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Quantum workforce

How to give your career an edge

Opinion

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Quantum hype

The quantum sector won't grow forever, but it's still a great place to start your career

Last year I completed a PhD in soft-matter physics, a subject I've long been passionate about. However, it sometimes occurred to me that if my goal was to make a lot of money, I had picked my discipline poorly. Working in the same building as a quantum technologies laboratory, it was evident that this was where a lot of the funding and industrial partnerships in the department were concentrated.


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Quantum technology is certainly a burgeoning area. Last year, for example, the UK government announced a 10-year, £2.5bn quantum strategy that includes doubling the number of quantum Centres for Doctoral Training. In the US, the Department of Energy recently announced $65m for quantum computing research. That's good news for physics graduates looking for jobs, as this graduate booklet makes clear.

There are, however, some clouds on the horizon. According to the *State of Quantum 2024* report, quantum investment has fallen by 50% since peaking in 2022. Then, earlier this year, the announcement that the Australian government has backed the computing start-up PsiQuantum to the tune of A$1bn was met with some pushback.

Quantum computing in particular has been accused of overselling the near-future capabilities of the technology. With so much money up for grabs, there's an incentive to kick tricky questions down the road and focus on securing the next round of funding.

I'm not trying to deter graduates from a career in the sector. Quantum technology might not reach all its lofty goals (at least not in the next decade) but that doesn't mean it isn't a smart bet career-wise. The rise of quantum technology has created a plethora of well-funded PhD and master's programmes, as well as a lively job market. Graduates who take up these opportunities will build skills that they can take with them, even if a million-qubit quantum computer is a long way away. And don't forget that computing isn't the only quantum technology in town – quantum sensing, for example, is already being deployed in commercial applications.

Finally, I think there's something to be said for pursuing science purely because it's interesting. Quantum mechanics challenges everything we know about how the universe works – that's what motivated many of us to pursue physics in the first place. Overhyped claims make me roll my eyes, but I'm still excited by the possibilities of this technology.

Katherine Skipper
Features editor, *Physics World*

GraduateCareers

Get set for the quantum workforce

Quantum experts **Abbie Bray**, **Araceli Venegas-Gomez** and **Mark Elo** give their advice for interviews, choosing the right PhD programme and managing risk and reward in the emerging quantum industry

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Great expectations The number and variety of quantum careers is expanding. Our experts explain what skills and qualifications you need in this burgeoning domain.

It's official: after endorsement from 57 countries and the support of international physics societies, the United Nations has officially declared that 2025 is the International Year of Quantum Science and Technology (IYQ).

The year has been chosen as it marks the centenary of Werner Heisenberg laying out the foundations of quantum mechanics – a discovery that would earn him the Nobel Prize for Physics in 1932. As well as marking one of the most significant breakthroughs in modern science, the IYQ also reflects the recent quantum renaissance. Applications that use the quantum properties of matter are transforming the way we obtain, process and transmit information, and physics graduates are uniquely positioned to make their mark on the industry.

It's certainly big business these days. According to estimates from McKinsey, in 2023 global quantum investments were valued at $42bn. Whether you want to build a quantum computer, an unbreakable encryption algorithm or a high-precision microscope, the sector is full of exciting opportunities. With so much going on, however, it can be hard to make the right choices for your career.

To make the quantum landscape easier to navigate as a jobseeker, *Physics World* has spoken to Abbie Bray, Araceli Venegas-Gomez and Mark Elo – three experts in the quantum sector, from academia and industry. They give us their exclusive perspectives and advice on the future of the quantum marketplace; job interviews; choosing the right PhD programme; and managing risk and reward in this emerging industry.

Quantum going mainstream: Abbie Bray

According to Abbie Bray, lecturer in quantum technologies at University College London (UCL) in the UK, the second quantum revolution has broadened opportunities for graduates. Until recently, there was only one way to work in the quantum sector – by completing a PhD followed by a job in academia. Now, however, more and more graduates are pursuing research in industry, where established companies such as Google, Microsoft and BT – as well as numerous start-ups like Rigetti and Universal Quantum – are racing to commercialize the technology.

While a PhD is generally needed for research, Bray is seeing more jobs for bachelor's and master's graduates as quantum goes mainstream. "If you're an undergrad who's loving quantum but maybe not loving the research or some of the really high technical skills, there's other ways to still participate within the quantum sphere," says Bray. With so many career options in industry, government, consulting or teaching, Bray is keen to encourage physics graduates to consider these as well as a more traditional academic route.

She adds that it's important to have physicists involved in all parts of the industry. "If you're having people create policies who maybe haven't quite understood the principles or impact or the effort and time that goes into research collaboration, then you're lacking that real understanding of the fundamentals. You can't have that right now because it's a complex science, but it's a complex science that is impacting society."

