How can we measure time?

Learning to tell the time is one of the key skills we are taught as children; but take a moment to think about it, and you may find the concept of time slipping away from you. How do we know how long a second is? Where did minutes come from? How do we actually measure time? At the **University of Queensland** in Australia, **Stefan Zeppetzauer** is using quantum mechanics to investigate time – one of the most familiar but least understood concepts in physics!

Stefan Zeppetzauer

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PROFILE

Field of research
Quantum engineering

Research project
Exploring the limits of measuring time with quantum clocks

Funders
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Talk like a ... quantum engineer

Absolute zero — the lowest temperature that is theoretically possible

Dilution refrigerator — a device used for maintaining very low temperatures

Electric current — the flow of charged particles through a space

Electrical resistance — a measure of how well an object can oppose an electrical current

Kelvin — a scale for measuring temperature

Noise — unwanted irregularities and fluctuations that mask the useful information in a signal

Oscillation — a back and forth movement in a regular rhythm

Quantum clock — a clock that uses oscillations in quantum systems, such as atoms, to measure time

Resonator — a device used in physics that oscillates with greater amplitude at certain frequencies

Superconducting resonator — a thin metal strip of a superconducting metal, such as aluminium, on an underlying layer

Superconductivity — a complete absence of electrical resistance that allows an electric current to continue indefinitely

When the big hand and the little hand are both pointing up, it's twelve O'clock. There are 60 seconds in a minute, and 60 minutes in an hour. At three O'clock (or thereabouts), it's the end of the school day. Although learning to tell the time is one of the first things that we are taught in school, it is a concept that physicists are still trying to understand.

"Is time continuous, or is there a smallest possible unit of time? Is time a fundamental property of our Universe, or does it emerge from a deeper, underlying principle? And is there a limit to how precisely time can be measured?" asks Stefan Zeppetzauer, a PhD student researching time and quantum clocks at the University of Queensland.

These are just some of the elusive questions that quantum engineers like Stefan are trying to answer. "In quantum mechanics, time is often represented as a parameter, typically denoted as 't', without much consideration," says Stefan. But what really is time, and how do we understand it?

A history of clocks

Clocks are devices that allow us to measure time, so they are crucial for investigating these questions.

Clocks work by using frequency references, which are devices that oscillate at set intervals and allow the passage of time to be measured. When clocks were first invented, the frequency references used were pendulums, like those found in grandfather clocks.

In 1927, scientists invented quartz clocks, in which a quartz crystal is used as the frequency reference. An electrical current causes the quartz crystal to oscillate precisely 32,768 times a second, and these oscillations keep the clock in


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time. Quartz clocks are still used today in watches and mobile phones but, unfortunately, they can be influenced by changes in temperature and pressure, which can reduce their accuracy.

More recently, scientists have discovered atomic clocks, which are far more accurate.

Atomic clocks

Instead of pendulums or pieces of quartz, atoms can be used in clocks as frequency references. This is because atoms of the same element are identical and produce exactly the same frequency when struck by a laser, allowing them to be nearly perfect indicators of time.

This discovery was such a breakthrough for measuring time that, in 1967, the definition of a second was changed to be the time that it takes a specific type of caesium atom, caesium-133, to oscillate 9,192,631,770 times!

Atomic clocks are already used around the world, most notably in global positioning system (GPS) technology. GPS satellites need to be extremely accurate when sending and receiving signals. If they are off by even one microsecond, the inaccuracy can cause a location difference of up to 300 metres on the ground.

So, what limits are there on timekeeping now that we have atomic clocks, and how accurate can atomic clocks be? Stefan has been building a quantum clock, a specific type of atomic clock, with the goal of answering these questions.

Investigating time on a quantum clock

"Investigating the limits of timekeeping requires an understanding of the factors that inhibit the performance of today's clocks, in particular 'noise'," says Stefan. Currently, quantum clocks are limited by both quantum and classical noise. "While classical noise, such as the temperature and pressure changes that affect quartz clocks, can be reduced, quantum noise is a fundamental property of any quantum system and cannot be avoided," explains Stefan.

In many cases, the performance of a quantum clock is still limited by classical noise. Stefan has built a quantum clock and is designing an experiment that lets him look past this classical noise to investigate the limits that quantum noise imposes on the performance of a quantum clock.

Building a quantum clock

To build a quantum clock, Stefan used superconducting resonators, which are thin metal strips that allow electrical currents to flow through them without resistance.

"In order for the clock to work, we have to cool it to around ten milli-Kelvin above absolute zero using a dilution refrigerator in our lab," says Stefan. "This makes the resonators superconducting and allows for long-lived oscillations in the resonators, which would not be possible at room temperature."

