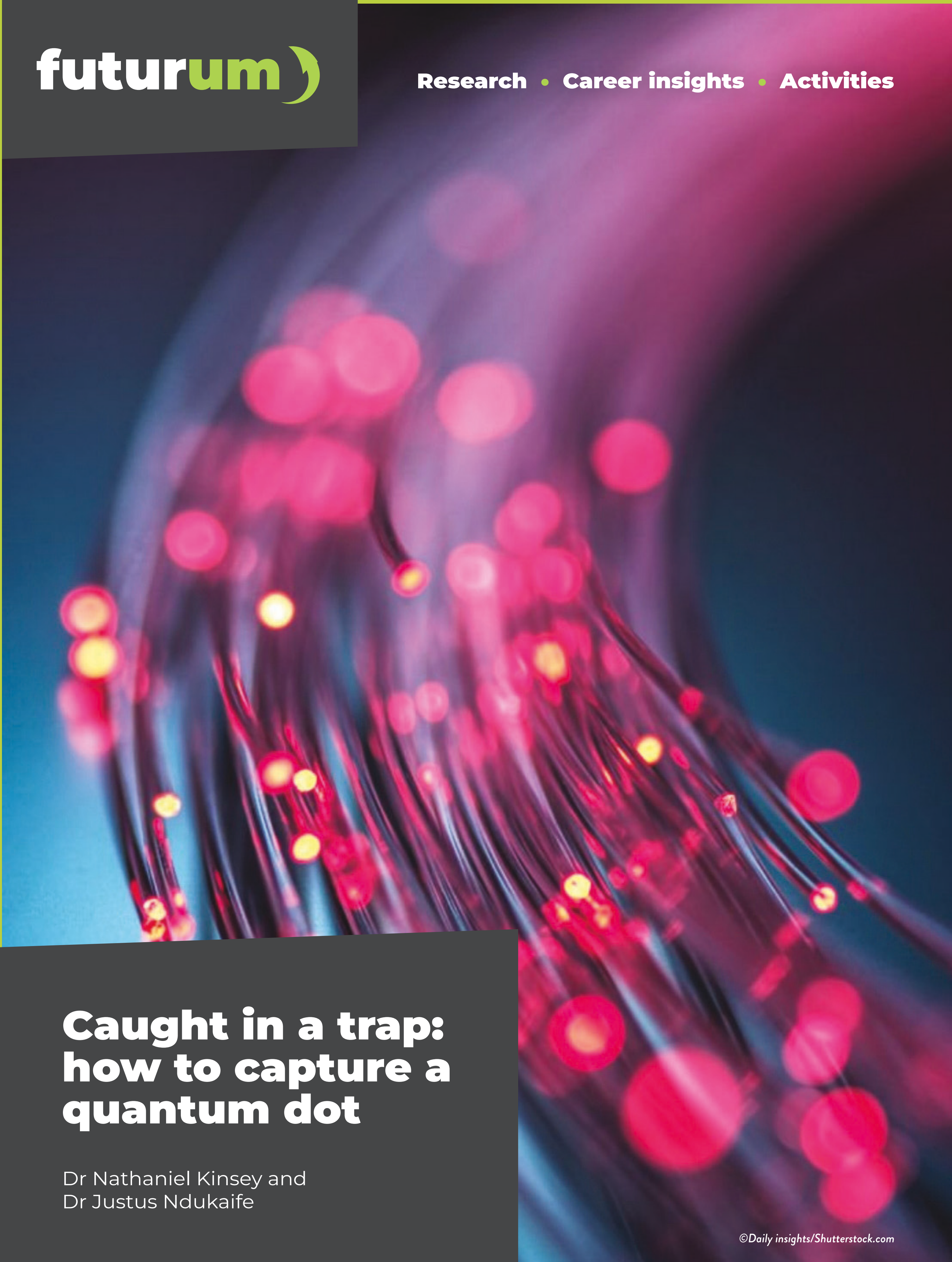

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Caught in a trap: how to capture a quantum dot