So whether you're a PhD student or an undergraduate, there are pathways into the quantum sector, but how can you make

> It's very important that during a PhD you do the research that you want to do


Henry Bennie

Abbie Bray "Theorists and experimentalists need to move at the same time."

yourself stand out from the crowd? Bray has noticed that quantum physics is not taught in the same way across universities, with some students getting more exposure to the practical applications of the field than others. If you find yourself in an environment that isn't saturated with quantum technology, don't panic – but do consider getting additional experience outside your course. Bray highlights PennyLane, which is a Python library for programming quantum computers, that also produces learning resources.

Consider your options

Something else to be aware of, particularly for those contemplating a PhD, is that "quantum technologies" is a broad umbrella term, and while there is some crossover between, say, sensing and computing, switching between disciplines can be a challenge. It's therefore important to consider all your options before committing to a project and Bray thinks that Centres for Doctoral Training (CDTs) are a step in the right direction. UCL has recently launched a quantum computing and quantum communications CDT where students will undergo a six-month training period before writing their project proposal. She thinks this enables them to get the most out of their research, particularly if they haven't covered some topics in their undergraduate degree. "It's very important that during a PhD you do the research that you want to do," Bray says.

When it comes to securing a job, PhD position or postdoc, non-technical skills can be just as valuable as quantum know-how. Bray says it's important to demonstrate that you're passionate and deeply knowledgeable about your favourite quantum topic, but graduates also need to be flexible and able to work in an interdisciplinary team. "If you think you're a theorist, understand that it also does sometimes mean looking at and working with experimental data and computation. And if you're an experimentalist, you've got to understand that you need to have a rigorous understanding of the theory before you can make any judgements on your experimentation." As Bray summarises: "theorists and experimentalists need to move at the same time".

The ability to communicate technical concepts effectively is also vital. You might need to pitch to potential investors, apply for grants or even communicate with the HR department so that they shortlist the best candidates. Bray adds that in her experience, physicists are conditioned to communicate their research very directly, which can be detrimental in interviews where panels want to hear narratives about how certain skills were demonstrated. "They want to know how you identified a situation, then you identified the action, then the resolution. I think that's something that every single student, every single person right now should focus on developing."

The quantum industry is still finding its feet and earlier this year it was reported that investment has fallen by 50% since a high in 2022. However, Bray argues that "if there has been a de-investment, there's still plenty of money to go around" and she thinks that even if some quantum technologies don't pan out, the sector will continue to provide valuable skills for graduates. "No matter what you do in quantum, there are certain skills and experiences that can cross over into other parts of tech, other parts of science, other parts of business."

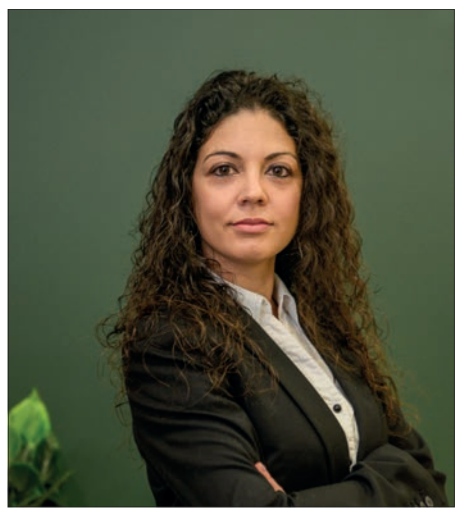
In addition, quantum research is advancing everything from software to materials science and Bray thinks this could kick-start completely new fields of research and technology. "In any race, there are horses that will not cross the finish line, but they might run off and cross some other finish line that we didn't know existed," she says.

Building the quantum workforce: Araceli Venegas-Gomez

While working in industry as an aerospace engineer, Araceli Venegas-Gomez was looking for a new challenge and decided to pursue her passion for physics, getting her master's degree in medical physics alongside her other duties. Upon completing that degree in 2016, she decided to take on a second master's followed by a PhD in quantum optics and simulation at the University of Strathclyde, UK. By the time the COVID-19 pandemic hit in 2020, she had defended her thesis, registered her company, and joined the University of Bristol Quantum Technology Enterprise Centre as an executive fellow.

It was during her studies at Strathclyde that Venegas-Gomez decided to use her vast experience across industry and academia, as well as her quantum knowledge. Thanks to a fellowship from the Optica Foundation, she was able to launch QURECA (Quantum Resources and Careers). Today, it's a global company that helps to train and recruit individuals, while also providing business development advice for for both individuals and companies in the quantum sphere. As founder and chief executive of the firm, her aims were to link the different stakeholders in the quantum ecosystem and to raise the quantum awareness of the general public. Crucially, she also wanted to ease the skills bottleneck in the quantum workforce and to bring newcomers into the quantum sector.

As Venegas-Gomez points out, there is a significant scarcity of skilled quantum professionals for the many roles that need filling. This shortage is exacerbated by the competition between academia and industry for the same pool of talent. "Five or ten years ago, it was difficult enough to find graduate students who would like to pursue a career in quantum science, and that was just in academia," explains Venegas-Gomez. "With the quantum market booming, industry is also looking to hire from the same pool of candidates, so you have more competition, for pretty much the same number of people."


