use them effectively. "The new abilities of ML to understand language and make complex connections are still not widely used in MS&E," says Dane. "There is a need to integrate the tools of ML into our existing workflows, to make our research faster, better and more cost-effective."

Computer vision

Much of MS&E characterisation data is in the form of images. "In recent years, the scale and complexity of electron microscopy data has increased exponentially, driven in part by improved detector technology," says Ryan. Researchers are often interested in determining which phases are present in a micrograph, or finding individual objects in an image, such as missing atoms or extended defects like dislocation loops or voids. Large, complex datasets necessitate the use of ML computer vision methods to automate this approach.

Computer vision ML algorithms encode the complex relationships present in images – like contrast changes or the presence of edges around an object – enabling the algorithm to 'learn' what a particular microstructure or defect may look like. "Once properly trained, we have found that computer vision methods can detect objects in images with about the same efficacy as human experts, but in a fraction of the time," says Ryan.

The robot age

Like all scientific fields, MS&E inevitably includes tedious and time-consuming tasks, such as mixing hundreds of combinations of different elements to test their properties. Increasingly, robots are being developed that can perform these tasks, saving researchers a lot of time, effort and human and financial capital. "Entire autonomous laboratories are being developed that can make and characterise multitudes of materials with almost no human intervention, allowing rapid exploration of properties," says Dane. "ML is excellent at performing the decision-making involved in this process, choosing which materials to explore and in what order, based on the data it receives as the experiments progress."

Dane predicts the rise of such autonomous laboratories could fundamentally change the nature of MS&E. "As ML and robotics become cheaper and more effective, researchers will focus more on building and refining the autonomous environments, and less on the detailed experiments and calculations themselves," he says. "This will change what skills MS&E researchers need."

Ryan is enthusiastic about this changing nature of MS&E and science as a whole. "I am excited by the prospect that ML will become mature enough to be coupled with nearly every research task," says Ryan. "I believe that each step of the scientific process, from hypothesis generation, extraction of existing knowledge from the literature, planning and running experiments and simulations, and analysing results will be aided by ML. This human-machine relationship will likely enable research to progress at a rate and precision that is presently unobtainable."

ABOUT *MATERIALS SCIENCE AND ENGINEERING*

MS&E is an ever-growing field that is increasingly taking advantage of increased computational power and other opportunities. Dane and Ryan explain more about what they love about their line of work.

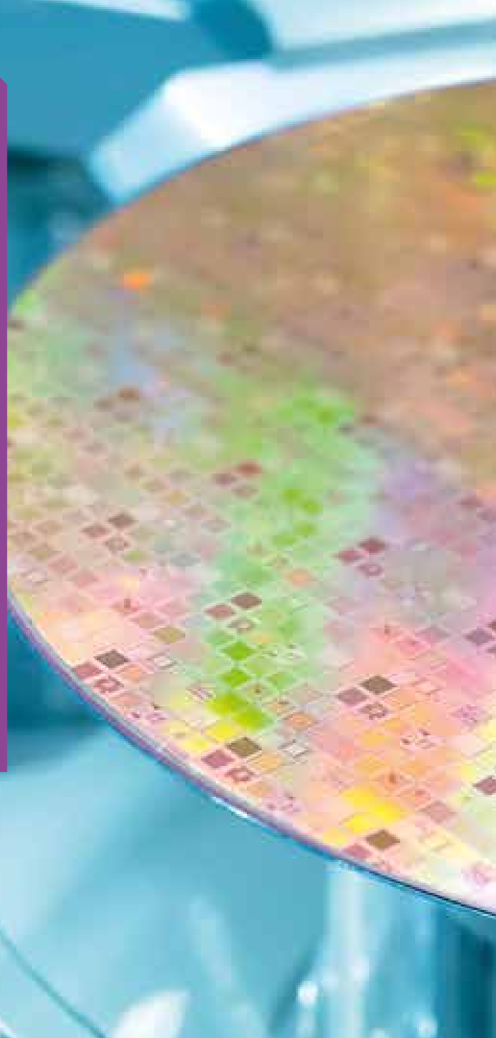
"Materials matter," says Dane. "They're at the core of most major advanced technologies. Examples are everywhere – the solar cells helping us move away from fossil fuels, the nanoscale transistors running your computers, your clothes that don't wrinkle."

"The development of new materials is at the forefront of solving our most pressing societal problems," says Ryan. "I find it very rewarding to see research done by materials scientists having a positive impact and pushing us collectively forward as a species."

"MS&E has a wonderful combination of deep fundamental problems, but also a strong connection to the real world," says Dane. "For me, I find it a great place to bring my love of scientific thinking together with practical applications to make a difference to the world."

"Future generations will be interacting with data at a scale and breadth that was never available to their predecessors," says Ryan. "Additionally, new scientists will be involved in cross-cutting modes of research integrating theory, computation and experiment at large scales."

"MS&E is a rapidly growing field with amazing opportunities," says Dane. "Now we can see and arrange individual atoms, predict atomic behaviour through simulations and integrate these methods with advanced AI to analyse data, predict behaviour and guide discovery far more rapidly than human brains could ever do. We can expect new breakthroughs in so many areas."



Explore careers in *materials science and engineering*

- Dane recommends looking into the Materials Research Society, which offers talks, activities and exposure to possible career paths in the field: **www.mrs.org**
- Dane and Ryan's department has a number of outreach opportunities and events, including the Teen Science Cafe, research experiences and participation in science festivals: **mrsec.wisc.edu**
- Informatics Skunkworks engages STEM undergraduates in practical and team-based scientific skills based on informatics such as ML. Dane and Ryan are part of the group and say it is helping future MS&E researchers gain the skills needed to work at the interface of ML, science and engineering: **skunkworks.engr.wisc.edu**

Pathway from school to *materials science and engineering*

- Ryan suggests physics and chemistry as the subjects most relevant for MS&E. He also recommends learning programming languages such as Python.
- Dane notes that there are only some schools that have undergraduate programmes specific to MS&E but says that as well as materials science, courses in mechanical engineering, chemical engineering, chemistry or physics are often relevant.
- For the growing ML aspects of the field, backgrounds in computing, coding and mathematics are helpful.

© xiaoliangge/stock.adobe.com

How did Dane *become a materials scientist and engineer?*

My father taught science and mathematics, and our house was full of science books. My mother was an English professor and telecommunications consultant and was deeply knowledgeable, too. They instilled in me a belief that science is a grand thing to be a part of, and I still agree. I also read a lot of comic books as a kid and always wanted superpowers – science is the closest thing in the real world to superpowers and magic, in my opinion!

My life as a scientist has been shaped by a hundred small moments. I remember reading Isaac Asimov and Steven Weinberg as a kid and being amazed by the immensity of their understanding. I had great arguments about mathematical proofs with my amazing grade school maths teachers and was a regular at Boston's science museum. Many incredible teachers, friends and mentors along the way have been essential.

You don't have to do science like other people do it. Some people might be great problem solvers, others great team builders, or others have a strong vision of potential outcomes. Personally, two things have helped my career enormously. Being interested in science and learning about it outside of standard schooling has helped me find academic success. Surrounding myself with great scientists and other talented people has exposed me to a range of approaches and examples, shaping me in the process.

In the future, I would love to discover a new material that has a significant impact on human welfare – maybe a better fuel cell or a stronger steel. I also aim to share what wisdom I have on how to approach science and use it to bring positive change. I hope to engage as many bright young people as I can in joining this vision.

Dane's *top tips*

1. Do a lot of science stuff outside of school. Make sure you are gaining the skills of technical thinking and practice.
2. Talk to people about their career paths, and make sure you understand the options available to you throughout your development – such as camps, competitions, programmes and career opportunities.
3. Figure out what you love and pursue it. We add so much more to the world when we believe in what we do.

How did Ryan *become a materials scientist and engineer?*

I was fascinated by planets and outer space when growing up. I remember checking out a book for each planet from my elementary school's library at once! While not explicitly tied to MS&E, such wonder for nature is important for scientists. We are often concerned with discovering and understanding the mysteries of the natural world.

I come from a long line of engineers and decided to keep up the trend. I was also inspired by well-known science communicators such as Carl Sagan, drawn by his talent for instilling scientific wonder in young minds.

Great instructors in college really drove home my passion for science and MS&E, in particular. My college undergraduate advisor pushed me to consider graduate school, which I hadn't really considered previously. The combination of interest in a subject with the support of a mentor was influential in shaping me as a scientist.

Determination and teamwork have helped make me successful. Failure is an unavoidable part of science, so having the determination to keep trying new things, creatively attacking a problem from new angles, and letting others help you are all essential. Science is highly collaborative, so surrounding yourself with good people with similar values will help aid your success.

In the future, I would like to branch out from the technical communication of science in peer-reviewed journals and try my hand at writing accessibly about MS&E for the broader public.

Ryan's *top tips*

1. Keep an open mind regarding your interests and goals. As you meet new people and are exposed to new things, you may become interested in things previously unknown.
2. Stay curious! Maintaining a sense of curiosity and asking questions will lead you to interesting, rewarding outcomes. There is so much we don't understand about the universe that is waiting to be discovered.

© StockPhotoPro /stock.adobe.com

ON THE FRONTLINE OF THE BIOMEDICAL REVOLUTION

The 21st century has seen a boom in biomedical advances, aided by increased recognition of the importance of working across different scientific disciplines. Materials and methods for the detection and treatment of diseases are better than ever, and a diverse array of scientists at the **University of Technology Sydney (UTS),** Australia, led by **Professor Dayong Jin**, are at the forefront of this continuous development.

Professor Dayong Jin FTSE

Director, Institute for Biomedical Materials & Devices (IBMD); Science Director, ARC Research Hub for Integrated Device for End-user Analysis at Low-levels (IDEAL); Co-Director, DISER Australia-China Joint Research Centre for Point of Care Testing, Technology Director, ARC Centre of Excellence for Quantum Biotechnology, University of Technology Sydney (UTS), Australia

Field of research
Biomedical Materials and Devices

Research project
Using photonics to investigate the behaviour of cells and molecules, to inform biomedical applications

Funders
Australian Research Council (ARC), Australian Department of Industry, Science and Resources, National Natural Science Foundation of China, Shenzhen Science and Technology Innovation Commission

TALK LIKE A ...

BIOMEDICAL SCIENTIST

Antigen — a substance, usually produced by a pathogen, that induces an immune response in the body

Biomedicine — the application of biological principles to medicine

Diagnostics — techniques used for identifying (for example) a disease

Imaging — making a visual representation of something through scanning it with a detector or electromagnetic beam

Materials science — the study of the properties of materials and how they relate to composition and structure

Organelle — the specialised structures within a cell

Photonics — the branch of science dealing with photons (light particles)

Have you ever taken a PCR or lateral flow test? Have you heard of PPE (personal protective equipment)? It is likely you can answer yes to both questions because biomedical science is booming – and for good reason. Our understanding of the world has changed irrevocably since the COVID-19 pandemic, and elements of biomedicine which we would not have considered before are now very familiar to us. Although the pandemic upended our lives, a silver lining of its devastating impact has been the worldwide recognition of the critical importance of biomedicine, leading to a tidal wave of resources, funding and expertise being channelled into the sector. "Now, you can see the field is thriving after the pandemic," says Professor Dayong Jin, Director of the Institute for Biomedical Materials & Devices (IBMD) at the University of Technology Sydney (UTS). "Diagnostics, imaging, materials science – people now realise how important it is."

Biomedicine in the limelight

Every response to the pandemic depended on biomedical materials and devices, ranging from straightforward prevention measures such as masks, through to the development of rapid detection methods, PCR (polymerase chain reaction) technology and vaccines. "These responses have only been possible in recent years," says Jin. "If COVID-19 had arisen twenty years ago, before ultrasensitive detection techniques, PCR technology and RNA vaccines were widely available, it would have been a much greater nightmare."

Despite successes in combatting the disease, though with heavy societal losses, Jin says that the COVID-19 pandemic highlighted the critical need for further biomedical advances. "Another pandemic will come in the future, and we need to focus on developing the technology and expertise to address it," he says. "Antibiotic-resistant bacteria are on the rise and could spark the next pandemic." Recognising this threat, Jin's team is starting to work on examining methods for detecting such bacteria. "You always have to look several steps ahead," he says. "If you only have the tools to address immediate problems, you're not prepared for problems of the future."

Into the light

Jin specialises in using photonics – the science of light – within biomedicine. "We developed the rapid antigen test for COVID-19, using

optical devices to detect viral proteins," he says. Jin's photonics research uses nanotechnology to see how light interacts with molecules themselves, which relies on drawing expertise from different areas. "We have photonics and nanoscale photonics, and we are even starting to have quantum photonics," he says. "These technologies were developed by scientists and then translated by engineers to be used within biomedicine."

A lot of this area of study depends on understanding the material properties of different substances and molecules. "We are constantly discovering new material properties that show fascinating light behaviour," Jin explains. "You can manipulate light for different applications. Handheld devices for detecting tell-tale molecules that indicate disease are increasingly becoming a reality." Jin's team is working on ever-more sensitive technologies for viral detection, alongside examining how viruses mutate and interact with host cells.

> "WE ARE CONSTANTLY DISCOVERING NEW MATERIAL PROPERTIES THAT SHOW FASCINATING LIGHT BEHAVIOUR."

Looking forward

Jin's team is currently investigating the fine but critical details of cellular science. "My team is trying to understand how cells function, how they metabolise, and how the organelles within cells work together and communicate with one another," he says. "In particular, we're developing new tools and technologies to examine these fundamentals of life, which has big implications for our understanding of how cells work."

On the broader scale, while there have been countless scientific breakthroughs in recent years, not all have yet made it into the real world. "There's a lot of exciting science out there, but for it to be useful for society, it needs to be translated into accessible technology that can be commercialised," says Jin. "The other potential limitation is people. We need to continuously train people to understand and use this new technology, as well as make further advances." For this reason, Jin sees high and ever-growing demand for biomedical scientists and engineers in the future, with exciting opportunities for new entrants into the field.

Jin's life as a *biomedical scientist*

"Growing up, I always asked lots of questions. I loved building things, such as with LEGO, and enjoyed mathematics – I was always quite good at it.

"I started my career as an experimental scientist. I was sure I would do something related to science and technology, but wasn't sure whether it would be in industry, government or academia. Fortunately, I didn't need to make that decision at that stage. I enjoyed playing with optics and lasers in the lab, which paved the way for my career progression. And I still enjoy playing with optics today – it's not so dissimilar to LEGO!

"Recognition is rewarding, and I'm always proud to say I'm a professor. My family is proud of me, and being a professor is also a well-paid job. Many professors are also entrepreneurs who start companies to get technologies into the market. Though we work long and sometimes unsociable hours, we have a good degree of flexibility.

"I think I've achieved a lot. I've won many awards and prizes, but when I look back, it's the people that really matter – the students I've trained and supervised, the colleagues I've collaborated with, the friendships I've made. They are my biggest source of pride.

"I always say to my kids that the most important skills are reading and writing, closely followed by maths. No matter what scientific profession you follow, you'll never avoid maths, and good communication skills are also a must.

"I confess, I'm a typical workaholic! But I feel this is okay as long as you like it. People say that you need persistence to overcome challenges, but I have a different strategy – if you find an obstacle, don't let it slow you down. Instead, find a challenge you feel competent to do. You can go back to the original obstacle when you feel ready. There is always plenty to do as a scientist, so if one task isn't working, you can set it aside for a while and work on other priorities."

GLOSSARY

Cardiovascular — relating to the heart and blood vessels

Nanoparticle — a tiny particle at the nanometre scale

Optical — relating to light

Probe — a molecule (used in research) that binds to a specific substance in a sample and can then be detected by a sensor

Dr Jiajia Zhou

Associate Professor, School of Mathematical and Physical Sciences, Faculty of Science, UTS

Fields of research
Materials Science and Engineering, Spectral Physics

Research project
Developing novel probes, sensors and diagnostic technologies for a range of societal and industry applications

Funders
Australian Research Council (ARC), The National Health and Medical Research Council (NHMRC)

PROFILE

Meet Jiajia

"My curiosity inspired me to become a scientist. I always wanted to know why and how things worked. My quiet personality is also well suited to a career in academia.

"I find it very rewarding to translate my research into useful probes and sensors. Going on to make devices that meet specific needs shows the real-world value of my work.

"Nanoparticles remain mysterious. There are plenty of questions still to be answered, such as how nanoparticles and antibodies interact. On the practical level, we also need to find ways to scale up nanoparticles to behave consistently, so we can roll them out to meet industry needs.

"I enjoy a great research environment in a rapidly advancing field. Working hard and working intelligently has helped me find success here."

Jiajia's *research*

The work of the Institute for Biomedical Materials and Devices (IBMD) demands the development of clever tools that can sense molecules at the nanoscale. This is where materials scientists and engineers, who have the expertise to do exactly that, come in. Dr Jiajia Zhou, Associate Professor at UTS's School of Mathematical and Physical Sciences, is leading the research and development of a range of innovative detection methods.

Probes and their uses

The development of optical probes, such as those used by Jin, is a core area of research for Jiajia. Probes are microscopic substances that are added to a sample and then change state in some way when attached to a specific molecule. They can then be detected by a specific sensor. Optical probes, for instance, change their optical properties when attached to their molecule of interest, meaning they interact with light in a different way. "My work on probe and sensor development is complementary to Jin's photonics and microscopy expertise," says Jiajia. "The unique probes and sensors we make are key elements for making biomedical devices."

Applications for such probes are diverse. "As well as testing for COVID-19 antigens, another practical application of these probes is quantifying proteins in dairy milk," explains Jiajia. "By measuring A1 and A2 proteins, we can provide dairy farmers with improved quality assurance processes." Milk with a lower proportion of A1 proteins may be more digestible for people intolerant to conventional milk products.

Nanoparticles

The rise of nanoscience is vastly increasing the potential for probes. Probes constructed from nanoparticles can enter cells themselves, attaching to proteins or other substances within the cell. Jiajia has discovered a new process to develop nanoparticles that convert light from infrared to visible at a high level of efficiency, which now have strong potential to be used as probes.

Now, Jiajia is leading her team to develop smaller, brighter nanoparticles that function as temperature sensors in living cells. "Temperature changes can be an indicator of organelle dysfunction, which can be an early sign of disease," she says. "Monitoring these changes could lead to important discoveries in early diagnosis and treatments for a diverse range of diseases – from cancer to cardiovascular diseases."

From theory to application

Like many researchers, Jiajia has seen her focus shift from theory to application in recent years. "Advances in physical sciences are being applied more and more to solve the needs of medicine and industry," she says. "Before the COVID-19 pandemic, my research was all about fundamental science, with the aim of publishing interesting findings in high-impact journals. Now, I've moved more to research translation – in other words, using my knowledge to address real-world issues like COVID-19."

Jiajia is becoming increasingly immersed in the practical applications of her research. "Over the next five years, I will specialise in ways to image and detect single molecules at high resolution," she says. "This will have applications for visualising interactions between viruses and host cells." Through advancing both the knowledge behind these behaviours, as well as developing methods and materials for detecting them, Jiajia's work will boost

GLOSSARY

Biomarker — a naturally occurring molecule that acts as a sign of a particular process (for example, a disease)

Clinical pharmacology — the study of the relationships between drugs and the human body

Point-of-care testing — a test with an analysis performed during or near to healthcare for the patient

Pre-eclampsia — a high blood pressure disorder that can occur during pregnancy

Dr Lana McClements

Associate Professor, School of Life Sciences, UTS

Field of research
Biotechnology

Research project
Developing biomarkers to detect early signs of pre-eclampsia and related conditions

Funders
Heart Foundation, NSW Cardiovascular Network, Maridulu Budyari Gumal: The Sydney Partnership for Health, Education, Research and Enterprise (SPHERE), Cardiac and Vascular Health Clinical Academic Group

PROFILE

Meet Lana

"My parents always encouraged my academic career. My father inspired me to be creative and innovative. I have also had some amazing supervisors and mentors throughout my career who have given me invaluable guidance and support.

"Biotechnology is a dynamic and constantly advancing field. New knowledge is being generated on a daily basis, with huge potential for improving people's lives and meeting industry needs. I find this scale of impact fascinating and inspiring.

"There are many opportunities in biotechnology, both in Australia and globally. The medical field always needs improved diagnostics, disease management and ways to boost people's quality of life. Digital health technologies are almost ready for home use, which will empower society with the knowledge and tools to take better care of their personal health.

"Hard work, passion, determination and resilience have been the keys to success in my field."

Lana's *research*

Dr Lana McClements is a trained clinical pharmacist who now manages a number of lab projects to develop new diagnoses and treatment methods. A core area of her research is finding ways to detect molecular indicators within blood – biomarkers – that reveal early signs of diseases such as pre-eclampsia, a complication of pregnancy. "Based on our discoveries in the lab, we're developing new tests to predict pre-eclampsia, both in the lab and at the point of care," she says. "These can then help develop the next generation of personalised treatments."

Pre-eclampsia

There is an increasing body of research indicating that many diseases begin to develop far before any physical signs are present, but, when digging down to the molecular and cellular level, the signs are there. Pre-eclampsia is the leading cause of death and complications when someone is pregnant, so addressing it before it develops would bring dramatic benefits. "Timely diagnosis and close monitoring can reduce risks of developing pre-eclampsia complications, including pre-term birth, and our biomarkers can identify pregnant women at risk of developing this condition even when they have no symptoms," says Lana.

Lana's work also goes beyond the pregnancy period and looks for solutions to safeguard long-term health. "For women who have had pre-eclampsia and their children, there is an increased risk of developing cardiovascular disease in the future," she says. Lana has worked with clinicians and biomedical engineers to screen for new biomarkers that detect early signs of cardiovascular disease in women who have had pre-eclampsia in the past, thus enabling the vulnerability to be addressed rapidly.

Knowledge base

Lana's research focuses on developing a biological understanding of disease. "Having a fundamental understanding of the underlying biology is critical when translating discoveries from the lab to the clinic," she explains. "We focus on building this knowledge base and developing advanced models of diseases in the lab, so our findings can be adapted and applied in a range of ways." This resource of knowledge is used by researchers of other specialisms, such as Jin, to develop practical applications based on these newfound mechanisms.

"We have been working with Prof Jin's group to translate our biomarkers into a point-of-care test to enable clinicians to make immediate and life-saving decisions for their patients," says Lana. "This test is highly sensitive, requiring only a small blood sample from the patient." This is an advantage for the research process, given that Lana's team can work with clinicians to gather samples from many patients to test the reliability and accuracy of their biomarkers, and also has big benefits for rollout in the real world too. "A key focus is making these tests as accessible as possible," says Lana. "Most pre-eclampsia deaths happen in remote areas or developing countries, so having point-of-care tests that are cheap and easy to use is critical for saving lives."

Like many diseases, pre-eclampsia can present itself in a multitude of ways, depending on the patient in question. "Our goal now is to understand the differences in the causes and manifestations of pre-eclampsia," says Lana. "This will help us develop personalised biomarker-based screening tests and treatments for patients, depending on the characteristics of the patient and disease."

GLOSSARY

Brillouin scattering — the process of light scattering on acoustic vibrations (pressure waves) within the material. Brillouin scattering is used to characterise mechanical properties of materials at the microscale

Brillouin microscopy — a microscopy technique where the sample is illuminated by a focused beam of light and the resultant Brillouin scattered light is analysed

Mechanical properties — physical properties such as elasticity and dissipation of mechanical energy

Optical physics — the study of the fundamental properties of light and its interaction with matter

PROFILE

Dr Irina Kabakova

Associate Professor in Optical Physics; Associate Head of School (Education & Students), School of Mathematical and Physical Sciences, UTS

Field of research
Optical Physics

Research project
Using Brillouin microscopy to examine micromechanical properties of cells and their responses to environmental changes and disease

Funder
Australian Research Council (ARC)

Meet Irina

"Being a scientist means that you always have a curious mind. Routine jobs might not satisfy your need to answer questions and learn more. This thirst for knowledge is rewarded within science – there's a lot of satisfaction to be had in a career in research, because you are able to propose and answer your own questions.

"I feel the 21st century is all about breakthroughs in biomedicine and biology. While the 20th century had many breakthroughs in physics, revolutionising our daily lives through the introduction of so many technologies (transistors, lasers and optical fibres), I believe the current century will see major advances in health and fundamental understanding of a cell. We will see advances in human lifespan, treatment of previously untreatable diseases, and new technologies that become fundamental to our future.

"All the biggest societal issues will require biomedical advances. Global pandemics, antibacterial resistance, climate change and energy crises all have serious implications for human health, with specific challenges that only biophysics and biomedicine provide the answers to."

Irina's *research*

Irina specialises in optical physics, in particular Brillouin microscopy, which uses a focused beam of light to examine micromechanical properties in biological samples. "In my lab, we look at the mechanical properties of biological materials and cells at tiny scales," she says. "Using light beams to do so means we don't damage the materials but can still examine how properties change when cells are showing signs of disease."

Exercise for cells

Cells are highly sensitive to their environment. This is especially true before they have become specialised, when they are still stem cells, such as within embryos or bone interiors. "Stem cells can differentiate in different ways, maybe becoming fat cells or muscle cells, depending on the environment they're in," says Irina.

Irina is specifically interested in how cells' mechanical properties – their local elasticity and viscosity – vary depending on their environment. "Just like us, cells need to exercise," she explains. "And, just like us, the type of exercise they do depends on what they are aiming for." While people might work out to change their mechanical properties – Pilates to increase their flexibility, weightlifting to improve strength, and so on – so cells adapt their mechanical properties to fulfil their ultimate function.

However, such changes are not always beneficial; cells also change when they are diseased. "When cells become cancerous, for instance, their behaviour and mechanical properties change," says Irina. "Their elasticity changes, and the cells become more flexible, helping them to detach from the tumour and spread throughout the body."

Fusion of disciplines

"For a long time, there were no tools to study how mechanical properties of the cells change as they react to their environment," says Irina. While the techniques that she uses were largely developed by physicists decades ago, they have only relatively recently been applied for biological purposes. "For about fifty years, the Brillouin scattering techniques we now use were only applied to physics and geology," she says.

"WHEN CELLS BECOME CANCEROUS, FOR INSTANCE, THEIR BEHAVIOUR AND MECHANICAL PROPERTIES CHANGE."

This all changed with the rise of interdisciplinary science. "About twenty years ago, optical scientists in biology realised that the mechanical properties of cells are actually very dynamic and important, and these optical techniques could help us study them." Since then, physicists, biologists and optical scientists have collaborated in greater depth, leading to the rise of important discoveries.

GLOSSARY

DNA — the self-replicating molecule in almost all living molecules, that carries genetic information

Epigenetics — the study of changes in organisms caused by changes in gene expression, rather than alteration of DNA itself

RNA — a 'messenger' molecule that carries instructions from DNA to inform the creation of proteins

Transcription — the process by which a cell makes an RNA copy of a gene

Translation — the process by which a cell reads an RNA molecule to create a protein.

Dr Yuen Yee Cheng

Associate Professor of Molecular and Cellular Biology, UTS

Field of research
Molecular and Cellular Biology

Research project
Studying how cells' epigenetic properties change in various cancers

Meet Yuen Yee

"As a kid, I always asked lots of questions and wanted to know the answers. I asked questions that not everybody did!

"Challenge energises me and keeps me working. My research has been very challenging, but once I've worked for a long time on one topic, I want to move on to the next challenge. Thinking about the application of research is always important. As scientists, there are always problems we want to solve, but a big part of good science is making sure the answers can be applied to real life. Yes, the science is amazing, but who is going to benefit?

"I enjoy the freedom I have at my current lab. Recently, I found an immunotherapy combination that could completely reject tumour growth in animals, and I also found a plant product that appears to suppress tumour growth. The practical applications of these findings are very exciting.

"Research still involves a lot of routine. For example, growing cells in the lab is repetitive, but the results can be amazing. While the process can be monotonous, it can be the trigger for something great."

Yuen Yee's *research*

Dr Yuen Yee Cheng is a molecular and cellular biologist, investigating how epigenetic alterations affect cancer development and progression. Epigenetics describes variations on top of our DNA that are interpreted by our body, which can change depending on the environmental conditions. While epigenetics underpins our development – it lets our cells adapt to different environments –, it also provides the answers for the cellular changes our body undergoes when diseased.

An epigenetics overview

"Epigenetics starts from very beginning of our development," says Yuen Yee. "For instance, in the womb, epigenetics controls how our hands separate into five fingers. During development, epigenetics leads to the death of cells between our fingers, so we develop five separate fingers. All our cells have the same DNA – different epigenetic profiles lead to different cell types," Yuen Yee explains. Her work investigates these epigenetic changes and how alterations in gene expression affect a cell's mechanical properties.

However, our cells' epigenetic properties can also be affected by agents that do not have the body's best interests in mind. While genetic diseases happen when there are errors in the DNA itself, most diseases emerge in different ways, such as through pathogens or particular environments. "While the DNA remains the same, our body's mechanisms for interpreting DNA change, causing changes to which proteins are expressed," says Yuen Yee. "It gets very complicated, very fast."

Cancers, Yuen Yee's principal area of interest, arise when something goes drastically wrong within a cell's genetic expression process, causing it to mutate and multiply in an uncontrolled manner. "I'm hoping that, soon, we will develop a lot of epigenetic biomarkers that are useful to identify early disease onset," she says. "Biomarkers help identify disease and also give an indication of how to develop treatment options."

> **"EPIGENETICS STARTS FROM THE MOMENT OUR CELLS BEGIN TO DIVIDE."**

Symbiosis

Currently, Yuen Yee is focusing on two types of RNA (circular RNA and microRNA), which are non-coding RNAs that move more freely through the cell and, ultimately, affect the translation of proteins. Her work depends on using methods developed by others. "I use the tools developed by other researchers such as Jin," she says. "His photonic instruments can be adapted to detect the properties of RNA." In return, Yuen Yee provides Jin's team with specialist biological knowledge to help it improve its tools for specific purposes. Sharing of knowledge and expertise is vital for all researchers.

Next, Yuen Yee wants to further use the nanoparticles that Jin and colleagues are developing. "The small scale of nanoparticles means you can get into the cell easier and introduce epigenetic biomarkers within cells themselves," she says. "These could light up RNA interactions, for instance – something that's never been done before. It's very exciting!

> YOU ALWAYS HAVE TO LOOK SEVERAL STEPS AHEAD. IF YOU ONLY HAVE THE TOOLS TO ADDRESS IMMEDIATE PROBLEMS, YOU'RE NOT PREPARED FOR PROBLEMS OF THE FUTURE.
>
> **JIN**

The team's *top tips*

YUEN YEE:

- Writing and communication skills are important. How you tell people about your amazing discovery is vital to ensure its real-world value and help secure funding.
- Practise your maths. It's training your brain!

LANA:

- As with any career, there will be ups and downs, but, as long as you love what you do, you will stay determined and resilient.
- Flexibility and adaptability are critically important.
- If you feel passionate about biotechnology, take opportunities to broaden your skills and your network. Engage in extracurricular activities, seek internships, and follow people and companies on LinkedIn.

IRINA:

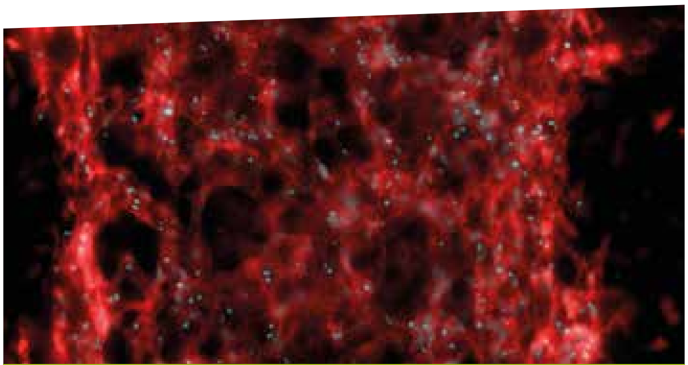
- A curious mind is essential to science. If you find yourself always wanting to find answers, you already have the scientific mindset.

JIAJIA:

- Follow your interests, and always work hard and work smart.

JIN:

- Curiosity is key. You need to ask "why?", and then be curious about why you asked it!



