Take a seashell and lift it to your ear and you will hear the sound of the ocean, swirling, crashing. If you lift a crystal to your ear, the only sound you are likely to hear is laughter from those around you. Take a walk through the basement labs of UWA’s School of Physics. Hear the sound of your footsteps resonating through the halls, loud and distinguished in the quiet stillness. A similar thing is happening inside a sapphire in Jeremy Bourhill’s lab.

Jeremy, a PhD student and winner of the Muriel and Colin Ramm Medal and Scholarship in Experimental Physics in 2011, is currently working on resonance within sapphire crystals. In July 2015 Jeremy supervised students from Beijing Normal University who were here as part of a research outreach programme. As part of the programme they simulated crystal impurities using software (for more information on crystal impurities, see Issue 3 of Particles) and he helped teach them a technique to characterise microwave resonances in crystals, an important element of his own work.

Inside Jeremy’s lab, photons (the particles that make up microwaves and light) bounce around the inside walls of a sapphire crystal. Round and round, the continuous signal oscillates more than a billion times a second. This signal is used to detect the tiniest physical fluctuations of the crystal. In order to do this as accurately as possible, all sources of extra ‘noise’ must be eliminated. That is the goal of Jeremy’s work.

The universe is full of ‘noise’, even when seemingly silent to our ears. There is a blanket of oscillating waves of energy that envelops our entire universe, most of which cannot be perceived by human senses. This includes sound, light, radio signals, and hypothetically even gravity. However, the human ear can only detect frequencies from 20Hz to 20kHz on average, and the human eye is limited to the visual spectrum of light. We are essentially ignorant to the vast, invisible world of waves that surround us. Even the basic building blocks of matter, the atoms that we and the rest of the universe are made of, are creating ‘noise’ by vibrating. The key to Jeremy’s experiment is limiting all this interfering noise, to make his results as accurate as possible. Only then...
will we be able to detect signals previously beyond our reach.

When photons enter a sapphire crystal, it oscillates at a certain frequency. Mechanical motion changes the dimensions of the device, creating a frequency shift which can be measured. You can think of this like a trombone; the motion of the instrument’s arm sliding changes the length the air has to travel, thus changing its resonant frequency. On a quantum scale, Jeremy’s experiment investigates the interaction between photons and phonons (the particles of mechanical vibration). For really small devices, a tiny amount of motion will create a relatively large frequency shift, whereas larger devices will have a much smaller change in frequency.

The extra ‘noise’ that exists all around us also contributes to this frequency shift, so to get a more accurate measurement we need to eliminate all the sources of unwanted noise. Jeremy says “Think of it like draining a pool so you can see what’s at the bottom.” Phase noise, which is broadband noise that exists everywhere at all frequencies, and narrowband noise, which in this case is thermal noise that comes from the vibration of particles. If you want to measure these very small signals from the device, you have to get rid of this blanket of noise, otherwise it’s going to overpower the signal and reduce the accuracy of your measurements.

“Think of it like draining a pool to see what’s at the bottom.”

Jeremy uses several tricks to get rid of this noise. For example, the temperature can be reduced by putting the device in UWA’s state-of-the-art BlueFors cryogenic refrigerator, which can go down to 7 milliKelvin, or 0.007 degrees above absolute zero. This brings the word ‘cold’ to a whole new level!

When that extra noise has been eliminated, the noise from quantum fluctuations is all that remains. These arise from Heisenberg’s Uncertainty Principle, which states that there’s a limit to the amount that can be known about the position and speed of any particular object. So if you knew precisely where a particle was, you would know nothing about where it’s going or its speed. By improving the accuracy and reducing the uncertainty, that fundamental limit can be reached. That is called being quantum limited, and that is the goal of Jeremy’s experiments; to get to that level of precision.

Jeremy describes his area of work as a burgeoning field that is growing in popularity. It has applications in gravitational research, including the search for quantum gravity. This has been a part of UWA’s story for a while now; in 1990 the Australian International Gravitational Research Centre was established by Professor David Blair in the School of Physics to focus on gravitational astronomy and the detection of gravity waves. Jeremy has based his experiment around a smaller scale gravity wave bar.

Most of the experiments designed to detect gravity waves are on the macroscopic scales. In the past, detectors used niobium bars that weighed around a tonne, but there have also been devices that are only 2mm thick, such as the one created by Dr Maxim Goryachev and Professor Michael Tobar (one of Jeremy’s supervisors) in 2014. Jeremy’s experiment weighs in at 0.53 kilograms, and could be considered either a very large optomechanical experiment or a very small gravity wave bar. However, the most interesting aspect of Jeremy’s experimental setup isn’t its size, but its unique dumbbell shape.

Other experiments in the same mass range use cylindrical sapphires, as they are an obvious choice for a continuous circular signal and the sapphires natural low loss properties; this means they maintain most of their photons and are very quiet. Jeremy’s dumbbell has additional properties as it is essentially two cylinders. The sapphire dumbbell gives phase noise a real workout: by having two optical resonators within one mechanical resonator, the two signals cancel out more of the unwanted phase noise. This further increases accuracy.

“We’ve built the lowest phase noise sapphire oscillator at the particular frequency range of 100 kHz. Our mechanical performance is as good as other experiments, with our unique architecture and without using fancy cooling techniques.”

However, it isn’t always smooth sailing in quantum physics. The instruments are extremely sensitive and require careful handling - you don't want any...
fingerprints on the sapphire. The dumbbell has to be suspended from an extremely thin piece of wire, and threading and tying can be very tricky. "Sometimes I can do it in 5 minutes, sometimes it takes half an hour. It's a very finicky little thing", Jeremy says.

