THE WILSON'S INTRIGUE

STEM Issue 8: November 2022

Introduction

Throughout this year, the Intrigue Team has been working hard to put together a new issue of the Wilson's Intrigue, filled with amazing articles from writers in Years 11 and 12. Issue 8 is particularly special as it marks a new chapter in the development of the Wilson's Intrigue, through the introduction of a new team of editors.

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 time to help format and refine the articles to the highest standard possible. We would also like to show appreciations for staff, namely Mr Lissimore, who selflessly engages and helps the magazine reach new and unimaginable heights. We look forward to growing and progressing the magazine by integrating more from within the entire school community.

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 Mr Benn, Mr Carew-Robinson, Dr Cooper, Mr Jackson, Mr Lissimore and Miss Roberts for once again proofreading and verifying the accuracy of our articles and the magazine as a whole.

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

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

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Can CRISPR-Cas9 be used to cure Cystic Fibrosis?

By Tushar Vinod (Y13)

Everyone who studies biology at A-level should be familiar with the genetic recessive condition Cystic Fibrosis (CF). A mutation in the cystic fibrosis transmembrane conductance regulator (CFTR) gene cause the CFTR protein channel to be non-functional or absent [1]. The CFTR protein channel, loacated on the apical membrane of epithelial cells, is involved in controlling the movement of chloride ions in and out of the mucus in the lungs and the tissue fluid as well as other tissues and organs such as the pancreatic duct. This movement of ions controls the water content of mucus and in CF patients, where this is not regulated properly, can lead to thicker and stickier mucus blocking the airways and trapping bacteria which the cilia cannot waft out of the trachea. This can lead to respiratory problems such as respiratory failure and lung disease due to infections along with issues in the reproductive, digestive and endocrine systems which can be kept under control by various drugs. Drugs introduced in recent years such as Trikafta increases lung function in CF patients by an average of 14% [2] but for patients where the CFTR protein channel is absent, this is not a viable option, leaving genetic therapies to be the best hope of leading a healthy life.

CRISPR-Cas9 is a technology that enables scientists to edit a patient's genes to possibly replace a "faulty" sequence of bases in the DNA such as the mutation in the CFTR gene with the "correct" sequence of bases. It works by having two components: a guide RNA (gRNA), to match the target gene (in this case the CFTR gene), and CRISPR-associated protein 9 (Cas-9) which allows for a double-stranded DNA molecule to unwind and be cut which allows for modifications to the genome [3]. In this case, the gRNA molecule has to be specific to the CFTR gene. This technology has to be delivered to patients using a virus vector as virus's have a natural ability to insert their genetic material into cells. A patient is injected with a non-pathogenic virus (adeno-associated virus vector or AAV) containing the gRNA/Cas-9 ribonucleoprotein (RNP). Once the genome is corrected, the correct mRNA strand is transcribed from the modified gene and so the functional CFTR protein is synthesised during translation of the mRNA molecule in the ribosome. During DNA replication, due to the correct genome present in the nucleus, new cells will have the gene that codes for a functional protein channel.

In the past CRISPR-Cas9 has been used in patients as an

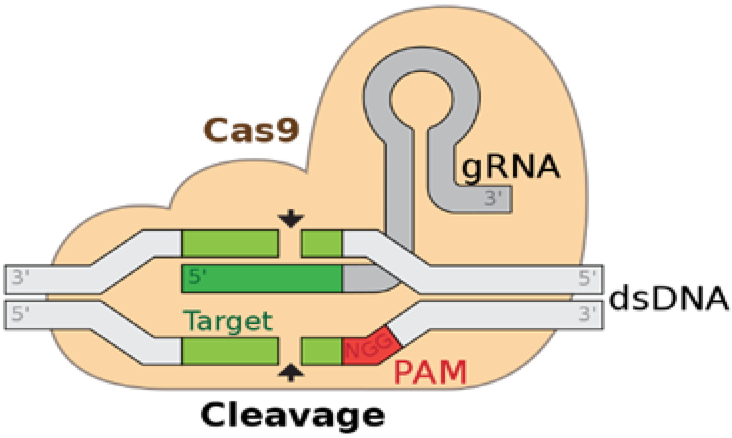


Figure 1: Use of CRISPR-Cas9 to edit the human

experimental cure for CF. For example, in February 1999 a group at Stanford University School of Medicine published the results from a clinical trial of ten patients with CF who were given gene therapy that used an AAV vector [4]. However, there were low improvement rates of the symptoms, though there were little adverse side effects to the AAV.

In recent years, there has been major breakthroughs in using CRISPR-Cas9 for CF. For example, in 2013, CRISPR-Cas9 gene editing technology was used to correct the CFTR locus in intestinal organoids (a biological construct made in the laboratory) which were cultured using stem cells from CF patients [5]. It was successfully done with the CFTR protein channel being corrected. In another study that was published in December 2019, upper airway tissues were collected from CF patients and cultured before the gene editing technology was used to correct the CFTR protein in the undifferentiated basal stem cells that differentiated into epithelial cells after being embedded into a scaffold [6]. It was noted that gRNA/ Cas-9 RNP and AAV can be used to efficiently gene edit human airway basal stem cells and that when the cells were embedded into the scaffold, they were able to differentiate.

Unfortunately, a limitation to this method is that it can be difficult to deliver the CRISPR-Cas9 technology to the airway stem cells that give rise to the rest of the cells in the airway and not to other, non-target cells. This explains the reason that the successful studies mentioned above have all been done in vitro (outside of the patient) due to the difficult method of delivery in patients. Furthermore, if there is a mistake in the gRNA then it may edit the wrong place in the genome which some scientists say could lead to cancerous mutations [7]. All the studies mentioned are somatic gene (body cell) editing but germ line (gametes) gene editing will be needed to ensure that the condition is not passed on to the patient’s children. This brings along with it many ethical issues of whether or not it is ethical to edit gametes. Another disadvantage is that although AAVs are an improvement from using adeno-virus vectors, which have a higher risk of a cytokine storm (part of a life-threatening immune response),[8] they are still too small to deliver additional gene sequences for additional protein production from the gene without which the healthy copy of the CFTR gene cannot be used [9].

So overall, even though technology has made gene editing possible, I would conclude that it is not yet possible to cure CF and that we will have to wait and see if technology gets advanced enough to target specific epithelial cells in the airways so that CRISPR-Cas9 technology can be used in vivo (inside the patient) and whether or not AAVs or other technological advancements enable more gene sequences to be delivered to cells, not to mention the ethical issues of gene editing that comes along with the development of the technology.

Edited by Agustya Iyer

‘Designer Babies’ and the Future of Reproduction

By Daniyaal Khizer (Y13)

Reproduction is the baseline for all existence on earth. The first bacterial cells reproduced by binary fission and we were formed from a single sperm cell and an ovum. This vital process allows us to evolve to adapt to our surroundings, with various adaptations occurring throughout our evolutionary biology. With the recent advancements in medicine however, we can be seen to be taking oppressive control of our biology : the human genome and deciding our own reproductive course. Is this ethical? Should we be prying into what is a 4.5-billion-year-old process?

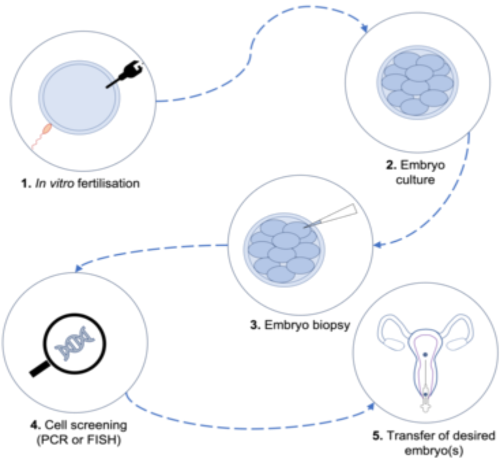


Figure 1: Process of pre-implantation genetic diagnosis. In vitro fertilisation involves either incubation of sperm and ovum together, or injection of sperm directly into the ovum. CC

Gene therapy is, by definition, the introduction of normal genes into cells in place of missing or defective ones to correct genetic disorders [1]. This procedure has the potential to be used when an incurable disease is found to be present within an adult person (e.g. Cystic Fibrosis).

After this identification of a disease, a new gene must be inserted in order to compensate for the specific gene not present or the defective gene. We cannot do this by inserting the gene directly so one of the ways they do this is via an adenovirus vector [2]. The process is as follows: a carrier called a vector is genetically engineered to deliver the gene. Certain viruses are often used as vectors because they can deliver the new gene by infecting the cell. The viruses are modified so they can't cause disease when used in people. Adenoviruses introduce their DNA into the nucleus of the cell, but the DNA is not integrated into a chromosome. This vector can be given intravenously directly into the target tissue or via injection. Another way in which they implement the vector is by taking a sample of the patient’s cells and exposing it to the vector in a laboratory. The cells are then reinserted into the patient. If everything goes according to design, the gene will produce a functioning protein in the host (in vivo) if everything goes according to design.

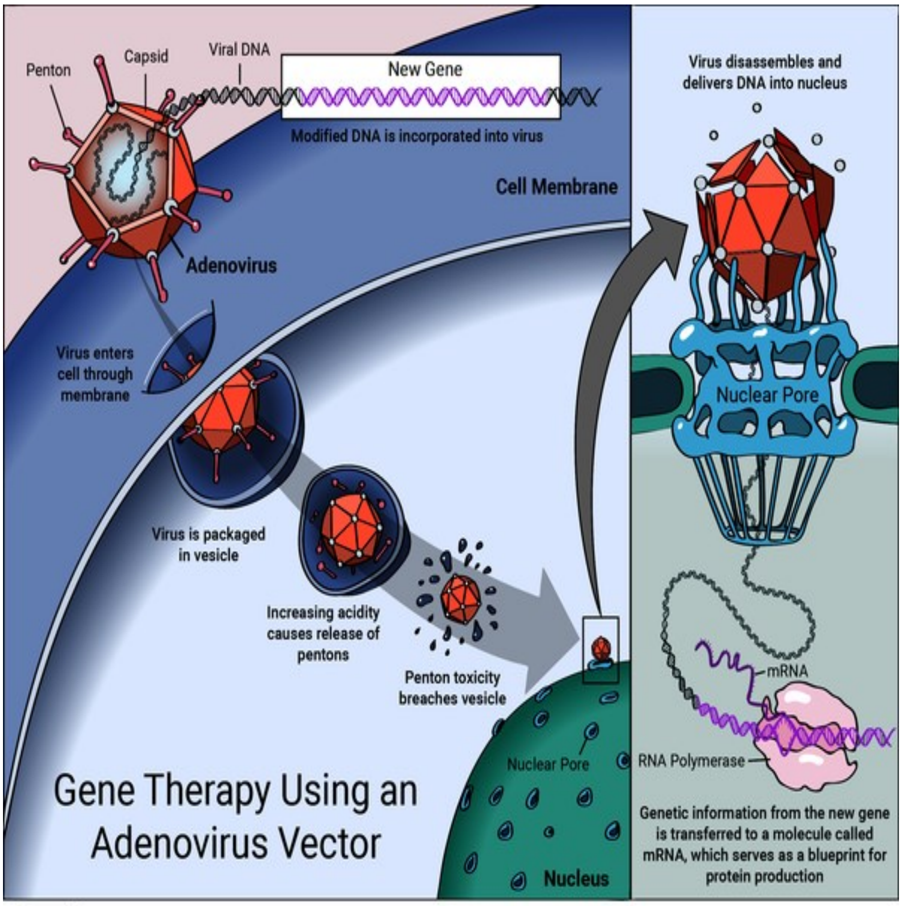
However, what is stopping us? Apart from current lack in technological precision, in using this process to change the genotype of babies in order to bring a ‘desired’ change in the phenotype of the baby before they are even born (e.g., height)? Currently, gene therapy is only being researched for diseases with no cures as the technique remains risky and is under study to make sure of its effectiveness and safety [3].

