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UOA

Scientific

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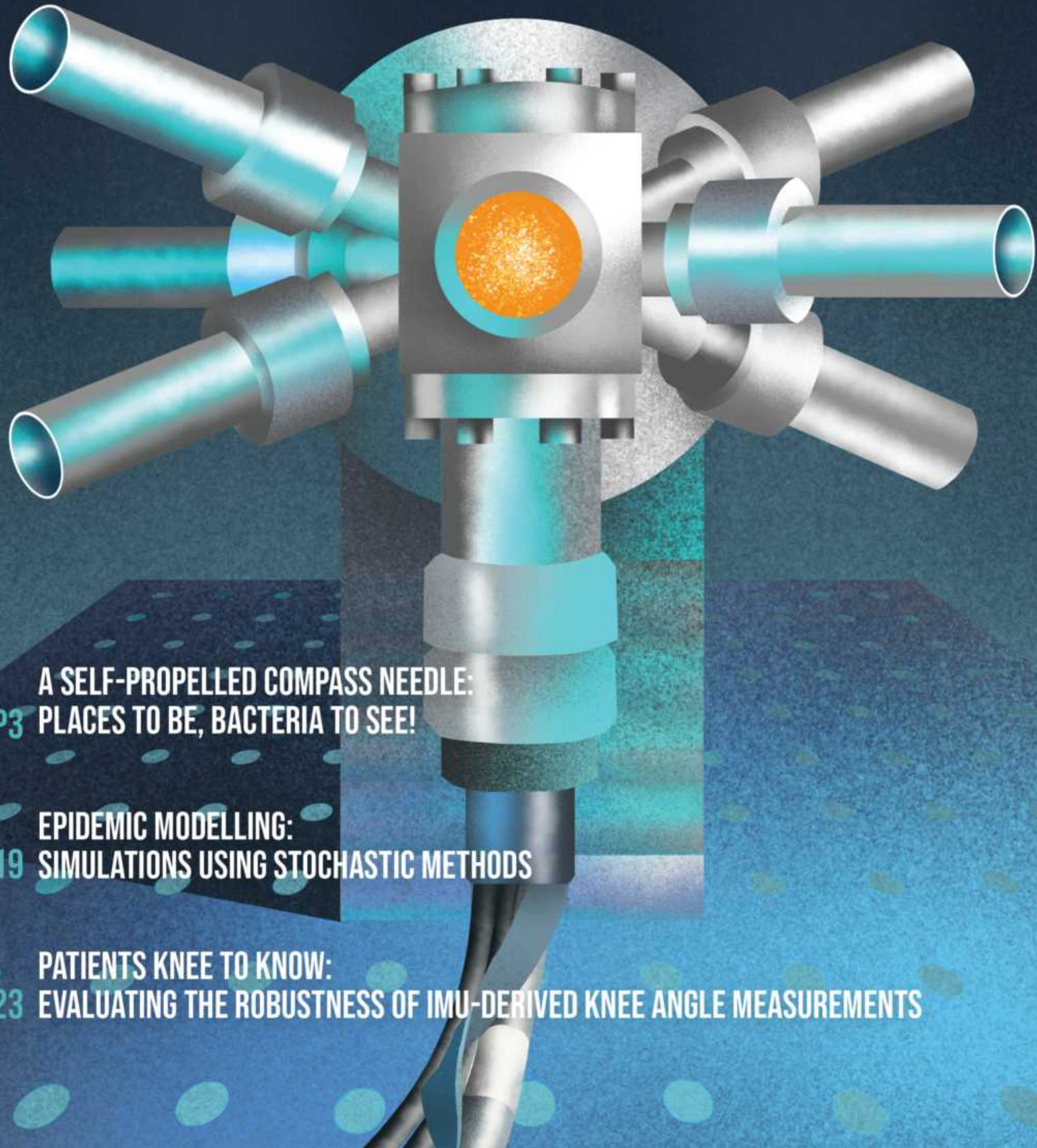
MEASURING THE SPEED OF TIME

Recent breakthroughs create quantum logic clocks that don't lose nor gain a second over 33 billion years.



Editors' Note

Nau mai ki te pukapuka tuarua putanga tuatoru o te *Scientific*,

As winter and Semester Two bluster on, we hope you are staying warm and curling up with our newest issue! It's wonderful to see physical copies of this publication, old and new, being shared and enjoyed on campus.

This issue is richer than ever with guest writer pieces, taking us from the black hole at the heart of the Milky Way, to the zoomy microbes that use magnetism to get around. You-Rong Wang explains how the Milky Way's supermassive black hole, for the first time this year, was imaged. Steph Claridge writes about the (colloquial) *magnetotaxi* phenomenon: microbial transportation via Earth's magnetic fields.

Timely as ever, Angeline Xiao elaborates on the use of stochastic processes for modelling epidemics. Jae Min Seo investigates whether Inertial Measurement Units can change the field of orthopaedics and biomechanics. Alicia Anderson looks at the current research and knowledge gaps in grief, and Caleb Todd concludes his series on Einstein's 'miracle year' papers with the world's most famous equation.

Our executive team has also contributed exceptionally to this issue. Jasmine considers science fiction and how to predict what future organisms will look like. Nina explores the five most invasive plant species in Auckland. Featured on our cover and in the centrefold, Alex's article details recent advancements in atomic clocks, which appear in technology all around us. The cover art is by yours truly.

The team is so proud of everyone's work. Each issue, bolstered by our growing online engagement and on-campus activities, feels new and improved. We hope reading this edition is as delightful as making it – or more!

Ngā mihi maioha,
Aimee Lew, Marketing Coordinator for UoA Scientific 2022

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Speculative Biology in Science Fiction

Jasmine Gunton

Some phenomena in biology will probably never be truly known to humans. For example, scientists will never get to know exactly what the first organism looked like. We will probably never know what it is exactly like to experience life as an animal that isn't ourselves. Concepts such as this can, however, be predicted through in-depth analysis of available evidence and thorough reasoning. Theoretical biology is so fascinating because it encourages a higher degree of imagination than other areas of scientific research. We can take well-defined biological concepts and apply them to our prediction of the far past and future. Theoretical biology can be applied to eras in which humans didn't exist, and planets other than our own.

When the field of evolutionary biology is combined with speculative zoology, it allows us to envisage populations of animals that we will never get to see. We can imagine new types of body plans, behavioural adaptations, and species interactions. Several scientists, authors, and artists have provided unique perspectives on what the biology of the future will look like. Some examples of outstanding works include *The Future is Wild* by Victoria Coules (2003) [1], *Alien Planet* by Wayne Douglas Barlowe (2005) [2], and *All Tomorrows* by C. M. Koseman (2006) [3]. Critiquing these publications under additional scientific scrutiny can bring forth new insights into what species will arise in a future world affected by rapid climate change, continental drift, and the birth of novel natural selection agents.

The Future is Wild is a documentary miniseries written by Victoria Coules and is based on the book 'After Man' by Dougal Dixon. This miniseries envisions Earth millions of years in the future where man is extinct and no longer alters the natural environment. The continents have moved with the shifting of the tectonic plates, forming new landscapes and ecosystems. Man-made agents such as climate change and urbanisation have been selected in favour of common pest animals such as termites and wild boars. Over several million years, these animals have evolved into the creatures that the show centres itself on. With each animal presented in the show, a range of scientists describe its respective niche and evolutionary history. The audience is also given detailed examples of similar modern-day creatures. 'The Future is Wild' does not aim to display an accurate prediction of how evolution will shape the fauna of Earth. Instead, it gives one possible outcome of the environmental and evolutionary patterns we are seeing today. The miniseries is split into 3 main eras; 5 million, 100 million, and 200 million years into the future. Some of the most interesting organisms are shown in the latter section, having diverged the furthest biologically from modern-day fauna. One such creature is the megasquid, a descendant of the modern-day squid species. The megasquid is a large terrestrial vertebrate, with a somewhat similar appearance to an elephant. It possesses six trunk-like legs with two smaller frontal tentacle appendages. This piece of theoretical biology does not come without its criticism. Some critics argue that squid are not able to evolve to develop terrestrial locomotion as their bodies are specially adapted to the deep sea. Despite the obvious challenges of not being able to see directly into the future, I believe that *The Future is Wild* still achieves its primary goal, and is an example of an extremely intelligent and entertaining television series.

While *The Future is Wild* focuses on the biology of Earth, *Alien Planet* focuses on the biology of the exoplanet Darwin IV. Life on Earth as we know it is rigidly defined as entities that hold certain attributes, including metabolism, reproduction, and growth. The 'life' of other planets, however, could operate entirely differently to that on Earth. Instead of being reliant on water, life on other planets may be reliant on some other liquid medium. This is all speculation, of course. But some speculation is better than none. In creating the universe of Darwin IV, author Wayne Douglas Barlowe assumed some similarity to Earth organisms, assuming the existence of both singular and multiple cellular life forms. Barlowe also created extraterrestrials that had somewhat similar niches and adaptations to the organisms found on Earth. Although *Alien Planet* is ironically conservative in its predictions, it is still wildly fascinating. The natural history of Earth must be appreciated for all of its glory, but extrapolating evolutionary theories to other planets is so much more interesting than the possible future animals of Earth. Finding evidence of alien life on another planet may arguably be the greatest scientific discovery of humans. So let us imagine a world far in the future, where humans are getting to see the splendour of extraterrestrial life for the first time. One interesting aspect of life on Darwin IV is that some of the main terrestrial apex predators use sonar rather than sight to hunt for prey. Perhaps this type of sensory adaptation could have appeared more often in Earth animals if evolution were to have taken a different path. At the time of its exploration by our robots, Darwin IV no longer has oceans. Rather, the planet possesses a 'sea' formed by a matrix of amoeba and other microorganisms. Creatures seven storeys high travel along this amoeba sea, absorbing the surface upon which they walk. The discovery of life on Darwin IV may have given humans a new appreciation for life in general, and our role in the universe.

The last piece of science fiction I wish to discuss is *All Tomorrows*. If you, the reader, have spent many hours on the science side of YouTube, you have likely heard of this book. Researcher and author Cevdet Mehmet Koseman wrote the book *All Tomorrows* as a theory of what species man will evolve into with the development of space travel and genetic engineering. Although C. M. Koseman is not formally trained in biological sciences, his predictions about the future of mankind are fascinating, nonetheless. Just because C. M. Koseman is not a biologist in the traditional sense, does not mean that the world he has envisioned will not be realised in some alternate universe. Besides, *All Tomorrows* discusses scientific concepts such as gene editing, cultural evolution, and artificial intelligence. Before I praise the book any further, I will give a brief summary of some of its highlights. As is common in other works of theoretical evolutionary biology, future humans have heavily altered the Earth's environment through accelerated climate change. Thousands of years into the future, facing overpopulation and resource depletion, the humans of Earth decide to colonise Mars. After a long period of separation between the two breeding pools, the humans of Mars evolve into the Martians. Martians are similar in appearance to their predecessors, but are taller and thinner due to the low gravity [4]. Modern science says that Martians may be exposed to more radiation per year than Earth humans [5], thus leading to a higher rate of mutations and therefore perhaps higher evolutionary rates than on Earth. After the colonisation of Mars, humans learn to colonise several other planets and galaxies. Through a combination of wars, death, and artificial selection, humans come to speciate into a multitude of forms. Some of these sub-species are highly intelligent, forming their own unique cultures on different planets spanning light-years across the universe. It is difficult to imagine a universe where several species of humans exist. However, all it takes for evolution to occur is a strong natural selection agent, sexual reproduction, and mutation. Perhaps, someday, only our genetically distant descendants will remain extant, unable to comprehend what it meant to be a *Homo Sapien*.

What does it mean to be human? What does it mean to be alive? Theoretical evolutionary biology attempts to answer some of the most challenging questions in science. However, unlike other disciplines, artists, philosophers, and scientists alike can appreciate the creativity that arises when we attempt to understand these concepts. The humans of today will never know for sure what is going to happen in two million years, but we know our atoms will still be present in some form, changing and moving through the universe.

Jasmine Gunton - BAdvSci(Hons), Ecology
Jasmine is a 2nd-year Bachelor of Advanced Science (Hons) student specialising in Ecology. She is particularly interested in researching areas in marine ecology and evolutionary biology. This year she is also a part of the Science Scholars programme.

A Self-Propelled Compass Needle: Places to Be, Bacteria to See!

Steph Claridge

Magnetotaxis and magnetoreception are abilities present across both the Earth and its phyla due to the planet's ever-present magnetic field. These species – such as bacteria, microbial eukaryotes, birds, molluscs, and reptiles — use the magnetic field to navigate during large migrations or for small movements, thus allowing species to inhabit more favourable environmental conditions. In eukaryotic microbes, this ability has been assumed to result from symbiotic relationships with magnetotactic bacteria (MTB), while the origin of magnetotactic abilities in macro-eukaryotes has remained largely unknown. One study [1] suggests that similar symbioses are a common occurrence among magnetotactic macro-eukaryotes. However, the recent discovery of microbial eukaryotes that can biosynthesise components necessary for magnetotaxis (rather than uptaking them from the environment or engulfing magnetotactic bacteria to form symbiotic relationships) will challenge current understandings, and add to a wide variety of bacterial biomedical and nanotechnological opportunities.

