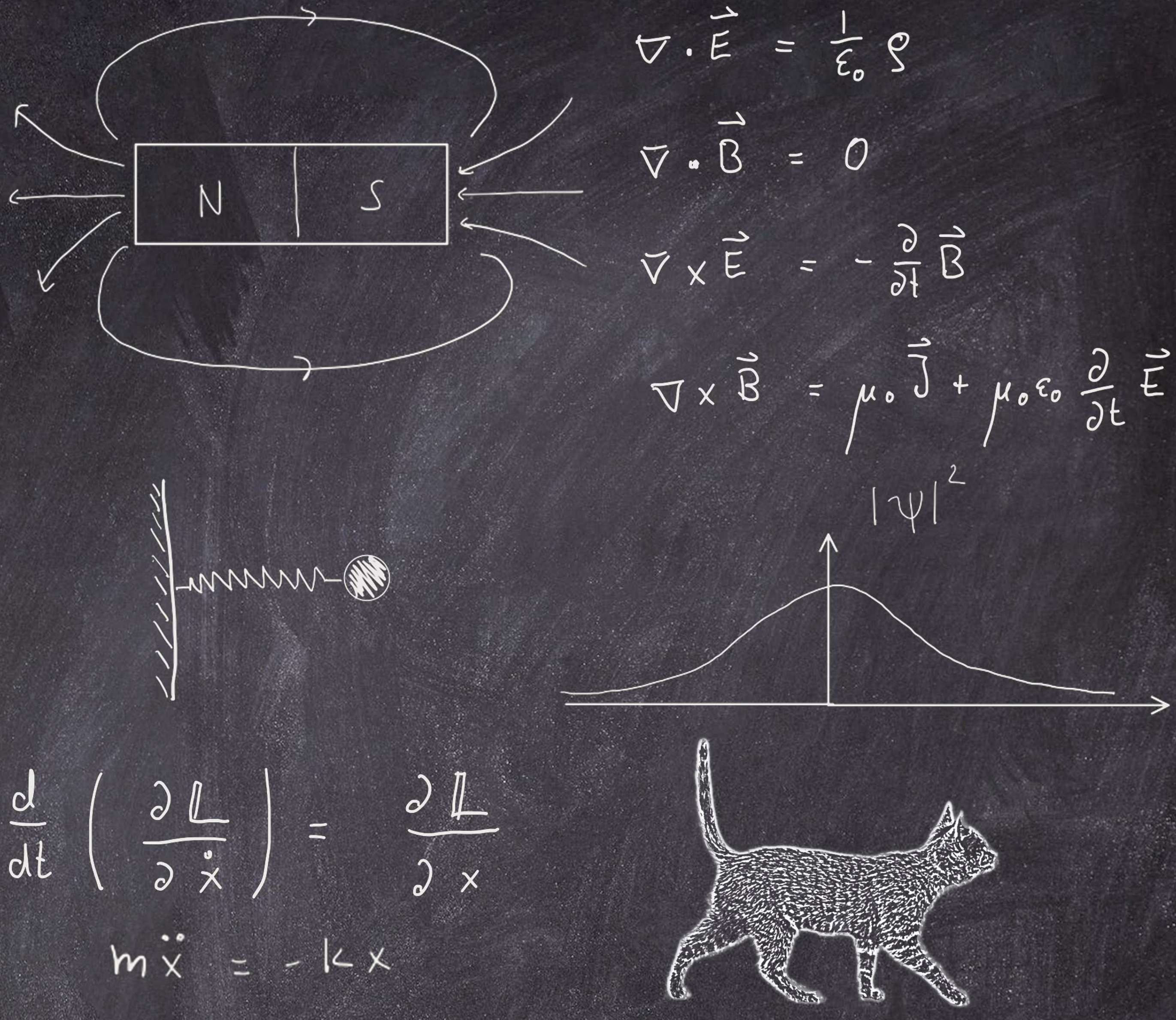
HERIOT WATT UNIVERSITY

Physics Department Newsletter

Volume 2, Issue 02



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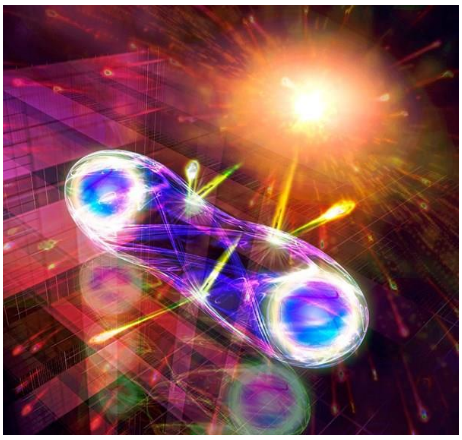
Physics Newsletter
Vol. 2, Issue 02 June 2022