Furthermore, it cannot be passed down to offspring because current therapy targets the patient’s body cells and not gametes. Gene therapy could be targeted to egg and sperm cells (germ cells), however, which would allow the inserted gene to be passed to future generations. This approach is known as germline gene therapy.

Genetic engineering has been successfully implemented in plants and it seems that it could be very viable for humans in the near future with the rate of medical advancement.

The term for babies produced via genetic engineering is coined as 'Designer Babies' because the parent is essentially deciding what is the best characteristic for their baby to have. But this very concept brings up various ethical issues. It could be said we are interfering with the autonomy of the baby by choosing what is 'best' for them because people who would be affected by germline gene therapy would not yet be born, there would be no regard for their will as it is something that is performed far before their mental maturity. Parents will be deciding their ideal human and forcing it on the baby.

Another major issue is the fact that if germline gene therapy is used for the enhancement of human traits, will it create a divide within society ? We see a divide in medicine already, some countries monopolising resources.



NIH U.S. National Library of Medicine

Figure 2: A new gene is inserted directly into a cell. A carrier called a vector is genetically engineered to deliver the gene. An adenovirus introduces the DNA into the nucleus of the cell, but the DNA is not integrated into a chromosome. CC BY-SA 4.0, by 'U.S. National Library of Medicine.'

Could we see a world where the richest countries get an even bigger advantage than ever before through this mechanism? This is all in speculation, but such are the implications of theoretical procedures.

Furthermore , if this is the case, this divide will cause a significant problem for future society as gene therapy might also be an expensive process, isolating it from the layman and allowing only the rich to access this controversial procedure.

These are all issues that are problems for such a concept and there will surely be many more that I cannot conceive due to the hypothetical nature of this topic. But this is a very tangible reality in the future. Should we be interfering with this, knowing the problems it can bring to society and to our world? We can only speculate however one thing is for certain: the eventual development of gene therapy, on our current trajectory, will change the way we view reproduction forever.

Edited by Agustya Iyer

Allergies – What? Why? and Treatments

By Ayush Patel (Y13)

What are allergies?

An allergy is the response of the body's immune system to typically harmless substances in the environment. Allergies are thought to affect more than 1 in 4 people in the UK at some point during their lifetime [1].

Common examples include allergies to grass and tree pollen (hay fever), medicines (e.g., aspirin) and foods (including milk, nuts and eggs).

Allergies are often confused with sensitivities and intolerances.

An intolerance is where a substance causes unpleasant symptoms (e.g., diarrhoea), but it does not involve the immune system. For food intolerances (lactose intolerance is a common one), the intolerance can involve issues with the digestive system.

A sensitivity is where the normal effects of a substance are exaggerated. For example, if someone drinks a single mug of coffee (containing 100mg of caffeine), the caffeine in the coffee can cause palpitations [1].

Exposure to an allergen tends to cause an allergic reaction within a few minutes.

Symptoms include sneezing, wheezing, coughing, swelling, itchy rashes and vomiting.

In extreme cases, exposure to an allergen can cause anaphylaxis (a severe allergic reaction) which can lead to anaphylactic shock (a life-threatening state of inadequate blood flow to tissues as a result of anaphylaxis).

Symptoms of anaphylaxis include: wheezing, breathing difficulties, rashes, swelling, anxiety.

In people suffering from anaphylactic shock, they can experience more severe versions of anaphylaxis symptoms, as well as debilitating dizziness and loss of consciousness. This can lead to death, since airways may be constricted, for example, preventing breathing.

How do allergic reactions occur?

The most common type of allergic reaction is IgE (immunoglobulin E - a type of antibody) mediated, causing symptoms to appear rapidly. It is a type 1 hypersensitivity reaction (over-reaction of the immune system).

The less common type of allergic reactions is non-IgE mediated, which have much more delayed symptoms, and are less well understood as a process.

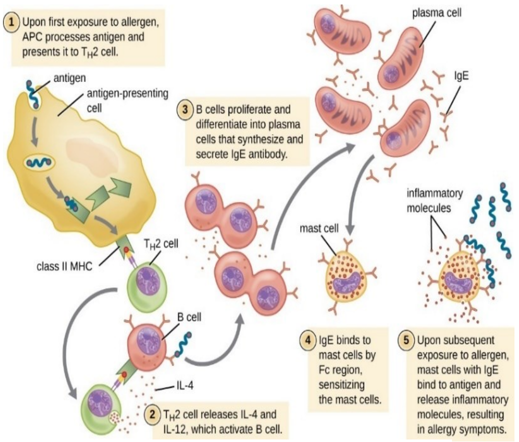


Figure 1 (above) – IgE mediated hypersensitivity

Process of IgE mediated allergic reactions:

Sensitisation – When the individual is first exposed to an allergen (antigens), the antigen is processed and presented by an Antigen-Presenting Cell (APC). The APC presents the antigen to a T_H2 cell, a type of T cell which produces a cytokine (small proteins important in cell signalling) called interleukin-4 (IL-4). IL-4, stimulates B cells to differentiate into plasma cells and begin production of large quantities of IgE. These antibodies bind to an IgE-specific receptor (FcεRI) on mast cells and basophils (both types of white blood cells), sensitising these cells to the specific allergen.

Re-exposure to the allergen – the allergen binds to IgE on mast cells and basophils, resulting in rapid degranulation (release of molecules from secretory vesicles known as granules) of these cells, releasing inflammatory compounds (including histamine – an organic nitrogenous compound which causes inflammation) into the surrounding tissue. This is what causes the symptoms of allergic reactions.

Why do allergies exist?

One theory states that allergies are "just an unfortunate side effect of defence against parasitic worms" [2].

Dr Ruslan Medzhitov, professor of Immunobiology at Yale University School of Medicine, believes that "We can't devise ways to prevent or treat food allergies until we fully understand the underlying biology," [3]. He compares it to the idea that "You can't be a good car mechanic if you don't know how a normal car works." [3].

Medzhitov states that the symptoms of an allergic reaction (e.g., sneezing, vomiting, runny nose) tend to have one thing in common – expulsion.

Medzhitov argues that allergies existed to protect our ancestors, by expelling toxic chemicals from their bodies.

He and his team believe that increased use of hygiene products, overuse of antibiotics, and the change in the composition of the gut microbiome are all factors which have contributed to making the immune system increasingly react to food proteins as it would to toxic substances, increasing the incidence of allergies [3].

Treatments

Someone with allergies may be given an antihistamine. These work by preventing histamine from binding to cell receptors, preventing some symptoms of allergic reactions.

Steroid medicines might also be given to someone with allergies. They help to reduce inflammation caused by an allergic reaction. They can be available in inhalers for asthma, for example. If someone is experiencing anaphylaxis, adrenaline (also known as epinephrine) is administered to them immediately, via an auto-injector, e.g., an EpiPen. These function by reversing the effects of inflammation, e.g., constriction of airways, allowing breathing to resume.

A form of longer-term treatment for allergies is Allergen immunotherapy, also known as allergy shots, which involves giving small doses of the allergen, as tablets, drops or injections, over the course of several years. It works by decreasing the body's sensitivity to allergens, reducing the symptoms of allergic reactions (not necessarily curing the allergy).

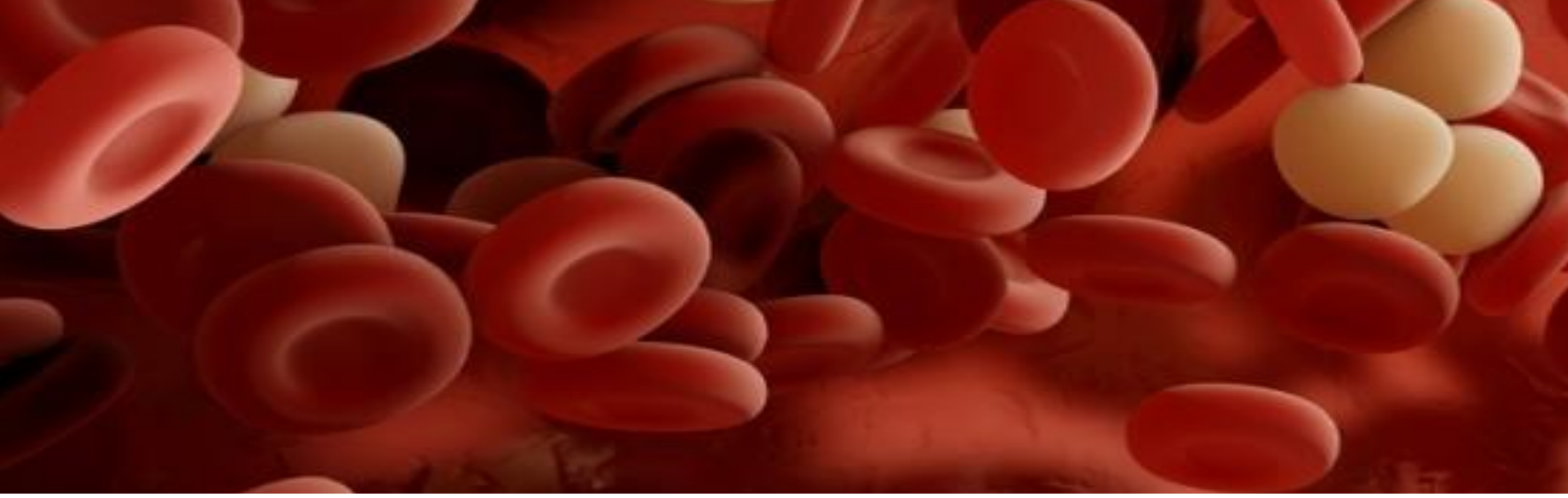
It is available as a treatment for allergic rhinitis (inflammation of the inside of the nose, caused by an allergen), for example, allergic rhinitis caused by hay fever.

Side effects: swelling at the injection site, sneezing, nasal congestion, and anaphylaxis (a rare occurrence).