Qureca

Araceli Venegas-Gomez "If you have a background in physics and business, everyone is looking for you."

Employers are looking for candidates who can show that they have been doing outreach and communication activities

Slow progress

Venegas-Gomez highlights that the quantum arena is very broad. "You can have a career in research, or work in industry, but there are so many different quantum technologies that are coming onto the market, at different stages of development. You can work on software or hardware or engineering; you can do communications; you can work on developing the business side; or perhaps even in patent law." While some of these jobs are highly technical and would require a master's or a PhD in that specific area of quantum tech, there are plenty of roles that would accept graduates with only an MSc in physics or even a more interdisciplinary experience. "If you have a background in physics and business, everyone is looking for you," she adds.

From what she sees in the quantum recruitment market today, there is no job shortage for physicists – instead there is a dearth of physicists with the right skills for a specific role. Venegas-Gomez explains that graduates with a physics degree in many fields have transferable skills that allow them to work in "absolutely any sector that you could imagine". But depending on the specific area of academia or industry within the quantum marketplace that you might be interested in, you will likely require some specific competences.

As Bray also stated, Venegas-Gomez acknowledges that the skills and knowledge that physicists pick up can vary significantly between universities – making it challenging for employers to find the right candidates. To avoid picking the wrong course for you, Venegas-Gomez recommends that potential master's and PhD students speak to a number of alumni from any given institute to find out more about the course, and see what areas they work in today. This can also be a great networking strategy, especially as some cohorts can have as few as 10–15 students all keen work with these companies or university departments in the future.

Despite the interest and investment in the quantum industry, new recruits should note that it is is still in its early stages. This slow progress can lead to high expectations that are not met, causing frustration for both employers and potential employees. "Only today, we had an employer approach us (QURECA) saying that they wanted someone with three to four years' experience in Python, and a bachelor's or master's degree – it didn't have to be quantum or even physics specifically," reveals Venegas-Gomez. "This means that [to get this particular job] you could have a background in computer science or software engineering. Having an MSc in quantum *per se* is not going to guarantee that you get a job in quantum technologies, unless that is something very specific that the employer is looking for."

So what specific competencies are employers across the board seeking? If a company isn't looking for a specific technical qualification, what happens if they get two similar CVs for the same role? Do they look at an applicant's research output and publications, or are they looking for something different? "What I find is that employers are looking for candidates who can show that, alongside their academic achievements, they have been doing outreach and communication activities," says Venegas-Gomez. "Maybe you took on a business internship and have a good idea of how the industry works beyond university – this is what will really stand out."

She adds that so-called soft-skills – such as demonstrating good leadership, teamwork and excellent communication skills – are very valued. "This is an industry where highly skilled technical people need to be able to work with people vastly beyond their area of expertise. You need to be able to explain Hamiltonians or error corrections to someone who is not quantum-literate and explain the value of what you are working on."

Venegas-Gomez is also keen that job-seekers realize that the chances of finding a role at a large firm such as Google, IBM or Microsoft are still slim-to-none for most quantum graduates. "I have seen a lot of people complete their master's in a quantum field and think that they will immediately find the perfect job. The reality is that they likely need to be patient and get some more experience in the field before they get that dream job." Her main advice to students is to clearly define their career goals, within the context of the booming and ever-growing quantum market, before pursuing a specific degree. The skills you acquire with a quantum degree are also highly transferable to other fields, meaning there are lots of alternatives out there even if you can't find the right job in the quantum sphere. For example, experience in data science or software development can complement quantum expertise, making you a versatile and coveted contender in today's job market.

Approaching "quantum advantage": Mark Elo

Last year, IBM broke records by building the first quantum chip with more than 1000 qubits. The project represents millions of dollars of investment and the company is competing with the likes of Intel and Google to achieve "quantum advantage", which refers to a quantum computer that can solve problems that are out of reach for classical machines.

iStock/Olemedia

Risk and reward "The right technical skills will always allow you to switch industries if needed."

Despite the hype, there is work to be done before the technology becomes widespread – a commercial quantum computer needs millions of qubits, and challenges in error correction and algorithm efficiency must be addressed.

"We're trying to move it away from a science experiment to something that's more an industrial product," says Mark Elo, chief marketing officer at Tabor Electronics. Tabor has been building electronic signal equipment for more than 50 years and recently started applying this technology to quantum computing. The company's focus is on control systems – classical electronic signals that interact with quantum states. At the 2024 APS March Meeting, Tabor, alongside its partners FormFactor and QuantWare, unveiled the first stage of the Echo-5Q project, a five-qubit quantum computer.

Elo describes the five years he's worked on quantum computing as a period of significant change. Whereas researchers once relied on "disparate pieces of equipment" to build experiments, he says that the industry has changed such that "there are [now] products designed specifically for quantum computing".

