The Wilson's STEM Intrigue

Issue 11
September 2025

Introduction

The Intrigue Team is back once again to present you with a new issue of the Wilson's Intrigue, filled with incredible articles from writers across various year groups.

As always, the magazine is completely independent and student-run; this requires enormous volumes of time from pupils all over the school. Alongside the writers who provide the inspiring articles, the editorial team also work diligently, sacrificing their own time to help format and refine the articles to the highest standard possible. We would also like to show appreciation for staff, who selflessly engage with and help the magazine reach new and unimaginable heights. We look forward to seeing what next year's editorial team brings to the table to help the Intrigue achieve new heights.

Our Mission

- Expand your knowledge
- Contribute to the Wilson's community
- Make complicated parts of science more accessible
- Popularise science and make it more interesting
- Inspire creativity through wider research

Acknowledgements

This issue would simply not be possible without the perseverance of the writers and editors, skilfully balancing their school and super-curricular explorations. Their intrigue for STEM and enthusiasm to share their research are the fundamental pillars of the magazine. A massive thank you to all students involved for their contributions!

A special thanks must go to all the teachers that have made the production and publishing of the magazine possible.

If you would like to write in the twelfth issue of the STEM magazine to indulge in researching and sharing a STEM curiosity, please email Oscar at *WONGO@wilsonsschool.sutton.sch.uk* for more information.

Founded by Devanandh Murugesan and his team of editors in September 2019.

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DID YOU KNOW?

The world's longest structure was completed almost 500 years ago, the Great Wall of China. It spans over 21,000 kilometres and is still the only human-made structure visible from space.

Building the Impossible:

The Engineering Behind Modern Skyscrapers

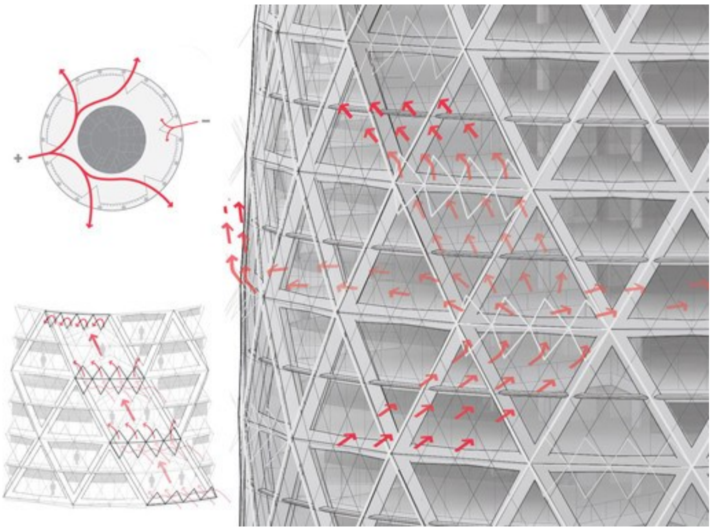
By Giovanni Cascini (Y13)

What if you could defy gravity? Not as a person, but as a structure, challenging the laws of physics and limits of human imagination. From the Empire State Building in New York, once symbolising the pinnacle of architectural achievement, to the Burj Khalifa, an equally fascinating marvel at a staggering 828 meters tall, skyscrapers are more than just buildings; they're testaments to human ambition and ingenuity.

The last decade of the 19th Century saw a vast demand for land. As businesses grew rapidly in the economic boom of the Century, there was an increasing desire to expand their floorplan introducing more private spaces and offices for more employees. Trade cities, such as Chicago and New York, experienced rocket high prices of downtown land. Manhattan, for example, saw an era of huge economic growth within American soil - what became known as the Gilded Age [1] . Pressure was exerted onto real estate develops to provide more volume for the same amount of land. [2] The only option left was to build up. The skyscraper was born.

Early skyscrapers like the Home Insurance Building in Chicago [3] (considered to be the world's first Skyscraper built in 1885), with their revolutionary steel-frame designs, laid the groundworks for the structural ingenuity we see today, pushing the boundaries of what seemed possible just a hundred years ago. The 1940s economic boom, following WWII, saw yet another pioneering turning point in the design of modern buildings. German Modernist, Ludwig Mies Van der Rohe innovated the 3D "tube" structures now present in most modern skyscrapers. Bangladeshi engineer Fazlur Khan made another bold step forward with these tube structures, using them as fundamentals to design the Willis Tower, what stood as the tallest building in the world for two and a half decades.

More recently, material science has become a key fundamental principle in order to improve the stability and strength of skyscrapers. J.E. Gordon's pivotal work in Structural Engineering has played a significant role in the development of such structures, highlighting the importance of material efficiency – using the least amount of material to achieve the maximum strength and resilience [4]. This approach has led to the use of high-strength steel and carbon-reinforced concrete, enabling taller and stronger structures such as the Burj Khalifa in Dubai. The use of carbon fibre is also one of the most crucial modern advancements in engineering; by placing a carbon fibre mesh into a concrete mixture instead of the traditional steel mesh, the overall weight of the structural unit decreases yet the structural integrity of it increases. [5] The interplay between tension and compression is also critical in skyscraper design, using structural systems like



diagrids (famously incorporated in the Gherkin, as shown above) to prevent catastrophic failure and collapse. These fundamental principles, outlined by J.E. Gordon, shed light on the immense challenges structural engineers face to construct the staggering towers we witness today in our city skyline.

In light of the ever-growing urgency to encourage the sustainability of modern infrastructure projects, many skyscrapers are now introducing sustainable design practices like green roofs and integrated vegetation. These not only add aesthetic value to the building but have practical advantages as well. The vegetative cover reduces surface temperatures and lowers ambient air temperatures, helping to combat the Urban Heat Island (UHI) effect which is prominent in many large urban cities. [6] Additionally, they help to improve air quality, filtering airborne pollutants such as PM2.5. A great example of these green engineering techniques take place in the Bosco Verticale in Milan, replacing the traditional materials of urban cladding with a polychromy of leaves for its walls. [7] Consisting of over 17,000 trees, shrubs and plants, this building acts as a prime example of how buildings could be designed in the future.

Ultimately, the engineering behind modern skyscrapers is a remarkable blend of innovation, precision and resilience that often goes unappreciated in the face of their sheer scale. From the rudimentary steel-structures of the late 19th century to architectural feats of the modern day, skyscrapers have evolved exponentially, both in height and in their ingenuity. Beginning in 1930 with the Chrysler Building, it took 80 years for New York City to see the construction of a half dozen skyscrapers. [8] Now, ten more of the supertall buildings have gone up in just the last ten years – and more are on the way. As the World's population continues to grow, much like the rapid urbanisation seen in Chicago during the late 19th Century, our only option will be to build upwards. With new supertall buildings emerging almost every year in areas such as Billionaire's Row, the question gets asked: how tall can man-made building truly go?

Edited by Arnav Prasad

Professor Edmund Happold, 1992

"Engineering is the improvement of nature for mankind's needs. It constructs a new nature, a supernature between mankind and the original nature ...each country has its own view of what engineering is, because this supernature is an expression of a nation's culture."

The Hydrogen Car Hoax

By Husniddin Hoshimov (Y12)

For as long as we can remember, hydrogen power has been an idealistic way out of the climate crisis for cars, and on the surface, it's easy to see why. Harmful greenhouse gases such as carbon dioxide are completely removed and replaced with water, and they have a seemingly greater range than electric cars, allowing for a lot more flexibility in driving. What's not to love?

As it turns out, a lot.

But before we jump to conclusions, let's see how these cars actually work. Hydrogen-powered fuel cell vehicles (FCVs) rely on fuel cells within the car, which are essentially sites of electrolysing redox reactions that generate energy using the following reaction:

$$2H_2 + O_2 \rightarrow H_2O$$

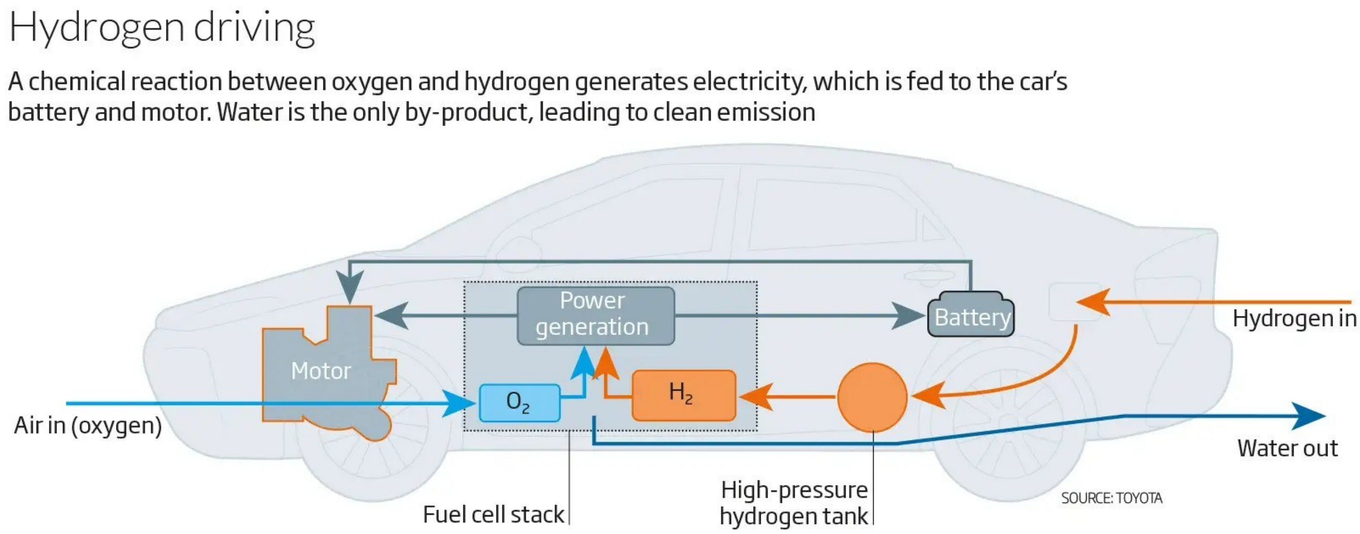
As anyone can expect, it is easy enough to source oxygen as we can find it in the air. Hydrogen, on the other hand, is a completely different story. Despite the fact that hydrogen is the most abundant element in the universe, it is nowhere to be seen in the atmosphere, so has to be synthesised by chemical means. The most common of the methods is steam methane reforming, whereby water reacts with methane:

$$CH_2 + H_2O \rightarrow CO + 3H_2$$

The glaring problem we find here is that the release of hydrogen also comes with the by-product of carbon monoxide. Alongside having an indirect effect on global warming by reacting to increase methane and ozone concentration in the air [Global Climate Change Linkages: Acid Rain, Air Quality, and Stratospheric Ozone (James C. White, Editor. Elsevier)], carbon monoxide is also poisonous. This is because it binds to haemoglobin in red blood cells used to circulate oxygen 200-300 times better than oxygen itself [Physiology, Oxygen Transport and Carbon Dioxide Dissociation Curve (Sagar Pater, Alvin Jose, Shamim S. Mohiuddin)] and so prevents oxygen from circulating in the body. The other most common process of extracting hydrogen is coal gasification, another harmful chemical process which uses coal:

$$3C + O_2 + H_2O \rightarrow 3CO + H_2$$

$$CO + H_2O \rightarrow CO_2 + H_2$$



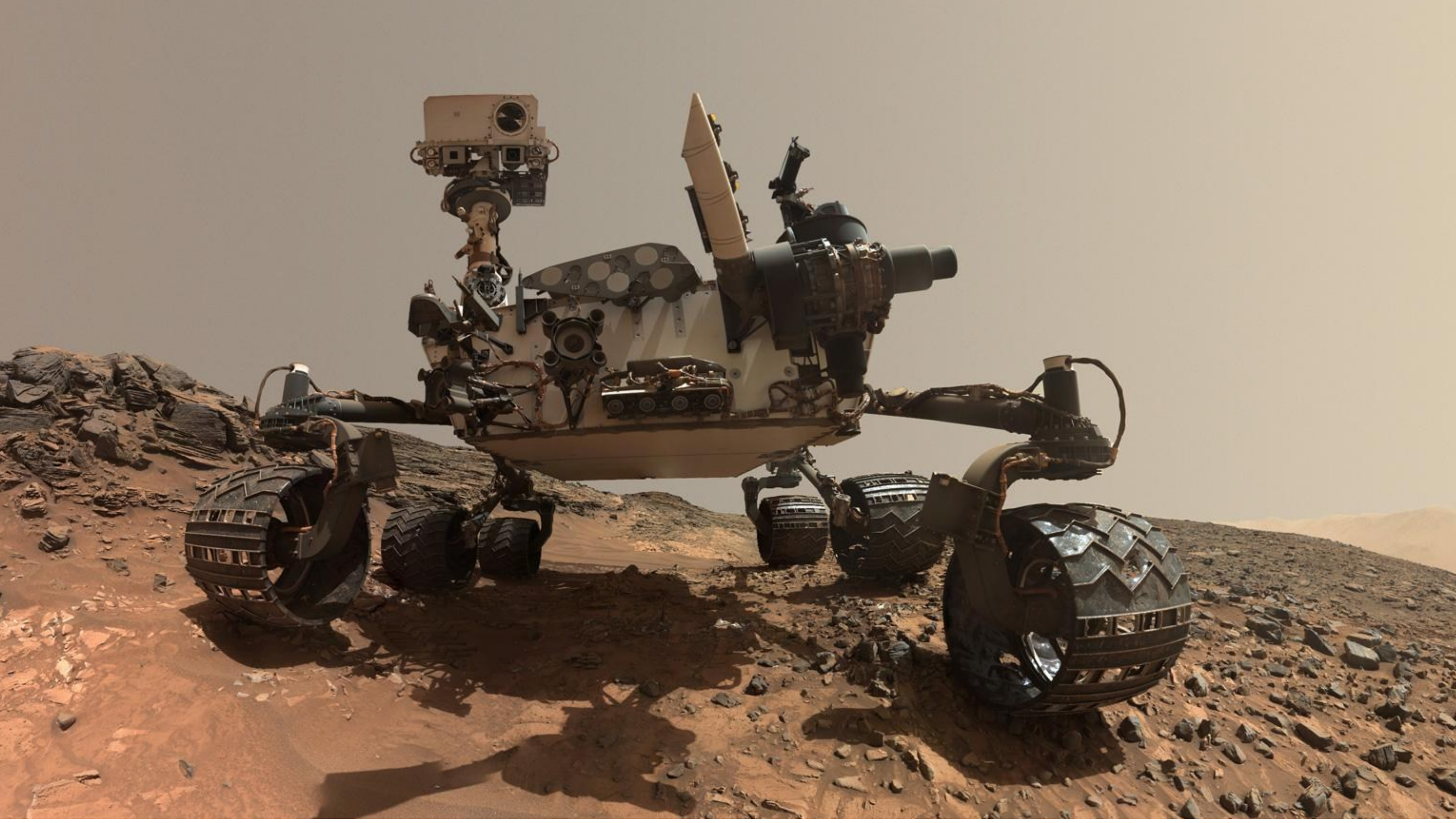
Coal gasification produces a whole 10-19 tons of CO_2 per ton of H_2 [The Colours of Hydrogen | The Belfer Centre for Science and International Affairs]: so much for clean energy considering these 2 processes constitute 95% of global hydrogen production.

So clearly hydrogen is unfit to be called 'green', but even then, what is preventing it from being used as an alternative in cars regardless? One thing is the price; hydrogen is too expensive to be used as a fuel, costing £10-15 per kilogram [Hydrogen cars: how fuel cell cars work, how much they cost and where you can refuel them] in comparison to £1.36 per litre of petrol [https://www.petrolprices.com/], whereby a litre of petrol is 0.737kg. This is made worse by poor energy efficiency; hydrogen cars have it at just 25-35% [Battery Electric Vs Hydrogen Fuel Cell: Efficiency Comparison] - similar enough to petrol cars yet it paling in comparison to the 70-90% efficiency of electric cars [Battery Electric Vs Hydrogen Fuel Cell: Efficiency Comparison].

This would be a significant problem at least if there was enough infrastructure for the fuelling of hydrogen for cars in the first place. In the entire UK, there are just six hydrogen refuelling stations [Where can I buy hydrogen and where is my nearest hydrogen filling station? | DrivingElectric], making extra range in comparison to EVs practically pointless. But there is more to the infrastructure problem than just fuelling stations: the storage of the high pressure hydrogen used in cars is incredibly dangerous, clear as in 2019, a massive blast at a Norwegian hydrogen fuel station injured several, with the cause of course being a simple loose tank plug [Norway fines Nel units $3 million over 2019 blast at hydrogen fuel station | Reuters]. The nail in the coffin has got to be though that this hydrogen has to be transported in trucks relying on fossil fuels, both endangering roads and increasing emissions.

However, amidst all the gloom and doom, there may be light at the end of the tunnel. The poor infrastructure and ridiculous price only align with a simple case of supply-and-demand: a low demand for hydrogen as a car fuel means that constructing vast infrastructure for it isn't economically feasible. And hydrogen extraction is being pioneered in range of environmentally friendly ways, including the electrolysis of water (funnily enough the exact reverse of the fuel cell reaction) and including the use of carbon capture and storage to reduce emissions. As a result, it isn't like hydrogen is ruled out for the far future considering the innovation of chemical engineers and the like to make it sustainable. However, considering that EVs are becoming cheaper and longer, and considering the revelatory opportunity of charging them at home passively, it makes more sense to use them as our free ticket out of the climate crisis instead of the premature technology in hydrogen cars.

Edited by Vivaan Goyal



The Curiosity Rover

By Vivaan Goyal (Y13)

Have you heard of the Columbia Space Shuttle? Mars has always captured humanity's attention, once revered as the fiery God of War by ancient Romans to H.G Wells' *"The War of the Worlds"* but more recently our real fascination comes from a quest to understand its past and potential life. Launched in 2011, the Curiosity Rover aimed to explore Mars 'surface, study its geology and climate, and assess whether it ever had the conditions to support microbial life but unlike its predecessors, Curiosity was engineered to tackle a broader range of scientific objectives, survive longer, and explore more rugged terrain. So how does one go about designing for the Martian environment?

Firstly, the design must address several unique challenges attributed to Mars: extreme temperatures, an atmosphere 1% the density of Earth's and its rough and varied terrain for prolonged periods of time. A reliable energy source is required – unlike Spirit and Opportunity, which relied on solar panels, Curiosity is powered by a Multi -Mission Radioisotope Thermoelectric Generator, converting heat from the radioactive delay of plutonium 238 into electricity. This change was enacted since the Exploration Rovers found

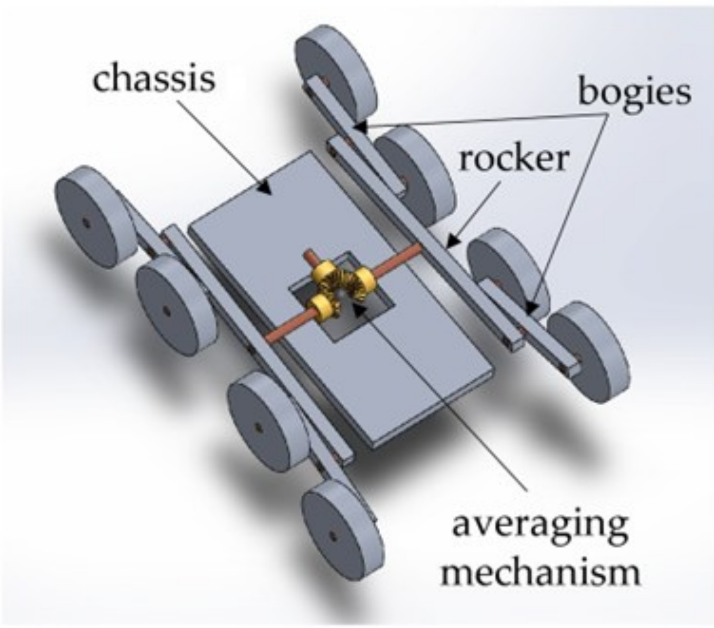
themselves short on power as dust set on their solar panels, a problem in the short days on winter. To tackle the terrain, around 200m a day, the rover has six independently powered wheels, each made from lightweight aluminium and equipped with cleats for traction. NASA prefers the rocker-bogie suspension system - unsprung (systems using springs tend to tip more easily as the loaded side yields) and using split axles, it allows a rover to climb obstacles up to twice the wheel's diameter while keeping all wheels on the ground. With a centre of gravity that supports 45-degree tilts (albeit automatic sensors limit it to 30), it operates slowly (10 cm/s) to minimise shock and prevent damage.

The "Seven Minutes of Terror" (Curiosity's Entry, Descent and Landing system) was the greatest challenge as traditional landing methods, such as airbags used for previous rovers, were not feasible due to Curiosity's large size and weight of 900kg. Curiosity entered Mars' atmosphere at 20,000km/hr and to protect it from intense heat (over 2100 degrees Celsius) a heat shield made of phenolic impregnated carbon ablator was used. Next, once the rover slowed down to supersonic speeds a disk gap band parachute to reduce its speed further to withstand the stress of deploying at Mach 2.2 and lastly , unlike previous missions, Curiosity was lowered to the surface using a sky crane, a rocket-powered descent stage that hovered above the surface and gently lowered the rover using nylon tethers. This method avoided the risk of dust and debris damaging the rover during landing. After landing, the rover waited 2 seconds to confirm solid ground, then triggered pyrotechnic fasteners to activate cable cutters, releasing itself from the descent stage. The descent stage then crashed, and the rover readied itself to start the science phase of the mission.

However, as is the case with rovers on Mars, there is a communication delay of around 14 minutes, so Curiosity was designed to operate semi-autonomously – its autonomous navigation system uses stereo cameras and hazard detection software to plan routes and avoid obstacles and uses visual odometry to keep navigation as accurate as possible. This capability not only reduces reliance on Earth-based navigation but also maximizes the rover's efficiency by enabling it to continue its mission even when real-time communication is impossible.

Curiosity's mission was a groundbreaking engineering achievement, pushing the limits of technology to explore another world. From its innovative landing system to its semi-autonomous operations and sophisticated scientific instruments, it set new standards for planetary exploration. The knowledge gained from Curiosity has not only deepened our understanding of Mars's history and potential for life but also paved the way for future missions, including Perseverance and the eventual goal of human exploration on Mars.

Edited by Aadarsh George

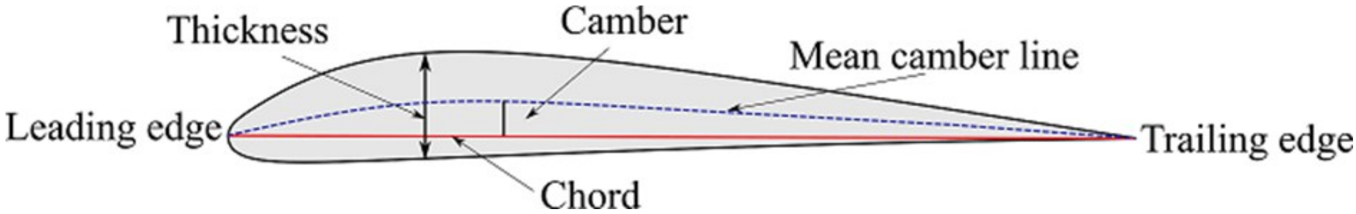


Aerofoil Flow Dynamics: Laminar, Turbulent, and Stalling

By Rohan Kott (Y13)

Aerofoil terminology

First, a brief introduction to the terminology related to aerofoils, that I will refer to hereon:



What is a boundary layer?

The boundary layer is a thin area of fluid flow that forms close to the surface of the aerofoil and is as due to the effects of viscosity. The fluid velocity within the boundary layer gradually increases from zero at the surface - due to the non-slip condition - to the velocity of the fluid the aerofoil is travelling through – far away from the surface. This is a velocity gradient.[1]

The boundary layer: (1) Is the source of the skin friction drag, (2) Alters the pressure distribution over the body, generating a resultant aerodynamic force due to pressure which has a non-zero component in the freestream velocity direction, known as pressure drag [2], and is (3) A thin layer of the lying very close to the surface of a body in motion. Airflow separates around this body due to the pressure, with the velocity of the fluid increasing as the distance from the body increases

The flow in a boundary layer can be either laminar or turbulent. Laminar flow is orderly and stratified without interchange of fluid particles between individual layers, whereas in turbulent flow there is significant exchange of fluid perpendicular to the flow direction. The type of flow greatly influences the physics of the boundary layer. For example, due to the greater extent of mass interchange, a turbulent boundary layer is thicker than a laminar one and also features a steeper velocity gradient close to the surface, i.e. the flow speed increases more quickly as we move away from the wall.[3]

The Reynolds Number

The Reynolds number Re is a dimensionless quantity that characterizes the flow regime of a fluid. It determines whether the flow is laminar (low Re) or turbulent (high Re), influencing the behaviour of the boundary layer on aerofoils and overall drag and lift forces.

(Dynamic viscosity measures a fluid's resistance to shear flow, whereas kinematic viscosity is the ratio of dynamic viscosity to fluid density, indicating the

$$\mathrm{Re} = \frac{\rho v l}{\mu} = \frac{v l}{\nu}$$

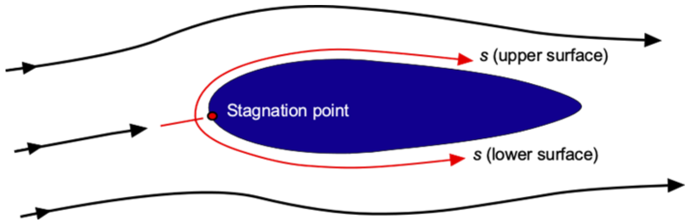
Where:

v = Velocity of the fluid
l = The characteritics length, the chord width of an airfoil
ρ = The density of the fluid
μ = The dynamic viscosity of the fluid
ν = The kinematic viscosity of the fluid

fluid's ability to diffuse momentum)

The developing nature of the boundary layer can be characterised in terms of a local Reynolds number, which is measured in terms of the distance s from the point where the flow initially develops on the surface.

For example, s = x is measured from the leading edge of a flat plate to some downstream distance. In many cases, the boundary layer will develop downstream from a stagnation point on a body, as shown in the figure below. Generally, the



downstream distance will differ for the upper and lower surfaces and depend on the geometric surface shape.

The downstream distance on a body is often measured from the stagnation point and will differ depending on the surface shape.