Dr Nathaniel Kinsey and
Dr Justus Ndukaife

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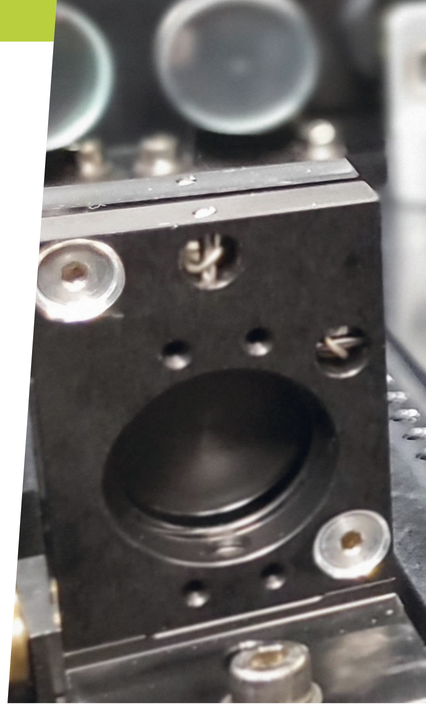

Caught in a trap: how to capture a quantum dot

Many new quantum technologies will rely on the precise manipulation of single photons; however, most light sources produce photons randomly. Quantum dots, which can reliably produce single photons, may provide a solution. From **Virginia Commonwealth University** and **Vanderbilt University** in the US, **Dr Nathaniel Kinsey** and **Dr Justus Ndukaife** are developing a device that can trap quantum dots and enhance their photon emission rates, paving the way for new quantum technologies.

Dr Nathaniel Kinsey

Engineering Foundation Associate Professor, Virginia Commonwealth University, Richmond, Virginia, USA

Dr Justus Ndukaife

Associate Professor of Electrical Engineering, Chancellor Faculty Fellow, Vanderbilt University, Tennessee, USA

Field of research
Nanophotonics

Research project
Trapping quantum dots and enhancing their photon emission rates for quantum applications

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Talk like a ...
nanophotonics researcher

Encoding key — a piece of information (e.g., a string of numbers) used to encode or decode data

Nanoscale — the scale at which objects are measured in nanometres (one billionth of a metre)

Optical nanotweezer — a device that uses focused lasers to trap and manipulate nanoscale objects

Photon — a particle that represents the smallest possible unit of light

Plasmon — an oscillation (back and forth rhythmic movement) of electrons within the bulk or on the surface of a metal

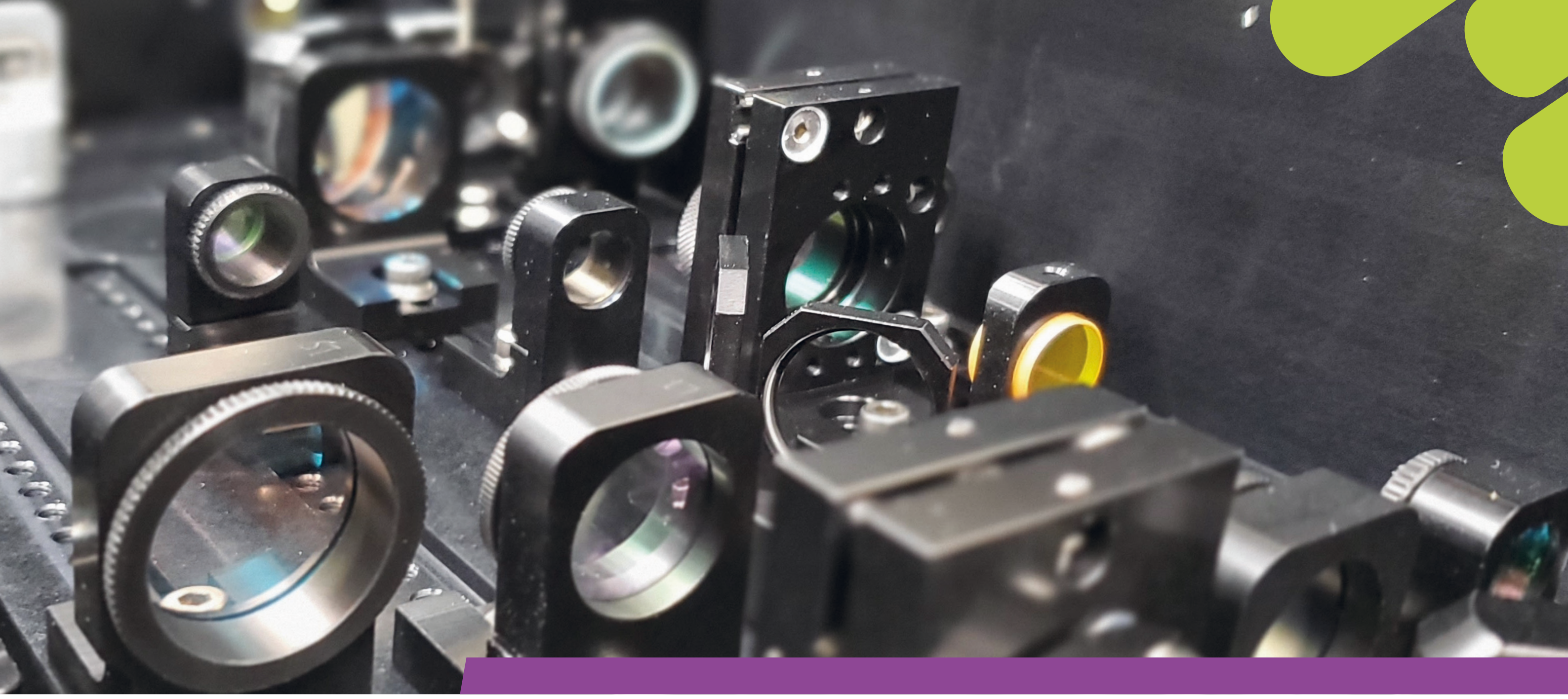
Quantum dot — a nanoscale volume of material in which electrons are confined to discrete energy levels (like an atom) meaning they are subject to quantum effects