The ultimate goal of companies like Tabor is a "full-stack" solution where software and hardware are integrated into a single platform. However, the practicalities of commercializing quantum computing require a workforce with the right skills. Two years ago the consultancy company McKinsey reported that companies were already struggling to recruit, and they predicted that by 2025, half of the jobs in quantum computing will not be filled. Like many in the industry, Elo sees skills gaps in the sector that must be addressed to realize the potential of quantum technology.

Elo's background is in solid-state electronics, and he worked for nearly three decades on radio-frequency engineering for companies including HP and Keithley. Most quantum-computing control systems use radio waves to interface with the qubits, so when he moved to Tabor in 2019, Elo saw his career come "full circle", combining the knowledge from his degree with his industry experience. "It's been like a fusion of two technologies" he says.

It's at this interface between physics and electronic engineering where Elo sees a skills shortage developing. "You need some level of electrical engineering and radio-frequency knowledge to lay out a quantum chip," he explains. "The most common qubit is a transmon, and that is all driven by radio waves. Deep knowledge of how radio waves propagate through cables, through connectors, through the sub-assemblies and the amplifiers in the refrigeration unit is very important." Elo encourages physics students interested in quantum computing to consider adding engineering – specifically radio-frequency electronics – courses to their curricula.

> There are some geniuses in the world, but if they can't communicate it's no good in an industrial environment

Transferable skills

The Tabor team brings together engineers and physicists, but there are some universal skills it looks for when recruiting. People skills, for example, are a must. "There are some geniuses in the world, but if they can't communicate it's no good in an industrial environment," says Elo.

Elo describes his work as "super exciting" and says "I feel lucky in the career and the technology I've been involved in because I got to ride the wave of the cellular revolution all the way up to 5G and now I'm on to the next new technology." However, because quantum is an emerging field, he thinks that graduates need to be comfortable with some risk before embarking on a career. He explains that companies don't always make money right now in the quantum sector – "you spend a lot to make a very small amount". But, as Elo's own career shows, the right technical skills will always allow you to switch industries if needed.

Like many others, Elo is motivated by the excitement of competing to commercialize this new technology. "It's still a market that's full of ideas and people marketing their ideas to raise money," he says. "The real measure of success is to be able to look at when those ideas become profitable. And that's when we know we've crossed a threshold."

Katherine Skipper and **Tushna Commissariat** are features and careers editors of *Physics World*

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Expert tutors open up new horizons for school students

Anyone who has a PhD or is currently studying for one can become a tutor for The Brilliant Club, a charity that aims to inspire young people from disadvantaged backgrounds to make the leap from school to university

The Brilliant Club

Shining Bright By engaging school students with ideas and concepts based on their own research experience, tutors working with The Brilliant Club can provide a first-hand insight into university-style learning.

"I feel so privileged to have the opportunity to spend every day thinking about some of the big unanswered questions," says Hannah Banks, a research fellow studying theoretical particle physics at Cambridge University in the UK. "At school I was very uncertain and almost didn't apply to university, but once I got there it was so liberating to start seeing physics as a field of discovery rather than just a list of facts and formulae to learn."

Banks is a tutor for The Brilliant Club, a UK-based charity set up in 2011 to improve university access for school students from less advantaged backgrounds – defined in this case as living in a deprived part of the UK, being eligible for free school meals, or having no parental history of higher education. By challenging pupils with ideas and concepts that are beyond the confines of the normal school syllabus, The Brilliant Club tutors can offer an insight into the richness and joy of exploring a subject within a more enquiring university environment.

"I wanted to get involved with The Brilliant Club to show young people that science is cool and amazing, and also to make them aware that university might not necessarily be what they think it is," continues Banks. "University changed my life because I was suddenly being asked to take control of my learning and think in different ways, and I want to help young people to see a future in which they can pursue whatever it is that interests them."

The Brilliant Club provides tutor-led courses for around 20,000 pupils every year, and has also introduced a smaller programme to guide and support students who have recently moved into higher education. All of its tutors are either studying for a PhD or already have their doctorate, with the aim of providing school students with a first-hand insight into the university experience.

"We want to harness our tutors' love of learning and knowledge of academic life to inspire a new generation of students," says The Brilliant Club's Zoë Morgan. "Tutors who are passionate about their research, and can bring that to life in a classroom, can have a huge impact on young people who might not otherwise think that university is an option that's open to them."

The charity is particularly keen to recruit new tutors with a background in science, engineering or mathematics, including people who may have moved on from academia. "There is often high demand from schools for physics and maths courses, Hannah Banks

Hannah Banks "I want to help young people to see a future in which they can pursue whatever it is that interests them."

Lauren Martin

Lauren Martin "Opportunities like this gives students the confidence that they can succeed at something that's quite challenging."

but we can find it more difficult to attract tutors in those subjects," says Morgan. "Some of our tutors may have retired or moved into a different profession, and find it really enriching to reconnect with their research and think about it again from a different perspective."