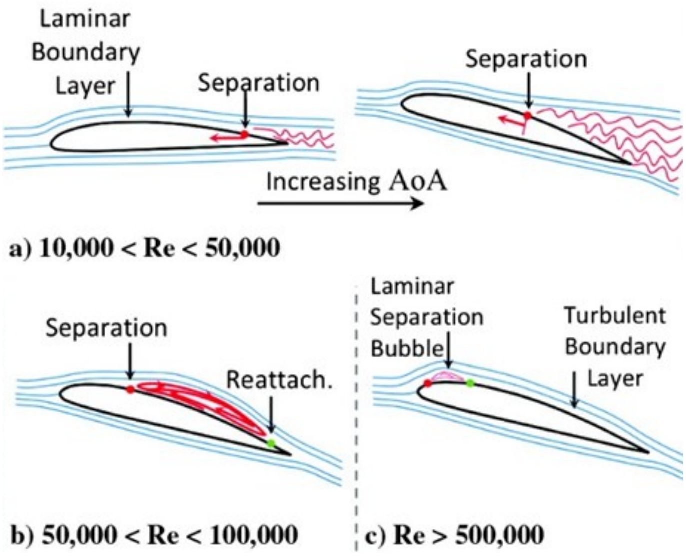
Many experiments with aerofoils and wings have examined a transition process from laminar to turbulent boundary layer flows. In all cases, the transition region has been found to correlate strongly with the Reynolds number based on downstream distance. For a smooth NACA 0012 (a symmetrical streamline shape) aerofoil, the critical Reynolds number for laminar-turbulent transition has been shown to be consistently about 10at moderate to higher angles of attack. However, the critical Reynolds number will depend somewhat on the aerofoil's shape. On most wings and aerofoils, the transition region occurs just downstream of the minimum pressure at the leading edge. Laminar boundary layers are sensitive to adverse pressure gradients because of their low velocities near the surface.

Because the turbulent mixing during transition occurs progressively, the transition from a fully laminar boundary layer to a fully turbulent one occurs over some distance. It is not a fixed point, per se. Although this distance is usually relatively small, perhaps 1% to 2% of the chord, it is still finite. In some cases, the transition will occur at the point where a short laminar separation bubble forms on the surface, which is typical for aerofoil sections at chord Reynolds numbers over 10.[4]

Real World Applications

Boundary layer separation in aerofoils occurs when the laminar or turbulent boundary layer, loses its adherence to the aerofoil due to an adverse pressure gradient, causing the flow to detach and form a turbulent wake.

One effect of boundary layer separation in aircraft wings is aerodynamic stall. At relatively low angles of attack, for example during cruise, the adverse pressure gradient acting on the top surface of the wing is benign, and the boundary layer remains attached over the entire surface. As the angle of attack is increased, however, so does the pressure



gradient.

At some point the boundary layer will start to separate near the trailing edge of the wing, and this separation point will move further upstream as the angle of attack is increased. If an aerofoil is positioned at a sufficiently large angle of attack, separation will occur very close to the point of maximum thickness of the aerofoil and a large wake will develop behind the point of separation. This wake redistributes the flow over the rest of the aerofoil and thereby significantly impairs the lift generated by the wing. As a result, the lift produced is seriously reduced in a condition known as aerodynamic stall. Due to the high pressure drag induced by the wake, the aircraft can further lose airspeed, pushing the separation point further upstream and creating a deleterious feedback loop where the aircraft literally starts to fall out of the sky in an uncontrolled spiral. To prevent total loss of control, the pilot needs to reattach the boundary as quickly as possible which is achieved by reducing the angle of attack and pointing the nose of the aircraft down to gain speed.[5]

Edited by Haayed Aslam

Swing Wings

By Aarush Raj (Y13)

The concept of 'swing wings', initially conceived during WW2 Germany, was rapidly developed upon by the US in a desperate attempt to compete with Soviet bombers and fighters. The need for an aircraft to be not only manoeuvrable enough to engage in dogfights but also rugged enough to withstand hard landings on aircraft carriers resulted in fighters which were crucial in the Cold War from both the Americans and the Soviets.

To understand how swing wings operate, we need to understand how wings work to generate lift. Key to this is Bernuolli's Principle - an increase in the velocity of a fluid causes that fluid to have a lower pressure. Aircraft wings are more curved on the top of the wing on the bottom, which means air travels faster on the top of the wing as compared to the bottom. Using Bernoulli's Principle, this means an area of low pressure is generated at the top of the wing, and an area of high pressure on the bottom. This pushes the wing up, resulting in the generation of lift.

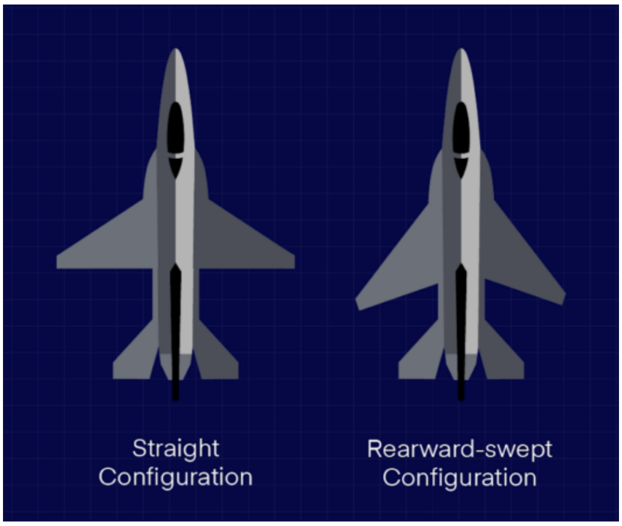
The main principle of swing wings is to change the angle the wings are perpendicular to the fuselage, i.e how far the wings are 'swept back'. A variable-sweep wing imitates nature - to glide or slow down, birds extend their wings; to speed up in a dive, birds tuck their wings close. Similarly, at low speeds the wings are extended outward to increase lift and improve stability, but at high speeds, the wings are swept back to reduce drag and enhance aerodynamic efficiency.
Fundamentally, swing wings change an aircraft's aspect ratio - the ratio of a wing's span to its mean chord (the average width of the wing). Aircraft with higher aspect ratio, e.g gliders, have better lift-to-drag ratios, whereas aircraft with low aspect ratio, e.g fighter jets, are more suited to high-speed and highly manoeuvrable flight.

A prime example of swing wings in action is the F14 Tomcat. When taking off, the F14 has a sweep angle of 20° - the increased surface area (around 19.5m2) of the wing means that the difference in air pressure caused by Bernoulli's Principle acts on a larger area, increasing the force of lift generated at such a low speed.

However, an effect of this larger lift force is induced drag, again as a consequence of Bernoulli's Principle. The areas of low and high pressure created by the wing are not static - air wants to flow from high pressure to low pressure; this means that high pressure airflow below the wing forms a 'vortex' around the wingtip to equalise the pressure. These vortices act as a drag force on the aircraft, slowing it down. Significant to this is that the creation of vortices around the wingtips cause induced drag, not the vortices themselves - it's the movement of high pressure air from the bottom of the wing to the top that causes induced drag. It's also worth noting that as angle of attack increases, the wing generates more lift, leading to a greater difference in pressure, leading to stronger wingtip vortices and more induced drag.

At the other extreme, the F14's wings can sweep up to 68° when moving between Mach 1.2 (920mph) and Mach 2.38 (1544mph). This sweep angle means that there is a lower wing surface area (11.6m2) for lift to be generated, but also means that the effect of induced drag is much less as there is less high and low pressured air.

Swing wings also affect an aircraft's stability by altering its centre of pressure (CoP) - the average location of pressure. When the CoP shifts forward, it acts as a counterbalance to any forces that may pitch the nose of the aircraft up or down, leading to more stable flight at lower speeds. This is instrumental to the F14's carrier based operations, where, coupled with the larger wing area when the wings are swept forward, ensures that maximum lift is generated while keeping the aircraft on a stable path at lower speeds. Conversely, when the wings are swept back above Mach 0.8, there is increased manoeuvrability for supersonic flight, as the CoP is closer to the centre of mass - this



means that the control surfaces become much more sensitive. The effects of shockwave interactions - increased drag, the generation of turbulent air behind the wing and aerodynamic instability - are reduced when the CoP moves rearward, making control surfaces much more efficacious.

One of the biggest considerations taken when designing the F14 was the hinges around which the wings 'swing'. These hinges needed to support immense forces acting on the wing (just imagine putting your hand out the car window travelling down the motorway!) including lift, drag and torsion. To combat this, these hinges were made with high-grade titanium. Alongside this, the hinges incorporated high-performance load-bearings to reduce the effects of friction and wear. The pivot points were positioned close to the centre -of-gravity, minimising the effects of friction on the wing. The F14 could sweep its wings at a rate of 7.5°/sec, for a total sweep time of 6.4s.

Whilst swing wing technology is being increasingly lost to the history books, the advancements made from developing swing wing technology impact air travel in every single flight, from developments in air safety and 'wing flex' to developing more efficient control systems for the future.

Edited by Arnav Prasad

Using Complex Numbers in Aerodynamics

By Haayed Aslam (Y1 Uni)

Complex numbers, which consist of real and imaginary parts (the latter of which definitely exist!) have a surprising application for calculating the airflow around an aerofoil (cambered surfaces such as aircraft wings). To appreciate this fully, an understanding of imaginary numbers is required from A-Level Further Mathematics, particularly their visual representations. If you are familiar with these concepts, then read on!

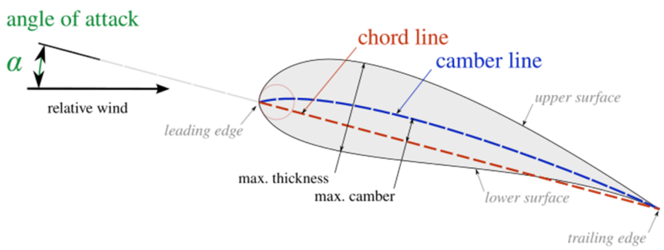


Fig. 1: cross-section of an aerofoil with nomenclature annotated

Most real-world fluid dynamics problems can be solved by deriving and solving the relevant differential equation of fluid motion (such as the Navier-Stokes equations). However, in practice, to find the airflow pattern around a plane wing you will need to consider its complicated shape, notably the sharp trailing edge (Fig. 1). Conversely, finding the flow pattern around a right circular cylinder is significantly easier, as its cross-section is just a circle (Fig. 2) [1].

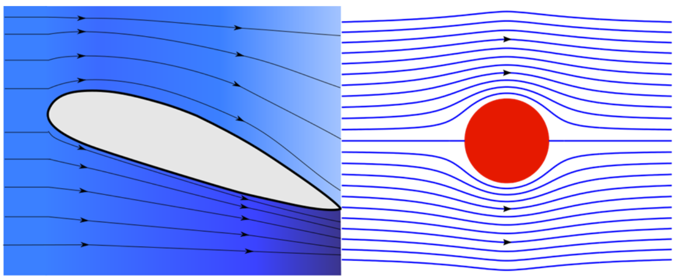


Fig. 2: visualisations of the streamlines around an aerofoil (top) and a circular cylinder (bottom)

Complex Analytic Functions

Fortunately, we can simply apply a transformation to the streamlines around the cylinder to obtain the flow pattern past the aerofoil. To do this, we must make some modelling assumptions: our air must be an incompressible, non-rotating, and non-viscous fluid. This allows us to generate a 'complex analytic function' of the air. This function is a combination of the 'velocity potential' and the 'stream function' [2]. These are derived from Stokes' and Euler's equations, respectively, though deriving these are beyond the scope of this article.

Velocity potential (φ) corresponds to the mean speed of the airflow in a specific direction (typically the x-direction, hence it is represented as the real part in the complex plane). We can only use this for fluids with no rotation (recall that this was one of our assumptions stated above).

Stream function (ψ) corresponds to the direction of the airflow and ensures that this flow remains incompressible (which we already assumed above).

Let z be a complex number, then $z = x + iy$. In the same way, the complex analytic function $\Omega(z)$ is given as:

$$\Omega(z) = \phi(x,y) + i\psi(x,y)$$

Where $\varphi(x,y)$ is our velocity potential (real part) and $\psi(x,y)$ is our stream function (imaginary part). To clarify, the velocity potential is not the speed of the air itself, rather the air velocity is the gradient of this potential. The function we have just created is very powerful, as we can now place it on a conformal map.

Joukowsky transformation using Conformal maps

As mentioned earlier, we can now apply a transformation using our complex analytic function to represent our aerofoil on a special type of complex plane called a conformal map. These are maps that preserve the shape and angles of infinitely small parts of an image but may not always preserve their total size or camber. We can use the Joukowsky transform, which requires us to first map a right circular cylinder onto the conformal map (hence why I referred to this specific shape at the beginning). The Joukowsky transformation can then be applied as follows:

$$\omega = z + 1/z$$

Where ω is a complex number x + iy which is the transformed point, and z is a complex variable from the original cylinder. Across several points on our circular cylinder, this transformation will translate z to a new point on the map, which is ω (consisting of the co-ordinates of a point on our newly generated aerofoil).

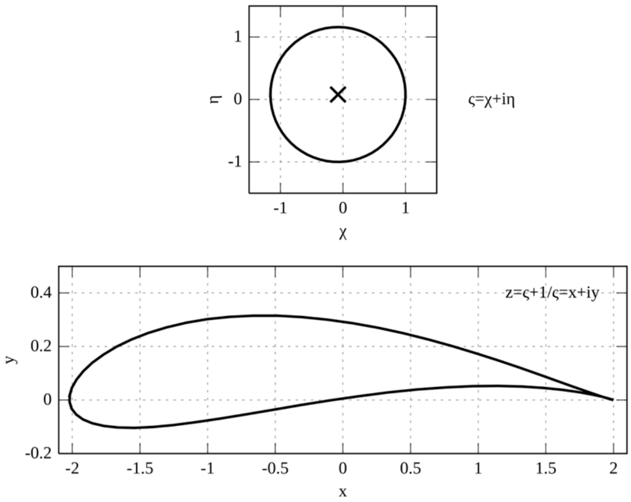


Fig. 3: example of the Joukowsky transformation. The cross-section of a cylinder is a circle (top) which is first drawn on the map; following the transformation the Joukowsky aerofoil (bottom) is created.

The main benefit of using this transformation (as opposed to alternatives such as the Kármán–Trefftz transform) is its similarity to real aircraft wings, such as those found on commercial airliners. Joukowsky aerofoils have a 'cusp' at their trailing edge [3]. This is the furthest-back point on the aerofoil, with co-ordinates (2,0) in Fig. 4, where the direction of that point much reverse for subsequent point transforms. This means that the angle pointing towards the front of the aerofoil is virtually zero, akin to real wings. Other transforms feature a non-zero angle at the trailing edge. While this difference is negligible, it is a reason as to why the Joukowsky transform is preferred.

Once this transformation is complete, it is possible to run simulations where the initial streamlines incident on the leading edge of the wing are uniform and horizontal. This is demonstrated in Fig. 5.

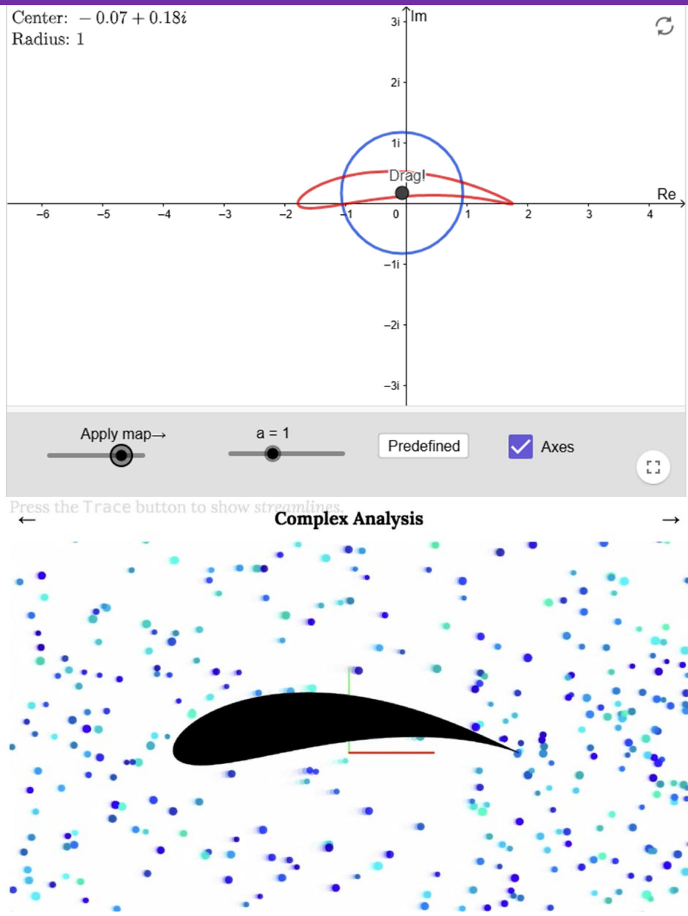


Fig. 4: emulating the Joukowsky transform on a conformal map (top), then simulating the aerofoil created by the transform (bottom); the blue and green particles represent air travelling left to right.

But what was the point of this process? How can we now calculate the lift of this aerofoil? The answer: using the Kutta-Joukowski theorem. This calculation is heavily simplified by our use of complex analytic and conformal map, because the lift per unit span (L') can now be determined as:

$$L' = \rho_\infty V_\infty \Gamma$$

Where ρ and V are the air density and airspeed, respectively, and Γ is the air circulation defined by integrating V with respect to the length of the curve of the aerofoil (s). We are only interested in the circulation around a fixed contour C enclosing the aerofoil and in the clockwise direction. We use the integrand V cosθ as we are just interested in the component of airspeed in the direction of the tangent to C. All of ρ, V and C can be found from the aerofoil simulations above. We are therefore left with the calculation for circulation as:

$$\Gamma = \oint_C V \cdot ds = \oint_C V \cos\theta \, ds$$

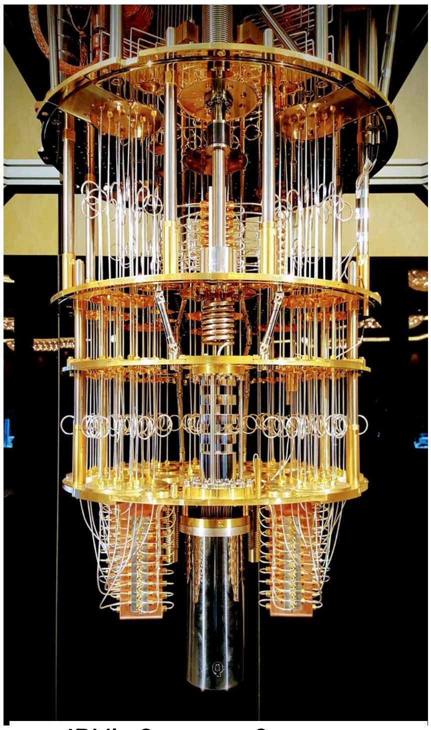
In summary, we have explored how the joint usage of complex analytic functions and a unique transformation can enable us to compute an aerofoil in the complex plane and hence calculate the airflow around it. This reveals the true beauty of complex numbers and their usefulness for mathematicians and engineers alike.

Edited by Arnav Prasad

The Quantum Mania

By Shourya Gupta (Y12)

Quantum computing stands out as one of the most groundbreaking and intricate technological advancements in history. Its ability to transform various industries, including cryptography and healthcare, is unmatched. Operating on principles from quantum mechanics, which governs the behavior of particles at atomic and subatomic levels, quantum computing differs significantly from classical computing. While classical computers handle data in binary bits (0s and 1s), quantum computers utilize quantum bits, or qubits. These qubits can exist in multiple states at once - 0, 1, or both - due to a property called superposition. This capability enables quantum computers to manage enormous amounts of data and execute numerous computations at the same time. Another essential aspect of quantum mechanics is entanglement. When qubits become entangled, the state of one qubit is intrinsically connected to the state of another, no matter how far apart they are. For instance, consider two entangled qubits, A and B. If we measure qubit A and find it in a specific state, qubit B will immediately take on a corresponding state, even if they are light-years apart. Albert Einstein famously referred to this as “spooky action at a distance,” but it is now a well-established phenomenon that underpins many quantum technologies. This remarkable property



IBM's Quantum Computer

greatly boosts the speed and efficiency of quantum computations, allowing quantum computers to address challenges that classical systems cannot even begin to solve.

The advancements in quantum computing have surged impressively over the last decade, fueled by improvements in both hardware and software. In 2023, IBM introduced its 433-qubit processor, Osprey, marking a significant leap from its previous 127-qubit Eagle processor released in 2022 [1]. Google reached an incredible milestone in 2019 with its Sycamore processor, showcasing quantum supremacy by solving a problem in two hundred seconds that would take classical supercomputers thousands of years.

However, the real-world application of quantum computing relies heavily on effective error correction, as quantum systems are particularly vulnerable to noise. The practicality of quantum computing relies significantly on effective error correction. Quantum systems are particularly vulnerable to noise and decoherence, which can interfere with qubit states and result in computational errors. To tackle this issue, researchers have created advanced error correction techniques. One promising method is the use of bosonic codes, which encode quantum information within the states of a harmonic oscillator. By distributing information across several states, bosonic codes can greatly lower the logical error rate, leading to more dependable quantum systems. Various architectures, such as superconducting qubits, trapped ions, and photonic systems, are being investigated by companies like Rigetti Computing and IonQ, making scalability more achievable. By 2024, over $40 billion has been invested in quantum technologies [2], underscoring the global interest in this area. Collaborative initiatives, like the Quantum Open Source Foundation, are making quantum development tools more accessible and driving innovation

Quantum computing is set to transform industries and tackle challenges that were once thought insurmountable. It has the potential to revolutionize cryptography, as current encryption systems that depend on the difficulty of factoring large numbers could become outdated with the advent of quantum algorithms like Shor's algorithm [3], which is a significant advancement in quantum computing. By utilizing the principles of superposition and entanglement, Shor's algorithm can solve problems that would take classical computers billions of years to resolve, posing a serious threat to RSA encryption. RSA depends on the challenge of factoring large numbers to protect digital communications, but with Shor's algorithm, quantum computers could make this encryption method ineffective.

Nevertheless, quantum cryptography also brings forth new security measures, such as quantum key distribution, which provides nearly unhackable communication. By transmitting encryption keys through entangled photons, Quantum Key Distribution (QKD) [4] ensures that any attempt to eavesdrop on the communication disrupts the quantum state, alerting both the sender and receiver to the intrusion.

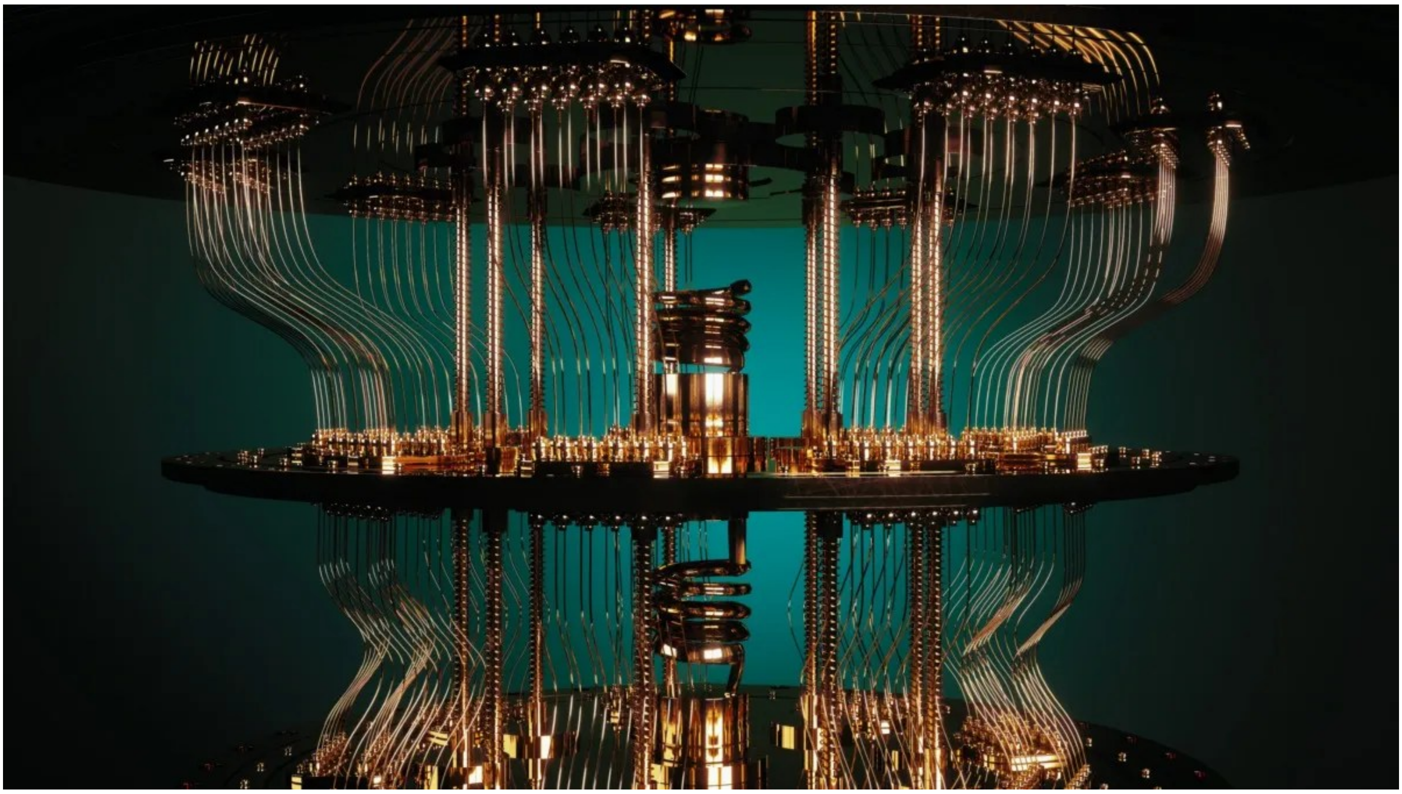
In the realm of optimization, quantum computers excel at tackling challenges that range from supply chain logistics to urban traffic management. For instance, Volkswagen has implemented quantum algorithms to improve traffic flow in Beijing [5]. The ability of quantum computing to simulate molecular interactions is set to accelerate drug discovery for diseases such as Alzheimer's and Cancer, with collaborations like Pfizer's partnership with IBM [6] highlighting its potential.