Quantum key distribution — a secure method for sharing encoding keys that makes use of quantum mechanics

Single-photon emitter — a light source that emits single photons

Almost all sources of light, from lightbulbs and lasers to stars and fireflies, emit photons randomly. In most situations, this is perfectly fine. However, if you are attempting to pioneer advancements in state-of-the-art quantum technologies, you'll need something a little more predictable. Unlike classical sources of light, single-photon emitters can be triggered to reliably emit single photons, one at a time. This ability is crucial for many quantum technologies, such as quantum computing and quantum communication.

Unfortunately, manufacturing single-photon emitters is not easy. "Currently, most systems use low-cost emitters where the spacing between photons in time is random, making it hard to predict exactly when the photon will arrive," explains Dr Nathaniel (Nate) Kinsey from Virginia Commonwealth University. "They may also produce no photons or multiple photons, when we ideally want just one." These flaws add uncertainty into a system, slowing it down and making it inefficient.



Nate and his collaborator, Dr Justus Ndukaife from Vanderbilt University, are developing a new device, called the Nanoscale Trap and Enhance Device (NOTED), that they hope will be able to produce more reliable single-photon emitters with higher photon emission rates. They hope that their device will allow them to scale up production of single-photon emitters, potentially including thousands of them on a single computer chip.

Light you can rely on

Nate and Justus believe that NOTED will reliably produce single-photon emitters that can generate a single photon on demand. "Essentially, our device will be like pressing a button that produces one photon (and only one) that is identical to the last one every time," says Nate. "The best way to do this would be to harness a single atom that reliably emits photons; however, this is incredibly challenging." Instead, NOTED uses quantum dots - nanoscale structures made up of a handful of atoms that are easier to work with.

Although they are easier to work with than single atoms, quantum dots emit photons at a slower rate. To overcome this issue, Nate and Justus are using optical nanotweezers to place the quantum dots at specific locations on a chip that will increase their emission rate. Optical nanotweezers trap light emitted by lasers into tiny nanostructures, creating an energy gradient that attracts and traps nearby nanoparticles. "In our device, we are using new techniques that enable the long-range transfer of quantum dots, pulling them in from afar until they reach the short-range optical gradient force of the nanotweezers," explains Justus. "With these latest advancements, we can trap quantum dots much faster than previous approaches, even when they are in low concentrations."