Beyond Binary Quantum Information – High Dimensional Entanglement

Prof. Mehul Malik, Beyond Binary Quantum Information Lab

Quantum technologies today rely on the precise manipulation and control of qubits, which are quantum states composed of "zeroes" and "ones." Qubits are usually encoded in two-level quantum systems such as the energy levels of an atom, or the polarisation of a photon. However, quantum states in nature can be significantly more complex, consisting of many more levels that just two. Such high-dimensional quantum systems or "qudits" can be used to push the limits of modern quantum technologies by unlocking exciting new functionalities, such as encoding vast amounts of information on a single photon or, allowing delicate quantum entanglement to survive the conditions posed by a real-world environment.



High-dimensional quantum states of light or "qudits" can enable entanglement to survive extreme conditions of noise and loss, making practical entanglement-based quantum communication a reality.

In the Beyond Binary Quantum Information Lab (BBQLab) at IPAQS, we study high-dimensional quantum states encoded in the spatial and temporal structure of light, developing cutting-edge techniques for their generation, transport, control, and measurement. These methods are then applied in developing exciting new quantum technologies for communication, computation, and sensing. An area of focus within our group is high-dimensional entanglement, which is a uniquely quantum physical phenomenon involving two or more quantum particles that share strong non-classical correlations irrespective of how far apart they are. Entanglement forms the backbone of many quantum technologies today, ranging from error correction in quantum computers to ultra-secure quantum encryption systems. Below, I briefly describe two exciting results from our group in this field.

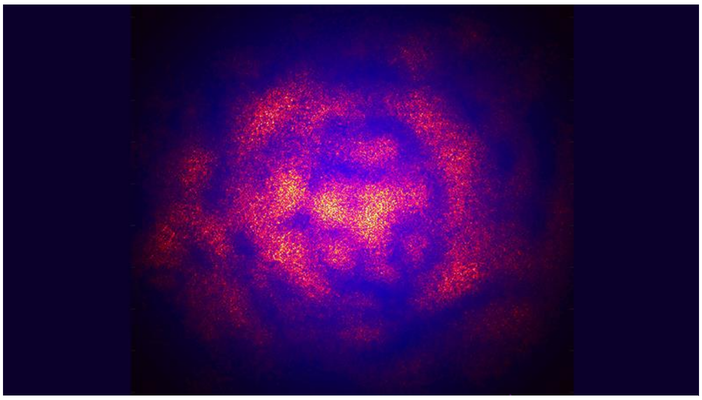
Quantum entanglement enables the most secure form of communication possible—one where the communication devices themselves can be in the hands of an adversary, and security is still guaranteed. However, distributing entanglement over long distances and through a noisy environment is no easy task. Entangled photons can be lost while propagating through fibres and detectors can be compromised by large amounts of noise. As a result, tests of quantum nonlocality—the most stringent form of entanglement—have only been performed under very controlled conditions. Quantum steering relaxes the strict technological requirements of nonlocality by assuming an untrusted device only on one side of an (untrusted) channel.

In recent work from our group[1], we harnessed the advantages of high-dimensional entanglement to demonstrate quantum steering under extreme conditions of noise and loss. We developed a new test of quantum steering that requires only a single detector at each party, regardless of the dimension of the entanglement used. Using this test, we were able to "steer" entanglement through loss and noise conditions corresponding to 79km of telecom fibre and 36% of white noise. Remarkably, our technique also led to a dramatic reduction in the total measurement time needed—by simply doubling our entanglement dimensionality, we were able to reduce our measurement time by almost two orders of magnitude.