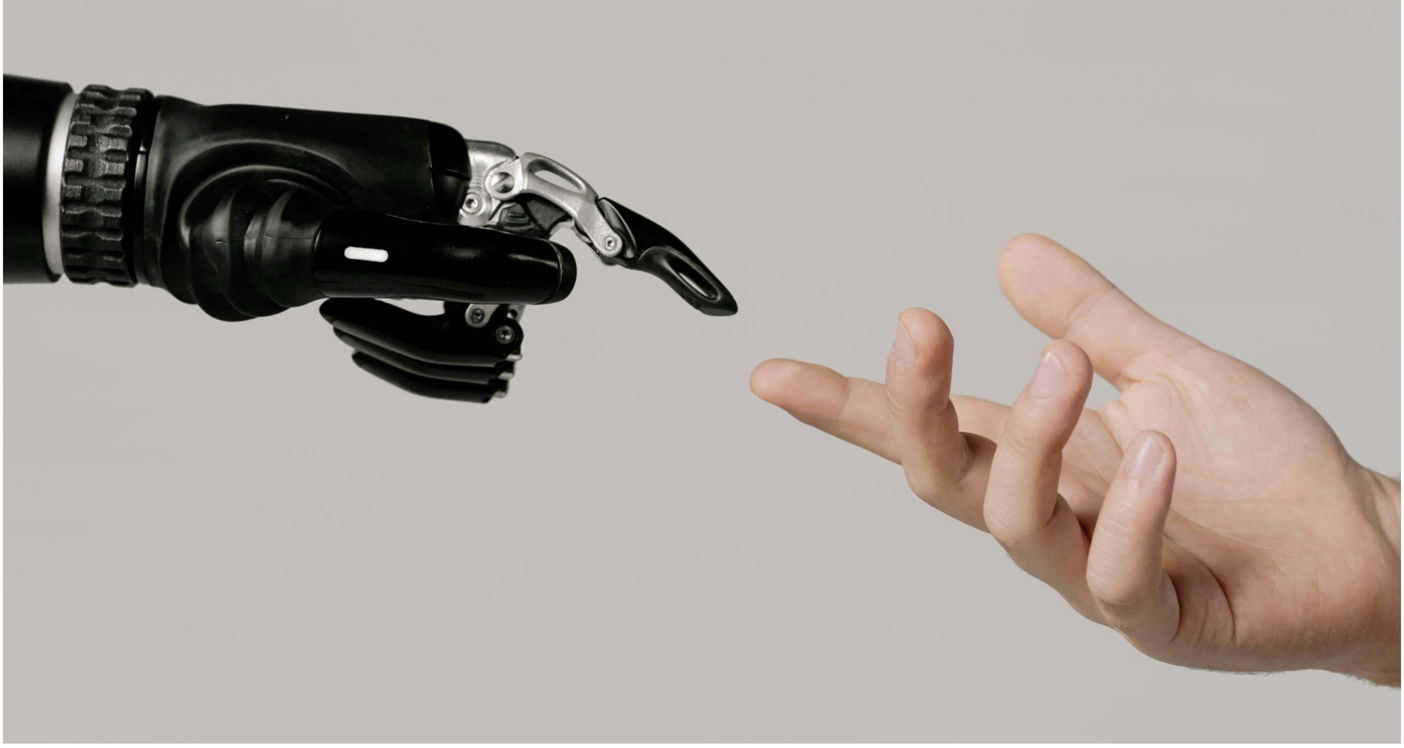
Traditional methods of simulating molecules often demand immense computational resources due to the intricate nature of quantum interactions. In contrast, quantum computers can model these interactions directly, allowing scientists to identify promising drug candidates more swiftly and accurately. For example, quantum simulations can assist researchers in understanding protein folding, a crucial factor in many diseases, with unprecedented precision. Artificial intelligence is poised to gain significantly, as quantum machine learning facilitates the processing of vast datasets and pattern recognition at remarkable speeds.

However, despite its promise, quantum computing encounters several challenges and ethical dilemmas. Scalability and the maintenance of low error rates present significant obstacles, necessitating ongoing research in materials science and error correction. The global competition for quantum supremacy raises concerns about unequal access and potential misuse, particularly in the realms of cybersecurity and military applications. While quantum computers offer computational efficiency, their cooling and operational systems require substantial energy, highlighting the need for sustainable solutions. Furthermore, as quantum computing automates complex problem-solving, certain roles in IT and data science may become obsolete, underscoring the importance of workforce reskilling. [7]

The journey of quantum computing is both ambitious and transformative. By the 2030s, we could see practical, fault-tolerant quantum computers that can tackle real-world problems on an unprecedented scale. It is essential for governments and organizations to invest in quantum education and infrastructure to get ready for this significant shift. Moreover, establishing global regulations and cooperative frameworks will be vital to ensure fair access and prevent misuse. Quantum computing is not just an advancement in computational power; it is a revolution in how we approach problem-solving. Its potential to transform various fields, including cryptography, medicine, and climate science, highlights its significant impact. As we approach this new quantum era, the real challenge will be to ensure that the benefits of this technology are shared fairly and used responsibly.

Edited by Raghav Vaidya





How close are we to computational sentience?

By Felix Luo (Y13)

From "The Matrix" to "2001 - A Space Odyssey", AI has always been represented as something able to take over the world. We used to think that such a fictitious dystopia was left to movies and books, but with the rapid development of AI in only the last few years, concerns seem to grow ever greater as AI becomes more accessible but also more advanced. From the introduction of Siri and Alexa to the rapid rise of ChatGPT, many people may feel that AI is advancing at a rate that we may no longer be able to control. However, people seem to forget the human input behind these powerful machines and, as such, the elements of humanity that are hidden behind what we see on the surface. So, can AI really be perfect and have the ability to take over the world, or will it be another tool that only aids in humanity's rise?

What defines intelligence?

To truly understand what AI is (and eventually the difference between AI and Artificial General Intelligence, AGI), we need to understand what intelligence is. You may have heard how some animals, such as elephants or dolphins, are "intelligent" creatures, but what does intelligence really mean? The Cambridge Dictionary defines intelligence as "the ability to learn, understand, and make judgements or have opinions that are based on reason." [1] Based on this definition, what do you see as intelligent? I imagine most people think of intelligence as a trait used to describe someone or something - for example, saying "they're so intelligent" or "that was such an intelligent way of doing it. However, when it comes to AI and AGI, we must look at what intelligence is in a broader sense. Intelligence is a function, not a characteristic. We are all intelligent beings, but what does that truly mean? Researchers generally hold that intelligence is needed to do some of the following:

Learn [2]

How does AI learn? AI models, like ChatGPT, learn by processing substantial amounts of data and looking for patterns, which helps the model make sense of it. The primary approach in achieving this is currently through machine learning. Machine learning primarily falls under 3 categories: supervised, unsupervised and semi -supervised learning [3]. Supervised learning involves training the AI model using labelled data sets to classify data or predict outcomes more accurately, and as more input data is fed into the model, the more the model adjusts how it perceives the data in order to provide a more accurate interpretation of the data around it. [3] On the other hand, unsupervised learning removes this predictable element and tries to train the model in a way that allows it to independently form connections and identify patterns without human intervention. One way of enabling these AI models to learn in this way is through neural networks [3]. Neural networks are the "artificial brain" behind AI that reciprocates from our understanding of our own brain. Like our own neurons forming different connections, artificial neurons are used, which are connected by "edges" used to replicate the synapses (gaps) between neurons in our own brain [4]. Signals are received from different neurons, processed and sent down. To each of these incoming signals, the node will assign a number called a weight [5]. When these signals are received by the neuron (which are just real numbers), they are multiplied by the weight and the products are added together to get a single number. If this product is above a set threshold value, the node will fire (send the signal to the next neuron) else, no data is passed. All this and a few adjustments to the weights during the learning process yield a model that can identify patterns, similar to that of our own minds, and form judgements (more on this later). But anything can learn - this knowledge must be able to be used somehow…

Reasoning and Knowledge [2]

You may have been asked to "prove X" in a math problem. Proof is an important mechanism that is utilised in all of our lives - without proof, how could we objectively reason anything? Automated reasoning is the study of the logical foundations that make a proof valid and give reasoning its structure and meaning. [6] Unlike machine learning which focuses on the ability of the model to be able to make predictions and inferences, automated reasoning allows these models to deduce an outcome based on these mathematical proofs and represent its "knowledge" in a justified way. But what is knowledge? Knowledge refers to the fact of knowing something that has been gained through experience or through learning [7]. In relation to AI, this might be achieved in the machine learning process of gathering information through data sets and absorbing information that is provided through them like the human brain does (usually achieved by neural networks aforementioned). This knowledge is then applied to the task the AI model has at hand - for example, in terms of solving puzzles, the applications of this knowledge will mean that the AI model will only perform a specific action based on a specific condition only if it has gained this experience from the past (i.e. it can only do things it knows how to do). However, it is not complete to say that only this premise is "knowledge". To achieve the entirety of knowledge, we must also factor in commonsense knowledge - being able to make assumptions about things in the real world based on existing knowledge about the world. This can link to the idea of syllogism in philosophy where, based on given propositions, one is able to conclude something if the given premises are true [8]. However, even though we may now have all this knowledge we need a way to express it…

Natural Language Processing [2]

AI needs to communicate, as do all intelligent beings. The premise of NLP is to allow these AI models to receive communicative data (such as speech or text), interpret its meaning and respond in a similar way that can be coherently understood. Once more, as aforementioned, ML is usually used to train the AI model in this way but with tokens and embeddings. [9] Tokens are ways of splitting natural language into subunits that can be more easily understood by an AI model, whilst embedding allows meaning to be inferred by the AI model to interpret what is the true intent behind what is being said, such as tone. Take the sentence "I like dogs." The tokenization of this could assign a dictionary where "I" = 1, "like" = 2 and "dogs" = 3 and these tokens can be recycled and reused to interpret different sentences that include the same tokens. In this way, these AI models can interpret different meanings and understand language in different ways, allowing them to understand the outside world and interact with the outside world.

Singularity?

You may have realised that I haven't really mentioned anything about AGI throughout this article, referring to everything as AI. This is because intelligence and general intelligence are two vastly different concepts that seem to be merged at times. When people talk about the uprising of super-intelligent AI, it is not AI they are referring to but AGI. AI is used to solve difficult tasks at a human-level, whereas AGI can do things with the mental capabilities of humans and generate inferences without human intervention. People seem to exaggerate the capabilities of AI when we ourselves do not even understand what is meant by what we believe AI is. We also need to factor in this idea of "consciousness" - the point where AI becomes "sentient" and self-aware, seeing itself as separate from other individuals and being able to understand its own actions. Additionally, with all that has been mentioned in terms of how we have achieved "intelligent" AI is still flawed and there are many problems with current models that need to be addressed…

Flaws

There are many issues with the implementations. We must remember that with human intervention comes human error. For example, the process of word tokenisation in NLP doesn't allow the model to interpret anything about the word itself - to the model it is just some arbitrary number that has some weight assigned to it. You can see this with Microsoft's CoPilot if you ask it to count how many 'r's there are in strawberry, replying with 2 instead of 3! Additionally, with human intervention in training, the training data may inherit biases; one such example usually given is that if you wanted a model to identify what pictures depict a "party setting" and you were to unknowingly give training data that only includes a certain race of people, it may not be able to identify that a party can include people of other races. Therefore, we can see that there are still many problems associated with AI implementation that need to be addressed before we even think about progressing to AGI.

The Future?

The implementation of this supposed superintelligence or general intelligence is shrouded by ethical considerations and our own shortcomings in this relatively new field of computer science. There are many other methods being developed to implement this, such as through entire brain emulation, where the entire biology of the brain is meticulously replicated as a computer program to achieve true computer consciousness. However, AI is still far from this progression and while it might be taking over some professions, just remember that it is currently for our benefit rather than our demise.

Edited by Arnav Prasad

How does the growth of AI affect sport?

By Shabd Goyal (Y12)

Artificial intelligence (AI) is described in a recent BBC article as something which "allows computers to learn and solve problems almost like a person" and is a system which is "developing at high speed". It does this by being given quite a large amount of information, which it can use to answer questions from the user – a "human-like conversation". Organisations around the world, are therefore, trying to revolutionise and develop artificial intelligence, as a result, to help with their own personal tasks.

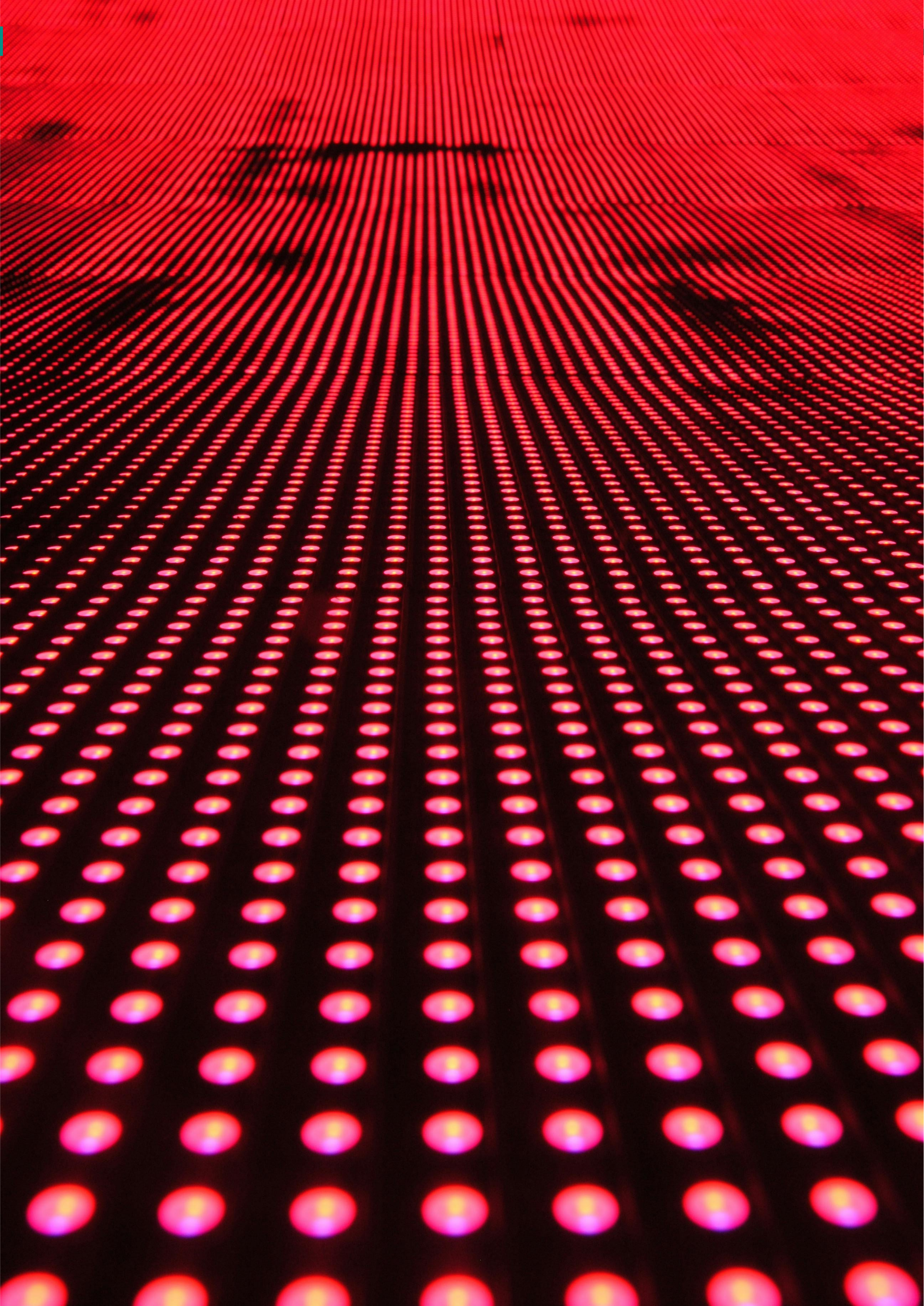
Take the sport, Formula One, for example, a science-fair sport which encourages teams to manufacture the best possible car to race against others across a variety of tracks. Teams want to go as fast as possible, and maximise every point they get from races, to win the championship. However, as you may expect, the changing factors in the sport are immense. For example, the tyre wear can be variable to the car that you are using, or the conditions of the track that you are on; fuel consumption can be variable to how much power you want to use at certain points, where it is more competitive; setting up the car can be checked by AI, to ensure that you have the fastest possible car for that particular circuit.

As you can see, Formula One is driven by the vast amount of data and information that teams can collect in order to formulate the best possible plan for the race. Christian Horner, CEO of Oracle Red Bull Racing describes data as the "team's lifeblood" and says that "every element of performance – how we run a race, how we develop a car, how we select and analyse drivers – it's all driven by data."
So, according to this interpretation, AI would be perfect to assist teams in interpreting large amounts of data, as it is trained by being given a large amount of information, and can only develop its understanding of it in the future.
So that is what teams are doing. Recently, lead teams such as Red Bull Racing, Ferrari and Mercedes have been investing in billion-dollar AI-powered simulations that serve as the backbone of a Formula One team's success, a growing importance as teams develop and get more technical. In partnership with giant tech companies, such as Oracle or AWS, Formula One teams are provided access to the best data analytics, to develop the best strategy for the race, despite the huge number of factors that change the outcome of each race, such as the weather, or the competition against other teams. Therefore, it is no secret that the growth of AI would only continue to positively impact sport, especially in data-driven sports such as Formula One.

Furthermore, betting companies, an important business related to sport, may be affected by the growth of AI. Betting companies regularly advertise odds and chances of a particular occurrence happening in events, but these odds are purely mathematical. If AI could get access to the data that betting companies used, perhaps the accuracy of these predictions could be even better and would potentially allow bettors to make more informed decisions as well as potentially increasing their chances of winning. This would allow the betting business to increase their credibility and create a more enhanced user experience, which would allow the company to grow and become more successful. However, there are many risks and problems associated with the use of AI in betting organisations. For example, there are many ethical accounts to take into consideration, such as data collection from these organisations. The collection of personal data may not be something which users agree with, especially when paired with AI being able to access and interpret this data, to create a highly personalised experience. Therefore, the growth of AI may harm the sporting business, as data privacy leaks are a huge issue, especially at a time when technology is constantly developing, and there are more intricate and complex ways of storing data, and also breaching it.

In conclusion, AI is a constantly developing tool that we can use in order to help make our lives much easier. Of course, there are risks involved with the use of AI, but I believe that the benefits significantly outweigh the risks, especially in the world of sports. Perhaps AI can be finetuned in order to remove some of the negative aspects, such as providing inaccurate results and responses, which will definitely change the future of technology as a result.

Edited by Arnav Prasad



Chaos Theory

How simple equations can lead to complex results

Vihaan Nuka (Y13)

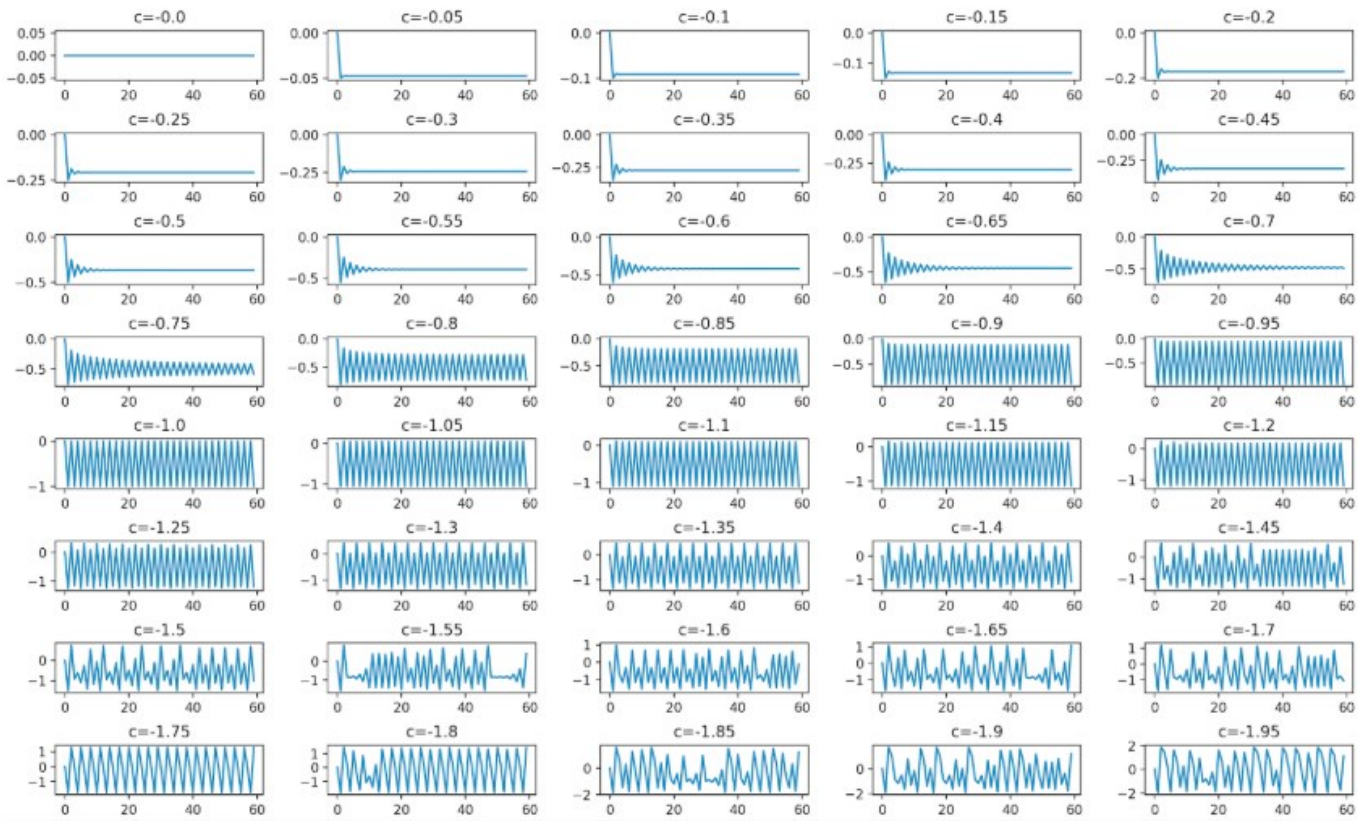
No matter where you are right now, it is inevitable that surrounding you is a set of exceedingly complex phenomena. The way electricity flows to the lights surrounding you, the way enzymes and chemicals react within you to achieve some larger purpose and the way the blood in your veins flows to the heart. The way these and many other complex phenomena seem to appear from such simple principles has fascinated philosophers for the better part of 400 years, and today modelling these phenomena is a job shared by thousands of mathematicians across the globe. Today, I would like to shed some light on how seemingly complex and erratic phenomena stem from simple mathematical principles.

Part 1: Chaotic Orbits.

To show how strange results can stem from the most innocent seeming equations, let us consider the equation $x_{n+1} = x_n^2 + c$ where c is some constant between 0 and 2 and our initial value is 0.

Don't worry if that equation looks a little complicated at first. All it is a sequence where the next term is the previous term squared minus a constant.

In order to take a look at what happens to this sequence when we subtract different constant terms, we can graph this sequence, placing the value on the y-axis and what index the term we are looking at (n) is on the x-axis. This yields the following set of graphs.



Notice how for each value of c, something different happens, as initially, we see our expression converges, but as we increase c, we begin to cycle through a set number of points. The process by which the period of our orbit (the number of values the sequence hits) appears to double, (with our period initially being 1, then at around c=0.85 doubling to reach 2) is known as bifurcation.

Eventually, at around c = 1.4, the output appears to follow no discernible pattern and appears to be "chaotic" and hence we describe this as a chaotic orbit.

These chaotic orbits obey no discernable rules, not converging, not oscillating between any two points. This is what lies at the heart of chaos theory, a slight change in our initial conditions (in this case our value of c) leads us to completely different results. To me, it is simply fascinating how such unpredictable chaos can stem from such a simple equation.

Note that if we choose a value of c greater than or equal to 2, our sequence diverges (trends to infinity) as we obtain more and more terms of our sequence.

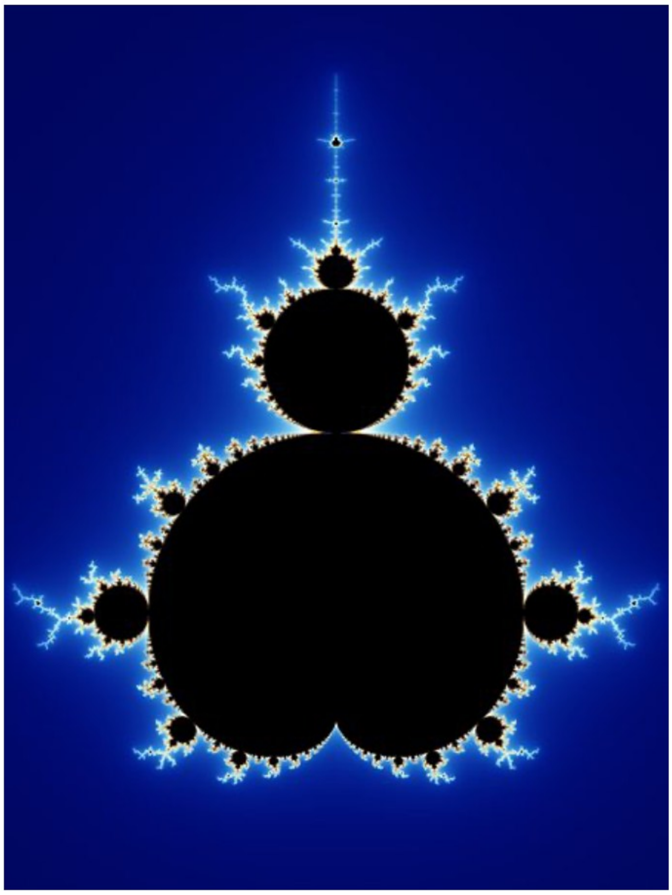
Part 2: The Mandelbrot set

The study of systems that undergo drastically different behaviours under slightly different initial conditions is known as chaos theory, and it is a truly fascinating branch of mathematics, which I encourage you to learn more about, but I will be focusing on one hauntingly beautiful result that stems from this branch of mathematics.

In order to reach this result, we need to look at different values of c, more specifically complex values of c.

For those unaware, complex numbers are sort of like two dimensional numbers, with an a value and a b value where a and b are real or "normal" numbers. They take the form $a+bi$ where $i^2=-1$. With these numbers, we can perform different operations such as addition where $(a+bi)+(c+di)=(a+c)+(b+d)i$, subtraction, which is simply done by adding negative numbers, multiplication where $(a+bi)*(c+di)=(ac-bd)+(ad+bc)i$ and various other operations. Complex numbers and their uses are also something I encourage you to explore in more detail as they are a pillar upon which modern mathematics rests.

Now, if we examine our initial equation, taking complex values of c, and plotting all of those that don't have x tend towards infinity, and plot the a component against the b component, (a on the x-axis and b on the y-axis) we get one of my favourite shapes in mathematics, the Mandelbrot Set.



This shape has some incredible properties, it is self similar, has infinite perimeter but a finite area and it obeys a strange and wondrous symmetry; it is a fractal you can spend hours zooming into, unravelling its strange behaviour.

The way that this infinitely complex and strange beast can emerge from what appears to be a simple equation has helped me appreciate that however complex the world around us seems, it can always be deciphered and the rules governing it might be simpler than you think.