Under the charity's flagship initiative, The Scholars Programme, expert tutors design and deliver a short course of seminars based on their own area of research, with The Brilliant Club providing support and training as well as arranging placements with partner schools. To encourage discussion tutors work with small groups of students, who at the end of the course are expected to complete a university-style final assignment.

"The tutorials are designed to be quite interactive, and for some students the small-group environment is a really positive experience," explains Lauren Martin, another physics tutor who so far has worked with around 350 students in Kent, which operates a selective grammar-school system. "The Brilliant Club works exclusively with students attending non-selective state schools, and opportunities like this can make a real difference because it gives them the confidence that they can succeed at something that's quite challenging."

It may seem daunting to create a course that engages school students with complex scientific concepts, but The Brilliant Club provides plenty of support, training and feedback to help tutors pitch their seminars at the right level. "The Brilliant Club organized a fantastic workshop that showed me how to develop my course by thinking about the learning outcomes I wanted to achieve," comments Banks. "The training made me realize the importance of active learning to get the students involved, by making sure that they work out the solutions for themselves."

The courses are designed to stretch the students' knowledge and understanding beyond the national curriculum, with schools choosing participants who they believe will benefit most from the programme. "We want the courses to challenge the students and emulate the learning environment within a university," says Morgan. "At the end the students also have the opportunity to visit an academic institution to celebrate their graduation, which for many of them will be a completely new experience."

When creating their courses both Martin and Banks took inspiration from the ideas and experiences that first piqued their interest in science. "It was hard to get started, because when you get involved in research it's easy to get so focused on the details that you forget the big picture," recalls Martin. "I went back to the concepts that interested me in physics when I was at school, and so my course explores Einstein's theory of special relativity and how it changes our perception of time, as well as the importance of symmetry in understanding the universe."

Martin also valued the coaching and feedback she received from The Brilliant Club when she was developing the course, as well as from the teacher who arranged her first placement. "It was a great first introduction because the teacher was there during my first session," she explains. "She provided some really useful feedback, to talk a bit slower, to ask questions in a different way, and she gave me some tips on how to engage students who may need more encouragement."

Martin has also tutored younger pupils, although in this case the courses are pre-designed by The Brilliant Club to ensure they are suitable for each specific age group. "For students in the last two years of primary school I have taught a course on statistics, in particular encouraging them to question how they are interpreted," she explains. "For years 7 and 8 we have focused on cracking ciphers and codes."

With ambitions to become a teacher herself, Martin's experiences with The Brilliant Club have helped her to develop vital classroom techniques within a gentler small-group environment. "I have learnt the importance of adapting the session to meets the needs of the people in the room," she says. "If your carefully prepared explanation doesn't work, you need to think on your feet and present the material in a way that works for the students in front of you."

For Banks, who is intent on pursuing a research career, the experience of tutoring school students has helped her to develop the skills needed to communicate her work to scientists working in other areas. "We are always presenting our research results in seminars and conferences, and working with The Brilliant Club has helped me to introduce my work to people who are not focused on the exact same problem," she says. "In research it's important to explain complex topics in an accessible way, and tutoring has helped me to develop those softer skills that are often neglected in formal study."

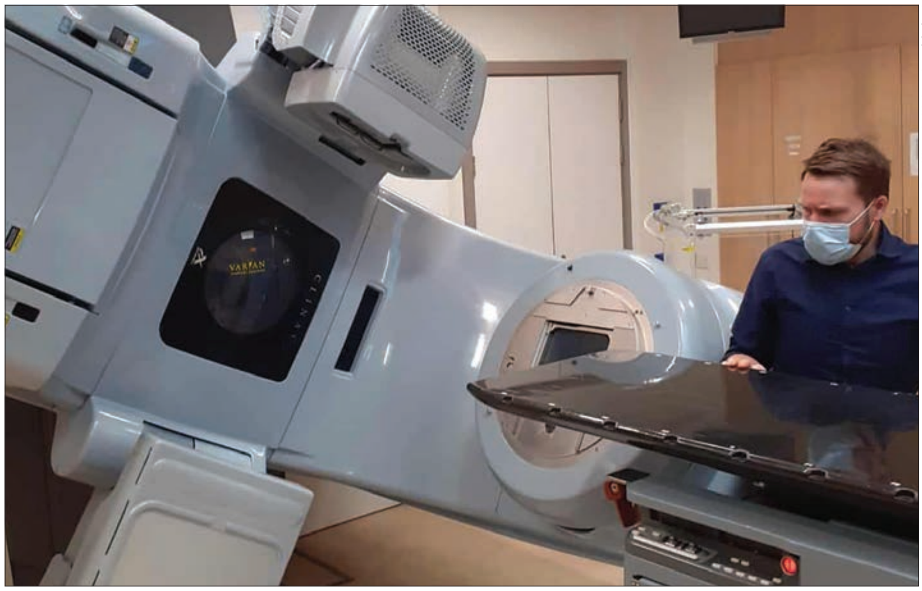
The Brilliant Club pays tutors for their time, but for Martin and Banks the biggest benefit has been the opportunity to inspire young people and introduce them to scientific concepts and ideas they would not normally be exposed to. "I have loved the opportunity to meet all these brilliant kids, and hopefully to pass on my love and passion for science to them," says Banks. "Sometimes you can see the light bulb go on, when they see something differently or have really understood something properly for the first time, and that has been so rewarding."

www.thebrilliantclub.org

This article was written by *Physics World* on behalf of The Brilliant Club. Read more on *physicsworld.com*.