Another key challenge in the realisation of entanglement-based quantum communication networks is the transport of quantum entangled states over a realistic channel. High-dimensional entanglement encoded in the spatial structure of light is susceptible to detrimental effects such as atmospheric turbulence or mode-mixing in multi-mode fibres, which normally result in the fragile quantum correlations being lost. Over the past decade, researchers working in the field of photonics have shown how the propagation of classical light through a multi-mode fibre can be precisely controlled, allowing them to achieve remarkable feats such as sending an image down an optical fibre no thicker than a human hair! However, extending this control to quantum entanglement has remained a difficult task until now.

In another result from our group[2], we demonstrated how high-dimensional "pixel" entanglement can be reliably transported through a commercial multi-mode fibre. Here, entanglement was also used to measure the transmission matrix of the fibre via the quantum mechanical principle of state-channel duality. The input entangled state captured a "snapshot" of the multi-mode fibre, encoding all the information about the scrambling channel onto itself. By measuring this state at the output, we were able to completely characterise the scrambling process inside the fibre. Interestingly, by using a property unique to entanglement, the scrambling could be undone without ever manipulating the fibre or the photon sent through it. Instead, we carefully scrambled the photon that remained outside, regaining the quantum correlations that were initially lost.

More recently, our group has developed ways to use the complex scattering process inside a multi-mode fibre for programming high-dimensional quantum optical circuits using inverse-design techniques, allowing us to transport, manipulate, and measure



A laboratory image showing a chaotic speckle pattern that results from quantum particles of light being scrambled by a complex medium such as a multi-mode optical fibre.

entanglement within the transmission channel itself![3] In addition, we are exploring ways to harness the coupling of space and time inside a fibre for realising general transformations in the temporal domain. The field of high-dimensional quantum information is rapidly growing, and we at BBQLab are excited to be at its forefront, with many transformative quantum technologies on the horizon!

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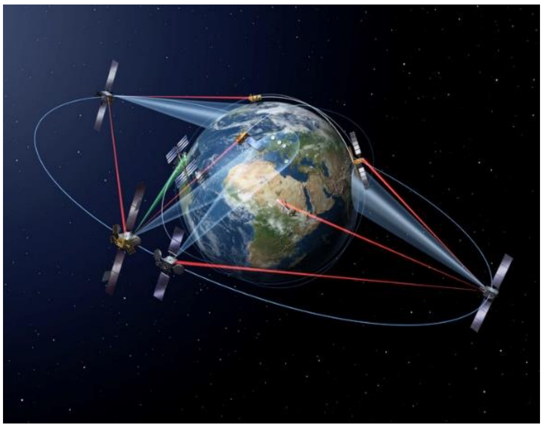
Making Sure Your Facebook Password Is Unbreakable Using Satellites

Alfonso Tello Castille, Single-Photon Group

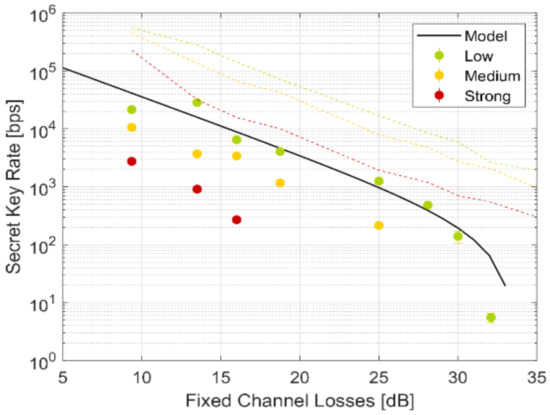
Everyone uses the Internet nowadays on the assumption that their stuff cannot be read by an eavesdropper. This is true so far, as long as the right encryption protocols are used (RSA, DSA, ECC, …). In theory, if the parameters of these protocols are chosen randomly then it will take long enough to hack that, by the time it is done, no one will care about that information anymore. However, this scenario will change drastically when quantum computers become commercially available. Ever since Shor discovered in 1994 that RSA could be easily broken using his famous algorithm (Shor's algorithm), people immediately realised the magnitude of the security threat. From that point on different quantum protocols have been found to break many, but not all, of current protocols. However, you may not care if your Facebook password is broken, after all, who uses Facebook anymore? But think about this, banks, governments or defense organisations are exchanging top secret messages right now using these very protocols. If someone just saves those messages and patiently waits until they can buy a quantum computer, a lot very secret information will be revealed very quickly.