Riemann - Zeta Function and the Riemann Hypothesis

By Aidan Brown (Y13)

What is 1+2+3+4+… for every single infinite number of integers? Perhaps you said infinity and perhaps you identified this as a diverging sequence. But no, its −1/12 and the answer lies in the Riemann-Zeta function. In English this could be described as summation of all numbers raised to the power of s or as the harmonic series raised to the power of s. The function itself is represented as the Greek letter zeta whilst the number you input is represented by s. One of the most important features of this function is the range of numbers which it works for, when s > 1. Making 1+2+3+4+…=-1/12 a very liberal use of the equals sign, since to create such a sequence using this function you must use s=-1. Another peculiarity of inputting values smaller than 1 is that all negative even numbers 'equal' 0, these are known as trivial zeroes. Overall, the general function can be shown as such:

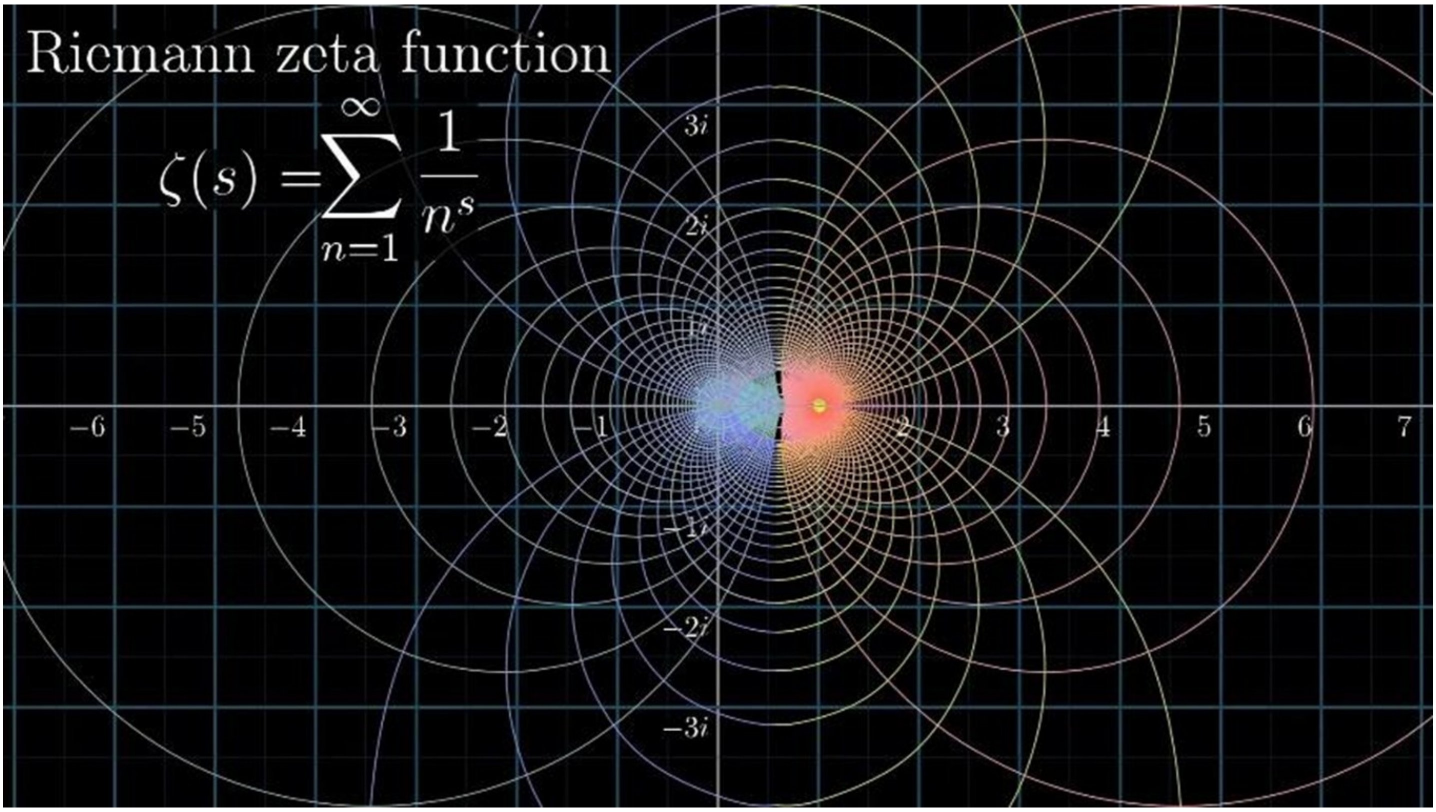
$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s} = \frac{1}{1^s} + \frac{1}{2^s} + \frac{1}{3^s} + \cdots$$

Whilst -1 is invalid value of s there are a number of values of s for which the function is true and defined one such example is zeta(2) which equals(pi^2)/6. zeta(2) could also be described as the summation of the reciprocal of all square numbers and is also known as the Basel problem. This series was solved and proved by Euler 100 years before Riemann was born.

$$\sum_{n=1}^{\infty} \frac{1}{n^s} = \prod_{n=1}^{\infty} \left(1 - \frac{1}{p_n^s}\right)$$

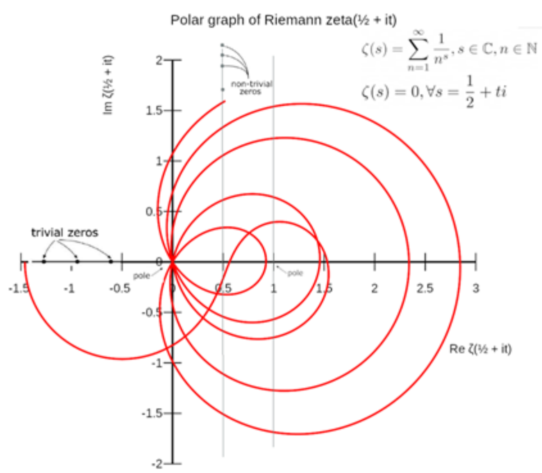
Euler's only contribution to the Riemann-Zeta function is not the solution to the Basel problem, he also had created a prototypic version of the function, known as Euler's Product. A key difference between Euler's product and Riemann's function is the type of numbers used. The product form of this arose from the need for an analytical tool for dealing with problems with prime numbers and so only allowed for them to be entered whereas Riemann investigated not only the use of real numbers for s but also of complex numbers for s where for the Riemann-Zeta function to work the real part of s must be greater than 1.

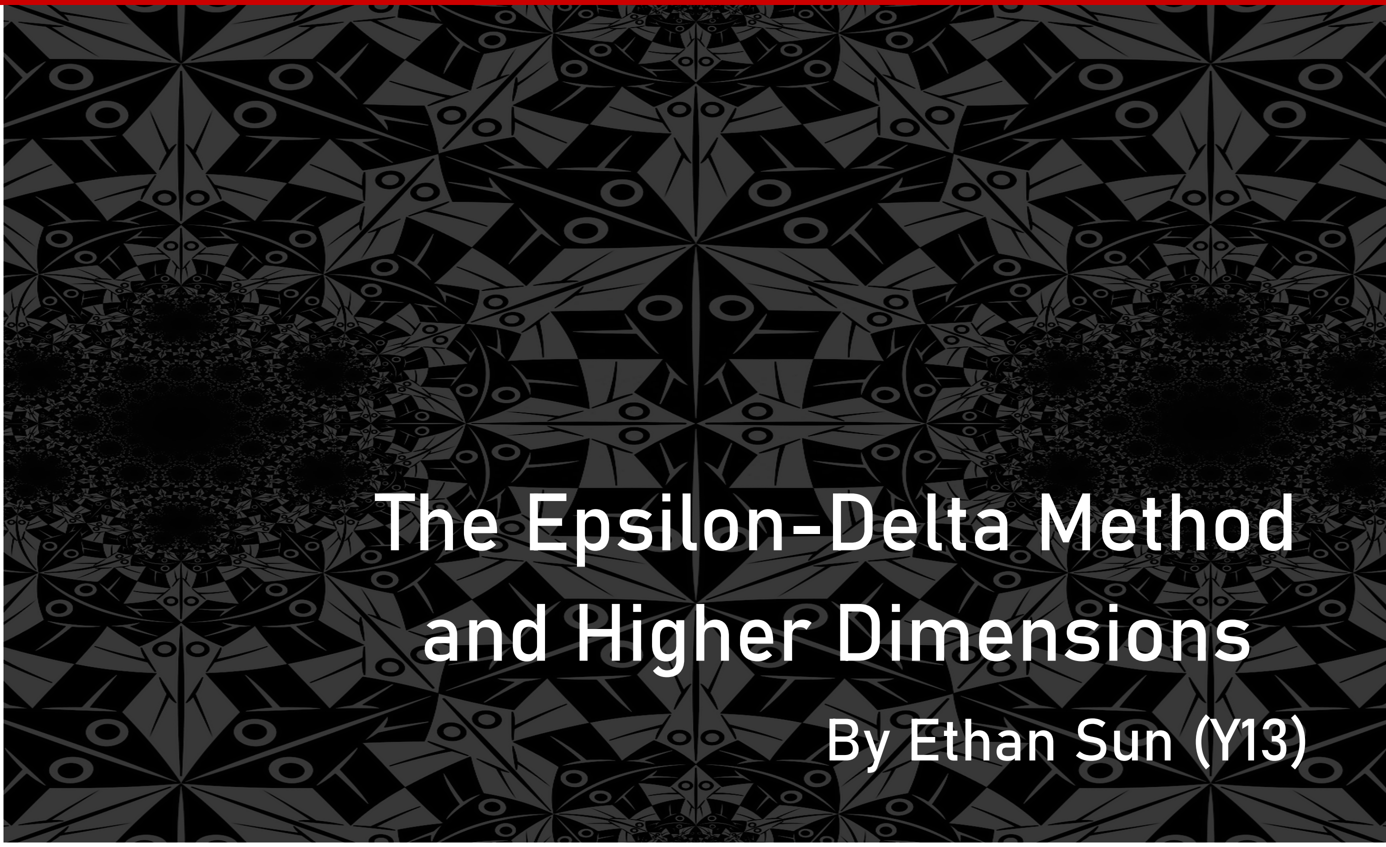
When raising any number to the power of a complex number such as raising ½ to the power of 2+i, we can separate it to (½ ^2) (1/2^i). When plotted in an argand diagram we get a line of length ¼ that is rotated and so when we take s to be 2+i for the Riemann-Zeta function it graphs a spiral of length pi^2 /6. When we raise a number to purely imaginary number the result is a point that sits on the unit circle in the complex plane, and increasing the distance of the denominator from 1 the point moves around the circle quicker than a denominator. It is also possible to graph the function as a whole in an argand diagram. One of the first noticeable points is that there is an abrupt point where the colour of the lines change. This signals the point at which the function is defined by the given formula to by analytic continuation. This is required since the function is only correctly defined for values of the real part of s that are greater than 1. The point at which there is this abrupt change is the Euler-Mascheroni constant (a number defined by the limiting difference between the harmonic series i.e. zeta(1) and the natural logarithm or ln and roughly equals 0.577).



The analytical continuation of the function is not merely a reflecting in the line x=0.577 as it may appear. Since we cannot use the same method for the left as the right side of the graph given [3] the fact that it only works for real parts of s greater than 1, you may question how we can be certain that this is true and an accurate depiction of the Riemann-Zeta function. In theory we could draw any function on the left side of this graph, and it would it be just as valid as any other function including the one shown because we do not know a function that graphs correctly for values of s less than or equal to 1, right? Yes and no, we cannot use just any function it must fulfil criteria. The new extended function must have a derivative everywhere, with this sole, seemingly very broad criterion there is only one possible option for the extended function. Instead of needing a derivative everywhere this can also be thought of as needing to preserve the angle at which lines intersect, as the graph was made by transforming grid lines, they must all meet at 90 degrees to one another. This is because the function is analytic like e^x or log(x) or ln x or sin x or many others and are all infinitely differentiable.

There are however a few holes within this extension one of which is a million-dollar problem, the question is what numbers are mapped onto the origin. As you may remember from earlier all negative even numbers are mapped onto the origin, however these are known as trivial zeroes. Coined as such since they are well understood, however there are also non-trivial zeroes. Riemann hypothesised that all non-trivial zeroes have the real part of s equal to ½. The graph shows the spiral for zeta(½), and if you can show that all non-trivial zeroes are on this line you are given 1,000,000 US dollars. This is known as the Riemann Hypothesis.





The Epsilon-Delta Method and Higher Dimensions

By Ethan Sun (Y13)

Mathematics is not just a tool; it is the language e of everything around us. The epsilon-delta definition of limits, a fundamental concept in analysis, is one of the purest forms of mathematical thinking. It is the meeting point of accuracy and intuition, and understanding it equips you with the kind of thinking required to tackle real, challenging problems.

The Foundation - One Dimension:

At its core, the epsilon-delta method is straightforward: it involves understanding how functions behave when we zoom in closely. Let us take a basic example: for f(x) = 2x+1 , and wanting to know the limit as **x→ 3**, we ask how close **f(x)** is to 7 when x is close to 3.

The Epsilon-Delta Foundation is not about vague ideas of "approaching" - it is precise. If **|x - 3|** is small enough, then **|f(x) - 7|** must also be small. The delta gives us that smallness, and epsilon shows us the limit we are approaching. In one dimension, this is straightforward, yet still powerful. It is a foundation for exploring this concept in further dimensions.

The Jump to Higher Dimensions:

When you apply the same idea to functions of two, three, or more variables, the game changes. Now, we are no longer just moving along a line but through space. The distance between points is not just |x - c|; it's the Euclidean distance:

$$\sqrt{(x_1 - c_1)^2 + (x_2 - c_2)^2 + \cdots + (x_n - c_n)^2}$$

The Euclidean distance represents the starting point where limits get hard. We have the functions **f(x,y)** or **f(x,y,z)**. As we approach a point, we need to ensure that the difference between the function's value and the limit continues to decrease, regardless of the path we take.

Real-World Example - Multivariable Limit:

Let us consider a function in two dimensions:

$$f(x,y) = \frac{2x+y}{x^2+y^2}$$

We want to determine if there is a limit. The idea is simple: As we approach the origin, does the function approach a specific value? However, here is the thing: the limit does not exist. Along different paths to (0,0), the function gives different values. For example, if you approach at **y = 0**, the function unboundedly large. If you approach it at **x = 0**, it diverges.

This example shows how much more complicated limits get in higher dimensions. This example illustrates the increased complexity of limits in higher dimensions. Limits are the actual behaviour of functions in the real world; they are not merely theoretical concepts.

Hyperdimensional Spaces - The Next Level:

Now, let us go further: beyond three dimensions to hyperdimensional spaces. Imagine spaces with hundreds, even thousands of dimensions. The problem of defining "closeness" becomes more complex. Euclidean distance is no longer sufficient. The challenge is not just finding limits in higher dimensions. It is about understanding how things behave when they are spread out over a large area. Euclidean distance is where the real work happens - this is where we use methods like dimensionality reduction to make sense of data in high dimensions.

In fields such as machine learning, hyperdimensional spaces are the norm, not the exception. Functions defined in these spaces do not behave the same way as functions in low dimensions. Whether optimising algorithms or training deep learning models, we rely on methods that are based on limits - whether it is backpropagation in neural networks or gradient descent. These methods are all rooted in the same idea: understanding how a function behaves as you approach a point in a very high-dimensional space. The practical applications of the epsilon-delta method in these fields make it more than just a theoretical concept; it is a powerful tool for real-world problem-solving.

Conclusion - Precision in Every Dimension:

The epsilon-delta method is more than a theoretical tool - it is a cornerstone of our understanding of the world in all its complexity. Whether we are looking at basic limits in one dimension or tackling problems in high-dimensional spaces, the idea of precision - of rigorously defining how functions behave as we approach certain points - never goes away. Moreover, the beauty of mathematics is that no matter how complicated the space or the problem, the core ideas still hold. The challenge, then, is learning how to apply these ideas in the most efficient, most impactful ways.

Understanding limits in higher dimensions is not just for mathematicians. It is for anyone who needs to model, predict, or optimise. These core concepts guide our problem-solving in fields such as physics, data science, and machine learning. Investigating these concepts further also creates new opportunities for reasoning, logic, and problem-solving.

Edited by Raghav Vaidya

How can one overfill an Infinite Hotel?

"To infinity and beyond!" – Buzz Lightyear

By Raghav Vaidya (Y13)

Imagine there is a hotel with an infinite number of rooms – i.e. rooms numbered 1, 2, 3 and so on - this is known as Hilbert's Hotel, a thought experiment devised by the German mathematician David Hilbert who was famous for adopting Georg Cantor's set theory and transfinite numbers [1]. This example, in particular, is a useful introduction to understand the properties of infinite sets and how it relates to Cantor's transfinite numbers.

Suppose one day the Infinite Hotel has as infinite number of guests in the hotel's infinite rooms – there are now no vacancies as the hotel is fully occupied. However, a new customer comes to the reception desk and asks for a room.

What should the manager do?

Initially, it seems that the customer would need to be sent to a different hotel, because how would it be possible to accommodate a new customer if the hotel's infinite rooms are being infinitely occupied? Luckily, for the customer as the hotel has an infinite number of rooms, the manager can tell everyone to move from their current room **n** to their new room, **n + 1** – i.e. the customer in Room 1 moves to Room 2, the one in Room 2 moves to Room 3 and so on. This means that Room 1 is free for the now happy customer [2]. This method can be applied whenever any **finite** number of guests turn up when the hotel is fully occupied. The manager would again tell their customers to move from their room n to the room **n + k** creating the first **k** rooms free.

However, what if an infinitely long bus with an infinite number of guests turns up? The manager realises that there are an infinite number of even numbers and an infinite number of odd numbers so he can tell all the current customers to move from their current room number n to the room **2n** – i.e. the customer in Room 1 moves to Room 2, the one in Room 2 moves to Room 4 and so on. This means that all the previous customers are in even-numbered rooms, resulting in there being an infinite number of odd-numbered rooms remaining for the infinite guests [3]. Once again, everyone is accommodated.

To complicate matters even more for the manager, what if an infinite number of buses, each being infinitely long and each having an infinite number of guests turns up? There are in fact multiple ways this could be solved, the first relating to Euclid's Theorem, while the second is a more elegant method. One way the manager could solve this is by realising that there is an infinite number of prime numbers, as proved by Euclid – known as Euclid's Theorem. As a result, the manager can move all of the current guests from their current room **n** to the room of the first prime to the power of their current room number **(2n)** – i.e. the customer in Room 2 goes to Room 4 and the customer in Room 3 goes to Room 8 and so on. Now for each bus, the manager assigns the next prime number to the power of the passenger's seat number as their room (p_c^n) [4][5]. However, the problem with this is that many rooms would be left empty, such as 10 as it is not a power of any prime number. A more elegant solution can be used where a table can be made showing each

Hotel	Hotel Room 1	Hotel Room 2	Hotel Room 3	...
Bus 1	Bus 1 Seat 1	Bus 1 Seat 2	Bus 1 Seat 3	...
Bus 2	Bus 2 Seat 1	Bus 2 Seat 2	Bus 2 Seat 3	...
Bus 3	Bus 3 Seat 1	Bus 3 Seat 2	Bus 3 Seat 3	...
...	...	...	...	...

hotel room and a unique ID consisting of a passenger's coach and seat number and the current room for existing customers at the hotel. Starting from the first cell diagonal lines are drawn and the IDs covered by each cell can be put in order to give an infinite line that can be mapped to each room. [6]

This method ensures that there are no empty rooms and is derived from Cantor's Proof for the Enumeration of the Positive Rationals to show that the cardinality – i.e. the number

Room 1	01100...
Room 2	10101...
Room 3	00110...
Room 4	11001...
Room 5	01011...
...	...
Passenger with no room	11010...

of elements in a set – of the set of positive rational numbers is equal to the cardinality of the set of natural numbers [7].

The Infinite Hotel seems to be able to accommodate all customers regardless of the conditions, however, this is possible so far because each person in each bus could be put into a one-to-one relationship with the room numbers. Suppose an infinitely long coach pulls up but instead of the passengers having a seat ID they are identified through a unique infinitely long name – let's assume that their name is a binary name represented by 1s and 0s. Putting the infinite list of infinite names against the infinite room numbers seems to work initially. That is until we realise that there is a way to write a name that is not included in the infinite list. This would be to take the first digit from the first name then the second digit from the second name and so on and flip it – i.e. if it's a 0 make it 1 and vice versa. This would leave you with a name that is nowhere on the infinite list as it differs by at least one digit [8].

This means that for once, the Infinite Hotel can no longer take customers.

But why does this happen?

This method is known as Cantor's Diagonal Argument [9] and is used to show that there are infinite sets which cannot be put into a one-to-one correspondence with the infinite set of natural numbers [9]. The number of rooms in the Infinite Hotel is *countably infinite* because the set of room numbers is equal to the set of natural numbers. This means that their cardinality is $\aleph_0$ (aleph zero). In the final scenario, the cardinality of the set of passenger names is larger than $\aleph_0$. This means that there are infinities which are bigger than other infinities. This now leads to ordinal numbers as the set extends past the natural numbers to the first transfinite ordinal number is ω (omega) [10] and this now delves much deeper into set theory.

While the Infinite Hotel may not always be able to accommodate everyone it certainly shows the wonderful properties of infinite sets and how it all goes back to the foundations of Set Theory.

What's more is that, while perhaps not entirely intentional, the creators of Toy Story may have certainly wanted us to introduce us to Cantor's theory when we were younger through Buzz Lightyear's famous quote:

"To infinity and beyond!"

Unravelling the Mathematics of Knots

By Hritesh Karthikeyan (Y13)

Knot theory, a fascinating branch of mathematics, might seem like it's all about the knots we tie in shoelaces, but it's much more than that.

At its heart, knot theory explores the properties of mathematical knots, which are closed loops without ends. These knots exist in abstract spaces, and unlike the ones you tie with your shoelace, they can't be untied without cutting.

What's more intriguing is how mathematics, through geometry, topology, and algebra, can help us classify and understand these seemingly simple but actually quite complex shapes.

What is a Mathematical Knot?

Imagine a piece of string twisted into a loop. Now, this isn't your usual knot; it's a *mathematical knot*. In mathematics, a knot is a closed, non-self-intersecting curve that exists in three-dimensional space. The simplest knot is the *unknot*, a basic loop with no twists.

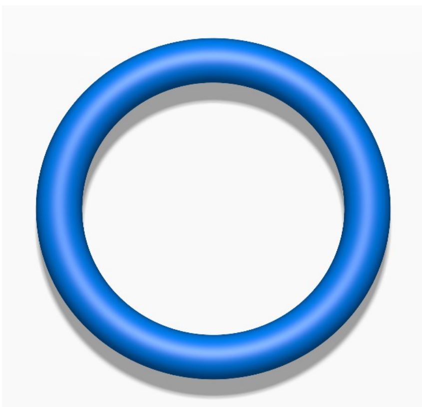


Figure 1 – An unknot

But when you start adding twists and crossings, things get interesting. Take the trefoil knot, for example - it's the first "non-trivial" knot, with three crossings. These crossings are where the string goes over or under itself, and it turns out that no matter how much you twist, this knot can never be undone without cutting it.

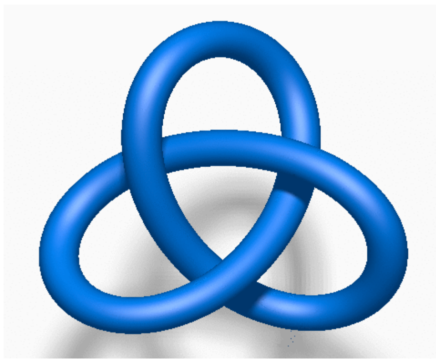


Figure 2 – A trefoil knot

To classify these knots and understand their complexities, mathematicians use a variety of tools, namely:

Crossing Number:

number of crossings needed to represent a knot in a diagram. For example, the trefoil knot has a crossing number of three because it takes three crossings to draw it. The higher the crossing number, the more intricate the knot.

Knot Invariants:

Knot theory also uses something called *knot invariants*, which are properties that stay the same no matter how you manipulate the knot (without cutting it). These properties are crucial because they help mathematicians tell knots apart. Two famous examples of knot invariants are the Alexander polynomial which assigns a specific value for each knot and the Jones polynomial.

$$V_{\text{trefoil}}(t) = t - t^2 + t^3$$

Figure 3 – Jones polynomial for a trefoil

Knot Diagrams and Reidemeister Moves:

To make sense of these knots, mathematicians often use *knot diagrams*, which are flat, 2D representations of the knot. These diagrams show how the string crosses over and under itself. But here's where it gets fun: mathematicians can manipulate these diagrams using *Reidemeister moves*. These are a set of three moves that allow you to twist and turn the diagram without changing the underlying knot. Type I involves adding or removing a twist, Type II swaps crossings between two strands, and Type III moves one strand through a loop formed by others. These moves are crucial in knot theory for simplifying diagrams or proving that different representations of a knot are equivalent.

Knot Signature:

Finally, let's talk about the *knot signature*, which is a number that provides information about the crossings in a knot. It's calculated by looking at the number of positive and negative crossings in a knot diagram. A positive crossing happens when the string goes over itself, and a negative crossing occurs when it goes under. The formula to calculate the knot signature is:

$$\sigma(K) = \frac{1}{2} \sum_{c \in C} \text{sign}(c)$$

Figure 4 – Formula to calculate root signature

In simple terms: you're counting the "twists" at each crossing, giving a +1 or -1, then dividing the sum by two to get the final number that represents the knot.

What could possibly be the use of knot theory?

Knot theory isn't just for figuring out how to untangle your headphones - as some might think! It has multiple applications in:

Biology: DNA strands can get knotted during processes like replication. Knot theory helps scientists understand how enzymes untangle these knots, ensuring DNA works properly.

Chemistry: Chemists have even created molecular knots, which have unique properties and could be useful in fields like nanotechnology.

Physics: Knot theory helps physicists study knotted structures like vortex lines and magnetic flux tubes, which are essential in understanding complex systems like fluid dynamics and plasma physics.

To conclude, knot theory is much more than a quirky branch of mathematics; it's a deep, fascinating field that touches on algebra,

Black-Scholes Model

By Aarya Srinivasaa (Y13)

Also known as the Black-Scholes-Merton (BSM) model, The Black-Scholes model is one of the most famous formulas in finance and estimates the theoretical value of derivatives based on other investment instruments. It's used to price options and derive the "fair value" of financial instruments based on factors like volatility, time to maturity, and risk-free rates.

Fischer Black and Myron Scholes first met at the Massachusetts Institute of Technology (MIT) and published the theory in 1973, which was Nobel prize winning. It is a very important part of finance history where the mathematical equation further adapted by Robert C. Merton to our modern understanding, made it possible to control the risks of option trading and thus encouraged the development of derivatives markets and quant courses.