Vasculature forming within the placenta-on-a-chip model (© Ms Sahar Ghorbanpour)

Lana in lab

Explore careers in *biomedical science*

- The University of Technology Sydney has a variety of outreach programmes for high-school students, such as hands-on workshops, campus visits, work experience and public lectures. It also hosts a wealth of online outreach resources: **www.uts.edu.au/about/faculty-science/outreach/outreach-and-community**

- Optica is the leading society for optics and photonics research. It has a number of resources for high school students, schools and families to learn more about the field: **www.optica.org/en-us/get_involved/education_outreach**

- Careers in biomedicine vary widely and can involve working in academia, industry or government. According to SalaryExpert (**www.salaryexpert.com/salary/job/biomedical-scientist/australia**), the average base salary for a a junior biomedical scientist (with a PhD degree) in Australia is $110,739 (AUD) per year.

> **AS SCIENTISTS, THERE ARE ALWAYS PROBLEMS WE WANT TO SOLVE, BUT A BIG PART OF GOOD SCIENCE IS MAKING SURE THE ANSWERS CAN BE APPLIED TO REAL LIFE. YES, THE SCIENCE IS AMAZING, BUT WHO IS GOING TO BENEFIT?**
>
> **YUEN YEE**

© Dan Race/stock.adobe.com

Pathway from school to *biomedical science*

Jin and his colleagues emphasise the importance of a strong foundation in mathematics for most scientific careers. In addition, they note the importance of being able to communicate effectively, showing the value of subjects like English. Depending on interests and possible future specialisms, combinations of the three sciences will often be an expectation for universities.

CONTROLLING AND ENGINEERING SYSTEMS FOR THE BENEFIT OF ALL

Professor Zi-Qiang Lang is an automatic control and systems engineer based at the **University of Sheffield** in the UK. Three of his former PhD students, a former PhD supervisor and Zi-Qiang share what it means to be an automatic control and systems engineer. Together, their commentaries highlight what is required to succeed in the field.

Professor Zi-Qiang Lang

Professor of Complex Systems Analysis and Design, Department of Automatic Control and Systems Engineering, University of Sheffield, UK

Field of research

Automatic Control and Systems Engineering

Research projects

Zi-Qiang is engaged in various projects to develop better engineering system design processes, create novel engineering system operational condition monitoring methods, and apply newly devised system and control approaches to multi-disciplinary areas from advanced manufacturing to medical diagnosis. The results of his studies have demonstrated significant improvements in these important application areas and the potential of the use of systems and control engineering methods across a very wide range of fields.

Funder

UK Engineering and Physical Sciences Research Council (EPSRC)

This work was supported by the EPSRC under award number EP/R032793/1.

TALK LIKE AN ...

AUTOMATIC CONTROL AND SYSTEMS ENGINEER

(WORKING ON COMPLEX ENGINEERING SYSTEMS)

Artificial Intelligence — makes it possible for computers and machines to perform human-like tasks while learning from their experiences

Big data — a collection of information in massive volumes too complex and large to be processed by traditional methods

Composite material — a substance that is made up of different components with different chemical and physical properties

Data-driven modelling — using previously collected data and information to create an understanding of how an engineering system would operate

Engineering system — a combination of elements and components that work together to perform a useful function

Machine learning — a type of artificial intelligence that allows computers to predict outcomes more accurately by learning from historical data and information

Prototype — a model or sample of a product that is created to test its functionality

Prototype fabrication — the process of creating a prototype

Automatic control and systems engineering might be a subject you have not heard too much about, but it is one that permeates many aspects of your life and the lives of those around you. For instance, if you have ever taken a flight, train or car ride, this has been made possible by automatic control and systems engineers such as Professor Zi-Qiang Lang.

Zi-Qiang is a systems engineer based at the University of Sheffield in the UK and has worked on multiple projects. One of these projects involves the application of systems and control approaches to the optimal design of complex engineering structures such as designing aircraft landing gears made of composite materials.

Why is systems engineering important?

In the area of complex engineering system designs, a systems and control engineering approach enables manufacturers to build a physically meaningful model of a system. “A key challenge is how to integrate domain knowledge into a generic data-driven model that can

© Gorodenkoff/stock.adobe.com

> **A KEY CHALLENGE IS HOW TO INTEGRATE DOMAIN KNOWLEDGE INTO A GENERIC DATA-DRIVEN MODEL THAT CAN ACCURATELY REPRESENT THE UNDERLYING PHYSICS ASSOCIATED WITH A GIVEN DESIGN PROBLEM.**

accurately represent the underlying physics associated with a given design problem," explains Zi-Qiang. "Achieving this implies that the well-established field of system science can be applied to address many challenges that cannot be solved by conventional engineering system design approaches."

Questions and research methods

The fundamental question Zi-Qiang and his team have been trying to answer is how to build a physically meaningful model of an engineering system that can be designed from data collected from a limited number of prototype tests. In addition, Zi-Qiang wants to understand how to perform an optimal design of systems based on physically interpretable data-driven models. "A modelling and design integrated approach uniquely proposed by my team at the University of Sheffield has been used to develop new engineering system design processes," says Zi-Qiang. "This produces a powerful computer-aided design tool that uses data from only a limited number of prototype tests to produce an optimal design for complicated engineering systems including, for example, mechanical and civil engineering structures and complex dynamics materials."

Importantly, the applications for the intended outcomes of this project extend to fields as diverse as aerospace, healthcare, infrastructure and transport.

Key findings and successes

The key findings so far include determining the methodologies that can be used to build physically meaningful, design-oriented data-driven models, as well as the development of a range of successful feasibility studies, which is an assessment of the practicality of a project or system. Together, these demonstrate the significance and potential applications of this unique modelling and design integration approach in various industrial sectors.

"One feasibility study on the study of auxetics (which are structures or materials that, when stretched, become thicker perpendicular to the applied force), showed that the new design approach can achieve a 70% reduction in the fabrication of prototypes, compared with traditional designs," explains Zi-Qiang. "This has many applications including in body armour, packing material, knee and elbow pads, robust shock-absorbing material and even sponge mops!"

ABOUT *AUTOMATIC CONTROL AND SYSTEMS ENGINEERING*

Automatic control and systems engineering is a subject area that applies engineering mathematics and computing technology to solve scientific and engineering problems. For instance, aircraft engine control, wind turbine operational condition monitoring and robot control are all sectors that rely on automatic control and systems engineering expertise. The applications of the field are involved in almost every area of society.

Why consider a career in automatic control and systems engineering?

Automatic control and systems engineering is a highly rewarding field that can contribute significantly to society. It relies on the design, manufacturing and operation of almost all engineering systems and, as a result, engineers with expertise in the field are needed in almost every industrial sector.

What does Zi-Qiang find most rewarding about his career in the field?

Zi-Qiang tells us that he most enjoys the multidisciplinary nature of his career and the opportunities it provides for close collaboration with colleagues. "The nature of the field provides excellent job opportunities across a broad range of disciplines," explains Zi-Qiang. "I get to work with people from a variety of science and engineering backgrounds and resolve challenging problems in various subject areas that have significant importance to society."

What challenges will the next generation of automatic control and systems engineers encounter?

One of the most significant challenges the next generation will face is how best to integrate artificial intelligence (AI) and machine learning (ML) into system and control engineering. If we can find a way to achieve this, it will allow sufficient exploration of the advantages of AI and ML in big data processing and human intelligence–based decision making, enabling intelligent design, manufacturing, management, operation and control of various engineering systems.

Pathway from school to *automatic control and systems engineering*

- Zi-Qiang suggests students take as many maths courses as possible, as well as one or two other science subjects, such as physics, chemistry or biology.
- Two or three A-levels, or equivalent, in a relevant subject for a degree.
- When pursuing a systems engineering degree, you'll likely first obtain a bachelor's degree in systems engineering and then focus specifically on your desired industry when pursuing a master's degree.

Explore careers in *automatic control and systems engineering*

- The International Council on Systems Engineering (INCOSE) is an essential resource for anybody interested in pursuing a career in the field: **www.incose.org**
- MITRE is another resource that features an extensive knowledge-sharing culture, including people from academia, industry and other non-profits: **www.mitre.org/focus-areas**
- According to Glassdoor, the average salary for a systems engineer in the UK is £41,400, depending on the level of experience: **www.glassdoor.co.uk/Salaries/systems-engineer-salary-SRCH_KO0,16.htm**

How did Professor Zi-Qiang Lang *become an automatic control and systems engineer?*

I grew up on a university campus and became interested in systems and control engineering subjects when I was very young. My father was a university professor in Automatic Control. Many of his friends and colleagues were well-known scientists in this area. My academic interests have been significantly influenced by this background – it is the research achievements and experiences of my father and his friends and colleagues that inspired me to become an automatic control and systems engineering scientist.

One of my proudest achievements is that an innovative concept I proposed in 2005 in the subject area of system science known as Nonlinear Output Frequency Response Functions (NOFRFs) has been widely recognised in relevant communities. The concept and associated approaches have now been applied by many researchers to solve challenging problems in different disciplinary areas including robotics, renewable energy, and advanced manufacturing.

I regularly engage in sports like running and squash. I also like to study history, from which I realise many principles of systems and control engineering can also be applied to explain phenomena in human history. For example, according to the system and control theory, the stability of a system is completely determined by the inherent natures of the system itself rather than external interference. From the history of human beings, we know that this principle also works in social systems.

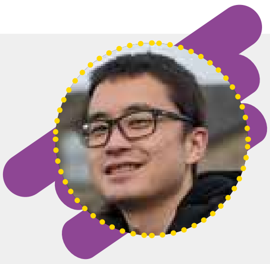
Zi-Qiang's *top tip*

It is essential that you develop a systematic view of the things around you as soon as possible. This is critical for conducting multidisciplinary studies where integration of a system and control approach with different domain knowledge is the key to achieving a solution.

Meet *former PhD students*

We spoke with three of Zi-Qiang's former PhD students – Dr Uchenna H. Diala, Dr Sikai Zhang and Dr Rafael S. Bayma – to learn about their experiences as automatic control and systems engineering PhD students.

Dr Uchenna H. Diala



Dr Sikai Zhang

Dr Rafael S.Bayma

What does a typical day in the life of an automatic control and systems engineering PhD student involve?

Dr Sikai Zhang (SZ): After making a cup of coffee or tea, I start my research work, which includes reading literature, coding and writing. Around noon I would have lunch and chat with other PhD students in our department.

Dr Uchenna H. Diala (UD): It involves carrying out research related to the modelling and analysing of control systems, as well as the design of controllers for the engineering system of interest.

What are the main challenges in systems and control engineering research and how do you manage them?

Dr Rafael S. Bayma (RB): It depends on what specific area we are investigating. In the topic that I undertook, the main challenge was the development of a consistent and systematic approach to understanding and describing very complicated dynamic systems.

UD: The main challenge is formulating a model that closely represents an actual system. This is usually managed by making certain assumptions to enable a good representation of the system of interest.

SZ: The research in control and systems engineering generally requires a solid foundation in mathematics. The first year of a PhD is a good time to deeply understand the basic maths knowledge, such as Fourier transform, Laplace transform, autoregression model, etc.

Who or what inspired you to become an automatic control and systems engineer?

SZ: My interest in control systems started in 2012 when I participated in a smart car rally organised by a Japanese company called Renesas.

RB: I always liked subjects related to maths and computers. I studied fractals in my first year in college. I was also fascinated by the fact that all of those theories had real applications. When I was about to finish my undergraduate course, I went to a conference and learned about system identification. At that time, I met a professor who undertook his PhD at the University of Sheffield in the subject area, and I think that attracted me a little more to it.

UD: The versatility of automatic control systems was the major inspiration because the course enables you to fit into any professional field, whether science, engineering or finance. I enjoy the possibility of engaging in multidisciplinary research because of the overlap control systems engineering provides across most other professional fields.

What are your plans for the future?

UD: I have graduated and currently work at a university as a lecturer in electrical and electronic engineering. I hope to become an outstanding professor in the future, developing technologies that will make the world a better place.

SZ: I am working as a senior research engineer at Rockwell Automation. My ambition is to make the industry more energy-saving and summarise my work into a book.

RB: In the past, my priority was to get back to my workplace because my graduation was bound to it by contract. The plan was to set up a research group and activities in this area. However, this did not prove easy owing to local conditions. At present, I am more inclined to consult or perhaps start a business in either technology or education in areas related to the knowledge I have been able to gather so far.

Meet *Professor Stephen A. Billings*

Professor Stephen A. Billings

Emeritus Professor, Department of Automatic Control and Systems Engineering, University of Sheffield

We had a conversation with Professor Stephen A. Billings, who supervised Zi-Qiang during the latter's time as a PhD student, to get a sense of what it is like for an experienced professor working in the field of automatic controls and systems engineering.

Professor Zi-Qiang became my student initially. He then became my research assistant before becoming a professor himself. It was great to see his development and know that I assisted in some way. I have successfully supervised 55 PhD students, each one being as special as it was when I first began supervising.

Dynamic systems are almost everywhere and span the entire range of engineering and scientific disciplines. The developers and users of these systems need to understand their behaviours and learn how to study and control these systems.

Management of the team who work for you is very important and a lot of time is spent planning and thinking about these issues. Does everyone know what they are supposed to be doing, does anyone need help, do they know and understand the plan for the future etc.? This may involve meeting individuals, meeting as a small group or planning and thinking through projects.

The main challenges are to be good at maths, computing and experimentation. This is a challenge but equally provides very interesting opportunities. Control and systems engineers also need to be open to new developments that arise and to utilise and advance these.

A career in automatic control and systems engineering provides systems engineering skills that can be applied to a wide range of challenges, from industrial processes, space weather, and machine vision to biology, medicine etc. This is much wider than people first appreciate and can lead to the development of multiple skills over a range of interesting problems.

PATHOGEN-BUSTING NANOSURFACES INSPIRED BY INSECT WINGS

Keeping surfaces clean is more complex than you might expect. Pathogens can adhere to and multiply on almost any surface – but not all. **Professor Prasad Yarlagadda**, from the **Queensland University of Technology** in Australia, is taking inspiration from insect wings to design nanosurfaces that destroy any bacteria or viruses that land on them. This has major implications for the next generation of super-sterile materials, especially within the medical field.

Professor Prasad Yarlagadda

Faculty of Engineering,
Queensland University of Technology, Australia

Field of research
Smart Systems Engineering
(focusing on Bio-Manufacturing)

Research project
Developing nanostructured surfaces that repel or destroy pathogens

Funders
Australian Research Council (ARC), Metro North Hospitals, Princess Alexandra Hospital, Queensland Children Hospital, Australia India Strategic Research Funds, Stryker, Advanced Queensland Industry Research Fellowship Scheme

TALK LIKE A ...

SMART SYSTEMS ENGINEER

Bacteria — single-celled microorganisms typically about a tenth of the size of our own cells, some of which are pathogens (can cause disease)

Biofilm — a community of bacteria or other microbes, held to a surface by a thin layer of viscous material that they secrete

Colony forming unit — a unit used in research to estimate the number of microbial cells in a sample that are able to go on to multiply into a colony

Fluorescence — the ability of a chemical to absorb a certain radiation and retransmit it as visible light

Nano — a prefix used for many terms (e.g. nanomaterial, nanoparticle, nanostructure) to indicate the substance exists at the nano scale – in other words, the substance itself or its key features are very, very small

Orthopaedic — the branch of medicine that addresses issues with bones or muscles

Pathogen — a bacteria, virus, or other microbe that causes disease

Virus — an infective agent, many times smaller than bacteria, that multiplies only within infected cells, and can be pathogenic

Infectious diseases are one of the main causes of death worldwide. Tuberculosis, for instance, killed around 1.6 million people in 2021, while the recent COVID-19 pandemic highlighted the deep societal impacts of a highly infectious virus. Finding ways to treat these diseases is paramount, but finding ways to stop diseases spreading in the first place has the potential for even greater societal benefits. Lots of pathogens multiply or spread via surfaces – so by making critical surfaces hostile to pathogens, rates of infection can potentially be mitigated. This has significant implications for healthcare and hospital environments, and other crowded places such as transport and infrastructure hubs.

Take orthopaedic implants – hip or knee replacements, screws and plates to support damaged bones, and so on. While orthopaedic procedures bring great benefits to most patients, they also entail risks. "Orthopaedic implants are susceptible to a range of different types of infection," says Professor Prasad Yarlagadda, of the Queensland University of Technology. Even with the most fastidious sterilisation techniques, there is a risk that surgical instruments or the implants themselves are hosts to colonies of bacteria, which are called 'biofilms' when they multiply on a surface. The tissues exposed by surgery can provide an easy infection site for such colonies, which can lead to serious health issues for the patient, with worst case scenarios resulting in amputation of the affected limb or even death.

Nanotextured structures

Prasad has long been interested in ways to design surfaces at the nano level that repel or even destroy pathogens. His team, the Smart Structures and Bio-Interface Group (SSBIG), focuses its research on pathogenic bacteria. "Some studies suggest that when bacteria cells come into contact with certain nano-structured surfaces, they rupture and die," he says. SSBIG's recent research has looked closer into this, finding that nanostructures involving a series of pointy 'nanospikes' can provide pressure points on the cell walls of bacterial cells that come into contact with it. It is not dissimilar to rolling a water balloon across a floor covered in barbed wire, albeit on a much, much smaller scale. Bacteria


© Oleksii/stock.adobe.com

are so tiny themselves, that it requires even tinier structures to burst them.

Coating orthopaedic implants with such nano-structured surfaces could help make them far less likely to pose an infection risk. "Such antibacterial surfaces prevent the initial attachment of bacteria and have the potential to restrict biofilm formation and associated implant infection," says Prasad. His team is focused on practical applications, always thinking about how its findings can bring benefits to society.

Insect inspiration

While anti-pathogenic surfaces are a modern and innovative area of research for humans, as is often the case, the natural world got there first. Dragonflies and cicadas have naturally antibacterial wings, helping them to avoid infections on these fragile but essential surfaces. Researchers used powerful microscopes to examine these properties and found that the wings are covered in nanospikes. These findings have gone on to inspire Prasad's team, which is imitating this structure in its own research.

SSBIG employs a method called hydrothermal synthesis, which is widely used for nanofabrication due to its reliability, efficiency, environmentally friendly nature and capacity for fine control. "This method involves high temperatures and pressures to dissolve and recrystallise materials to form nanoparticles," explains Prasad. "Adjusting the conditions of these reactions, such as the temperature, the concentrations of dissolved materials used, or the duration of the reaction, alters the shape, size and roughness of the nanoparticles formed." Prasad's team has used this method to create nanostructures that mimic those found on dragonfly wings, with similar antibacterial properties.

Findings

Once the nanostructures are created, the next step is to test their effectiveness. "We tested the effects of our nanostructured surfaces on two common bacterial species, both of which are highly pathogenic and problematic for society, using two main methods," says Prasad. The first involved counting colony forming units (CFUs), by incubating bacterial cells on different surfaces (including nanostructures), and then growing survivors on nutrients and counting the number of colonies that resulted. The second method involved staining bacteria with fluorescent dyes that change colour depending on whether the bacteria is alive or dead, and then assessing the coverage of live and dead cells on different surfaces after a set period of time. "Additionally, we also used scanning electron microscopy to directly see how bacterial cells were behaving and being affected by different surfaces," says Prasad.

"Our research indicated that nanostructured surfaces can rupture bacterial cells of different species, and work just as well when these nanostructures are present on flat or non-flat surfaces," Prasad explains. "We also found that introducing fluid flow over the surface led to even better performance, with the flow removing live bacteria from nanostructured surfaces because they were not able to easily adhere." These findings are very promising, indicating significant practical bonuses to including nanostructures on key surfaces.

From bacteria to viruses

Viruses are even smaller than bacteria, yet a number of viruses are devastating pathogens, as the recent COVID-19 pandemic indicated. Prasad and his team have been on the frontline of developing solutions to viral spread. spread. This work was supported by virologist Professor Kirsten Span and PhD student Miss Tejasri Yarlagadda of the School of Biomedical Sciences at the Queensland University of Technology. They contributed various activities around developing protocols and training Prasad's postdoctoral reserchers Dr Amar Velic and Dr Alka Jaggessar to undertake anti-viral studies. "We began studying the antiviral properties of nanostructure surfaces against respiratory viruses in mid-2019, before the pandemic," he says. "We eventually submitted a publication just three days after the pandemic was declared worldwide."

The publication showed that nanostructured aluminium could significantly reduce the viability of certain viruses compared to untreated aluminium. "Soon after, we further tested the nanostructured aluminium against SARS-CoV-2 (the virus responsible for COVID-19) and found a dramatic reduction after six hours, with almost all viral particles being eliminated," explains Prasad. "We also began developing these surfaces for other materials such as titanium, aluminium, stainless steel and certain polymers, given the usage of these materials in the medical field."

Next steps

While such surfaces have potential practical applications across a wide range of industries, the first on the list is the medical sector. "The primary application of these surfaces would be on biomedical equipment," says Prasad. "However, their application is not limited to this – in fact, in theory they could be added to any surface found in a hospital that is prone to bacterial colonisation."

While SSBIG research has robustly demonstrated the effectiveness of nanostructured surfaces against pathogens, there remain unanswered questions it is keen to address. "Firstly, we are interested in understanding how nanostructured surfaces repel or destroy pathogens at the molecular level," says Prasad. "To investigate this, we'll conduct large molecular simulations (using multi-scale molecular dynamic modelling at cell level) of pathogen interactions with nanostructured surfaces, alongside analysing molecular responses themselves via changes in protein and lipid compositions."

The team's second aim is further translation of their findings into practical applications for the real world. "We'll continue to develop nanostructures that can be applied to an ever-expanding range of relevant materials," says Prasad. "We will also investigate ways to improve the stability and durability of nanostructured surfaces, and to further study their behaviour under complex flow conditions."

ABOUT *SMART SYSTEMS ENGINEERING*

Smart systems engineering involves the integration of all engineering disciplines to science, health and medicine. Prasad talks more about the field and his own career path within it.

"Smart systems engineering crosses over disciplinary boundaries. People from engineering backgrounds can solve real-life problems by working alongside health professionals, medical researchers and mathematical modellers, to name a few. Any sector, ranging from aviation to food, to mining, has a need for integrated, cross-disciplinary work.

"It's very difficult to become bored with a career in smart systems engineering. New opportunities will always arise, which can transform the world. For instance, the rise of computing over the last few decades has changed every aspect of our lives. In the future, the integration of smart systems will do the same.

"Around 18 years ago, when I became full professor, our university was looking to encourage more applied research by integrating different disciplines. I became the Founding Director of the Smart Systems Research Theme, which has since run many flagship projects focused on ideas such as future airport design, digital manufacturing and design of medical devices. It was clear that the development of products or support of a sector was not possible with the involvement of professionals from only a single discipline."

"SMART SYSTEMS ENGINEERING CROSSES OVER DISCIPLINARY BOUNDARIES. PEOPLE FROM ENGINEERING BACKGROUNDS CAN SOLVE REAL-LIFE PROBLEMS BY WORKING ALONGSIDE HEALTH PROFESSIONALS, MEDICAL RESEARCHERS AND MATHEMATICAL MODELLERS, TO NAME A FEW."

Explore careers in *smart systems engineering*

- The Queensland University of Technology, where Prasad is based, promotes STEM careers through engagement with high schools, including on-campus workshops and events for high school students. Find out more: **www.qut.edu.au/study/career-advisers-and-teachers/stem-for-schools**
- Engineers Australia has a wide range of resources for teachers and students, including engaging learning materials, careers advice and national competitions: **www.engineersaustralia.org.au/about-engineering/study-engineering**
- Future Makers hosts a substantial bank of links to STEM resources for Australian students, ranging from science events, education kits and career programmes: **www.futuremakers.org.au/links**
- According to Indeed, the average annual salary for an engineer in Australia is AUS$53,000. Prasad says, "In the current post-COVID market, average salaries are increasing substantially."

Pathway from school to *smart systems engineering*

- At school and post-16, Prasad recommends mathematics as essential for most STEM degrees. Additionally, he says that subjects focused on science, technology, engineering, computing and medicine will all help set the stage for a career in engineering.
- He also suggests finding out about study opportunities in smart systems engineering disciplines at the University of Southern Queensland: **www.unisq.edu.au/study/degrees/bachelor-of-engineering-honours**


© vchalup/
stock.adobe.com

Meet Prasad

Despite underprivileged beginnings, Professor Prasad Yarlagadda has had an illustrious career, focusing on research that improves the quality of life for many. This includes the development of innovative medical devices and anti-pathogenic surfaces, as well as an array of community-led development projects. He has worked with non-government organisations (NGOs) to enhance the mobility of landmine victims in Cambodia and Vietnam, led community efforts for Queensland multicultural organisations, and shown leadership of international professional organisations too. Cumulatively, these achievements led Prasad to be awarded the prestigious Order of Australia Medal. Prasad explains more about his life and achievements.

"I was the first person in my family to enter middle school. As both my parents were illiterate due to economic conditions preventing their education, I did not get much educational guidance during my early years. Despite their financial hardship, my parents always encouraged my desire to learn. I am always grateful to them for supporting my education, which has not only changed my life but has paved the way for my younger family members too.

> ***"WORK BEYOND ANY ONE DISCIPLINE, AND APPRECIATE THE BENEFIT OF INTEGRATION WITH OTHER DISCIPLINES."***

"Even as a child, I have always wanted to be an engineer. I enjoyed mathematics and physics at school, and my teachers encouraged me to learn more about engineering. My physics teacher, Tummala Seshagiri Rao, and my classmate's father, G.Rama Krishna Raju (who is an engineer), were my first and most influential mentors.

"Once I completed my undergraduate studies in mechanical engineering, I worked for a year to understand more about the practical applications of engineering. My academic career has frequently been paused while I have worked for a couple of years in industry, which has helped me better appreciate real-world problems and develop my own problem-solving skills.

"Always being willing to collaborate and respect and acknowledge other contributions has greatly helped my career. Similarly, mentoring and nurturing young colleagues gives me a lot of satisfaction, with several of my students going on to very prestigious positions in Australia, India and around the world.

"There is no single solution to overcoming challenges in the workplace. However, having a positive and collaborative attitude has always helped me overcome both professional and personal obstacles.

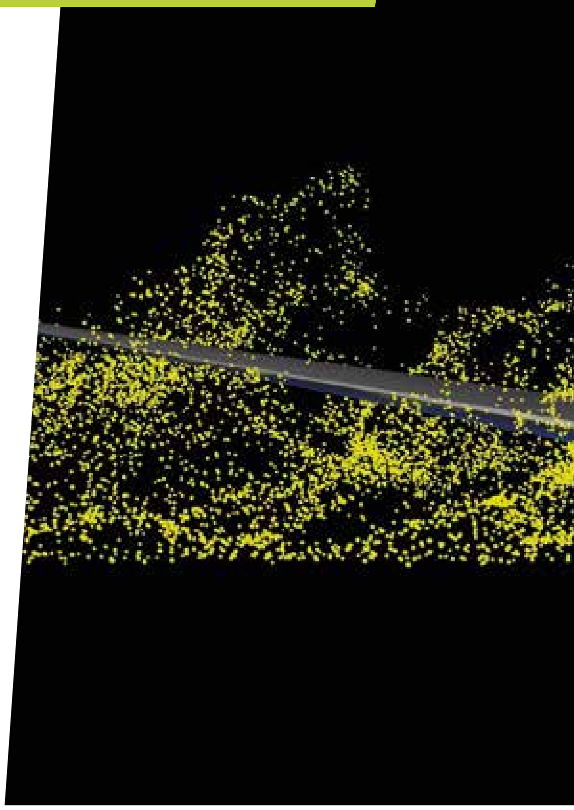
"Beginning my undergraduate studies was one of my proudest career achievements. Similarly, completing my PhD, becoming a full professor and receiving a number of fellowships and awards have been proud moments for me. The most notable award is the Order of Australia Model, which recognises my accomplishments in both engineering education and support of the Queensland community. I also received the Researcher of the Year award following my efforts to prevent the spread of COVID-19 in hospitals and other facilities."

From his own experiences, Prasad knows how education can change an individual's life and their family's well-being. With his interest in the development of rural areas and providing educational opportunities to regional residents, he has recently accepted a new role as Dean (of Engineering) at the University of Southern Queensland (UniSQ), Australia. Commencing in February 2023, his new role will see him working to improve educational and employment opportunities in South-East Queensland regional areas such as Toowoomba, Ipswich and Springfield.

Prasad's *top tips*

1. Follow your passion. Don't be swayed by pressure from peers, family or society. If you choose something you care about, you will have a fulfilling career.

2. Work beyond any one discipline, and appreciate the benefit of integration with other disciplines. This is the best way to find work that benefits both you and the society you live in.



HOW CAN WING DESIGN IMPROVE AIRCRAFT FLIGHT?

Aviation technology has come a long way since the Wright brothers made the first successful motor-powered flight in 1903. Today, aeronautical engineers are focused on improving the efficiency of aircraft, by designing longer, thinner, more flexible wings. At the **University of Bristol**, UK, **Dr Punsara Navaratna** and **Dr Alessandro Pontillo** are developing new testing and modelling techniques for novel wing design and the added complexities of a flexible aircraft.

PROFILES

Dr Punsara Navaratna

Research Associate in Aeroelastic Modelling

Field of research
Experimental Flight Dynamics

Dr Alessandro Pontillo

Research Associate in Experimental Flight Dynamics

Field of research
Flight Dynamics of Flexible Aircraft

Department of Aerospace Engineering, University of Bristol, UK

Research project
Developing new testing and modelling techniques for exploring flight dynamics of flexible aircraft within a wind tunnel environment

Funder
Engineering and Physical Sciences Research Council (EPSRC)

Other team members: Professor Mark Lowenberg (Principal Investigator), Professor Jonathan Cooper, Dr Djamel Rezgui, Professor Simon Neild

TALK LIKE AN ... AERONAUTICAL ENGINEER

Aerodynamics — the study of air flow and its interaction with a body moving through it

Aeroelastic model — a mathematical representation of a flexible structure over which air is flowing, used to study its dynamic response to aerodynamic, structural and inertial (mass) loads, i.e. to study its 'aeroelastic' behaviour

Drag — the force which opposes the motion of an aircraft through the air, generated by every part of the aircraft

Induced drag — drag caused by the generation of lift (because the distribution of lift is not uniform across a wing) which is a large component of the overall drag

Lift — the upwards force generated as air flows over a wing

Linear — when two variables plotted on a graph are related by a straight-line

Non-linear — when two variables plotted on a graph are not related by a straight-line

Thrust — the push force that moves something forward, the opposite of drag

Wing root — where a wing is attached to an aircraft

In the 15th century, Leonardo da Vinci produced one of the first flying machine concepts, taking the first step towards fulfilling the human dream of flight. However, it took over 400 years for this dream to become reality. It was not until 1903 that Orville and Wilbur Wright successfully flew the first motor-powered aircraft. Since then, aviation has really taken off. Today, aeronautical engineers are responsible for the exciting new developments in aircraft technology, from improving the design of commercial aeroplanes to creating drones that can fly on Mars.

To improve fuel efficiency and reduce emissions, aeronautical engineers are exploring the potential of making aircraft wings longer, thinner and more flexible. When developing new aircraft designs, aeronautical engineers test models in wind tunnels and apply numerical modelling to predict and analyse their behaviour. However, for these new, flexible wings, current testing methods are not adequate for the added complexities their design brings in aircraft flexibility and its interaction with overall aircraft motions. This is why Dr Punsara Navaratna and Dr Alessandro Pontillo, Research Associates in aeronautical engineering at the University of Bristol, are developing new testing and modelling techniques to investigate the flight dynamics of flexible aircraft in a wind tunnel environment.

© vrx123/stock.adobe.com

How are new aircraft developed and tested?

"A wind tunnel is one of the most valuable tools used in experimental studies of aircraft," says Punsara. A wind tunnel consists of large tubes with fans that produce a controllable stream of air. By placing a scaled model of an aircraft in the tunnel, engineers can assess how it behaves when exposed to airflow and use this knowledge to predict how a full-sized aircraft would behave.

Usually, testing is done by placing a stationary model in the wind tunnel, but at the University of Bristol, a new 'manoeuvre rig' has been developed that allows engineers to move the model aircraft while it is in the airflow. "The model aircraft can be 'flown' in the wind tunnel, similar to how a real aircraft would fly," explains Punsara. Sensors on and around the model collect data on how the air moves around the aircraft and how the aircraft itself responds to the airflow, which can then be compared with numerical models of how an aircraft is expected to behave.

Aeronautical engineers create two different numerical models to test aircraft designs – structural models and aerodynamic models. "The structural model captures the aircraft's structural stiffness, whether it is rigid or flexible," explains Alessandro. "The aerodynamic model captures the behaviour of the airflow relative to the aircraft and is used to calculate the forces the air creates on the aircraft." These two models can then be combined, along with mass effects, to create an 'aeroelastic' model of an aircraft.