Recently, NHS England announced that thousands of children and young people will receive pioneering allergen immunotherapy (Palforzia treatment) for peanut allergy, reducing the risk of anaphylaxis, and death after exposure to peanuts [4].

Whilst a cure for allergies is not currently in sight, allergen immunotherapy presents itself as a promising treatment, with the potential to allow allergy-sufferers to live much safer lives.

Edited by Daniyaal Khizer



Sickle Cell Anaemia

By Kirthigan Kirupakaran (Y13)

"It's almost like being born again": the words of a man who has suffered from sickle cell for over three decades, namely, Jimi Olaghere [1].

He is one of the first successful recipients of an innovative gene-editing treatment for this life-altering condition.

What is Sickle Cell Anaemia?

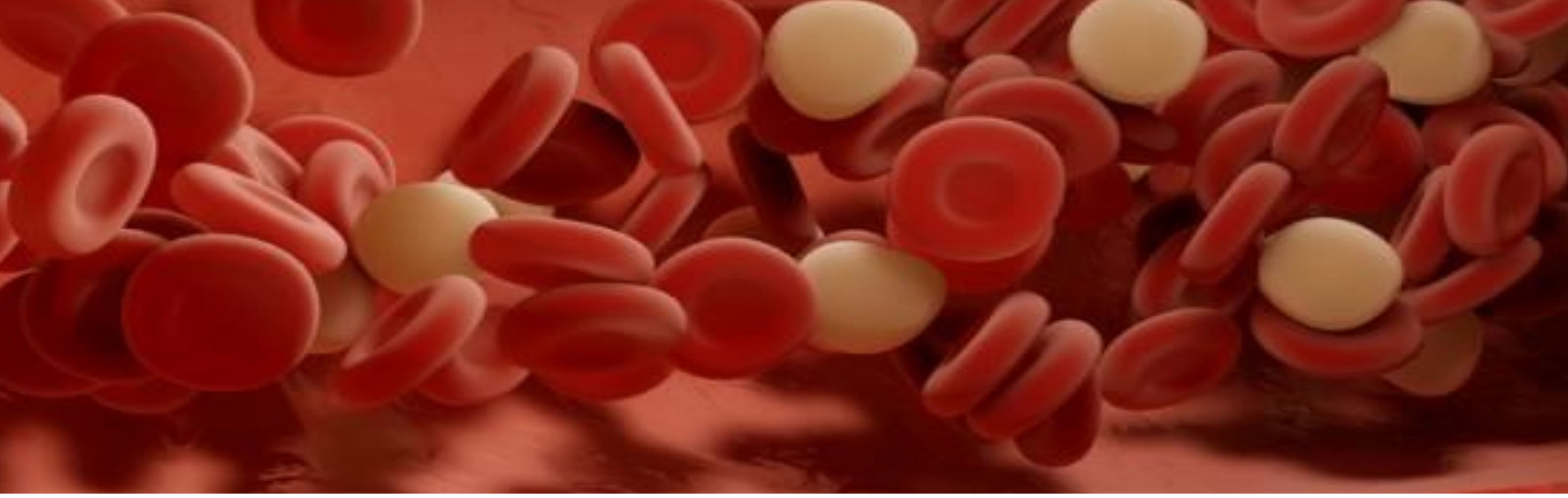
It is an inherited blood disorder that affects red blood cells and in particular the oxygen-carrying molecule haemoglobin. A typical red blood cell (RBC) is biconcave and disc-shaped in order to maximise its oxygen-carrying capabilities. However, the abnormal haemoglobin caused by this disease results in rigid, sickle-shaped RBCs that clump together restricting blood flow, as shown in Figure 1 [2] . This loss of elasticity and low oxygen content does not allow the RBCs to deform, as they attempt to pass through narrow capillaries which then leads to vessel occlusion (blocked blood flow through a blood vessel) and ischemia (lack of oxygen from poor blood flow). This condition is significantly reduces life expectancy by about 22 years [3] . Despite babies being born with the disease (due to genetic inheritance), the symptoms are predominantly experienced from the age of 5-6 months [4] .

What are the symptoms of Sickle Cell Anaemia?

Symptoms include excruciating pain episodes called sickle cell crises that are described as 'shards of glass flowing through your veins or a hammer to your joints' by Jimi, alongside the symptoms of anaemia. These commonly include tiredness and shortness of breath. In Jimi's case he developed avascular necrosis where the blood supply to his hip joint was cut off causing the bone tissue to die permanently. Unfortunately, his only option was to get a hip replacement which is a complex and risky surgery.

What are the types of Sickle Cell Crisis?

There are four types of sickle cell crisis: vaso-occlusive, aplastic, splenic sequestration and hyperhemolytic [5]. Vaso-occlusive is where the sickle red blood cells block blood flow to a tissue thus depriving it of oxygen which is what Jimi experienced. Hyperhemolytic crisis occurs due to infections, certain drugs, or toxins and results in an increase in the destruction of RBCs. This is life-threatening as the haemoglobin levels fall faster than the bone marrow can manufacture new RBCs that contain haemoglobin. In an aplastic crisis, infection with parvovirus B-19 causes a temporary suppression of the precursor cells (erythroblasts) in the marrow which are derived from stem cells that differentiate to form a new red blood cell [6] . Splenic sequestration crises are characterised by a bacterial infection that causes the spleen to enlarge rapidly, trapping RBCs and preventing them from re-entering the bloodstream after entering for filtering and potential destruction and it may require the full removal of the spleen via a splenectomy.



What Causes Sickle Cell Anaemia?

It is a recessive condition caused by the mutation of a single nucleotide where the GAG codon of the β-globin gene changes to GTG which results in glutamate (Glu) being substituted for valine at position six of the polypeptide. However, this is normally a benign mutation as it has no effect on the structure of the haemoglobin in normal oxygen concentrations yet under low conditions the haemoglobin with the mutation polymerizes forming fibrous precipitates. The presence of these long-chain polymers distorts the shape of RBCs and makes them fragile/susceptible to breaking within capillaries. The allele responsible for the condition is found on chromosome 11 (11p15.5). Offspring of two sickle cell carriers have a 25% chance of developing sickle cell and a 50% chance of being carriers of the condition.

What are the available treatments and management for Sickle Cell?

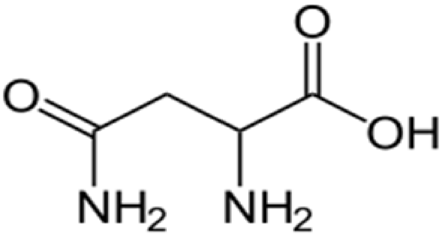
There are many options for minimising the effects of sickle cell but very few actually cure people of the condition. Some of the management strategies include the use of hydroxycarbamide (which makes RBCs bigger, rounder and more flexible) which reduces the frequency of crises and the need for a blood transfusion as well as crizanlizumab-tmca to reduce vaso-occlusive crisis. Crizanlizumab is a monoclonal antibody that inhibits P-selectin in endothelial cells as the translocation of P-selectin to the cell surface results in the adhesion of sickle RBCs to vessels thus developing vascular occlusion [7] [8]. Curative treatments are allogeneic haematopoietic stem cell transplantation and CRISPR-Cas9 gene editing[9] [10]. The stem cell transplantation involves using chemotherapy to destroy their own bone marrow stem cells and then implant donor haematopoietic stem cells from a suitable brother or sister (the only donors that will not lead to immune rejection) which then produce healthy RBCs without the abnormal haemoglobin S which cures them of sickle cell as their body will no longer produce the mutated blood cells. However, only 15% of patients have a suitable donor so the more viable option is Gene editing. The life-changing treatment Jimi received was CRISPR-CAS9 Gene editing by Dr Haydar Frangoul which again uses chemotherapy to destroy the bone marrow stem cells. These are then replaced by gene-edited cells with higher foetal haemoglobin which prevents RBCS from becoming elongated. He described waking up one week after the infusion as 'without any pain' which was abnormal for him after living most of his life with this almost inexorable pain. However, this treatment is not perfect as some of the adverse effects include pneumonia and abdominal pain yet this is not going to hinder this groundbreaking treatment from developing any further.

Edited by Agustya Iyer

Protein Folding and the Phenomenon of Protein Dynamics

By Padmesh Ayyappan (Y12)

Since the early nineteenth century, there has been a widespread interest on the true building blocks that make up proteins. French Chemist Louis-Nicolas Vauquelin and Pierre Jean Robiquet separated a compound from asparagus to discover the first ever discovered amino acid - asparagine (pictured to the right). Then came American chemist Linus Pauling who discovered the spiral structure of proteins in the mid twentieth century, consequently taking the name of 'the founder of molecular biology [1].'



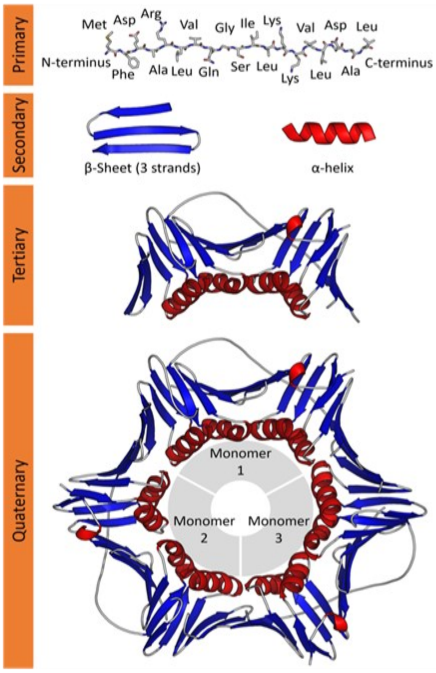
The amino acid Asparagine

An Introduction to Proteins

Proteins. What are they? Proteins are commonly described as polypeptides with specific amino acid sequences, which give them a unique, fixed structure. However, although this may seem baffling at first, this is not the case. Proteins are made up of folded polypeptide chains, consisting of 20 different amino acids linked to each other by covalent peptide bonds. The atoms in every amino acid repeat in a sequence in the peptide bonds, forming the polypeptide backbone. Each amino acid has different chemical properties due to different R groups of the amino acids, which are also known as side chains.

Protein Structures and corresponding conformations

Proteins exist with four different levels of structure: primary structure, secondary structure, tertiary structure and quaternary structure. In the primary structure, the 20 amino acids are simply joined together by the covalent peptide bonds to form the polypeptide chain. The atoms that make up the peptide bonds can move from their positions, which opens a key gateway to protein dynamics. Since the atoms can move, they can spatially rearrange, without breaking any bonds. Thus, the protein can shift between various conformations, although this does happen on time scales from 'nanoseconds to seconds and lengths of scales from one billionth of a nm [2].'