Well…before you read any further, you need to know what an option is. An option is a financial contract that gives the holder the right to buy or sell an asset at a specific price within a specific time frame. The two types are call and put. Call options give the buyer the right to buy an asset at a specified price and profit is made if the price increases. A put option gives the buyer the right to sell an asset, and profit is technically made if the price of the asset reduces. The asset can be anything like stocks, exchange traded funds or even currencies.

$$C(S,t) = N(d_1)S - N(d_2)Ke^{-rT}$$

$$d_1 = \frac{\ln\left(\frac{S}{K}\right) + \left(r + \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}}$$

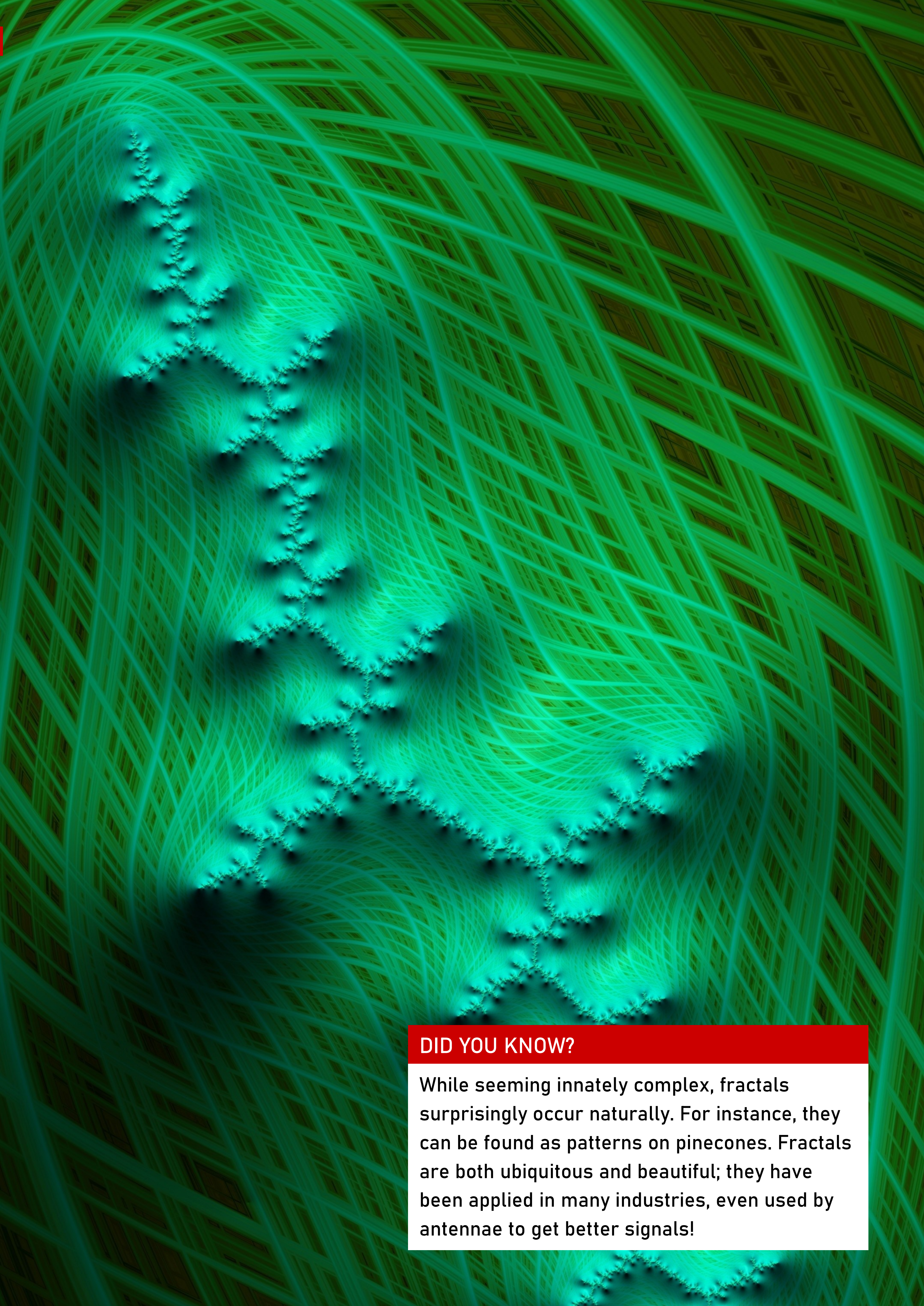
$$d_2 = d_1 - \sigma\sqrt{T}$$

$C(S,t)$	(call option price)
$N()$	(cumulative distribution function)
$T = (T_1 - t)$	(time left til maturity (in years))
S	(stock price)
K	(strike price)
r	(risk free rate)
σ	(volatility)

$N(d_1)S$ in essence is the present value of the expected stock price at expiration and hence (the upside potential of the option). $Ke^{-rT}N(d_2)$ is the present value of the strike price you'll have to pay and hence the cost of exercising the option and the downside. It takes into account risk free interest rate (r) and the time since the strike price is paid in the future and d_2 (the probability of having to pay the strike price in accordance with the normal distribution). Lastly the two key variables d_1 and d_2 represent the risk adjusted return and the adjusted probability of return respectively. What that means is if d_1 is positive and high, it means the stock price is likely to end up above the strike price. D_2 on the other hand represents the probability that the option will be exercised and is obviously always less than d_1 because uncertainty increases over time.

Standard deviation is used massively to assess the volatility and hence the distance away from the mean price. The formula shows that higher volatility increases the value and price of the option. **Why?** Because higher volatility means more chances for the stock to swing above the strike price. The longer the time to expiration, the more valuable the option. This is because there's more time for the stock to move favourably. A higher risk-free interest rate makes the present value of the strike price lower, which increases the call option's value.

The Black Scholes model as previously mentioned is not just a "fancy" mathematics formula but is used immensely by investment bankers, trading analysts, hedge funds and financial experts. One such example and a famous one is delta hedging- the sensitivity of an option's price to changes in the underlying stock price and is used by traders to hedge their positions and reduce risk. Building on this, if a call option has a delta of 0.5, for every £1, the price of the option will increase by £0.50. To hedge this risk, traders would short 50 shares of the underlying stock for every 100 shares so that the loss in the options value is offset by the gains in the short stock position.



DID YOU KNOW?

While seeming innately complex, fractals surprisingly occur naturally. For instance, they can be found as patterns on pinecones. Fractals are both ubiquitous and beautiful; they have been applied in many industries, even used by antennae to get better signals!

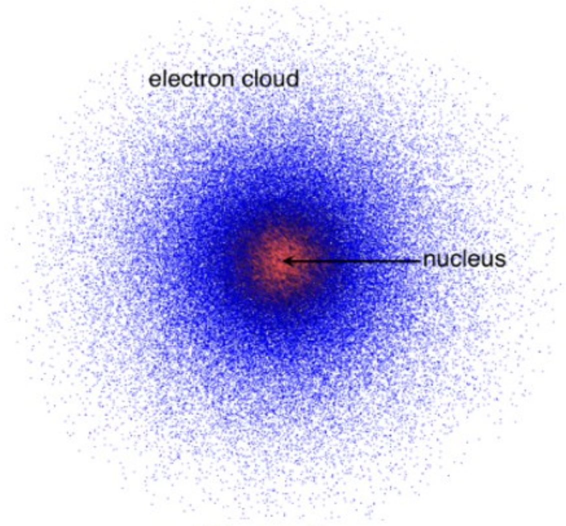


Figure 1

Figure 1 shows an atomic nucleus surrounded by an electron cloud

Quantum Superposition

Once and for all, what exactly is quantum superposition and how do we observe it in the atoms around us?

By Philip Nanias (Y13)

I'm sure many of you reading have heard of that notorious cat stowed away inside a box, somehow alive and dead at the same time until we check upon it. Indeed, this "Schrodinger's Cat" expresses the foundational idea of superposition and the observer's effect – we do not know whether the cat is alive or dead until we 'observe' and find out what its state is at that moment in time. Whilst it may be difficult to think about a real-life cat being both alive and dead at the same time, when thinking about quantum systems, one must simply let go of the expectations the world of classical physics forms.

What exactly is it?

The essence of quantum superposition is that, if a particle exhibits two properties, one cannot know what the true property is until one measures it. For example, one such property could be the state of the cat's health in the box when we do not know its condition, though sadly, Schrodinger's cat is limited to one aspect rather than two, simplifying this idea.

One way of thinking about this is using some simple colour machines. Imagine you have a set of particles, and they have two properties – colour (red or blue) and shape (circular or square) [1]. We can add sorting machines to the system, so that there is one that sorts the colour into two piles and one that sorts the shapes into two piles, so we can arrange them in order so that they separate the colours and shapes. And so, we can arrange a colour separator, followed by shapes, and then colour again. One would think that we would achieve only one colour coming through the final colour separator. However, since we know there is only one shape coming through, we cannot know the colour (according to Heisenberg's dispersion/uncertainty principle), meaning that there will still be blue and red particles coming out of the final separator. Paradoxical, I know, but we must simply accept this for now from a quantum mechanics viewpoint (until one learns the derivations of equations backing it), despite it making little sense in the classical world.

The main reason for quantum superposition stems from wave-particle duality. Whilst one would commonly canonically quantise light as "energy packets" known as photons, we can show electrons acting in a wave-like fashion too. This was first discovered by Thomas Young in 1801, in his double slit experiment [2]. Using electrons fired from a beam gun, the scientist targets them at a double slit, after passing through which the electrons would scatter onto a screen behind. Young noticed that they would form an interference pattern not unlike the pattern produced when you would simply shine light through the double slit, and so realised that the electron exhibited wave-like properties, albeit initially being thought as pure matter. And so, the initial theory of wave-particle duality was established, an idea that led to electrons being defined as a wave function at the quantum level.

How do we see it in the atoms around us?

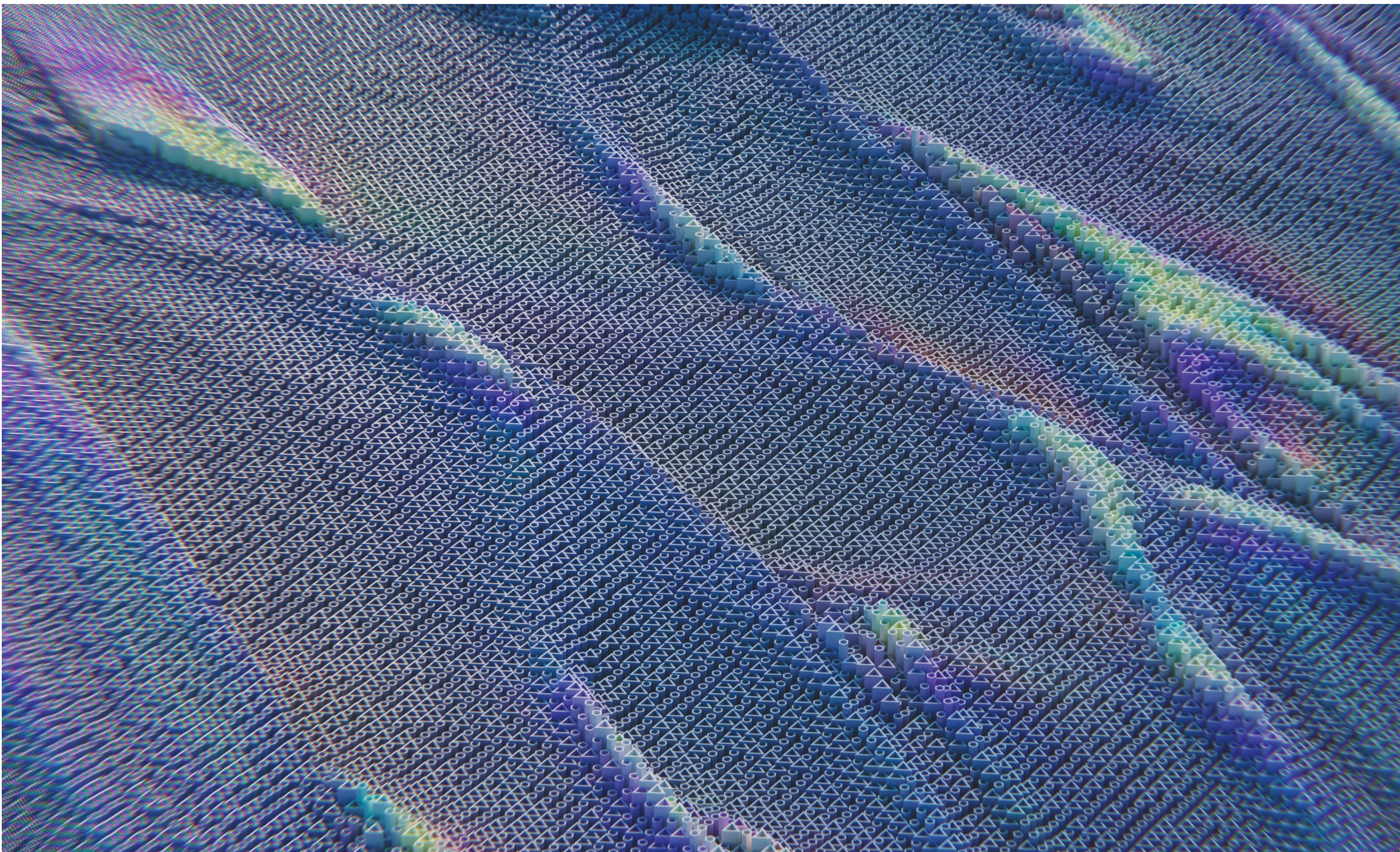
More specifically, we would define the superposition of light or electrons to be of its momentum and position at a moment in time, which the dispersion principle defines as $\Delta p\Delta x>=\hbar/2$, where $\hbar$ is Planck's constant divided by 2π. Indeed, this shows that the more we know about the position of a photon or electron, the less we know about its momentum, and vice versa. Just a year before the discovery of this equation, using a similar concept of wave-particle duality, Schrodinger proposed his atomic model. Unlike Neil Bohr's model, it did not have defined energy shells in which the electrons orbit the nucleus. Rather, using his wave function, he suggested that electrons had a probability of being in a certain position around the nucleus at a certain time, in an "electron cloud".

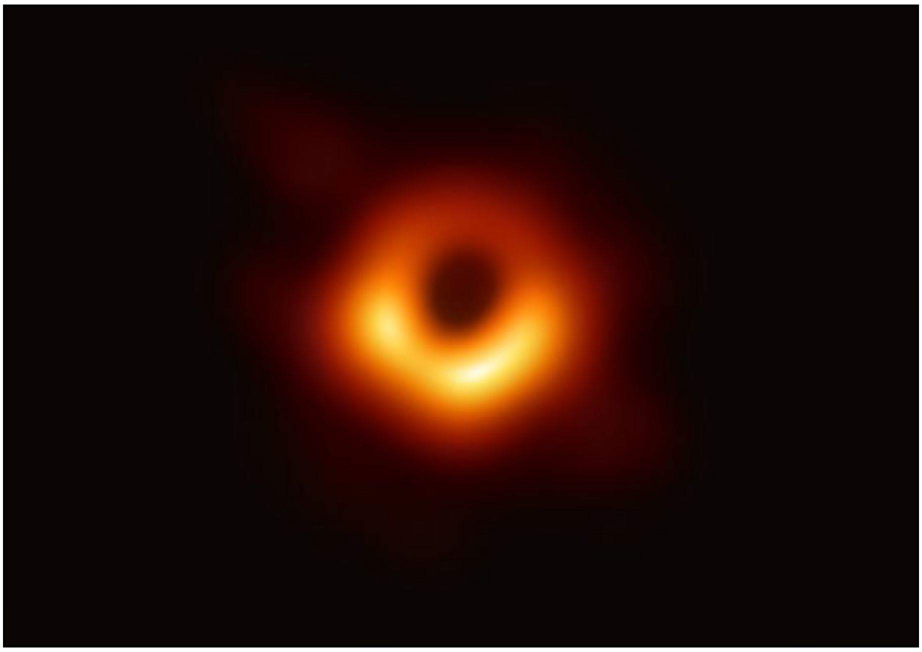
And so, this idea of superposition brings us to the field of quantum tunnelling. Imagine a wall supposedly "blocking" an electron. This wall represents a barrier of potential energy, one that is greater than the electron's kinetic energy, making it initially seem as if the electron cannot pass through this barrier [3]. However, armed with the new knowledge of quantum superposition, we know that we can model the electron as a wave function, with nodes and antinodes, due to Heisenberg's dispersion principle. If the potential energy is not too great compared to the kinetic energy, there will be a small probability that the wave will pass through this barrier, and so "tunnel" through.

Indeed, these ideas are much more common throughout the universe than one may expect, having a use in quantum computing as well as within a theory concerning the beginning of the Big Bang, in a period known as Inflation.

As exciting as this concept is, we are still discovering much in the realm of quantum theory, which is much newer compared to the familiar classical physics that humanity has known for many centuries. And so, I bring you to the summary of quantum superposition. In essence, this is simply the concept that it is impossible to know everything about a quantum particle – the more you know about its momentum, the less about its position. Unfortunately, in this article, we were unable to get into the true complexity of this concept, where we would uncover all equations determining this. If you are craving further information on this subject, I strongly suggest that you do research and learn a bit about it yourself. It is incredibly interesting and rewarding to study the true derivations of quantum theory – push yourself!

Edited by Amey Bhatia





Black hole at centre of M87 galaxy, first ever image of

Black Hole Evaporation

How does Hawking radiation affect black holes?

Jashn Agarwal (Y13)

Black holes are considered some of the most enigmatic of all entities in the universe. Heightening our understanding of these mysterious cosmic objects can lead to a deeper insight of the universe, as it is within the event horizon where it is believed that quantum mechanics and general relativity are combined. Perhaps the most influential mind to work on black holes, alongside Roger Penrose and Karl Schwarzschild, was Stephen Hawking. He most notably published a paper in 1974 entitled 'Black hole explosions?' where he detailed how black holes are not static, but black bodies with a temperature that lose mass and evaporate.

A common explanation for Hawking radiation is in terms of matter and antimatter particles. Particle-antiparticle pair production is a phenomenon where a neutral fundamental boson (essentially a force carrying particle), such as typically a photon, splits up into a subatomic particle and the corresponding antiparticle, such as an electron and positron. However, in the case of black holes, 'virtual' particles are created by quantum fluctuations. Energy is converted to the mass of the pair of particles based on probably the most famous equation in the world: $E = mc^2$. The opposite of this process is annihilation, where a collision between the two produces energy. This phenomenon can occur in proximity to the event horizon of a black hole. If the particle carrying negative energy were to be sucked into the black hole, then the one we see as this Hawking radiation is the remaining particle (carrying positive energy). Again, referring to $E=mc^2$, the black hole is losing energy which is the same thing as losing mass. This culminates in it evaporating[1] .

However, this is a rather heuristic and vague explanation. In fact, it is said that Hawking only explained his findings in this way in 'A Brief History of Time' as it was more digestible for the reader – understandably so: his goal was to spread science and make it understandable for the public.

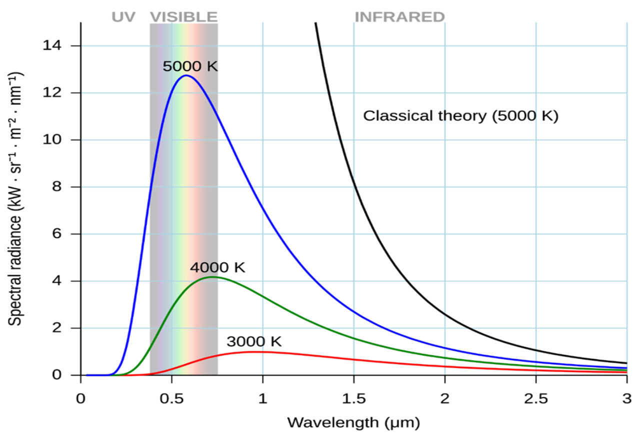
First, we can be more precise in defining these 'virtual particles'. It is believed that all matter is made up of particles, but quantum field theory states that space is all made up of fields, and all particles are oscillations of the fields at certain frequencies. However, even without the oscillations due to actual particles, there can still be an excitement within these fields due to a quantum uncertainty principle, and it is these that we call virtual particles. Even if we consider a completely empty vacuum – devoid of even energy, these virtual particles can still come in and out of existence due to the uncertainty principle: $\Delta E \Delta t$□2□ with □ being the reduced Planck's constant. This states that the conservation of energy can briefly be violated for a time if the inequality holds.

A problem arises when we try and describe a particle (an oscillation in a field) in the field's position space, as all points in space are connected or 'coupled' so that forces such as gravity which have an infinite range can act upon them. This coupling of space makes it more difficult to use equations to figure out where the particle is. So, rather than sticking to coordinate space, we can use a Fourier transform on the position space function and get the function in momentum space. We can express this momentum space as the integral of unlocalised momentum spaces, which means we can now use equations to describe where particles are, as a field operator (consisting of a creation and annihilation operator) can aid us mapping points in spacetime. In a vacuum, we can loosely say that that excitements of the virtual matter and antimatter annihilate each other such that they don't create any real particles, and only existing real particles remain.

However, this only really applies to normal, flat spacetime. In areas where spacetime is curved massively, such as near the event horizon of a black hole. To see how quantum field theory worked in this area, principles of general relativity – defining how spacetime was curved by the event horizon, and quantum mechanics – describing the actual matter near the black hole, would need to be united in a concept known as a theory of everything, something which will probably remain elusive for a while.

First, Hawking thought of a null geodesic (the path of a massless particle, such as a photon, through spacetime) of a quantum field at vacuum state. This null geodesic passed through the event horizon the instant before it was formed and barely emerges from that area as the event horizon is being formed. Hawking then used an important tool in quantum mechanics known as the Bogoliubov transformation. Hawking used this to relate the creation and annihilation operators of the quantum fields in a normal, flat area of spacetime, to the curved spacetime near an event horizon. He found that the field's frequencies were disrupted in such a way that the outgoing field seemed to have excitements corresponding to real particles[2].

Hawking explored how certain modes of the field are scattered by the black hole, meaning they're no longer on the null geodesic and therefore are lost to the event horizon. This results in the leaving field being distorted as it must use only the remaining modes of the field to achieve the vacuum state, as fields need to be consistent. The distortions are a result of changing the field operator by forming new creation and annihilation operators, and these make the field look like there are particles. Since the event horizon tends to deflect modes of the field of a similar wavelength to its own scale, the outgoing modes of the field also have a De Broglie wavelength being of similar wavelength to it. These wavelengths are very similar to those of black body radiation, giving the event horizon a Hawking temperature.



The radiation graph of a black body (and a black hole)

However, this derivation is not without flaws in its validity. Hawking's goal wasn't to show that black holes lose mass, but rather simply that they emit radiation. This led to his calculations having the flawed assumption that the black hole remains static as the radiation was emitted, neglecting

its dynamic changes. Furthermore, Hawking's model of thermal radiation led to the information paradox, where the black hole's radiation fails to preserve information, violating quantum mechanics' principle of unitarity.

Hawking also failed to account for the blue shifting of the particles as they are traced back in time, such that their wavelengths would decrease to be less than the Planck length. Their energies would increase to the point where quantum gravity effects (which are still unknown) are predicted to be relevant. Yet, due to the (even now) lack of such a theory, Hawking was forced to extrapolate in treating the fields as ordinary at this level.

In 1999, rather than writing the radiation off as some unknown quantum fluctuation which occurs in the event horizon, Parikh and Wilczeck posited that quantum tunnelling is its cause. This not only sidestepped or evaded the criticisms but also provided a more concrete physical interpretation of the phenomenon. The introduction of a tunnelling barrier that the particles had to overcome circumvented the issue of the wavelengths decreasing below the Planck length. They also recognised the need to account for the black hole's mass dynamically changing. Furthermore, this derivation could mean that the emergent particles, to some extent, are encoded with information from the derivation, potentially suggesting that further investigation could resolve the information paradox. The duo ultimately also calculated the same formula for a black hole's temperature as Hawking.

Hawking's work, although flawed, was undoubtedly revolutionary: a groundbreaking application of quantum field theory to curved spacetime and mingling its framework with that of general relativity. His equation for the temperature of a black hole, now known as Hawking temperature, has been etched into his gravestone. Although still highly enigmatic, Hawking paved the way to further understanding of the black hole, and we are left only wondering what the next big revelation in black hole physics will be.

Where's the Flux? - Tabby's Star and Dyson Spheres

By Amey Bhatia (Y13)

The year 2009 saw the launch of the Kepler Space Telescope. Its mission: to survey a portion of the Milky Way in search of exoplanets, in an attempt to help better estimate the number of planet-hosting stars in our Galaxy. Kepler's sole scientific instrument was a photometer, which continually monitored the brightness of the approximately 150,000 stars in the field of view, taking a reading every 30 minutes.[5] This data was then analysed to detect planets orbiting these stars by use of the transit method: a planet passing between its host star and our line-of-sight obscures some of the light from the star, reducing the intensity emitted.

On the 5th of March 2011, Kepler recorded a 15% dip in a star's flux and again 726 days later, this time by up to 22%. In comparison, a planet as large as Jupiter would only cause a 1% decrease in the star's flux when passing our line of view, indicating that whatever was blocking the starlight was too large to be a planet.[1]

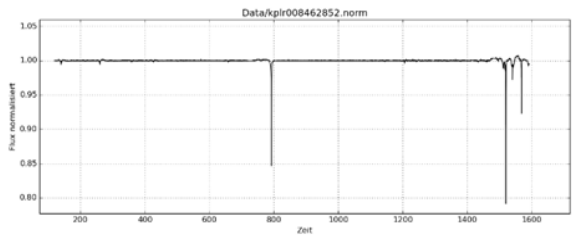


Fig. 1 Changing flux readings of the star

This star is KIC 8462852, better known as Tabby's Star, named after Tabetha Boyajian, the researcher who led the investigation of the star. These findings were extraordinary, prompting a cascade of theories about the cause of this immense dimming; literally – where's the flux?

The idea of a protoplanetary debris disk did well to pose a possible cause for the dimming but was shot down for being inconsistent with the fact that the star was too old for such a disk to still be around it, having been on the main sequence for millions of years already.[4]

Another theory was that light from the star could have been obscured by the dust from an interplanetary collision. However, this was disregarded after no evidence of glow from any of the material was found, despite it having to have been heated up by the star's light.[5] Finally, scientists posed the idea that a swarm of comets passing across the star could have, in theory, resulted in a reduction in brightness of up to 22%. Although unlikely due to the number of comets needed to obscure this amount of light, this was the best natural explanation proposed by Boyajian in 2015.[5]

A popular hypothesis was that the reduction in flux was the result of a Dyson sphere - a hypothetical megastructure thought to be constructed by advanced civilisations as a way to harness energy from their host star. As far-fetched as this sounds, it was a viable option, being consistent with the results and unable to be disproved at the time. This potential for the discovery of alien life captured the imagination of many across the world, making it a focal point of scientific and public curiosity.