The Ocean is Full of Tiny Microbial Compass Needles

A range of microbes use Earth's magnetic field in orienting and navigating themselves toward anoxic environments; this is often paired with aerotaxis, a movement and directionality driven by oxygen availability. Many microbes move through random Brownian movement[1], but this magnetotaxis directs flagellated microbes towards anaerobic and micro-aerobic sediments[2]. This ability arises from the magnetosome. This organelle is present in two forms, each with a lipid bilayer membrane: an iron oxide magnetosome with a magnetite crystal or an iron sulphide magnetosome with a greigite crystal [2]. In prokaryotes, these magnetosomes are bullet-shaped or prismatic and form chains in the cytoplasm along a dipole (thus creating a "compass needle") (Fig. 1).

Magnetotaxis is not confined to one bacterial clade but rather has developed across many taxa. Because of this, MTBs are globally distributed and have been found across a wide range of environments (many of which qualify them as extremophiles). The presence of MTBs in extreme environments — for example, as alkaliphiles [4] and thermophiles [5] — suggests that magnetosomes can form and tolerate a large range of environmental extremes. Typically, MTBs are anaerobic or microaerobic and occupy both marine and freshwater environments and sediments. Rather than being dependent upon iron-rich environments (for the formation of the magnetite and greigite) MTBs tend to require an oxic-anoxic interface (OAI), such as those that form at the sediment-water interface. The highest concentrations have been found in the OAI — typically the top 1-4cm of sediment — although some MTBs have been identified at the water-sediment interface in oxic environments [6]. Magnetite-producing MTBs are concentrated around the OAI, while greigite-producing MTBs occupy habitats below the OAI in the sulfidic anoxic zone. This segregation is due to high concentrations of sulphide in the anoxic zone, promoting the formation of greigite (Fe_3S_4), while the OAI has greater inputs of oxygen and thus forming magnetite (Fe_3O_4) [7].

The reliance upon and interaction with the Earth's magnetic field by certain bacteria creates three classifications of MTB. North-seeking MTB dominate the northern hemisphere, while south-seeking MTB dominate the southern hemisphere (and the equator has a roughly equal population of each). When inhabiting chemically and vertically stratified waters, anaerobic MTBs will swim away from the magnetic field and thus downwards to anoxic sediments. However, there are exceptions to this, as populations of north-seeking MTB are present in the southern hemisphere and vice versa. The reason for this discrepancy was initially credited as an increasing redox potential [8], but further study is required to understand the relationship between MTB densities and other abiotic factors [9].

The Independent Microbial Eukaryotes That Don't Need No MTB

Until recently, magnetosomes have only been found in bacteria, and any magnetotactic abilities in eukaryotes were thought to be the product of ectosymbiotic relationships with bacteria and magnetosomes. These relationships occur by non-flagellated bacteria[3] latching onto the surface of the eukaryote, and thus granting magnetotactic abilities to the eukaryote [10]. However, a deep-ocean foraminifera — *Resigella bilocularis* — has been identified and distinguished as one of the few known eukaryotes capable of biosynthesising magnetosomes without a symbiotic

[1] Brownian movement is the random movement of microbes which results in chance encounters on ideal environmental conditions.

[2] Microaerobic environments have very low concentrations of oxygen, while anaerobic environments are devoid of oxygen. This corresponds to different microbial respiratory environments.

[3] These non-flagellated bacteria cannot be called magnetotactic bacteria because they cannot independently move in regard to the magnetic field lines, and instead must rely on the host eukaryotes.

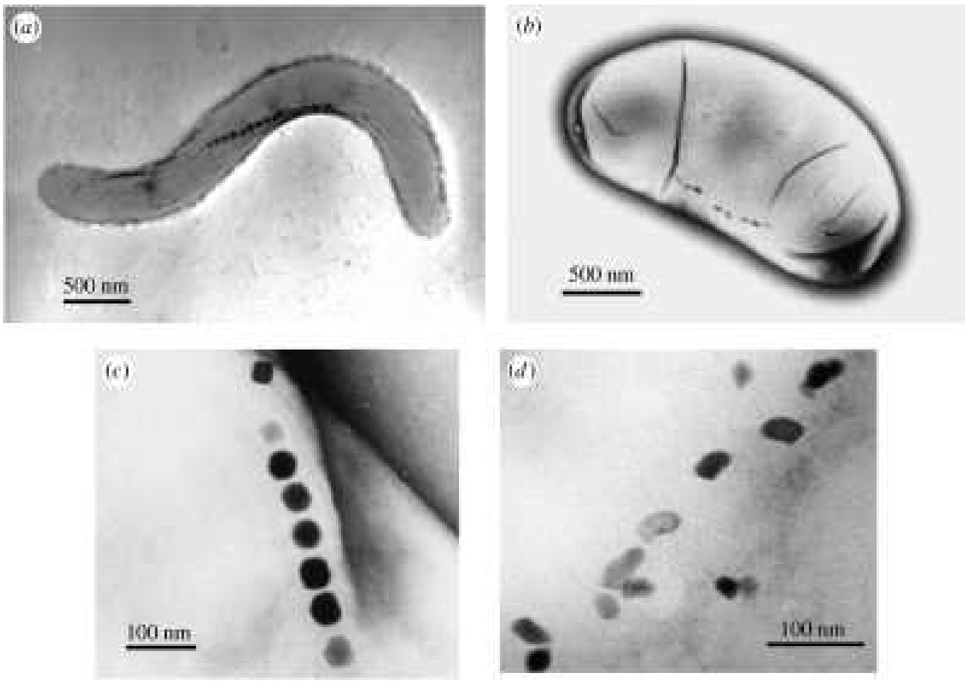


Figure 1: This shows transmission electron microscope images of different magnetotactic bacteria. The magnetite magnetosomes are the black lines, often seen in a single line. Scale bars represent 100 nm.

relationship with an MTB [11]. This protist inhabits the depths of the Mariana Trench and produces magnetite that is morphologically distinct from that produced by MTB or found in nearby sediments. The magnetite of *R. bilocularis* is porous, octahedral, and of varying sizes (11, Fig. 2), while the magnetite of MTB is typically smooth-surfaced, cuboidal, and arranged in one or two chains [12]. Environmental magnetite also differs because it typically has an irregular (but smooth) shape of a larger size and lacks an organic envelope. Another study [13] found a similar magnetotactic protist that likely biomineralised bullet-shaped chains of magnetite magnetosomes within its cell. However, while this evidence supports the biomineralisation of magnetite in eukaryotes, it is possible that an endosymbiotic event with

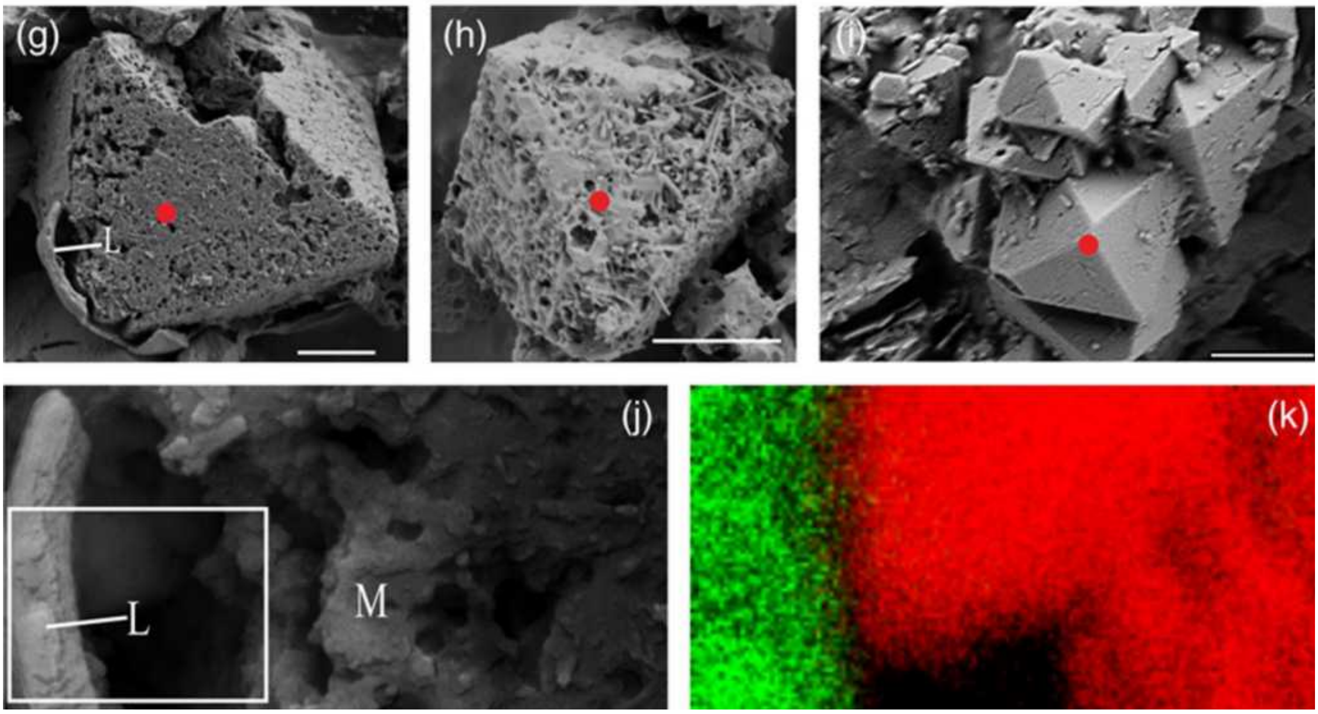


Figure 2: This shows the magnetite produced by R. bilocularis. The porous and octahedral structure of this magnetite can be seen (g, h, i, where scale bars are 2µm). The carbon-containing membrane (L) and the magnetite structures (M) are present in (j). (k) denotes elemental mapping of the white square shown in (j), where the red represents iron and green is carbon. Both (j) and (k) have scale bars of 0.5 µm.

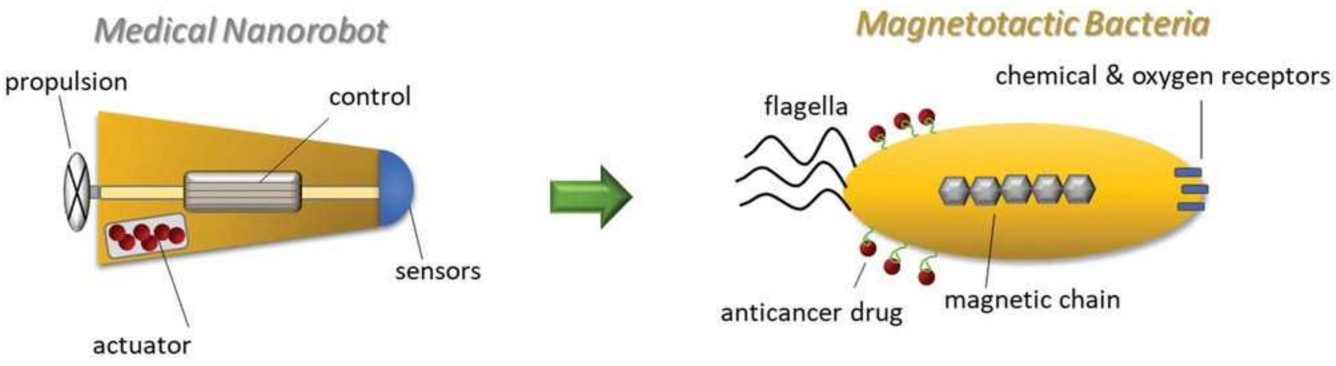


Figure 3: This shows the required features of a medical nanorobot compared to the biological, features of the magnetotactic bacteria. These MTBs can be paired with a targeted magnetic field for navigation. Note the MTBs ability to easily secure anticancer drugs and molecules to its surface.

MTB occurred early in their evolutionary history. Further research is required into the evolutionary history and relationships of these protozoa and bacteria.

A Working-Class Microbial Compass Needle

MTBs have proven effective in fulfilling a variety of nanobiotic roles in both artificial and microvasculature environments. Traits like their chemical purity, low toxicity, and surface morphology have caused some researchers to turn to bioengineering microbes for biomedicine and healthcare, rather than using artificial nanorobots to perform complex procedures. Magnetotactic microbes and their magnetosomes provide a means to control and direct the microbes to specific targeted tissues by manipulating local magnetic fields (14, Fig. 3). For example, it was found that an MTB, *Magnetococcus marinus*, could penetrate an anoxic tumour further than passive, artificial agents [15], in addition to bearing no negative effects. However, while microbial nanorobots such as MTBs are often more effective than their artificial counterparts, they are currently obstructed by their own physiology. For example, while the cell may often grow faster in relatively oxygen-rich environments, magnetosome growth is optimised in oxygen-poor environments [16]. Meanwhile, magnetotactic eukaryotes have the potential to provide solutions for MTB shortfalls. The highly ciliated *Tetrahymena pyriformis* is a magnetotactic protozoan that reaches greater speeds than MTBs, and like MTBs, can be controlled via artificial magnetotaxis [17].