Where radiation physics meets radiobiology: opening up diverse career paths for students

Physics for patients, physics for health, physics for good: that's the high-level career opportunity that awaits students heading to the University of Oxford, UK, this September to take up their places on the newly launched MSc in Medical Physics with Radiobiology



Tom Whyntie/University of Oxford

Targeting the talent pipeline The University of Oxford's new MSc in Medical Physics with Radiobiology gets under way this month, with applications now open for the 2024/25 academic year. Above: a medical physicist demonstrates the rotating gantry of a radiotherapy linac during a clinical visit.

John Cairns/University of Oxford

Daniel McGowan "The flexibility afforded by our MSc is key."

University of Oxford

Tom Whyntie "What we're focused on is the inherent interdisciplinarity spanning physics, biology and medicine."

This one-year, full-time master's programme is tailored for graduate scientists intent on pursuing a professional pathway in medical physics – from a clinical or academic research perspective – as well as related roles that require an in-depth understanding of medical physics (radiation protection and security, for example, or product development and engineering functions within the specialist technology companies serving the medical imaging and radiotherapy communities).

Launching with an initial cohort of 15 students for the 2023/24 academic year, the MSc is a collaboration between the University of Oxford's Department of Oncology and the Department of Medical Physics and Clinical Engineering at Oxford University Hospitals (OUH) NHS Foundation Trust. The academic cycle being what it is, applications are already open for the 2024/25 academic year (starting September 2024) from candidates who hold, or are predicted to achieve, a first-class or strong upper-second-class undergraduate degree with honours in physics or a closely related subject.

"Our teaching priority is to elaborate on how ionizing and non-ionizing radiation are used in clinical practice, both in the context of radiotherapy and medical imaging," explains Daniel McGowan, academic and clinical lead for the MSc (as well as Head of Education and Research in the OUH Department of Medical Physics and Clinical Engineering). That focus on radiation physics is reinforced by dedicated teaching modules on the fundamental principles of radiobiology to give graduate students a granular understanding of the effects of radiation at the molecular and cellular level (for example, how radiation induces DNA damage and how that feeds through into advanced treatment modalities in radiation oncology).

"We're trying to differentiate this MSc versus other medical physics courses by addressing gaps in the learning market," adds McGowan. "So, while radiobiology is front-and-centre, we're also putting significant emphasis on a range of other hot topics that early-career medical physicists increasingly need to understand – from the design of clinical studies, for example, to the clinical impact of machine learning in cancer diagnosis and treatment planning for radiotherapy."

University of Oxford

Nathalie Lövgren Prioritizing collaboration in her DPhil research studies.

Pushing the boundaries in radiation oncology

Nathalie Lövgren is a medical physics student undertaking a DPhil in oncology at the University of Oxford. Here she tells *Physics World* about her research experience to date and the learning opportunities for graduate students considering MSc or doctoral studies within the department.

What's the focus of your DPhil work?
I'm a member of Kristoffer Petersson's multidisciplinary team investigating the biological mechanisms underpinning FLASH radiotherapy and optimal ways to implement the technique in clinical practice. My DPhil work focuses on clinical translation: evaluating the feasibility of deploying FLASH proton therapy into clinical practice and how the FLASH effect (normal tissue-sparing) can be accounted for in the treatment planning system.

How important is collaboration to you as an early-career scientist?
It's fundamental – and essential. The Department of Oncology is a cosmopolitan research environment, with visiting doctoral students from other UK and EU institutions conducting their research with us in Oxford, either coming for weeks or months at a time. For me personally, that means exposure to diverse research backgrounds, cross-fertilization of ideas, and an opportunity to build up a network across the medical physics and oncology communities.

What about opportunities for learning and development beyond your core research?
We're encouraged to push the boundaries in terms of our broader skills development, prioritizing opportunities that will be useful to us down the line in our research careers. A case in point: I've just enrolled on a seven-month online Python course – Training in Data Science and Machine Learning for Health, Disease and Bioscience – at University College London. The course coverage forms a great base for a wide range of programming or machine-learning-based projects in the future. Outreach and engagement are also key. I've presented my research at several international conferences so far and, in the process, have initiated valuable contacts and collaborations with other early-career scientists as well as radiotherapy equipment vendors.

No shortage of options

Another focus for McGowan and his teaching colleagues is to showcase the diversity of career pathways available to graduates pursuing combined studies in medical physics and radiobiology.