But thanks to the many follow-up observations, we can say for certain that this theory is incorrect. In 2017, scientists were able to observe the star's luminosity dip in real time

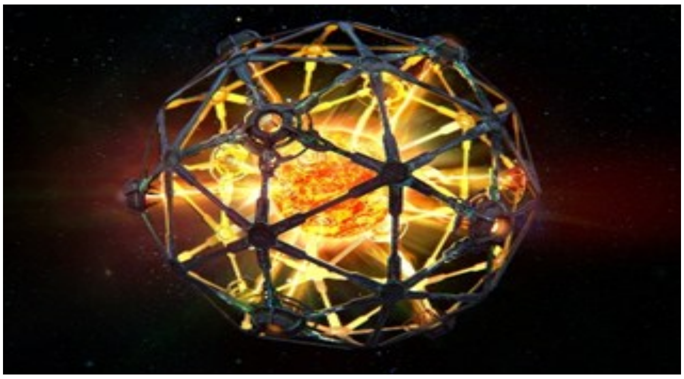


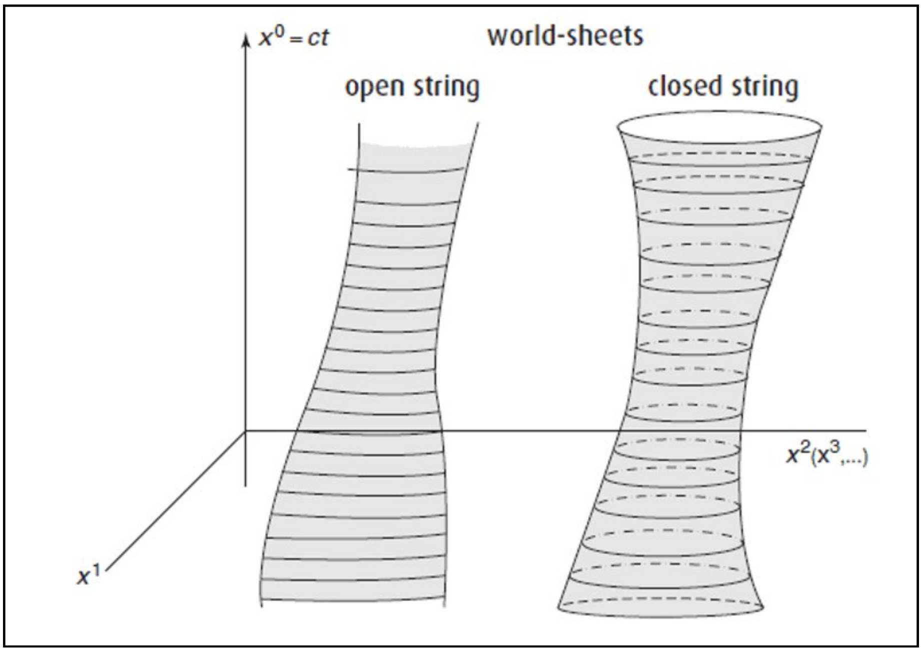
Fig. 2 theoretical model of a Dyson sphere

using several different wavelengths, so as to better infer what kind of material was blocking starlight. The results showed that the object could not be anything opaque, like a Dyson sphere, as the colours of light dipped unevenly, with shorter wavelengths being blocked to a greater extent than longer ones.[3] Based on the strong ultraviolet dip, researchers concluded that the blocking particles in the star's atmosphere must be larger than interstellar dust. These particles cannot stay in orbit around the star as the radiation pressure would push them out into space. Circumstellar dust, which orbits a star, is neither too small nor large enough to uniformly block light at all wavelengths, and is currently regarded as the best explanation.[2]

However, we are still uncertain of the cause of the dimming. Tabby's star remains shrouded in mystery: we don't know exactly where this dust comes from, nor why we don't see the excess infrared radiation which should be emitted from the hot dust.

Even though we are reasonably sure the dimming has nothing to do with aliens, it does not distract from the fact that KIC 8462852 is an oddity of the natural world, and reinforces the idea that there will always be bizarre findings in science, waiting for someone to come along and explain them. As the mysteries of the universe grow, more scientists will be needed to unravel them. Maybe that scientist is you?

Edited by Jashn Agarwal



The Quest for the Graviton

Where did this search begin and how do we hope to discover such particles in the future?

Nicolas Nanias (Y13)

The graviton is a hypothetical elementary particle proposed to be a tensor boson in the Standard Model of particles. While gravity is one of the four fundamental forces of nature (gravity, electromagnetism, strong nuclear, weak nuclear), it is still the least understood at a quantum level [1]. Despite being the pioneer that may unify quantum and classical physics, the particle remains entirely hypothetical, with no experimental evidence concluding its existence.

Where did it all begin?

In 1915, Einstein published his revolutionary theory on General Relativity, detailing gravity as a geometric property of space and time, in particular, the curvature of spacetime to be directly proportional to the energy and momentum of whatever is present [1]. However, it held a crucial flaw: since it was from the final era of classical physics, it failed to describe what happens at the quantum nature of reality. This, therefore, prompted Einstein to discuss the idea of gravitational waves in 1916. His mathematical formulas showed that massive accelerating objects would disrupt space-time in such a way that "waves" of space-time would propagate in all directions from the source [4].

Yet, the existence of these gravitational waves wasn't confirmed until 1974, when Joseph Taylor and Russell Hulse discovered the signal of a pulsar in a binary system. The pulsar had a period of 59 milliseconds and was the direct model of what Einstein's equations predicted would radiate gravitational waves. Observations of this pulsar revealed that the energy decay matched the predictions of general relativity with extraordinary precision. 40 years later, LIGO (Laser Interferometer Gravitational-Wave Observatory) made a groundbreaking discovery of signal GW150914. It was the first successful observation of gravitational waves, finally solidifying the concept of gravity behaving as a wave seen with classical physics [3].

Quantum field theory and mathematical consistency strongly suggest that the force of gravity must be mediated via particles that arise from quantised fields, similarly to how photons mediate the electromagnetic force. As such, the theory deduces that gravitons will be spin-2 particles. This means that they carry two units of intrinsic angular momentum, which their "tensor" label can derive. This means that the particles are responsible for mediating the effects of space-time curvature, causing the stretching and squeezing of spacetime in perpendicular directions. Furthermore, they must be massless entities because of our current understanding that gravity operates in infinite distances without diminishment, thus resulting in the Planck scale (10^19 GeV) determining their interaction strength. This is an extremely tiny level, placing gravity as the weakest of the four fundamental forces.

Open and closed string world-sheets

How will we discover them?

The search for the graviton involves the use of gravitational waves as a key indirect pathway to understanding the particle. However, the detection of gravitons directly is far more complex because of their weak interaction with anything, making it very hard to isolate their signals from other background effects. For example, detectors such as LIGO based at MIT can measure gravitational wave strain, as they did in 2015, but the single effects of gravitons are so weak that they have been considered impossible to detect. To maximise the chances of detecting one, researchers have followed theoretical theories such as string theory or loop quantum gravity to provide frameworks, where gravitons would be expected [2].

String theory, for instance, suggests that gravitons are closed-loop strings. These closed-loop strings, therefore, allow gravitons to act freely across numerous dimensions, because they aren't constrained to the typical "branes" of the string – i.e., confined to 4D space-time. As a result, they can act freely in dimensions that are curled up to such an extent that we cannot detect any irregularities in space-time [2]. However, although this is widely believed, it is just a theory, which may be completely wrong! There is no doubt that within the next 20 years, the quest for the graviton will lead to groundbreaking discoveries on the matter. As our understanding of this universe deepens, the integration of theories with experimental data may finally bring conclusive proof to the mysteries of the graviton.

Edited by Amey Bhatia

Stringing it together: unifying general relativity and quantum mechanics

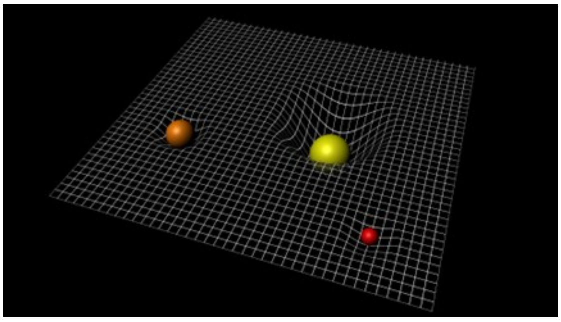
Calling it a cover-up would be far too dramatic, but for decades, amidst what can be considered a golden age for science, physicists have been quietly grappling with a seeming dark cloud on the horizon. The two foundational pillars, forming our understanding of the universe itself, are mutually incompatible.

By Zane Firdose (Y13)

Whilst Einstein's revolutionary theory of general relativity provides an elegant framework for understanding gravity and the universe on an immense scale: stars, planets, galaxies - quantum mechanics governs the bizarre behaviour of particles on the most infinitesimal scale: beyond atoms to quarks and electrons. Despite these theories both underlying the monumental progress of physics in the last hundred years – progress ranging from explaining the workings of black holes down to understanding the fundamental structure of matter – these two titans of modern physics both inexorably lead to the same troubling conclusion: *quantum mechanics and general relativity cannot simultaneously be correct.*

General Relativity:

In 1915, after exhaustive means of experimenting, Einstein discovered that accelerated motion and gravity were effectively indistinguishable, from which he hypothesised the framework for general relativity: that gravity is the warping of space-time itself. He envisioned that, in the absence of any matter or energy, space-time is "flat" (here, space-time is modelled in 2d for illustrative purposes and ease of explanation) and in the presence of a massive body, such as the sun, the fabric of space-time warps. This distortion in space-time affects the motion of other objects, causing them to follow a curved path towards the sun – this is gravity. A particularly useful analogy is that of a bowling ball weighing down on a trampoline, where the warping of the trampoline causes objects to roll towards the bowling ball, hence mimicking the effects of gravity. More massive objects warp space-time more therefore leading to a stronger gravitational force.



Quantum Mechanics:

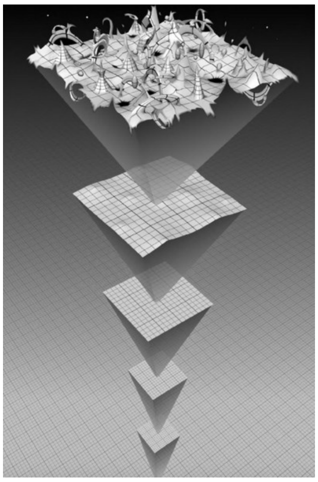
On the other end of the universal scale to general relativity, quantum mechanics describes the behaviour of subatomic particles, which exhibit properties similar to both waves and particles, and exhibit probabilities rather than definite outcomes, when observed on a miniscule scale. Spearheaded by Heisenberg's uncertainty principle, which states that we cannot exactly determine both the velocity and position of a particle, quantum mechanics tells us that the microscopic realm is intrinsically frenuous and turbulent. Hence, these frenzied particles can exist in superposition — multiple states simultaneously until observed, or become entangled – where measuring one particle instantaneously affects the other. Though quantum mechanics is far more intricate and advanced than described here, this is the fundamental tenet of the theory.

General Relativity vs. Quantum Mechanics:

For two theories with such little overlap - since they are applied on different extremes of the universal scale - how could this ferocious antagonism come to fruition? The conflict arises when space is examined in its microscopic properties, by sequentially magnifying ever smaller regions of spatial fabric. Einstein's general relativity suggests that all space in the absence of mass is flat, and indeed at the first three levels of magnification, the structure of space retains its basic, flat form. However, only when space is viewed at a sub-Planck-length (10^{-35} m) scale, it is violently distorted and frenzied; a spectacle coined "quantum foam" by John Wheeler. For scale, if we were to magnify an atom to the size of the known universe, the Planck-length would only be the height of an average tree.

Although general relativity implies that empty space has zero gravitational field, quantum mechanics shows that it only averages out to zero: that its actual value undulates up and down slightly due to quantum fluctuations. Everything is subject to the fluctuations inherent in the uncertainty principle and gravitational fields are no exception.

Spatial fabric observed at different levels of magnification



Superstring Theory:

Attempts to revise either relativity or quantum mechanics to form a unified theory have been met with failure upon failure, until the discovery of superstring theory: that the elementary foundations of matter are not point particles, but tiny, vibrating loops of "string" at roughly a Planck-length in size, and different particles arise from different vibrational patterns. This can resolve the quantum foam, which occurs due to sub-Planckian fluctuations, because the strings are too large to be affected by these fluctuations, being larger than a sub-Planck-length and also the most elementary object in the universe. Hence, these fluctuations cannot be measured and so, according to string theory, do not actually ever arise.

Therefore, superstring theory beautifully unites general relativity and quantum mechanics, to resolve one of physics' most perplexing problems.

Artificial Sun: the technology creating and controlling stars on Earth

By Jamie Shaw (Y12)

220 tonnes of metal made their way from Guangzhou, China to Saint-Paul-lez-Durance, France last November as construction continues on the ITER fusion reactor, the latest of its kind developing the technology for nuclear fusion. [1] This particular shipment contained 48 of 440 blanket modules which will serve the important role of protecting the outside of the reactor from the 150,000,000K plasma within its chamber. [2] But this is just one small part of many in one of the largest, most complex and most ambitious engineering megaprojects of recent decades.

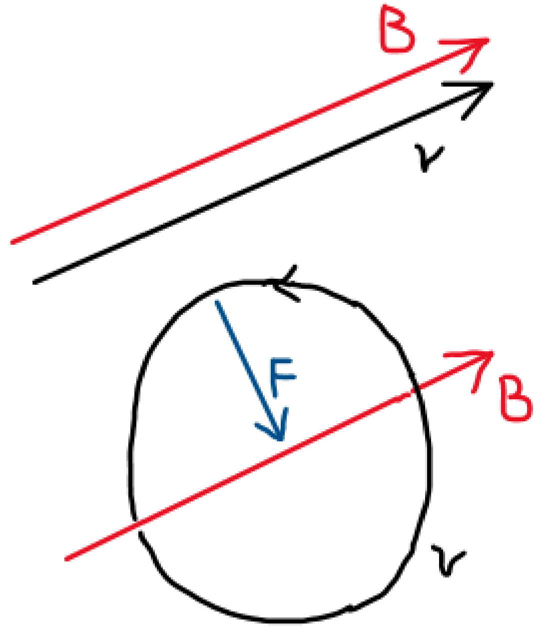
The principal goal of any fusion reactor is to cause nuclei to fuse, releasing energy. In order for this to happen, two nuclei must collide with sufficient kinetic energy to overcome electrostatic repulsion between their like charges. This is known as the Coulomb barrier which nuclei must 'get over' this, like climbing a hill. This is why fusion can only happen at high temperatures. Additionally, to ensure there is a high enough frequency of collisions to produce a reasonable power output, particles should be close together – which is where the necessity for a high pressure comes in. On the Sun, the pressure comes from its own immense gravity, and high temperature from energy released by fusion – but how can this be managed here on Earth, without a star to hand?

ITER's answer, like many of its predecessors, is to use magnetic confinement: strong magnetic fields contain and compress a plasma (the fourth state of matter, consisting of free charged particles when the electrons and nuclei of atoms become separated) under high pressure. The plasma used is usually one of deuterium and tritium, two isotopes of hydrogen.

Scottish Physicist James Clerk Maxwell published his "Dynamical Theory of the Electromagnetic Field" in 1865, which revolutionised the understanding of electromagnetism. Maxwell's equations also showed the existence of an 'electromagnetic wave', which were formed by electric and magnetic fields. These led to Maxwell discovering the speed of these waves - 299,792,458 m/s in a vacuum[1]. This discovery was that of light, and went under the radar for a while, until it was finally picked up by a physicist working in the Swiss Patent Office, of the name Albert Einstein.

The idea of a 'constant', unchanging speed of light was a problem - the leading train of thought on motion, known as Galilean Relativity, stated that it was impossible to say whether an object was moving or at rest[2]. In other words, motion could only be described relative to another object, not in absolute terms e.g., a car on a motorway travels at 70 mph relative to the road beneath. However, the speed of light being an absolute constant has odd consequences:

The magnets that ITER uses aren't any ordinary ones though: the main structure of its reactor weighs 3,400 tonnes and is 17m tall, containing 18 D -shaped magnets which are each 330 tonnes. In the centre, a 13m monolith, the central solenoid, produces a current of 15,000,000A through the plasma, essentially making the plasma an electromagnet. Larger structures surrounding this fine-tune and correct the field, as any imperfections can be catastrophic. On top of this, the reactor walls must be engineered to withstand the plasma, protecting itself and anything around it. It is equipped with features like blanket modules (as I mentioned at the beginning), a cryostat to cool the system, and a divertor to reduce the impact of heat surges – but I won't go into detail on those here. [3]



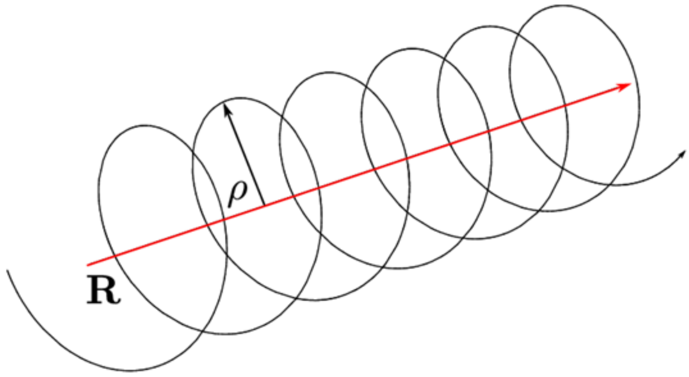
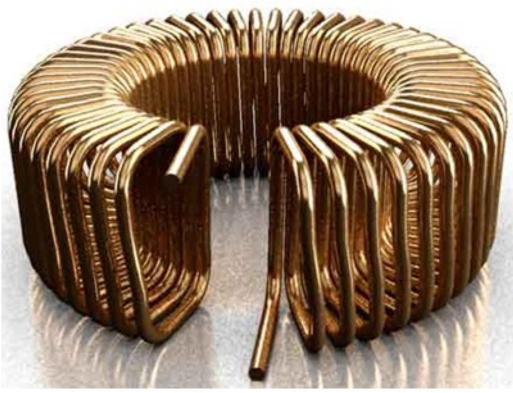


Figure 1 - the helical motion of a positive charge (right diagram, black line) along a magnetic field line (red line) is the product of linear motion along the field, when no force is experienced, and circular motion perpendicular to it, when there is a centripetal force (see for yourself with Fleming's Left Hand Rule)

The ions and electrons which make up the plasma are moving charges so follow magnetic field lines, tending to spiral around them. It is because of this that their motion can be controlled. The difficulty is in creating a magnetic field that won't let the plasma escape, as this could allow it to contact the reactor wall, causing damage. If we had just a simple solenoid (wire coil with current), where magnetic field lines go in one end and out the other, charged particles would do the same and get out before fusion had a chance to occur. So what if we take the ends of this solenoid and join them together, creating a torus? This means that particles can circle round the torus indefinitely, eliminating end losses.



[5]

Figure 2 – a solenoid curved into the shape of a torus

The Tokamak is essentially this, with some additions – it is the most commonly used (the one ITER is using) and most successful type of magnetic confinement fusion there is, and its name is an acronym of several Russian words meaning 'toroidal chamber with magnetic coils'. As well as

[6]

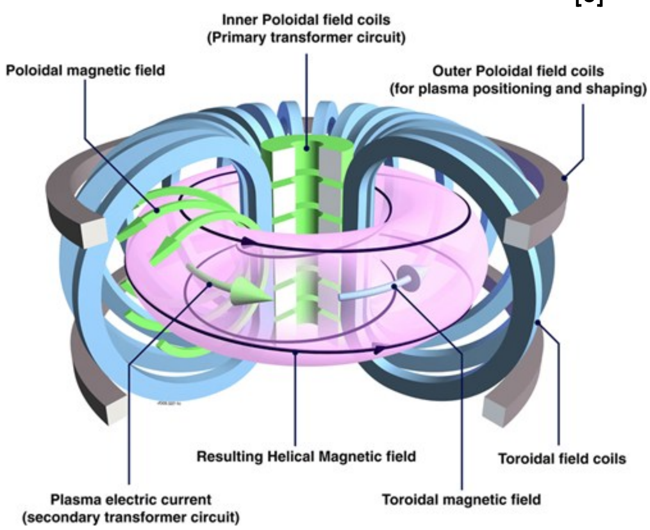


Figure 3 – a Tokamak, showing the magnets, magnetic fields, plasma and electric current

having coils around the torus like the previous design did (shown in light blue), the Tokamak has an electric current running through the plasma, creating another magnetic field that acts with

[2]

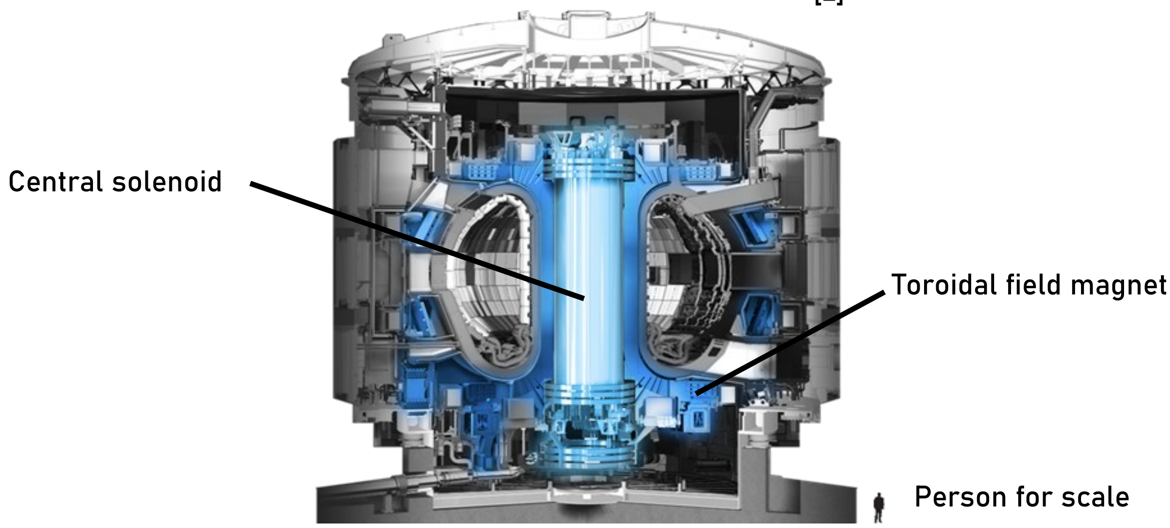


Figure 4 - a cross-section of the Tokamak at IT-ER, with the components responsible for the magnetic field in blue

perpendicular to the first in rings around the torus (shown in green). Figure 3 demonstrates this more clearly.

The two magnetic fields interact to produce a twisted helical field (black arrows) around the plasma (pink). This prevents an issue which a simple toroidal solenoid allows: plasma particles drift towards the chamber's walls due to an uneven field (stronger near the middle). The helical magnetic field causes the direction of drift to change so plasma doesn't reach the edge. That doesn't mean Tokamaks are free from other problems. For example, the plasma is magnetohydrodynamically unstable, which means that plasma can spread outwards rather than being contained, and it 'drags' magnetic field lines with it so can continues to spread out further. As a result it is extremely difficult to contain plasma for any significant length of time, and this is the main problem which reactors try to overcome.

So that's how to get a high pressure, but you can't have a star without a high temperature too. Thankfully, this is the (relatively) easy part. The current generated by the central solenoid already is already heating the plasma but not quite enough for fusion. Energy is added to the system by firing electromagnetic waves at particles, known as cyclotron resonance heating [7]. It can also be done beams of fast-moving particles, transferring energy to the system. This enables us to reach thermonuclear temperatures – impressively, those in fusion reactors are ten to twenty times greater than those in the Sun's centre.

With the completion of ITER recently being delayed until 2039 (from 2035) [8], we may not soon see this technology put into action. But the work it is capable of is of immense importance and something to be admired, for controlling the material of stars is no mean feat. Maybe one day, it will succeed.

[6]

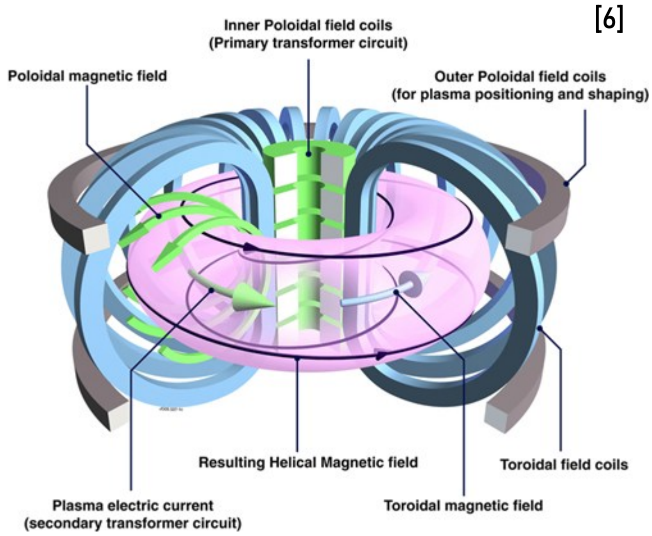
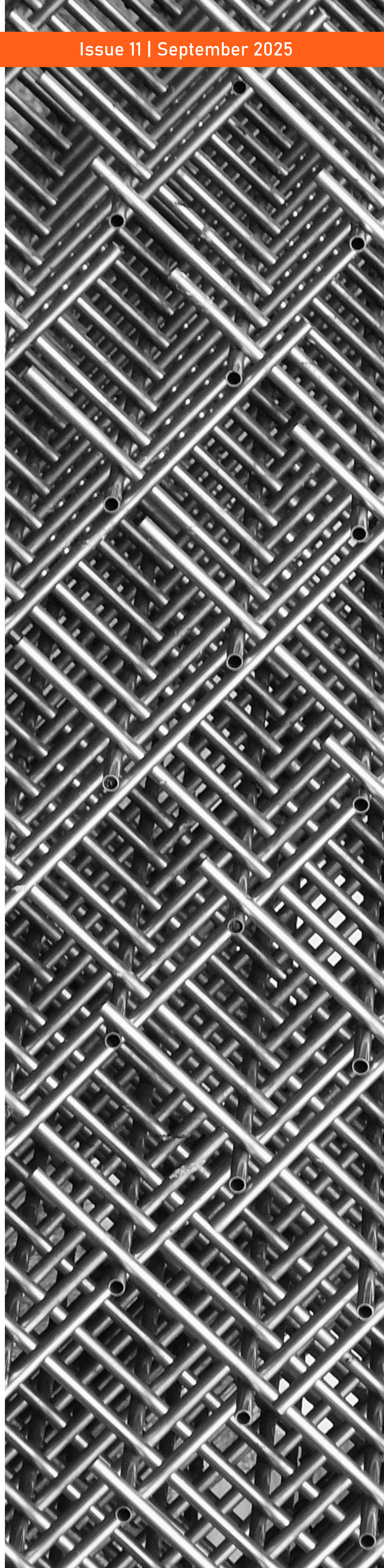


Figure 3 – a Tokamak, showing the magnets, magnetic fields, plasma and electric current



Superconductivity

By Alex Pownall (Y13)

Before I begin explaining superconductivity, it is probably best to explain how resistance works. Put simply, resistance is the measure of how hard it is for electrons to flow through a material. This hindrance of electron motion is largely caused by collisions of electrons with two things: impurities in the material and thermal excitations. Impurities (other materials being mixed in with the original) lead to irregularities in the structure of the material as their atoms are different sizes, meaning collisions can happen more easily. Thermal excitations are when atoms in the material vibrate, which can sometimes lead to a collision with electrons. In general, the higher the temperature of a material the larger the vibrations are, leading to more collisions with electrons and therefore more resistance.