Increasing emissions

Quantum dots can be 100 times smaller than the wavelength of a photon, making interactions between the two very unlikely. Unfortunately, it is these interactions that cause a quantum dot to emit a photon. In order to increase the rate at which quantum dots emit photons, the team is using findings from a new field of research called plasmonics, which uses metals to control and manipulate light.

"We use plasmonics to couple photons of light with the motion of electrons in metal," says Nate. "The product, called a plasmon, can be 'squeezed' so that it becomes much smaller than the photon's original wavelength." By squeezing the photon down to a similar size as the quantum dot, the chances of interaction increase dramatically, meaning the quantum dot can emit photons at a much faster rate.

A question of scale

Nate and Justus are trying to improve the scale and speed at which they can manufacture their device. "Our system seeks to address the key challenges of using quantum dots as single-photon emitters, making it easier to integrate them into a device and then enhancing their emission," says Nate. "We are trying to do this on a photonic chip so that we can form many single-photon emitters on a single wafer and place them all simultaneously. This would increase the scale of manufacturing and lower the costs for next generation secure communication systems."

However, there is still lots of work to be done. "We are focusing on building the device with the correct dimensions and geometrical features to ensure reproducible results," says Justus. "We also need to be able to monitor the quantum dot assembly process to ensure that they are being placed accurately." If Nate and Justus can successfully manufacture their device, it could be a gamechanger for new quantum technologies, such as quantum key distribution.

Quantum key distribution

Fibre optic technology can be used to send information from one place to another by bouncing photons along thin, glass fibres. To keep this information private, the data being sent is often protected with an encoding key which allows a sender to 'scramble' their information, protecting it from prying eyes. "Traditionally, encoding keys are sent over conventional communication links like fibre optic cables," explains Nate. "However, these can be intercepted by siphoning off a few photons without the receiver's knowledge."

Quantum key distribution takes a similar approach, but with one important difference. "In quantum key distribution, the key is exchanged over fibre optics using single photons," explains Nate. "As there is only one photon, if someone were to intercept the key, the intended recipient wouldn't receive it, and so they would know that the key had been compromised and could take appropriate action to protect their information." In order for such a system to work, we need devices, like NOTED, that are capable of trapping and enhancing the emission rates of single-photon emitters.

About *nanophotonics*

Nanophotonics involves studying how light behaves and interacts with other objects at the nanoscale. Such objects are incredibly tiny. To put it in perspective, one sheet of paper is about 100,000 nanometres thick. It is only in recent years that studying and manipulating things at this scale has become possible, and the many and varied applications of this field are still being discovered.

"In my lab, we focus on using nanophotonics to develop high-efficiency optical nanotweezers," says Justus. "One exciting opportunity that we are pursuing is using optical nanotweezers to trap and study extracellular vesicles, the tiny capsules that carry messages and nutrients between cells in the body." Justus hopes to use this technique to understand how extracellular vesicles transport therapeutic drugs around the body. "Another exciting application of nanotweezers is to trap and characterise nanoplastics," says Justus. "This will be critical to understanding their impacts on human health, which has been challenging to study via other means."

Nanophotonics makes use of cutting-edge computing technology and artificial intelligence. "Without these technologies, most of our calculations, simulations and designs would not be possible," says Nate. "We also use advanced nanofabrication techniques to build our materials and devices. This is a hands-on field that really makes use of the latest technological advancements."

While nanophotonics research was theoretical for quite some time, many areas of research are now being used in practical and commercial settings. "It's cool to see the things I studied during my PhD leading to start-up companies and new products," says Nate. "It shows that fundamental research really does impact society. Nanophotonics is currently in the middle of this transition; it's exciting to see what will be next!"

Pathway from school to *nanophotonics*

A foundation in mathematics and science, in particular physics, is important for most nanophotonics careers. Statistics and linear algebra will help you explore quantum applications, and programming skills are useful for data analysis and simulations.

"Nanophotonics is hands-on, so having a good sense of how to fix things or build things is also useful," says Nate. "Subjects like woodworking, metalworking and mechanics, where you work with your hands, build things and troubleshoot problems, provide applicable skills and understanding, even if not directly related to nanophotonics."