The different structures of a protein

In the secondary structure, many hydrogen- bonds lead to interactions between neighbouring amino acids to form two types of polypeptide chains – alpha helices and beta pleated sheets. In the tertiary structure, non-polar and polar amino acids are patterned to form a polypeptide chain with a specific, final three- dimensional arrangement. The amino acid's property of polarity or non-polarity depends on the monomer's R groups (side chains). The non-polar side chains of amino acids come together when dissolved in water. When diving into the reasoning behind this, we must look at the equilibrium positions of the non-polar amino acids in the aqueous environments. They are interconnected by weak Van der Waals forces [3]. This means that the majority of non-polar amino acids is inside the interior of the protein. Thus, they don't react with hydrogen bonds of surrounding water molecules. The polar amino acids are located on the exterior of the protein. It is clearly evident here that the final conformation in tertiary structure proteins is not only as a result of the nature of equilibrium in the surrounding environment, caused by thermodynamics and kinetics, but also due to the chemical properties of each amino acid in the polypeptide; again, another instance where the essence of protein dynamics fundamentally determines the final structure and, hence, function of a protein.

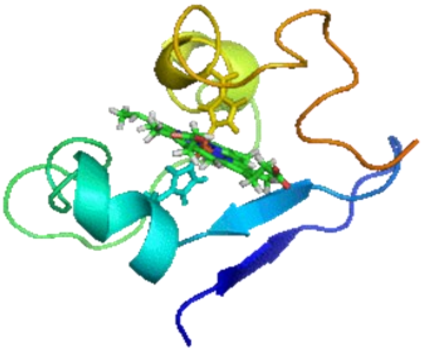
In quaternary structures, two or more polypeptide chains interact to form a more complex protein. The protein consists of several domains, which are specific structures in the protein that fold and function independently from each other. Tertiary structure proteins can also contain protein domains.

The transitions between conformations, in the end, depends upon the protein's structure, whether it be primary, secondary, tertiary, or quaternary.

The Significance of Protein Dynamics

By studying the reasoning behind protein dynamics, scientists have been able to help explain the way proteins behave better. According to the theory, dynamic proteins interact with atoms in their environments, such as by taking in more protons than stable proteins, which shows how the environment plays a key part in protein dynamics. Not only this, but the binding site of dynamic proteins, for example in enzymes, is much more flexible than stable proteins and when a substrate molecule attempts to bind to the region, it may be difficult in less stable proteins due to the absence of a fixed binding site structure. However, when a special molecule (called an effector) comes in close region with the binding site, it causes the site to become more fixed in position, allowing the protein to bind to the dynamic protein's binding site much better. This is called allosteric regulation and it has allowed many scientists to discover more about biochemical processes, with this particular topic being a particularly exciting and phenomenal discovery, thanks to protein dynamics.

some of the most useful and fascinating applications of protein dynamics is that it helps scientists to understand more about, and interfere with the control of, immune responsiveness. For example, during the immune response, B lymphocytes release antibodies that are complementary and bind to specific proteins on certain molecules, such as pathogens, called antigens. By analysing how these antigens bind to antibodies and interact between the proteins that make up the antibodies, on a biomolecular level, we have now been able to 'understand and manipulate the immune system in normal and diseased states [4].' This has also enabled scientists to more accurately develop vaccines to prevent or limit the impact of outbreaks of diseases. For example, by studying the dynamics of the PfRH5 protein within its quaternary structure of an antigen lead to the development of a vaccine against malaria caused by Plasmodium falciparum.



A Dynamic Cytochrome

Indeed, this is also being applied to the SARS-CoV-2 vaccine where technology, such as AlphaFold2, and models derived from AlphaFold2 are being used to analyse or, even, predict the structural information about the CASP 14 protein so that we can better design a vaccine for it.

Edited by Daniyaal Khizer

What is Tissue Engineering?

By Thomas Rinson (Y13)

Tissue engineering can be defined as the synthesis of 3D tissues outside of the body. The tissues can be Tuned in size, shape and function to fulfil a required structure and to do this, cells and biomolecules are combined with scaffolds under optimal environmental conditions in the laboratory. The tissue grows on these scaffolds and mimics the biological process or structure that is being replaced.

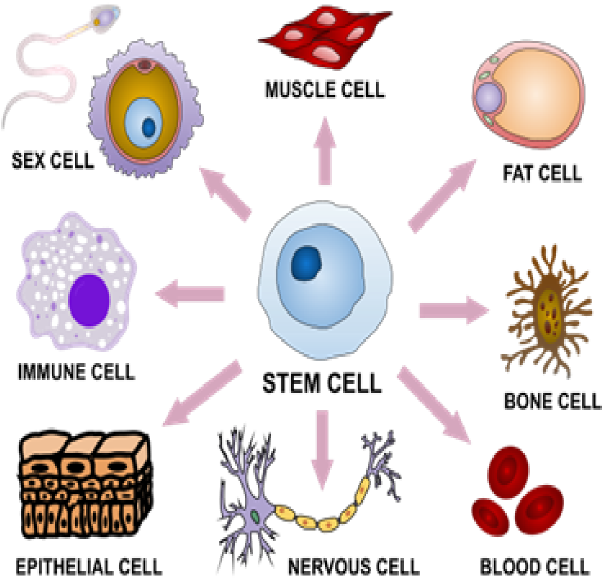
This highly complicated process requires the three pillars of tissue engineering [1]:

- Cells
- Scaffolds
- Bioinformation

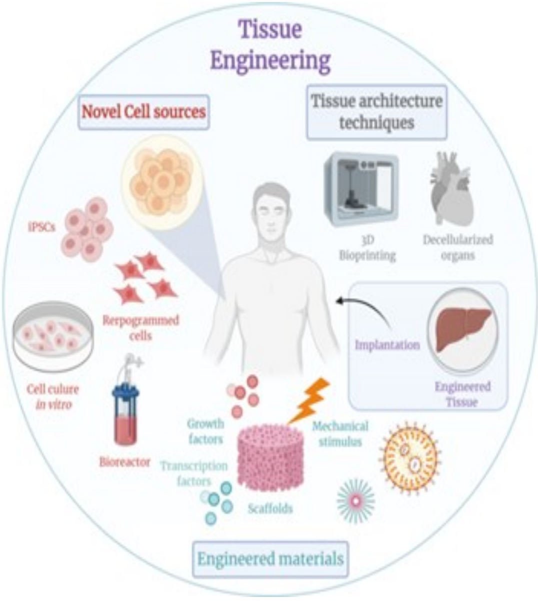
The first pillar of tissue engineering is stem cells, which are used due to their ability to differentiate into multiple specialised cells. However, there are two types of stem cells that can be used: pluripotent and multipotent.

Pluripotent stem cells have the ability to differentiate into all cell types (except extraembryonic tissue i.e. placental tissue) and include embryonic stem cells (ESCs) and induced pluripotent stem cells (iPSCs), which are stem cells that are induced/ reversed engineered from differentiated cells..

However, the use of ESCs in tissue engineering is controversial and more limited due to the destruction of the embryo that they are obtained from. Multipotent stem cells, on the other hand, can differentiate into the various cell types in a family of related cells and these are obtained from adults. For example, mesenchymal stem cells (MSCs) which are located in the bone marrow can differentiate into bone (osteoblasts), muscle (myoblasts), fat (adipocytes) and cartilage (chondrocytes) cells [2].



The Potential of Stem Cells



Tissue Engineering Fundamentals

Scaffolds provide the structural support and shape to the cells as they develop into the specified tissue/organ; these are very complex structures since they need to replicate the macro-architecture and bio-functional microenvironment of the organ they are replacing. They should allow cell attachment and model cell behaviours in order to help support the cells' growth and differentiation. Furthermore, they enable the diffusion of vital cell nutrients: otherwise, the cells they house will not survive and be biocompatible (non-toxic and produce a low immune response in the body). The end goal for producing a scaffold is for it to biodegrade in the body and be replaced by regenerative tissue from the body. Different scaffold materials have different properties and are used for different parts of the body. There are three main biomaterial groups: natural polymers, synthetic polymers and ceramics [3]. Ceramic scaffolds, like HA and TCP, are more porous (useful for the diffusion of nutrients and oxygen) and replicate bone structure in a way that is more similar to its natural state. Similarly, synthetic polymers, like PGA and PLLA, can be formed into highly specific shapes and are extremely adaptable but have poor biocompatibility due to potential toxicity when broken down. Natural polymers such as collagen and fibrin have a high biocompatibility and can easily be modified; however, they generally have poor mechanical properties [4]. One promising new method of creating a highly specific and bio-functional scaffold is decellularisation and recellularization [5]. This works by removing all the cellular components of the tissue being engineered, whilst keep the whole geometrical structure of the native extracellular matrix (or ECM) of the organ in place. The new cells are then added and recellularise the original ECM and a fully functional organ should be formed. In theory, this may seem ideal but in reality, the transplanted cells do not seem to integrate into the native ECM and so recellularisation is not yet completely viable, as if there is a loss of some ECM proteins, it could lead to less adhesion of cells onto the ECM.

Bioinformation are signals that control differentiation of the cell by influencing the environmental conditions,
growth factors, cytokines and ECM. These components connect cells and scaffolds together through signalling pathways and cell-cell interactions and make the whole system structurally and functionally sound.

Benefits of Tissue Engineering

Tissue engineering has a huge potential but currently it is only being used for a variety of small scale procedures such as skin grafts, repairing cartilage and providing small arteries and bladders for patients. Lab grown tissues have been useful for testing and developing new drugs as they reduce the number of live test subjects required. These also allow researchers to study cancer growth and the effects of drugs on cancer cells [6]. In the future as technology develops further, tissue engineering could be used to develop whole organs, which can be used for all organ transplants. The dilemma of organ rejection would be removed as these new organs would be grown with a patient's own cells, thus also bypassing the need for organ donation altogether. In addition, the overall quality of organs used in transplants would improve as they wouldn't have the natural wear and tear of a donor's organ. The organ transplant waiting list would also be much shorter as patients wouldn't have to wait as long for a suitable organ, for example, the average time a person spends on the waiting list for a kidney transplant is two and a half to three years, this could be reduced to less than a year as organ synthesis develops.

Current Limitations of Tissue Engineering

At present, there is a lack of fully bio functional scaffold materials which slows down the progression of the technique. Tissue engineering can also be a very costly process and a lot of funding is required. Furthermore, building scaffolds specific to patients is a major challenge due to the uniqueness of each patient and the difficulty in creating complex geometrical micro-shapes. Another challenge is getting a sustainable stem cell source as obtaining iPSCs suitable for use in tissue engineering is estimated to cost around £37,000 [7] and there is a large ethical issue in using ESCs.

To conclude, while tissue engineering is hugely important and is going to transform organ transplantation, there is still a long way to go. Until fully bio functional scaffolds can be made and sustainable cell sources can be found, tissue engineering will still remain in its infancy.

Edited By Daniyaal Khizer

Treating Cancer in Patients with Immunodeficiency

By Jaenushan Naguleswaran (Y13)

Charles Mayo said ‘while there are several chronic diseases more destructive to life than cancer, none is more feared.’ According to WHO, cancer is the second leading cause of death globally, with 10 million deaths recorded in 2020 alone.