As well as the repurposing of the MTB as nanorobots, their magnetosomes can also be of use when extracted and replicated. The magnetosome can be bound to the drug and targeted to specific tissues, as shown by the coupling of antitumor drug doxorubicin to the isolated magnetosomes of *Magnetospirillum gryphiswaldense* [18]. Another study [19] also found that magnetosomes could be used for hyperthermia cancer treatments[4]. Magnetic hyperthermia heats magnetic nanoparticles in a controlled manner to deactivate or kill cancer cells. This method efficiently destroys the tumour by utilising chains of magnetosomes, compared to the limited anti-tumour activity of individual magnetosomes. Alternatively, bacteria like *Magnetospirillum gryphiswaldense* can increase temperature to 45°C by applying an external magnetic field. *M. gryphiswaldense* has no direct impact on the viability or proliferation of the cancer cells, but rather its effect occurs only through its heating (i.e. the hyperthermia treatment) [14]. In addition to biomedicine, isolated magnetosomes can also be used to detect and separate pathogens in food (e.g. *Salmonella* [20]), and in key laboratory processes like protein assays, enzyme immobilisation, and as MRI (magnetic resonance imaging) contrast agents. Finally, MTB cultures (or isolated magnetosomes) can be used to generate a small amount of electricity through the application of Faraday's law [21]. This study observed the movement of magnetic nanoparticles through a solenoid (a wire coil); while the electricity produced is minute, it may still have applications in bio and nanotechnology.

[4] Hyperthermia cancer treatment heats tissue to 45°C to impair or kill cancer cells, thus increasing the susceptibility of these cells to radio and chemo-therapy.

Magnetotactic microbes are typically motile, gram-negative bacteria that inhabit aquatic and endobenthic environments. Their use of magnetosomes to create an internal compass allows them to navigate to optimal oxygen conditions, providing an advantage over microbes that rely on Brownian movement. However, magnetotaxis is also present in protozoa; while this ability is typically the result of symbiotic relationships with the magnetotactic bacteria, some have developed the ability to independently biomineralise their own magnetosomes, thus redefining understanding around magnetotaxis, magnetosomes, and magnetotactic microbes. Both magnetotactic bacteria and eukaryotes ultimately have the potential to be beneficial in a range of biotechnological applications in the future.

Steph Claridge - BSc, Biology, Environmental Science

Steph is a third-year biology and environmental science major with an interest in astrobiology, microbiology, and extreme environments. She plans on moving into science policy in the future to bridge the gap between science and government/corporations, and perhaps someday working with space organisations.

Grief and Learning — the Limits in Our Current Research

Alicia Anderson

Grief is usually felt after the death of a loved one but can present itself when experiencing loss such as breakups, food insecurity, estrangement, and numerous other challenges [1]. This article will focus on the grief that follows a death, particularly in university-aged students, however, it is overall applicable to other types of loss. Symptoms of grief can present immediately or may be delayed. This article will focus on when the mind feels emotionally safe to begin processing. Grieving is a process with common symptoms over a timeframe, but the specifics are unique to each person [2].

Different cultures have different customs and expectations for acclimatising to loss. The American Psychiatric Association of 1964 defined a "normal" bereavement period as two months. Since then it has been extended to twelve months and acknowledges that grief varies with cultural norms, but still lists criteria for what is "normal" and "abnormal" grief [1]. Social norms of grief in western academia are that of keeping it private, with the expectation of being able to go back to "normal" shortly after bereavement, despite extensive research against this mentality [1]. This has been identified in grief research as a problematic approach because the brain "… needs to learn how to be in the world without someone we love in it" [3], which requires time and experiential feedback [4].

Grief research in general is rather underfunded as it is not a disease, nor is it classified as a mental disorder [5]. By extension, grief and loss are rarely represented in pedagogical research, leaving those in mourning isolated from academic spaces and learning [1]. Grief can affect anyone at any age, but when, for example, 22-33% of university students are within twelve months of a close bereavement, the lack of grief research in pedagogy means that these students are disadvantaged in their academic pursuits as they come to terms with their circumstances [6].

Lack of funding results in fewer and less diverse researchers as well as limits in experimental equipment and experimental data. For the most part, the psychological symptoms of grief are well-known, but only a handful of researchers study its biology. Of those who do, most are psychologists with biological interests [5]. Our understanding of grief at the biological level is limited by having only one field of science researching this topic deeply, when an interdisciplinary approach would produce a more fruitful yield.

From the data that does get collected, there is precision missing. Grieving is a process over time, but neuroimages from neuroimaging studies are taken from a single time point. There is also no distinguishing between acute grief, typical grief, and/or prolonged grief. When almost all neuroimaging studies are about grief rather than grieving, it limits what conclusions can be drawn from the data about the biology of grieving [4].

Emotional bonds with loved ones produce feel-good chemicals such as oxytocin, dopamine, and serotonin. Loss triggers both a halt of these, and an increase in stress chemicals such as adrenaline, cortisol, and norepinephrine causes a range of physical and psychological symptoms [7]. In the body this can look like dizziness, sleep disturbances, nausea, and issues with appetite, while emotionally there are often feelings of numbness and disconnect [3,7]. Sadness and anxiety are also common to experience, though in deeper losses these can develop into yearning and hopelessness [1,3]. A combination of the above leaves university students physically and mentally exhausted as they struggle through their studies with memory problems, intrusive thoughts, difficulty staying organised, and a lack of concentration [6]. They are also often navigating higher levels of independence for the first time, such that grief can isolate them from their standard support systems. Students from minority communities may also be navigating an education system not designed to support their needs, which would put them at further disadvantage in their studies [1].

The biology of grieving shows locations of interest in the brain. fMRIs are used to show grief present, which are seen as the periaqueductal grey, anterior cingulate, nucleus accumbens, and somatosensory cortices. These are the same areas which show separation anxiety in babies crying for reconnection, and the same as physical pain in adults. This is why intense grief can physically hurt [7]. The size of the hippocampus prior to grieving is hypothesised to be an indicator of adapting to loss as well. Brain scans showing a smaller than average hippocampus before bereavement in participants predicted trouble accustoming to loss. The hippocampus has also been shown to shrink in those who have lost a child (with and without PTSD) [4].

When the psychological symptoms of grief are interfering with day-to-day life several months after the bereavement, we start to see prolonged grief disorder (PGD) in about 10% of people [3,5]. This is where the loss is all-consuming to the point of significant social withdrawal [5]. It has already been mentioned in this article that university students are experiencing more independence and therefore are less connected to their standard support networks [1], which increases their risks of developing PGD.

Image by Thoa Ngo from Unsplash

People do go on to live successful and happy lives as they process their loss, sometimes with a treatment plan that their general practitioner has helped form if that is what is needed [2]. Not all students want or need such help though. From some of the grief pedagogy research that has been conducted, it has been suggested that one potential tool could be a training program for non-bereaved students to provide informal support to grieving peers, as friends often feel under-equipped to provide the needed emotional support [6].

There seems to be extensive knowledge on the symptoms of grief, but more work to be undertaken on how to alleviate those symptoms for students in academic spaces. Without up-to-date research on how best to support grieving students, the support that education institutions provide for students experiencing loss is limited. More research into what is helpful and unhelpful for grieving students would result in education institutions assisting students in moving forward from their losses and making gains in their learning.

Alicia Anderson - BSc, Geophysics

Alicia is an undergraduate BSc student majoring in geophysics. She is particularly enthusiastic about exploring how different disciplines relate to each other, and spreading the message that science is for everyone. If not in a lab or a library, you will likely find her kicking it around the wop-wops in tramping boots, kayak kit, some skiis, or a wetsuit.

Humanity's First Portrait of Sagittarius A* — the Supermassive Black Hole at the Core of Our Galaxy

You-Rong F. Wang

Sagittarius A (Sgr A) is a prominent source of radio waves in the constellation Sagittarius. Astronomers have believed that Sgr A*, the source's core object, to be the supermassive black hole (SMBH) at the centre of our galaxy, around which billions of stars, including our sun, revolve.

On 12 May 2022, in several press releases held simultaneously around the world, the Event Horizon Telescope (EHT) collaboration unveiled the first direct image of Sgr A*, using several years' worth of observation data and improved Earth Telescope techniques compared to what was used to obtain the first ever black hole portrait for M87* in 2019.

Literal to their name, black holes do not emit light. Therefore, what the image captures is the shadow "cast" by a black hole onto its accretion disk — extremely heated plasma orbiting the black hole at high speeds.

The long-anticipated radio-frequency image is a strong piece of evidence supporting the black hole nature of Sgr A*, and marks a milestone in an exciting new era of astrophysics and related fields.

An Elusive Attraction

I feel like I've finally got to see an old friend face to face.
Dr. Fiona Panther, U. Western Australia

On a Swedish winter day in 2020, three physicists shared the Nobel Prize in Physics: Roger Penrose, Reinhard Genzel and Andrea Ghez. The latter two shared half the prize "for the discovery of a supermassive compact object at the centre of our galaxy." The modern Nobel committee was noticeably gingerly with words — it was speculated that the committee chose not to call their discovery a "black hole" just yet due to the lack of conclusive evidence to rule out other models by the time of the award.

While weighing in at the equivalent heft of over 400 million suns and surrounded by hot gas, Sgr A*, the Milky Way's central black hole, is surprisingly among the dimmest and least active known in its class. Not helping the matter, there exists considerable interstellar dust between the galactic core and the Earth, which are over 26 thousand light years apart (246 quadrillion kilometres). In brief, it has been extremely challenging to observe anything at the centre of our galaxy.

Nevertheless, the scientific endeavour into understanding our galactic core has been ongoing for more than a hundred years, even from the days before Einstein's theory of general relativity and the proposal of the black hole model.

At the turn of the 20th century, just as astronomers were starting to realise that some "island universes" — diverse and complex structures previously assumed to be part of the Milky Way — were separate galaxies far, far away [1], they also began to study the motion of stars by analysing the Doppler shifts in their emitted light. Soon, most galaxies were established to host a dense and massive object at their cores, around which everything revolved.

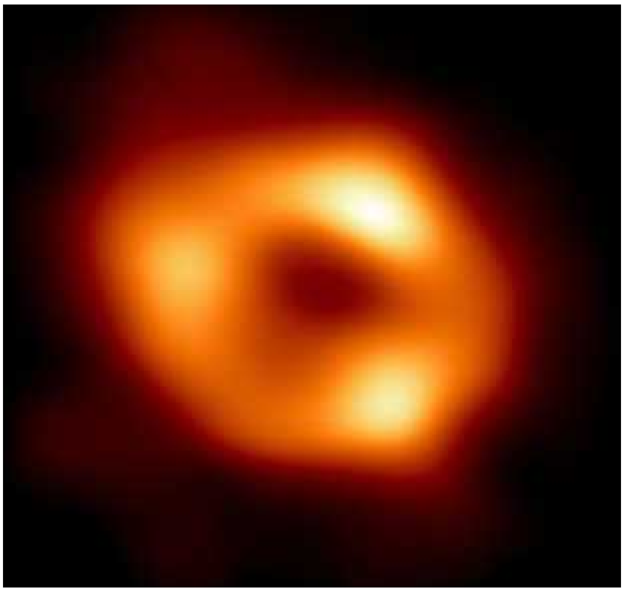


Figure 1: The first radio-frequency photo of Sgr A*. ESL / EHT

Since the 1950s, the nature of such massive objects were extensively studied and debated. An idea eventually prevailed that most galaxies — including our own — host an SMBH at their centres. Key advances during this period include theoretical formulations by Lynden-Bell (1969) [2] and radio observations conducted by Balick and Brown (1974) [3], which were one of the first to definitively measure the radio waves emitted by Sgr A* itself.

Indirect observations of Sgr A* and astrophysical bounds on its characteristics were continually improved. For example, the aforementioned 2020 Nobel prize was awarded to one of such efforts. Since 1995, scientists at both UCLA and the Max Planck Institute have been tracking several stars in tight orbits around Sgr A*, just like planets going around a star, except at much higher speeds. These stars can reach speeds as high as a few percents of the speed of light, and they seem to go around an invisible attractor. Careful orbital mechanical analyses of their trajectories agreed with predictions from general relativity, and allowed a good estimation of the mass of Sgr A* to be performed.

The Earth Telescope

To put the distance of Sgr A* in better perspective, the entire accretion disk looks as big in our night sky as a bagel placed on the surface of the moon. To directly image it requires an extremely high resolution. This means that very-long-baseline interferometry (VLBI) is the observational technique most likely to accomplish our goals.

In simple terms, VLBI combines the signal received by multiple radio telescopes in different places, correlates their time and orientations, and constructs a "virtual telescope" with the effective size equal to the separation between the telescopes — if telescopes around the globe are carefully chosen and coordinated, one can construct a telescope the effective aperture size of the earth.

Of course, if you think of an actual radio telescope or TV receiver the size of the earth that is capable of utilising every inch of its surface simultaneously, and compare that with the surface traced by our real telescopes as they rotate with the earth, the signal we actually detect can only make up a tiny fraction of the full aperture, and requires vastly elaborate post-processing.

Not only did the scientists need to sync up, filter, and combine terabytes upon terabytes of raw data for each frame, but they needed to find the most likely source image. This is because there are infinitely many possible full images that could have given rise to each set of EHT raw readings, and a model-indifferent reconstruction algorithm had to be developed. While the full technical details of these are beyond the purview of this report, if you are an applied mathematics student, you might recognise this as a classic inverse problem.

Using 230 GHz radio wave, the observation procedures for both Sgr A* and M87* began at about the same time, in early 2017. One might ask — rightfully so — why the Milky Way black hole, which is thousands of times closer to us, has taken much longer to image?

One of the main astrophysical reasons is in the sizes again. Sgr A* is much lighter and smaller than M87*, and that means the innermost stable orbit is much smaller, allowing matter in its accretion disk to complete a lap in mere minutes, in contrast to the case for M87*, which might take tens of hours.