One way to help students figure out their next steps is the extensive guest speaker programme within the department of oncology – whether that's a clinical physicist talking about the implementation of MR-guided radiotherapy in a hospital setting or an R&D scientist from industry specializing in imaging software. "The flexibility afforded by our MSc is key," he explains. "As such, we encourage students to maintain an open mind about their long-term career choices."

By extension, choice and flexibility are hard-wired into the MSc research project and dissertation – a piece of work that's undertaken after students complete their six months of MSc taught-course modules. The 2023/24 cohort will have a long list of research projects to choose from, including experimental studies in FLASH radiotherapy (to elucidate how radiation delivered at ultrahigh dose rates can drastically reduce collateral damage and toxicity in normal healthy tissue while preserving anti-tumour activity); patient safety and QA in MR-guided radiotherapy (in which an MR-Linac configuration allows clinicians to see what they treat in real-time and adapt radiation delivery accordingly); as well as investigations into the use of virtual reality for improving the patient experience.

Wanted: multidisciplinary physicists

Other project options include the provision of targeted R&D support to industry partners – for example, on the testing and optimization of advanced imaging algorithms for PET or MRI systems – or collaboration with government scientists specializing in radiation protection, safety and regulation at the nearby Harwell campus of the UK Health Security Agency (UKHSA).

Alongside the twin-track focus on medical physics and radiobiology, another differentiator of the new MSc course is the opportunity it affords students to learn directly from clinical physicists working at the sharp-end of diagnosis and treatment in a hospital setting at OUH. "What we're focused on is the inherent interdisciplinarity spanning physics, biology and medicine," notes Tom Whyntie, a teaching fellow in the Department of Oncology with responsibility for MSc student learning and development.

Whyntie himself took a somewhat convoluted route into medical physics, having completed a PhD in dark-matter research at CERN's Large Hadron Collider (LHC). "Given my background, I recognize the importance of blue-sky physics that's driven, for the most part, by intellectual curiosity," he explains. "What blows me away about my current research – developing novel pulse sequences for MR-guided radiotherapy – is seeing the direct impact of the work on treatment outcomes and patient care. This is physics in action – that straight line between research lab, clinical translation and at-scale clinical application."

• The Institute of Physics and Engineering in Medicine (IPEM) accredits master's programmes in medical physics and biomedical engineering in the UK. Given that it is a new course for the 2023/24 academic year, the University of Oxford's MSc in Medical Physics with Radiobiology has provisional accreditation status from IPEM. The course will be subject to further inspection for full accreditation once the first cohort of students completes the taught-course and research modules in autumn 2024, with the initial cohort and subsequent student intakes receiving the IPEM-accredited degree qualification.

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The route to ‘net zero’: how the manufacturing industry can help

Research teams at Cranfield University in the UK are developing novel materials and processes in the quest for greener, more sustainable manufacturing

Cranfield University

Towards a greener future Cranfield University aims to make the manufacturing industry more sustainable.

The manufacturing industry is one of the largest emitters of carbon dioxide and other greenhouse gases worldwide. Manufacturing inherently consumes large amounts of energy and raw materials, and while the sector still relies mainly on fossil fuels, it generates emissions that directly contribute to climate change and environmental pollution. To combat global warming and its potentially devastating impact upon our planet, there’s an urgent need for the manufacturing industry to move towards net zero operation.

Cranfield University, a specialist postgraduate university in the UK, is working to help the industry achieve this task. Teams at the university’s science, technology and engineering centres are devising ways to accelerate the journey towards more sustainable manufacturing – whether by introducing manufacturing processes that use less energy and raw materials; investigating renewable and low-carbon energy sources; creating new materials with enhanced recyclability; or implementing smart functions that extend the life of existing assets.

Greener manufacturing

One way to lower the carbon footprint of manufacturing is to move to 3D printing, an additive fabrication technique that inherently reduces waste.

“The machining techniques used in conventional manufacturing require a lot of power and a lot of raw material, which itself requires energy to create,” explains Muhammad Khan, acting head of Cranfield’s Centre for Life-cycle Engineering and Management and reader in damage mechanics. “In 3D printing, however, the amount of power required to generate the same complex part is far less, which impacts the overall carbon footprint.”

Materials used for 3D printing, particularly polymeric or other organic materials, are generally recyclable and easier to reuse, further reducing emissions. “Within our centre, we are working on polymeric materials to replace existing metallic materials in areas such as aerospace and automotive applications,” says Khan.

3D printing also enables manufacturers to rapidly tailor the design and properties of a product to meet changing requirements.

“We’ve seen this a lot in Formula One,” says David Ayre, a senior lecturer in composites and polymers in Cranfield University’s Composites and Advanced Materials Centre. “They’ll 3D print prototyping materials to quickly push out the structures they need on their cars. Twenty years ago, the resins used for this were brittle and only suitable for prototyping. But now we have developed more robust resins that can actually be used on working structures.”