Superconductivity is the property of a material that, under certain conditions, can lead to current indefinitely flowing through the material - there is zero resistance whatsoever (as far as we're able to measure).

So, how does it happen?

For all metals, resistance decreases as temperature decreases (as there are smaller and fewer thermal excitations). For some however, there is a temperature above absolute zero at which their resistance suddenly drops to zero. This phenomenon is largely explained by the formation of Cooper pairs, which are electrons that are linked together by a very weak attractive force (as opposed to the expected repulsion due to their identical charge).

Cooper pairs form because an electron moving through a lattice of positively charged ions (as found in a metal) very slightly attracts the ions, causing a region of higher positive charge density around the electron. This positive region then attracts another electron, resulting in an indirect attraction between the two electrons. The attraction leads to the total energy of the electrons being reduced by a small amount (essentially meaning that they occupy lower energy states than before). Therefore, the electrons are considered 'bound' in a Cooper pair.

However, calculations show that only electrons with energy close to the Fermi energy (the energy of the maximum energy level occupied by electrons in a material) experience significant interaction. Other calculations show that electrons in a Cooper pair must have opposing momenta and spins so that the pair has net 0 momentum - meaning that electrons must be travelling in opposite directions - and 0 spin (Cooper pairs can actually have spin of 1 as well, but these form under more complex circumstances). There are many pairs of electrons that satisfy these conditions in a superconductor, resulting in many Cooper pairs forming. These pairs then overlap with each other, both in space (there can be around 10,000,000 electrons in other Cooper pairs between two electrons in a given pair) and energetically - as Cooper pairs have an integer spin number, they sometimes behave like bosons (a classification of particle) and therefore can occupy the same energy state. Electrons have half-spin values (½ or -½) and so are classified as fermions, and Pauli's exclusion principle states that if two fermions have the same spin, they cannot occupy the same energy level (this principle does not apply to bosons). Therefore, a maximum of two electrons can occupy any given energy level (one has spin ½ , one has spin -½).

When lots of Cooper pairs overlap they form what is called a condensate as the pairs 'condense' into the same energy level. Breaking a single pair in this condensate would change the energy of the condensate as a whole, meaning that the energy of all constituent pairs must change simultaneously. This process requires a minimum amount of energy, known as the 'energy gap'.

If all the electrons in the material have their momentum increased by an identical (small) amount, through an applied voltage or magnetic field, the Cooper pairs formed do not have 0 momentum, but it is the same for all pairs so Cooper pairs still form. As there is a net movement of electrons, current flows. Once a current is flowing, it cannot be disrupted by collisions with thermal defects or impurities. This can be explained by considering both possible cases: one is where a collision doesn't lead to a pair breaking and the other is where a pair is broken. In the former, we would expect the momentum of the pair to change (as one of the electrons' courses must have changed due to the collision). However, this would lead to the electron occupying an already occupied energy state - forbidden by Pauli's exclusion principle. In the latter, in order to break a pair to be broken, energy at least equal to the energy gap must be supplied. This will most likely take the form of thermal energy, and at any given temperature there is a probability that one of the thermal defects has enough energy to break a pair. However, the electrons will soon reform the Cooper pair so at any given time only a small fraction of pairs are broken and the rest continue to flow without resistance. As temperature increases, the fraction of pairs that are broken increases (reinforced by the observation that the energy gap decreases as temperature increases) - once a 'critical temperature' is reached, Cooper pairs cannot form and superconductivity is impossible.

DID YOU KNOW?

Incandescent light bulbs were not actually invented by Thomas Edison! Prior to Edison's designs, twenty-three other bulbs had been developed. For example, in 1809, Sir Humphrey Davy produced the first ever electric arc lamp. Later, in 1820, Warren De la Rue developed the first ever incandescent light bulb.

Fluoroscopies are an example of an imaging technique that uses

Nanoparticles in Industry

Are nanoparticles revolutionising industries or a risk to public safety?

Harshaa Kumar (Y13)

Current-day medical advancement is tremendously rapid and with this comes the emergence of more autonomous and precise forms of treatment. These treatments deviate from the age-old reliance on the immune system and knowledge of the human body. Instead, they bring more precise and refined solutions with minimal damage. One method of precise treatment is through nanotechnology in order to administer localised medication. Nanotechnology is the science of creating miniscule structures: the study of synthesis, characterisation, or the application of materials in the range of nanometres (1-100nm) where they affect atoms and small molecules.[2] [5]

How is nanotechnology used in current-day medicine?

Currently in hospitals nanotechnology is mainly used in Fluoroscopy or Angiography where they are used as contrast agents in X-ray scans, microbiology through tools and targeted antibody treatment.[1]

Localised antibody treatment targets specific tissue that is cancerous with chemotherapeutic drugs, allowing easy elimination of the cancer without affecting other healthy bodily cells.[1] The development of monoclonal antibodies to be synthesised with nanoparticles provides this targeted treatment to occur. Monoclonal antibodies are formed through the fusion of myeloma cells and B-lymphocyte white blood cells to form hybridoma cells.[3]

Other applications include the use of gold nanoshells to force a heat induced ablation of the cancer cells and gene therapy. The ablation of cancer cells with nanoshells is through a Near Infrared Light or NIR passing through the body till it reaches the gold nanoshell. The gold's electrons tend to convert light energy to heat energy in order to retain a low energy state. The heat energy then kills the cancer cell.[4] Similar to monoclonal antibodies, this technique of cancer eradication is cell specific and does not usually affect normal living bodily cells.

Gene therapy is the alteration of genetic material to produce a different phenotype to the coded genes of a patient, to prove a more useful and better form of life. Initially gene therapy was more prevalent in curing single-gene disorders such as sickle cell anaemia, cystic fibrosis and haemophilia. These were particularly prevalent in the late 20th century and early 21st century, so alternate forms of cure which had minimal reported pain proved to be major breakthroughs. Gene therapy became a more recently adapted method with its institution in Gendicine in 2003 and nanoparticles are adopted to administer the altering effect to a cell through means of a genetically modified virus or other nanoparticle. This allows the DNA itself to be directly altered in the cell, through methods such as CRISPR (usage of DNA sequences to destroy DNA from similar bacteriophages) or zinc finger nucleases (artificial restriction enzymes).

However, given all the positive applications of nanoparticles, there are some potential issues in research, preventing the global release of all nanotechnology research and why nanotechnology treatment tends to be final stage treatments.[1]

Issues associated with nanotechnology and the employment of nanoparticles

Nanoparticles present uncertainties due to their unique behaviour at a nano level, influenced by quantum mechanics. Concerns include potential toxicity, as nanoparticles could cross the critical blood-brain barrier, posing unforeseen risks. Additionally, challenges in mass-producing nanowires, microprocessors, and small molecules are still being faced. Nanotechnology requires substantial investment and has ethical concerns about misuse (biological weapon creation).[6] Whilst offering promising medical advancements, the rapid development of nanotechnology demands serious ethical and safety considerations, as its impact could reshape society, depending on its intentions and applications.

How is nanotechnology progressing and what is yet to come?

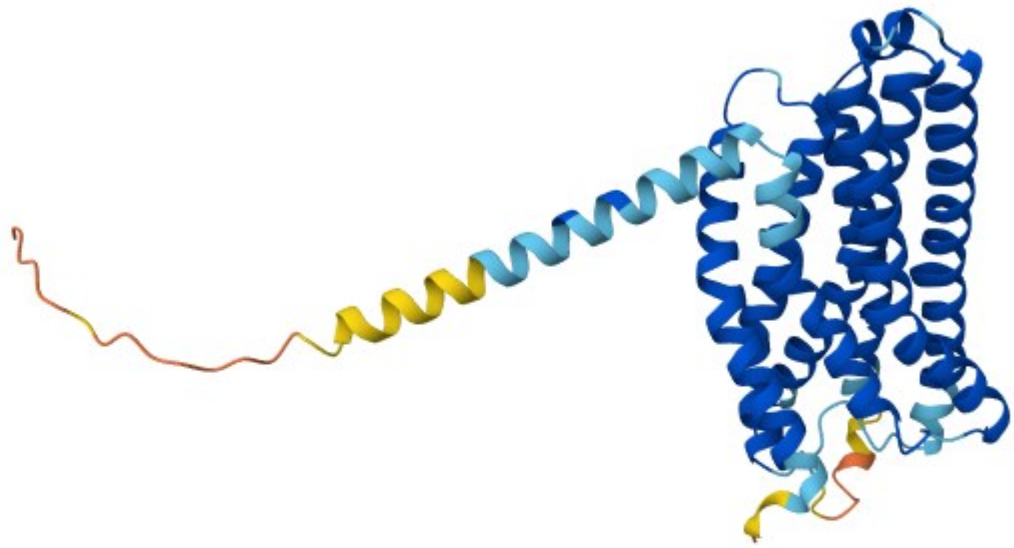
There are many potential avenues where Nanoparticles can continue to be incorporated within, but two ongoing research topics are the creation of respirocytes and microbivores. These two ideas are purely hypothetical projects which may have some forms of testing but no official releases.

Respirocytes appeal to replace normal red blood cells with artificial ones. The artificial red blood cell would have around 18 billion atoms with oxygen and carbon dioxide within it that can be used to maintain the concentration gradient of the blood. These artificial cells would allow constant oxygen supply to patients suffering with red blood cell defects or bone marrow defects, which could be a massive step in limiting the effect of diseases such as sickle cell anaemia.

On the other hand, microbivores are another potential creation which feed upon microorganisms which may enter the body, such as bacteria. This is useful in suppressing infection from spreading and mitigating dangerous diseases.

These two potential ideas are purely limited by current technology and research into nanotechnology, but one day could be massive considerations in improving the quality of life for people.

Edited by Henry Li



AlphaFold: how AI is Revolutionising Biochemistry

By Henry Li (Y13)

A protein's structure underpins its function, so it is important for researchers to have a means of determining their structure. Previous techniques such as X-ray crystallography and NMR spectroscopy proved cumbersome, often requiring expensive and time-consuming preparation of samples. However, the recent development of the Nobel Prize winning AlphaFold AI allows structures to be predicted with greater accuracy and far less input, improving efficiency of research involving proteins[1].

Proteins are found in all living organisms, performing functions necessary for life. In fact, they make up about 42% of our dry weight[2]. They are made when a gene is transcribed then translated into a sequence of amino acids, each having a unique R group with properties that affect how they fold in the final protein. For example, thiol groups in cysteine's R group can form disulfide bridges and serine's polar R group makes it hydrophilic locating it on the surface of proteins[3][4]. In the final protein, the polypeptide chain is folded into a mixture of alpha helices, beta pleated sheets and loops [5] and is often represented by a ribbon diagram showing only the protein's backbone.

The steady growth of identified proteins stored in the Protein Data Bank allows AlphaFold to draw similarities to evolutionarily similar proteins. This allows for multiple sequence alignment (a technique that looks for similar amino acid sequences between proteins) and pair representations (separate representation of every amino acid pair in the protein) to work together to map the protein's 3D spatial arrangement. Finally, it feeds the multiple sequence alignments, pair representations and structure back through the neural network 3 more times to improve the accuracy of the final structure[6].

Naturally, such a fast and accurate method of predicting protein structure has great implications on our ability to carry out research. For example, researchers were able to use AlphaFold to predict several proteins of SARS-CoV-2, the virus responsible for Covid-19, including its spike protein – the mechanism with which the virus attaches to and infects body cells. Researchers could then attempt to use this information to develop protein-based inhibitors, which can bind to the identified spike proteins preventing infection[7]. Another approach was to simply use the spike protein itself to generate an immune response, brought into fruition with Pfizer's mRNA vaccine[8]. Without AlphaFold, understanding Covid-19 and its mechanisms and eventually developing treatments and vaccines against it may have been much more difficult.

Another example of AlphaFold being put to the test in research is in the fight against Malaria, the lethal protist that is one of the leading causes of death in low-income countries[9]. Because Malaria has hundreds if not thousands of proteins, and is notorious for being a shapeshifter, it presents a much bigger challenge to study than Covid-19. However, the gamete surface protein Pfs48/45 essential to the parasite's development was identified as the crucial protein with which a vaccine could be developed. Older techniques such as X-ray crystallography and cryo-electron microscopy were tried with little success, yielding imperfect, low-resolution images. The turning point came with the release of AlphaFold, which allowed the researchers to identify the protein's structure and isolate the parts which would be included in the vaccine[10], which is currently showing a lot of promise in clinical trials[11].

AlphaFold shows great promise overall, but currently still has slight limitations. Professor Higgins behind the Malaria vaccine development remarked that there were instances where the AI's 3D visualisations were slightly incorrect, stating that it is best used in conjunction with traditional methods such as cryo-electron microscopy rather than as a substitute[10]. Furthermore, AlphaFold struggles to predict protein interactions, such as those between antigen and antibody, and post-translational modifications, such as phosphorylation or glycosylation[12].

However, AI is an ever-advancing tool, and these limitations could probably be overcome in the next few years, facilitating a phase of rapid acceleration in biochemical research. Despite the myriads of problems caused by AI, it is impossible to deny that as a resource, it has great implications for scientific advancement in general.

Cancer Vaccines and Adjuvants: A Biochemical Revolution in Immunotherapy

By Arya Chougule (Y13)

Traditionally cancer has been fought with the use of long, intensive and often physically and emotionally painful chemo/radiotherapies or more invasive surgical procedures. However the growing development and increased research into the biochemical functions of **mRNA based immunotherapy** has facilitated the rise of cancer vaccines.

What Cancer Vaccines Are and How They Work?

Cancer vaccines encourage the body's immune system to recognize, target, and destroy cancer cells. Unlike traditional vaccines that prevent infections, cancer vaccines are specifically designed to treat or prevent cancer by stimulating the immune system to fight existing or future cancerous cells.

This can be done by introducing specific cancer -related molecules from an internal/external existing tumour to the body via an injection so that the **antigens** on these cancer cell surfaces can be recognised. The more commonly used alternative is injecting mRNA samples of the specific cancer to encourage the body to code for its production itself (in a weakened/non functional form).

Once the vaccine is administered, dendritic cells, which are immune cells responsible for identifying pathogens, capture and process the antigens. These dendritic cells then travel to the lymph nodes, where they present the antigens to **T-lymphocytes** (a type of white blood cell responsible for killing infected or cancerous cells) and **B-lymphocytes** (which produce antibodies). These antigens are found on the surface of cancer cells but are absent or very limited on healthy cells. So when the immune system detects these antigens, it responds by producing immune cells to only attack cancer cells displaying them {1}.

Cancer vaccines also promote immune memory. This means that if the body encounters cancer cells with the same antigens in the future, the immune system can recognize and destroy them more efficiently by releasing **memory lymphocytes** stored from the induced immune response. This long-lasting immunity is crucial for preventing cancer recurrence from malignant tumours.

Types of Cancer Vaccines

Therapeutic cancer vaccines are designed to treat existing cancers. They work by stimulating the immune system to target and kill cancer cells as discussed above. Therapeutic vaccines are often **personalized**, meaning they are tailored to the unique characteristics of an individual's cancer cells. Thus they are more likely to use samples of the cancer from a tumour currently within the patient (**Intratumoral Therapy** {2}).

Approved therapeutic cancer vaccines include Provenge (sipuleucel-T) used to combat prostate cancer and Bacillus Calmette-Guérin (BCG) for countering bladder cancer {3}.

Preventive vaccines however aim to reduce the risk of developing cancer in the first place. They are usually designed to target viruses that are known to cause cancer. These vaccines prevent cancer by targeting the viruses that are responsible for initiating cellular changes (mutations) that can lead to cancer.

Approved preventative cancer vaccines include the HPV and Hepatitis B vaccines, preventing the occurrence of cervical and liver cancer {3}.

The Role of Biochemical advancements

In some cancer vaccines, adjuvants are added to enhance the immune response. **Adjuvants** stimulate the immune system, making it more likely to respond effectively to the cancer antigens in the vaccine. They help increase the duration and intensity of the immune response.

Alum (aluminum hydroxide) is the most common adjuvant used. It is formed from a reaction of aluminum sulfate and sodium hydroxide: $Al_2(SO_4)_3+6NaOH \rightarrow 2Al(OH)_3+3Na_2SO_4$. Once the aluminum salt is synthesized, it needs to be processed into a form that can be used in a vaccine. Thus it's converted into a **gel** by adding water and adjusting the pH {4}.

This gel form helps slow the release of antigens at the injection site, allowing for a sustained immune response.

Problematically, the mRNA coding for these cancerous proteins + antigens can struggle to even penetrate the cell membrane, given their fragility. When wrapped around a delivery mechanism like **Lipid Nanoparticles** however mRNA can be shielded from destructive enzymes and shuttled into cell cytoplasm {5}.

Lipid nanoparticles are made from ionizable lipids whose positive charges bind to the negatively charged backbone of mRNA, pegylated lipids that help stabilize the particle, and phospholipids and cholesterol molecules that contribute to the particle's structure {5}.

Conclusion

The creation of cancer vaccines and biochemical engineering of nanoparticle technologies has set us bounds forward in our scientific crusade against cancer.

Genetic Circuits - Electrical Circuits for Organisms

By Rayyan Ali (Y12)

What if we could program living cells to process information and make decisions like computers? Could we reimagine biology to create solutions for our challenges, such as disease treatment and agriculture? How far are we from engineering life itself? These questions are no longer science fiction - they are the core of synthetic biology and by designing and assembling genetic circuits, synthetic biology reimagines living cells as programmable systems.

Genetic circuitry refers to networks of interacting genes, proteins, and other molecular components within a cell that are designed to process information and regulate biological functions, much like electronic circuits in a computer or a device. Genetic circuits have a few main components:

- Promoters: DNA sequences that initiate the transcription of a gene, acting as binding sites for RNA polymerase.
- Repressors and Activators: proteins that inhibit or promote gene expression by blocking RNA polymerase from promoters, or recruiting the RNA polymerase to the promoters.
- Regulatory RNA: for instance "siRNA (small interfering RNA)", which can "regulate the expression of genes" and is described as "one of the most important advances in biology" [1]. Regulatory RNAs influence when, where, and how much protein is made.
- Gene: the final component, a base sequence of DNA that codes for a protein.

This toolkit can assemble components into networks to perform logic-based operations, parallel to the 'AND', 'OR' and 'NOT' gates in electronics. These can be replicated e.g. a gene is expressed only if two conditions are met ('AND' gate), or create toggle switches - turning one gene on or off in response to a signal. Further implementations include oscillators, which would create periodic patterns of gene expression (like a biological clock), and even sensors, where specific environmental inputs, like temperature or toxins, can be detected, and a response can be triggered. Professor Bollenbach, from the University of Cologne, describes how the "components of these circuits are not capacitors, resistors, transistors, etc.", rather "genes from living organisms – most often, transcription factors and promoters from bacteria like Escherichia coli" [2]. Like in electronics, feedback loops are used to stabilise or adjust the circuit's behaviour. Positive loops exacerbate the circuit's response upon detecting a stimulus, and negative loops dampen the response to maintain a balanced state.

Genetic circuits can be used in gene therapies to treat diseases like cancer. By engineering certain immune cells, scientists have developed effective ways to target and destroy tumours. CAR-T cells (type of immune cell) help specifically target antigens on cancer cells' surfaces. The National Cancer Institute explains that "they are made by collecting T cells from the patient and re-engineering them in the laboratory to produce proteins on their surface called chimeric antigen receptors, or CARs" [8]. By doing so, the CARs recognise and bind to the antigens in a cancer cell's surface, shortly destroying it. Genetic circuits add an element of control to the CAR-T cells, such as safety switches, which deactivate the T cells if adverse reactions occur. This offers a highly personalised approach to cancer treatment, incorporating smart safety features that minimise negative side effects.

Genetic circuitry can also be applied to agriculture - to create stress-tolerant plants, a genetic circuit can facilitate the detection of stress (salinity, heat, water scarcity) and activate the protective genes. Another layer of control is assured by using miRNA and siRNA, which silence certain stress-sensitive genes when plants are experiencing drought or saline conditions. For instance, miRNA can silence genes that promote water loss (via transpiration) during drought. This improves overall crop resistance, improving yield for farmers in more challenging environments, and providing a larger food supply to vulnerable communities. Though this technology offers transformative and exciting solutions, "further work is needed to shape a reliable pipeline for engineering diverse crop varieties, starting from the generation of genetic circuit designs and including the process of porting knowledge from lab to field", says PubMed Central [3].

According to the University of Cambridge, there will be an estimated 11.2 billion people on the planet by 2100 [4], and this staggering fact highlights the importance of overcoming problems such as disease and food insecurity, which will become inevitable if we don't act soon. With the world nearing its tipping point, exploiting the numerous benefits of genetic circuitry, such as its flexible nature, ability to be implemented repeatedly, and predictable outcomes, will become necessary as we must turn science into solutions for our global concerns.

The Science Behind Organ Donation

By Vishal Patel (Y13)

Organ donation is a revolutionary medical procedure used to treat patients with severe chronic organ failure or dysfunction, in which a healthy organ or organ tissue sample acquired from a registered donor is transplanted into the affected patient. This life-altering process relies on incredible advancements in medical science, surgical techniques, and knowledge of immunology, which this essay explores.

Biological compatibility is a measure of how similar in blood type, tissue type as well as how physiologically similar the two individuals are, which dictates the likelihood of a successful transplantation. In order to guarantee suitable compatibility, a rigorous process of crossmatching is undertaken to find a viable donor with healthy and intact organ tissue.

The first thing considered is blood type compatibility by ABO groupings. This is one of the first criteria, as organs donated from donors with incompatible blood types are prone to immediate rejection, as the recipient's immune system will identify the organ as "foreign" and trigger a specialised immune response to destroy the cells of the transplanted organ.

Secondly, human leukocyte antigens (HLAs), proteins found on cell surface membranes, must closely match the recipient's to prevent an immune response. In addition to HLAs, minor histocompatibility antigens can also elicit an immune response. While their role is less pronounced, they can contribute to chronic rejection and are an area of ongoing research. Incorrect HLA identification is often the greatest cause of hyperacute rejection, in which the organ is subject to an immune response within mere hours.

Additionally, several tests are performed in vitro using laboratory methods.

Panel reactive antibody testing (PRA) measures the level of pre-formed antibodies in a recipient's blood. The recipient's blood is tested against a panel of HLA antigens, often represented by synthetic beads or cell-free antigen preparations. This identifies the presence and level of antibodies that could react with potential donor organs, and therefore risk of rejection. If several of the tested antigens which triggered an immune response were donor-specific HLA antigens, the recipient may have a high proportion of donor-specific antibodies (DSAs); therefore, the risk of chronic rejection is more acute in the recipient.

Finally, a more refined version of HLA matching may be employed called epitope matching, whereby specific epitopes (the molecular structures on HLAs recognised by the immune system) are analysed. This is particularly crucial with tissue graft procedures, which often have lower success rates.

The immune system's primary function is to protect the body from foreign invaders. Unfortunately, this defence mechanism can complicate organ transplantation by identifying donor organs as threats. This phenomenon can lead to hyperacute, acute, or chronic rejection. Immunosuppressant drugs are taken by recipients following a transplant and are important in mitigating the mid- to long-term rejection risk to increase the longevity of the organ. There are three main types:

Calcineurin Inhibitors (such as cyclosporine and tacrolimus) inhibit T-cell activation, reducing the immune response against the transplanted organ. Antimetabolites (such as mycophenolate mofetil) suppress the proliferation of immune cells. Corticosteroids have broad immunosuppressive effects and are often used in combination with other therapies.

Part of the challenge of a successful transplant, as medical dramas may often exemplify, is preservation in transportation. To allow this, the organ will be removed from the host at the latest possible point before the surgery (and only kept in a host with terminal organ system failure for 90 minutes after removal of life support). While in transit, it will undergo machine perfusion (artificial circulation of a preservation solution with oxygen and glucose akin to blood around the organ's vascular network), which prevents cell death. This is employed in conjunction with cold storage, which is used to slow metabolic activity, reducing short-term demands of the cells.

Perhaps the most topically relevant challenges are often the ethical and logistical ones. With a shortage of viable donors and an excess of people suffering with chronic organ failure, how can we choose who deserves to live?

The scientific community, however, has been trying to address these issues. For example, xenotransplantation involves the transplantation of organs from genetically modified animals such as pigs. This has already been somewhat partly employed via the use of porcine or bovine valves to treat heart failure; however, it carries the risk of zoonotic infections and even greater immunological barriers. Indeed, the most exciting idea is bioengineering and 3D printing of lab-grown organs and tissue from stem cell technology; by using totipotent embryonic stem cells, the antigens of the tissue would perfectly match those of the target host. Furthermore, advances in developing medical devices such as ventricular assist devices may negate the need for transplants for the foreseeable future.

Organ donation is a testament to the synergy between medical science and human altruism. It combines cutting-edge technology, meticulous surgical expertise, and a deep understanding of immunology to save lives. Despite significant progress, challenges such as organ shortages, rejection, and ethical dilemmas persist. Continued research in immunosuppression, bioengineering, and public policy will be pivotal in overcoming these obstacles and ensuring that the life-saving potential of organ donation is fully realised.

Genetics: A New Wave of Discrimination?

By Arjun Bhatt (Y13)

With the rise of genetic testing in the world of preventative medicine, it is easier for people to learn everything about their medical history than ever before. While genetic testing offers remarkable scientific advancements such as diagnosis of cancer, cardiovascular medicine and overall disease prediction, it threatens to perpetuate new forms of discrimination rooted in our genetic codes.

Modern eugenics were established more than 150 years ago by Sir Francis Galton, cousin to one of the most famous names in science - Charles Darwin. [1] Using his cousin's theory of evolution by natural selection, Galton developed this pseudoscience based on farmers intentionally breeding their animals to grow larger, and he believed that intelligence could similarly be passed down through reproduction with specific people. This was then reinforced when Mendel's works were found in 1900, fuelling this idea of characteristic inheritance. [2] However, this would then become much more hateful as it was the basis of Hitler's Aryan ideology. This problematic idea would be corrupted and used to achieve "racial pureness" and would result in genocides like the Holocaust. Eugenics was recognised after WW2 as a discredited theory that would be criticised especially during movements like the Civil Rights Movement and had been forgotten from public opinion.

Genetic testing has resulted in the rise of organisations like 23andMe and Ancestry.com and millions have submitted DNA samples to understand more about themselves and their heritage. However, over time 23andMe has amassed a genetic database of more than 15 million people and is not subject to the HIPAA code of the USA due to it being a biotech company.