What a satellite QKD system could look like.

Quantum key distribution (QKD) is one of the ultimate solutions that have been proposed for the security threat of quantum computers. In reality, it does not offer the technology to exchange messages securely (regardless of the computer you use). This was invented back in 1948 by Shannon, and can be summarized as follows: if you encrypt a message using a random key with the same length as the message, and only use it once, that is as secure as it gets. Although theoretically very simple, to share these keys securely has been proven to be so difficult that basically no one does it. This is where QKD comes in, as it offers a solution to create these keys in a secure and unbreakable way (mathematically proven). It relies on a few "simple" quantum concepts such as the no cloning theorem, quantum superposition of states and quantum entanglement. Explaining how QKD works will take a wee bit longer than the words that I have here, but the concept can be easily understood in one of the thousand of introductions to BB84 (the first QKD protocol) that exist on the Internet.

The use of QKD is very cool, very quantum, and all that stuff, but it has a very important limitation: the power of the source. After all, you must work with very few photons for all these properties to be true. QKD was first investigated in optical fibres, but these offer a fixed attenuation that very soon became a bottleneck for generating secure keys fast enough. Many solutions for this problem have been proposed, but the one with by far the coolest name is the satellite quantum key distribution network. The theory goes that if we communicate two parties using a satellite channel, the attenuation suffered in the channels are going to be lower, therefore secret key rates can be generated further and faster. The main challenge of this technology is to overcome the atmosphere, which is there just to give a lot of headaches to those working on free space communications. Nevertheless, it is a viable solution that has been proven many times. Recently, we at the Single-Photon Group have published a paper where we investigated some technology to take the receiver design further. With some new designs for some of the optics, we can handle atmospheric turbulences and pulse the system at gigahertz frequencies, which gave us secret key generation rates in the order of kilobytes.



Effect of atmospheric turbulence on satellite QKD channel losses.

If you would like to read a bit more about QKD, you can check it out here: https://doi.org/10.1364/OE.451083. Hopefully, you can find something interesting in there and be curious enough to continue reading about the field.

Breaking The Mirror Of The Universe

Dr. Fabio Biancalana, Nonlinear Photonics Nanostructures Group

Imagine human physicists trying to communicate with alien physicists of another planet about physics. A lot of confusion arises when we say "left" or "right", the aliens are puzzled, because the notion of left and right is arbitrary, and the aliens do not know which is which. The same ambiguity arises when the human physicists try to discuss about "positive" and "negative" electric charges – those notions are also arbitrary, and so the aliens cannot understand which is which in this case too.

The situation described above is due to the presence of *symmetries* in physics: for example, when we raise our left hand and we look at ourselves in the mirror, we see our mirror image lifting the right hand, and vice versa. This is because the laws of physics are symmetric under mirror reflection, or, in other words, the experiments that we do in the real world would be completely identical to the experiments that an imaginary mirror world could carry out.

Gravity, light, etc., would work precisely in the same way in the real world or in the mirror world. Well, if you have a beam of light that is right-circularly polarized in the real world, in the mirror world the beam would be left-circularly polarized, because the mirror inverts the left and the right *chirality*. But the experiments would work anyway, because the mirror image of any physical process also represents a perfectly possible physical process, since the laws of physics are mirror symmetric. Or are they??

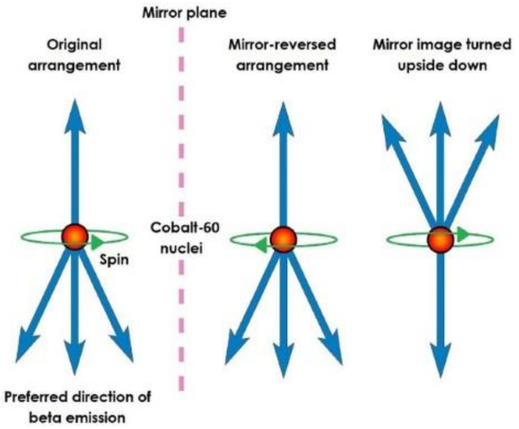
Prior to the year 1956, it was taken for granted that the laws of physics are *ambidextrous*; it came as an enormous shock that a specific particle physics experiment showed consistently that mirror symmetry is *not* an absolute symmetry of nature – and thus there is an *unambiguous* way to identify left and right chirality and communicate this difference to an alien civilization.