Patients with primary immunodeficiencies (people born without a normally functioning immune system) are at much greater risk of developing cancers because the cancer cells, that occur as a result of genetic mutations in normal cells, are much more likely to spread and develop into cancer because the cells divide uncontrollably and are not recognised, and killed, by their non-functional immune cells. Primary immunodeficiencies (PIDDs) are usually a result of a genetic mutation inherited from their parents and this means the protein molecules that are responsible for aiding most of the jobs that an immune cell carries out (such as antibodies that are responsible for detecting the antigens found on the cell surface membrane of cancer cells) are rendered useless. These mutated genes that prevent cells from undertaking their primary functions are usually active and expressed in immune cells that have differentiated from hematopoietic stem cells. Therefore a person with PIDD will consider different treatments so that their body can be equipped with healthy immune cells to effectively fight against cancer and other complications that they may experience.

Stem Cell Transplants

Stem cell transplants are used to treat blood cancers like leukemia and lymphomas and they work by initially collecting healthy haematopoietic stem cells from a donor, which can be done in many different ways such as:

- Driving a needle through the cortex of the pelvic bone and bone marrow (which contains hematopoietic stem cells) is drawn from the bone marrow cavity
- Collecting hematopoietic stem cells from the circulating blood of the donor using an apheresis machine
- Drawing hematopoietic stem cells from the umbilical cord blood (which is the blood that remains in the placenta or the umbilical cord a few weeks after the birth of a baby)

In order to prepare for the bone marrow transplant, the patient has to isolate for at least six weeks in the hospital and they are given high doses of chemotherapy or radiotherapy in order to kill off their stem cells that may be contaminated with leukemia or lymphoma cells. By doing this, space can be made for the donor’s stem cells to occupy. The stem cell infusion can begin now, via an IV drip, and the healthy hematopoietic stem cells that are infused can differentiate into new healthy immune cells that can recognise and kill cancer cells, thus reducing cancer risk. However, bone marrow transplants are not always considered to be the most viable option because:

- There is a moderately high risk of dying from the procedure because the high doses of chemotherapy (or radiotherapy) will kill all the cells that are responsible for producing immune and blood cells, and the donor stem cells from the infusion will take about two weeks to find their niche in the bone marrow space, so if the patient becomes exposed to an infection in the two weeks after the infusion, they will die as they do not have any blood or immune cells that can fight off the infection.
- There are not many non-Caucasian stem cell donors registered, so this means that it is

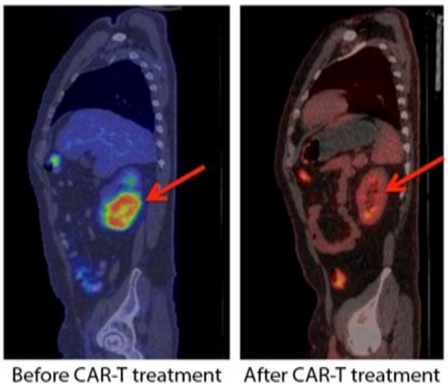
extremely difficult and rare for non-Caucasian patients to find a donor with stem cells that will not lead to rejection and this poses an ethical issue (because it would be unethical if stem cell transplants are only an option for Caucasian patients).

Therefore, a patient may need to consider other options so that they can reduce the risk of developing cancer.

Gene Therapy

Gene therapy is used to correct and replace missing or disadvantageously mutated genes, and it is used to alter non-functioning immune cells so that they can effectively fight against cancer cells.

One way that they can be used to reduce the risk of cancer for patients with primary immunodeficiencies is by extracting stem cells and introducing a working copy of the healthy gene into the stem cells. This is done by using specially designed viruses (which are unable to replicate and cause infections) to deliver a healthy gene into the stem cell. The genetically modified stem cell is infused back into the patient. Therefore, this is a much more viable alternative to doing a stem cell transplant due to the reduced risk of dying from an infection when the cells have been transplanted, as the patient's own cells are being corrected in the laboratory and the haematopoietic stem cells do not have to be killed prior to the transplant. However, gene therapy is an extremely expensive treatment option and is not accessible for patients with PIDDs who live in countries without free or universal healthcare (like the USA).



This diagram shows the PET scan of a patient before and after CAR-T treatment. There was a massive reduction in the number of metabolically active cancer cells in the kidney after 2 months of CAR-T cells being administered.

Another way that gene therapy can be used to reduce the risk of patients with PIDDs dying from cancer is by extracting T cells from the patient and modifying them with the introduction of a gene that encodes for a protein receptor (found on the plasma membrane of the T cell) and they will be able to recognise and kill cancer cells. These modified CAR-T cells are infused back into the patient and they are extremely effective at killing cancer cells

Despite being extremely effective at killing cancer cells, CAR-T cells may not always be considered the most viable option because:

They are extremely expensive, it is estimated that a single dose of CAR-T cells is worth £30000. This means that this option is only easily accessible to patients who live in more developed countries with a universal healthcare system (like the UK) which poses an ethical issue as poorer people do not have access to this very effective cancer treatment method due to their financial status.

The CAR T cells target the CD protein that is also found on B-lymphocytes which therefore means that healthy B-lymphocytes that the body produces are also killed. This means that the body may be unable to fight against infections increasing the risk of the patient dying from an infection that they may be exposed to

Even though stem cell transplants and gene therapy are feasible options for patients with primary immunodeficiencies who are at risk of dying from cancer, they still pose other challenges so they are not considered to be the most 'ideal' option. However, due to increasing levels of research in regenerative medicine, there is the potential of generating new tissues and organs from individual patients (instead of transplants from donors), which means that scientists are not far from finding a solution to treat cancer with personalised medicine.

Edited by Daniyaal Khizer

Omicron: A new name or a new threat?

By Mert Gul (Y13)

Omicron, the newest variant of the Covid virus, was first announced by South Africa on 24 November 2021 with the first sign of its presence dating back to 9 November. Here in the UK, the first few cases were reported on 27 November, where both cases had links based off their travel to and from South Africa. It's easy to read the facts on a news article online or listen to the news, but what does this all mean, will it bring anything new that the other variants did not? According to early reports of cases in other countries, Omicron is the most mutated form of coronavirus that has been detected so far, and its origins are unknown as of now, but it is speculated to have evolved due to an immunocompromised patient who did not overcome the virus.

Compared to the original SARS-Cov-2 variant that put the UK into lockdown throughout 2020, Omicron has made headlines in many countries for being more transmissible, meaning that its ability to be passed on from person to person is greater than its counterparts. Its transmissibility when compared to the Delta variant, which was first detected in India in late 2020, is found to be greater by around 2.7 to 3.7 times due to various mutations but it is assumed that Delta is a variant with much more severe symptoms compared to the previous variants as well as Omicron.

A report completed by the Imperial College London COVID-19 response team, had made estimates of the Omicron variant's risk of reinfection was around 5.4 times greater than the risk posed by the Delta variant. Another recent study, which was led by researchers from the University of Hong Kong, had determined that the causes for increased transmission and risk of reinfection were the fact that the Omicron variant multiplies 70 times faster in the human bronchi compared to the Delta Variant. The virus may also be more concentrated in the throat as a result of the optimal conditions for multiplication. As a result of this, when a person infected with Omicron may unknowingly come in to contact with colleagues and other civilians throughout their day-to-day life, the transmission of the virus from them to those people may be faster.

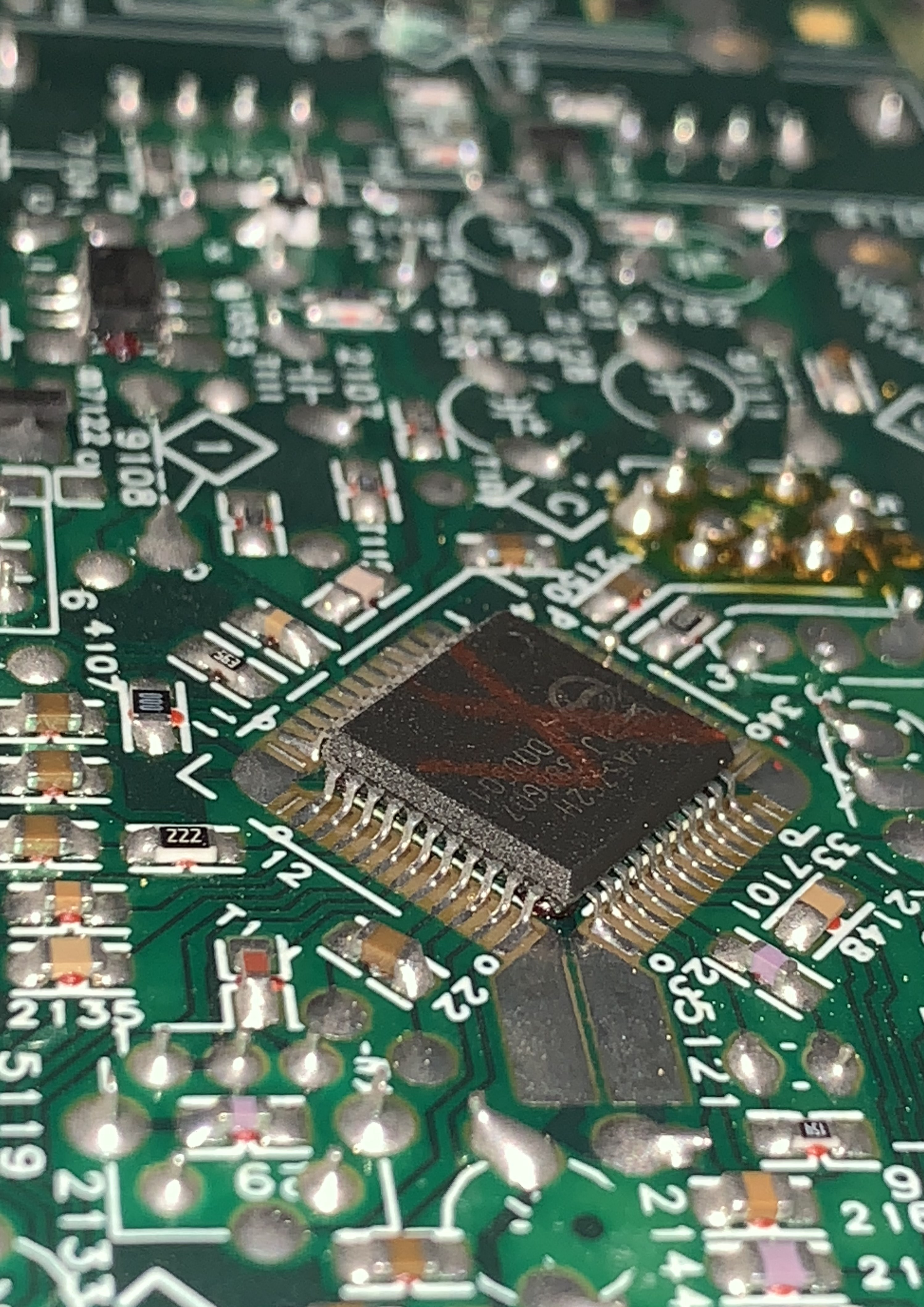
Whether or not the Omicron variant is more deadly than other variants may not be the main cause for concern, if the transmission potential is great, then the number of deaths will certainly increase. In terms of symptoms for the Omicron variant, they are similar to that of Delta, but with some being rarer in comparison. The most common symptoms of Omicron are a runny nose, headaches, fatigue, sneezing and a sore throat. While a cough can be a potential symptom of the Omicron Variant, it was more common with Delta and its predecessors.