Because VLBI relies on the rotation of the earth, and the pattern of the accretion disks changes significantly faster than that, additional processing steps must be taken to recover useful information. Within the constraints of EHT hardware, a mix of three error reduction strategies were employed. Variability reconstruction: instead of fitting the observed data to an image, the output is explicitly fit to a movie; variability circumvention: the data series are

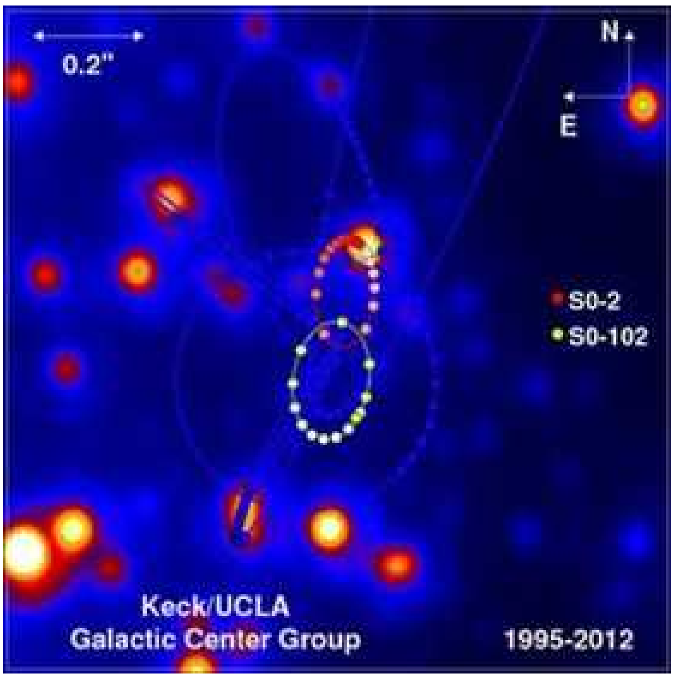


Figure 2: Full orbits of two stars close to Sgr A*, S2 and S102, imaged for 17 years.

truncated into short enough segments so the source can be taken as basically static; variability mitigation: the shape of the accretion disk is assumed to be constant, and its changing details were simply absorbed into the error bars of the final fit.

In addition to variability, directions matter too. Because M87 is quite far off from our galactic disk, while Sgr A* lies right at the heart of it, the signal from M87 is actually subject to less distortion in the form of refractive and diffractive scattering caused by the dust in the Milky Way. Adequately correcting for these also meant the reconstruction took more time.

Almost a decade ago, the Earth Telescope was described to my high-school self as a far fetched-idea. It is remarkable how it has not only successfully been established, thanks to an extensive interdisciplinary collaboration system between astronomers, physicists, statisticians, signal engineers, and computer scientists, but is on track to become bigger and better.

Figure 3: A illustration of the EHT VLBI setup.

A Unique Window of Physics

Thanks to the first image of Sgr A*, results from orbital mechanical (star-tracking) observations and measurements at the scale of the event horizon could be cross-checked against each other, highlighting the consistency of general relativity at this scale for the first time in scientific history. This, alongside the 2019 results for M87, suggest that general relativity is consistent with reality even in extreme conditions.

Further, similar to how M87* got an updated image a few months after the initial 2019 data release, we can expect EHT to release a version of the Sgr A* portrait with polarisation information too, where the magnetic field information around the black hole will be revealed.

As more observation facilities join the EHT project, and as more data are gathered, the tools developed to circumvent signal variability may also be able to give us the first animated movie of Sgr A*, revealing more about the dynamics of the black hole accretion disk, one of the most extreme environments we know. It has been reported, for

Figure 4: Impression of an SMBH rising over an alien horizon near a galactic core. Artwork by Author.

example, that Sgr A* occasionally gives out flares in near infrared and X-ray, where the proposed mechanisms in literature are as of yet unverifiable.

In all, given its unique position as the nearest SMBH to us, Sgr A* is poised to provide for humanity, from today to the distant future, an exotic laboratory with which we could test the nature of spacetime and study fine details in black hole astrophysics.

Across the galactic dust and debris, through the shadow of the black hole at the heart of our galaxy, for the first time, we can glimpse into the stories of our cosmic past, and wonder the directions of our future scientific endeavours.

I hope that Einstein would be happy if he could hear about this.

You-Rong F. Wang - PhD, Physics

FW is a second-year doctoral candidate at Auckland Cosmology under the supervision of Prof. Richard Easther, who takes an interest in black hole-related physics. He has even written some orchestral music celebrating them, titled *Not Even Light*. You can access additional recommended reading and stream the music at FWPhys.com/NEL. The author photo was taken during my visit to UCLA Galactic Center Group, whose work is key to our understanding of the physics near Sgr A*.

Einstein's Miracles Part 4: Mass-Energy Equivalence

Caleb Todd

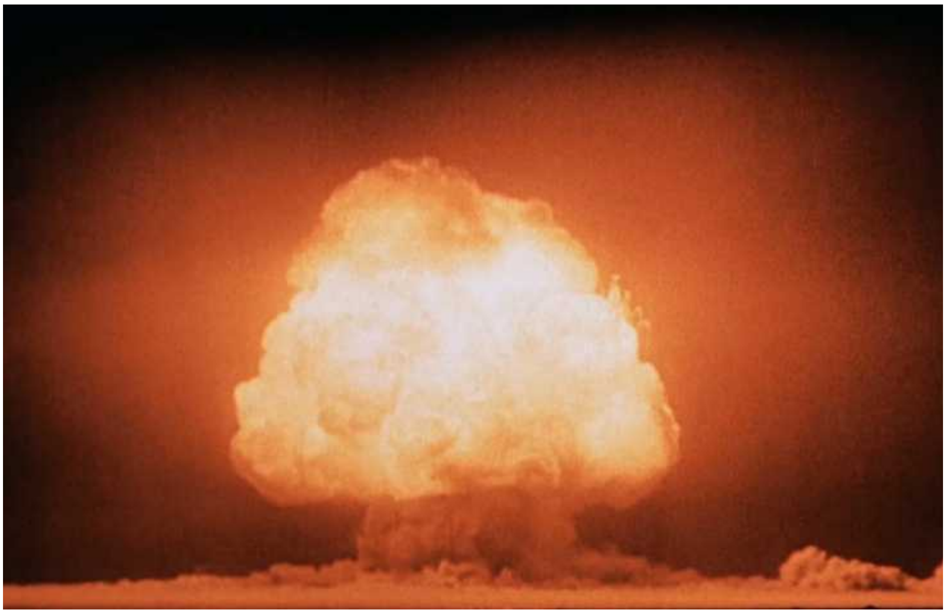
The world's first nuclear weapon detonated on July 16th, 1945. As the sun-like flash died away to be replaced by a mushroom cloud, the physicist Robert Oppenheimer quoted immortal words from a Hindu text [1]:

"Now I am become Death, the destroyer of worlds."

Never before had such destructive force been generated by mankind, and no one knew that better than those who had brought it about. However, the beginnings of the nuclear age were far more unassuming. Forty years earlier, a patent clerk named Albert Einstein was about to publish the last of his four 'miracle year' papers and, in doing so, pave the way for the most definitive technology of the 20th century: nuclear power.

comes directly from an equation Einstein presented in his previous paper (albeit, not one we covered last time). So, it is not the origin of this equation that we will consider; its significance is far more interesting.

To understand $E = mc^2$, we should begin by defining its terms. The E stands for energy. An object's energy is its ability to perform work; to make something move, lift it up, change its state, or some such thing. We often speak of 'kinetic energy': the energy stored in motion (an object has more kinetic energy the faster it moves). There is also 'potential energy', which is energy stored in interactions between different things. For example, an Acme anvil held stationary above Wile E. Coyote has no kinetic energy, but due to its interaction with the Earth (via gravity), it has substantial potential energy that can be converted into



The mushroom cloud from the first nuclear weapon ever to be detonated: the Gadget.

The geopolitical influence that Einstein's paper would have could never have been suspected at the time — not even by him. In fact, it's hard to imagine a more nondescript journal article, given that it could easily fit on a single page and was named quite blandly (as is traditional in physics) *Does the Inertia of a Body Depend on its Energy Content?* [2]. Really, this paper can be seen as a mere addendum to his previous paper on special relativity, which we covered in the last edition of *Scientific*. But its key result identifies the foundational principle behind the nuclear age and has become perhaps the most famous equation on Earth:

$$E = mc^2$$

As the paper's brevity indicates, the derivation of this equation is not particularly convoluted and more or less

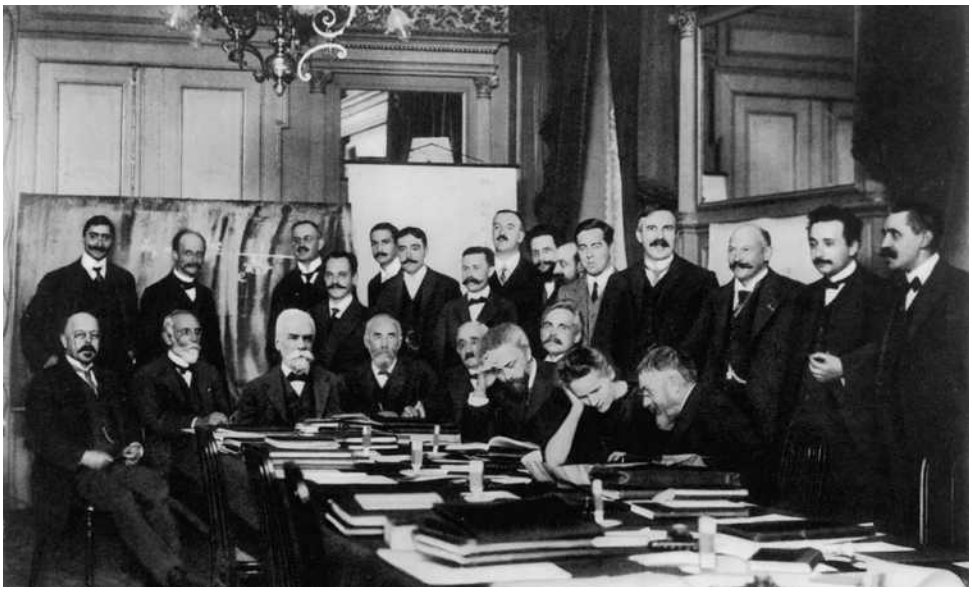
kinetic energy when the anvil is released. Your body stores considerable amounts of potential energy in chemical bonds — interactions between atoms. On the other side of the equation, m represents the mass of an object (also known as its inertia, hence the title of Einstein's paper), while c is the speed of light.

The equation, when put together, leads us to a simple but remarkable conclusion: the more energy an object intrinsically possesses, the greater its mass will become. When you take the elevator from the ground floor to your luxury penthouse apartment, the increase in your gravitational potential energy will make you heavier by E/c^2.

Importantly, the speed of light is a very big number (approximately 300,000,000 m/s). Even a moderately large change in your energy will result in an immeasurably small variation in your mass. Conversely, though, if enough energy were released to produce a noticeable change in mass, then you will have released a very large amount of energy indeed. This is exactly the idea behind nuclear power and The Bomb. Nuclear reactions (far more than chemical reactions) can involve non-negligible changes in the reactants' masses, and thus release extraordinary amounts of energy. When controlled, such reactions power entire cities, but uncontrolled, they level cities to the ground.

Before concluding, we should clarify one final point. Some people describe $E = mc^2$ as being about converting mass into energy, as though it meant you were using mass as fuel to burn and bring about energy in its stead, but that is not the case. Rather, the principle of mass-energy equivalence is exactly that: equivalence. The existence of mass implies the existence of energy; wherever you find mass, you already have energy. Mass disappearing and energy coming out is not a conversion process — the energy has left, therefore that mass has also left.

The history of nuclear power and the Cold War involves far more stories than Einstein's, of course. The pioneering work of Ernest Rutherford (New Zealand's greatest physicist), Marie Curie (one of the greatest scientists of all time), and other atomic scientists played a major role. However, mass-energy equivalence provided a fitting capstone to a year of miracles. $E = mc^2$ has become the equation most deeply associated with Einstein's legacy — and fair enough, given its significance — but 1905 must be known for more than just that one equation. In a single year, Albert Einstein kickstarted the quantum revolution, brought atoms out of the realm of speculation, invented special relativity, and then used it to demonstrate a fundamental truth which would define the 20th century. Physics has never been the same since. Einstein would go on to make substantial contributions to the fields he helped invent — most significantly by generalising special relativity to form our modern theory of gravity. However, he was never able to match 1905. Perhaps no one ever has. Fortunately for us, though, there is still a great deal about our universe we do not understand. It's about time we got another Einstein to have another crack at it. Any volunteers?