Why are flexible wings being developed?

It is the shape of an aircraft's wings that cause it to fly. As aeroplane wings are curved on top and flatter on the bottom, air flows faster over the top of the wing than it does underneath it. This reduces the air pressure above the wing, resulting in an upwards lift force and causing the plane to fly.

Aeronautical engineers are looking to make flying as efficient as possible, in part to reduce carbon emissions. A longer and thinner wing reduces induced drag, which means that less thrust is needed to counteract the overall drag. As thrust is generated by the aeroplane's engines, less drag means less fuel consumption.

However, the structure of long, thin wings will be heavier than that of an equivalent conventional wing, as a longer wing will have greater bending at the wing root. "One way of keeping weight down is to allow the wing structure to be more flexible," says Punsara.

How are flexible wings tested?

Understanding how these flexible wings behave and interact with the whole aircraft is a new challenge. It is important to examine the whole aircraft as the flexibility of the wing can significantly affect characteristics such as passenger comfort and the pilot's workload in flying the aircraft. "These wings require the development of new numerical tools that have the capability of capturing the highly non-linear characteristics of the wing, which typical linear models cannot capture," explains Alessandro. After creating new computer models of flexible wings, he and Punsara must then conduct experiments to validate them.

Typically, flexible wings have been mounted on the side of a wind tunnel, and then the angle of the wing relative to the airflow is changed to measure wing deformation. Using the 'manoeuvre rig', the full aircraft can be tested instead, and the interaction and coupling of the flexible wing with the aircraft body can be examined. Punsara and Alessandro have developed a new testing technique for investigating the flight dynamics of a flexible aircraft in the wind tunnel. This new technique allows unexpected phenomena to be identified, such as those related to the coupling of the flexible wing dynamics with the flight mechanics behaviour. It also allows new aircraft configurations to be tested, as well as verifying numerical models to support aircraft design.

> **"A WIND TUNNEL IS ONE OF THE MOST VALUABLE TOOLS USED IN EXPERIMENTAL STUDIES OF AIRCRAFT."**

So far, Punsara and Alessandro have manufactured three wings with different levels of flexibility. They are currently putting them through wind tunnel testing, allowing them to study a range of structural properties. They have also developed a new numerical model which rapidly simulates a flexible wing connected to a rigid aircraft. This model can capture the non-linear effects of big wing deformations.

Where else can these techniques be applied?

The knowledge gained from testing and modelling flexible-winged aircraft can also be used to test wind turbine blades. As these blades are very long and thin, they are similar to flexible aircraft wings and can be modelled in the same way. "Wind turbine blade dynamics can potentially couple with the turbine tower motions in a similar way to a wing interacting with the rest of the aircraft," says Punsara, explaining how aircraft testing and modelling techniques can be extended to other applications.

Aeronautical engineering is at the forefront of modern technology and the future of the sector is wide open. Punsara and Alessandro's work is an essential contribution to the continued development of aircraft, as well as addressing the environmental challenges facing the aviation industry.

ABOUT *AERONAUTICAL ENGINEERING*

Aeronautical engineering concerns the science of flight and the designing, manufacturing, testing and operating of flight-capable machines. It is one of the two arms of the aerospace engineering field. The other arm, astronautical engineering, includes vehicles for space flight, such as satellites and rockets.

What topics do aeronautical engineers work on?

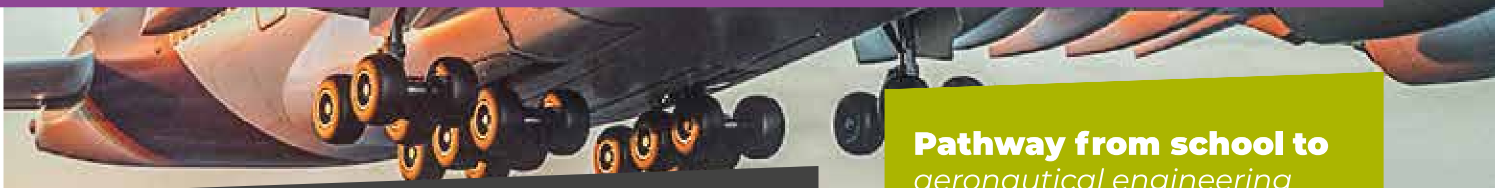
There is a broad range of areas for aeronautical engineers to work in. Aerodynamics is an important field of study as it impacts aircraft performance, such as range and fuel efficiency. Flight dynamics investigates the 'quality' and stability of aircraft flight. Engineers are also involved in avionics (the electronics used for aviation) and might find themselves designing or testing control systems, fuel systems or landing gear. Modern aircraft use composite materials to reduce weight, thereby saving fuel and reducing emissions, making structural design and material selection very important current topics in aeronautical engineering.

What skills do aeronautical engineers have?

Aeronautical engineering is multidisciplinary, with different skills, topics and areas of interest overlapping and interacting with one another. Engineers need to have strong mathematical, analytical and problem-solving skills. "The process of making, trying and (often) failing is what distinguishes a good engineer from a lazy one. Never give up!" says Alessandro.

Having background knowledge of the big areas of engineering will help in whatever field of expertise you specialise in. Aeronautical engineers must understand engineering physics, such as thermodynamics, fluid flow, structures, mechanisms and feedback control. Mathematics and numerical computation skills are also essential, to derive, run and analyse models. Engineers will also need to master Computer Aided Design (CAD).

Anything that flies is subject to very strict certification requirements by the relevant authority, for the safety of everyone involved. This means the development and innovation of new technologies must face a long and expensive certification process. "It's up to engineers to find compromises between the great invention and the need to produce something safe, usable and cost-effective in a reasonable time scale," says Alessandro.



Explore careers in *aeronautical engineering*

- The Royal Aeronautical Society (**www.aerosociety.com**) has free membership for students and a wealth of information about careers in the field (**www.aerosociety.com/careers-education**). Its magazine, Career Flightpath, is dedicated to career development in aviation: **www.aerosociety.com/careers-education/resources/career-flightpath-magazine**
- The Faculty of Engineering at the University of Bristol conducts various outreach events, including some focusing on aerospace activities: **www.bristol.ac.uk/engineering/outreach**
- With a career in aeronautical engineering, the sky is not the limit! You could find yourself designing aircraft for other planets, such as NASA's Ingenuity helicopter on Mars: **www.nasa.gov/aeroresearch/nasa-aeronautics-on-mars-and-earth**
- The UK aviation and aerospace sectors have launched a Charter for Women to promote gender equality in the field: **www.gov.uk/government/publications/women-in-aviation-and-aerospace-charter/women-in-aviation-and-aerospace-charter**
- Prospects provides information about the different roles you might do as an aerospace engineer, and the salary you can expect: **www.prospects.ac.uk/job-profiles/aerospace-engineer**

Pathway from school to *aeronautical engineering*

- Studying maths, physics and computing at school will be extremely useful for a career in engineering.
- In the UK, you can become an aeronautical engineer by studying a university degree or college diploma, or by completing an apprenticeship: **nationalcareers.service.gov.uk/job-profiles/aerospace-engineer**
- Many universities offer bachelor and master's degrees in aerospace and/or aeronautical engineering.
- Aerospace companies in the UK that offer apprenticeships include Airbus, Rolls-Royce and BAE systems.
- UK citizens can also pursue aeronautical engineering through the Royal Air Force: **www.raf.mod.uk/recruitment/engineering**
- Careers in Aerospace offers detailed information about pursuing a career in aeronautical engineering and the routes you could take to achieve this: **www.careersinaerospace.com**

How did **Punsara** *become an aeronautical engineer?*

When I was younger, I was always making things out of LEGO and Meccano, or building aeroplanes from plastic bottles, cardboard and lots of imagination! I was inspired to become an aeronautical engineer by my father. He was a mechanical engineer, and I wanted to follow in his footsteps.

My career has enabled me to spend my time learning more about the things I love. My PhD has been the highlight of my career, so far, and I have been lucky enough to work with many great thinkers. I have learnt so much from each of them.

In the future, I would like to continue my career in research and deliver insights into new investigative tools to aid the process of future aircraft design.

Alessandro and I won the Engineering Faculty Post-Doctoral Research Prize for a previous project involving a flexible wing skin design. Having our work recognised gives us motivation to pursue different areas of research interests, especially knowing that we will receive support from the university.

> **“MY CAREER HAS ENABLED ME TO SPEND MY TIME LEARNING MORE ABOUT THE THINGS I LOVE.”**

I think that having a logical thinking style has helped me as an engineer as problem-solving is at the heart of aeronautical engineering. The ability to think creatively is also useful as it is important to think outside the box to find creative solutions to problems.

Punsara's *top tips*

1. Follow your interests, and remember to have fun!

2. Keep persevering in your own journey.

3. Don't be afraid to ask for help, resources or guidance.

How did **Alessandro** *become an aeronautical engineer?*

I was fascinated with how things worked when I was young. I loved taking things apart, so my mum had to hide household appliances from me! I was always inspecting toys' circuits and gears and reusing electronics in other projects that got more complicated and advanced as I learnt more. Although my projects failed most of the time, I learnt a lot through this process, and it was a great training for my imagination!

When I was younger, I wanted to be a pilot. When that didn't work out, it was natural for me to still choose a career in aviation. My work in aeronautical engineering is what I want to do for the rest of my life. It has enabled me to travel widely and enjoy many different cultures and traditions. I have met interesting people and amazing scientists from whom I have learnt so much.

I am inspired by Nikola Tesla, who dedicated his life to science and engineering. His ideas were well ahead of the times, and he never gave up pushing the boundaries of knowledge. The technology that he developed one hundred years ago is still powering our houses and offices today!

I think that engineering merges art and science. The development of the technology that we use every day was often the result of very futuristic and artistic thinking. For example, when the Wright brothers created the first aircraft, they ran downhill with their machine, without even knowing whether it was going to fly!


© auremar/ stock.adobe.com

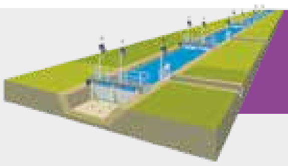
Alessandro's *top tips*

1. Don't be afraid to fail; you can learn so much from it.

2. Working in science can be tough, but the reward is worth it.

HOW ARE CONTROL ENGINEERS IMPROVING THE SUSTAINABILITY OF IRRIGATED AGRICULTURE?

Globally, less than 60% of the water diverted into irrigation networks is used productively. This inefficiency is partly due to outdated infrastructure and manual operating practices that can result in wasteful spillage at the end of the open-water distribution channels and poor service to farmers. In Australia, control engineers from the **University of Melbourne** and **Rubicon Water** have developed a system that automatically adjusts water supply to more efficiently meet demand.



TOTAL CHANNEL CONTROL™

PROFILE

University of Melbourne and Rubicon Water, Australia

Field of research
Control Engineering

Research project
Automation of open channels for gravity-powered water distribution

Funders
Australian Research Council (ARC), Rubicon Water, University of Melbourne

TALK LIKE A ... CONTROL ENGINEER

Actuator — a device for imposing the value of a variable as a control input. For example, an adjustable gate for setting the flow between sections of an irrigation channel

Compensator — the part of a feedback control system that determines the actuator settings across time in response to sensor measurements. It is often implemented in software on a computer

Feedback control — achieving desired behaviour by measuring what is happening and using this information to adjust the control inputs

Off-take — extraction of water from an irrigation channel

Pool — in an irrigation network, a stretch of open channel with gates at each end. Pools can range from hundreds to thousands of metres in length

Sensor — a device that produces measurements of a variable

Setpoint — the desired value of a controlled variable. For example, in irrigation networks, there are setpoints for the water levels at the supply points to irrigators

Signal — the values of a variable across time. For example, the varying water levels and gate flows in an automated irrigation channel

Supply point — in an irrigation network, where off-takes occur

Humans have been finding innovative ways to divert water for thousands of years. In Ancient Egypt, canals were used to distribute water from the Nile across large plains to grow crops such as wheat and barley, while in Southeast Asia, people learnt how to partially flood fields to increase yields of rice. As irrigation can double or even triple crop yields, technologies such as these laid the foundations for much of modern agriculture.

At the University of Melbourne, Professor Michael Cantoni and Professor Erik Weyer are collaborating with engineers at Rubicon Water, including Professor Iven Mareels, Dr Adair Lang and Dr Yuping Li, to improve the efficiency of gravity-fed irrigation networks. They are applying techniques from control engineering to automate the networks of open channels used to distribute water to farms. Their work is reducing water losses from irrigation networks and improving the quality of water distribution services for farmers.

What challenges do irrigation networks face?

"Half of the world's accessible fresh water is used in large-scale irrigation for our food and natural fibre production," explains Iven. Population growth, food security and rising living standards are driving increased demand for irrigation water. On the other hand, climate change and competing uses for water outside agriculture impact the supply side. "Without large gains in water productivity, the world could run out of economically available water," Iven warns.

Most agricultural water distribution systems consist of a network of open channels and the flow of water through the system is powered by gravity. Channels are partitioned by gates into stretches of stored water, called pools. The gates are used to set the flow of water between these pools. To irrigate their fields, farmers extract water at supply points.

It is important that the supply of water through the network is set to meet the demands of farmers extracting water. In networks with limited opportunities to adjust gate settings, unpredicted changes in demand can result in wasteful spillage of water out of the network and poor service to irrigators, which can limit efforts to improve on-farm efficiency.

Total Channel Control™

These challenges motivated the team to enhance the capabilities of irrigation networks by developing 'Total Channel Control™' (TCC). TCC is an automatic control system for maintaining desired water levels at the supply points in an irrigation network, so that the water demands of farmers can be reliably supplied under the power of gravity.

With TCC, the gates between pools are equipped with sensors to monitor the local upstream water level, actuators to adjust the gate positions to set the downstream flow, and radio communications for the exchange of information between the gates. "The goal is to coordinate the gate flows along the channels to keep water levels at supply points close to target values as demand varies across the network," explains Michael.

Providing a high-quality service to irrigators requires steady water levels at supply points. "However, the scale of the system and uncertainty in future demand for flow make the problem of coordinating the gates non-trivial," says Michael. To address the challenge of supplying water to match unpredictable demand, the TCC system relies on feedback control.

The importance of feedback control

"Feedback control is one of the essential elements of life as we know it," Iven says. For example, it keeps warm-blooded animals at a constant internal body temperature. If our body becomes too warm, we sweat to reduce our temperature, while if we get too cold, we shiver to warm up. In this way, our core body temperature is maintained close to 37 °C.

In feedback control, adjustments are made to the system when the measured value of a quantity does not match its target value. It involves observed signals, produced by sensors, and signals imposed on the system by a compensator via actuators in response to the observed signals across time. "Together, the interconnection of the system and compensator is a feedback loop," says Michael.

Feedback in TCC causes the gates to respond to measured water level errors by adjusting the gate flows along the channel. Under steady operating conditions, the upstream inflow to each pool will match the off-take and downstream outflow, and the water level at supply points will remain constant. Any changes to the off-take or downstream demand will perturb the net flow of water and cause a change in local water level.

With TCC, the outflow gate at the downstream end of each pool measures the difference between the observed water level and the desired water level. This information is communicated to the inflow gate, which determines how the upstream inflow to the pool should be adjusted in order to return the downstream water level to the desired setpoint. "This feedback control action at the upstream gate also changes the net flow of the upstream pool, resulting in water level error there and adjustment of its upstream gate by feedback compensation," explains Erik. "This continues automatically, until the inflow at the top of the channel has been adjusted to match the change in demand."

How do models inform the design of feedback loops?

The data furnished by the water level sensors and the actions taken by the gates' automatic adjustment mechanisms form a feedback loop that keeps water levels at the desired setpoint, regardless of changing demand.

The design of feedback loops can be complicated. "It is well known that poorly designed feedback loops can lead to very undesirable outcomes, such as the excitation of waves that can lead to channel damage and flooding," says Yuping.

The team avoids the possible pitfalls of feedback by using mathematical models to inform the design of the compensators for each pool. For example, these models are used to guide the selection of compensator parameters and used in simulations to validate performance ahead of operational deployment. The models are informed by the physics of channel flow and encode the dynamic relationships between upstream inflow, downstream outflows, supply point off-takes and downstream water levels. The models are calibrated against experimental, historical and synthetic data.

Successes of TCC

A key advantage of TCC is that the supply of water from the environment is adjusted to match the varying demand, which avoids spillage and wastage of unused water at the end of distribution channels. Automation means the system does not require human input to adjust water flow when demand changes. Also, the system does not need predictions of future demand as the feedback control system autonomously reacts to real-time changes in demand, although when available, such information can be incorporated to enhance performance.

To date, Rubicon Water has installed over 35,000 control gates in irrigation networks around the world. The Goulburn-Murray Irrigation District in northern Victoria, Australia, has been operating under TCC for more than a decade, resulting in water losses being reduced by 50% compared to pre-automation operations. Development of the TCC technology continues as Rubicon Water expands into new markets.

As our global demand for water increases, control engineers will play a key role in helping to ensure our world has water security.

ABOUT *CONTROL ENGINEERING*

Control engineers are often responsible for the design and implementation of crucial components in larger engineering systems. "Feedback control systems enable intended behaviour to be achieved in unpredictable operating environments," explains Michael. For example, in power and water distribution networks, control systems allow the supply of electricity and water to be automatically adjusted to meet unpredictable changes in demand.

"Control engineering is everywhere around us," says Iven. "For example, our mobile phones use just enough power to make a call, but as little as possible to avoid draining the battery." Cruise control on a car maintains the car's speed and the autopilot in aircraft maintains specified altitude and direction. Thermostats use simple controls to keep your home at a constant temperature, regardless of the weather outside.

Bridging the gap between academia and industry

The partnership between the University of Melbourne and Rubicon Water underlies the initial success and continued development of TCC. "As the industry partner, Rubicon Water is the source of real-world problems that need solutions," Erik says. "The university team of academics contributes expertise in modelling and control of dynamic systems." In all fields of engineering, it is important to work with stakeholders to ensure the needs of end users are met. To improve irrigation network efficiency, for example, the team works with water authorities and farmers to learn what each requires from an automated irrigation network. "As well as having strong technical skills, control engineers must also have the interpersonal skills necessary to interact with different stakeholders," says Yuping.

The future of control engineering

"Control engineering is a discipline that has very wide applicability," says Iven. It is essential in all modern industrial settings, playing a critical role in improving the energy and resource efficiency of processes. While this project is reducing water waste, control engineering can also increase sustainability in other contexts. "Control engineering has a significant role to play in making our industrial society more sustainable," says Erik.

Pathway from school to *control engineering*

- "To become an engineer, maths and physics are fundamentally important at both school and university level," says Michael. "Computer science is also important."
- Computer programming skills are essential in most engineering jobs, so learn coding languages as soon as you can. "Working on hobby projects that involve coding is a great way to practice and develop these skills," suggests Adair.
- "Keep studying maths, as it is the foundation of engineering," advises Adair. "Don't just learn the formulas, try to understand the theory and how to use maths to solve problems. This is what makes an engineer."
- If you are interested in the biomedical applications of control engineering, it will be useful to study chemistry and biology.
- At university, control engineering is taught within general undergraduate engineering degrees, such as electrical, mechanical, aerospace and chemical engineering. Some universities will then offer postgraduate degrees specifically in control engineering.

Explore careers in *control engineering*

- Control engineers can find themselves working in a wide range of industries. From contributing to the green energy revolution in electric power grids, to enhancing the sustainability of water and transportation networks, control engineers are always in demand. You could also find yourself developing artificial intelligence for surgical robotics or designing autopilots in the aerospace industry.
- Prospects provides information about careers in control engineering, including the work you are likely to do, the skills you will need and the salary you can expect: **www.prospects.ac.uk/job-profiles/control-and-instrumentation-engineer**
- The Control Systems Society of the Institute of Electrical and Electronics Engineers has published a report on the impact of control technology with examples of how control is used in a huge range of applications, from drones to medical rehabilitation to Formula One racing: **www.ieeecss.org/impact-control-technology-2nd-edition**

Meet *the team*

Professor Michael Cantoni
Professor of Electrical and Electronic Engineering, University of Melbourne, Australia

What were your interests when you were younger?

My main interest was in spending time outside with my brother and neighbours – riding our bikes, kicking about in nature reserves, swimming in the ocean. When stuck inside, I spent hours playing with LEGO and with an early personal computer. After my family relocated from one side of Australia to the other, I became more interested in school and playing music.

Who inspired you to become an engineer?

My father is an electrical engineer, my mother trained as a civil engineering draftsperson and I have grandparents who were technicians – so perhaps it is in my genes! At the end of high school, it was maths and physics that I enjoyed the most, so engineering seemed like a natural path to follow at university.

What do you most enjoy about your job?

I enjoy the process of applying mathematical thinking to achieve desired outcomes and to balance competing objectives. There is such a wide range of practical contexts in which control engineering is relevant – water and power distribution networks, heating and ventilation systems, telecommunications, manufacturing and aerospace.

What has been the highlight of your career?

I am proud to have contributed to the success of Rubicon Water, both through my own research and by training engineers who played a key role in translating innovations from research into real-world outcomes. Iven, Erik and I jointly received an award for this work from the Control Systems Society of the Institute of Electrical and Electronics Engineers.

Professor Iven Mareels
Non-executive Director, Rubicon Water, Australia

What were your interests when you were younger?

At school, I liked studying, reading and sports (especially handball and table tennis). At home, my dad was handy around the house so we did a lot of home projects together. I enjoyed working with my grandad in his timber workshop, where I became interested in creating and building things.

Who inspired you to become an engineer?

My dad was an electrical engineer, as were two of my uncles, so engineering was always in the family. I was encouraged to take things apart and put them together again, and my dad would explain technical ideas to me. At school, I was advised to study classics at university, but my interest in science and maths always seemed to point me towards engineering. In the end, I got sufficient marks to go to Gent University in Belgium, where I studied electro-mechanical engineering.

> **"I WANT TO SEE SCIENCE AND ENGINEERING MAKE A POSITIVE DIFFERENCE FOR PEOPLE AND FOR SOCIETY."**

What have been the highlights of your career?

The collaboration with Rubicon Water is certainly one of the highlights of my career. In 1998, when I worked at the University of Melbourne, I was approached by someone at Rubicon Water who was a former engineering student of mine. Rubicon Water was having control problems with an irrigation channel system they were managing, and my former student wondered if I could help. The University of Melbourne has worked with Rubicon Water ever since.

I am also proud to have trained over 50 PhD students. I know that these new generations of engineers will change the world, which is greatly rewarding. I have an ongoing interest thinking about how best to educate young engineers, in the context of new tools, such as artificial intelligence, which affect how we perceive and use knowledge. I want to see science and engineering make a positive difference for people and for society.

Field technicians install gates in Chile

Rubicon gates in use in New Zealand

Professor Erik Weyer

Professor of Electrical and Electronic Engineering, University of Melbourne, Australia

What inspired you to become an engineer?

At school, I always liked maths, and then later, physics. At university, it was natural for me to study something where mathematics played a big role.

What qualities have made you successful as an engineer?

I have always paid attention to details. The overall design and concept of a project are, of course, very important. But, for a project to work, all the details also need to be right. At the same time, I like to do things my own way, which sometimes has led me to new ideas and improved methods for problem solving. Even if I discover that the standard approach works better than my new suggestion, I know I have learnt something new from trying it my own way.

What do you most enjoy about your job?

I enjoy working on interesting and challenging problems. The first time we tested a control system on an irrigation channel was a memorable moment. Although everything worked well in simulation on a computer, I still had worries that we may have overlooked something and that it wouldn't function when tested on the real channel. It was very rewarding to see that it worked. There is a satisfaction in seeing that a system works after you have designed, implemented and tested it.

Dr Adair Lang

Innovation Manager, Rubicon Water, Australia

What inspired you to become an engineer?

During high school, I didn't really know what an engineer was. I pursued my interests in physical sciences and maths and, while still in school, I was fortunate enough to undertake work experience at the National Measurement Institute in the Australian Government's Department of Industry, Science and Resources. This experience led me to enrol in physics, maths and introductory engineering courses at university. After learning more about engineering, how it sits at the interface between scientific study and practical application, I chose to major in electrical systems.

What motivated you to do a PhD in engineering?

After completing a master's degree in engineering, I spent three years working as a control engineer at Rubicon Water. However, I had a desire to gain more knowledge and to develop new research skills, so I returned to university to do a PhD. In my research, I used mathematical analysis to find solutions to problems that arise in irrigation networks. This involved developing computer models and methods to solve complex maths problems. Fortunately, I was able to continue working part-time at Rubicon Water during my PhD, keeping me close to the practical applications of engineering while conducting theoretical research.

What does your current role at Rubicon Water involve?

I contribute to the roadmap for the technology being produced by the company. This involves meeting with managers and the CEO and discussing ideas with clients and sales staff. Part of my work is prioritising the large number of potential products to ensure that the company focuses on the highest value ideas first. I also lead the research and development of the control engineering side of the company. This involves computer coding, mathematical analysis, writing specifications for products and working with other teams to implement solutions.

What do you most enjoy about your job?

I enjoy designing and implementing novel solutions to real-world problems that have a large impact on saving water and increasing farm productivity. I like getting involved with multiple projects, both at a technical level and in a coordination role. A real highlight is when a solution is deployed and the client is able to witness the benefits of automation in their water distribution network.

The team's *top tips*

1. Engineering is about creating the world around us, which begins with a problem to solve. Know that there will be an engineering pathway to a solution (within the limits of feasibility – not everything we dream of is feasible!).
2. Creativity is given to all of us – it is part of being human. Use your creativity to help others and don't lose the joy of it.
3. Don't be satisfied with a superficial understanding of something, or the first solution you find to a problem. Instead, be a lifelong learner and constantly seek out new challenges
4. Respect what you do not know. Always ask questions to learn more.

"EVEN IF I DISCOVER THAT THE STANDARD APPROACH WORKS BETTER THAN MY NEW SUGGESTION, I KNOW I HAVE LEARNT SOMETHING NEW FROM TRYING IT MY OWN WAY."
ERIK

Gate installation in Queensland, Australia

Dr Yuping Li

Senior Control Engineer, Rubicon Water, Australia

Who inspired you to become an engineer?
My mum is an electronics engineer and she inspired me to follow this career. As a child, I liked playing with a Rubik's Cube and I also enjoyed painting, and still do today.

What does your job as a control engineer involve?
My research interests are in the distributed control of large-scale water distribution networks, model approximation and validation. At Rubicon Water, I do research and development work on irrigation networks and provide technical training on our systems, both internally and to customers. Part of my operational work is to identify control issues within existing irrigation networks and organise ways to rectify them.

"WORKING ON IRRIGATION NETWORKS, I GET THE OPPORTUNITY TO SEE CONTROL ENGINEERING PROBLEMS IN PRACTICE, WHICH MOTIVATES ME TO LEARN NEW TECHNIQUES AND USE THE KNOWLEDGE THAT I HAVE TO HELP SOLVE THEM."

What do you most enjoy about your job?
I enjoy seeing a design implemented in a real system and achieving the performance aims that we were targeting. Working on irrigation networks, I get the opportunity to see control engineering problems in practice, which motivates me to learn new techniques and use the knowledge that I have to help solve them. I am proud of the fact that the CEO of Rubicon Water recently gave a presentation to the board of the company which heavily featured work that I have contributed to over the past four years.

EMPOWERING GIRLS, INSPIRING ENGINEERS

Decades of gender stereotyping, discrimination and prejudice have resulted in an engineering work force that is largely made up of white males. Despite changing opinions and increasingly equal access to opportunities, more diversity and inclusion is still needed in the field. **The Society of Women Engineers (SWE)** in the US is addressing this issue by inspiring young girls to get excited about engineering and to know that they belong.

Markita C. Riley

Outreach and Student Programs Manager, Society of Women Engineers (SWE), Chicago, USA

Fields of research
Engineering, Technology

Research project
SWENext – supporting girls to become part of the engineering and technology community

TALK LIKE AN ...

ENGINEER

Bipoc — Black, Indigenous and People of Colour

Technical skills — skills that are specific to a particular field. In the field of engineering, these might be the ability the perform equations, build models and design concepts

Soft skills — personal skills that are relevant in most careers, such as leadership skills, conflict resolution and self-confidence

In 1950, a group of women engineers from the US founded the Society of Women Engineers (SWE). Their goal was to empower women to reach their full potential in the field of engineering and to demonstrate the benefits of inclusion and diversity. Despite significant progress in recent years, women currently account for just over 14% of the engineering workforce.

SWE is working hard on a number of projects to help to turn the tide on engineering's gender imbalance. One such project is SWENext, a programme designed to enable girls to join the SWE community as students before they turn 18. As SWENexters, students get access to programmes, mentors and resources designed to set them up for a career in engineering. Markita Riley, Outreach and Student Programmes Manager for SWE, is working to inspire young girls to not only consider a career in engineering and technology but to know that their inclusion in the field can make a difference for wider society.

What are the benefits of becoming an engineer?

Whether it is creating solutions for their local communities or tackling global issues like climate change, engineers have the opportunity to improve the world around them. "Engineering allows you to give back and to pull others up with you," says Markita. "For example, a few of our corporate partners that are SWE members have been involved in the interior design of The Obama Presidential Centre, a new cultural hub being built in Chicago. The centre will run many programmes aiming to help the communities in its surrounding area."

Engineers are often at the heart of the projects that they are involved in. From developing a concept to building the finished product, engineers get to contribute to the entire process. The feeling of accomplishment that accompanies the completion of a project is one of engineering's major benefits. The engineers involved in The Obama Presidential Centre, for example, will be able to look at the finished building in a few years' time and say, "I had a part in that".

What opportunities will the future offer?

The next generation of engineers will be at the forefront of solving many of society's challenges, such as how to address climate change and how to feed our growing population. They will also have many opportunities to discover new innovations in fields and industries that may not even exist yet. It is hard to tell what the world will look like in the future, but the next generation of engineers is sure to play an important role.

How can students prepare for a career in engineering and technology?

Markita explains that students must develop both their professional "technical skills" and their personal "soft skills". Technical skills include being able to learn new information, perform calculations and formulate new designs. Often, these skills are seen as the basis of a good career in engineering and technology, but it is also important for students to develop their soft skills.

Leadership, conflict resolution, work-life balance and public speaking are all soft skills that are vitally important for a successful career. "You might have to conduct meetings, work on a team project, or pitch ideas to clients, so you really have to work to develop these soft skills, in addition to technical skills," explains Markita.

© Shutter B/stock.adobe.com

How can SWENext help students prepare for their careers?

SWENext is designed to help students develop both their technical and soft skills.

Students are encouraged to build their technical skills and STEM knowledge by taking advantage of SWENext's resources. For example, the STEM pathways library contains digital workbooks on a variety of engineering disciplines. Students can also gain practical experience by connecting with a SWENext club in their local area.

SWENext also helps students develop their soft skills. For example, the SWENext High School Leadership Academy (SHLA) gives students the opportunity to develop their leadership skills within their own communities.

Students can participate in any number of inspirational sessions on topics ranging from self-development to cultural awareness. "We let them have the freedom and autonomy to build their own leadership portfolio rather than telling them what to do," says Markita. Instead of prescribing what the students take part in, the SHLA programme encourages individuals to take charge and create their own experience. "These students are already doing amazing things in their local communities," says Markita. "Why would we limit them?"

What does SWENext aim to teach students about engineering?

"I think that sometimes students can become intimidated by engineering," says Markita. "I want them to know that it's not as complex as they might originally think." Often, engineering is about simplifying processes to make certain tasks easier or more efficient. Although engineering is based around science and mathematics, it can give you other skills that are useful in everyday life.

SWENext also wants to instill in students the understanding that everyone belongs in engineering. Many people, particularly women and people of colour, often think they have no place in engineering and other STEM disciplines. "I want students to know there are plenty of engineers out there who are just like them and they can carve out their own pathway to success in any industry," says Markita.

How can diversity, equity and inclusion be improved?

According to a 2018 study by Pew Research Centre, 9% of people in STEM careers are Black, 7% are Hispanic, 17% are Asian and 14% are women. "It's clear that we need to see more diversity in engineering," says Markita.

Back in the 1960s and 1970s, which is relatively recent, the few women engineers who had access to a career in engineering had to try and 'blend in'. "Some women engineers I've spoken to have said that you really had to be 'one of the boys' to pursue this career," explains Markita. Thankfully, a lot has changed since then, but there are still issues that need to be addressed. "It's not enough to just have women and BIPOC professionals visible in these companies," says Markita. "We need to make it clear that they are an integral part of the company that they are contributing to."