Since the outbreak of the Omicron variant, the UK government has reduced the required waiting time between the second dose and the booster dose of the Covid-19 vaccine from three to six months, as well as recommending the booster dose to the younger population rather than just adults over 40 years. This was an important change to make, as the vaccines for COVID-19 are highly effective for preventing severe symptoms when infected, as well as prevention of infection. Whether the existing Covid-19 vaccines are extremely effective against Omicron or not is important for everyone, as any small guarantee of safety from infection can potentially reduce the formation of new variants as a result of mutations from the virus multiplying whilst an individual is infected.

Along with the changes made by the government to the vaccine process, new regulations were also made to travel and entry to higher capacity venues. Travel wise, the government placed eleven African countries on a "red list", which enforced rules that make people who travelled between the UK and these countries undertake quarantine for an extended length of time in government approved facilities in order to reduce risk of spreading the virus. However, in recent times, these eleven countries have been removed from the red list as a result of Omicron cases in the UK increasing. This was done to prevent the infected from leaving or entering the UK, as the variant has already been established. The regulations that the government put in place for entry into venues of high capacity are simple, having two doses of the COVID-19 vaccine or having a negative lateral flow test within the last 48 hours, but necessary to mitigate infection. Masks are no longer required in most public spaces, but they are still recommended in some spaces such as hospitals, GPs as well as at retailers which have requested that masks are to be worn in stores.

Whether or not we should be worried about Omicron on an individual level depends on how serious we take the pandemic and follow the restrictions put in place by the government. And while Omicron is not the most dangerous variant of COVID-19 we have faced, there is always the possibility of mutations of the virus taking place, so depending on how the Omicron variant is approached by the government, these risks may be diminished.

Edited By Daniyaal Khizer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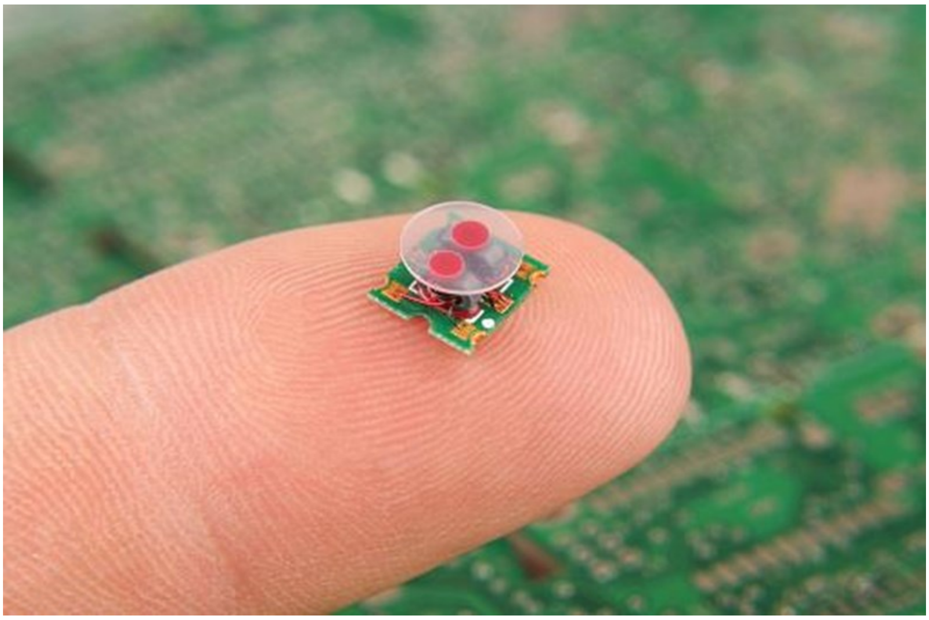


Developments in Modern MEMS Technology

Microtechnology: Humanity's Glorious Legacy?

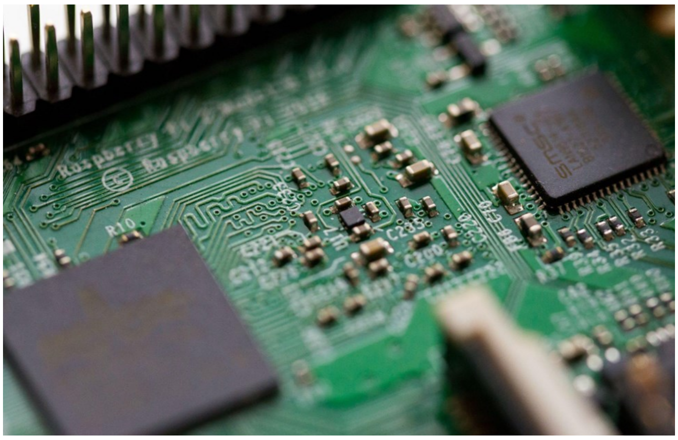
By Joseph Nestor (Y13)

The year is 12022, and the news can be heard throughout the Solar System; the Milky Way has been completely cleansed of all life. Man-made Microbot swarms have scoured every dark corner of the galaxy, sourcing unprecedented wealth and resources to the growing reaches of humans allowing for unprecedented expansion and trade. Humans prosper and live in wealth, whilst extreme advances in their technologies allow effortless gain. Whilst this scenario sounds like something out of a 60s Sci-Fi novel (or a mediocre Disney Film), the concepts for technology that would allow this to happen lie within our grasp - in the fascinating and dangerous world of Microtechnology.

Since the first commercially available computer processors were mass manufactured by Intel in 1971, micro-robotics has presented itself as the next step in the field of autonomy [1]. From being developed by worldwide secret services as a way to revolutionise surveillance during the late Cold War, to aspirations to use these technologies for civilian rescue and evacuation, Microtechnology has often been an exciting technology that had the potential to solve many of humanity's issues. However, much like other exciting technologies during the Atomic Craze, Nanotechnology did not experience a major breakthrough until wireless networking was revolutionised with continued developments to Wi-Fi, allowing unprecedented cooperation and communication easily between machines. Suddenly, the potential of Microtechnology exploded onto the scene, with them being discussed in the field of medicine, where small clusters of cooperating microbots could be used to make precise incisions in patients, or in construction, where larger swarms were theorised to be able mock-up scaffolding for building work to carry out [2]. Harvard University trialled the tech, when after mass manufacturing 1024 microbots known as "K-Bots" displayed the swarm's ability to form basic patterns and move as a herd [3]. But how precisely could microbots work, and - perhaps more excitingly - how could they be used to explore, or even cleanse the Galaxy?

Microtechnology is defined as any man made structure that is sized under 1mm. Micro-robotics, an exciting and developing area of science, is a field of research into autonomous robotics on such an extremely small scale. Microbots are facilitated via Miniature Mechanical Systems on Silicone (MEMS) that allow sensors, processors and other components to be produced precisely on a miniature level [4]. Microbots vary wildly in design depending on their usage, from the Harvard envisioned model, where vibration motors in each cardinal direction are controlled at various different levels to allow 360 degree movement of the device. Whilst simple and cheap, these microbots only work on smooth flat surfaces, allowing limited range of movement. Another common model proposed is in medicine where a thread-like Microbot, less than a millimetre in diameter is being combined with a flagella-like flexible tail (mimicking bacteria) to deliver drugs from within blood vessels [5] . Microbots have even shown some destructive capability, however small, through showing an ability to target and dissolve cancer cells from within tumours, delivering accurate, high powered drugs to treat patients. Moving away from existing technology to theory, one could argue that the infinite possibilities of these nanobot swarms has not even begun to be explored yet. The scarily powerful nature of nanomachines, lies in two theories for the future - The advent of self-replicating machines facilitated via Artificial Intelligence, and more accurate guiding technology such as laser guidance systems, allowing further cohesion and processing power from within microbot swarms.

Many futurists and researchers have aspirations of a microbot swarm that could in theory, cleanse the galaxy of life and resources; an Artificial Intelligence driven hive mind that enabled the swarm to carry out three tasks. Move through space using small amounts of propellant built into each robot, spreading to external planets. Use massive swarms of microbots to deconstruct everything on said planet down to basic materials that could be used to build more machines: ; silicone, precious metals, polymers . Finally, using Artificial Intelligence's extreme adaptive capabilities to replicate as many machines as possible. Such a machine - dubbed the "Xenobot '' by many futurists, would present itself as the ultimate large scale doomsday device - a swarm that would constantly grow in number, stripping entire planets of resources simply to continue their destructive task [6] . Such a system, quite poetically, would ensure humans' impact on the Universe would far outlive any influence we could ever hope to have, and provided the microbots were designed to be robust enough, it would ensure the Human species' legacy of releasing this ultimate, final destruction would last for billions of years after us. But would this system work? . Whilst such a system seems to be within our grasp given our current technology, and without delving into the ethics of releasing such a destructive weapon, there is one critical flaw with this thought experiment - Travel speed. Communications technology has progressed with processes such as 5G allowing faster transfer information, to a point where a swarm of specialised microbots could work together in sync with each other, space is massive, to an unimaginable scale, and we currently lack the means for such small devices to travel at the necessary velocities to even escape Earth. So for now, at least, we should put our destructive tendencies to the side, focussing instead on the extraordinary uses that microbots can have on our lives today.



So we remain on Earth, biding our time, the realisation dawning that perhaps humans can only have a finite impact on the Environment. The Doomsday weapon remains safely confined to the deepest reaches of Human imagination whilst development of cheaper microbots allow advances in the field of medicine, construction and autonomy. We prosper, life expectancy increasing, the speed and efficiency in which we construct our homes and develop increasing at an exponential rate. We chose not to harm others, but merely to better ourselves. Unsatisfying, but perhaps for the best.

Edited by Matteo Cascini

Modular Design: The Key to a Sustainable Future

By Shanjai Mathialagan (Y13)

Sustainable engineering is the process of designing systems and structures in a way in which resources are used and maintained so that they do not compromise the ability of future generations to meet their own needs. In the design of buildings and structures, sustainability has many implications, one of which is the major role it has played in the rise of modular architecture in recent years.