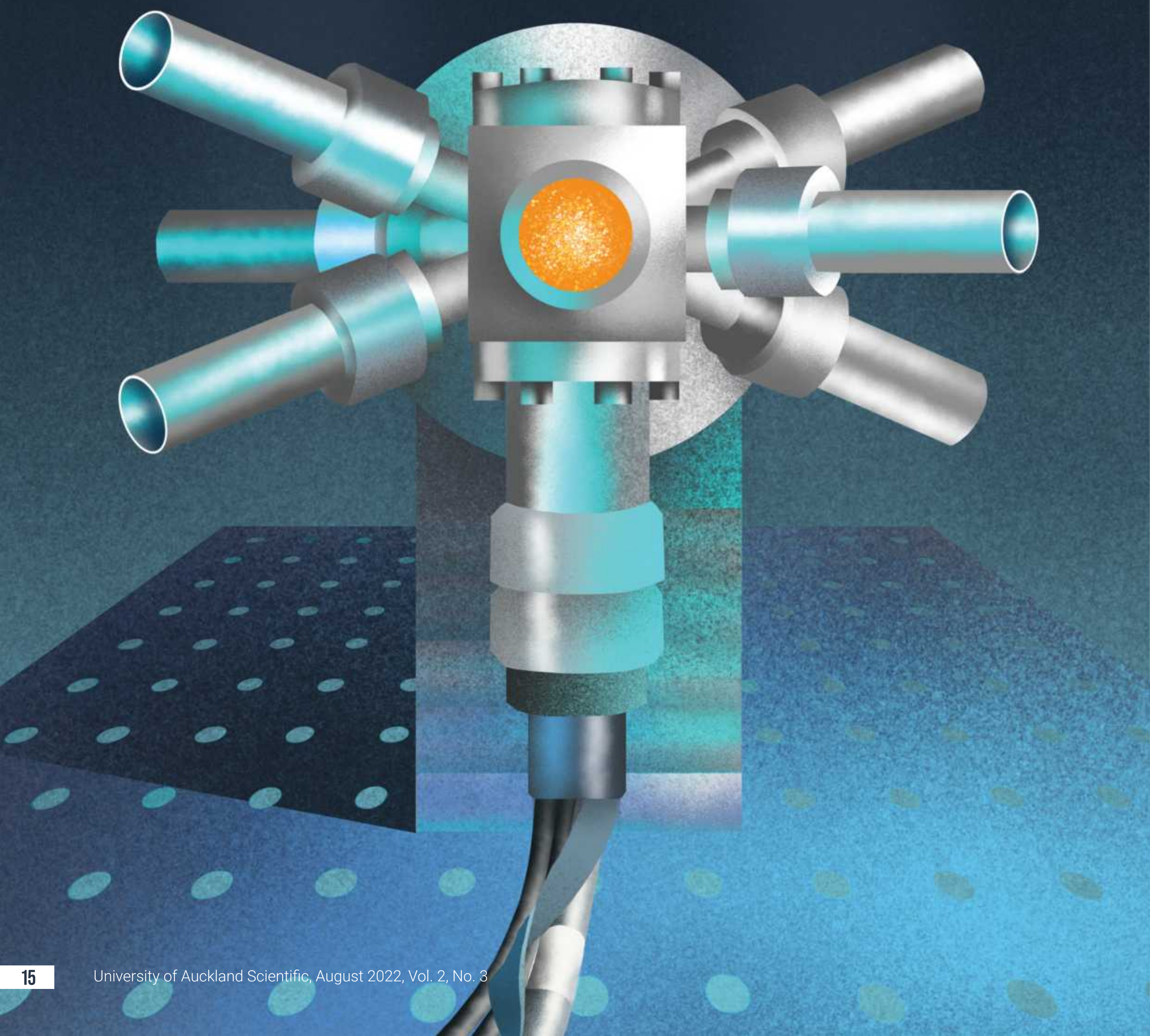
Participants in the first Solvay conference (1911). Einstein and Rutherford can be found standing second and fourth from the right, respectively, while Curie is seated second from the right. The sponsor, Ernest Solvay, was crudely edited into the original before it was released — you should be able to pick him out!

Caleb Todd - BSc (Hons), Physics

Caleb is a Research and Teaching Assistant in the Department of Physics at UoA newly finished with his BSc(Hons) degree. His research is in nonlinear optics and laser physics; in particular, the dynamics and control of ultrashort pulses of light.

MEASURING THE SPEED OF TIME

Recent breakthroughs create quantum logic clocks that don't lose nor gain a second over 33 billion years.



Amongst the beautiful mountainous scenery of the Rocky Mountains and the iconic Flatirons of Boulder, Colorado, sits a device that counts seconds better than almost any device on earth. It is the NIST-F2, the clock that was unveiled by the National Institute for Standards and Technology (NIST) in 2014, which does not gain or lose a second in 300 million years (i.e., with an inaccuracy of approximately 10) [1]. To give some perspective, 300 million years ago the earth had one continent, the Pangea, and reptiles were just rising into dominance. The NIST-F2, alongside its predecessor NIST-F1, serves as the primary standard for civilian time in the US [2]. The International Atomic Time (TAI) is based on the readings combined from many of these high precision clocks worldwide. It is the basis of civilian time and Coordinated Universal Time (UTC) [3].

It is hard to overstate the importance of clocks in our world. Contrary to the readers' current thoughts, clocks with an inaccuracy of 10 serve various purposes in our everyday lives. Accurate clocks are used to synchronise GPS systems, utilise radars for both commercial and military purposes, improve geodesy and metrology, timestamp financial transactions, and can even be used to confirm Einstein's theory of general relativity [4-6]. All of the above applications require a precise measurement of time to operate, and new applications of accurate clocks are realised frequently. At the launch of the NIST-F2, Steven Jefferts, the lead designer said, "If we've learned anything in the last 60 years of building atomic clocks, we've learnt that every time we build a better clock, somebody comes up with a use for it that you couldn't have foreseen" [1].

The most common clocks used for accurate timekeeping are known as atomic clocks, as they take advantage of the stable energy level structures of specific atoms. Atomic clocks arose several decades after the rapid establishment of quantum mechanics in the early 20th century when scientists started to understand the detailed structure of atoms. Lord Kelvin first suggested such a device in 1879[1], but the technology to realise them only came into prominence in the mid-twentieth century [7]. Much of the foundational work on atomic oscillations was laid out by Isador Rabi — a Nobel laureate in physics — in the 1930s and 40s [8,9]. Several laboratories in the UK and US started working on creating an atomic clock a decade later [7].

Atomic clocks work by exploiting the energy levels of atoms. The electrons that surround an atom have discrete energy levels and require a particular amount of energy for it to move to the next energy state. The amount of energy required to transition between energy levels is unique and consistent with each atom[2] [7,10-12]. This property plays an essential role in mitigating any manufacturing errors as every element is identical to one another. The basic principle behind atomic clocks is as follows[3]. An ensemble of atoms is cooled to several milli-Kelvin (near absolute zero) in order to access its ground state energy level. The ensemble is then exposed to radiation at a frequency close to their resonant frequency — the frequency that excites the atom and transitions it to the next energy state (in this case, the first excited state). It is for this reason that we must ensure the initially prepared ensemble is in its ground state. A magnet filters out those atoms that are not excited, and the remaining atoms are fed into a detector. The detector then counts the number of excited atoms, and uses this information to adjust the frequency of the radiation until the maximum number of excited atoms is detected. This feedback control and these self-adjustments are what make atomic clocks so precise. The adjusted frequency is then counted by a separate device to keep track of the time elapsed[4]. Figure 1 illustrates the general idea.

The most common element used in modern atomic clocks is the Cesium-133 atom [7]. Its heavy mass makes it slow and easier to confine, and its comparatively high resonant frequency makes for a more accurate measurement. In fact, the definition of the SI unit "second" is the duration of 91,926,317,70 periods of the radiation corresponding to the transition between the hyperfine levels of the unperturbed ground state of the Cesium-133 atom [13]. Other common elements used are Hydrogen and Rubidium, though both weigh less and have lower resonant frequencies in their ground states.

The significance of the measurement of time can not be understated when almost all measurements we make are in some form compared to time. Until the mid-1990s, Cesium based atomic clocks reigned supreme in accuracy. Though most clocks used nowadays for government, commercial, and military purposes are still Cesium based (owing to its well-known stability and reliability), various research groups worldwide have realised clocks that have higher accuracies. Here we will explore two promising avenues in

[1] Oscillations from resonant transitions in atoms had been known prior to the 20th century, but their detailed nature was not understood until the onset of quantum mechanics in the early 20th century. Lord Kelvin first suggested an atomic clock using Sodium and Hydrogen atoms in 1879.

[2] More specifically, atomic clocks use atoms cooled to near zero kelvin temperatures in order to access the bottom two energy levels of the atom. The transitions happen in those two isolated energy levels.

[3] Note that here we are only stating the general principle of atomic clocks and that most sophisticated clocks are much more complex with their implementation and geometry.

[4] An excellent video on how atomic clocks work can be found here: https://www.youtube.com/watch?v=l8Cl3bs9rvY

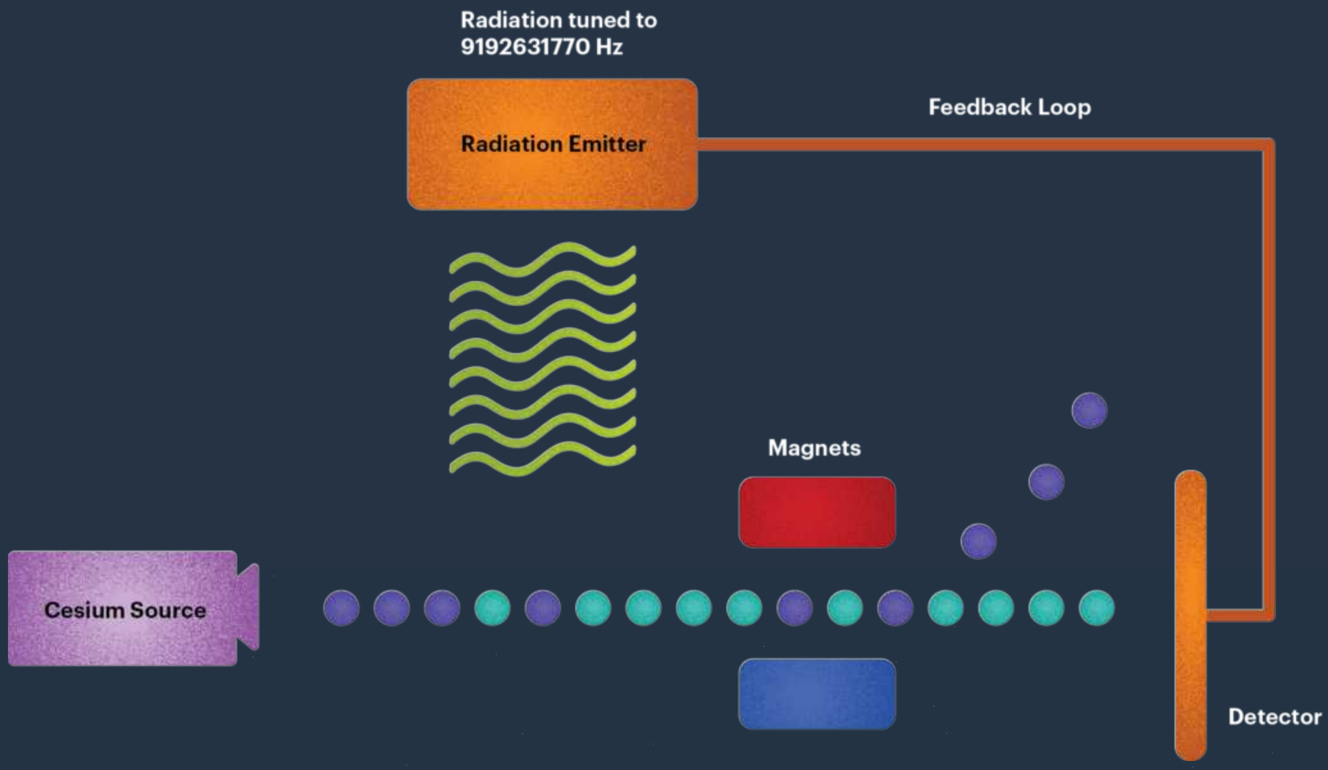


Figure 1: Purple (Cyan) particles represent ground (excited) state Cesium atoms. Emitted atoms are exposed to the radiation of a particular frequency, after which a magnet removes all the remaining ground state atoms that were not excited in the process. A detector then counts the number of excited atoms and uses this information to fine-tune the radiation frequency until the maximum number of excited atoms is detected.

next-generation high-precision clocks, the first of which is the optical lattice clock.

An optical lattice clock is created by using several lasers to produce a single or even multilevel egg carton-like potential that traps atoms in its valleys (see Figure 2 [15]). By using numerous lasers and external magnetic fields, the entrapment of the atoms can be finely tuned. The absorption frequency of the atoms can then be measured highly accurately. It was first proposed and realised by Hidetoshi Katori at the University of Tokyo, and since then, various research groups have improved upon it [14]. The most common elements used are Strontium and Ytterbium atoms. A recent optical lattice clock created by researchers at NIST demonstrated an inaccuracy of approximately 10^{-18}, which at the time proved to be the most precise. A significant advantage of the optical lattice clock is its stability paired with its accuracy, such that the Strontium based clock is regarded as the second definition of the SI unit "second". Many believe it will replace the primary definition in the coming years [14, 17]. The excitement surrounding this new clock is not unfounded. The 2022 Breakthrough Prize in fundamental physics was awarded to Hidetoshi Katori and Jun Ye (NIST / University of Colorado Boulder) for their significant work in optical lattice clocks — the very first winners from the field of photonics.

The second promising next-generation clock plays a tug of war with the optical lattice clock for the title of the world's most accurate clock. It is the quantum logic clock, the most precise clock ever to have been created at the time of writing. A quantum logic clock utilises the extremely stable vibration of a single Aluminium ion that has been trapped and laser-cooled. These clocks utilise lasers in the optical frequency in order to cause the ion oscillation, which results in higher accuracy compared to Cesium based atomic clocks that utilise microwave frequencies (frequencies about 100,000 times less). However, manipulating the Aluminium ion using a laser has not proven to be easy. In order to overcome this hurdle, researchers at NIST made a breakthrough in 2005 when they used a partner Beryllium[5] ion to cool the Aluminium ion and count its oscillations simultaneously [18-19].