A wide range of further education qualifications could lead to a career in nanophotonics. For instance, degrees in subjects such as nanotechnology, physics, materials science, electrical engineering and chemical engineering can all lead to nanophotonics careers

Explore careers in *nanophotonics*

Justus recommends Nanohub to learn more about nanotechnology and nanophotonics. Among many varied resources, it has a free course on nanophotonics from Professor Vladimir Shalaev, Nate and Justus' former PhD co-mentor: **nanohub.org/courses/NP**

The Pathways to Science directory lists a wide range of nanotechnology summer schools, internships and research placements at research institutions and universities in the US: **pathwaystoscience.org/Discipline.aspx?sort=TEC-NanoTech_Nanotechnology**

Meet *the team*

Nate

I love learning more each day. I like the freedom to tackle the problems that I want to investigate, and my job offers me many opportunities to work with other experts in the field to create new things.

I am proud of all of the students that I mentor and teach. I have enjoyed working with each and every student that has joined my team. Seeing them come in, learn, do great research and move on to their next step is incredibly rewarding. For me, that's what it's all about – supporting the next generation of technical leaders in optics and photonics.

Curiosity and determination have defined my career. Curiosity is necessary to ask questions and take on new problems. But determination is also critical; research is built on failures, and most of what you try won't work the first time. Learn from what didn't work and keep trying.

Nate's *top tip*

Think deeply about what you love and enjoy, and turn that passion into a career. If you haven't found that 'thing', pursue as many experiences as you can through clubs, projects, internships and so on.

Justus

As a teenager, I had a deep passion for mathematics. I spent many of my summer breaks solving maths problems from any textbooks I could find! My parents initially encouraged me to pursue a career in medicine, but I was more taken by mathematics, innovation and inventing things that benefit society. This led me to pursue engineering.

I love being able to tackle important problems I am excited about. I enjoy doing work that can be used by other researchers and society at large. I also like being a role model to the younger generation and helping them excel in their research and build their careers.

Determination, resilience and openness to diverse ideas have been essential to my success. I actively seek knowledge beyond my immediate field, as major breakthroughs often emerge at the intersection of different disciplines. I also have a commitment to effective communication, conveying my research as a compelling story to make it more accessible and engaging.

Justus' *top tip*

Don't be afraid to try something new, and never doubt your capacity to learn. Stay open to ideas from different disciplines.

Samprity Saha

Graduate Research Assistant,
Virginia Commonwealth University

My role on this project has been to evaluate the feasibility of the Nano-scale Trap and Enhance Device through simulations and to enhance the device's performance using numerical analysis. This project has truly been an eye-opener for me, and it's been amazing to collaborate with such inspiring individuals in this field.

If you're fascinated by how technology works at its core, I wholeheartedly encourage you to explore quantum engineering and nanophotonics - it's a really cool field with plenty of opportunities to help shape the future of technology!

Theodore Anyika

Graduate Research Assistant,
Vanderbilt University

My role on this project involves conducting experiments and assisting with device design and simulations. Working on this project has improved my ability to combine different perspectives and expertise from various teams, which has strengthened my problem-solving skills.

Engaging in hands-on projects, such as joining a research lab during your undergraduate studies or completing internships, can be very beneficial. Additionally, seek mentorship from experienced professionals, as the field can feel daunting at first. Over time, you will find that the learning curve becomes more manageable.

Nanophotonics

with Dr Nathaniel Kinsey and Dr Justus Ndukaife

Talking *points*

Knowledge

1. What are optical nanotweezers?
2. What is quantum key distribution?

Comprehension

3. What are quantum dots and what role do they play in the Nanoscale Trap and Enhance Device (NOTED)?
4. Why are reliable single-photon emitters so important for quantum technologies?

Application

5. What questions would you ask Nate and Justus to learn more about how they are developing NOTED? What parts of the process are you most interested in learning more about?
6. Justus mentions that optical nanotweezers could be used to study extracellular vesicle drug delivery and nanoplastics. Can you think of other potential applications for this technology that can capture and manipulate nanoparticles?

Analysis

7. The defence, finance and healthcare sectors are already beginning to use quantum key distribution systems. Why are these systems especially valuable to these sectors? What other sectors would also benefit from these systems?
8. Although plasmonics is a relatively new field, its potential applications are huge. What do you think are the rewards and challenges of working in a new scientific field?