Engineers have to make sure that the innovations they create work for everybody. Technology advances at a rapid pace, and it is easy for people to be left-out or forgotten. For example, facial recognition technology does not always recognise darker complexions. As a developer, if you are not considering every kind of person during the design process, your product will suffer, and entire groups of people may miss out. "This is why we need to make sure everyone is considered when we make innovations," says Markita. "To make progress, we need to ensure everyone's voice is heard."

> **"TO MAKE PROGRESS, WE NEED TO ENSURE EVERYONE'S VOICE IS HEARD."**

SWENext exists to help girls break into the world of engineering and STEM. "It starts with the girls," says Markita. "Letting them know how important they are, that they are not limited by their circumstances or by people's opinions, and that they can do things that are beyond their current situation and what they think they're capable of." Having the support of people who believe in them can make all the difference. "In reality, it's already in them; SWE is empowering them to use the tools they already have," explains Markita.

© ake1150/stock.adobe.com

WHAT DOES THE SWENEXT PROGRAMME *OFFER PARTICIPANTS?*

There are currently over 6,200 members of SWENext who benefit from the activities and resources on offer.

What types of activities does SWENext offer students to develop their leadership skills?

The SWENext High School Leadership Academy (SHLA) is a virtual, year-round programme that helps students prepare for college and develop their technical and soft skills. In addition to SHLA, SWE offers SWENext Awards to recognise SWENext students and clubs doing exceptional outreach work in their local STEM community. These awards are designed to recognise outstanding students who have demonstrated leadership in STEM activities. The recipients get the chance to present their ideas and connect with SWE members at the annual conference. "All of this builds leadership skills and allows students to connect with the wider SWE community," explains Markita.

What does the mentor programme offer?

Members of SWENext receive mentorship from both their peers and from professional engineers. Participants of SHLA and SWENext clubs often act as informal mentors to each other. They can answer questions about challenges that they have faced and offer advice on how to connect with the STEM community. Additionally, SWENext Connect, a virtual project, allows students to connect with SWE members who have expertise in various fields of engineering. SWE also has many sponsors and partner organisations that volunteer their time, allowing students to get advice from experts in the field.

What role can SWENext play in building students' self-confidence?

"SWENext aims to build a network of support around students," says Markita. "Research shows that one issue girls face when they're transitioning from middle school to high school is that there are no resources that cater to their specific needs." SWENext fills this gap by creating content and programming that is specifically tailored to young engineers at every age, from primary school through high school.

Once SWENext members have left high school, they can join their local collegiate SWE section and participate in the Collegiate Leadership Institute (CLI). Here, they will continue to build their skills and knowledge to become leaders in the field of engineering. A lot of the programming SWE provides is free or affordable. "When you don't have to worry about the cost, you can explore more," says Markita. "That helps students know they can do it and that there are many tools to help them along their journey."

How does SWENext help students form networks?

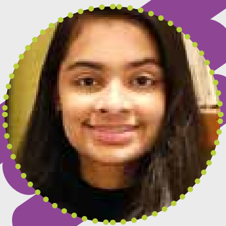
"One of the best ways for SWENexters to tap into a network is to join or form a SWENext club," says Markita. Currently, there are over 375 SWENext clubs located in more than a dozen countries. Joining one of these clubs is a great way for students to find their STEM community. Many clubs host outreach events to engage younger students in engineering. Markita explains, "Our goal is to prepare students to take what they've learned and not only use it for themselves, but also use it with younger students who might have a similar path in pursuing engineering." In this way, SWENext helps students form their own networks and encourages them to expand their circles by reaching out to other people in their communities.

© Drobot Dean/stock.adobe.com

Join SWENext

If you are aged 13 or over, join SWENext here using the "FUTURUM" event code: **bit.ly/3JtUjWm**

If you are under 13, your parent or guardian can join SWENext for you here using the "FUTURUM" event code: **bit.ly/3oVh8Zl**



Q&A
Meet Kavya

Kavya is a 10th grade student from New Jersey in the US. She is also a SWENext Influencer.

What has inspired your interest in STEM?
I've always been drawn to the topics that define our future. Whether it's healthcare or sustainability, I know that my generation will face a great variety of challenges. Through STEM, I can pursue the problems I care about deeply and work in service to my community.

What motivated you to participate in the SWENext programme?
I constantly seek opportunities to learn and to reinvent myself. I hoped to gain new perspectives on the possibilities of technology and an understanding of which pathways to pursue.

What was the highlight of the SWENext programme for you?
My highlight was the speed networking sessions with the STEM professional mentors. Our conversations touched on a range of topics – from the future of big tech to breaking the bias in the engineering field. Hearing about the mentors' interdisciplinary backgrounds made me appreciate the interwoven nature of science, technology, engineering and mathematics.

What relationships has SWENext enabled you to form, and what have you gained from these?
Because of SWENext, I found mentorship from leading female innovators and support from passionate students. They continue to give me the confidence and energy to push forward on my journey in engineering.

Why is community so important in engineering and technology fields?
I've realised that in any field, community is like a match, lighting thousands of candles and helping each individual harness their inner potential. By joining a community like SWE, you can light the imagination of others and transform ideas into actuality.

How has SWENext helped you to develop confidence and leadership skills?
SWE helped me discover the type of leader I want to be: deeply reflective, holistic and connected. I believe that the best leaders share opportunities in the right places, which is something I strive to do.

What does your role as an ambassador for SWENext entail?
As a SWENext Influencer, I serve and strengthen the amazing SWENext Community. I've moderated STEM panels with industry professionals and led networking sessions for students from the SWENext High School Leadership Academy (SHLA).

You've developed an app that predicts a person's COVID-19 mortality risk. What was your inspiration?
Throughout the COVID-19 pandemic, many members of my community lost their loved ones, so I decided to act. I came across several datasets that contained COVID-19 statistics with breakdowns of age, state and gender. I analysed the data using artificial intelligence to see if there were correlations between these factors and COVID-19 mortality rates. This was a steep learning curve and I had to take online courses on neural networks, teach myself advanced concepts, and seek mentorship from medical professionals.

What are your proudest achievements, so far?
I'm excited to be an honoree for The 74's '16 under 16 in STEM' inaugural class. I'm also honoured to have received the National Honorable Mention from the National Center for Women in Technology. These achievements motivate me to work even harder.

What are your ambitions for the future?
I want to pursue a career at the intersection of computer science, healthcare and social entrepreneurship. I also hope to use my voice to elevate others and be a visible female leader in engineering.

Kavya's *top tips*

1. Be excited about your future! Your journey in engineering will be filled with both highs and lows, but the connections you form and the impact you create will keep you driven.

2. Remember, the power to be the change you wish to see lies in your hands.

WHY STEM EDUCATION IS FOR THE PUBLIC GOOD

MISHA SCHUBERT

Science & Technology Australia's mission is "to advance the public good and social and community welfare, and strengthen civil society through education, outreach and programmes". **Misha Schubert,** CEO, tells us why education is key.

Why is education a key component of Science & Technology Australia's (STA's) mission?

Education enables an informed society – a society that can consider complex issues and make rational decisions. And education is a powerful enabler of equity.

An inspiring early foundation in science, technology, engineering and maths concepts can equip young people for a life of curiosity-driven learning. And what a powerful skillset for every aspiring problem-solver to have. When we encourage students to ask 'why' or 'how' something works the way it does, it encourages them to look around them, explore the world and try to understand it more deeply.

How skilled in maths and science are school students in Australia?

The Organisation for Economic Co-operation and Development's Programme for International Student Assessment (OECD PISA) tests compare the school performance of 15-year-olds around the developed world every three years. In 2018, it benchmarked Australian students at the OECD average for maths and slightly higher for science. However, compared to past performance, the average test results for an Australian 15-year-old was one full year of schooling behind in maths than where they were in 2003, and almost a year behind in science than where they were in 2006. We need to turn that trend around with a concerted effort.

Why has Australia seen this long-term decline?

Australia is not alone in these challenges – other advanced economies are grappling with these pivotal issues too. One driver is that many students aren't being taught maths and science by subject matter specialists, particularly so in rural, regional and remote areas. Having an inspiring science and maths teacher with deep knowledge, confidence and skills can be the difference that makes a student excel at STEM subjects.

Why is there a chronic shortage of maths and science teachers in Australia, and how might this be addressed?

Again, this challenge is not unique to Australia – we face a projected shortage of teachers in coming years across the board. A review currently underway has been asked to recommend how to strengthen teacher education at universities and boost the numbers of people graduating from teaching degrees. Science & Technology Australia has also called for a national plan to elevate the status of teaching as a profession and a campaign to dispel the myths around teaching as a career, with a focus on opportunities for career advancement and the chance to become a specialist teacher.

Misha Schubert speaking at the gala dinner of Science Meets Parliament, 2022. © Ben Calvert.

What should a new initiative to inspire school students to grow their skills, knowledge and love of STEM look like?

We think students learn best when they are fully engaged in what they're learning – when they understand the concept but can also see the application, the relevance and how it affects their lives and the lives of people around them. Science needs to be *DONE*, not just read about or absorbed through videos and textbooks. The more interactive, engaging and relevant we can make school content taught in science, maths and technology, the better.

How is STA working with the Australian Government?

Since the Australian Federal Election in May 2022, STA has been engaging closely with the new government on issues to support the STEM sector in Australia – one of which is education.

What is your vision for STA?

For STA to be a powerful voice for our sector and its people, reflecting the aspirations of its inspiring, diverse and brilliant talent. That we are the nation's key connector of people and ideas in STEM, shaping policy settings with deep influence to advance opportunities for Australia and make us a global STEM superpower. That we are a champion and supporting partner of leaders and communities in First Nations science, technology, engineering and maths. And that we lead on equity, inclusion and diversity in all its forms, especially to drive gains to improve the under-representation of women in STEM, so our nation can reach into its full talent pool – and all our talent can thrive.

Meet Misha

With a master's in journalism from Columbia University in the US, Misha's career has evolved from political journalism to communications and now CEO of STA. Starting out as a journalist for *The Australian Newspaper*, Misha took up the post of CEO in March 2020.

What inspired you to become a journalist?

Insatiable curiosity – and a love of great stories. I've always had a drive to understand how things really work, and to understand the story behind the story. Journalism has a crucial role in societies to probe, question, illuminate and inform.

Do you take opportunities as they come, or do you have a clear career goal or life plan in mind?

Like many people with a wide array of professional interests and skills, I haven't had a set masterplan for my career. I'm a generalist by instinct – I read widely, keep a keen eye on key developments in journalism, policy and politics, and I'm deeply interested in people and what makes them tick. Across my career, I've worked hard and sought to excel in each role I've had. Happily, that has opened a door to each next opportunity. Friends describe me as a collector and connector of people – it's a lovely concept. I feel fortunate to have had such stimulating, interesting and enjoyable career opportunities.

How do your journalism skills inform your current position as CEO.

The skills I learned as a young journalist are invaluable for a CEO. That early foundation taught me how to gather and verify reliable expert material quickly on a complex topic, master an understanding to confidently explain it to a general audience, write quickly and synthesise material clearly, and how to build rapport with a wide array of people. My team often observes that I have a journalist's memory for people, faces, words and phrases – which is a powerful asset in policy advocacy.

What is one thing you know now that wished you had known when you were younger?

That you don't need to do all the things all the time! In a busy and full life, it's important to make time to recharge.

Top picture: Misha Schubert at the launch of National Science Week 2022. © Ben Calvert.

About Science & Technology Australia

STA is Australia's foremost body in science and technology. Representing more than 90,000 scientists and technologists, it is an influential voice for evidence and expertise in public policy.

Connect with STA

- **ScienceAU**
- **ScienceAU**
- **Science Technology Australia**
- **science_aus**
- **ScienceTechnologyAustralia**
- **scienceandtechnologyaustralia.org.au**

> **"SCIENCE NEEDS TO BE DONE, NOT JUST READ ABOUT OR ABSORBED THROUGH VIDEOS AND TEXTBOOKS."**

STA President Professor Mark Hutchinson, Science Minister Ed Husic, and Misha Schubert at the launch of National Science Week 2022. © Ben Calvert.

CREATING SOFTWARE THAT WORKS FOR EVERYONE

From monitoring our health to finding a parking spot, there are now apps to help with every task in life. However, as we become ever-more reliant on software, ensuring it is accessible for all of society is a growing necessity. At **Monash University** in Australia, the **Human-Centric Software Engineering (HumaniSE) Lab** is developing software that can be used by everyone.

HumaniSE Lab

Human-Centric Software Engineering (HumaniSE) Lab, Monash University, Australia
www.monash.edu/it/humanise-lab

Field of research
Software Engineering

Research project
Developing accessible software for diverse end users

Funder
Australian Research Council (ARC)

TALK LIKE A ...

SOFTWARE ENGINEER

Accessible — can be obtained easily and used by everyone

App — a computer program used to perform a specific function (e.g., finding and paying for a parking space)

End user — the person who uses an app or software

Human-centric — with human needs and values as key considerations

Software — the set of programs and other information that enables a computer or app to function

Software developer or software engineer — someone who designs and develops software

User interface — the place where an end user interacts with a computer (e.g., a webpage or app display)

"Every human is different," says Professor John Grundy. "They have different ages, languages, cultural backgrounds, personalities, and physical and mental characteristics. Software should take these differences into account." However, most software does not. Developers commonly design software with a one-size-fits-all approach, based on their own assumptions of what end users want from the software. This results in software that is not accessible to everyone, leaving users confused or frustrated when trying to interact with the software, or excluded from it entirely.

To address this problem, John founded the Human-Centric Software Engineering (HumaniSE) Lab at Monash University. Through a variety of creative approaches, John's team is developing inclusive software that considers the unique needs and characteristics of today's diverse populations.

Software challenges

The range of different needs and preferences exhibited by people around the world means that ensuring software accounts for all these differences is no easy task. A lot of existing software is not accessible to certain demographics, which raises issues for equity and inclusion.

For example, elderly people may struggle to use certain technologies because they are unfamiliar with them, do not understand how to navigate software, cannot read small text or do not have the dexterity to control a touchscreen. Dyslexic users may struggle to read text, colour-blind users may struggle to understand images and graphics, and users with visual impairments may be unable to access any visual information.

"People are not all the same, so software cannot assume one kind of end user," says Dr Hourieh Khalajzadeh, a member of the HumaniSE Lab. "Software should take these differences into account." For example, inclusive software should support different colour schemes, font styles, text and button sizes, interaction styles (e.g., written text or spoken voice) and languages. Most importantly, to be accessible, software should allow the user to adapt the user interface according to their personal preferences.

These issues highlight the human element of software, both in production and consumption. As software is developed by people who are very well-versed in how software functions, they may not appreciate the challenges that others face when interacting with software.

"Software developers face numerous challenges when trying to engineer more human-centric software," explains Dr Anuradha Madugalla, another member of the team. "It can be hard to interact with the range

of target end users, meaning developers struggle to understand the issues users face and are unable to collect feedback on the usability of their software." The HumaniSE Lab hopes to address these challenges by creating personas of diverse end users to ensure the software it develops meets the needs of the target audience.

> **PEOPLE ARE NOT ALL THE SAME, SO SOFTWARE CANNOT ASSUME ONE KIND OF END USER. SOFTWARE SHOULD TAKE THESE DIFFERENCES INTO ACCOUNT.**

What are personas?

"Personas are fictional representations of software users," explains Hourieh. "They are used to help developers think about catering to different demographics with different user goals and desired features." While not as informative as testing software on real people, personas are a practical solution when real end users are unavailable to give feedback.

"Without consideration of diverse personas, there is a danger that the needs of some end users are missed during software development," says Anuradha. In the HumaniSE Lab, the team creates personas and associated 'user stories' that identify the different requirements end users may need from the software.

Developing a parking app

The HumaniSE team has put its methods to use by developing an accessible parking app to help drivers find and pay for parking. After reading reviews of current parking apps, which informed the team of the issues with current apps, a set of representative personas and user stories were created that identified the requirements different people have of a parking app.

Examples of specific personas and user stories include: a student who wants a quick and easy way to book a parking spot and whose priority is having a secure payment method; a young adult with English as their second language who requires multilingual support and wants a clean and simple user interface; an aging user with mobility challenges who wants information to be provided in a large font size and for the app to find an accessible parking spot that reduces the walking distance to their final destination; and a colour-blind user who owns multiple cars who needs an accessible colour scheme and who wants to easily switch between different car registrations when paying for parking.

"Using these requirements, we designed a prototype parking app that would meet all the needs of all target user groups, represented by the different personas," explains John. "We then tested our prototype app against each persona to see if the personas' goals were fulfilled and their frustrations prevented." This involved a 'cognitive walk-through' of the app, with different team members taking the role of each persona and assessing whether the app met their requirements. Ideally, the team would have evaluated the app by working with people from the different target user groups and collecting their feedback, but the COVID-19 pandemic prevented this during the app development stage.

While personas are a powerful tool, they cannot necessarily capture all end user requirements given the massive diversity of people's needs and preferences. "Using personas to assess the app can only give some indications of feature suitability, as different people experience different challenges in different ways," explains Anuradha.

Through this process, the team developed a human-centric parking app that offers multiple ways to find and book a parking space, addresses concerns around data privacy and payment, and has an adaptable user interface allowing the user to choose the language, colour scheme, font and interface complexity.

The importance of inclusive health apps

Increasingly, health services and people with health conditions are being supported by apps. Technology provides a powerful tool for healthcare. It can supply specific information about illnesses, give reminders


© pressmaster/stock.adobe.com

> WE ARE AIMING TO SET UP A 'LIVING LAB' TO TAKE A MORE CO-CREATIONAL APPROACH TO HUMAN-CENTRIC SOFTWARE DEVELOPMENT. SOFTWARE DEVELOPERS AND TARGET END USERS WOULD CLOSELY COLLABORATE TO DESIGN, TEST AND REFINE SOFTWARE REQUIREMENTS.

to take medication, capture and monitor health-related measurements such as heart rate, alert health professionals to emergencies and provide support to maintain a healthy lifestyle. Nevertheless, for this potential to be fully realised, accessibility of health apps needs to be a top priority.

"Different people experience illnesses and chronic conditions in different ways, so health apps must be adaptable to the individual's needs," says Hourieh. "Health conditions also change over time in different ways, and apps must adjust for this." Given that the management of illnesses is critical for people's well-being, ensuring that health apps appropriately cater to everyone is a key concern. A one-size-fits-all approach to healthcare apps can even be dangerous as everyone has their own unique healthcare needs.

The HumaniSE Lab has undertaken several projects related to the accessibility of health apps. After reviewing existing guidelines for health app development, the team identified gaps in current protocols that failed to address the needs of diverse end users. "We then worked with a number of health app development teams to use human-centric software development practices," says Anuradha. "These included participatory design (where target app users are involved in the app design process), using human-centric personas, creating adaptive user interfaces, and establishing a review process to detect, analyse and fix any issues."

> DIFFERENT PEOPLE EXPERIENCE ILLNESSES AND CHRONIC CONDITIONS IN DIFFERENT WAYS, SO HEALTH APPS MUST BE ADAPTABLE TO THE INDIVIDUAL'S NEEDS.

The outcomes of these projects have led to the development of guidelines and support tools for software developers to use when designing future health apps. These help developers to identify human-centric issues and develop health apps that address the needs of diverse end users. Software developers around the world are therefore benefitting from the work of the HumaniSE Lab, as they now have the means to ensure their health apps are suitable for all users. As a result, the people who use apps to help manage their health are also benefitting from technology that is inclusive, accessible and adaptable.

What next?

Through the HumaniSE Lab's research, it has become increasingly apparent to the team that a more inclusive approach to software design is needed. Including target end users in the design phase, rather than just collecting their feedback once the software has been developed, leads to the creation of software that considers user accessibility at every stage, rather than relying on tweaks at the end of the process that might not satisfactorily address usability challenges.

The team has a bold vision for bringing this approach into reality. "We are aiming to set up a 'Living Lab' to take a more co-creational approach to human-centric software development," says John. "Software developers and target end users would closely collaborate to design, test and refine software requirements." A key concept of the Living Lab is that all participants, both developers and users of software, are fully involved and treated as equals throughout the software development process, ensuring the needs and opinions of the users and developers are always considered. "We want to use the Living Lab as a place to create better software for everyone."

Pathway from school to *software engineering*

- "At school, take any subjects you enjoy!" advises John, as most universities will not expect you to have a software engineering background before beginning your degree. However, if you are interested in a career in software engineering, it would be useful to study mathematics, computer studies/ICT and physics at school. These will provide useful knowledge, develop your problem-solving skills and may be requirements for some university degrees.
- Hourieh advises learning programming as soon as possible by exploring the range of free courses and tutorials available online. "Block-based programming (which is visual-based rather than code-based) can give students a good overview of how programming works," she explains. "Scratch (**www.scratch.mit.edu**) and Code (**www.code.org**) are great tools to learn the fundamentals of computer science by creating your own games and animations." Once you understand the concepts of programming, you can then learn coding languages, such as Python.
- At university, many degree options could lead to a career in software engineering. These include degrees in software engineering, computer science, information technology, data science and information systems.
- "Alongside your computing degree, I would recommend taking a course in psychology, as this will help you become a software engineer who understands your end users," advises Anuradha. John agrees that combining studies in computing with science, social science or business courses will not only give you a broader education but will allow you to apply your software engineering skills in a wider range of applications (e.g., finance, manufacturing, agriculture, etc.).
- If you want to train and learn skills while working, look for organisations that offer software-related apprenticeships.

ABOUT *SOFTWARE ENGINEERING*

Software engineering, or software development, is the branch of computer science that involves designing and developing software – the instructions and programs that enable computers to function. The field of software engineering is growing rapidly as computers are becoming integrated into all aspects of our lives.

The joys of software engineering

The HumaniSE Lab members all enjoy their work as software engineers due to the satisfaction, challenges and diversity of the job. "I like what I am doing as I believe I am making life better for humanity," says Anuradha. Hourieh likes the fact that software engineering is "a challenging job that involves continuously learning new skills and improving your capacities for problem-solving and creativity".

"I like the range of problems I get to work on," says John. "I have worked on software development for health, manufacturing, local government, education and games. You can get involved in lots of different disciplines, meet a wide variety of people and build software solutions that make a big difference in people's lives."

Why should you consider a career in software engineering?

If you have software engineering skills, you can work anywhere in the world, in any sector. "Software engineering pays well and has great long-term career prospects," says John. "You can work on globally important problems, such as addressing climate change through building software for energy-efficient 'smart' buildings."

Hourieh highlights how the diversity of options in software engineering gives you scope to work in your preferred role. "Is it the design part that most interests you?" she asks. "Or do you enjoy coding? Or would you like a role in project management?" There are software engineering positions for all of these. "Software engineering gives you the opportunity to make your ideas a reality with only the effort of your mind and fingers," says Anuradha.

With the global rise in automation and artificial intelligence, and an ever-increasing amount of data being collected about end users, the next generation of software engineers will have to ensure all technologies are designed and used responsibly and ethically. There will be challenges surrounding privacy and security to overcome, along with the issue of ensuring future software is accessible for everyone. Where could a career in software engineering take you?

"SOFTWARE ENGINEERING PAYS WELL AND HAS GREAT LONG-TERM CAREER PROSPECTS. YOU CAN WORK ON GLOBALLY IMPORTANT PROBLEMS, SUCH AS ADDRESSING CLIMATE CHANGE THROUGH BUILDING SOFTWARE FOR ENERGY-EFFICIENT 'SMART' BUILDINGS."

PROFESSOR JOHN GRUNDY

Explore careers in *software engineering*

- As technology is now so ingrained in our lives, software engineers are needed to develop software in all fields. Depending on your interests, you could create the next social media app, design software to reduce energy use or program a new virtual assistant.
- Hays provides information about the type of work software engineers do, the skills you will need and the salary you can expect: **www.hays.com.au/it/software-engineer-jobs**
- Participate in an internship or industry placement to gain real-world experience of software engineering. You will learn how software teams work, how businesses function and about the diverse range of end user needs.
- To connect with software engineers and learn about careers in the field, John recommends joining a professional society as a student member, such as Engineers Australia (**www.engineersaustralia.org.au**) or the Australian Computer Society (**www.acs.org.au**). International societies include the Institute of Electrical and Electronics Engineers (**www.ieee.org**) and the Association for Computing Machinery (**www.acm.org**).
- Anuradha suggests that girls interested in software engineering should explore Girls Who Code (**www.girlswhocode.com**) and Women in Engineering (**www.wie.ieee.org**), organisations helping women engineers to reach their potential.

Meet *the HumaniSE team*

Professor John Grundy

Professor of Software Engineering, Monash University, Australia

I was first exposed to computers in my mid-teens. At university, I planned to major in chemistry or progress to medical school. I enjoyed my first-year computer science courses so much that I switched paths as I decided building software would be more satisfying and enjoyable. I have since worked on many health systems, so have still had the opportunity to contribute to healthcare.

I enjoyed playing cricket and football when I was young. I even created animated cricket and football computer games in my teens! I have also always been fascinated by military and ancient history, and I would love to combine these interests with software engineering. Perhaps I will develop software to analyse historical artefacts one day.

As an undergraduate, I enjoyed developing computer games, robot programs and software to manage information. Completing an industrial placement at a software company, working on financial systems, showed me the huge flexibility and good pay offered by a career in software engineering.

Software engineering is more people-oriented than most people imagine. I enjoy working with other software engineers and the end users of our software. I have been fortunate to work with a wide range of people over the years on all sorts of interesting software development projects.

I face a number of challenges using software myself, and I have many family members and friends who also have challenges using software. These include colour-blindness, hearing issues, cognitive challenges, neuroatypical problem-solving styles and different languages. This has led to me being passionate about ensuring software is human-centric.

I founded the HumaniSE Lab after winning an Australian Laureate Fellowship in 2019. This provided funding for several researchers and PhD students to work with me on developing better ways to engineer human-centric software. The lab is a focal point for this sort of research and development. Establishing the HumaniSE Lab has been a great highlight of my career.

In my free time, I enjoy running, watching cricket and football, reading about ancient Egypt, and listening to audiobooks and 80s music. I also love spending time with my wife and children.

John's *top tips*

1. Do what you enjoy doing – you can apply software engineering to almost any other field!
2. Find people who accept and respect you for who you are, and do the same for them.
3. Keep a good work-life balance. Overworking leads to mistakes, which could be catastrophic (you want the person who designed and tested the software in your car to have been concentrating while they did it!). Besides, time with family and friends and pursuing hobbies is hugely valuable.

"I FOUNDED THE HUMANISE LAB AFTER WINNING AN AUSTRALIAN LAUREATE FELLOWSHIP IN 2019. THIS PROVIDED FUNDING FOR SEVERAL RESEARCHERS AND PHD STUDENTS TO WORK WITH ME ON DEVELOPING BETTER WAYS TO ENGINEER HUMAN-CENTRIC SOFTWARE."

PROFESSOR JOHN GRUNDY

Dr Hourieh Khalajzadeh

Lecturer in Software Engineering, Deakin University, Australia

I wasn't especially interested in computers as a young kid. Initially, I wanted to go to medical school because everyone around me said I should. Then, when I discovered I loved maths, I wanted to be a mathematician. When I started learning programming, I really enjoyed it, so I decided to study software engineering at university.

I was the first girl in my family to become an engineer. I'm pleased to say I'm not the last! It was my interest in maths and programming that inspired me to become an engineer, and software engineering was the branch that was closest to my heart. At university, I met incredible female academics who motivated me to continue with postgraduate studies.

Completing a master's, PhD and postdoc all motivated me to pursue software engineering research. I am fortunate that John supervised me during my PhD as he is a top researcher in the field. When he established the HumaniSE Lab, I was one of the lucky researchers who was selected to join the team.

Being a researcher gives you the freedom to work on the topics you most enjoy, collaborate with the people you enjoy working with, find the gaps that others haven't been able to explore, and solve the problems that can improve people's lives. I became interested in computer science research as I enjoy exploring the untapped areas in different domains where software can be a life changer.

We design software to help people. This means we must ensure it is inclusive of everyone, no matter what they do, where they are located, how old they are, what language they speak, and what preferences and characteristics they have. If software is designed based on the developer's own assumptions of end users' needs, then the software may be unusable or even dangerous. For instance, if a health application recommends a solution that is not appropriate for a specific user, it could put their life at risk. This is why I am passionate about ensuring software is human-centric.

I have developed many tools that have been used in software for different applications, including health, transportation and banking. I aim to make not only software, but also software development, more accessible for everyone, even those without a technical background or without access to the latest infrastructure.

When I'm not working, I enjoy spending time with my family and friends. We do lots of outdoor activities such as hiking and cycling. I also enjoy travelling to new places and experiencing new things – most recently, skydiving and scuba diving!

Hourieh's *top tips*

1. Do what you most enjoy doing.
2. Explore different career pathways to find the one most suitable for you. Talk to people from different professions, take a range of courses and attend information sessions to find what interests you.
3. If you are interested in software engineering, follow the latest technology news to stay aware of what's happening around us and what changes software engineers can make.

Dr Anuradha Madugalla

Research Fellow in Software Engineering, Monash University, Australia

I used a computer for the first time when I was eight, to play games. As I grew older, though I liked computers, my interests were broader and covered all technology-related things. This led me to study IT as my university degree, which is when I started to truly fall in love with software.

I always wanted to be the first to set up any new technological device in the house and play with it. My mother saw my love of technology and encouraged me to consider a future in IT. It was her belief and my personal interest in technology that led me to software engineering.

Growing up, there were not many girls doing software engineering around me. I love a challenge, so this motivated me to pursue this career path and to perform well in it. Many great women in IT, such as Anita Borg and Sheryl Sandberg, have inspired me to continue working in software engineering.

My research has always focused on developing software to make lives better. This has included software that can reconstruct faces from skulls, to help forensic scientists identify victims, and software to help people with visual impairments understand graphics. I first joined the HumaniSE Lab to develop tools and techniques for aged care, and now I help to develop human-centric software for all sectors of society.

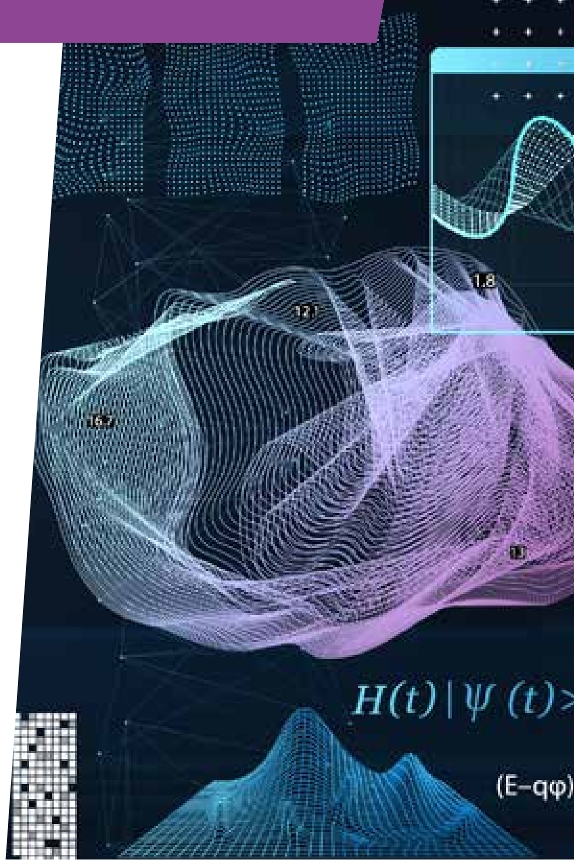
During my PhD, I worked closely with many blind people as I helped develop software for people with vision impairments. I accompanied them as they visited our lab and visited their homes to collect their feedback on our software. I experienced how challenging life can be for blind people and was fascinated by how well they overcame these challenges. I was impressed with how blind people use software such as screen readers but realised how much they are missing when software is not accessible to their needs. This inspired me to think more about how to make software more user-focused and helpful, not only for those with vision impairments, but for all end users with different challenges depending on their unique characteristics.

I am proud of many of my achievements in my studies and career. These include winning a gold medal for the best undergraduate research, winning the Faculty of IT's Three Minute Thesis (3MT) competition where I presented my PhD research in just three minutes, and winning the Google Women Techmakers award.

I love reading in my free time. I enjoy all types of fiction, from magical fantasies to thrillers, historical fiction to classic literature. I also love travelling to see the world and spending time with my family.

Anuradha's *top tips*

1. If software engineering and computers interest you, start learning programming and coding as soon as you can.
2. Work hard at school to achieve the best grades you can, especially in maths.
3. Enjoy life as best you can, as it will go by without you realising!