"Our clock is special in that we avoid a significant source of classical noise stemming from the measurement-based feedback used in other clocks," Stefan continues. Measurement-based feedback involves acquiring information about a system through measurement and then adjusting the input based on that information. However, quantum states are fragile and this type of feedback introduces noise, degrading the quantum state and limiting the accuracy of the clock.

To avoid the issues caused by measurement-based feedback, Stefan's clock relies on something called coherent feedback.

Coherent feedback, which is only possible in quantum systems, allows quantum states to persist by avoiding the need for measurements which could disturb these fragile systems. An example of a coherent feedback device is a mirror reflecting single photons back to the emitter. No measurement is taken, but the photons can still influence (feed back on) the subsequent behaviour of the emitter. In Stefan's clock, the feedback is provided by the special properties of two superconducting resonators which allow them to stabilise themselves without external feedback.

By removing the noise caused by measurement-based feedback in classical clocks, Stefan is able to look directly at the effects of quantum noise instead.

What has Stefan discovered so far?

"Last year, we showed that stable oscillations exist in our system, which we had not done before," says Stefan.

Stefan is close to finishing the analysis for this project and hopes to publish his results soon. "The next step is to explore how the quantum noise of our clock is related to its accuracy and resolution, and if there is a fundamental limit to its performance," says Stefan. "Although our clock is not comparable to the most advanced clocks currently available, it serves as a novel tool to deepen our understanding of the fundamental limits of timekeeping and, ultimately, the nature of time itself."

About *quantum engineering*

Quantum engineering is becoming an increasingly exciting and important field. Quantum clocks are already essential devices for GPS satellite navigation, and there has been a steady increase in investment and interest in these clocks in recent years.

Quantum engineering can be applied to numerous areas, and may be useful in fields as diverse as medicine and computing. “Quantum sensing, for example, allows us to measure magnetic fields more precisely than with any classical sensor, and has helped researchers to improve the quality of image-taking in microscopy and medicine,” says Stefan.

Quantum engineers use just atoms, theories and equations to get started on their work. “We design and build artificial quantum systems instead of only using what is provided by nature. It’s incredibly rewarding to see a device that I designed from scratch, after months of fabrication and preparation, finally functioning in the lab,” says Stefan. “Since everything in quantum engineering is designed by researchers, we can tailor the properties of our systems to what we need. It’s amazing to see how well we can control the properties of our engineered quantum systems nowadays.”

There is also lots of excitement around quantum computers, which may be a possibility in the near future! Read this Futurum article to learn more: **www.futurumcareers.com/why-is-it-hard-to-build-quantum-computers**.

What are some of the challenges in quantum engineering?

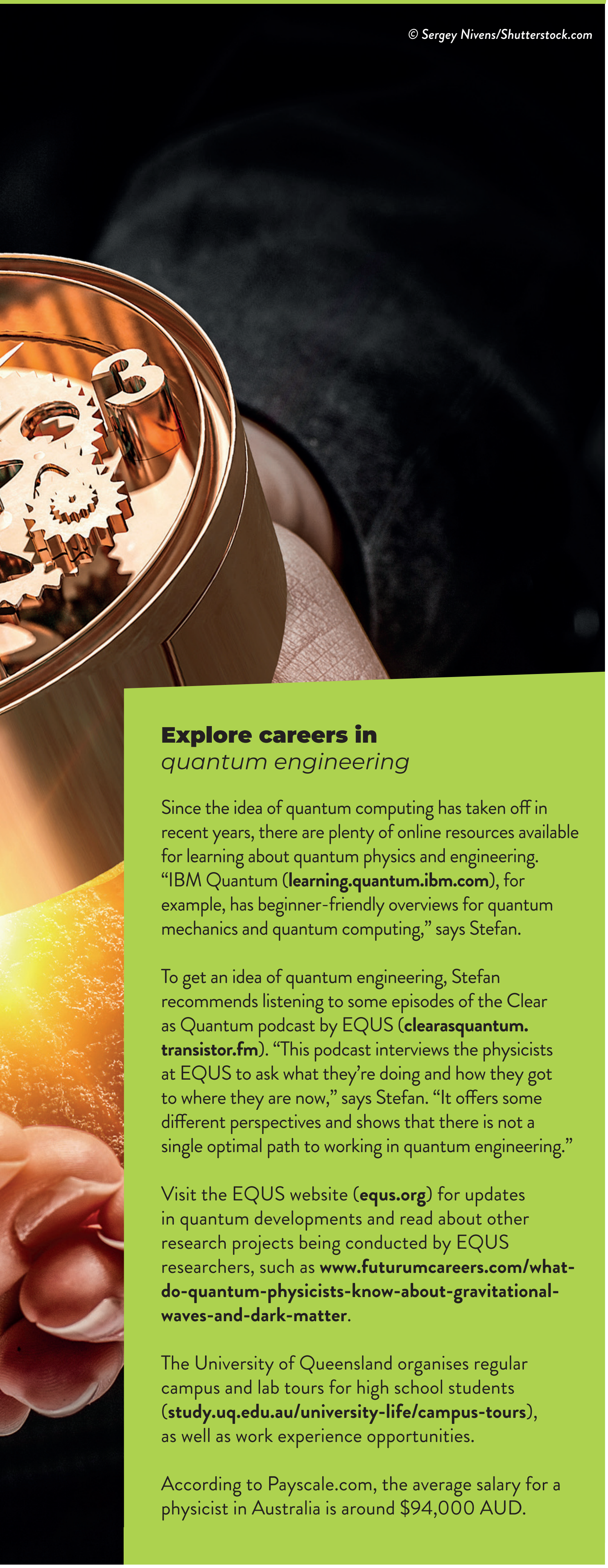
“The challenges of working in quantum engineering often depend on the specifics of the system being used,” says Stefan. There are several challenges that are related specifically to superconducting circuits. “For superconducting circuits to behave ‘quantumly’, we need to cool them to around ten milli-Kelvin, which requires special and expensive refrigerators,” explains Stefan. “And, since our circuits consist of thin metal strips on an underlying substrate, there will always be some defects and imperfections that limit the lifetime of our quantum states. New materials and cleaning procedures have led to continuous improvements in that regard, but there is still much to be done.”