Evaluation

9. What steps do you take to make sure that the information you send online (in emails, texts and social media messages, for example) is secure? How could you take more care to ensure that your personal information remains private?
10. With the rise of quantum computing, many experts are concerned that private information might become harder to secure. To what extent do you think this is a serious issue, and why?

Activity

Nanoplastics are miniscule pieces of plastic no bigger than 100 nanometres. Although they are so small, they can still cause harm to living things. Using optical nanotweezers, Justus traps, studies and characterises nanoplastics to better understand how they might impact human health.

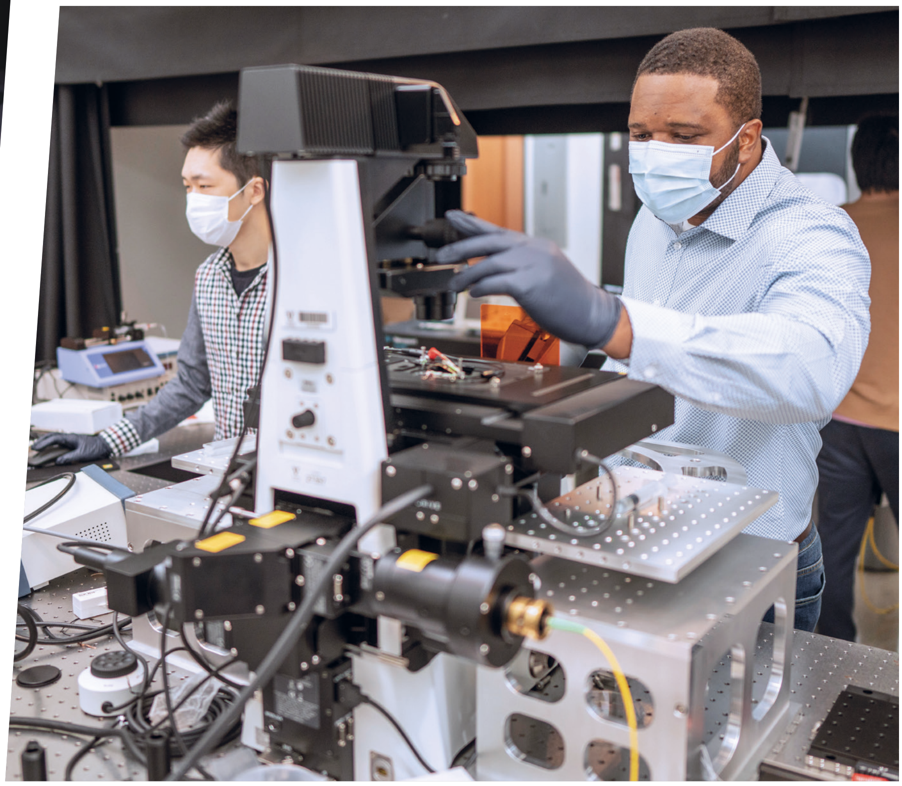
Do some online research to learn more about nanoplastics, where they are found and the dangers they pose. These dangers might be directly related to human health (how nanoplastics affect the body) or they may impact us indirectly (how nanoplastics impact our environment and the plants and animals that we rely on).

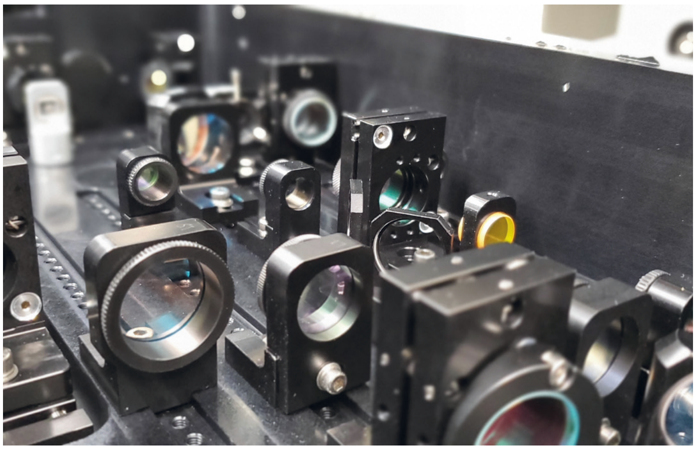
Design an experiment that Justus could use to study a specific danger posed by nanoplastics. How could he collect samples of nanoplastics? How could he use optical nanotweezers to study these samples? What would he need to find out about the nanoplastics within the samples? How could he measure and quantify the danger posed by the nanoplastics? How could he use his findings to mitigate this danger?