CAN QUANTUM PHYSICS MAKE THE INTERNET MORE SECURE?

Associate Professor Jacquiline (Jacq) Romero, a quantum physicist at the **University of Queensland** in Australia, is conducting experiments with photons to investigate quantum entanglement. Her research is helping to develop the quantum internet — the internet of the future will be very different from the internet today.

PROFILE

Associate Professor Jacquiline Romero

School of Mathematics and Physics, University of Queensland, Australia

Fields of research
Quantum Physics, Quantum Technology, Optics

Research project
Investigating quantum entanglement and developing the quantum internet

Funders
Australian Research Council (ARC), Westpac Bicentennial Foundation, L'Oreal-UNESCO For Women In Science Foundation

TALK LIKE A ...

QUANTUM PHYSICIST

Bit — the smallest unit of data that a computer can process and store

Photon — a quantum of light, the basic unit that makes up all light

Quantum — the smallest unit involved in an interaction

Quantum entanglement — the physical phenomenon that occurs when a group of particles interact in such a way that the quantum state of each particle cannot be described independently of the state of the others

Qubit — stands for 'quantum bit' – the quantum equivalent of a bit

Superposition — in quantum physics, the notion that a quantum state is a combination of many possible states, as in the possibilities are superposed until a measurement is made

Most of us use the internet every day. Whether to message our friends on social media, research a topic we want to know more about, or do some online shopping, the internet has become an integral part of our lives. The current version of the internet, however, is liable to being attacked. News reports tell stories of hackers who reveal individuals' credit card details, health records or other sensitive information. This is why Associate Professor Jacquiline (Jacq) Romero at the University of Queensland is helping to develop the quantum internet – a new version of the internet that will provide the most secure kind of communication possible within the laws of physics.

How is the quantum internet different to the regular internet?

The current internet works by using 'bits' that are always in one of two physical states, like the on/off switch of a light or TV. The state of these bits is usually represented by a single binary value, either 0 or 1. "The quantum internet differs from the regular internet because it will transmit quantum information ('qubits') instead of classical information ('bits')," says Jacq. "Quantum states are very different."

Compared to regular bits, quantum bits (known as qubits) can take on superpositions. Because the qubits are neither 0 nor 1 before measurement, qubits represent multiple combinations of 0 and 1 at the same time. By using these qubits and entangling them, Jacq and her team have been working towards developing the quantum internet.

What is entanglement?

The 2022 Nobel Prize in Physics was awarded to physicists Alain Aspect, John Clauser and Anton Zeilinger for investigating photon entanglement. They describe entanglement as a distinctly quantum phenomenon in which objects "exist in a shared state, regardless of how far apart they are". This is such a strange concept that even Albert Einstein once described entanglement as "spooky action at a distance"! Entanglement is a tricky idea to understand,

© SergeyBitos/stock.adobe.com

but, fortunately, Jacq has a helpful analogy to explain it: "Let's take a thought experiment with two parties: Alice and Bob," says Jacq. "Imagine there are two cards, labelled either 0 or 1, and each is placed in a closed box. The boxes could contain either number, but both boxes contain the same card. Alice takes one box to one room, and Bob takes the other to another room. The moment Alice opens her box and sees her card, she knows that Bob's card has the same number, without even communicating with him. The same is true for Bob when he opens his box."

Seems obvious so far, right? "There is nothing extraordinary about this correlation," says Jacq. "Alice and Bob know what the other person has because they know that the boxes contain cards of the same type. More importantly, the cards are ordinary objects: the 0-card is labelled 0 and the 1-card is labelled 1, regardless of whether Alice or Bob were looking in the box."

Quantum entanglement: When Alice opens her box, she knows what card is in Bob's box

However, the story is strangely different if the cards are entangled and the number on the card is a qubit. Quantum objects can be in a superposition of states, which means they can be either 0-cards or 1-cards, and this is not definite until someone looks inside the box. At that instant, the card randomly becomes either a 0 or a 1. In this version of the experiment, if Alice were to open her box and see a 0-card, then when Bob opened his box, he would see his card is also a 0-card. "Seeing a 0-card in one box depends on seeing a 0-card in another box," explains Jacq.

"Alice and Bob observe the same correlations as in the first version of the experiment, but the origin of the correlation is now superposition, not the well-defined labels on the cards that were there before they were put inside the boxes," says Jacq. The other interesting thing about qubits is that if Alice and Bob were to repeat the experiment with another pair of cards, the results will be totally random. "Whether they see 0 or 1 on their cards is totally random, but the two labels will always be the same as each other," Jacq adds. Overall, this means that when two particles are entangled, they behave as one. "The label of one card can no longer be separated from the label of the other, hence the term 'entangled', and the phenomenon we call 'entanglement'," says Jacq.

Are there different types of entanglement?

There are! The scenario above is an example of bipartite qubit entanglement. Bipartite refers to the two parties, Alice and Bob, and qubit to the two possible outcomes, 0 or 1. However, if the experiment extends to include a third person, we have multipartite entanglement. If there are more than two possible outcomes (for instance, if the cards in the box could be labelled from 0 to 5) then we have qudit, instead of qubit, entanglement.

What methods does Jacq use to conduct her research?

Jacq specifically studies the entanglement of photons. "I shoot a special crystal with ultraviolet light and, once in a while, this ultraviolet photon becomes two infrared photons that are entangled in their various properties," she says. One example of an entangled property of the photon is the shape of its cross-section intensity. "Usually, we think of light as a bright spot – intense at the centre and becoming dimmer the farther you are from the centre," says Jacq. "But light can also have other shapes."

Not only is Jacq creating entangled photons, she has also developed the technology needed to measure their shape, creating new opportunities for other quantum physicists. "I am proud that many researchers are now using the shape of photons for quantum information, thanks to the technique we introduced."

What are the applications of this research?

One application of Jacq's research is developing the quantum internet, which will be much more secure than the regular internet. If Alice sends an online message to Bob through the regular internet, a hacker might be able to read the message without either of them knowing. However, if the message is sent on the quantum internet using entangled qubits, then someone sneaking in to read the message would be detected immediately. "When quantum information is being sent from one point to another, any eavesdropper disturbs the quantum information," explains Jacq. "This means the eavesdropper can be discovered."

This new version of the internet will enable us to connect quantum computers, achieve more powerful computation and allow secure quantum communication. According to scientists, a global quantum network might be available as soon as 2030, thanks to the work of quantum physicists such as Jacq.

© Siarhei/stock.adobe.com

ABOUT *QUANTUM PHYSICS*

Quantum physics is the study of the universe at its most fundamental level. It challenges our notions of reality and often overlaps with the philosophy of science. “Quantum physics asks deep questions about how nature operates, what knowledge is, and what the role of an observer is,” says Jacq. “Future quantum technologies will need the untethered imaginations of not just physicists, but also computer scientists, material scientists, engineers and people from technologies adjacent to quantum physics.”

What other discoveries has Jacq made?

While it has long been known that the speed of light slows down when travelling through a different material, such as glass or water, Jacq and her team made headlines a few years ago when they discovered the speed of light can be slowed in space too.

“In one of my favourite experiments, we showed that light slows down by a tiny fraction (around 3000 km/s) if you give it a particular shape,” says Jacq. This had never been shown before in single photons and was only possible because the team had so much experience working with photons.

How do gender and culture affect Jacq’s work in quantum physics?

The most famous physicists tend to be white men – think of Albert Einstein, Isaac Newton, Stephen Hawking and James Clerk Maxwell. “It is really important to have cultural and gender diversity in science,” explains Jacq.

“When I first left the Philippines to do a PhD in the UK, I realised I had an inferiority complex and I lacked confidence,” says Jacq. “I think it is very easy to feel this way, especially for people from countries that were colonised. The Philippines was controlled by Spain for more than 300 years, and the mentality that ‘white is better’ is deeply ingrained.”

Having grown up in the Philippines, Jacq was soft-spoken and very polite. While these are good attributes to have, she soon realised that scientists need to be forceful (you can be both forceful and polite, after all!) to make their ideas heard. “I realised I had to recalibrate to get my point across, especially when scientific discussions get intense!”

“IT IS REALLY IMPORTANT TO HAVE CULTURAL AND GENDER DIVERSITY IN SCIENCE”

Explore careers in *quantum physics*

- Jacq recommends learning about quantum computing using resources such as Qiskit (**www.qiskit.org**) and Black Opal (**try.q-ctrl.com/blackopal-app**).
- The University of Melbourne has useful information about careers in physics and advice from former university students who studied physics: **science.unimelb.edu.au/students/careers/careers-in-science/physical-sciences**
- Jacq loves the book *“Quantum Mechanics: The Theoretical Minimum”* by Leonard Susskind and recommends reading it if you are interested in learning more about quantum physics.
- According to the Economic Research Institute, the average salary for a physicist in Australia is $149,000 AUD a year.

Pathway from school to *quantum physics*

- At school and post-16, study physics and maths to learn the fundamentals of the field. Jacq recommends having a strong understanding of linear algebra, because quantum states are treated as vectors or matrices.
- At university, degrees in physics or maths could lead to a career in quantum physics. However, scientists from a range of disciplines can work in the field. “Even a chemist could find themselves working on quantum technologies, because there are many interesting materials that could be useful for quantum devices,” says Jacq.

Q&A

Meet Jacq

What were your interests when you were younger?

I loved mathematics from very early on. When I was 8 years old, my uncle gave me a book on algebra which was full of word problems. I was fascinated to see mathematical equations as English sentences. When I went to high school, I was naturally drawn to physics because it was just like maths, but with the purpose of describing nature and the world around me. My interests were not all academic. I also enjoyed reading books, playing badminton, watching movies and spending time with good friends.

Who inspired you to become a quantum physicist?

When I was 15 years old, my physics teacher commented that quantum physics was the branch of physics that he liked the least. I was curious and googled what quantum physics was, and I've been hooked ever since! As I read more, I got more interested in how philosophical and yet experimentally testable, and potentially technologically revolutionary, the ideas in quantum physics were.

You have won numerous awards, including two L'Oreal-UNESCO Women in Science awards. What do these recognitions mean to you?

I am deeply honoured to have received many awards and fellowships over the years. When I left the Philippines to pursue a PhD in quantum physics, I felt a great deal of uncertainty. I even remember one professor asking me if I was sure that quantum physics was not just a fixation. I am proud to have pursued my dream, and the awards I have received are recognition of the good work and fun that I try to have every day. You can't plan to make winning an award a goal. I think the best that you can do is try to do well every day. These recognitions mean a lot to me because they inspire me to do better.

More importantly, the awards have given me space to showcase my story and show that scientist mothers can succeed. The L'Oréal-UNESCO awards were especially good for that. It has been heart-warming to receive touching emails from fellow women scientists. People are inspired by stories, and I hope my story as a member of a minority group in science (Filipino, woman and mother) can inspire others.

You are passionate about encouraging more women to enter STEM fields dominated by men. What message do you want to give girls and young women hoping to pursue a career in science?

I think that the first thing to do (regardless of your gender) is to be good at whatever you choose to do. Follow what drives your curiosity, build on small successes, and always ask questions. There are no dumb questions. The situation for women in STEM has improved, but unfortunately sexist environments still exist. If you find yourself in such an environment, find support (this is very important!) so that it will be easier to stand up for yourself.

> "YOU CAN'T PLAN TO MAKE WINNING AN AWARD A GOAL. I THINK THE BEST THAT YOU CAN DO IS TRY TO DO WELL EVERY DAY."

What do you enjoy doing in your free time?

I like spending time with my husband and three kids. We read books, play, go for walks and watch movies. I enjoy going on holiday with my family and having unstructured time together. I also love running and painting. When I feel stressed, I take a day off and paint.

Jacq's *top tips*

1. Your attention is your most important resource so use it well. Be present and focused on whatever it is that you are doing.
2. The best way to learn is by doing. To improve at something, you have to try it and learn from your mistakes.
3. Most importantly, have fun and enjoy yourself!

HOW WILL CLIMATE CHANGE AFFECT FORESTS?

As the Earth's climate continues to heat up, forests will have to adapt. **Associate Professor Craig Nitschke** of the **University of Melbourne** in Australia studies how the distribution of plant species might change as the climate does.

Dr Craig Nitschke

Associate Professor of Ecosystem and Forest Sciences, The University of Melbourne, Australia

PROFILE

Field of research
Forest and Landscape Dynamics

Research project
Modelling plant species distributions to understand species' suitability under climate change

Funders
Department of Environment, Land, Water, and Planning – State Government of Victoria, Australian Research Council (ARC) grants DP220103711 & LP140100580, Greening Australia, Parks Victoria, Melbourne Water, Australian Alps Liaison Office, Eucalypt Australia

TALK LIKE A ... FOREST ECOLOGIST

Anthropogenic — caused by human activity

Ecophysiology — the study of how plants or other organisms respond to changes in environmental conditions, such as water availability and temperature

Ecological niche — how an organism or population interacts with the resources and competitors in its environment

Forest regeneration — the process by which plant seeds spread and new seedlings become established

Hydraulic conductivity — the measure of water being conducted

Simulation and statistical model (SSM) — a type of model that predicts the distribution of a species based on environmental data, such as temperature and precipitation

Stomatal conductance — the measure of how much a plant's stomata (the tiny pores on its leaves and stem) open, taking in carbon dioxide and releasing water vapour

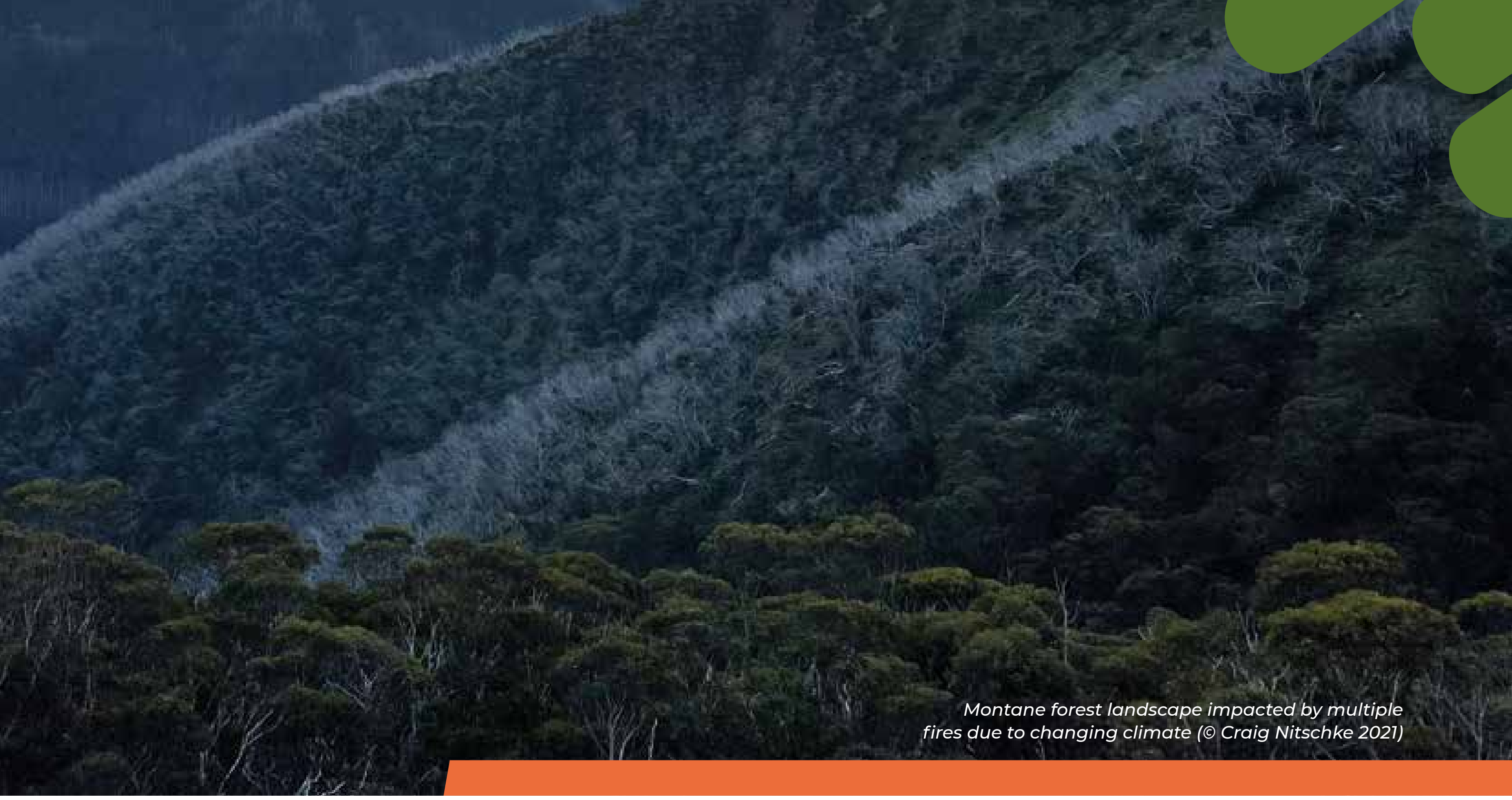
Turgor loss points (TLP) — a plant's capacity for retaining cell pressure in a dehydrated state

Anthropogenic climate change is affecting every corner of the Earth, from the icebergs of the Arctic to the forests of Australia. As our environment transforms, scientists are racing to understand how, why and what the future may look like. Dr Craig Nitschke of the University of Melbourne uses plant science and sophisticated computer modelling to study how the distribution of tree species in Australia could evolve as the climate changes. As a forest ecologist, he is helping to provide answers to many important questions: What are the most dangerous negative effects on forests? How are plant species already adapting? What species might even benefit from climate change?

How is climate change affecting Australia?

We are all aware that climate change is impacting every country on Earth. For example, while headlines about Australian bushfires captured the world's attention in 2019-2020, so too did deadly wildfires in California and along the west coast of the United States. Daily news reports drive home the global character of climate change and its role in disasters around the world. As average temperatures rise, many regions of the world will become warmer and drier, desiccating plant life and creating more fuel for fires.

"Climate change is a major driver of forest fires, but it is having many other impacts in Australia," explains Craig. Extreme weather events, such as droughts and floods, are occurring more frequently. These affect plants and other life. Average temperatures in continental Australia have risen by 1.4 °C since 1910. Night-time temperatures have risen more than daytime ones, enough to affect nocturnal animals. Rainfall is also changing all over the continent. In northern Australia, rainfall has increased by 15-20% since the 1950s, while in most other regions, including Tasmania and southern Australia in general, it has decreased. Less rainfall means a drier climate. Droughts lead to dry and compacted earth, and floods are often too intense and rapid to rehydrate the soil. Craig says, "These changes pose grave challenges to Australia's existing ecosystems."



Montane forest landscape impacted by multiple fires due to changing climate (© Craig Nitschke 2021)

How might these environmental changes affect plants?

The germination, regeneration and growth of plant seeds and seedlings is sensitive to local environmental conditions. Some species require cold winters to germinate and will not germinate if temperatures are too high or the soil is too dry. These species will struggle to reproduce in a warming, drying climate. "Arid conditions also reduce productivity in many species because soil moisture is crucial for supporting plant growth," explains Craig. Soil moisture can also impact nutrient availability. Some species can grow in nutrient-poor soils, but others cannot as they require nutrient-rich environments. Changes in moisture and nutrition will likely reduce plant productivity, which has implications for the capacity of forests to absorb carbon dioxide.

Species vary in their resilience to drought, and this can change the composition of a forest as some species survive repeated droughts while others are unable to thrive. Older trees also tolerate drought better than younger ones, meaning that a forest will have fewer and fewer young trees as it undergoes stresses due to a drier climate. At some point, however, even drought-resistant species and mature trees will die. "In a drought, regeneration will fail first, then growth, then mortality," Craig explains. "In extreme heatwave and drought events, however, mortality can occur quickly."

Forest ecologists research how plants respond to environmental challenges and how they die. They look at individual plants, especially at leaves. "We measure, amongst many variables, photosynthesis, stomatal conductance, hydraulic conductivity and turgor loss points (TLP)," Craig says. "The latter indicates the ability of a plant to maintain cell pressure while drying out and is a good predictor of drought response in plants." Species that are less resistant to drought cannot maintain their cell pressure while drying out and must slow or stop photosynthesis, leading to reduced growth and eventually death. Ecophysiology gives forest ecologists clues about how plant species may respond to climate change in the future.

> **"BEING ABLE TO PREDICT WHERE PLANTS CAN REGENERATE, AND WHERE THEY CANNOT, PROVIDES CRITICAL INSIGHTS INTO A KEY LIFE HISTORY STAGE. IF A FOREST CANNOT BE REGENERATED, WE CANNOT MANAGE IT SUSTAINABLY!"**

How can computer modelling help predict the future of forests?

Simulation and statistical models (SSMs) are types of mathematical models used in ecology. In forest ecology, SSMs use data on the absence, presence and/or abundance of plant and animal species in the current environment, combined with other information such as climate, physical features and land-use. SSMs relate key processes such as regeneration, growth, and mortality with species abundance/occurrence or, more simply, relate the presence or absence of a species to the other variables in the model and calculate the statistical strength of the relationship. "When used with climate variables, these models allow for what we call the 'ecological niche' to be identified," Craig says. "If a robust model influenced by climate can be produced, these models can be used to predict where a species' niche may shift to under climate change."

So, can SSMs foretell the future? Craig is careful to emphasise that models are "always wrong". Modelling can suggest possible trajectories or trends, calculate the likelihood of some outcomes over others, and place limits on what we think is possible. However, models are full of uncertainties and simplifications. SSMs cannot take into account the individual history of a forest or the genetic adaptive capacity of a living species. "Improving models and developing more sophisticated methods is an important task for future forest ecologists," says Craig.

What do we know about how forests are responding to climate change?

Forests have adapted to environmental challenges many times in the past. In a warmer, drier climate with more fires, forest composition will change to favour drought- and fire-resistant species. Craig also expects some species to evolve through natural selection pressures and give rise to new ones, like Darwin's famous finches. Species that cannot adapt will die out.

Although evolution can shape the forests of the future on its own, humans have a role to play in maintaining the forests we need. Modelling forest regeneration, germination and survivorship of seeds, and the impact of temperature and moisture on young tree growth can help us manage forests sustainably. "Being able to predict where plants can regenerate, and where they cannot, provides critical insights into a key life history stage," Craig says. "If a forest cannot be regenerated, we cannot manage it sustainably!"

We need forest ecologists like Craig to tell us where to plant what kind of trees, so we can protect our existing forests and plant new ones – an indispensable tool in drawing down carbon dioxide from the atmosphere and supporting biodiversity. Forests matter, and we do not need a computer model to tell us they will matter even more in the future.

ABOUT *FOREST ECOLOGY*

A branch of forest science, forest ecology is the study of the ecosystems in forests, including trees and other plants, animals, fungi and micro-organisms. Forest ecosystems are very complex because of the high density and diversity of species and their interdependence. Because forests are also important to human comfort and well-being as producers of timber and other products – not to mention oxygen –, forest science is closely associated with forest management. Forest management aims to keep tree populations at certain levels and maintain biodiversity and soil fertility. Forest scientists may study something as tiny as soil microbe populations or as large as the contribution of global forests to the carbon cycle.

What makes forest science a rewarding field to study?

It is a fantastic field for people who love nature and the outdoors. Forest and other environmental scientists often spend a lot of time doing fieldwork in their habitat of choice, amidst giant trees and awe-inspiring landscapes. Studying forests is intellectually rewarding because of the complexity and dynamism of these ecosystems. As an interdisciplinary field, forest science also offers the opportunity to bring together many different skills and areas of knowledge. It is an important field because of our reliance on forests. "Without forests, we would not be able to live on this planet," Craig says. "Research into how forests work and how they change is rewarding because it addresses the needs of humanity, as well as the needs of flora and fauna."

What research opportunities await future forest scientists?

Forests will remain crucial ecosystems and levers in the fight against climate change. The changing climate will be the central challenge for future forest scientists, as well as environmental scientists of all kinds. Craig lists some of the key questions the next generation of researchers will address: "Where and what type of adaptation do we undertake? Where do we fight to maintain forests in their existing state? Where do we transition forests based on human values? Where do we allow forests to find their own way? Where and how do we restore forests? What are the consequences of these decisions?" If you feel inspired by any of these questions, forest science might be for you!

Pathway from school to *forest ecology*

- Becoming a forest ecologist starts with studying fundamental sciences like biology and chemistry in school. Some schools may offer classes or units in ecology. Statistics is also a useful subject for ecologists.
- The first step towards becoming a professional forest scientist or forester is a bachelor's degree in forest science, forestry, ecology, forest management or a similar field. This level of qualification is enough to work in commercial forestry. An alternative pathway is to complete an apprenticeship in forestry.
- In Australia, Forestry Australia (**www.forestry.org.au**) is the professional organisation for tree professionals. The UK equivalent is the Institute of Chartered Foresters (**www.charteredforesters.org**). Other countries will have their own national organisations which provide advice to students interested in a career in forestry.
- Working as an academic researcher in forest science requires a PhD. Research in this area is very interdisciplinary, and people with training in other fields can enter a forest science PhD programme, as long as they have the skills needed for their research project.

Explore careers in *forest ecology*

- Craig emphasises that the most important asset for aspiring forest scientists is a love of forests, nature and the outdoors.
- One way to dip your toes into forest science is to participate in a field school or programme such as the Rainforests of Australia field school offered by the School for Field Studies: **fieldstudies.org**
- The University of Melbourne (**ecosystemforest.unimelb.edu.au**) is one of the top Australian universities for forestry. In the UK, the University of Bangor (**www.bangor.ac.uk/courses/undergraduate/d500-forestry-bsc-hons**) has the oldest and most well-known forestry department.
- In Australia, an average salary for foresters falls between AU$70,000 and AU$90,000. University professors in Australia earn AU$150-200,000 a year, depending on the field and years of experience.

Q&A

Meet Craig

What were your interests when you were growing up?

Fishing, hiking, camping, horse riding, playing ice hockey and taking part in biathlons!

Who or what inspired you to become a scientist?

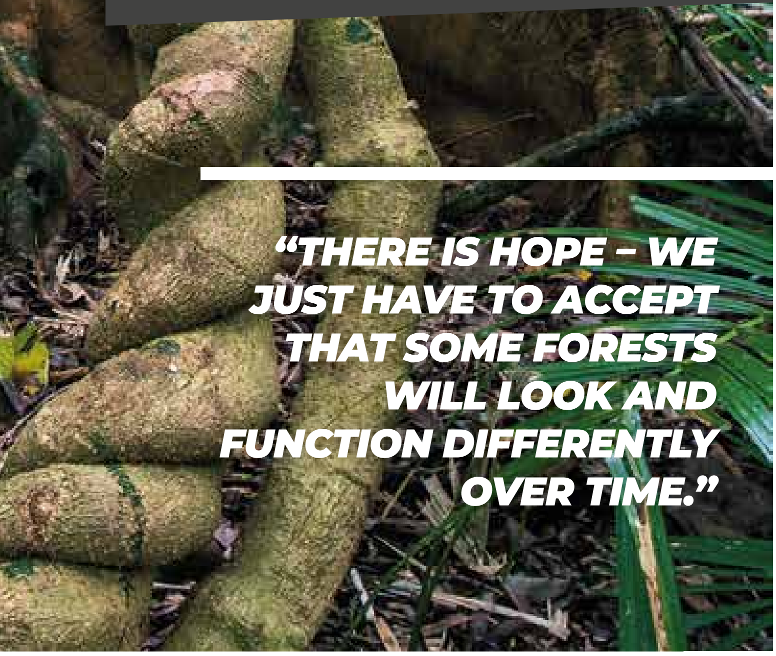
I fell into being a scientist by accident! I owe my journey to my lab mates at the University of British Columbia in Canada who encouraged me to pursue my PhD.

Which experiences have shaped you as a scientist?

I grew up in a forest-dependant community and spent many hours in nature when I was growing up. I ended up in forest science through living in this environment. What shaped me was a series of challenges that exposed the conflict between society's use of forest resources with conserving forests. At the nexus of these two opposing forces, I found myself inspired to understand the complexity of forests and people.

How do you stay motivated when focusing on climate change?

When I started my research into climate change and forests, I received many eye rolls and headshakes. "An interesting academic exercise" was a common retort to my work. What has motivated me is the change that has occurred in governments and people in the climate change space. It was slow, but this has sped up with time. It is inspiring to see the research mainstreamed and the arguments of "is climate changing?" shifting to "what we do about this?" because we are now seeing the impacts of the changing climate. I am optimistic because not every place or species will be impacted negatively.



"THERE IS HOPE – WE JUST HAVE TO ACCEPT THAT SOME FORESTS WILL LOOK AND FUNCTION DIFFERENTLY OVER TIME."

Measuring the forest – establishing and monitoring plot in montane ash forests in Victoria, Australia (© Craig Nitschke 2021)

Understanding the vulnerabilities and risks of forests means we can manage these if we desire. Forests are complex and full of surprises. I have seen this in the fire-impacted landscapes of southeast Australia. In areas burned three times in 15 years (that usually burn once every 75-100 years) we still find a functioning ecosystem. There is hope – we just have to accept that some forests will look and function differently over time. But this has always been the case! The one constant in forests is change.

What are your proudest career achievements so far?

Every master's and PhD researcher I supervise to graduation is a proud achievement. They are courageous, inspiring and brilliant. They make my career as a forest scientist.

Craig's *top tips*

1. Find your passion! Your passion for a subject is what will motivate you.
2. Spend lots of time outdoors.
3. Focus on positive change and stay optimistic!

FIRE TRACKERS: HOW CAN WE USE MODELLING TECHNIQUES TO PREDICT WHERE WILDFIRES WILL OCCUR?

Climate change is making many parts of the world hotter and drier. As a result, wildfires are becoming increasingly prevalent and pose a serious threat to human life, local communities and natural ecosystems. Researchers from the **FLARE Wildfire Research Group** at **The University of Melbourne** in Australia are developing models that can help predict where wildfires are most likely to occur and how fires behave under different weather conditions. Their research explores how fire management can be used to reduce the risk of damage to human values while maintaining or improving environmental values in the landscape.

Professor Trent Penman

Dr Kate Parkins

Dr Erica Marshall

The University of Melbourne, Australia

Field of research
Fire risk analysis

Research
Investigating fire behaviour and impacts, and developing models that can help predict where wildfires are most likely to occur

Key Funders
e.g. Victorian Government Department of Environment, Land, Water and Planning; Greening Australia; Forest and Wood Products Australia; Energy Networks Australia

For more information on FLARE's project partners, visit: www.flarewildfire.com/partners

TALK LIKE A ... BUSHFIRE RISK ANALYST

Bushfire or Wildfire — an unplanned fire that burns through large areas of scrub or forest

Variable heat flux — a measure of how quickly heat energy moves through or across a material

Prescribed burns — the controlled application of fire, also referred to as 'controlled burns', 'hazard reduction burns' or 'planned burns'. This type of fire is deliberately applied to a pre-determined area at the time, intensity and rate of spread required to achieve the desired management objectives, and occurs under a strict set of environmental conditions

Fire suppression techniques — the various strategies for stopping a fire once it has started. These include: spraying a fire with large volumes of water or fire retardant (from the ground or through aerial attack); creating fuel breaks (areas cleared of vegetation by heavy machinery) to stop fire spread or provide safer places for fire fighters to work from; back-burning to reduce or remove fuel/vegetation in strategic areas (e.g. in areas where a fire is predicted to travel)

Fuel management — management aimed at reducing connectedness within and between different layers of fuel, by increasing the gap to the canopy to reduce the likelihood of fire reaching the upper layer of fuel, and removing bark to reduce spotting

During Australia's "Black Summer" bushfire season of 2019-20, an area the size of the UK was impacted by bushfires. Tragically, more than 30 people lost their lives as a direct result of these fires, and over 3000 homes were destroyed. It is estimated that over a billion animals perished in these fires and that some species may even have been driven to extinction.

The total economic cost of the Black Summer fires has been calculated at around $80 billion, making them the most costly natural disaster in Australia's history. Worryingly, extreme bushfire events of this scale are becoming more frequent, not just in Australia, but in many places around the world.

This increase in the frequency and severity of bushfires is being driven by, among other things, human-induced climate change. Since the industrial revolution, humans have emitted more than two trillion tonnes of carbon dioxide and other greenhouse gases into the atmosphere. These gases trap heat from the sun in the Earth's atmosphere, which has led to the destabilisation of climate systems all around the globe. In many places, dry seasons are becoming longer and hotter, which can create perfect conditions for bushfires to start.