Another benefit of 3D printing is that it can be performed on a smaller scale, enabling manufacturing sites to be installed locally. This could be next to the resource that the printer will use or next to the consumers that are going to use it; in either case, reducing transportation costs. While the cost implications of this “end of the street” model haven’t yet won through, the pressure to reduce CO^2 emissions “might be the driver that starts to change the way we look at manufacturing”, Ayre notes.

Recycling opportunities

The introduction of novel advanced materials can also help increase sustainability. Thermal barrier coatings developed at Cranfield, for example, enable jet engines to work at higher temperatures, increasing efficiency and reducing fuel consumption. “There’s a huge role for engineers to play,” says Ayre.

Designing materials that can be recycled and reused is another important task for Ayre’s team. Producing raw material requires vast amounts of energy, a step that can be eliminated by recycling. Aluminium, for instance, is easy to process, highly recyclable and used to create a vast spectrum of products. But there are still some challenges to address, says Ayre.

“The aerospace industry likes to machine parts. They’ll take a one tonne billet of aluminium and end up with a 100 kg part,” he explains. “I worked with a student last year looking at how to recycle the swarf that comes from that machining. Unfortunately, aluminium is quite reactive and the

Cranfield University

David Ayre "It's important that everyone makes a move towards net zero, because we're not going to make any impact unless the whole world is on board."

Cranfield University

Muhammad Khan "If you can extend device life by utilizing smart mechanisms, this can positively contribute to the net zero agenda."

The machining techniques used in conventional manufacturing require a lot of power and a lot of raw material, which itself requires energy to create

swarf oxidizes back to the ore state, where it's not really easy to recycle. These are the sorts of issues that we need to get around."

The centre also focuses on composite materials, such as those used to manufacture wind turbine blades. Ayre notes that turbine blades built in the 1970s are now reaching the end of their usable life – and the composites they're made from are difficult to recycle. The team is working to find ways to recycle these materials, though Ayre points out that it was such composites that enabled growth in the wind turbine market and the resulting source of renewable energy.

Alongside, the researchers are developing recyclable composite materials, such as bioresins and fibres produced from natural products, although work is still at an early stage. "These materials don't have the same properties as petroleum-derived resins and ceramic, carbon and glass fibres," Ayre says. "I don't think we're close yet to being able to replace our super-lightweight, super-stiff carbon fibre composite structures that motorsport and aerospace are utilizing."

Smart materials

Meanwhile, Khan's team at Cranfield is developing materials with smart functionalities, such as self-healing, self-cleaning or integrated sensing. One project involves replacing domestic pipelines used for wastewater distribution with 3D-printed self-cleaning structures. This will reduce water requirements compared with conventional pipelines, reducing the overall carbon footprint.

With a focus on maintaining existing assets, rather than creating new ones, the researchers are also developing self-healing structures that can repair themselves after any damage. "If you can extend device life twice or thrice by utilizing these smart mechanisms, you can reduce the amount of raw material used and the emissions generated during manufacturing of replacement parts," says Khan. "This can positively contribute to the net zero agenda."

Another project involves developing structures with integrated sensing functionality. Such devices, which monitor their own health by providing information such as displacement or vibration responses, eliminate the need to employ external sensors that require energy to construct and operate. The diagnostic data could provide users with an early warning of signs of damage or help determine the remaining useful life of a structure.

"Life estimation is challenging, but is something we are looking to incorporate in the future – how we can utilize the raw data from embedded sensing elements to model the remaining useful life," says Khan. "That prediction could allow users to plan maintenance and replacement routines, and save a system from catastrophic failure."

Building for the future

Cranfield University also aims to embed this sense of sustainability in its students – the engineers of the future – with a focus on net zero integral to all its engineering and related courses.

"The majority of our manufacturing and materials students will go on to an engineering career and need to appreciate their role in sourcing sustainable materials for any parts they're designing and investigating manufacturing routes with low CO^2 footprint," Ayre explains. Students also learn about asset management – choosing the right product in the initial stages to minimize maintenance costs and extend a component's life.

Elsewhere, Khan is working to ensure that standards agencies keep sustainability in mind. His centre is part of a consortium aiming to bring the goal of achieving net zero into standards. The team recently demonstrated how the existing asset management standard – ISO 15,000 – can be modified to incorporate net zero elements. The next step is to convince ISO and other agencies to accept these concepts, allowing people to manage their assets in a more environmentally friendly way without compromising availability or performance.

Ultimately, says Ayre, alongside "trying to encourage humanity not to want more and more and more", lowering global emissions could rely on engineers getting creative and finding innovative ways to produce products that people want, but at reduced cost to the environment. It's also vital that customers take on these ideas. "There's no point us coming up with new-fangled manufacturing process and new materials if nobody has the experience or the confidence to take it anywhere," he points out.

"It's important that everyone makes a move towards net zero, because we're not going to make any impact unless the whole world is on board," says Ayre.

This article was written by *Physics World* on behalf of Cranfield University. Read more on *physicsworld.com*.