Pathway from school to *quantum engineering*

In school and beyond, choose to study mathematics, physics and any other science or computing subjects. “University courses can be quite different to how high school classes are taught,” says Stefan. He recommends watching a quantum physics lecture online or, if you can, attending one in person to get a realistic idea of what studying quantum engineering involves.

“While some universities have started offering quantum engineering degrees, the most straightforward route today is to study physics and focus on courses in quantum mechanics,” says Stefan. However, there is not one correct way to become a quantum engineer. “Not everyone goes from high school straight to an undergraduate degree in physics,” says Stefan. “We have people from engineering, mathematics and computer science at EQUS and one of the Chief Investigators used to be a doctor.”

Quantum engineering also relies on coding and computer programming, so taking courses in computer science or electrical engineering can be useful.



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Explore careers in *quantum engineering*

Since the idea of quantum computing has taken off in recent years, there are plenty of online resources available for learning about quantum physics and engineering. "IBM Quantum (**learning.quantum.ibm.com**), for example, has beginner-friendly overviews for quantum mechanics and quantum computing," says Stefan.

To get an idea of quantum engineering, Stefan recommends listening to some episodes of the Clear as Quantum podcast by EQUS (**clearasquantum.transistor.fm**). "This podcast interviews the physicists at EQUS to ask what they're doing and how they got to where they are now," says Stefan. "It offers some different perspectives and shows that there is not a single optimal path to working in quantum engineering."

Visit the EQUS website (**equs.org**) for updates in quantum developments and read about other research projects being conducted by EQUS researchers, such as **www.futurumcareers.com/what-do-quantum-physicists-know-about-gravitational-waves-and-dark-matter**.

The University of Queensland organises regular campus and lab tours for high school students (**study.uq.edu.au/university-life/campus-tours**), as well as work experience opportunities.

According to Payscale.com, the average salary for a physicist in Australia is around $94,000 AUD.

Q&A

Meet *Stefan*

What were you interested in as a teenager?

I was always fascinated by the Universe and space science, so I wanted to become an astronaut. When I got older, that seemed unrealistic, so after high school and mandatory social service, I enrolled in astronomy at the University of Vienna. During my second year, I attended a lecture about quantum mechanics where I learned about entanglement and entanglement swapping, which fascinated me because it sounded so weird and contradictory to everyday life. Shortly after, I switched to physics and have been studying and working in quantum mechanics ever since. (Read this Futurum article to learn about entanglement: **futurumcareers.com/can-quantum-physics-make-the-internet-more-secure**).

What do you love about quantum engineering?

I'm still regularly amazed by the new things people discover and develop using theories that have been around for 100 years.

What is it like studying quantum engineering?

This is true for most subjects, but the learning curve, especially at the beginning, is very steep. If you're not genuinely interested in what you're doing or unwilling to put the time in, you will have a hard and unenjoyable time.

What do you do to unwind from work?

During my undergraduate degree, I did martial arts and Krav Maga (a form of self-defence) to get my mind off work. Nowadays, I mostly go to the gym and run which I find to be very relaxing, almost meditative, activities. I also like to just sit and read to get some time away from screens.

Stefan's *top tip*

Attend open days and career fairs, and talk to people in the field you're interested in. The reality of working in a particular field can differ significantly to what you might imagine, so it's important to know what to expect before committing to it.