One of the first quantum logic clocks made by NIST in 2010 caught vast media attention. It had a high enough accuracy to test time dilation proposed in Einstein's theory of general relativity with only 33 centimetres of height. They had demonstrated that time goes by quicker when you're higher off the ground, as well as that time moves slower when you're moving faster. It was one of the first realisations of Einstein's theory on a small, laboratory scale [20-21]. Future advancements in high precision clocks could lead to

[5] Magnesium is more common in recent implementations.

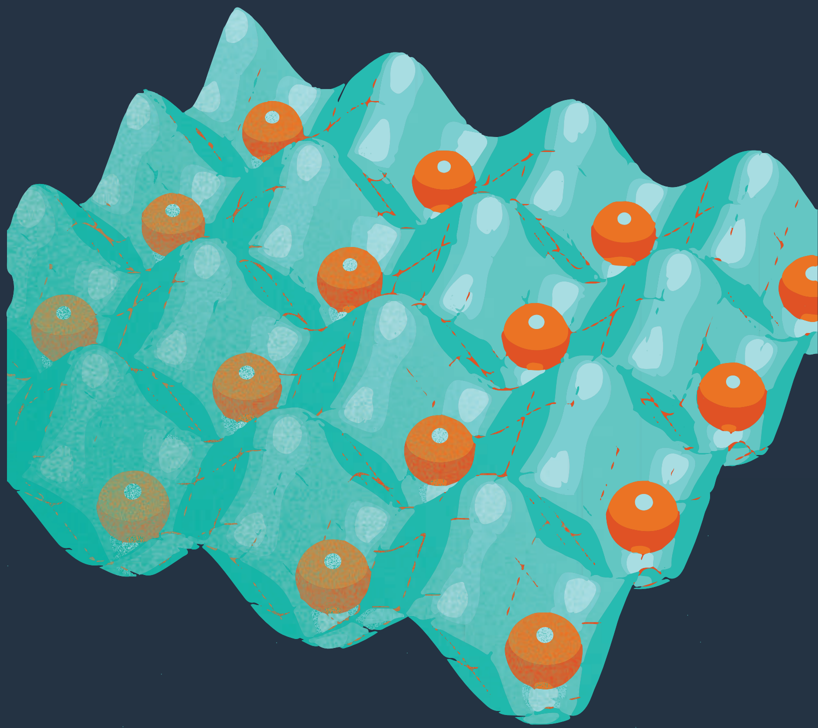


Figure 2: An egg carton-like potential traps atoms in its valleys as illustrated [15].

experiments investigating the intertwining effects between relativity and quantum mechanics, something that has stumped physicists for decades.

NIST's most recent quantum logic clock surpassed the optical lattice clock in terms of its accuracy (but not in stability, which is about ten times worse). The quantum logic clock does not gain or lose a second in 33 billion years, about twice the universe's age. It is the first clock to have an inaccuracy of less than 10^{-18} [22].

Both the optical lattice clock and the quantum logic clock are competing to become the next standard clock that defines a second. Though clocks are not often in the limelight, they are the bedrock of many technologies used every day. Hence, it is paramount to keep measuring the speed of time.

Alex Chapple - MSc, Physics

Alex is a Master's student in the Department of Physics. He likes pretzels and churros.

Epidemic Modelling: Simulations Using Stochastic Methods

Angeline Xiao

Branching Processes are a method of modelling the processes of populations that evolve independently with chance. These stochastic models can be used to simulate epidemics. Say we have an infected individual, they will inflict more cases with a certain probability, and the new infected individuals will independently continue to infect at the same rate. [1] The offspring distribution, and mean daily offspring are very useful in showing how epidemics may spread stochastically, given different parameters and models. Over summer, as part of the UoA summer research programme, we conducted epidemic simulations for a variety of models and infection rates.

We can determine if a branching process will die or not based on its mean daily offspring, popularly known as an R_{eff} value. If each individual has on average less than 1 offspring per generation then it will almost surely die. We call this process the subcritical process. If the mean offspring is 1, this is the critical process, and the population will still, almost surely die. If R_{eff} is greater than 1 then we call this a supercritical process, and it is not certain that the process will die out, although it is still possible. [2]

We can have branching processes in both discrete and continuous time. Both have their uses, with discrete time being a simpler model to use and understand. Continuous time branching processes are still useful as viruses do not adhere to human set intervals such as days, and a more accurate picture can be painted.

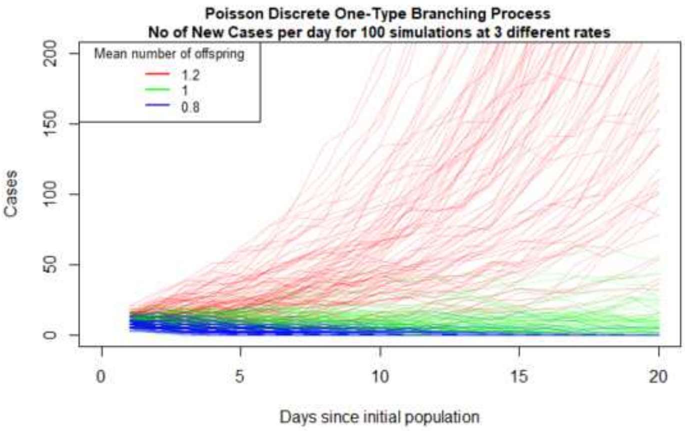
For a discrete time branching process model, the offspring of a population can be expressed by the sum of all the offspring that each member of the population will have, independent of each other. For a population in generation *n*, Z_n, the population in the next time generation, Z_{n+1}, can be expressed by the sum of independent identically distributed random variables which is same offspring distribution, $X_{n,i}$, where $X_{n,i}$ represents the offspring per individual per time generation.

That is, $Z_{n+1} = \sum_{i=1}^{Z_n} X_i^{(n+1)}$

To simulate total active cases, we define that when an individual has n infected offspring in a new day, $n-1$ of those offspring are new infections, and 1 offspring is the individual surviving. If an individual has 0 offspring then they have 'recovered'.

Perhaps the most intuitive offspring distribution is the Poisson distribution. Every day each infected individual infects more individuals at a rate λ, where $\lambda - 1$ is the mean number of individuals they infect (as they are not infecting themselves again). 100 iterations of this simulation were performed with λ rates of 0.8, 1 & 1.2 to demonstrate a subcritical, critical & supercritical process. We can observe the trend towards death of the subcritical process population while the supercritical process population explodes (Fig. 1).

Figure 1:

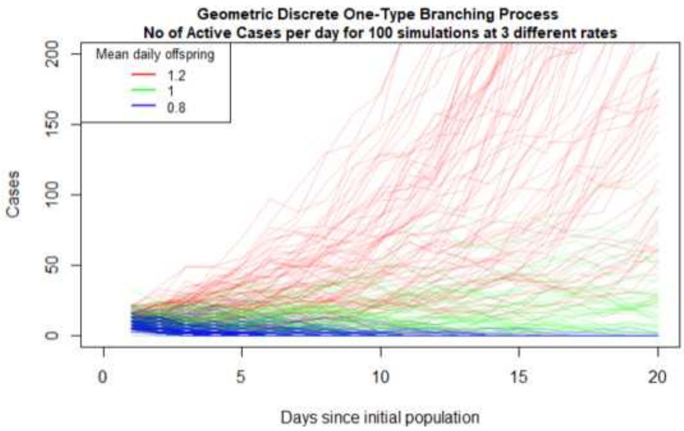


An extremely important but less intuitive offspring distribution we can use is the Geometric distribution. We define a Geometric distribution to represent the probability of the number of failures before the first success in a sequence of Bernoulli trials, where we can set the parameter *p* to be the probability of success. In context, this would signify the number of individuals infected before an individual stops infecting for the time unit.

For X ~ Geom(p), $\mathbb{E}[X] = \frac{1-p}{p}$

The Geometric distribution has special properties that allow us to explicitly calculate the branching process with a Geometric offspring distribution using generating functions. This allows us to conduct sanity checks on our simulations before we dive into more complex, non-calculable simulations. To compare subcritical, critical, and supercritical processes, *p* values of $\frac{5}{9}, \frac{1}{2}, \& \frac{5}{11}$ were used so that we have a mean daily infection rate of 0.8, 1, and 1.2 respectively. We can see that the simulation run for our 3 mean daily offspring rates looks similar to the Poisson model (Fig. 2). However what we are really interested in is the extinction proportion. On an arbitrary day (take day 10) we can see the distribution of extinction for each other mean daily offspring rates. (Fig. 3, Fig. 4, and Fig. 5).

Figure 2.



By comparing the histogram on day 10 to the explicit survival probability on day 10, we can confirm the accuracy of our simulations.

Using the generating function in the geometric case, we can find the extinction probability on day *n*,

$\mathbb{P}(Z_n = 0) = \pi_n$, for an initial population of 1 explicitly. [3]
Given the offspring distribution:

$$\mathbb{P}(X = k) = pq^k \text{ for } k \in \mathbb{Z} \text{ and } q = 1 - p \in (0, 1)$$

$$g(\theta) \quad = \mathbb{E}(\theta^x) = \sum_{k=0}^{\infty} pq^k\theta^k = \frac{p}{1-q\theta} \quad \Rightarrow g_n(\theta) = \mathbb{E}(\theta^{z_n})$$

Let us assume $p \neq q$, with $\mu = \frac{p}{q}$, for n > 1

$$g_n(\theta) = \frac{(p\mu^n - p) + \theta(q - p\mu^n)}{(q\mu^n - p) + \theta(q - q\mu^n)}$$

Notice $g_n(0) = \mathbb{P}(Z_n = 0) = \pi_n$

Hence for $p \neq q$:

$$\pi_n \quad = \frac{p(q^n - p^n)}{q^{n+1} - p^{n+1}}$$

We can apply this formula to find π_n for our simulations.

For p of $\frac{5}{9}, \pi_{10} = 0.9765$

For p of $\frac{1}{2}, \pi_{10} = \frac{10}{11}$

For p of $\frac{5}{11}, \pi_{10} = 0.8074$

To properly compare with the simulations run, these results need to be adjusted for 10 initial population, which is equivalent to having 10 independent branching processes with population 1 all dying out.

Figure 3:

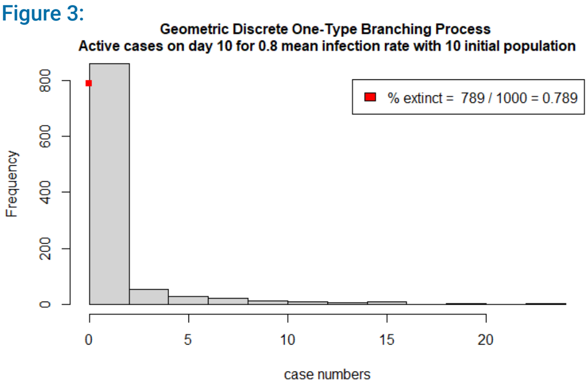


Figure 4:

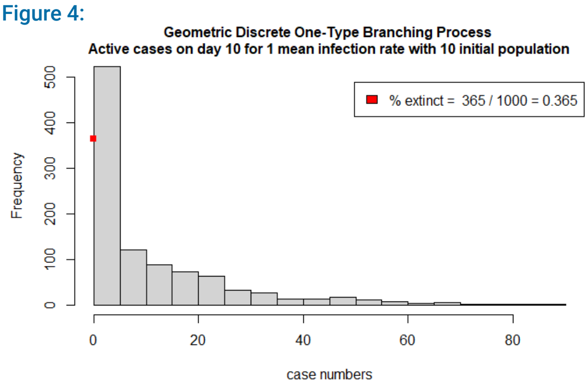
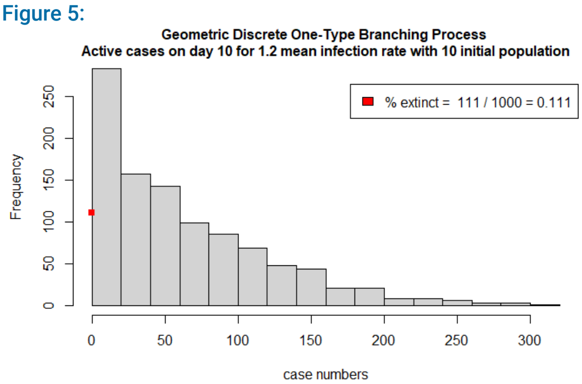


Figure 5:



Therefore with an initial population of 10:

For p of $\frac{5}{9}, \pi_{10} = 0.9765^{10} = 0.7884$ (simulated: 0.789).

For p of $\frac{1}{2}, \pi_{10} = \left(\frac{10}{11}\right)^{10} = 0.3855$ (simulated: 0.365).

For p of $\frac{5}{11}, \pi_{10} = 0.8074^{10} = 0.1177$ (simulated: 0.111).

We can see that the theoretical values line up with our simulated extinction proportions.

From these basic models we are able to adjust and add variables, such as shortening the generation time, or adding more complex offspring distributions (such as piecewise distributions) to accurately model epidemics.

As previously mentioned, branching processes can also operate in continuous time, where after a certain time calculated by an exponential distribution, an individual infects a number of individuals represented by an offspring distribution. Specifically, in a birth death process, an individual infects a new individual at rate α or recovers at rate β independently. These birth and death times are exponentially distributed. [4]

Let the population at time t be Z_t .