Modular design involves the assembly of various prefabricated components to produce a specific, working structure that can be adapted and altered to meet the constantly changing needs of today's architecture [1]. The individual modules are made independently in a factory and then transported to the location where the final structure is to be constructed. Modular architecture has a plethora of benefits and has great impact over significant global projects and events, such as the 2022 FIFA World Cup in Qatar. A key benefit of modular design is its inherent capability for maximum efficiency. It rapidly speeds up the construction process on the site of the project, as all the components of the building have been premanufactured in a factory. This means all that is required on site is the assembly of these modules. Another crucial benefit is the reparability and replicability of the components themselves. If a specific part of the structure becomes damaged or worn, it can easily be replaced with another identical module. Not only is this a quick process, but it also has little impact and disruption on the rest of the structure, which would otherwise occur in a standard building.

A modern example of sustainable engineering is Stadium 974, a football stadium located in Doha, constructed with the purpose of hosting some of the games of the 2022 World Cup in Qatar. Assembled from repurposed shipping containers and modular steel components, the mesmerising stadium boasts the rather prestigious recognition for being the FIFA World Cups' first ever temporary, demountable stadium - it epitomises the changing environmental concerns of the world and marks a turning point in the approach of football clubs and nations in their goal to preserve the environment. It hopes to set a new benchmark in sustainable engineering, driving other hosts for major sporting competitions to be more environmentally conscious in their planning. Stadium 974 gives global stadium developers a grand example to follow [2].

The name of the stadium, which may seem at first to be rather bizarre, originates not only from the international dialling code for Qatar (+974) but also the total number of containers that were used in the construction of the stadium [2]. As the stadium has a modular design, composed of recycled and repurposed shipping containers, the stadium can easily be disassembled and reused for other purposes. The temporary nature of the stadium and its modular design meant that fewer construction materials were required than usual, which helped to keep construction costs down. After the 2022 FIFA World Cup, the stadium will be dismantled, and the recycled containers will be reassembled in a new location or perhaps reused for various smaller venues [3]. In addition, plans have been made for the seats and other parts of the stadium to be reused for other projects, promoting the sustainable practice of recycling and repurposing. Moreover, the design of the stadium, accompanied by water efficiency methods, will help to reduce water usage by 40% in comparison to an average stadium [3]. All in all, the stadium is a physical embodiment of sustainability.

Another very important use of modular engineering was in response to the COVID-19 Pandemic in China. Both the Leishenshan Hospital and the Huoshenshan Hospital were constructed in 2020 in a matter of days, acting as emergency field hospitals to treat those with Covid-19. Both hospitals were built using prefabricated units and assembled on site, which helped to significantly reduce the construction time. Construction initially involved laying down the foundations, installing sewage systems and electrical systems, before assembling the components [4]. The units had been specially designed in order to minimise the transmission of COVID-19 within the hospital itself. For example, each unit had excellent ventilation systems and negative room pressure. This meant that air would flow into the room (from areas of higher pressure), but this contaminated air could not flow out of the rooms. This was a vital way in which patients were isolated and was essential in treating as many people as possible without spreading the virus. The modular construction of the hospital allowed for this high level of technical design to be implemented quickly and efficiently, playing a pivotal role in treating as many people as possible in Wuhan, the epicentre of the pandemic [5].

In an increasingly eco-conscious society, modular buildings offer a high level of sustainability in a variety of ways. As many of these projects, like Stadium 974, either repurpose shipping containers or use modules manufactured in factories, waste can be minimised, reducing the stress on the environment. In addition, there is much less disruption and activity on the construction site, since the assembly is a fast process, minimising the cost. Whilst modular design cannot by itself solve all our environmental problems, it can provide the key to the door behind which architecture no longer acts simply as a mere structure or even a form of art, but rather as the bridge between efficiency and sustainability.

Edited by Shanjeev Mathialagan

Technologies at LIGO

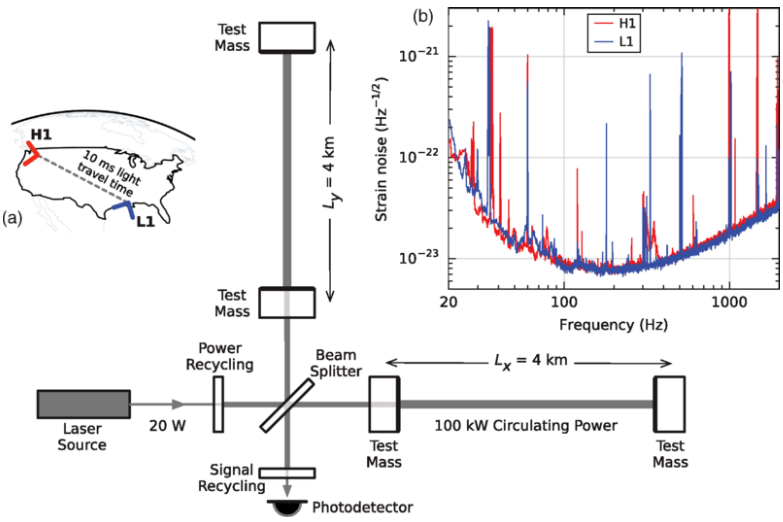
By Craig Lobo (Y13)

The relationship between physicists and engineers is often thought of in the following way: physicists aim to discover the laws of the universe whilst engineers use that knowledge to create new technologies and innovations that improve our way of living. However, with physics and science at such an advanced level in the modern age, it is becoming increasingly more common for engineers to have to provide the groundwork for physicists to conduct their research. A perfect example of this is the Laser Interferometer Gravitational-Wave Observatory (LIGO), located in Hanford and Livingston, on opposite sides of America. It was built to detect gravitational waves that could give us a greater insight into areas of physics that currently fall into some ambiguity (e.g. astronomical phenomena such as black hole mergers).

The interferometer consists of two, four-kilometre-long beam lines with Gires-Tournois etalon arms (a double-surface mirror which has high reflectivity and phase shift dependent on the wavelength of light).

A 1064 nm laser beam with 20 W power is passed through a recycling mirror which transmits light through one side (incident from the laser) and reflects light on the other, increasing the power of the laser light to 700 W between the mirror and the beam splitter. Partially reflecting mirrors then support the creation of Fabry-Perot cavities (an optical cavity through which optical waves can only pass through when they are in resonance with it), enhancing the light field to a power of 100 kW. When a gravitational wave passes through the interferometer, the spacetime in the local area is distorted, much like a ripple of water passing through a lake. This causes a change in the effective size and length of one or more of the cavities, depending on the wave’s characteristics, such as its polarisation. This results in the laser light traveling through either arm to shift in phase.

Without any gravitational disturbance, the beams are in antiphase and so interfere destructively with no light arriving at a detecting photodiode. When the phase difference changes however, the lasers are no longer in perfect antiphase and some light is detected. The changes are incredibly small and gravitational waves are expected to distort the four-kilometre length by about 10^{-18}m (less than a thousandth of the charge diameter of a proton) [1].

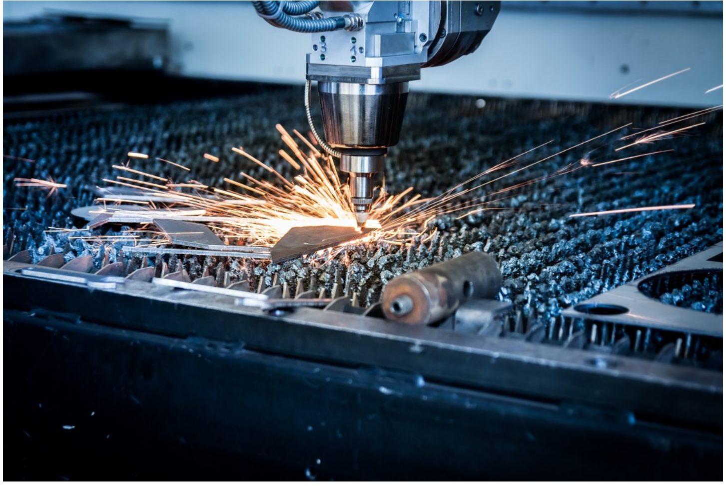


Any genuine waves will be detected at both observatories, lowering the chances of a false-detection due to vibrations from human activity.

As you can see this process is delicate and detailed, as is necessary for detecting such small fluctuations. However, creating the interferometer is only the first part of the process, since many problems arise as a result of operations.

One such problem is to do with thermally-induced laser-beam wavefront distortions. When a high-powered laser like those at LIGO pass through a nominally transparent optical element, a small amount of residual optical absorption causes the element to be heated where the beam is at its most intense. This in turn causes wavefront errors through the thermo-elastic distortion of the element or thermo-optical changes in the refractive index. These small interferences are enough to disrupt operations at the observatory so laser beam shaping techniques were needed to be put in place. A second transparent element was placed in front of the first with its edges heated to apply a compensating, heat-induced distortion, flattening the wavefront again. Several of these elements can correct more complicated distortions. This same technology has since managed to find its way into a wider variety of laser systems including laser weapons, radars and cutting or drilling where similar issues arise [2].

With such high precision experiments, all factors down to the materials used must be carefully monitored. When jointing silicon carbide during the fabrication of silica suspensions at LIGO, an oxide bonding technique based on the original hydroxy-catalysis technique was used. It was specifically selected due to not only its high strength with thin bonding layers but also its low mechanical loss in operation (friction and heating). These factors help reduce thermal noise which would have negative consequences similar to the problems that required beam shaping previously [3].



Finally, the optical design of the apparatus achieves a tolerance of one degree misalignment in pitch and yaw (rotation around the side-to-side and vertical axis respectively). This means that accurate and meaningful data can still be obtained in the event of such errors with regards to apparatus [4].

Despite all these great challenges associated with the development of LIGO, great engineering innovations have resulted in the creation of technologies that make the process practically viable and even have further applications in more widely related fields. All of this can help physicists obtain some of the most precise data available to scientists in any area of research so that they can draw more informed conclusions about the world around us.

Edited by Shanjeev Mathialagan

The Superconducting Super Collider

By Avaneesh Balaganapathy (Y13)

The Superconducting Super Collider (SSC) was a planned particle ring accelerator that first began to seem possible in 1983, when the initial plans for the particle accelerator were drawn up. This was followed by the USA, under the Reagan administration, authorising the plans for the particle accelerator to go ahead just four years later. The location chosen for construction was Waxahachie in Texas as the terrain and geology was suitable for digging the vast tunnels needed, the climate was stable and free from natural disasters and the population of the town was rather small[1].The project had initially begun with the financial standpoint of sparing no costs, during the end of the Cold War, when the USA was the biggest global economic power and the main goal of the USA at the time was to place itself at the forefront of science and innovation. This therefore meant that the plans for Superconducting Super Collider were colossal, with the proposed tunnels being 87.1 km in length. To provide context, the largest current-day particle accelerator is the Large Hadron Collider, at 27 km long. The SSC collider was not based on a radically different principle to what the Large Hadron Collider works on today, however with the unprecedented magnitude came new issues to overcome which ultimately led to the project's cancellation and the missed-out opportunities for the advancement of our understanding of the universe at the smallest level, all of which is covered in this article.