It has all to do with the *weak interaction*. The forces that we usually deal with in our everyday life are the force of gravity and the electromagnetic force. These are the forces that we can "feel" with our human body, when we sunbathe or when we fall down the stairs. However, there are other two forces in nature: the *strong force* and the *weak force*. The strong force is responsible for keeping the atomic nucleus together, a kind of super-strong glue that works very similar to the electromagnetic force, but it is way more intense and can be felt only at *very* short distances. We know today that the strong force is mirror symmetric, like gravity and the electromagnetic force, and does not violate the mirror symmetry (called *parity* symmetry by physicists).

The weak force is another kind of animal, which is responsible for the *disintegration* of particles and atomic nuclei. It is the force that leads to radioactivity, for instance, which particle physicists call *beta decay* for historical reasons. Another important example of a phenomenon involving the weak force is the nuclear fusion of hydrogen into helium that powers the Sun's thermonuclear process. So, the weak interaction, despite being the strangest and most obscure force we know, is essential for life and for the existence of stars.

A simple experiment carried out in 1956 by Madame Wu's group showed that radioactive decay of the atom cobalt (^{60}Co) into nickel (^{60}Ni) does not respect the mirror symmetry, in the sense that the same experiment performed in the mirror world would not give a mirror image of the real world.

In this experiment (left part of the figure opposite), it was observed that cobalt emits electrons due to the beta decay (a radioactive process where a neutron decays into a proton and an electron), which occurs thanks to the weak force, mostly in the *opposite* direction of the spin of the atom (about 60% of the total electrons emitted).



Now, the presence of such preferential direction is devastatingly shocking for physicists. In fact, if you apply the mirror symmetry to *all directions* (change all the coordinates (x,y,z) into (-x,-y,-z), which we call *parity inversion*), we can see that the "mirror experiment" would look like the rightmost part of the figure above. In that case, the "parity" world experiment would look opposite to real world experiment.

It turns out that, for some reasons, the weak force can "see" only some specific "parts" of certain particles. Each physical particle is composed of a *right-handed* component and a *left-handed* component. When the particle walks across the spacetime, it oscillates in regular fashion back and forth from right-handed part to left-handed part and from left-handed part to right-handed part. From analysing the above experiment of parity violation, it can be deduced that the weak interaction *involves only the left-handed part of the particle* (or the right part of the antiparticle). The right-handed part of the particle simply does not feel the weak interaction.

In other words, there *is* a difference between left and right in our world. You can perceive this difference only when the weak force is at play – in some specific particle interactions like the one described above. Think about it: this breaks one of the fundamental symmetries of Nature, a symmetry that, for a long time, physicists thought was sacred and inviolable. It is no wonder that the physics community was shell-shocked at the time when this experiment was revealed.

It turns out that an even more obscure particle phenomenon, involving a so-called *Kaon particle*, indicates clearly that there is another symmetry (called CP symmetry) that is slightly broken. The breaking of the CP symmetry implies that one can distinguish between positive and negative electric charges, and therefore there is a way to communicate to alien physicists which charge is positive, and which is negative, in a totally unambiguous way. We shall talk about this in another issue of the Newsletter!

Will I Need A *'Light'* License?

Dr. Ross Donaldson, Opinion Piece

"Stop or I'll shoot! Your phone camera's flash contains an illegal wavelength."

Light pollution is a form of environmental pollution caused by the frivolous use of artificial lighting. Although it is relatively underreported compared to other forms of pollution, it is not "on-trend"; it nonetheless has a significant impact on the environment. In terms of ecosystems, one impact of light pollution is the reduction in insect populations, resulting in a lack of food for those further up the food chain, including protected mammals like bats. Over/underexposure to different wavelengths can also cause sleep deprivation or depression for human health.

The most important impact of light pollution, in my opinion, relates to my own research work, which focuses on the rollout of a photon-starved technology, quantum communications. Other photon-starved technologies or applications are astronomy, deep-space laser communications, and single-photon Light Detection and Ranging (LiDAR). In photon-starved applications, light pollution at the single-photon level can impact performance, resulting in equipment not working at the level needed.