But all the hard work is worth it for the final outcomes. Jeremy believes that, "The best results are the ones that surprise you. It happens occasionally, and it's exciting when you see something you didn't expect at all. There's a lot of frustration involved. You sort of need to learn to laugh at it, or you'll go insane."

Despite the trials and tribulations of physics, Jeremy's work has important implications in the search for quantum gravity.

Gravity is one of the four fundamental forces of our universe, alongside electromagnetism, and the strong and weak nuclear forces. Einstein's theory of general relativity describes gravity as the curvature of spacetime, but this description is not reconcilable with quantum mechanics, the study of physics at extremely small scales.

Gravity is extremely weak compared to the other forces, which makes it difficult to detect. All other noise must be reduced as much as possible to have any chance at all of detecting the elusive gravity waves. Gravity waves are predicted by Einstein's general relativity as being ripples that travel through our universe at the speed of light, created by the gravity of large masses such as supernovae and blackholes. These gravity waves are like soft whispers of faraway stories undulating through the fabric of our universe. To detect these whispers you would need equipment sensitive enough to detect a butterfly flapping its wings in North America all the way from Australia. The results of Jeremy's experiment can be used to help increase the sensitivity of said equipment.

You're probably wondering where gravity fits into the resonance of sapphires. As explained earlier, once you get rid of all the noise in your measurements, you'll reach the fundamental limit of accuracy. But if that limit is higher than expected, then you must be detecting some other fundamental quantum mechanical noise on top of what Heisenberg's uncertainty principle predicts. That could be gravity.

**“The best results are the ones that surprise you.”**

The detection of quantum gravity would provide another way to link general relativity and quantum mechanics, as there would be an explanation for gravity in each. Currently, calculations involving general relativity and quantum mechanics are messy and often lead to nasty infinities, but with the discovery of quantum gravity we would be one step closer to a unified 'theory of everything'.

If all this talk of gravity is weighing you down, you'll be relieved to hear that the process of creating a signal without any noise has every day applications too. By getting a measurement as accurate as possible we can improve devices that rely on extremely precise measurements of time. This is because the signal bounces off the wall of the sapphire at regular intervals and this can be counted and used like the pendulum of a grandfather clock, except it is far more accurate as there are a lot more signals per second.

More accurate timing devices have countless uses; from the obvious race timing or improved clocks to GPS. When determining your location, your GPS signals two satellites, which signal back. The difference in time between the returning signals allows the GPS to determine your location. If the difference in time between those signals can be made more accurate, so can the GPS. This becomes even more important in developments in self driving cars - you wouldn't want your car to miss a turn when you're late for work!

So maybe next time you see a sapphire you won't think of it as a mere piece of jewelry; maybe you will be reminded of the world of gravity, quantum limits and resonance. Maybe you too will want to listen in on the whisperings of the universe...
Heads Up!

In addition to its role as a teaching and research institution, one of the visions of the founders of UWA was that it would serve the community. This has recently been recognised by the creation of a new position on the Executive, Deputy Vice Chancellor Community and Engagement. Whilst it is likely that the origin vision of community was Western Australia, we now operate in a global community, our engagement as a university is both local and international.

For a long time, the School of Physics has had engagement as part of its mission. Initiated by Lance Maschmedt, and now run by our School Manager Jay Jay with able assistance from Joe Coletti, the School hosts visits by high school students from about 30 High Schools annually to undertake a range of ‘hands-on’ activities demonstrating fundamental principles of physics. Liquid nitrogen is a very popular element in these demonstrations, with freezing of flowers and leaves (and then shattering them!) and freezing a lead bell so that it produces more than a dull thud providing illustrations of materials physics, and shrinking balloons in a bath of liquid nitrogen providing graphic illustration of the ideal gas laws. Other activities include spinning bicycle wheels to illustrate gyroscopic effects, and electrical experiments including eddy currents and a dramatic demonstration of Lenz’s law with the ‘jumping rings.’ A recent addition has been a spectacular levitated ‘train’ using high temperature superconductors. An important part of this outreach is the involvement of undergraduate and postgraduate students as demonstrators, and the ‘ patter’ that goes with each demonstration has been passed down through many generations of willing helpers.

Jay Jay is also very active in ensuring that information about developments in the School reach the media, with the result that there are frequent articles about staff and students from the School of Physics in local newspapers. A recent new avenue for outreach has been live television appearances by some of our postgraduates and early career postdoctoral researchers on local community television via a programme called “The Couch.” For a taste, you can see Dr Daniel Creedon telling the public about his research in the Frequency and Quantum Metrology group at this link: http://bit.ly/1YiiVUQ

If you watch Daniel, I think you will agree that he does a great job of dispelling the myth of research physicists as eccentric old professors with weird hair unable to explain to the public what they are doing, let alone why investment in their research is a good use of public money. It is only by reaching out to the community in ways such as this that universities are going to be able to justify their research role in increasingly tough economic climates in which the public question return on tax dollars.

Professor Ian McArthur

School of Physics
The University of Western Australia
35 Stirling Highway
CRAWLEY WA 6009
AUSTRALIA
Phone: + 61 8 6488 2740
Fax: +61 8 6488 7364
Website: wwwwww.physics.uwa.edu.au
CRICOS Provider Code: 00126G

Editorial Team
Editor: Jay Jay Jegathesan
Sub-Editor: Ian McArthur, Jeremy Bourhill
Writers/Contributors: Holly Dear & Paris Javid
Layout & Design: Holly Dear, Paris Javid, Jay Jay Jegathesan
Photographers: Holly Dear & Paris Javid

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