However, the ethics of genetic ownership is not a modern issue. One of the earliest examples of this contested ownership was Henrietta Lacks who had her cervical tissue sampled without her consent in the early 1950s leading to scientific revolutions such as the ability to grow cells outside the human body and the development of the polio vaccine.[3] Another example is the case of Moore v. Regents of University of California where Doctor David Golde, a cancer researcher at the UCLA Medical Centre, treated John Moore for hairy cell leukaemia in 1976. Golde and UCLA went on to commercialise a cell line that was created from Moore's cancer cells. According to a California Supreme Court ruling, a hospital patient's leftover blood and tissue samples are not his personal property, and people are not entitled to a cut of the money made from research or commercial goods made from their cells. These landmark cases represent the ethical issues of owning someone's genetic information, a problem amplified in the modern era as private companies amass vast genetic datasets without sufficient oversight. [4][5][6]

So how do these cases from 70 and 50 years ago apply today? The precedent set in California was a dangerous one because now companies like 23andMe effectively "own" a lot of genetic information. With deals behind the scenes, private companies such as insurance companies could buy up your genome. The Genetic Information Non-discrimination Act (GINA) protects against discrimination in health insurance but does not extend to life or disability insurance, leaving individuals vulnerable to exploitation, life, long-term care, and disability insurers may require their clients to reveal genetic risk factors for certain diseases and, based on the information provided, refuse coverage (or increase premiums). [7] Even in the UK, while you may not be getting insurance as readily, those applying for life insurance over £500,000 [8] would be required to submit a test.

This could disproportionately affect some ethnicities such as those of African descent who are more likely to get sickle cell anaemia with a 1 in 10 to 12 chance compared to those of Mediterranean descent with a 1 in 40 chance [9] and may be discriminated against further due to their genetic predispositions. Whether those clients learnt about their mutations from a 23andMe kit or a test prescribed by a doctor would be irrelevant.

In our age, where the ownership of our genetic information can be in anyone's hands, will we be seeing an extremist view of the world where those with "better genetics" have a higher value in society or will the laws become stricter surrounding ownership of genetic information?

How Cell Mapping is changing Medicine

By Vivaan Parekh (Y13)

0.03 mm. That's the length of the average human cell. It's a remarkable and complex masterpiece designed to near perfection. We seem to think we have grasped the human cell's true capabilities but there is still uncharted territory within the span of a few micrometres. And scientists over the globe are ambitious to create a map of all human cells forming an identity of all the cells in our body, making a massive leap in biomedical research and redefining what is possible in modern medicine.

From the mapping of 1.6 million gut cells to prevent gut disease to mapping the human thymus to show early life developments in the immune response, is cell mapping the groundbreaking future of medicine revolutionizing treatments as we know it? Indeed it is. Helping understand cells is the key to understanding disease. But what is cell mapping? Well there are 37 trillion cells in the human body all with different roles and functions. Cell mapping is the profiling and characterization of the cells in our bodies; how they interact physically and how their genes interact and primarily the proteins produced in each cell by the types of genes.It can involve finding the location of these cells in the body and how they contribute to the function of organs and biological processes. It can allow us to understand the impact of gene alterations in a cell as well as can be used to compare different cells in different individuals, identifying which ones are healthy and what exactly makes the cells healthy.

Obviously we know that different organ cells have different functions; liver cells store biological molecules, kidney cells filter blood etc. But even within these organs, different types of cells are present all interacting differently with separate roles and the goal of cell mapping is to identify these interactions, by analysing its gene expression. As put by the Human Cell Atlas, "if the human genome project identified the book of life, cell mapping is how our body reads these books".

How is Cell Mapping done

Tissue samples are taken from specific organs. Samples can be taken from different development stages of the organ, healthy or non functional organs etc in order to compare the cells in different individuals. The cells from the sample are then dissociated into individual cells. The cells now need to be analysed.

Every cell in the human body has the same DNA regardless of the cell type so analysing just DNA of cells won't help create a proper cell map as the cells can't be differentiated and identified. Instead of DNA, it is the RNA transcribed by the cell during protein synthesis that is analysed. Each cell type will transcribe a different RNA sequence, depending on the genes it expresses and the genes it suppresses giving the cell its unique properties depending on the proteins coded for by the RNA. The extracted RNA is then reverse transcribed by finding the complementary DNA nucleotides to create a cDNA sequence. This cDNA is amplified which involves creating large copies of the cDNA fragment which will allow us to identify the genes expressed by the cell. Revealing the gene expression now creates a 'character profile' of the cell, identifying which proteins it synthesises and how it interacts within the organ.

But Why?

Why are scientists so eager to map these cells in the body? Well, a comprehensive cell map

could help understand our bodies on a cellular level, helping detect and treat diseases.

For example the Human Cell Atlas programme (a global initiative at the forefront of cell mapping research) mapped the origin of kidney cells and found that cases of paediatric kidney cancers originate from a cell type present in utero; this information could allow detection of cancers before a baby is even born. Cell mapping has helped analyse tumours in unbelievable detail, identifying that cancer cells use more energy and we have identified the exact cells that drive tumour growth. By using these pieces of evidence not only can we detect cancer in early stages of development drastically increasing life expectancy but also target specific tumour promoting cells to completely kill the tumour. In fact just last month the Human Cell Atlas discovered certain significant gene expression in immune cells in breast cancer patients which indicated immune exhaustion and directly led to this research being able to detect and prevent breast cancer early.

Not only does cell mapping help detect diseases early but the discoveries can help create treatments targeted for diseases. Analysis of RNA in a cell in the airways helped the Human Cell Atlas to discover a new cell in our airways called the pulmonary ionocyte which expresses the gene for the CFTR protein; a faulty protein in Cystic Fibrosis patients. Deeper analysis into the gene expression of this cell could transform genetic treatments for the millions around the world suffering from cystic fibrosis .

Even during Covid, while with world was stuck inside, scientists were hard at work, mapping the human body which helped them anticipate and recognise how the virus moved from tissue to tissue, identifying the riskiest points of entry into the body by the virus and treatments could be designed around this.

The HCA then went ahead and analysed millions of gut cells finding a new gut metaplastic cell, responsible for worsening inflammation in the bowels leading to conditions like Crohn's disease. Identifying these pathogenic cell types has meant new target drugs can be created to treat these conditions

So the future looks bright as we unlock more possibilities with cell mapping. As global initiatives like the Human Cell Atlas expand, we could be looking at upgrading what is possible with medicine, healing people and improving lives all by stopping to take a closer look at the tiny cells that make up life.

Exploring Vascular Surgery: A Pathway to Saving Lives

By Rajadithan Rajarajan (Y13)

Imagine the intricate network of rivers that nourish the land, carrying life-sustaining water to every corner. Your vascular system mirrors this, with blood vessels transporting oxygen, nutrients, and blood throughout your body, as well as transporting waste back to where it can be excreted. When this network faces a blockage, leak, or rupture, the results can be catastrophic. This is where vascular surgery steps in as a lifesaving discipline.

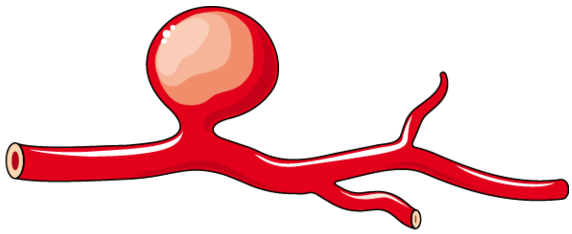
Vascular surgery addresses diseases of the blood vessels, including arteries, veins, and capillaries. These conditions can lead to serious health complications if left untreated. Vascular surgeons utilize advanced techniques, including minimally invasive procedures, to improve blood flow and restore patient health [1].

Common causes of vascular problems:

- High BP (Hypertension)[2]
- High Cholesterol[3]
- Diabetes[4]

Conditions:

One common condition is an **aneurysm**. They occur when part of an artery becomes weakened and bulges out due to high blood pressure. If left untreated, it can burst, leading to (potentially fatal) internal bleeding. In most cases, aneurysms are treated using endovascular aneurysm repair (EVAR), which is when a stent graft is guided to the site of the aneurysm and deployed, creating a new, reinforced channel for blood flow within the artery. This diverts blood flow away from the weakened artery wall, reducing pressure and the risk of rupture[5]. Historically, aneurysm repair required a large abdominal incision. However, utilising the interconnected nature of the vascular system, minimally invasive techniques now allow access and treatment through a small incision in the groin[1].



Another condition is **varicose veins**. These swollen veins, which often appear on the legs, can cause discomfort, pain, and ulcers. They can cause serious complications like non healing ulcers, pain, and even death due to clots. Treatment options include laser therapy, which uses focussed light to treat the vein[6].

Deep vein thrombosis (DVT) is another serious condition, which occurs when a blood clot forms in the deep veins, often in the legs, due to high blood pressure damaging arteries. These clots can dislodge and travel to the lungs causing a problem with oxygenation, sometimes leading to death. To treat DVT, doctors often prescribe blood-thinning medications called anti-coagulants[2].

Another condition treated by vascular surgeons is **carotid artery disease**, where plaque builds up in the arteries supplying blood to the brain, increasing the risk of a stroke. The common treatments for carotid artery disease are carotid endarterectomy, a procedure where the plaque is surgically removed from the artery, or carotid stenting, where a small mesh tube is inserted into the artery to keep it open and restore blood flow [7]. Both treatments reduce the risk of stroke by improving circulation to the brain.

For people with **diabetic foot**, which occurs when high blood sugar damages the blood vessels and nerves in the feet, treatment often involves angioplasty to restore blood flow. In extreme cases, bypass surgery may be required to reroute blood flow around blocked arteries in the legs. Since people with diabetes have 'sweeter' blood, insects often feed off the area resulting in inflammation and infections of the skin and bone. Some toes or even the whole foot could be amputated to prevent the spread of infection. To remove the pus coming from the infection you could use a vacuum machine connected to a dressing to continually drain any infective fluids[4]. If the blood flow is completely cut off to the legs it may result in the 'death' of the limb called gangrene, shown by the skin turning black[3].

The work of vascular surgeons:

- Multidisciplinary Team Meeting: Meeting of surgeons and interventional radiologists to plan treatment strategies [8].
- Ward Rounds: A daily review of patients to assess progress and optimize treatment plans[2].
- Clinics: Referred patients are seen for routine consultations and follow-ups

following GP consultation[5].
- Theatres: Surgical rooms where operations and procedures are performed[1].
- Emergency On-Call: Patients with sudden deterioration due to the above conditions that need very urgent care are seen[4].

How to prevent vascular problems:

- Don't smoke. Nicotine in it causes many problems to blood vessels[3].
- Check and treat high blood pressure, especially as you get older[2].
- Eat a healthy, balanced diet with good fibre content[1].
- Exercise regularly[5].
- Check and treat health problems early[8].

In summary

Vascular surgery has a significant impact on patients' wellbeing, improving their circulation, preventing strokes, and saving lives. Recent advancements in vascular surgery focus on minimally invasive techniques which make procedures less risky and reduce recovery times. As the field evolves, there are opportunities for continued research and innovation, such as the development of bioengineered blood vessels and better prosthetic grafts, all of which will help improve patient outcomes[9].

Edited by Oscar Wong

Seagrass – What is it and why is it important?

Oscar Wong (Y13)

Have you heard of the term 'seagrass'? It sounds like another buzzword used for 'green stuff' in the ocean, mixed with seaweed, kelp, plankton, algae and so on. However, seagrasses are a fascinating group of plants – both as individual organisms and as part of their wider ecosystem. They are present around the world in salty and brackish waters, mainly shallow areas. Imagine long flowing seagrasses forming meadows underwater. The lush greenery flourishes in the depths where sunlight can reach and, amongst the seagrass, fish and other marine animals thrive. They are species essential to ecosystems by creating these meadows – meadows which are rapidly declining. Vanishing.

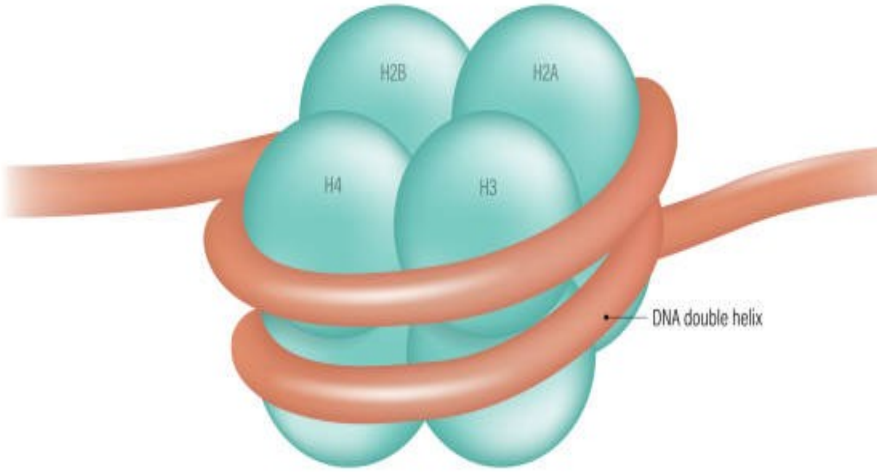
Firstly, I want to distinguish what seagrass is and explore it on its own. Seagrass is not one species of plant, but a functional group of around 72 species of angiosperms (flowering plants) that have reconquered and reentered the oceans. They are the only angiosperms which fully live submerged in salt water, and so also flower, pollinate (sexually reproduce), fruit and seed underwater. The seeds remain neutrally buoyant and can be pushed along the water until they settle. They differ from algae – and seaweed, a macroalga – as they have a complex root and vascular system. Algae only use diffusion to transport substances. Interestingly, this originates from how seagrass was created by first algae evolving into plants on land, then terrestrial plants further evolving back into the oceans. The complex evolution that occurred could help us understand the transition to gaining salt tolerance among other developments. Research analysing the genomes showed that instead of new gene functions evolving, there was simply the adjustment of many existing genes that let the plants have higher salt tolerance. This is, naturally, important research for modern-day crops.

As seagrasses can spread asexually easily, they form meadows – habitats for other species, hence often being known as keystone species or foundation species. They are essential to their ecosystems. Despite there being so many seagrass species, it is noted that all of them play similar roles in their respective distributions. They are sources of vegetation and habitats providing shelter, even from predatory echolocation. Sediment can accumulate in seagrass, clearing water and sequestering carbon, responsible for ~15% of carbon storage in oceans, part of the term 'blue carbon. Photosynthesis releases oxygen, resulting in it being known sometimes as the "lungs of the sea. Seagrasses as a result support commercial fishing, contributing to why they are incredibly valuable economically, also providing food security, particularly to the local inhabitants. The meadows also contribute to tourism, recreational fishing and act as habitats for declining endangered animals.

After discussing the importance of seagrass, it is tragic to remember how it is a rapidly declining habitat - a habitat that is so under researched that even its full distribution is full of unknowns and challenges. There are several reasons behind the decline. Coastal disruption affects the seafloor and sediment then clouds the water. Climate change impacts seagrass too, with the warmer waters leading to consequences such as algal blooms which prevent the seagrasses' photosynthesis. Pollution affecting water quality further affects seagrass habitats. Knock on effects such as reduced fish and birds which rely on the fish add more complications. Seagrasses are sensitive to a lot of the human induced changes and so are rapidly vanishing.

Overall, seagrasses create beautiful gardens, with leaves flowing, floating, twirling around in the underwater currents, sheltering tiny fish and crustaceans. They are a sight to behold. A marvel. And still, seagrasses are fascinating, both as a collection of organisms which have evolved back into saltwater, and as unique and essential habitats. Conservation measures are important to help reduce the decline of these lush green meadows, and to support their roles as part of 'blue carbon'. Such strategies are part of current research, needed to help identify effective monitoring and management of the habitats. Even studying the evolutionary past and structures of seagrass could contribute to other parts of plant biology, highlighting how every plant deserves to be conserved, protected, and studied to reveal what hidden secrets it could teach us about the natural world. Altogether, seagrass has a deceptively simple-sounding name which should not be forgotten, or used as a buzzword, but understood and valued.

Edited by Arya Chougule



A nucleosome, consisting of DNA wrapped around histones

Epigenetics and different approaches to gene therapy

Is DNA the sole component of our genome?

Quan Tran (Y13)

Most people have heard of genes and DNA, or "the blueprint of all life," but few have heard of epigenetics which describes factors beyond the genetic code. Epigenetic factors can determine whether a gene is expressed or not. Importantly, epigenetic modifications ("tags") are affected by your external environment and your choices and can be passed down through inheritance.

Firstly, some key information: DNA is wrapped around proteins called histones, creating nucleosomes, each containing 147 base pairs of DNAs which are wrapped around 8 histones. These are made up of H3-H4 histone dimers surrounded by two H2A-H2B dimers. H1 histone associates with linker DNA located between nucleosomes. The way nucleosomes are spaced and arranged determine the overall structure of chromatin (the DNA – protein complex). [1] DNA can be made accessible by how it is arranged in the chromatin. For example, if the DNA is wrapped more tightly to the histones, the DNA is less accessible and is less likely to be expressed and vice versa. epigenetic tags.

Epigenetic tags

Epigenetic tags are chemical modifiers to either the DNA or histone which can change how well a gene is expressed. There are several different epigenetic tags but the main types are as follows:

DNA Methylation - This only happens specifically at CpG sites (where guanine and adenine bases are adjacent), methyl groups are added to the DNA which usually causes repression of gene transcription. This may be through direct suppression where the methyl group physically blocks transcription factors from binding to DNA, e.g. blocking Sp1 and Sp3 transcription factors (proteins) from binding to GC-boxes[1] or through indirect suppression where methylated DNA attracts specific proteins (like MeCP2) that bind to methyl CpG. These proteins then recruit histone deacetylases (HDACs) and HDACs remove acetyl groups from histones, causing chromatin condensation. This condensation further represses gene transcription.[1]

Histone modification - Main types include phosphorylation, ubiquitination, acetylation, and methylation. These modifications occur on histone tails that protrude from nucleosomes. Different combinations create the "Histone Code" that regulates chromatin structure and gene expression.[1] For example, histone acetylation promotes gene expression by changing the accessibility of chromatin and allowing DNA binding proteins to interact with exposed sites and activate gene expression.[1]

These epigenetic tags can be inherited when cells divide. Certain enzymes such as DNMT1 maintain DNA methylation patterns during cell division, allowing for stable transmission of gene expression patterns to daughter cells.[1] Think of epigenetic tags like sticky notes in a textbook - they don't change the actual text (DNA sequence) but they can mark certain sections as "do not read" or "read me," affecting how the information is used. The existence of epigenetics suggests that our lives are not predetermined by the genetic code from birth and that our actions and our choices are influential.

Applications of epigenetics

How could this be applied in medicine? There are many upcoming treatments in the field of epigenetics:

DNA Methyltransferase (DNMT) Inhibitors which is used to reverse abnormal DNA methylation patterns and primarily used to treat blood cancers.[2]

Histone Deacetylase (HDAC) Inhibitors which target histone modifications to regulate gene expression. It is approved to treat diverse types of lymphomas.[2]

Histone Methyltransferase Inhibitors are still experimental but can affect histone methylation patterns and are showing some promise in treating some cancers.[2]

Combination Therapies which combine epigenetic drugs with conventional treatments. However, this is still in its clinical trials phase.2

Being only about 70 years old, the field of epigenetics is still relatively new, and science takes time. The advancements we have already seen in this time show great promise for the future, where methods such as gene therapy may be explored. Like DNA, the future is wrapped around our hands!

Edited by Henry Li

How to take Steroids the right way

How to safely and correctly take advantage of Performance Enhancing Drugs (PEDs)?

By Boyan Xiang (Y13)

While in previous years, athletes and bodybuilders were all too cagey about their performance enhancing drug (PED) use, among fitness communities now people seem all too happy to disclose, even glorify, usage of PED's- misinformation spread with back-alley sources prevalent and people just can't seem to get it right.

Trenbolone Acetate, a commonly used and accessible PED.

Here's the facts:

Testosterone is a naturally occurring hormone in humans, derived from cholesterol, which is responsible for male sexual characteristics as well as a massive number of other mechanisms. Principally for athletes, they are interested in its regulation of muscle repair and hypertrophy (the increase in volume of muscle tissue, due to the enlargement of component cells), thus artificially supplementing their testosterone levels with chemicals that mimic, or are copies of, testosterone and similar hormones. In males, natural healthy testosterone levels can range from 300-1000 ng/dL in the blood, while in females, it is 15-70. Following artificial supplementation, it can increase to anything as high as 10000 ng/dL, depending on the drug.

In humans, testosterone is produced in the Leydig cells of the testis and small amounts in the ovaries and adrenal glands from cholesterol, and other precursors, under the action of many enzymes. Testosterone can then be converted to dihydrogen-testosterone (DHT), using the enzyme SRD5A1/2, which is a more potent version of testosterone, binding to androgen receptors more strongly and persisting for a longer time as well as being responsible for slightly different effects. Testosterone is released into the bloodstream, transported by sex hormone-binding globulin (SHBG) and albumin, while 2% travel freely. Testosterone interacts with androgen receptors in skeletal muscle, thus is focussed on by athletes, and DHT interacts with sex-linked tissue. G-protein coupled receptors for SHBG on muscle cells bind to and uptake the testosterone, where it is taken into the nucleus and used.

PED's mimic the structure of testosterone, becoming more potent and longer lasting. PED's are injected into muscular tissue, dissolved in an aromatic oil which then makes its way into the bloodstream and is carried by SHBG. PED injection is commonly intramuscular as the uptake of steroids is fast, quick and less invasive than injecting into the bloodstream. Any oral medication likely will get broken down by the stomach and will not administer correctly. Compounds such as trenbolone acetate (Tren) modify other similar hormones (nandrolone), mimicking its powerful androgenic effects, being very effective at increasing muscle mass. Human growth hormone (HGH) instead is artificial somatotropin (a peptide) which encourages the liver to secrete Insulin-like Growth Factor 1 (IGF-1) which thickens and elongates bones, grows muscle and decreases fat storage. Testosterone replacement therapy (TRT) is injecting a controlled amount of testosterone to supplement the body's supply of testosterone in cases where either more is needed or less is produced.

Muscle hypertrophy is what athletes of all kinds strive for. Bodybuilders want larger muscles- thus emphasising sarcoplasmic hypertrophy (where the sarcoplasmic fluid accompanying muscular cells increase in volume), while strength sport athletes want stronger and denser muscles, thus prioritising myofibrillar hypertrophy (where more myofibrils, which are the areas that contract, increase in size and density). The cause of muscle hypertrophy is not entirely clear, but a combination of many factors can cause varying results. Increasing the voluntary muscular contractions will increase the amount of $Ca2+$ released, which binds to calmodulin (a sensor protein), which can stimulate an increased rate of protein synthesis, producing more of the proteins of the sarcomere (functional unit of muscular contractions including proteins actin, myosin and titin) via use of mTOR. Calcium ions are also released into extracellular fluid which stimulates an immune response and releases cytokines increasing growth factors and causing temporary inflammation. Additionally, mechano-growth factors (peptides) such as myokines will replenish muscle stem cell pools and create more muscle stem cells. Another hypothesis is that metabolic accumulation (lactate and $H+$ ions) has a mechanism and that microtears in the muscle will cause it to be replenished stronger.

PED's have various mechanisms increasing muscle hypertrophy- aromatase (enzyme) converts certain PED's to female sex hormones oestradiol and estrone, which in muscle cells block glucocorticoids from binding to receptors on the cell. Glucocorticoids such as cortisol decrease amino acid uptake by muscle tissue and inhibit protein synthesis, which is detrimental to muscle hypertrophy. Testosterone primarily stimulates protein synthesis and inhibits protein degradation by itself while increasing the number of satellite cells in the muscle, which are responsible for muscle regeneration.

However, such PED's have a wide array of side effects. Testosterone may be the only thing one can control for building muscle, but building muscle is not the only thing testosterone controls. The body requires and uses a precise amount of testosterone and other hormones and thus balances or systems often fall out of place under the use of PEDs. Directly, too much testosterone is detected by the pituitary gland and hypothalamus, which will stop release of hormones responsible for the release of testosterone by these PEDs suppressing the hypothalamic-pituitary-adrenal axis. This results in hypogonadism (shrinking and loss of function in the testis) due to a decrease in natural testosterone
and gonadotropins production requirements, making the body's supply of testosterone, even in excess, to rely on this outer hyper supplementation of testosterone, changing androgen receptor density. If this persists, TRT will be required to increase the production of testosterone to baseline. You are not meant to have such high levels of testosterone.

Misuse of highly androgenising (affecting male sexual characteristics) steroids such as Tren will cause disturbances in endocrine and immune function, as well as changes in the sebaceous system and skin, often sweating with purple skin even in the absence of strength training. Much of these androgenic symptoms are due to the action of enzyme 5-alpha-reductase which converts the steroid to DHT which then acts in the nucleus of target organs and tissue, which is highly androgenising. Other steroids such as HGH, apart from its growth effects, will stimulate the production of insulin while at the same time decreasing its effectiveness, causing diabetes. Under high doses of HGH, the somatotropin can also cause acromegaly (enlarged hands, feet and facial features) due to it increasing bone size and muscle composition. This can result in arthritis, sleep apnoea and heart disease. Somatotropins also enlarge other organs, possibly causing the large bellies of some bodybuilders, with their hearts growing to a massive size, its effectiveness decreases, thus having to pump harder and more often, causing a higher blood pressure and a higher risk for heart disease. Trenbolone acetate has its own array of side effects, causing oily skin, acne, seborrhoea and body hair growth while causing scalp hair loss. Much of this is due to the action of DHT, as well as testosterone stimulating the production of sebum, which is an oily substance that clogs pores and causes Tren's associated skin problems.

Worryingly, new compounds are being rolled out at such speeds that studies have not been keeping up with them. Long term, less obvious and miscellaneous or anecdotal symptoms are both unexplained and unconfirmed, thus the average uninformed consumer, and even researchers, do not know the effects of the drugs they are taking. Symptoms such as 'Tren cough' are often reported- bodybuilders on high doses often falling into a terrible coughing fit and struggling to breathe even just moments after injecting. Even less understood is how such compounds interact with the specifics of each athlete- bodybuilders often taking other drugs or diuretics to flush out water for a competition, or a strength athlete's unique body composition can have unknown effects when taken in conjunction with PED's.

Strictly speaking- people are too hung up on testosterone levels. Being the largest factor one can change, people treat their body as a blank canvas to be filled with testosterone enhancing drugs, but a massive number of factors impact athletic performance, physique aesthetics, muscular strength and size and even life span. Genetics are the largest part- look at males versus females. An aspiring woman might artificially augment her testosterone levels to 10x that of a man's, but the strength increase certainly isn't 10x. In strength sports, even the highest dosing woman will be beaten by natural men due to the inevitabilities that genetics place upon athletic performance. So, is it all worth it?

If you must take steroids, this is how you should take them: first contact a doctor to monitor blood levels, blood pressure, with scans regularly in place while informing them of your decision. Take low doses, focussing on steroids with little androgenising effects and those that are studied more intensively. Source your steroids reliably, making sure it is sanitary and pure, reading up on each steroid individually. During injection, make sure the surrounding skin is sanitised, not injecting when the skin is swollen or painful and ensure you do not inject directly into blood vessels or damage any nerves. Only cycle PED use for a limited amount of time and make sure all medication will not interact dangerously. Make sure your body reacts well to steroids- if the side effects are particularly bad, and you do not respond to its hypertrophic effects, cycle off the steroids. Above all, consider seriously if the quality of life and lower life span is worth it.

Edited by Arya Chougule

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