Many photon-starved applications have sought to overcome light pollution and illumination from the sun using two methods. The first is to primarily operate at night to negate spectrally-broadband illumination from the sun. The second is to shift the operational wavelength from the visible to the infrared, where the sun's blackbody emissions are lower and light pollution sources are (currently) insignificant.

However, the second method has a future issue caused by the rollout of new technologies that will utilise infrared wavelengths for communications or sensing purposes, such as fully autonomous vehicles. The scale of new infrared emitters that will be introduced into the world will cause significant problems for photon-starved technologies and applications. That issue raises the question of whether we should regulate the optical spectrum, as we do with the radio frequencies, to negate cross-technology impacts.

Given recent and current world leaders, it is interesting to ponder what the regulation of optical wavelengths would look like in practice. Would dictators make blue wavelengths illegal, creating a permanent seasonal affective disorder (SAD) population? Would governments force all street lamps to move into the deep red to help ecosystems?

Whatever happens, physics will play a critical role in creating future light sources, monitoring future light pollution, and helping to organise the optical spectrum.

Opening The Door On Scientific Adventure

Dr. David Bajek, Laser Innovation Lab

I am delighted to be writing to the Physics Department Newsletter again, this time with an update on our research achievements and a word of encouragement on the amazing journey on which students can embark when they pursue undergraduate research opportunities such as through summer research programs.

Last year I wrote to the newsletter (Vol 1, Iss. 03) discussing some recent developments in my research surrounding the measurement of ultrashort events using ultrafast lasers. The beauty of these techniques is the use of ultrashort pulses of light (hundreds of femtoseconds) to frame and investigate an event which occurs between them. This type of time-resolved spectroscopy has allowed the investigation of events which occur in all areas of science, from biological tissue, all the way down to the formation and break-up of chemical bonds. The aim of our research was to reduce the hefty price-tag and footprint associated with the conventional laser of choice for such applications, which is typically a solid-state system with a variety of complex external components. Mode-locked laser diodes could replace these entire systems due to their significantly lower-cost and compact nature, coupled with their ability to be electronically pumped and electronically tuned using clever biasing techniques. Last year I reported our publication of OSBERT (Optical Sampling By Repetition-Rate Tuning) in Optics Express (https://doi.org/10.1364/OE.413045) which was capable of distance measurements at rates of 1 kilohertz. We have since gone on to significantly improve upon this scan rate with a recent publication at Nature Scientific Reports (https://doi.org/10.1038/s41598-021-02502-w) showcasing acquisitions of 1 megahertz (1 million scans per second), which is a significant achievement in the field. I like to describe this to people who are as interested in both time and light as I am with the following quick summary: At a rate of 5 billion pulses per second, we fired one-trillionth-of-a-second laser pulses at each other and detected them at a rate of 1 millionth of a second. Feeling dizzy? Imagine how the pulses feel!

Even more exciting, I mentioned last year that an undergraduate physics student, Ife Ejidike, successfully made it through my (rather rigorous) recruitment process for a competitive AWE-sponsored summer studentship. In unpredictable times, we wanted to be able to maximise our research over the 8 weeks, so we opted for an entirely theoretical project which would allow us to work regardless of which new Covid-19 restrictions came up. We are absolutely thrilled to announce that after some hard work, not only have we developed this into his project, but we have just had the results published (https://opg.optica.org/oe/fulltext.cfm?uri=oe-30-3-3289&id=468568), with Ife taking the incredible place of first author. Here we show how our technique has the potential to replace conventional two-laser solid-state systems with just a single mode-locked laser diode. What I really hope to show, is that with drive and determination, anything can be accomplished at any level at University. It is so important to be proactive if you are interested in research, to seek out these opportunities, to discuss them with staff, and if you have ideas of your own which you believe could make a project, even better! The rewards may not always be as tangible as authorship on a scientific paper, but that doesn't mean they aren't as valuable. To be part of a real research group, learning something new, networking, conducting original research either by modelling or experimenting in the lab, will provide you with invaluable early insight into the scientific method, and indeed the scientific adventure.

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