The risks associated with extreme bushfire events are being magnified as human populations continue to expand into forested areas. As human populations expand, we are seeing the associated


© 2ragon/stock.adobe.com

expansion of the Wildland-Urban Interface (WUI). The WUI is defined as an area where people and houses are in close proximity to wildland vegetation. These areas are often characterised by very high fire risk due to the proximity of flammable vegetation and the difficulty of suppressing fires in these areas. As a result, understanding how bushfires behave and where they are likely to occur is more important than ever.

Professor Trent Penman, Dr Kate Parkins and Dr Erica Marshall are researchers from the FLARE Wildfire Research Group, based at The University of Melbourne. Through their research, Kate, Erica and Trent investigate bushfires in an attempt to better predict patterns of bushfire behaviour and occurrence. This will allow them to identify where future fire risks are highest, and help communities prepare for and manage the risks associated with bushfires.

What are the risks posed by bushfires?

"Bushfires can cause extensive impacts on the environment and people," says Trent. "The most serious direct impacts include the immediate loss of life and property during extreme events." Bushfires can also result in the widespread destruction of habitat and increase the risk to threatened plant and animal communities.

The impacts from extreme bushfire events can linger for a long time after the fires have been extinguished. This is particularly true for economic impacts, such as the loss of tourism, the destruction of farm crops and damage to local shops and businesses. Long-lasting economic impacts can put huge pressure on local communities. As families are displaced and community groups broken up, the mental health and well-being of people can come under serious strain.

The risks posed by bushfires may vary in different areas. Some communities may experience them more frequently and on larger scales than others, depending on their local climatic conditions and surrounding habitats. Gaining a deeper understanding of bushfires allows the team to more accurately assess the risks faced by different communities.

How does the team study bushfire behaviour?

The FLARE Wildfire Research Group has a purpose-built fire laboratory where it can investigate different aspects of fire behaviour. The fire lab is home to a variety of experimental equipment that allows researchers to conduct fire experiments in controlled, safe conditions. For example, the variable heat flux apparatus allows the team to study how different materials ignite and burn under different climatic conditions. The flame propagation apparatus allows the group to study how flames spread across different materials, and the IKA CA bomb calorimeter is used to determine how quickly heat is released from different substances. Fire experiments in the laboratory are just one part of how the team investigates fire behaviour. These lab-based studies are also scaled-up to a local or landscape scale through field experiments, where the team collects information about current fuel loads, as well as undertaking additional fire experiments in forested environments to capture real-time variability in weather and fuel moisture.

However, all of these devices pale in comparison to a new bit of kit that is currently under construction at the lab. A large-scale, 50 m wind tunnel will be used to generate large fires and investigate how they behave under extreme conditions, such as high wind speeds. The new wind tunnel, along with the other apparatus, will allow the team to collect all sorts of important data. These data can then be used to develop models which can help predict the occurrence, location and intensity of future bushfires.

How does the team study future bushfire risk?

The modelling programme that is most commonly used by the team is called FROST, which stands for Fire Regime Operations and Simulations Tool. This programme makes use of data that have been collected from lab experiments or field studies and combines them with fire behaviour simulations. This enables the team to determine how likely bushfires are to start in different places and under different climatic and weather conditions.

FROST can also incorporate data on biodiversity and the location of human settlements and structures. "For example, using data on the traits and ecological requirements of different plant species, we can examine how changing fire risk might affect different ecological communities," explains Erica.

Once the team has chosen a location that it wants to construct a model for, the researchers need to collect data. "These models we run use many, many data inputs," says Erica. "These data capture the location of assets in the area, the distance to roads, vegetation type, soil moisture, rainfall, fire history and a myriad of climate information." Collecting all these data can take a long time, and the team makes use of government databases, academic papers and its own field work and experiments to do so.

"It is essential that the information we collect and use in these models captures the unique ecological and environmental conditions of the region of interest," says Kate. This helps the team make better predictions about how these areas might be affected by bushfires over longer time periods and under changing climatic conditions.

How does the team apply the models?

The models produced by FLARE are used to help solve a range of management problems. "Our work helps local and state agencies make decisions about wildfire risk management," explains Kate. "Essentially, we help identify where current or future fire risk is the highest, and evaluate a series of different management strategies to determine which option, or combination of options, will provide the best risk reduction. This information provides a transparent and scientifically robust method for allocating limited fire management resources to ensure the biggest risk-reduction bang-for-buck."

As our climate continues to change, more communities will be threatened by bushfires. Many of them may not have the knowledge or experience to deal with these extreme situations. As such, the team at FLARE is playing an important role in helping communities and industry be better prepared for changing climatic conditions and a future characterised by more frequent fires.

ABOUT *BUSHFIRE RISK ANALYSIS*

Bushfires have been a part of the Australian environment for millions of years and have shaped the species and ecosystems we see today. Most systems require some fire to maintain diversity and function, and have evolved with natural fire regimes. However, these ecosystems can undergo significant changes in response to altered fire regimes caused by a changing climate.

As the effects of global climate change become more pronounced, bushfire management will become increasingly important. A better understanding of the economic, social and environmental consequences of major bushfires is important for reducing impacts to businesses, communities, individuals and ecosystems. Extreme bushfire events will increase in severity, intensity and duration. They will become a problem in more places around the world, increasing the demand for bushfire researchers and risk analysts.

How can the next generation of bushfire researchers be successful?

"Wildfire research is increasingly becoming an interdisciplinary field," says Kate. "It involves not just fire behaviour but also animal ecology, human ethics, social science, engineering, politics, environmental law, health science and mathematics." The future of wildfires globally poses a serious and complex challenge, and to manage the risks that come with a future characterised by more frequent and extreme fires, we need to integrate knowledge and learnings from many different disciplines. Having a range of skills is extremely beneficial as there will be opportunities for science communicators, media experts, policy makers and land managers, as well as researchers.

The next generation should make use of opportunities to incorporate both new and old knowledge into its work. "Fire managers and researchers are increasingly looking towards Indigenous knowledge on burning practices for insights into how we can better manage the landscape," says Trent. Many Indigenous communities have lived in close harmony with nature for centuries, if not millennia. As a result, they have an intimate understanding of their native lands and how best to manage them.

What range of expertise is there in FLARE?

FLARE Wildfire Research Group is one of Australia's largest fire research groups. "In our group, we have an incredibly broad range of skills and backgrounds including landscape and animal ecology, combustion engineering, forest science, mathematical modelling, and some data analysis and computer programming thrown in for good measure," explains Erica.

Every researcher at FLARE has followed a unique path to their current work. This diversity of research experience enables them to investigate and answer some of the complex questions that face fire management agencies all over the world. "Having this fantastic diversity of backgrounds and skill sets allows us to do innovative, unique and rigorous research on a range of wildfire related subjects," says Trent.

What is a typical day like for FLARE researcher?

Most of the day-to-day activities focus on conducting research, either through experiments, field-work or simulation modelling. The team also spends a lot of time writing up research papers, communicating with industry partners and carrying out statistical modelling.

Erica explains, "On an average day, we might be writing new code for our models, analysing field and experimental data, or engaging with collaborators about common research projects." Documenting the group's work in the form of reports, peer-reviewed publications and presentations is also vital. "This process is critical for getting our research into the scientific community and advancing the collective knowledge on wildfire risk," says Kate.

What is rewarding about being a bushfire researcher?

The work of bushfire researchers can have significant impacts on how land managers understand and manage fire. "Knowing that the work we do is respected and applied by local and state governments, as well as our private industry partners, is very rewarding," says Trent. "Every improvement to our understanding of bushfire risks can improve our management of those risks and potentially prevent impacts on the environment and our communities."

Q&A

Meet Kate

What were your interests when you were growing up?

As a kid, I always had my pockets full of something. I couldn't help myself – I was constantly picking things up to take home and investigate later. I collected rocks, plants, sand, sticks and shells… I was always rescuing injured birds, insects, lizards and worms. I just really loved being out in nature.

I had a strong environmental focus from an early age. When I was about 12, I joined a local 'Stream Watch' club that assessed water quality and surveyed the local aquatic wildlife once a month. This taught me a lot about how to run scientific experiments, and I was hooked. However, I also really loved acting and singing, so I was often torn between science and the arts. The best part of my current role is that I can combine my love of science with my love of communicating to explain science in fun and exciting ways.

Who inspired you to become a scientist?

David Attenborough's documentaries were mind-blowing to me as a kid. I would watch these films and make a 'bucket list' of species I wanted to see and places I wanted to go one day. I was also extremely lucky to have family friends who were working zoologists, so I spent many holidays with them wading through lakes, chasing frogs or spotlighting (a way of observing nocturnal animals in the dark). I knew from an early age that I wanted a job that felt meaningful, and that allowed me to be out in nature.

What attributes have made you successful as a scientist?

I think one of the key things that makes me a successful scientist is that I have a deep curiosity about the world around me and a drive to do research that will have direct and tangible impacts. I like tricky and complicated questions, and I am motivated to find the answers. Another important aspect that makes a good scientist is the ability to work as part of a team. Being a good listener, having excellent attention to detail, good communication skills, kindness, empathy and motivation! All of these are important aspects.

The variable heat flux apparatus allows the team to study how different materials ignite and burn under different climatic conditions.

What are your proudest career achievements, so far?

The day I found out that I had been awarded a scholarship to do my PhD was one of my proudest moments. Hard work and perseverance really do pay off. My parents always said to me, "you really can do anything if you just put your mind to it" and they were right. This is something I try to remember as I go through my career. I did a small research project through my master's, studying our largest owl species here in Australia (the powerful owl, *Ninox strenua*). Through this study, I started to have a lot of questions about how a series of prescribed burns might affect the population of owls I was researching, and I knew that I needed to pursue a career in research. So, getting accepted and then completing a PhD in fire ecology at Australia's top university was certainly one of my proudest moments.

What are your ambitions for the future?

I am very passionate about diversity and inclusion in science, and fostering the next generation of scientists. I hope to continue to mentor and encourage new students in this field. I aim to continue the work I am doing in fire risk and fire ecology research, in the hope that my research can help reduce the impact of future wildfires. I've never really had a big picture career goal; I have simply said yes to opportunities, worked hard, been kind and curious, and followed whatever path has presented itself to me. I plan to continue doing this for as long as I can!

Kate's *top tips*

1. You really can do anything you put your mind to!
2. Don't be afraid to ask questions.
3. Don't shy away from hard work.
4. Pay attention to the world around you, and be as focused as you can in statistics classes! (I learnt this the hard way!)
5. Take every opportunity and try lots of different things until you find your niche.

Pathway from school to *bushfire risk analysis*

- At school and post-16, take maths alongside other science subjects like biology and chemistry.
- Learn about the practical skills that you might need for field data collection. "For me, this is the best part," says Kate. "I love getting out in the field and collecting information on species, ecosystems or processes. You get to see some incredible places that not many people get to explore. It's amazing."
- As well as collecting data, you need to know what to do with them. A good knowledge of statistics and coding is vital for analysing data. "We use statistics on a weekly, if not daily, basis," says Erica. "A lot of the data analysis we do also involves coding, which helps to speed up our ability to answer complex questions and allows us to do incredibly complicated modelling over very broad time scales."
- Written and verbal communication is also key for sharing research findings. Studying English, drama or other art subjects can help with developing these skills. "Science should be shared widely with different and diverse audiences," says Kate. "The ability to communicate complicated science in a simple and engaging manner is really important. While they may seem very removed from the scientific world, the skills you will learn in these subjects will be very helpful if you choose a career in science."
- Studying a wide range of topics will make you a more well-rounded scientist. "I have a degree in acting and TV production, a master's in environmental science and a PhD in fire ecology," says Kate. "The skills I have gained in these vastly different fields has been more beneficial than I could have ever predicted."

© 2ragon/stock.adobe.com

"SCIENCE SHOULD BE SHARED WIDELY WITH DIFFERENT AND DIVERSE AUDIENCES."

Explore careers in *bushfire risk analysis*

- Volunteer with local environmental groups. Being curious and learning about the issues in your local area can give you an insight into the kinds of issues that people face in other parts of the world as well.
- Volunteer with the fire service in your town. Many of these organisations actively encourage young people to get involved. If you live in an area where fires are common, this is a great way to learn more about them. If bushfires are not common in your area, you will still learn a lot about how fire works and how people fight it. As well as learning a lot about fire behaviour and risks, you will also help people in your local area and become an active part of your community.
- Take opportunities to get out into nature and take note of the thing around you. "The more you know about the world around you, the better you can work to protect it," says Kate.
- You can learn more about FLARE and its research projects on its website (**www.flarewildfire.com**).
- The Leverhulme Centre for Wildfires, Ecology and Society website (**centreforwildfires.org**) is a great resource to learn more about bushfires and how they affect ecosystems and communities. Its website has sections for new research being published, the latest news in wildfire research and jobs. It also hosts events and talks where you can learn more about the field of bushfire research.
- Get in touch with your local university or college to see if it has a department that studies bushfire management and offers any volunteering or research opportunities. Gaining experience of working as a researcher of any kind can provide you with valuable experience and help you explore your career options.

Q&A
Meet Erica

What were your interests when you were growing up?

Growing up in New Zealand, I loved nature. I was very lucky to live near a beach, and I was always exploring rock pools or fishing with my family. When I was young, I wanted to become a marine biologist, but I also had a vivid imagination. Any time I got in the water, I was scared that sharks were surrounding me, waiting to attack. Unfortunately, this put me off marine biology fairly quickly! I was also really interested in ancient cultures, so I channelled that imagination into exploring ancient Greece and Egypt. This led to an interest in archaeology and anthropology. I actually ended up doing biological anthropology as a major when I went to university, alongside my biology degree.

> **"KNOWING THAT MY RESEARCH IS BEING APPLIED THROUGH GOVERNMENT POLICIES AND PROCEDURES TO IMPROVE RISK MANAGEMENT IS PROBABLY ONE OF MY PROUDEST ACHIEVEMENTS."**

Who or what inspired you to become a scientist?

I was always really interested in science, but I certainly did not think I was good at science in school. I had one science teacher in early high school who just knew how to make science accessible. She saw that I had the potential to do well if I applied myself, and she pushed me to do so. One day, I was sitting in the library working and she rushed over with a big grin and my latest test score. All she said was, "I told you so". Her excitement was infectious, and I was super proud of myself. She was passionate about science, but more importantly she was passionate about learning. She really inspired and mentored me to find a way of learning that worked for me, and that love of learning really helped me discover my passion for science.

What attributes have made you successful as a scientist?

I think some of the best attributes to have as a scientist are curiosity, collaboration and communication. No one knows everything, and you never need to know everything because, ideally, you are just one part of the solution. The rest of the solution might come from your research group, your collaborators, or the scientific community in general. Working well in a team is a key part of science and a skill that can be improved every day and as you gain more experience as a scientist. I am still learning new things.

What are your proudest career achievements, so far?

Since finishing my PhD, the work I have done in FLARE on wildfire research has been taken on board by several groups, including government agencies. Knowing that my research is being applied through government policies and procedures to improve risk management is probably one of my proudest achievements. It is really rewarding to know that the science you are doing makes a difference, even if that difference feels small.

What are your ambitions for the future?

I love research and the problem-solving aspect of my current research in particular. I hope that one day I can find a permanent research position where I can lead my own research. As a woman in STEM, I also think I have been really lucky in my life and career to have so many strong, inspiring female leaders to take example from. I hope I can pay it forward to future generations of researchers as a mentor or supervisor. I would like to see more amazing, unique and diverse people bringing their ideas into science.

Erica's *top tips*

1. Keep an open mind.
2. Keep going, even when it feels like you've failed. Everyone makes mistakes, and it's important to learn from them.
3. Maintain a balance between work and the other things that give life meaning.

MONITORING THE CANOPY TEMPERATURE OF FORESTS

Dr Sophie Fauset, from the **University of Plymouth** in the UK, and **Dr Shalom D. Addo-Danso,** of the **CSIR-Forestry Research Institute of Ghana,** are collaborating on a global project that seeks to monitor the canopy temperature of forests. The findings will help develop understanding of how forests are responding to climate change and, hopefully, be an impetus for action.

Dr Sophie Fauset

School of Geography, Earth and Environmental Sciences, University of Plymouth, UK

Field of research
Environmental Science

Dr Shalom D. Addo-Danso

CSIR-Forestry Research Institute of Ghana, Kumasi, Ashanti Region, Ghana

Field of research
Ecology

Joint research project
netCTF project – developing a global network for monitoring canopy temperature of forests monitoring

Funders
Natural Environment Research Council (NERC), Global Challenges Research Fund

TALK LIKE AN ... ENVIRONMENTAL SCIENTIST & ECOLOGIST

Earth system model — a climate model that explicitly models the movement of carbon through the earth system

Forest Canopy — the upper layer or habitat zone, formed by mature tree crowns

Microclimate — a local set of atmospheric conditions that differ from those in the surrounding areas

Photosynthesis — the process by which green plants and certain other organisms transform light energy into chemical energy

Stomata — tiny openings or pores in plant tissue that allow for gas exchange

Forests are not only beautiful and awe-inspiring to walk around, they are also home to a substantial amount of biodiversity and play a key role in the global climate system. Forests store large amounts of carbon, and we know that increasing levels of carbon in the atmosphere have contributed to climate change. For this reason, forests are seen as a key battleground in the fight against global warming and are a key focal point for ecologists and environmental scientists.

Dr Sophie Fauset and Dr Shalom D. Addo-Danso have come together to collaborate on a project that seeks to monitor the canopy temperature of forests. Sophie is an environmental scientist based at the University of Plymouth in the UK, while Shalom is an ecologist based at the CSIR-Forestry Research Institute of Ghana in Africa. Together, they are building a new network for monitoring the canopy temperature of forests in the netCTF project.

What issues is the netCTF project attempting to solve?

Most Earth system models tend to assume that leaf temperature is the same as air temperature, but previous studies have shown this is not the case. However, many of the physiological processes that these models simulate (such as photosynthesis and respiration) are temperature sensitive, so accounting for leaf temperatures can improve model performance. “There is little data available on leaf and canopy temperatures,” explains Sophie. “We have some small-scale datasets that are collected for short time periods on individual leaves. These can provide detailed understanding of those species included but only for a short time.”

© Marlon/stock.adobe.com

What determines leaf temperature?

There are two separate factors – the environment the leaf is in and the characteristics of the leaf itself. If conditions are sunny, the sunlight will heat the leaf above the air temperature, just like you will feel warmer if you stand in the sun. "Leaf temperature is driven by multiple factors, including conditions that exist outside the leaves and those related to the characteristics of the canopy and leaves," says Shalom. "Some of the environmental conditions that affect leaf temperature include air temperature, atmospheric humidity, wind velocity, light intensity and atmospheric carbon dioxide."

Understanding leaf temperature is important because it affects photosynthesis and many other critical functions and processes of plant leaves, as well as the microbial communities on leaves that influence tree growth and survival. If the leaves in forests are too hot and are unable to cool down, trees could die, further exacerbating the problems of global warming and climate change.

What methods is the team using to understand canopy temperatures?

Thermal cameras can be installed in forests to take images of canopy temperature continuously, over long periods of time. In these images, it is possible to differentiate between the tops of different trees, so researchers can look at how individual species of trees behave in terms of temperature, knowing that different species will have different leaf sizes and patterns of stomata opening and closing. The cameras can also be used to reveal mammal populations that live in the forest canopy.

These studies need to be conducted for a long period because forest systems are dynamic and the responses of forest species to global climate change are uncertain. More long-term data have to be collected by Sophie, Shalom and the team to enable them to understand how rising temperatures and other extreme weather conditions, such as drought, could impact the forests.

How will data captured by these cameras be analysed?

Once the thermal images are captured, they are processed and corrected using software. "We make a file that specifies our regions of interest (ROIs) – these are the tree canopies we want to look at. We are using a statistics and computing software called 'R' to open all the images, select the data just from the ROIs, and link the temperature data to the climate data collected at the same site," says Sophie. "In this way, we can assess patterns between different crowns and under different microclimate conditions."

Why is it so important that these data can be shared?

While the data the team collects are extremely important to their specific research, they can be useful for scientists in other research areas. For instance, the data can be used to test how well vegetation models predict leaf temperature, or show that temperature regulation is important for models to consider. "They will also be very useful for validating remotely-sensed land surface temperature data collected by satellites, such as the new NASA ECOSTRESS mission," explains Sophie. "Making canopy temperature data available for use by others is important as it will augment existing data collections and can be used for other ecological analysis. Importantly, policymakers can use the data for decision-making on forest management," adds Shalom.

> **"THE ULTIMATE GOAL OF THE NETWORK IS TO PROVIDE A PLATFORM TO DEVELOP, PROCESS AND SHARE DATA ON FOREST CANOPY TEMPERATURE."**

Why is an international, collaborative approach so important?

Forests, particularly tropical forests, are important to all of us; any efforts to tackle the factors impacting these forests involve a truly international community of researchers. "The ultimate goal of the network is to provide a platform to develop, process and share data on forest canopy temperatures," says Shalom. "A collaborative approach helps with the sharing of skills and data among many researchers, and also allows for outcomes that are not possible to achieve by people working individually at separate sites. It also helps us to better explain the impacts of climate change on forests with a broader global view."

View of Bobiri Forest Reserve, Ghana, with a thermal camera in the foreground © Sophie Fauset

ABOUT *ENVIRONMENTAL SCIENCE*

Environmental science is an interdisciplinary field which seeks to find effective means of understanding and managing the world in which we live. In particular, environmental scientists incorporate social science subjects to provide understanding relating to human relationships, perceptions and policies towards the environment.

Given the evidence regarding how human activity is impacting the climate of countries around the world, there has arguably never been a more important time to be an environmental scientist, if only so more evidence can be gathered that encourages remedying strategies to be developed.

Sophie acknowledges how challenging the field of environmental science can be but is keen to point out how much she enjoys her work. "It is exciting for me that my research helps us to understand the natural world and the impacts of climate change," explains Sophie. "It also provides a lot of opportunity to travel and work with people from other parts of the world, and I love passing on my passion for plants to students!"

At the moment, there is a huge emphasis on restoring forest cover to help mitigate climate change and biodiversity loss. Sophie tells us that she believes there will be lots of opportunities in this area in the future.

Pathway from school to *environmental science*

After studying science at school, it is important for students interested in environmental science to take a science subject at college. You should also consider taking maths at a higher level as there is often a lot of number crunching to do. Sophie says that communication is important too, so she recommends doing a subject that involves writing, such as history or English.

Prospects has detailed information about studying environmental science at university and at post-graduate level: **www.prospects.ac.uk/careers-advice/what-can-i-do-with-my-degree/environmental-science**

Explore careers in *environmental science*

- Sophie recommends getting involved with environmental issues in your local area to gain experience, such as by volunteering with local environmental groups.
- In the UK, the Institution of Environmental Sciences (**www.the-ies.org**) or the Chartered Institute of Ecology and Environmental Management (**www.cieem.net**) offer free student memberships and careers advice.
- According to Indeed.com, the average salary for an environmental scientist in the UK is £31,000 per year: **uk.indeed.com/career/environmental-scientist/salaries**

How did Sophie become *an environmental scientist?*

I was always interested in science and nature as a child and loved reading books. At different ages, my thoughts on what I wanted to be when I grew up ranged from vet to doctor to marine biologist, but I am happy with where I have ended up.

I always enjoyed science at school, and my dad was a chemistry teacher. He would spend a lot of time talking about science with me, although chemistry wasn't my strong point! My parents were always happy for me to pursue what interested me and have been a great support throughout my career. It is a bit of a cliché, but David Attenborough's natural history documentaries are definitely part of why I study the natural environment today.

I have found myself studying different areas of forest science since working on my PhD. I started out working on forest ecology with very low-tech equipment – mostly a tape measure! Following that, I saw that many jobs were asking for experience in either geographic information systems or modelling. Because of this, I took a research job working on model simulations of forests. This made me more interested in the physiological processes happening in the forest, and now I combine forest ecology with more in-depth studies of physiology and microclimate. I think working with different methods provides a broader view of your subject area. Programming is a key skill that I have learnt to manage and analyse data. This is really important for working with large or complex datasets.

I really enjoy getting outside and into nature. I cycle to work and am lucky that my route goes along a wooded estuary, so I get a good chance to de-stress and reflect on my day on my way home. I also spend time in my garden, which we are making more 'nature friendly' – it is very rewarding to see wildlife coming into the garden and feeling I am actively improving the local habitat.

My proudest career achievement is publishing my first scientific paper back in 2012. Publishing always feels great as it is recognition that you are working to the highest scientific standards. For the future, I hope to get more research funding to continue our canopy monitoring work.

Sophie's *top tips*

1. My advice is to follow your passion. I think it is much easier to be motivated when you are working towards something you are excited about.
2. Keep going, even when things are hard. Often, if you are completing a research project, there are obstacles, and you have to persevere to overcome them.

ABOUT *ECOLOGY*

Ecologists work to find ways of protecting and restoring the natural environment. They do this by collating and disseminating important information about the impacts that human activity has on individual species and ecosystems. Ecologists like Shalom are working hard to reverse human impact and make positive changes to the world.

Shalom says the most rewarding aspect of his work is the ability to generate knowledge and information on climate change. "My research activities focus on pressing issues in ecology that can be used to enact change in policies that have practical benefits to ecosystems and people at local, national and international levels," he explains. "I like to explore new places and interact with people, and my research activities have provided me with many travelling opportunities to explore and learn."

> ***"FORESTS WILL CONTINUE TO INTRIGUE RESEARCHERS BECAUSE WE KNOW SO LITTLE ABOUT THEM."***

There will be opportunities for ecologists around the world, but, in Africa, very few scientists are engaged in the field, so the continent is ripe for the next generation. "There are many unresolved questions surrounding important global issues including climate change, biodiversity conservation, plant-soil interactions, land use change and many more that need further probing," says Shalom. "Forests will continue to intrigue researchers because we know so little about them."

Explore careers in *ecology*

- Conservation Careers provides lots of useful information on careers in ecology: **www.conservation-careers.com/how-to-become-an-ecologist/**
- The Ecological Society of America (**www.esa.org/career-development/explore-ecology-as-a-career**) and the International Union of Forest Research Organisations (**www.iufro.org**) are also excellent resources for budding ecologists.
- According to Prospects, the salary for an assistant ecologist role is in the region of £18,000 to £22,000, depending on experience, while senior ecologists can earn between £30,000 and £45,000: **www.prospects.ac.uk/job-profiles/ecologist**

Pathway from school to *ecology*

Anybody interested in ecology will need to have the basics in biology, chemistry, physics and mathematics. Apart from these, the global challenges we face are complex and interconnected with different aspects of society, so students should focus on courses that are interdisciplinary in nature, including geography and communication.

A degree in a biological science or environmental subject is generally required.

How did Shalom become *an ecologist?*

As a youngster, I was interested in many things including writing and science. I loved asking questions about how to help people, and how things worked in nature. I also loved writing poems and short stories.

I was inspired to become a scientist by my inner passion to see changes in people's lives. I always told my teachers I wanted to be a scientist and teach in a university, although I was not sure about the specific area of interest. I began to love nature and was intrigued by how natural systems function.

I cannot mention one particular moment that shaped my career path. However, the interactions with my PhD supervisors, especially Professor Cindy E. Prescott, helped shape my perspective about research and, eventually, some of the interests I am pursuing now. I think I have developed my communication skills, which are important for scientists to effectively communicate our findings, especially to non-technical audiences.

I am an optimist and I believe everything is possible, if only I can commit myself to it. So, in times of challenges, I draw on that belief to take me through.

I have a few standout career achievements. One is collaborating with Sophie to build the tower for the canopy temperature study. This set up is the first of its kind in Africa to monitor forests, and the tower is an important infrastructure that can advance studies in different aspects of climate change, such as measuring gas exchanges from forests to the atmosphere. My ambition is to become one of the leading ecologists in the world and help train the next generation of ecologists from Africa.

Shalom's *top tips*

1. Be committed to whatever you find yourself doing.
2. Find mentors who can guide and help you grow your skills and leadership qualities.

HOW DO PLANTS PROTECT THEMSELVES FROM DISEASES?

It is estimated that plant diseases cost the global economy roughly $220 billion each year. Understanding how plants fight pathogens is, therefore, crucial to protecting crops and combatting food insecurity. At **Mississippi State University** in the US, **Dr Sorina Popescu** is studying the mechanisms that underlie plants' immune systems. Her research may help to identify new ways of protecting crop species from disease.

Dr Sorina Popescu

Associate Professor, Department of Biochemistry, Molecular Biology, Entomology and Plant Pathology, Mississippi State University, USA

PROFILE

Field of research
Plant Molecular Biology and Biochemistry

Research project
Investigating how plants use redox reactions to protect themselves against pathogens

Funder
US National Science Foundation (NSF)

TALK LIKE A ...

PLANT MOLECULAR BIOLOGIST AND BIOCHEMIST

Gene promoter — a sequence of DNA that controls when and how much of a gene is expressed

Immune response — a reaction that occurs within an organism to protect it from pathogens

Pathogen — an organism that causes disease. Many viruses, bacteria and fungi are plant pathogens

Reactive species — a highly unstable molecule that can oxidise other molecules

Redox reaction — a chemical reaction that causes a change in the oxidation state of the chemical components

In recent years, global food security has become an increasingly pressing issue. Plagues of locusts in East Africa, record-breaking heatwaves in Europe and floods in Southeast Asia have decimated harvests around the world. Soaring food prices are leaving millions of people hungry.

Climate change has direct impacts on food security by causing droughts and floods. These extreme weather events wreak havoc on agriculture by damaging crops and destroying farmland. Climate change also alters the conditions in which crops are growing and increases the risk of them becoming infected by pathogens. When this happens, entire harvests can be lost, posing a serious risk to food security.

Luckily, plants have in-built defence systems that help them fight off diseases. But, as the effects of climate change get stronger and the risk of pathogenic infection increases, many plants will have to adapt to survive. At Mississippi State University, Dr Sorina Popescu is studying the immune system of plants to understand how they fight pathogens and how they might adapt to a changing environment.

How do plants fight pathogens?

"Generally speaking, there are two types of plant immune responses," explains Sorina. The most immediate response to a pathogen is a 'local response' which is triggered in the infected area of the plant. For example, if a leaf becomes infected by a pathogen, the plant will kill cells in that leaf to stop the pathogen from spreading to other areas.

The other response is 'systemic immunity', which is not just limited to the site of infection. For example, systemic acquired resistance (SAR) triggers immune responses in uninfected parts of the plant. "The plant knows that it's been attacked and prepares the healthy leaves for an immune response," says Sorina. Thanks to SAR, a plant that has been exposed to a pathogen in the past will remember how to fight it in future infections. This mechanism is very similar to how vaccines work, and it allows the plant to produce a much more robust and comprehensive immune response.

How does Sorina study systemic acquired resistance?

Sorina studies SAR by conducting experiments on watercress (*Arabidopsis thaliana*). She infects the leaves of watercress plants with a bacterial pathogen. After a few days, she infects different leaves on the same plants with a similar but slightly different pathogen and observes how the newly infected leaves respond. By measuring the concentration

© shaiith/stock.adobe.com

of bacteria in the newly infected leaves, Sorina can understand how the pathogen spreads around each plant and whether SAR has been implemented.

In more recent experiments, Sorina and her team have developed a new method that uses bioluminescence to visualise the results. This method involves combining the enzyme luciferase, which is found in fireflies and produces luminescence, with a gene promoter from watercress. So far, the team has used the GRXS13 gene promoter, and they now plan to test others. Gene promoters control when and how much of a gene is expressed and are activated by external sources such as heat, light or pathogens. "For example, a pathogen may turn on the expression of a cohort of defence genes by activating their promoters," explains Sorina. Once the promoter sequence has been combined with the luciferase, the mutant gene is transferred into watercress plants.

Sorina then repeats the initial experiment described above using the mutant watercress plants containing bioluminescent genes. This time, when the leaves are infected with the pathogen, the gene promoter is activated, and the leaves glow with strong luminescence. Interestingly, Sorina has observed that the uninfected leaves immediately begin to luminesce as well, though at a lower intensity than in the pathogen-infected leaves, showing that the promoter was also activated in these leaves. This experiment suggests that a systemic immune response has been triggered throughout the whole plant, so all leaves will now be able to fight the pathogen in a future infection, not only the leaves already exposed to the pathogen. The plant is therefore primed to better initiate a defence response during future infections. It also suggests that the gene GRXS13 plays an important role in SAR and plant immune response.