$Z_0 = 1$

If $\frac{\alpha}{\beta} < 1$ then the population will die out, and for $\frac{\alpha}{\beta} > 1$, $\mathbb{E}[Z_t] = e^{(\lambda-1)t}$, and the population will not necessarily die out.

Two independent exponential distributions with α = population • infection rate, and β = population • recovery rate, were simulated. The smaller of the two results is taken as the time before the first event, with the events either being infection or recovery. A critical process occurs with infection rate = recovery rate. A one-type continuous branching process at critical was simulated below (Fig. 6). We can introduce different strains or types of viruses in the same model in what is called a multi-type branching process. (Note: This is possible for both a continuous and discrete time model, we are simply choosing to demonstrate it with a continuous model) A multi-type model of a branching process is when there are more than one type of individual in the population. For the different types of virus that exist, they each have independent infection and recovery rate, as well as a rate to change from one type to another.

A specific example could be when a virus has an incubation period and an infectious period like Covid -19 did. When people are first infected, they are in the incubation period and are not infectious. After an exponentially distributed amount of time, they become infectious, and then will recover after that following an exponential distribution. The graph below

Figure 6:

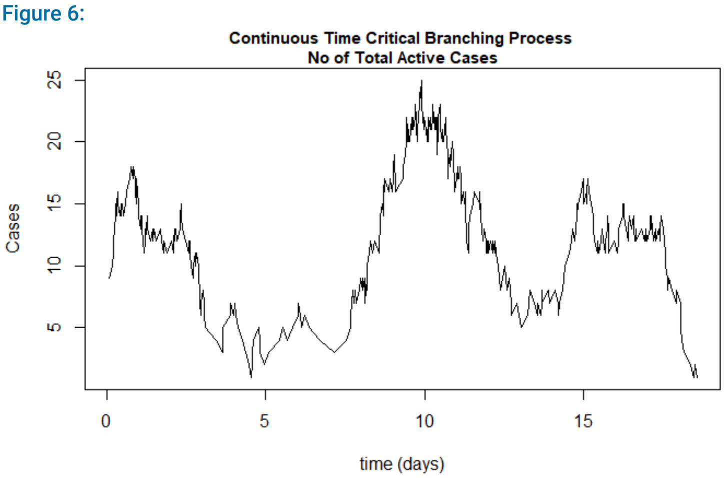
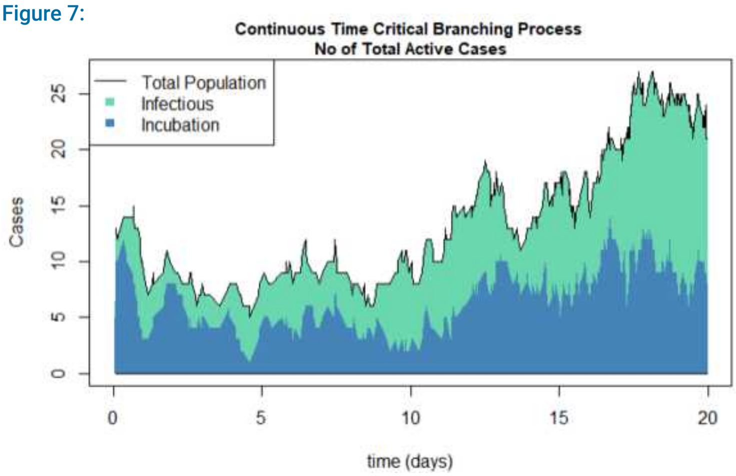


Figure 7:



shows a simulation of a two type branching process with an incubation and infectious period, with a critical infection and recovery rate (Fig. 7).

The simulations shown for branching processes in continuous time are all birth-death processes, which is a subset of branching processes. This simulation can also be run for different offspring distribution, such as a geometric offspring distribution, and for multi-types with more than two types.

Branching process models can be adapted and used to model epidemics, with a variety of offspring distributions, and using both continuous and discrete time. This report showed the different ways that stochastic models can be used to model epidemics. Simulating stochastic models can be very useful for results that cannot be explicitly calculated. The validity of the results in this report can be confirmed by comparing them to the explicit calculations. This research can serve as a base for more sophisticated stochastic population models combining more types, time inhomogeneity, as well as population size dependence branching.

This project was conducted under the UoA Summer Research Scholarship. I would like to thank the UoA Department of Statistics for making this possible, and especially to my supervisor Simon Harris, who has very patiently guided me through this project.

Angeline Xiao - BSc, Statistics, Mathematics

Angeline is in her final semester of her BSc, studying Statistics & Mathematics. She is the co-founder of Auckland University Women in Science, and is particularly interested in stochastic processes & probability theory. She enjoys swimming at the beach, playing Super Auto Pets, and annoying her siblings.

Patients Knee to Know: Evaluating the Robustness of IMU-Derived Knee Angle measurements

Jae Min Seo

Over 2.5 million people around the world turn to knee replacement surgery (also called total knee arthroplasty) to treat conditions such as osteoarthritis [1], and other degenerative joint diseases, which cause pain during gait and often prevent them from walking effectively [2]. The road to post-operative recovery and walking independently is a long and arduous process. The result of such invasive surgery is that patients' rotational range of motion about their knee is severely attenuated, and most patients can only extend their legs up to 80 degrees in their first two weeks post-operation, if at all [3]. In order to track patients' rehabilitation and to check for any abnormalities, it is important to measure how their range of motion about the knee improves over time [4-6]. How then, do we measure the joint angles about the knee?

Anatomical Considerations

One may think that the knee joint only has a single axis of rotation, but this is actually not the case; The knee joint has 6 degrees of freedom[1]: 3 rotational (flexion/extension, varus/-valgus, axial), and 3 translational (superior/inferior, anterior/posterior, medial/lateral) [7]. Try it! You can find the axial rotation of your knee by holding your knee still and moving your heel inwards and outwards. During knee flexion, the motion is caused by a combination of translation and rotation between the contacting tibia and femoral condyle surfaces [8]. Excess sliding or rolling about the joint is prevented by soft tissue structures, such as the menisci, the muscular connections via the tendons, and the ligaments between the femur and tibia [8]. The combinations of these muscle contractions and physical structures allow us to observe from a macroscopic scale what we know as knee flexion and its characteristic range of motion [7].

However, the knee-joint is often regarded as a perfect hinge-joint for modelling purposes. This is because the flexion-extension angle (~140°) of the knee joint is much larger than the varus/valgus angle (~10°), and the axial angle (~5°) [7-8], and in everyday movements such as walking and squatting, clinicians are primarily concerned about the restoring the flexion-extension angle of the knee [5,9,10].

Current Methods & Technologies

One may think that measuring the angle about the knee is quite trivial – you simply use a protractor and measure the angle between the thigh and shank when the leg is fully flexed and fully extended. And you thought right! There are in fact clinical tools that do just that, called goniometers [11].

However, clinicians often place the goniometers on different parts of the knee joint each time, and do not actually align them in line with biomechanical landmarks and bones [11]. This has shown to cause large inter-clinician (and in some cases, intra-clinician) variability in repeated measurements, causing large errors compared to ground-truth data measurements calculated using body scans [13-14]. There is also the added disadvantage of not being able to capture dynamic data, which is oftentimes more useful for biomechanists and orthopaedics [15].

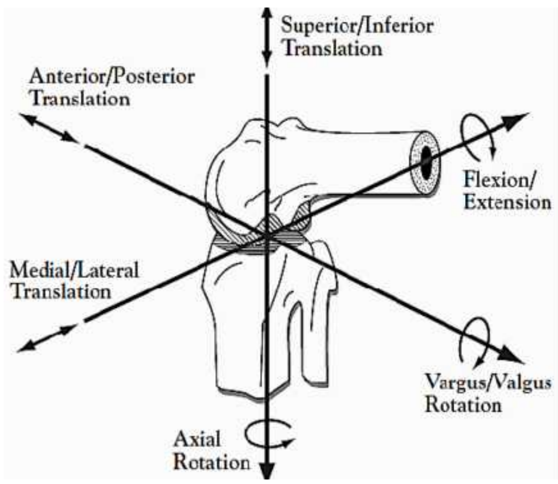


Figure 1: The knee has 6 degrees of freedom [7]

[1] Degree of freedom is the number of independent parameters that can define another parameter within a system. In this case of knee joint biomechanics, the degrees of freedom are the different possible movements, which superimpose together to give what we define as the 'range of movement'.

Figure 2: Long arm goniometers are a common tool by orthopaedics and biomechanists to determine the knee angle of patients undergoing rehabilitation [12]

The gold standard for calculating biomechanical measurements is to use Optical Motion Capture (OMC) [16]. This is where reflective markers are placed on the patient, and the movement of the markers is tracked in a room surrounded by high-rate, high-accuracy cameras [16]. You may have seen these being used in high-performance

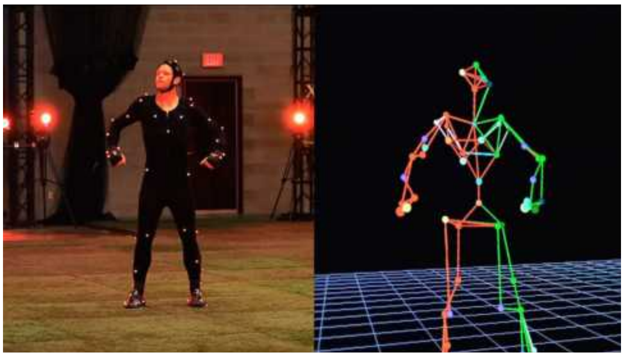


Figure 3: Motion Capture is used in a myriad of different applications [18]

athletes or other fields where human movement is tracked, like in video game animation captures [17].

The data collected from these cameras are processed by an open source software called OpenSim [19]. This software uses the marker information to calculate biomechanical variables using inverse kinematic techniques, which uses each time frame of marker positions and positions the model in a pose that "best matches" experimental marker and coordinates data for that time step [20]. This "best match" is the pose that minimises a sum of weighted squared errors of marker coordinates. OpenSim assumes that the marker position relative to the bones does not change over time. These Optical Motion Capture and optimisation techniques are the most accurate non-invasive methods for capturing knee angle data [18]. This method typically has a root mean square error (RMSE)[2] of less than 5 degrees and is used most widely as a ground-truth measurement for other prediction algorithms [19-20], [21-23]. We do not consider this RMSE to be significant as it is of a similar scale to the measurement errors that occur during data capture [22].

Optical Motion Capture is not perfect, however. This is due to the non-invasive nature of the markers; Reflective markers are placed on the skin, and oftentimes on top of other soft tissue such as muscle and fat. These soft tissues have large deformations for small changes in position,

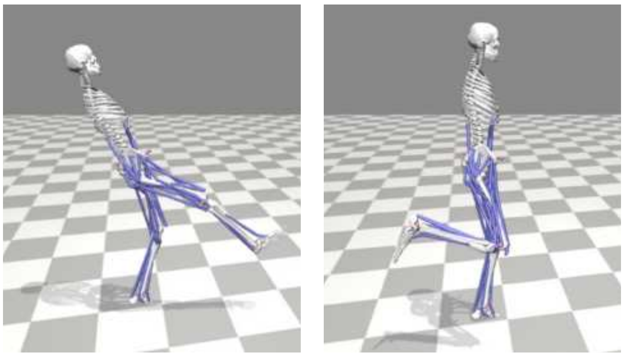


Figure 4: Markers on my leg as I do a range of motion exercise, visualised in OpenSim

which can cause variation over time in the distance between the markers and the anatomical landmarks/bones they are meant to represent over time [24]. These introduce noise called soft-tissue artefact into the data acquired, and can result in large inaccuracies if markers are not placed on landmarks with a lower proportion of soft tissue/fat/ muscles such as the ankle (where soft-tissue movement is

[2] Root Mean Square Error (RMSE) is the difference between two parameters. This is often used in scientific research and statistical analysis as a means of comparing one or multiple measurements to an expected value. The RMSE is calculated by taking the absolute value of the difference between the two parameters squared, and taking the square root of the result. One may see parallels between the RMSE, Euclidean norm and the Pythagorean theorem.

minimal) [25]. This is particularly of interest as we know that knee movements cause these soft tissues to jiggle, and we know that the knee joint doesn't jiggle-jiggle, it folds.

There exists an even more accurate form of data acquisition, and this is through bone pins. These pins are directly attached to the bones, which prevents any form of relative movement between the bones of interest and the markers, minimising soft-tissue artefact [26]. However, this method is typically for purely research purposes, and the bone pins can have a confounding effect on the gait of participants, which can render the data useless from a gait rehabilitation standpoint.

The three aforementioned methods come in varying degrees of accessibility, accuracy, and invasiveness. Whilst goniometers may be more accessible and non-invasive, they are not the most precise. Bone pins are extremely accurate, but are invasive and not very accessible for patients who have undergone surgery. Optical Motion Capture provides a nice middle ground, but these are typically only found in Biomechanics research institutes and require very expensive equipment. None of these options are favourable for patients who need accessible, accurate, and dynamic measurements of their knee angle during their rehabilitation.

Figure 4: IMeasureU is one of the leaders in wearable motion tracking (and was founded by research at the University of Auckland) [27]

Inertial Measurement Units

In the past decade there has been a surge in research regarding capturing joint measurement angles using portable and lightweight devices called Inertial Measurement Units (IMUs). IMUs capture linear acceleration, angular acceleration, and magnetic field strength through on-board accelerometers, gyroscopes,and magnetometers respectively. Research has been done by strapping one IMU on each segment about the joint (one IMU on the thigh, one IMU on the shank), and running the rate information through a data processing pipeline that can predict the angle using these different measurements.