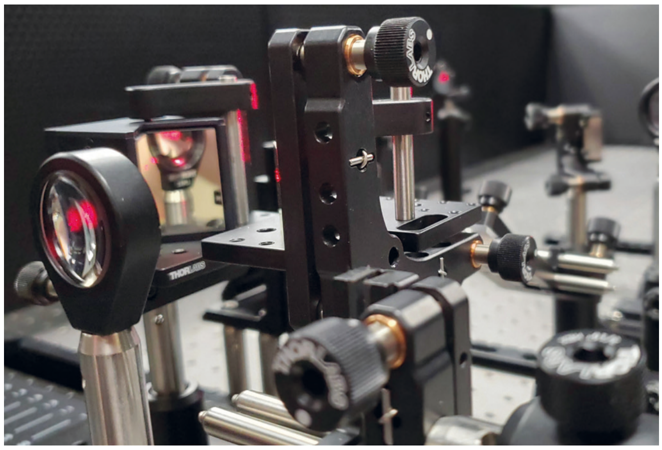
Create a poster to inform other people about your experiment. You should include information on why your experiment is important, how you will conduct your experiment, what results you are expecting to find and how your results could be put to practical use. Share your poster with your classmates, answer any questions that they might have, listen to their feedback and reflect on how you could improve your experimental design.

More *resources*

- This video from Nanowerk gives an absorbing introduction to the world of nanophotonics: **youtube.com/watch?v=I5-tBPigWLM**
- This article from TechTarget gives an overview of how quantum key distribution works: **techtarget.com/searchsecurity/definition/quantum-key-distribution-QKD**
- This article explores the history of the quantum dot, from theory to reality: **chemistryworld.com/features/the-quantum-dot-story/4018219.article**
- This TED Talk discusses the potential of silicon nanophotonics: **youtube.com/watch?v=vLEU_sEeiSU**







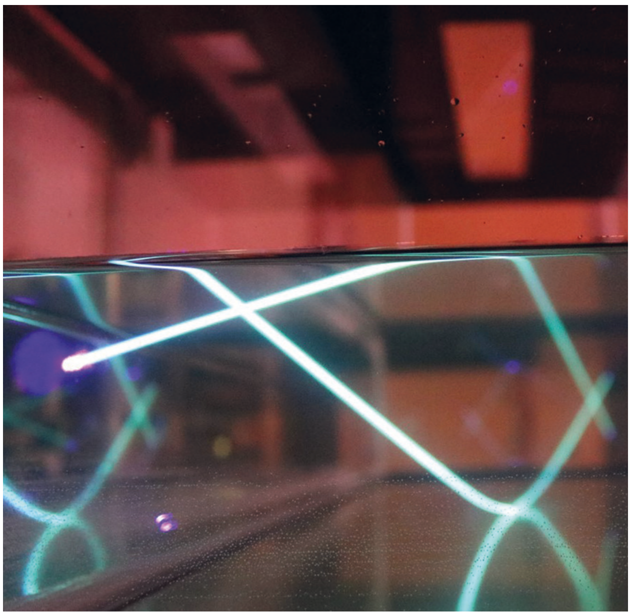


Photo *montage*

Top: *Justus and a student working with an optical microscope to observe particle trapping with nanophotonic devices. © Vanderbilt University*

Middle row: ***Left:*** *Various optics inside an optical parametric amplifier, a device which uses nonlinear optical processes to change the colour (wavelength) of a laser.*

Right: *Optical components placed on an optics table which directs laser light (red spot) towards a sample to measure optical reflection and transmission.*

Bottom: *An example of total internal reflection which occurs when light tries to pass from a material with a higher refractive index to a lower refractive index. In this image, a blue laser is directed into a fish tank that is partially filled with water. When the laser hits the surface of the water it reflects off the surface due to the change in refractive index of water (1.33) to air (1). This is how fibres and waveguides guide light around bends!*

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