What mechanisms control systemic acquired resistance?

Both local and systemic responses rely on redox reactions and the production of reactive species.

> **“ LUCKILY, PLANTS HAVE IN-BUILT DEFENCE SYSTEMS THAT HELP THEM FIGHT OFF DISEASES. BUT, AS THE EFFECTS OF CLIMATE CHANGE GET STRONGER AND THE RISK OF PATHOGENIC INFECTION INCREASES, MANY PLANTS WILL HAVE TO ADAPT TO SURVIVE. ”**

Reactive species can promote cell death or directly harm a pathogen to provide a local response. "However, the most remarkable action of reactive species is their ability to activate redox signalling," says Sorina. This signalling is thought to play a major role in systemic immune responses like SAR.

When molecules exchange electrons, their oxidation state changes. For example, when a molecule gains electrons, its oxidation state decreases in a process known as reduction, and when a molecule loses electrons, its oxidation state increases in a process known as oxidation. The term 'redox' describes a reaction in which one molecule is reduced while another is oxidised.

When a molecule is reduced, its energy increases and it becomes unstable. These unstable molecules are called reactive species, and they are more likely to react with other molecules and oxidise them. When protein molecules are oxidised by reactive species, their structure and function can change, often irreversibly. These irreversible changes cause a lot of damage to the cells around them. It is through this mechanism that the local immune response promotes cell death and kills off pathogens.

Redox signalling is also essential in systemic immune response, but the full mechanisms are still poorly understood, which is why plant scientists are interested in reversibly oxidised proteins. In some instances, an oxidised protein will change into an activated state and then revert to its original shape when it is reduced in another redox reaction. This process is known as oxidative activation, and it may be involved in the signalling that controls SAR. As the proteins engage in redox reactions and become active, they may form part of a pathway that sends signals to other parts of the plant, warning them of infection.

Why is this work important?

Through her research, Sorina is hoping to advance our understanding of the genes that are involved in plants' immune responses. As well as GRXS13, Sorina has identified two other genes, TOP1 and TOP2, that are vital to producing efficient local and systemic immune responses. Identifying and understanding these genes is important because they control how effectively a plant can fight off diseases.

Recent evidence suggests that some pathogens can fight against a plant's immune response. They may be able to manipulate the host's redox responses and use them to their own advantage. When redox processes don't function properly, the plant becomes more susceptible to disease so is in danger of dying. Studying these redox processes and the genes that control them is, therefore, fundamental to understanding how plants respond to pathogens.

As climate change continues to increase the risk of pathogenic infection, this research will only become more important. Pathogens are already causing significant losses in many crops, including wheat, rice and coffee. As food prices continue to rise and global food security continues to plummet, any knowledge that might help protect valuable crops will be vital.

ABOUT *PLANT MOLECULAR BIOLOGY AND BIOCHEMISTRY*

Plant molecular biology is the study of the molecular structures and processes that underlie plant life. It often focuses on how the information stored in DNA is translated and manifested in the plant. For example, Sorina is interested in how the information stored in certain genes results in immune responses like systemic acquired resistance.

Biochemistry is closely tied to molecular biology and explores the chemical processes that occur in living things. For example, the redox signals that form a key part of a plant's systemic immune response are chemical reactions. Sorina requires a strong foundation in both molecular biology and biochemistry to gain a comprehensive understanding of how plants' immune systems function.

Plant molecular biology and biochemistry both play important roles in the wider field of plant science, which also encompasses aspects such as agricultural science, forestry science and seed technology. The applications of plant science cover an incredibly broad scope, but food security is at the heart of many of them. To ensure our global population has enough to eat, plant scientists are developing crops that contain more nutrients, produce larger yields and are able to grow in the increasingly uncertain climate of the future.

The joys and challenges of plant molecular biology and biochemistry

Observing individual molecules in action can give valuable insight into the mechanisms that control different cellular processes. "I enjoy probing the inner workings of cells and peeking into small windows of life's complex machinery," says Sorina. This research often involves tackling complex and elusive questions which can be challenging but can provide solutions to many real-world problems.

However, analysing molecular parts of cells in isolation can lead to misleading conclusions. Proteins work together in extensive cellular networks and are connected to countless other molecules. "In isolation, proteins may behave differently," says Sorina, highlighting the importance of considering plants as a whole organism, rather than the sum of their constituent molecules.

The questions that Sorina is trying to answer often require advanced knowledge from many different disciplines, so her lab group contains analytical chemists and computational biologists as well as plant biologists. "Teamwork is paramount," says Sorina. "One researcher or laboratory cannot successfully tackle all aspects."

Pathway from school to *plant molecular biology and biochemistry*

- "A strong background in sciences, including biology, chemistry and physics, is essential," says Sorina.
- At university, consider degrees in plant biology or molecular plant sciences. Sorina recommends taking as many courses as you can in plant biochemistry, molecular biology and metabolism.
- Degrees in agricultural science and biotechnology will be useful for pursuing careers in the agriculture industry.
- Mississippi State University offers a wide range of degrees in the Department of Biochemistry, Molecular Biology, Entomology and Plant Pathology. Explore the courses on offer to learn about the different things that plant scientists can get involved in: **www.biochemistry.msstate.edu**
- Attend a plant science summer school to learn some practical skills before you go to college or university, for example: **www.saps.org.uk/growth-hub/saps-plant-science-summer-school**

  www.gatsby.org.uk/plant-science/programmes/gatsby-plant-science-summer-school

Explore careers in *plant molecular biology and biochemistry*

- As a plant molecular biologist or biochemist, you could find yourself working in a research laboratory investigating how plants function at a cellular level or helping to develop new breeds of plants that will increase global food security.
- As climate change threatens current crop species, demand for plant biologists is predicted to grow by 9% between 2020 and 2030. Many new jobs will open in the industry sector.
- The American Society of Plant Biology (**www.aspb.org/education-outreach**) and the European Plant Science Organisation (**www.epsoweb.org**) are great places to learn about plant science research and to find related educational resources.

Q&A

Meet Sorina

What inspired you to become a plant scientist?

I always loved plants, so it was a natural career path to follow. As a kid, I kept a herbarium and I remember having fun memorising the scientific names of the plants around me. I always enjoyed figuring stuff out, so science is a lot of fun for me. Imagine coming to work and doing something new every day!

What journey has led you to your current position?

I was born and did most of my schooling in Romania. I graduated from the University of Bucharest with a master's in microbiology, then moved to the US where I earnt a PhD in molecular plant sciences at Rutgers State University of New Jersey. I specialised in high-throughput molecular biology during my postdoctoral work at Yale University. I achieved all this while raising two children, which taught me how to prioritise tasks and to remain focused in the lab. These skills helped me tremendously with managing a group of junior researchers in my first job as a principal investigator with the Boyce Thompson Institute for Plant Research in New York.

What have been the highlights of your career, so far?

Since my ground-breaking postdoctoral work on developing protein microarrays for a plant model system, research in my lab has advanced knowledge on signalling networks, molecular host-pathogen communication and systems-level analysis of immunity. My team has published the results of our research in numerous peer-reviewed publications about plant science, biochemistry and proteomics.

What are your ambitions for the future?

I am interested in exploring translational aspects of plant immunity and finding ways to impact crops' health. A new project in my lab is surveying root microbiomes in healthy and diseased plants. We are searching for bacteria that can inhibit pathogen growth and prevent disease development in crops. In these projects, I collaborate with Romanian scientists and professors who are former university colleagues of mine. It feels good to be connected and contribute to Romanian science.

Mentorship has always been and will continue to be a priority for me. Women scientists still face many external and internal barriers to developing their early careers and maintaining a network of productive collaborations. I had little constructive mentorship during my formative years as a scientist, which is why I consider it essential. Many former female students from my lab are now leading researchers in academia and industry.

> “MANY FORMER FEMALE STUDENTS FROM MY LAB ARE NOW LEADING RESEARCHERS IN ACADEMIA AND INDUSTRY.”

What do you enjoy doing outside of work?

Nature photography. My husband and I like to hike and travel – I always have my camera ready to capture life and nature.

What is your favourite fact about plants?

Plants are excellent communicators, and they speak biochemistry! For instance, a plant's methyl salicylate (MeSA) levels are often increased in response to infection by pathogens. Volatile MeSAs can spread through the air, warning neighbouring plants of the danger.

© Tomas Vynikal/ stock.adobe.com

Sorina's *top tips*

1. Work on topics that excite you – work can be a lot of fun when you enjoy what you're doing.
2. Work on important problems – don't be afraid to ask big questions and chase answers.
3. Learn to talk about your work so that everybody understands what you're doing.
4. For the young women striving to become scientists – find a mentor and learn by example how to navigate a scientific career.

A STAR IS BORN: USING NEXT GENERATION TELESCOPES TO EXPLORE STAR FORMATION

Without the Sun, life on Earth would likely never have formed. But how did the Sun, and the other 100 billion stars in our galaxy, come to be? The process behind the formation of stars is an intricate dance that is influenced by complex forces and interactions. Using a new generation of state-of-the-art telescopes, **Professor Snežana Stanimirović**, from the **University of Wisconsin-Madison** in the US, is hoping to unravel the mysteries of this cosmological choreography.

Professor Snežana Stanimirović

Department of Astronomy,
University of Wisconsin-Madison, USA

Field of research
Astrophysics

Research project
Using state-of-the-art telescopes to investigate how clouds of interstellar gas form and become stars

Funders
US National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), University of Wisconsin-Madison

PROFILE

TALK LIKE AN ...

ASTROPHYSICIST

Exoplanet — a planet outside our Solar System

Interstellar cloud — an accumulation of gas, dust and plasma that may go on to form a star

Phased array feed — a large group of receivers on a dish antenna that allow for a larger area of the sky to be imaged

Red giant — a star that has expanded to a tremendous diameter during the final stages of its lifetime

Solar mass — the mass of the Sun, often used as a unit of measurement in astrophysics

Stellar feedback — energy, momentum and turbulence emitted by stars that interferes with the process of star formation

Synthesis array — a collection of antennae, often spread out over a large area, that work together to form a powerful telescope

White dwarf — the extremely dense remnant core of a dead star

In the middle of winter, when rain is pouring down and a fierce gust of wind turns your umbrella inside out, it can be easy to forget that the Sun exists! But, even when you are soaked through and chilled to the bone, you should be grateful that we have our very own ball of hot plasma watching over us. Without the Sun, life on Earth would not exist.

Our sun is one of roughly 100 billion stars in the Milky Way. In about 5 billion years, it will expand into a red giant, swallowing the Earth along with all the life that it helped create, before eventually shrinking into a white dwarf and fizzling out, roughly 8 billion years from now.

That is how it all ends, but how did it begin? The Sun formed around 4.5 billion years ago when a giant cloud of gas and dust collapsed in on itself under the force of its own gravity. This is the process by which all stars form, but there is still a lot that we do not know about it. Professor Snežana Stanimirović from the University of Wisconsin-Madison has been working with two surveys, GASKAP and LGLBS, to try and shed some light on the processes of star formation.

What is the GASKAP survey?

The Galactic Australian Square Kilometre Array Pathfinder survey (GASKAP) makes use of a giant synthesis array in Australia. A synthesis array is a collection of radio antennae that work together to act as one huge telescope. The ASKAP telescope is made up of 36 antennae spread out over 6km^2. Each antenna is equipped with a phased array feed (PAF) made up of 188 receiver elements that detect radio waves that have been emitted from astronomical sources like stars or galaxies.

The PAF technology is brand-new in radio astronomy and provides a significant upgrade on traditional radio telescopes, which have only a few receivers, at most. As a result, the ASKAP telescope can capture images of a much higher quality. ASKAP can image large swathes of the night sky faster and in more detail than traditional radio telescopes. This is a huge step forwards as, traditionally, researchers would have to choose between high resolution

© ardanz/stock.adobe.com

images or a large field of view; now they can do both.

What is the GASKAP survey looking for?

"GASKAP is providing a super high-resolution view of how interstellar clouds form and evolve, maturing to the point of making stars," says Snežana. The incredibly detailed images that GASKAP produces will allow her to study many important physical processes for the first time. These processes are involved in the formation of stars and have a big impact on how galaxies evolve and change.

For the last four years, the GASKAP survey has been working on pilot studies. These are trials that allow researchers to test out their observation and data processing strategies. So far, researchers have surveyed two of our closest galactic neighbours, the Small and Large Magellanic Clouds. These two galaxies are both part of the same galactic cluster as the Milky Way, which means they are close enough for ASKAP to view them in great detail.

As the pilot studies draw to a close, Snežana and her colleagues are preparing to start surveying much larger areas of the sky. They plan to map a large area of the Milky Way, as well as something known as the Magellanic Stream. This is a long tail of gas extending from the Magellanic Cloud galaxies that has been formed by interactions between them and the Milky Way. These interactions are likely to have a big effect on how the galaxies evolve.

What is LGLBS?

The Local Group L-Band Survey (LGLBS) is using a telescope known as the Karl G. Jansky Very Large Array (VLA). This telescope is in New Mexico, in the US, and uses a similar method to ASKAP to create the sharpest possible images. Like ASKAP, this survey is observing galaxies within our local cluster. LGLBS is taking observations of the Andromeda and Triangulum galaxies, as well as four dwarf galaxies also within the cluster. Besides the Magellanic Clouds, these are the only star-forming galaxies that current radio telescopes can observe in high-resolution.

What is LGLBS looking for?

The images produced by LGLBS will allow Snežana to study the distribution of atomic hydrogen within these galaxies. "Atomic hydrogen is important because it represents the very first seed for making molecular clouds," explains Snežana. By observing clouds of cold atomic hydrogen, Snežana will be able to glimpse the conditions that eventually lead to the formation of new stars.

Snežana hopes that by studying the distribution of atomic hydrogen in these galaxies, she will also be able to shed light on one of astrophysics' most pressing questions. The Milky Way contains about a billion solar masses worth of gas that could go on to form stars – an amount of gas that is a billion times more massive than the Sun. Even so, only one solar mass of stars is formed each year. Why is this process so inefficient?

One of the main barriers to star formation is something known as stellar feedback. This is turbulence generated by the activity of stars that prevents clouds of gas collapsing under their own gravity and forming new stars. Stellar feedback can be caused by fast-flowing streams of particles that are emitted by stars, known as stellar wind, or by stars exploding into supernovae. "The basic idea is that by kicking the gas around, turbulence makes it harder for gravity to cause clouds to collapse and form stars," says Snežana.

LGLBS will also study radio wave emissions from these galaxies and observe how interstellar gas moves around and interacts with its surroundings. This is a massive project that will likely require over 2000 hours of observations and produce an immense amount of data.

How will the data be handled?

Both the GASKAP and LGLBS surveys involve marathon amounts of observation time and will produce about a million gigabytes of data. These data sets will allow Snežana and her team to investigate scientific questions from a diverse range of disciplines. "To handle the observations, data processing and the highly diverse areas of science, large international teams with a broad range of technical and scientific expertise are needed," explains Snežana. Large supercomputers will be required to process all these data and whole teams of scientists will be needed to manage these systems.

> **"BOTH THE GASKAP AND LGLBS SURVEYS INVOLVE MARATHON AMOUNTS OF OBSERVATION TIME AND WILL PRODUCE ABOUT A MILLION GIGABYTES OF DATA."**

What are the overall aims of these projects?

Snežana hopes to uncover the mysteries of the star formation process. There are three main questions that she hopes to provide answers to: how is atomic gas distributed within galaxies, and how does this change in different galaxies? What drives interstellar turbulence, and how does this affect the distribution of gas within galaxies? And how do star-forming clouds of gas accumulate from this interstellar atomic gas?

Both GASKAP and LGLBS are producing images that will help Snežana answer these questions. "The survey is still collecting observations and processing the data we have so far," she says. "This requires a lot of work and the use of very powerful supercomputers." Snežana and her fellow researchers are starting to get some early results, and there is a lot of fascinating work still to come.

© Joe/stock.adobe.com

ABOUT *ASTROPHYSICS*

Astrophysics is the branch of science that seeks to understand the nature of the Universe and the things in it by applying the methods and principles of physics and chemistry. Fields of research in astrophysics include the lifecycle of stars, the formation of planets and the evolution of galaxies. By exploring these topics, astrophysicists can help us understand our place in the Universe.

What research opportunities will be open to the next generation of astrophysicists?

With the recent launch of NASA's James Webb Space Telescope and the development of other next-generation telescopes, the field of astrophysics finds itself at an exciting moment. Future astrophysicists will have the chance to work on some ground-breaking projects. Studying the formation of exoplanets, observing the oldest galaxies in the Universe and exploring new fields such as dark matter, dark energy and gravitational waves are all research opportunities that may be available to new astrophysicists.

What makes a successful astrophysicist?

Success in this field is not determined solely by your understanding of maths and physics. Good scientists are able to communicate well, collaborate with others and ask for help when they need it. Being curious and asking questions is crucial to making new discoveries. Snežana also emphasises that keeping active outside of your career is important. "Especially during more stressful career stages, exercising, walking or enjoying a hobby really helps to get a fresh perspective and relax," she says.

WITH THE RECENT LAUNCH OF NASA'S JAMES WEBB SPACE TELESCOPE AND THE DEVELOPMENT OF OTHER NEXT-GENERATION TELESCOPES, THE FIELD OF ASTROPHYSICS FINDS ITSELF AT AN EXCITING MOMENT.

Pathway from school to *astrophysics*

- Focus on mathematics, physics, chemistry, astronomy and computer science. Remember the importance of writing skills. Being a good scientist involves communicating your research through papers, talks and lectures.
- Astrophysics courses at university usually start with lots of mathematics and physics before specialising into more advanced physics and astrophysics.
- Taking courses in computer science and statistics can also be very useful, as astrophysics involves processing large amounts of data.

Explore careers in *astrophysics*

- The American Astronomy Society (**www.aas.org careers/aas-career-center**) and the British Royal Astronomical Society (**www.ras.ac.uk/education-and-careers/careers**) both have careers pages with lots of useful information.
- NASA runs an internship programme which has many short-term projects that you can get involved in: **intern.nasa.gov**
- Local planetariums or astronomy clubs are a great way to meet like-minded people who share your interests. For example, the Alder Planetarium (**www.adlerplanetarium.org**), in Chicago in the US, and the Planetarium at We The Curious (**www.wethecurious.org/category/stargazing-and-night-sky**), in Bristol in the UK, host many talks and shows.
- There are many citizen science projects that you can get involved with. You can even help NASA discover new planets and galaxies: **www.nasa.gov/kepler/education/citizen**

Q&A

Meet Snežana

Who or what inspired you to become a scientist?

My interest in astronomy started during high school. In particular, books like *"Cosmos"* by Carl Sagan and *"A Brief History of Time"* by Stephen Hawking left a strong impression on me. Participating in small research projects was also important for me. I was able to go to a research centre called Petnica (www.petnica.rs), where they offered workshops, talks and research projects for high school students. I enjoyed participating in hands-on astronomy activities there, and this secured my passion for astronomy and encouraged me to study it for my undergraduate degree.

Your career path has seen you travelling the world. What have been the challenges and rewards of this?

Travelling around the world and living in several different countries has broadened my horizons and allowed me to meet wonderful people from different cultures. It also enabled me to use world-class telescopes and learn from exceptional scientists. The key challenge has always been living far away from my family and not being able to be there when something important happens. I have a young son, and being far away from family makes it harder for him to interact with his grandparents as frequently as he wants.

What would students be surprised to learn about your life as an astrophysicist?

Probably one surprising thing is that I am making a comic strip for kids! This started about 10 years ago as an outreach project with the goal of encouraging middle school students to pursue STEM careers. My collaborators and I thought that one way we could contribute is by telling stories about the daily life of scientists and featuring innovators and scientists in a realistic and positive way. While I provide science ideas and explanations, I work with a wonderful team that includes an artist/illustrator and several educators – it's a super fun and enjoyable experience! The comic is called "Galaxy Scouts: Space-ventures with Stella and Riley", and the project web site is: www.astro.wisc.edu/astro-comic

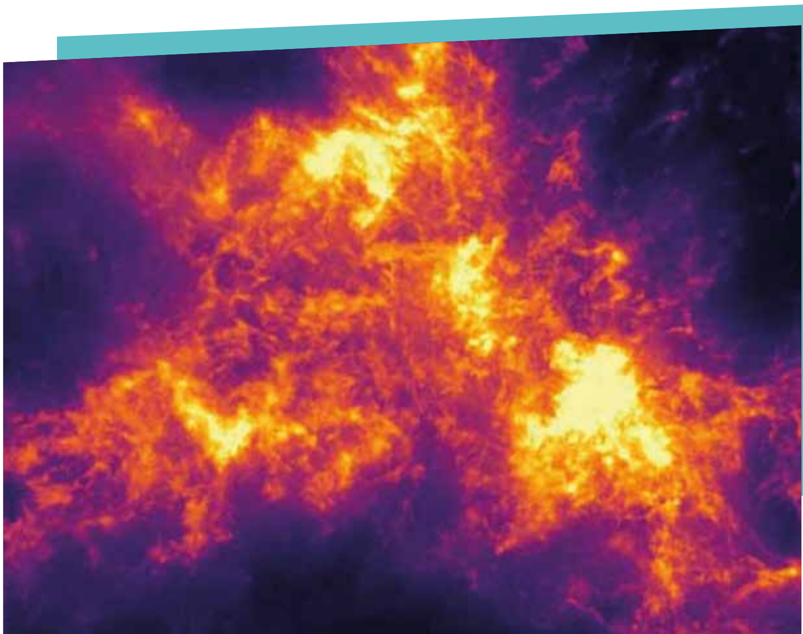
What are your proudest career achievements, so far?

I have received several really cool awards and fellowships, e.g., the Guggenheim fellowship, the American Association for the Advancement of Science fellowship and the National Science Foundation CAREER award. But I think one of the most important recognitions for me has been to be asked to write an article for the Annual Review of Astronomy and Astrophysics (ARAA). These articles are the most prestigious as you are asked to summarise an entire sub-field of astrophysics. In fact, I've just finished another ARAA article where I am a co-author, and this is also an exceptional honour.

> **"PROBABLY ONE SURPRISING THING IS THAT I AM MAKING A COMIC STRIP FOR KIDS!"**

What are your ambitions for the future?

I want to learn how to use the James Webb Space Telescope and study the influence that low-mass stars have on the surrounding interstellar medium. While the effect of massive stars – with their violent winds and high energy – is often apparent, less is known about the influence of the more numerous low-mass stars. As they form, these smaller stars create narrow, opposing jets which can inject a lot of momentum and energy into the clouds.



Snežana's *top tips*

1. Don't be afraid to ask for help or advice.
2. Be curious and passionate about what you do, and remember to ask questions about what you are studying.
3. Get involved with research through local outreach centres, by applying for NASA internships, or by participating in various citizen science projects.

Photo caption: A radio-telescope image of the Small Magellanic Cloud obtained by GASKAP. The image shows distribution of atomic hydrogen (H) in this galaxy, with brighter colours corresponding to a larger number of H atoms. © Nickolas Pingel et al. (2022).

BLACK HOLES: THE MEETING OF GRAVITY AND QUANTUM PHYSICS

We know that black holes exist through a mix of complex mathematics and astrophysics but linking mathematical ideas to what we can observe in the Universe is no easy task. **Dr Daniel Terno** and his team at **Macquarie University** in Sydney, Australia, are building a framework of characteristics that can be used to search for black holes in the Universe, but their findings may challenge our understanding of the fundamental laws of physics.

Associate Professor Daniel Terno

The Centre for Astronomy, Astrophysics and Astrophotonics; The Centre for The Macquarie Centre for Quantum Engineering (MQCQE), School of Mathematical & Physical Sciences, Faculty of Science & Engineering, Macquarie University, Sydney, Australia

Field of research
Quantum Physics

Research project
Using quantum theory to understand the gravitational traits of black hole physics, and how this can help us link up mathematical theory and physical proof

Funders
Australian Research Council (grant ARC Discovery project DP210101279), Asian Office of Aerospace Research and Development, US Air Force (grant FA23862014016)

TALK LIKE A ...

BLACK HOLE PHYSICIST

Apparent horizon — the last surface from which the light that is aimed outwards still bends backwards

Event horizon — the boundary of the region from which nothing can ever escape

General relativity — a theory of gravitation which describes gravity as geometry and relates its curvature to masses and their motion

Mathematical black hole (MBH) — the definition of a black hole provided by mathematical relativity – the region of space where everything that is hidden by the event horizon

Astrophysical black hole (ABH) — ultra dense, very massive dark objects observed by astrophysicists

Physical black hole (PBH) — a region of space from which nothing can escape now (regardless of what will happen in the future)

Quantum mechanics — a theory in physics that describes the properties of atoms and subatomic particles

Quantum physics — the study of matter and energy at the most fundamental level, where matter behaves both like particles and waves

Singularity — the point at which space and time become meaningless and tidal forces may become infinite

Ultra-compact object (UCO) — an object with sufficient density and mass to cause light to circle around it

A scientist's definition of a black hole depends on their discipline. While there are elegant mathematics pointing towards certain conditions, these properties cannot be physically observed. This means that astrophysicists have to use a different set of conditions to understand what they observe and calculate – but quantum physicist Associate Professor Daniel Terno, based at Macquarie University, is not convinced they are looking at the same thing, or if mathematically defined black holes even exist at all.

Daniel and his team are studying ultra-compact objects (UCOs), which include black holes. Specifically, they are exploring what properties UCOs would need to have to be defined as black holes, and how this can be solved with quantum mechanics. Their findings will help link observable properties of physical black holes (PBHs) to different competing mathematical descriptions. Finding which one is correct may require rethinking our assumptions about the basic laws of physics.

History of black hole research

In the early 20th century, Einstein came up with one of the most important scientific theories in existence: general relativity. This theory gives an understanding of how gravity can warp time and space. A few years later, physicist Karl Schwarzschild

© elen31/stock.adobe.com

provided solutions to the equations of general relativity, but only by including some unusual by-products. When not dismissed outright, they hinted at ultra-dense spots throughout the Universe that did not obey normal physical laws. "Work by many people over the following decades found that these solutions did actually make sense and may describe something important," says Daniel.

It was these mathematical equations that first suggested that black holes exist, but it was in the 1970s that the first physical evidence for their existence became apparent, based on studying gravitational waves. However, linking this physical evidence with the existing physical theories led to the emergence of paradoxes that scientists struggle to solve.

Differing definitions

"A mathematical black hole (MBH) is a solution to the Einstein equation of general relativity that includes two important features: an event horizon and a singularity," says Daniel. An event horizon is the threshold between the inside and the outside of the black hole – the point at which gravity is so strong, even light cannot escape. Related to this is the singularity, which is a condition where gravity is so intense that spacetime itself breaks down and becomes infinite, so any definitions related to time and space become irrelevant.

Finding evidence for event horizons is incredibly challenging. "There is no way that a mortal observer can detect the event horizon," says Daniel. "We may even live inside one." However, we can possibly detect the side-effects of an event horizon, related to the trapping of light. According to mathematics, when light travels close to a black hole, there will be a certain point where light on one side will keep on moving outwards, whereas light on the other side will be trapped and non-observable. This boundary is called the apparent horizon and is what defines a physical black hole (PBH) – one that is observable. "According to classical physics, the apparent horizon sits within the event horizon, so a PBH sits inside an MBH," says Daniel. "However, while we can observe a PBH, we cannot say for certain whether it has an event horizon and singularity." Because these traits of MBHs are non-observable, our only 'proof' of their existence comes from mathematical equations that are not guaranteed to be correct.

> **"I HAVE LEARNED THAT THE MOST IMPORTANT TOOL OF A THEORIST IS A WASTEBASKET. MOST CALCULATIONS END UP DISCARDED. BUT, AFTER A LOT OF PANNING, OCCASIONALLY YOU GET A FEW SPECKS OF GOLD."**

Ultra-compact objects

"An ultra-compact object (UCO) is any object with a high enough density to bend light to such a degree that it circles around the object," says Daniel. "Black holes are a type of UCO." Daniel's team has been studying UCOs to pinpoint the set of conditions that make PBHs different from MBHs. Most importantly, their research suggests that black holes need 'exotic' material – a term used to describe types of quantum matter that are not fully understood – to form.

"After the work of Steven Hawking, we know that quantum mechanics allows the apparent horizon to be outside the event horizon," says Daniel. "Given our research suggests black holes need quantum consideration, this hints that the MBH model is limited and that PBHs may not have event horizons at all." This has big implications for our understanding of black holes and the laws of the Universe. The introduction of quantum physics requires a whole new set of rules which are not currently accounted for in mathematical proofs.

Maths and methods

"An important aspect of this project is clarifying the logical structure, and being cautious about the assumptions that are involved," says Daniel. "We start from basic premises – for instance, the minimal definitions of black holes, without worrying about event horizons and singularities – and then think about how we can identify these conditions in the Universe."

The project work involves many meetings, reading up on new research and techniques, and constantly looking out for assumptions to challenge. "Very often, when the results don't add up, we realise something was overlooked, often due to almost imperceptible beliefs that things work in a certain way even if they don't," says Daniel. "I have learned that the most important tool of a theorist is a wastebasket. Most calculations end up discarded. But, after a lot of panning, occasionally you get a few specks of gold."

Daniel's team has made significant headway, so far. "We understand how the spacetime near the apparent horizon of a freshly-formed, perfectly spherical PBH should behave," he says. "One surprising result is that a PBH can only lose mass, and not gain it. Another result is that the formation of wormholes, connecting distant regions of the Universe, becomes virtually impossible."

Next, Daniel's team wants to calculate how PBHs produce gravitational waves and understand the characteristics of these waves. The researchers also aim to dig deeper into the quantum mechanics required for properly understanding black holes, and how this affects how matter behaves.

ABOUT *QUANTUM PHYSICS*

© elen31/stock.adobe.com

Quantum physics is a complex but increasingly relevant field of science. Daniel explains more about its importance and what makes it so rewarding.

"As far as we know, the most basic rules of physics are quantum. Gravity is what shapes our world and our Universe. Deep down, everything is quantum. My research allows me to see how these fundamental laws affect us but also how apparently tiny quantum effects can be harnessed by technology. Everything under the quantum umbrella is amazing in its own way and lets me get a little closer to appreciating how the Universe works.

Over the last few decades, the 'weird' side of quantum mechanics has moved from theory and thought experiments to a tool of new technology. This second quantum revolution has already impacted communications and remote sensing and is likely to affect computing – perhaps helping us solve hard problems and, more immediately, helping us design and simulate new materials. There is rising investment in quantum mechanics and its importance in technology will only increase, alongside rising demand for scientists and engineers who can understand and utilise it.

Almost nothing can be calculated exactly, even in pure science, so numerical simulations are essential. While claims of quantum theory's 'weirdness' may be overblown, our normal everyday intuitions are not very helpful. Mathematics and clear thought processes can help you acquire new intuitions for understanding the field."

"AS FAR AS WE KNOW, THE MOST BASIC RULES OF PHYSICS ARE QUANTUM. GRAVITY IS WHAT SHAPES OUR WORLD AND OUR UNIVERSE. DEEP DOWN, EVERYTHING IS QUANTUM."

Explore careers in *physics*

- Universities often offer relevant outreach activities. For instance, the Santos Science Experience operates across many Australian universities and research institutions, including Macquarie University, providing fascinating science activities for Year 9 and 10 students: **www.scienceexperience.com.au/about-the-program**
- Macquarie University holds an annual Astronomy Open Night, including physics magic shows, planetarium experiences and robotics demonstrations: **www.mq.edu.au/faculty-of-science-and-engineering/departments-and-schools/school-of-mathematical-and-physical-sciences/news-and-events/events/astronomy-open-night-2021**
- The Sydney Quantum Academy aims to "build Australia's quantum economy" and runs outreach programmes and internships for undergraduates: **www.sydneyquantum.org**

Pathway from school to *physics*

Daniel says that mathematics is a "non-negotiable" component of any STEM career. He also recommends learning coding and data handling as crucial skills.

For school subjects, Daniel suggests physics and astronomy as the most immediately applicable, followed by chemistry and biology. He emphasises all are interlinked and believes an understanding of different STEM fields can help draw connections and fuel inspiration.

Be prepared for your education pathway to be ongoing. As Daniel says, "Learning never stops!"

How did Daniel become *a quantum physicist?*

My dad was a car mechanic who became a telecom engineer, and my mum was a physicist and, later, computer programmer in the USSR. My dad taught me about codes and transistors, and my mum about black holes and the Big Bang. My mother gave me my first lesson in coding and helped with my first numerical calculations for science projects.