IMUs by nature do not have an absolute frame of reference. If you have two IMUs in motion, you cannot directly determine the distance or angle between them without using some analytical or computational tools. Research has been done by placing IMU markers as parallel as possible to anatomical coordinate systems, but depending on the algorithm used, this may not be the optimal method for capturing the angle of the knee, or having participants perform simple calibration movements.

Angle Prediction Algorithms

Initial research on IMU-derived angle-calculations was done in 2001 by simply integrating the rate data at each capture to get from the angular acceleration to absolute angle measurements, from some known calibration pose (eg. full extension or full flexion) [28]. Any offsets were removed by subtracting the average angle from a static pose, and the initial angle was found by taking the inverse tangent of the acceleration in the first few seconds of each trial. The calibration procedures were done at the beginning of each trial to zero the effects of any accumulated drift on the next trial. Some studies have tried running calibrations by assuming IMUs are mounted exactly parallel to anatomical reference frames/axis, but have found that results are quite heavily corrupted by kinematic crosstalk[3].

A new approach was taken by Seel [29] where kinematic constraints were applied to the joint axis algorithms. This works under the assumption that the joint axis is a perfect hinge, whereby the only degree of freedom is the flexion-extension angle. This is done by projecting all knee motion vectors onto a shared plane that is defined by the range of motion of the thigh and shank. The angle was found by integration using the Gauss-Newton algorithm[4]. However, the problem of drift and measurement bias were not addressed in this paper.

Seel extended upon his work in 2014 to find the flexion/extension angle of the knee, by estimating local joint positions using data from the gyroscope and accelerometer [4]. This allows a data-fusion approach to find the real-time angle without any drift, as no integration is involved. However, only information about the flexion/extension

[3] Crosstalk is the phenomenon whereby one parameter's output is incorrectly recognised as another parameter. In biomechanics this is called Kinematic Crosstalk, and in the context of the knee, an example could be the some part of the internal/external rotation being recognised as an abduction/adduction movement.

[4] The Gauss-Newton Algorithm is an iterative algorithm that is used to solve nonlinear least squares (overdetermined) problems. This allows us to make the best possible approximation to overspecified systems (where the amount of degrees of freedom is negative) by minimising the squared sums of the residual errors. This is used in scenarios such as this, where there are more known parameters than the number of equations.

angle is found, with no mention of abduction/adduction or internal/external rotation.

An extension is offered by Laidig et al., where knee flexion/extension angles are accurately estimated by exploiting the knee's hinge axis to control misalignment about the vertical axis due to drift and/or magnetic field interference. Vitali [30] provided yet another approach similar to the above, but was able to extract abduction/adduction and internal/external rotation angles, though they did not mention the extent of kinematic crosstalk. Baudet used Principal Component Analysis[5] to minimise kinematic crosstalk, and has been very successful in minimising crosstalk, especially in the abduction/adduction and internal/external rotation angles [31] .

Research Objectives

Lots of measurements have been made by researchers that know exactly where and at what orientation to place their IMUs for optimal results. There is a plethora of research in this field that claim to have the best results for IMU-derived predictions, but do not disclose their robustness to different dynamic movements and slight variations in IMU placement. In order to make IMU-derived clinical measurements more accessible, we must assess the robustness of different prediction algorithms, as well as at which IMU positions and orientations the error in the predictions are minimised. My research will determine just that, by comparing the error associated with different combinations of IMU positions, orientations, prediction algorithms, and movements, to find the optimal conditions in which the error is minimised. Through this research, clinicians can better advise their patients on how to get the optimal readings from IMU-derived knee-angle measurements. This should vastly improve the accessibility of current postoperative total knee arthroplasty patients undergoing rehabilitation, ultimately improving patient outcomes.

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Jae Min is in his honours year of a BE (Hons) degree specialising in Biomedical Engineering. He has an interest in applying computational models and optimisation to solve problems in the realm of medical sciences, and hopes to one day work in the neurotech space, creating medical devices to assist people with motor or neurological disorders.

[5] Principal Component Analysis is one of the key cornerstones of feature extraction and statistical analysis. The vector which best explains the variation in data is considered the principal component, and the next best vector that is orthogonal to this principal component is the next principal component and so on. In this context, the largest principal component of the three rotations is assumed to be the flexion/extension angle of the knee.

Botany of Auckland Pest Plants

Nina de Jong

There are over 40,000 exotic plant species in Aotearoa, a number that completely swamps the 2,400 native species that were here first [1]. Most exotic plants arrive in Aotearoa intentionally for cultivation. Many of these species then 'jump the garden fence' and become naturalised in their own wild populations, some becoming invasive species that outcompete native plants [2]. As the country's most populated city, Tāmaki Makaurau is absolutely packed with invasive plant species. They travel by animal and wind to every nook and cranny of our parks, maunga, street-sides, and gardens. But who are these plants? What is their ancestry and where have they come from? How different are they to what is already here? This article will explore the botany of some common invasive plant species and also give advice on removal should readers be inspired to do some weeding of their own.

To form sustainable populations in any place, a plant must be able to survive and reproduce under the conditions presented to them. In pre-human times, Auckland provided diverse substrates on which many different plants could grow. For example, the volcanic ash and rock that is abundant across Auckland has allowed fertile, granular soil to develop [3]. Additionally, sediment deposition along river floodplains, such as near the Manukau Harbour, has allowed fertile silt soils to develop [3]. In contrast, greywacke rock uplifted in the Hunua Ranges has created steep, weathered infertile slopes [4]. These different landscapes allow all sorts of plant species to find a place that suits them and develop diverse communities.

In more recent times, settlers' arrival to Auckland and the subsequent development of agriculture has made soils more suitable for plant growth. Fertilisers, lime application, irrigation and drainage activities involved with farming reduce the limitations that soil conditions can have on plant growth, and create a more homogenous landscape [5]. This results in far less opportunities for plants with tolerances for difficult conditions to colonise space. Consequently, introduced plants that can more efficiently exploit the nutrient and water resources available to them, are fast-growing, and spread quickly, are excellent competitors in these conditions.

Beyond agriculture, Auckland is now heavily urbanised, and has become the largest city in the country. There has subsequently been an increase in introduced and exotic species as people bring all kinds of plants from all over the world to plant in their private gardens [6].

With such intense changes in water, nutrient, and light availability in Auckland landscapes, native plants have plenty on their plate. The addition of exotic competitors makes the conservation of native forest communities in the urban world incredibly challenging. It's important for Aucklanders who want to reduce invasive plant populations in the city to 'know their enemy', and understand as much about the origins and ecological function of these invasive plants as possible.

As a refresher, plants are classified in increasingly smaller groups of genetic relatedness: Division, Class, Order, Family, Genus, Species.

Climbing Asparagus Fern
Asparagus scandens

Climbing asparagus fern is one of the most common invasive species in Auckland. It is a monocot, which are not woody plants, and as a result they don't get incredibly large like trees. Monocots diverged earlier on the evolutionary tree than the Eudicots, which comprise most other flowering plants, and are characterised by a lack of secondary growth. This means that their shoots cannot get wider as they get

Climbing asparagus fern. Image from weedaction.org.nz.

Tradescantia. Image from forestflora.co.nz.

taller, and so limits the structural stability and subsequently the height that these plants can achieve. The climbing asparagus fern, for example, can grow prolifically but all of its stems remain as delicate, thin tendrils, which achieve height by growing on other plants. Although it is described as a 'fern' in its common name, climbing asparagus has been historically considered part of the Lily family (Liliaceae), related to lilies and tulips. It is now placed in the family Asparagaceae, and neither of these families are remotely related to ferns[1]. The Asparagaceae family is home to many popular houseplant species, and climbing asparagus fern is one of these. Its genus, the *Asparagus* genus, is made up of around 300 species that grow mostly as vines in the forest understorey, and this species, *Asparagus* scandens, is native to the understorey of coastal South African forests [7]. In Auckland, climbing asparagus smothers understorey plants and grows all along the ground in shady areas, preventing seedling germination of other species [8]. If you see it around, you can get rid of this plant by spraying it with common glyphosate herbicide repeatedly.

Tradescantia

Tradescantia flumenensis

This species is one of the hardest weeds to get rid of. Like the climbing asparagus fern, it is a member of the monocots and related to the Lily family, although rather than being from the asparagus family it is from the Commelinaceae family [12]. Commelinaceae are mostly tropical and subtropical herbs, and are mainly used by people for ornamental value. Native to South America, Tradescantia is a well known houseplant, and although the green variety is no longer allowed to be sold in Aotearoa, the purple and white variegated variety is still very popular with Auckland residents [13]. If you have this houseplant, make sure you don't throw it outside in a compost or rubbish bin. It needs to be burned or sprayed with herbicide to kill it. This is because Tradescantia can regrow from cut stems, allowing fragments to wash up along rivers and waterways [14]. From these fragments, Tradescantia creates large mats of groundcover in forest understoreys that prevent native seedling germination [15]. An alternative form of weed control is chickens — they love eating the leaves! Interestingly, although Tradescantia has detrimental effects on forest understorey regeneration, it is used as shelter by endangered native skinks [16]. In ecosystems there are always multiple ecological functions of each organism, and it can be difficult for conservationists to evaluate the net effect that each species has on communities with so many different needs.

Woolly Nightshade

Solanum mauritianum

Woolly nightshade is a small tree with large, fluffy oval leaves. It germinates and grows to reproductive age easily, and its fruits are eaten by native and exotic birds, promoting its spread. Woolly nightshade is part of the very large clade of the Asterids, which is the most recently diverged group in plant evolution, and also the largest clade with around 80,000 species [9]. Unlike their earlier diverging sister group of Rosids, which comprise the majority of other flowering plants, Asterids usually have fused petals, so that the flower forms a tube around the stamens and carpel [10]. The purple flowers of woolly nightshade follow this trend, with a fused base and five pointed lobes which would have once been five separate petals in an ancestral species. Woolly nightshade is part of the Solanaceae (nightshade) family, which is a famous family with many toxic plants. This species is no

[4] Ferns occur much earlier on the evolutionary tree. Although actual ferns and climbing asparagus have a similar looking leaf, ferns don't have flowers or fruits, and instead reproduce by spores.

Woolly nightshade. Image from weedbusters.org.nz.

exception, and it produces toxins which prevent other plants from colonising the soil around it, known as allelopathy [11]. Plants of the Solanaceae family are found all over the world, but are most diverse in South America, which is where woolly nightshade is from. Its genus, *Solanum*, includes globally popular cultivated species that millions of people rely on for food, including potatoes, eggplant, tomatoes, and chillies. The woolly nightshade plant has a faint smell that I personally think is nauseating. If you see it in your area, you can handpull small plants and cut the trunks of large plants (the wood is very soft) and paste the stump with tree killer.

Tree Privet

Ligustrum lucidum

This tree is a member of the Olive family, Oleaceae. Unlike the other invasive species mentioned in this article, privet is from the northern hemisphere, from temperate regions in East Asia [17]. Like the well-known olive, tree privet has small, dark purple berries. These berries are poisonous and are thought to have negative effects on native insects [18]. Another famous exotic species from the Oleaceae family that has invasive characteristics in Auckland is jasmine, which has very sweet smelling flowers. These species, like most other Asterids, have petals that are fused at the base, and members of the Oleaceae family have four petals per flower [19]. Tree privet is an invasive species in Auckland because it produces high quantities of viable seed and is long-lived, surviving as a small tree species for around 100 years [20]. Like woolly nightshade, tree privet forms a subcanopy that outcompetes other native species, preventing native regeneration and succession processes [21]. This species is much harder to pull out than woolly nightshade and also has much harder wood, making it more difficult to saw through. Most of the time removing it involves cutting the base of the trunk and painting the stump with strong stump-killer — tree privet will reshoot from a cut stump so it is very necessary to apply herbicide.

Moth plant

Araujia hortorum

Moth plant is a vine from the Apocynaceae family. The common name of this family are the milkweeds, and this is because these plants release white latex when their stems are broken. Moth plant is no exception, and its milky latex

Tree Privet. Image from weedaction.co.nz.

is irritating on skin and stains clothes. Most of the species of the Apocynaceae family are endemic to the tropics, including the moth plant, which is native to South America [22]. As another Asterid, its five white petals are fused at the base and can trap and kill insects [23]. The fruits of the moth plant are very distinctive: massive pods that are about the size of a hand and shaped like a rugby ball. Inside these pods are hundreds of seeds, each with a feathery plume attached to one end to help them disperse by wind. Moth plants germinate in massive numbers, and smother and strangle other plants. Small moth plant seedlings can be pulled out, and large vines should be cut at the base and painted with weed killer. It's also important to remove the pods (as once they open they cause further infestation), and destroy them so that they don't open.

These five weeds are arguably the most common in Auckland, but there are thousands more invasive plant species growing happily in the city. Once you start looking for weeds, it can be overwhelming just how many there are, particularly those growing along roadsides and on unmanaged land. Conservation is a strongly value-driven science and activity, and is the result of human conceptions of nature and wilderness being projected onto the non-human world. Consequently, significant conservation outcomes require huge amounts of effort and intervention. Exotic plant control is a central component of conservation, and understanding where such plants come from, and how they grow and spread, is important for achieving plant conservation goals.

Moth Plant. Image from ourauckland.aucklandcouncil.govt.nz.

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Grief and Learning - the limits in our current research

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