As a youngster, I loved reading and history. I was good with maths, surprisingly ok with chemistry, and very clumsy at actually building stuff! It looked like becoming a theoretical physicist was quite inevitable.

As an undergraduate, I worked on a project with my future supervisor, Asher Peres, on one classical chaotic system. It was a lot of fun and even led to my first scientific publication. After a period in the army, I joined Asher in the emerging field of quantum information. As I learned more, I realised that I like relativistic physics, and pushed my PhD research towards the relativistic side of quantum information theory. Since then, some combination of relativity and quantum mechanics has been a constant theme in my research.

I have had two strange eureka moments – both related to sports accidents. Failing to bench press a weight led to a moment of clarity on relativistic quantum information, while missing a head kick in Thai boxing sparring helped me understand black hole collapse!

My career highlights cover steps forward in understanding quantum physics. They range from helping develop relativistic quantum information, to designing pioneering experiments using quantum technology, to my current project understanding how to derive the existence of black holes.

Understanding what observed ultra-compact objects really are is my main focus for the next few years. In general, I also want to learn more areas of physics. This is an over-ambitious goal, but I want to work more on complex systems and to understand their behaviour. This covers about one third of modern physics, so I'm definitely not going to be bored for the next few years – or at least until artificial intelligence takes over!

Daniel's *top tips*

1. Ask yourself what you want and why you want it. Then, think about what you would be ready to risk and willing to sacrifice to succeed.

2. Try to get a taste of more challenging science and experience in research as early as possible. Keep in mind that you will fail many times, and it will be painful, but this is an experience common to even the most accomplished physicists.

Meet Pravin

Pravin Dahal works closely with Daniel, using quantum physics to understand black holes.

Growing up, my parents wanted me to be a doctor or an engineer. In later years of school, I grew interested in pure science, especially physics and mathematics.

For me, the purpose of life is to pursue the path of truth and understand the Universe. During my education, I realised that being a physics researcher would assist in achieving this purpose.

The path to working with Daniel was somewhat accidental, although the aim was not. After finishing my master's degree in physics in Nepal, I was unsuccessful in securing a PhD position in the USA. I then applied to Australia and got an offer there. As Australia is not a familiar destination for Nepalese PhD candidates, getting a PhD position was difficult and getting scholarships was even more challenging. I genuinely believe that I got lucky!

Our research into the nature of massive compact objects in our Universe involves a combination of study, calculation and critical thinking. Thought influences calculation, while calculation influences thought, and this process continues until one obtains a consistent result. Communication with the group and taking feedback from them is an essential part of scientific research practice.

I am also working independently to see if black holes could be alternatively characterised, which could assist in uncovering their new features. In simple terms, I am just adding yet another definition of the black hole boundary to the long list of definitions, in the hope that we can understand it more.

Talking physics outdoors

Pravin's *top tip*

Your passion, limitations and some luck lead you to a career path. Spend most of your time developing whatever skills you find interesting and useful, whether academic or not. The skills you acquire will become the purpose of your life in the future.

ANIMALS IN PAIN: WHO FEELS WHAT?

At **The University of Queensland** in Australia, **Professor Deborah Brown** and **Professor Brian Key** have created a unique team of philosophers and neuroscientists to investigate which animals have the capacity to feel pain.

Professor Deborah Brown

School of Historical and Philosophical Inquiry,
The University of Queensland, Australia

Field of research
Philosophy

Professor Brian Key

School of Biomedical Sciences,
The University of Queensland, Australia

Field of research
Neurobiology

Joint research project
Investigating which animals have the capacity to feel pain

Funder
Australian Research Council (ARC)

The University Of Queensland Australia

TALK LIKE A ... NEUROPHILOSOPHER

Analogous structures — examples of convergent evolution. For example, butterfly wings and bird wings are analogous structures

Cerebral cortex — the outer layer of the brain, responsible for language, memory and decision-making (among other processes)

Convergent evolution — where two distinct species have evolved a similar physiological structure from different ancestors

Epistemology — the area of philosophy which examines the foundations for knowledge and justification

Homologous structures — similar structures that have evolved from a common ancestor. For example, the whale flipper and the bat wing have skeletal similarities which are evidence that their common ancestor had a forelimb complete with humerus, radius and metacarpals

Necessary condition (for X) — a condition which must be fulfilled in order that X can occur. For instance, it is a necessary condition for sodium that each atom in a sample has eleven protons. In contrast, it is not a necessary condition for sodium that each atom in a sample has eleven electrons (ions of sodium in a solution have ten electrons)

Neurophilosophy — the interdisciplinary study of neuroscience (the study of the brain and nervous system) and philosophy (the study of knowledge, reason and how humans understand their existence in the world)

Nociception — the process by which damaging (noxious) stimuli are communicated in the nervous system. This involves the transmission of information about damaging chemical, mechanical and thermal stimuli from the peripheral nervous system to the brain

Pain — the brain's awareness of nociception that is experienced as an unpleasant feeling

Quadruped — an animal that walks on four feet

Sentience — the ability to experience feelings and sensations

Animals have evolved a remarkable range of species-specific behaviours. For example, birds can use their forelimbs to fly in the air, while quadrupeds use them to run across the ground. One of the most challenging problems in biology is understanding what motivates animals to perform such behaviours. Is it because, like humans, they have sensory experiences of pleasure and pain? Do they fly away or run from environmental stimuli due to pain, and do they seek the warmth of sun because of pleasure?

How can we know what other animals experience? How can we even know whether other animals experience anything at all? Questions like these sit at the intersection of science and philosophy, and Professors Deborah Brown and Brian Key, Dr Oressia Zalucki (postdoctoral fellow) and Jacob Taylor (PhD student) from The University of Queensland are addressing them using a mix of scientific and philosophical methods. The answers to these questions are extremely important practically and theoretically. For example, whether an animal feels pain informs the way we treat that animal in agriculture and research settings. It has implications for the food security of many, particularly developing, nations, and it informs our general

understanding of one of the great mysteries of the Universe: consciousness.

What is the philosophical problem of other minds?

A long-standing problem in epistemology is the 'problem of other minds'. Its most basic form is captured in the question 'How do you know that there are any minds other than your own?' You will only ever have direct, conscious access to your own mind, so how do you know that the people around you (who you think have minds) are not just sophisticated zombies or robots? Even if you are sure other people exist and have minds, you might still wonder if their experiences are like your own. This leads to other questions such as 'How do you know that someone else's experience of green and red is the same as yours?' After all, you never see how green and red things look to anyone else. You describe grass as 'green' and strawberries as 'red', but these are labels attached to private experiences which you can never compare against the experiences of anyone else. The sky that looks blue to you might look like the colour of a ripe banana to others. This is known as the 'inverted spectrum' thought experiment, and it is one example of a general problem that arises because experiences are private to those who have them.

How does biological structure determine function?

It is a simple truth that without specialised light-detecting cells called photoreceptors, you cannot see. Humans with certain eye conditions gradually go blind as the photoreceptor cells within their eyes die, so we can say that photoreceptor cells are a necessary condition for normal vision. Neurobiologists know a great deal about the way the visual system works and can explain necessary conditions for vision. For example, people who are colour blind are missing certain proteins in their photoreceptor cells; these cells can no longer react to the full spectrum of colour normally experienced. The structure of the visual system – beginning with proteins in the photoreceptor cells – determines the functions the visual system can perform.

What does this have to do with animal pain?

Like colour blindness in the visual system, there are disorders in the pain system which can tell us about the necessary conditions for pain. For example, people with a disorder called congenital insensitivity to pain are born without the ability to feel pain. Although this might sound like a beneficial condition, it is actually very dangerous. For example, a sufferer could drink a hot beverage and scald their mouth without being aware of it. The nerve cells that would normally respond to damaging injuries are dysfunctional due to the altered structure of a protein necessary for sensing in these cells. The structure of the nervous system is important for explaining sensory function.

And what about convergent evolution?

Convergent evolution may result in analogous structures – that is, distinct species may evolve similar biological structures. The challenge here is to analyse the structures at an appropriate level of description. While it is true that butterfly wings and bird wings evolved independently of one another, both must obey the principles of aerodynamics for the animal to fly. The structure of the wing still determines the function of the wing, so whether the structure is homologous or analogous, it is the sameness of structure that explains the sameness of function.

What is the difference between nociception and pain?

Another complicating factor in the question "Which animals feel pain?" is the distinction between nociception and pain. Nociception is the non-conscious signalling in the nervous system that takes place following a noxious (tissue damaging) stimulus. There is no feeling of pain with nociception. A common example is a simple reflex where you quickly withdraw your hand from a hot surface before any feeling of pain. There is a noticeable lag between the quick nociceptive responses (which are mediated by short spinal pathways) and pain (which involves the longer pathways that traverse from the spinal cord to the brain). For an animal to experience pain, it needs the nociceptive structures as well as homologous or analogous brain structures that process nociception into pain.

Which animals feel pain?

Answering this question requires the neurophilosopher to answer the question "What is the right level of description of structures which determine the functions responsible for pain?" Is it enough to say that an animal has a nervous system, or a central brain, or do we have to be more specific? This involves juggling several complicated sub-questions such as "Which are the neural structures responsible for pain in humans?" and "What are the presumed analogical structures in animals?" It also requires thinking about the philosophical assumptions we make when we try to answer such questions. For example, is the meaning of 'pain' tethered to a certain kind of structure or, as many philosophers and scientists think, could it be attached to very different kinds of structures?

What conclusions has the team reached, so far?

In their project, Deborah, Brian and their team argue that a nervous system must be capable of performing a certain kind of neural computation – which they refer to as the parallel forward models algorithm – by means of which the organism is aware of their brain's nociceptive processing and without which an organism is not able to feel pain. In arguing this, the team has had to defend not just the science behind the model but also philosophical theories, including the idea that sometimes an absence of evidence for the existence of something is evidence of its absence. Deborah and Brian have also had to defend the idea that nociception and pain are distinct kinds of phenomena and that evidence for the first is not sufficient evidence for the second. While evidence suggests that mammals meet the structural requirement to support their brains' awareness of nociceptive processing, no analogous structure has been shown to exist in fish, molluscs or insects.

What are the next steps?

The team is embarking on an ambitious project that involves investigating sentience in different species, the evolution of that sentience and the ethical implications of their research. Whether or not an animal species can experience pain has welfare implications for how it should be treated, and the team's work will help to establish a better understanding of the interplay between scientific and ethical reasoning.

ABOUT *NEUROPHILOSOPHY*

Difficult problems in science can be approached in a new light when subjected to philosophical questioning and analysis. For example, physicist and philosopher Ernst Mach's questioning of Isaac Newton's philosophical assumption that space existed independently of the objects occupying it (Newton's assumption was that space was 'absolute'—i.e., not dependent on or relative to objects) influenced Einstein's thinking while he was formulating the General Theory of Relativity. Likewise, difficult problems in philosophy can be approached best using the knowledge scientists already have, and scientists benefit from the kinds of critical questions raised by philosophers.

The secrets of the brain are yet to be unravelled. This is an area of research which thrives on collaboration between neuroscientists, biologists, linguists, philosophers, computer scientists and psychologists. Consciousness is one of the great mysteries of the Universe, and to gain a better understanding of it, the field of neurophilosphy needs bright, ambitious minds!

"CONSCIOUSNESS IS ONE OF THE GREAT MYSTERIES OF THE UNIVERSE, AND TO GAIN A BETTER UNDERSTANDING OF IT, THE FIELD OF NEUROPHILOSPHY NEEDS BRIGHT, AMBITIOUS MINDS!"

© altitudevisual/ stock.adobe.com

How did Deb become *a philosopher?*

"*Philosophy* was not a word that was ever passed around our working-class dinner table in Brisbane, Australia, in the 1960s-1970s, so I cannot say that I always wanted to be a philosopher. In fact, I had never heard of philosophy before I went to university, and even then, I only ended up in a philosophy course by accidentally going into the wrong room when I should have been in a political science course! Luckily, it was a political philosophy course, so it was relevant. I quickly discovered that the philosophers were asking questions of a fundamental nature and importance. I remember questioning how we can investigate and address inequality, oppression, discrimination, injustice, etc., if we don't first ask what inequality, oppression, discrimination, injustice, etc., are? So, I enrolled in the wrong-room-course and have been a philosopher ever since.

'Philosophy' means 'love of wisdom'. That all sounds fancy, but it captures something fundamental and unique about human nature – namely, that we are the kinds of creatures who can investigate and come to have knowledge about the world around us, which is something to love for its own sake. Philosophy asks the foundational questions, clarity about which benefits other fields of study, including science. Philosophers also identify the norms and methods of good reasoning, such as the logical structures of arguments that support drawing true conclusions and avoiding false ones. These are essential skills for any field of research or inquiry, and are also useful for general life and work. One could even say that philosophical thinking is unavoidable; everyone thinks, but not everyone thinks well. This is where the study of philosophy can help. In my neurophilosophical work, I show how the integration of philosophical methods of reasoning can both enhance and help to clarify and evaluate neuroscientific research findings about animal consciousness, enabling us to make more informed judgements about where consciousness exists in the tree of life, with implications for science, food and agricultural industries, and animal welfare.

Deb's *top tips*

1. Ask for reasons. Ask critical questions. Do not settle for assertions of the form 'Here's how it is…' or 'I think that…' without reasons to back them up. Practise giving and taking reasons for what you believe and for your decisions and actions.

2. Be prepared to change your mind when confronted with better reasons, evidence or counterarguments. This is the mark of a critical thinker.

3. Reason collaboratively with others whenever possible. Being in dialogue with others who challenge your thinking is the best way to correct your own personal biases. From a diversity of views comes a better understanding of the problems and more creative solutions.

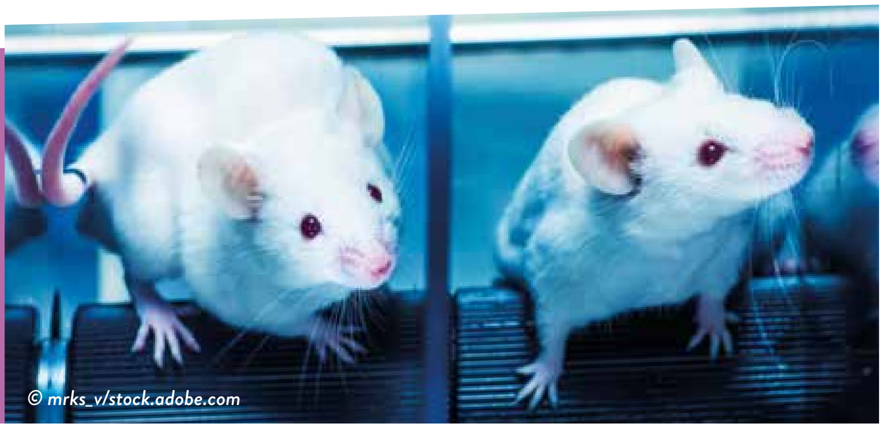
How did Brian become *a neurobiologist?*

I was raised in a working-class environment where if something was broken, it wouldn't get fixed unless you did it yourself. This meant you had to pull it apart, see how it worked, find the broken part, replace it, and then put it back together.

I never took biology classes at school, and it was only in my first year of university when I enrolled in an anatomy subject that I became exposed to what was going on inside our bodies. I learned how important anatomical structures are in determining physiological function. Combining that with my desire to pull things apart and put them together again, it was no wonder I immersed myself in the study of anatomy and physiology.

Early in my training, I was obsessed with mechanisms at all levels. Why did the protein do this? How did the cell do that? How did this clump of cells give rise to an organ? My obsession with mechanism ultimately led me to questions about how nervous systems control behaviour at the level of circuits. I was intrigued by classical perturbation studies in neurobiology where researchers removed and rearranged parts of the brain and asked how the brain responded. Who would have thought that if one removed a frog's eye, rotated it 180 degrees and reattached it, that the frog would subsequently see the world upside down? I really needed to understand that mechanism, and I spent 30 years happily tackling it.

More recently, my focus has shifted to understanding how sensory experiences such as pain and pleasure are generated by electrical activity in the brain. It is a simple question to ask, but it is one of the hardest problems in nature. Is the human brain smart enough to understand itself? I only hope that I am around to see the next generation of neurophilosophers solve that puzzle!



Brian's *top tips*

1. Study things that interest you. It is easy to excel when partaking in activities that interest you.

2. Find a good mentor. It is often espoused that it is easier to win a Nobel Prize if you have previously worked with a Nobel Prize winner. Let the wisdom of a good mentor guide you.

3. Seek out mechanisms. Always ask how something is possible and what the underlying mechanism is. This advice applies equally well to everyday life challenges.

Meet *the team*

Dr Oressia Zalucki

Oressia applies the 'structure-determines-function' principle to the *C. elegans* nervous system to examine the neural basis of subjective experience.

"I have tackled many diverse questions in my research to-date, from how axons navigate in the developing brain, the control of neural stem cell division, and the mechanisms underlying general anaesthetics. My current job integrates everything I've learnt and continue to learn in neuroscience about how the brain works, to understand the neural basis of consciousness – no small problem! I enjoy the challenge and working with great people."

Jake Taylor
PhD Student

Jake examines the arguments used in comparative neurobiology in order to uncover and explore the philosophically loaded presumptions that researchers in this field rely upon.

"EVERYTHING ABOUT THE QUESTION OF ANIMAL PAIN IS PHILOSOPHICALLY INTERESTING AND PROFOUNDLY DIFFICULT. THERE IS NO END TO THE INTELLECTUAL STIMULATION TO BE FOUND IN THIS INTERSECTION OF PHILOSOPHY AND SCIENCE."

CAN WE CONTROL THE ELECTRICAL ACTIVITY IN OUR BRAINS?

Neuroscientists aim to understand how our brains work and what happens when they are not functioning properly. At the **University of Oxford** in the UK, **Dr Adam Packer** and his team are exploring how neurons transmit electrical signals and discovering how they cause us to feel sensations, by manipulating the neural activity in mice. This research has the potential to deepen our understanding of the human brain, paving the way for treatments of conditions such as epilepsy and schizophrenia.

PROFILE

Dr Adam Packer

Department of Physiology, Anatomy and Genetics, University of Oxford, UK

Field of research
Neuroscience

Research project
Using calcium imaging and optogenetics to investigate neural activity in mice

Funders
Wellcome Trust, The Royal Society, European Research Council, Biotechnology and Biological Sciences Research Council

TALK LIKE A ...

NEUROSCIENTIST

Epilepsy — a medical condition in which abnormal electrical activity in the brain causes seizures

Express — the technique of protein expression involves synthesising a protein in a cell

Fluorescence — the emission of light by a substance that has absorbed light

Neuron — a type of brain cell that generates electrical activity

Opsin — a protein that reacts to light

Schizophrenia — a mental health disorder in which a person experiences hallucinations that they believe are real

Spike — an electrical pulse, also called an action potential, generated by a neuron

Stimulus — an event that causes a specific reaction

The human brain is the most complex structure known in the Universe. It contains about 100 billion neurons, all working together to keep you alive and functioning. When you decide to do anything, from swallowing your food to tying your shoe, the neurons in your brain must communicate with each other to make then enact that decision. When you feel the wind on your cheek or the heat of the sun on your face, it is your neurons in your brain that generate the sensation you are experiencing.

We still do not fully understand how our brains function, which is why neuroscientists like Dr Adam Packer are investigating how neurons control processes in the brain and body. In his lab at the University of Oxford, Adam is leading a team of neuroscientists to explore how the neurons in mice control the sensations they feel. By learning how neurons function in mouse brains, scientists can develop a greater understanding of how neurons function in human brains. This will lead to greater understanding, and hopefully treatment, of issues in which the brain does not function as normal, such as developmental disabilities, mental health disorders and degenerative diseases.

How does Adam monitor neural activity in mice?

To transmit information, neurons emit pulses of electrical activity, known as 'spikes'. Adam measures the electrical activity in the brains of mice using a technique called calcium imaging. "During a spike, lots of calcium ions rush into the neuron," he explains. "By measuring the concentration of calcium in neurons, we can therefore infer the amount of electrical activity occurring."

To do this, Adam expresses a fluorescent protein in the mouse's neurons. The greater the concentration of calcium in the cell, the brighter the protein will fluoresce. By taking an image of the mouse's brain, Adam can see exactly which neurons were spiking at that instant in time, as these cells will be more fluorescent. He can then determine what neural activity occurs when different stimuli are given to the mouse. For example, he can observe which neurons spike when he flicks the mouse's whiskers compared to when he strokes its ears.

© neurobite/stock.adobe.com

How does Adam control neural activity?

Adam also uses a technique called optogenetics, in which he artificially generates activity in the mouse's neurons. To do this, he expresses an opsin, a light-sensitive protein, in the neurons. "In response to light, the opsin allows ions to rush across the cell membrane. This generates electrical activity, as electricity is the flow of charged species," he explains. "By shining light on the brain, we can therefore artificially activate the opsin-containing neurons and cause them to spike."

Adam's all-optical approach

Adam has developed an 'all-optical interrogation technique' that combines calcium imaging and optogenetics. "We use calcium imaging to discover what function individual neurons are responsible for, then stimulate these specific neurons using optogenetics, and then record the artificially generated neural activity using calcium imaging," he explains. For example, he recorded which neurons were activated when he flicked the mouse's whiskers, and therefore which neurons are responsible for perceiving that specific sensation. He then expressed an opsin in these neurons and shone light on them. This artificially caused the neurons to activate, and so the mouse should have experienced the sensation of having its whiskers flicked, even though no one was touching it.

Adam used calcium imaging to observe that the targeted neurons were spiking. To test whether the mouse was actually experiencing the intended perceived sensation, the mouse was trained to report when it felt its whiskers being flicked. To do this, Adam taught the mouse to lick a waterspout to its left when he physically flicked its left whiskers and to lick a waterspout to its right when he physically flicked its right whiskers. Then, he shone light on the mouse's brain to artificially stimulate the neurons responsible for perceiving a flick of either the left or right whiskers. When the optogenetics technique successfully gives the mouse the perceived sensation, it will feel like its left or right whiskers have been flicked, and so it will lick the corresponding waterspout.

How does neuroscience research on mice benefit humans?

"Understanding how brains normally work is critically important for understanding what is happening when brains don't function properly," says Adam. If neuroscientists can discover the neural activity underlying perception, this could help treat schizophrenia, a mental health disorder in which people hallucinate and perceive things that are not physically there. If neuroscientists can understand how electrical signals are transmitted between groups of neurons, this could help treat epilepsy, a condition in which abnormal electrical activity in the brain causes seizures.

Adam is now using his all-optical approach to investigate whether optogenetics could be used to treat these conditions. About 70 million people in the world have epilepsy, one-third of which cannot be medically treated, so finding alternative treatments is vital. Adam artificially induces local seizures in mice, then uses calcium imaging to observe how the abnormal electrical activity propagates through nearby brain areas. Using this approach, he has shown that certain neurons fail to hold back the seizure, causing it to spread through the brain.

Once neuroscientists understand how neurons cause epilepsy, they can then try to use optogenetics to prevent abnormal electrical activity in the brain from causing seizures. If they can achieve this in mice, they will then turn their attention to the much greater challenge of applying this in humans. "It is important to consider what the animal will experience during such experiments, and to balance this against the potential rewards of the research," Adam explains. "If a few mice experience epilepsy but this could save millions of humans from experiencing it, the animal experimentation is considered ethically justified."

A major breakthrough in optogenetics occurred in 2021, when a group of neuroscientists injected opsins in a human eye and restored partial vision to a person who was completely blind. "We cannot yet make blind people see," clarifies Adam. "However, this person, who was completely blind, was able to perceive sensations of dark and light. The fact that this is even remotely possible is hugely exciting!"

When optogenetics was first developed in the early 2000s, people did not think it could be used in humans. It sounded like the stuff of science fiction. But this breakthrough demonstrates opsins can safely be used in humans, opening the door to a huge range of possibilities, and providing hope for millions of people living with conditions that, in future, could be cured with optogenetics.

FUN FACT

Adam's fluorescent calcium indicators are based on green fluorescent protein (GFP), a protein found in some jellyfish that causes them to glow a luminous green. First discovered in the 1960s by Dr Osamu Shimomura, GFP has revolutionised many fields of science. In 2008, Dr Shimomura was awarded the Nobel Prize in Chemistry for his pioneering work, alongside Dr Chalfie and Dr Tsien. Read more about their research: **www.nobelprize.org/prizes/chemistry/2008/illustrated-information**

© Matthieu/stock.adobe.com

ABOUT *NEUROSCIENCE*

As the study of the brain and nervous system, neuroscience has the potential to make remarkable breakthroughs that will benefit the lives of millions of individuals. It requires knowledge from a range of disciplines, including biology, chemistry, physics, maths, computer science and psychology, which is why neuroscientists with different areas of expertise work together in teams. For example, in Adam's lab at the University of Oxford, there are experimental biologists who train the mice and record their brain activity during experiments, data scientists who analyse and interpret experimental data, technicians who maintain the experimental equipment as well as other specialists, each with their own roles. "We all rely on each other," Adam explains. "You need lots of people with different expertise to work together to answer any one question."

Why is neuroscience interesting?

"I think what most fascinates me is just how little we know about the brain," says Adam. This fascination began when dissecting a brain during an introductory neuroanatomy course as an undergraduate student. Adam asked his professor how different types of touch on the skin result in different signals being sent to the brain. "You know what? We don't completely know," was the professor's reply. "You can come to the lab tomorrow and figure it out." This amazed Adam. "Fundamentally, we still don't understand how our brains work!"

Why do neuroscientists conduct experiments on animals?

"We cannot understand brains without studying brains," says Adam. Brains are so complex that, although scientists have tried to recreate them as computer simulations, they can never replicate the complexity of a living brain. Neuroscientists cannot understand all the interconnected functions and processes that occur in the brain without studying real brains. It would be too dangerous (and unethical) to conduct experiments on live human brains which is why mice are commonly used instead.

Conducting research on animals is a contentious ethical issue. In the UK, there are very strict laws in place to safeguard the animals used in scientific research labs. The possible benefits of the research must outweigh any suffering experienced by the animals. "It is considered ethically justifiable to experiment on animals if the research has the potential to help millions of humans," explains Adam.

Pathway from school to *neuroscience*

- "Studying all the sciences is useful because neuroscience is quite broad, so you can come at it from many angles," says Adam. "Having a firm basis in biology is first and foremost. Chemistry is useful for understanding the chemical reactions that happen in cells. Physics provides an understanding of electricity in neurons. And maths explains how groups of cells work together."
- "Programming or coding is an absolute must," Adam adds, as the ability to analyse and understand data is crucial for neuroscientists.
- Some universities offer degrees in neuroscience. You could also become a neuroscientist after a degree in biochemistry, biomedical science, computer science, psychology or physics. The British Neuroscience Association (BNA) has a list of neuroscience degrees in the UK: **www.bna.org.uk/careers/courses**
- To work as a neuroscientist in a research lab, you will usually have to complete a master's or PhD after your undergraduate degree.
- If you want to apply neuroscience in a clinical setting as a neurologist or neurosurgeon, you will have to complete a medical degree and qualify as a medical doctor.
- The University of Oxford organises the UNIQ summer school, allowing students from UK state secondary schools to experience university life and sample different undergraduate courses, including biomedical sciences: **www.uniq.ox.ac.uk**

Explore careers in *neuroscience*

- Neuroscientists study the brain, usually working in research labs at universities or biotechnology institutes. You could also apply your skills in a clinical setting as a neurologist or neurosurgeon (medical doctors specialised in diagnosing and treating brain conditions).
- The BNA has a wealth of resources about careers in the field, including FAQs, tips on finding neuroscience work experience and an informative guide for school students: **www.bna.org.uk/careers**
- This video from the BNA about 'Careers in neuroscience (and beyond!)' is packed with information on what it's like to be a neuroscientist: **www.youtube.com/watch?v=22wTaLje9ew**

Meet Huriye and Sarah, *neuroscientists in Adam's lab*

Dr Huriye Atilgan
Postdoctoral Fellow,
University of Oxford, UK

Field of research
Neuroscience

When I was younger, I wanted to be an astrophysicist and explore space. It was the remarkable similarity between the brain and space that inspired me to become a neuroscientist. It is sometimes hard to distinguish images of the brain from images of the Universe! After recognising this, my interest shifted from space to the brain. I love exploring the space-like structure that makes us who we are.

I am currently exploring the role of the claustrum, a puzzling brain structure that has an extensive connection to other areas of the brain. It has been linked to many functions, such as sensory integration, sleep and consciousness, but we still don't know exactly what the claustrum does! I am currently exploring whether the claustrum has a role in neural signal processing.

I like the challenge of learning something novel and adapting techniques to explore the unknown. Each project is a long journey and, although there are plenty of boring stops along the way, there are many joys and a lot of excitement in research. The challenges of how to conduct experiments, the novelty of collecting unknown data and the curiosity to uncover what the data mean keep me motivated.

My graduate research focused on how visual cues can be used to help people hear better in situations when listening is difficult. I am proud of this work because it has a clinical application and will help people with hearing difficulties. In the future, I would like to develop different multi-disciplinary methods for answering complex questions about neural circuits.

My favourite fact about the brain is that it is highly dynamic – adaptation, compensation and plasticity in neural circuits are fascinating.

Huriye's *top tips*

1. Be bold and have the courage to try whatever you want to do.

2. Don't be discouraged by self-doubt or the prospect of failure.

Sarah Armstrong
PhD candidate,
University of Oxford, UK

Field of research
Systems Neuroscience

I was interested in technical things like computers and coding from a fairly young age. I also enjoyed making stop-motion animations and playing the guitar.

An interest in science came late for me. I think this is because school taught science as a collection of facts rather than as a process of understanding the world and solving exciting problems. Exposure to unsolved problems sparked my curiosity. The first was coming across theories of consciousness in English literature and the second was learning about schizophrenia in a psychology class. I was shocked at the lack of effective treatments for mental health problems and thought that research in neurobiology might help.

I am currently trying to understand how the brain learns. As we get better at a task, how are the neurons in the brain changing, and what causes them to change? With computers, I use machine learning and artificial neural network models to understand how different learning algorithms might change the brain. Then, I use calcium imaging to look for specific changes in the neurons of mice as they learn tasks.

I am proud to have presented some of my research, which used mathematical methods I have learnt during my PhD, at a conference. I didn't take maths A-level at school, so I never thought this would be possible. It felt surreal talking about that work with well-known professors in the field.

My role in the lab allows me to learn transferrable technical skills which will open more career options. The programming and data analysis are my favourite parts of my project, so I think I would like to try a career in data science. In the future, I'd like to use science to make a positive impact in the world – in health, technology or tackling climate change.

Sarah's *top tips*

1. Get research experience as early as you can.

2. Learn to code. There are tons of free online courses in python programming that you can explore. It helps to learn coding while working on projects so you can apply the skills while learning.

How to use our education and career resources

You will find a great range of free, inspiring research articles at **futurumcareers.com/articles**

Learn key terminology relating to the field

Meet the people behind the research

Read about fascinating research projects that are happening right now

Explore fields of research, and learn about future career opportunities

Consider different educational options

Find out how the researchers got to be where they are today

Read advice from inspiring people

Many of our articles are accompanied by an animation, PowerPoint and/or podcast:
futurumcareers.com/education-resources

POWERPOINTS
Our career PowerPoints summarise research projects, highlight researchers' careers guidance and prompt you to reflect on your own skills:
futurumcareers.com/ppts

ANIMATIONS
Our animations bring the research project to life and include a downloadable script with suggested activities.:
futurumcareers.com/animations

PODCASTS
Listen to researchers recount their own experiences and career pathways, and be inspired!
futurumcareers.com/stem-shape-podcasts

ACTIVITY SHEETS
Check your understanding, develop your knowledge, think critically, evaluate and continue your learning:
futurumcarees.com/activity-sheets

Keep in touch.

Thanks for reading Futurum. Did you know that all our articles and accompanying activity sheets, PowerPoints and animations are available online?

Visit our website: www.futurumcareers.com

We regularly publish new articles, activity sheets, PowerPoints and animations. Keep up to date by signing up to our monthly newsletter: www.futurumcareers.com/sign-up

Contact the researchers in the articles

Go to futurumcareers.com/articles → **Select the article** and scroll to the bottom → **Type your question** in the comments field → **Click** 'Notify me of follow-up comments via email' → **Click** 'Submit Comment'

Follow us

for updates on new instant articles, blogs and events:

Tell us what you think

We would LOVE to hear from you: send us a message through social media, comment on our articles or blogs, or send us an email: info@futurumcareers.com

futurum
Inspiring the next generation

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.