A part of the 87.1 km long tunnel under construction

Particle accelerators work by using a source of particles, typically protons or ions, fired at each other at immense speeds through circular tunnels, gaining more and more energy. The CERN accelerator system, for example, is a chain of machines with increasingly higher energies than the one before. Each machine accelerates a beam of particles to a given energy before injecting the beam into the next machine in the chain. This next machine brings the beam to an even higher energy and so on. The Large Hadron Collider (LHC) is the last element of this chain, in which the beams reach energies of 6.5 TeV per beam in the CERN complex, meaning they produce 13 TeV collisions - this energy is the highest our particle accelerators are currently capable of. However, in the context of our everyday lives, this energy is equivalent to the energy of a safety pin dropped from a height of just two centimetres. Inside the LHC, two particle beams travel at close to the speed of light (99.9999991% of the speed of light) before they are made to collide. The beams travel in opposite directions in separate beam pipes – two tubes kept at ultrahigh vacuum. The vacuum conditions include a pressure of 10-13 atmospheres, and temperatures of 1.9 K. They are guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets. Superconducting materials have very special properties when they reach a critical temperature - they enter a superconducting state and offer no resistance to the passage of electrical current. The electromagnets in particle accelerators are therefore chilled to 271.3°C (1.9 K) – a temperature colder than outer space in order to take advantage of this effect [2]. There are then detectors placed around the point of collision to record and reveal the particles that emerge from the collisions.

Most of the SSC would have been similar to current systems the current day accelerators operate with. But it would have been the world's biggest and most powerful accelerator. It was planned as a 20 TeV x 20 TeV proton-proton collider, a combined 40 TeV collision, yielding more than 108 collisions per second. This is compared with the 10,000 collisions per second at CERN. Due to the very high rate of interactions, both detector operations and data handling capabilities were challenged, with detector plans calling for two large general-purpose detectors and several smaller ones with more specialised goals. Due to the large amounts of data needed to be collected to observe not only charged particle interactions but uncharged particles, the detectors were set to weigh 30,000 tons with each detector being as large as a several-story building and was to cost upwards of half a billion dollars [3]. The superconducting magnet systems were somewhat premature compared to the system at CERN, as the project was a decade older, though the basis of both systems were very similar, from the cryogenics for the superconducting magnets to the chain acceleration system, where the particles gain more and more energy. The issues mainly arose after the project was underway when the scientists decided that the ring magnet design needed an overhaul, with the addition of 10,000 magnets, and this ended up hiking costs further. In total, the project was going to need twelve billion dollars for its completion. Unfortunately, the US government was not as concerned about investment in science as it was for its military as time progressed. As a result, the already limited funding was being almost competed for, against NASA who also required increased funding. The public had indeed favoured NASA, perhaps as its findings were more understandable to the general public. After two billion dollars had already been spent on the project ($400 million from the state of Texas, the rest from the Department for Energy), with tunnels being dug and research being conducted, the House of Representatives rejected funding on October 19 1993, and Senate negotiators failed to restore it.

This leads to a possible conclusion that can be made - that modern day institutions in power favour hierarchy in the global political system, through greater military force and means of economic development than the collaborative force that these scientific projects achieve. The reality is currently that nations prefer to invest in methods of deterrence against threats they create themselves, the paradoxical nature of which highlights even more the insignificance placed on science and the advancements missed out on as a result. In fact, particle physicist Brian Cox stated that The Higgs Boson particle would have been discovered a decade earlier if the SSC had been finished. Indeed, current projects such as the detection and study on neutrinos would undoubtedly have been accelerated if the SSC had received sufficient funding.

The Superconducting Super Collider was truly a missed opportunity to make advancements and produce new research that could have been used to accelerate our understanding of the universe, but one that is still testament to what is possible by the world’s brightest scientists and engineers, without the restrictions of those in control of the vast majority of money.

Edited by Shanjeev Mathialagan

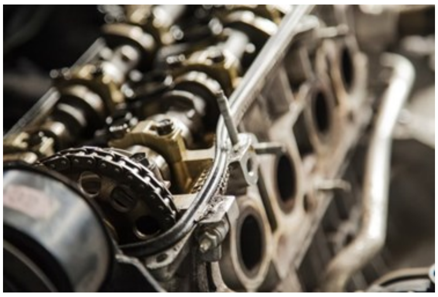
The Importance of Engineering

By Shanjeev Mathialagan (Y13)

The term ‘engineering’ is derived from the Latin words ‘ingenium’ and ‘ingeniare’, which mean "cleverness" and "to devise" respectively [1]. Engineering is the creative application of science to solve real-world problems. While maths and science help us to understand life and the universe, engineering is what puts this knowledge to work in exciting and practical ways. At the heart of engineering lies innovation, the process of converting an idea into a practical reality. Here are three inventions that have greatly impacted the lives of our ancestors, impacts us today and will certainly impact future generations.

Many argue that the light bulb has been the most important invention in our history, ever since man first marvelled at sparks from a fire a million years ago [2]. Although the modern light bulb is the result of continuous improvements by various innovators over 150 years, the name that comes to mind is Thomas Edison. Although he did not come up with the light bulb, he was the inventor of the first light bulb that was long-lasting, practical and economically viable for widespread use [3]. It has completely changed our lives for the better, establishing human life after sunset, as seen from the picture of the USA seen from orbit. By extending the workday into the night, it has boosted the productivity of economies around the world, enabling both local communities and whole nations to prosper.

The internal combustion engine is another example of an invention that has shaped our future. It was developed during the Industrial Revolution in the 19th Century, physicists were beginning to understand the field of thermodynamics. This meant that inventors were now able to calculate the efficiency and power output of different types of engines. In 1876, Nikolaus Otto released the ‘Silent Otto’, which was both quiet and fuel-efficient [4]. An inducing gas of high temperature and pressure that in turn apply a direct force to the piston, thus rotating the crankshaft and driving the motion of the wheels.



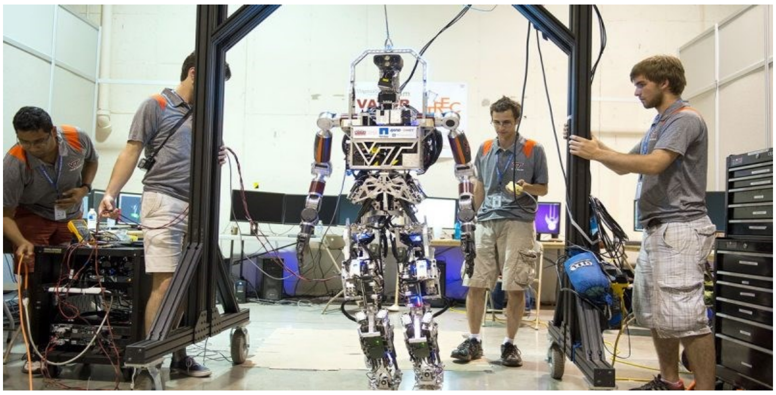
A four-stroke engine is an internal combustion engine in which the piston completes four strokes when the crankshaft is turned. Otto’s engine set the standard, and its design remains almost identical to modern times. This was a pivotal point in our history, because this invention would not only help to liberate men from the difficulty of arduous manual labour and make large-scale production a very real possibility, but it would then also lead to the conception of efficient transportation methods in use today.

The launch of Steve Jobs’ iPhone in 2007 opened the gateway to the most competitive technology market in the world - smartphones. Despite being smaller than a paperback book, the role of smartphones in revolutionising human interaction in the 21st century has been truly dramatic, with around half of the world’s current population owning a smartphone [5]. It enables social interaction, rapid flow of information as well as efficient data storage. We can keep up with friends, family and almost anyone around the globe, while also staying updated with current affairs, all at the tap of a finger.

Engineering remains one of the most important industries in the modern economy and it has inevitably led to the rapid advancement in technology that continues to transform our society.

Edited by Matteo Cascini

Computer Science Section



The Laws of Robotics

By Jesse Lou (Y12)

In 1942, Isaac Asimov published I, Robot, a collection of short science fiction stories. In the story Runaround, Asimov introduced three rules for his fictional androids to follow in order to protect and preserve humanity, listed as follows [1]:

A robot may not injure a human being or, through inaction, allow a human being to come to harm.

A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.

A robot must protect its own existence as long as such protection does not conflict with the First or Second

The 1940s were a different world from today. Robotics and Artificial Intelligence have taken a perhaps unexpected direction for people of that era. Instead of flying cars and teleportation devices, autonomous robots fill factories, assembling parts and pieces faster than any human could, and magical invisible beings

called 'AIs' seemingly run the world through a box and a brightly coloured rectangle. How do these three laws, set in a fictional world, compare to robotics today?

Justice

In the first Law, Asimov states that a robot must always act to prevent harm to humans and to protect their interests, yet do algorithms used in the judicial system reflect this?

The justice system is unfair [2]. In 2011, Nicholas Robinson was 23 and walking home during the London riots when he entered a looted Lidl and decided to take a case of water with him. When police entered the supermarket, he dropped the water and started to run, before being arrested and charged with six months in prison [3]. Humans are not good at being fair - we all have innate preferences for certain attributes, and it is unrealistic to institute measures to ensure that every crime is treated equally. What is needed in the justice system is a way of looking at only the raw data provided in the crime, and to reach a completely neutral conclusion based on those facts without the influence of context and preference - a perfect job for algorithms and machine learning. In theory, if a computer is trained on a large dataset, it should be able to identify patterns that are not linked to biases, such as the race and gender of a criminal, and to reach an unbiased conclusion, because a computer does not understand human concepts like racism and wealth inequality, only ones and zeros.

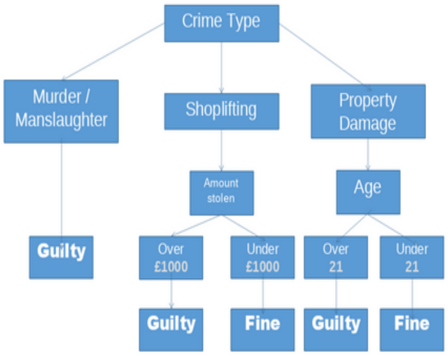


Figure 1: Example of a decision tree

The simplest way of implementing this would be to take the data set and construct an enormous flowchart, which predicts the behaviour of the new offender by going down the flowchart - a decision tree. This works if every single criminal followed a specific pattern and are all the same, which obviously does not reflect the real world. A better method would be to construct millions of these trees and then give random sections of the offender's data to each tree, and output what the majority of the trees think would be the right punishment. With this, if two offenders have the exact same data, the same output is given - we've eliminated bias in the justice system!

However, ultimately data fed into these algorithms to train them is collected by humans. Whenever we are involved, bias is involved. COMPAS [4] is an algorithm designed to rank how likely a criminal will reoffend, on a scale of one to ten. In an algorithm like this, a false negative would be someone who really should have spent a few more years in prison, but were let out scot-free, and vice versa for a false positive. In the case of Paul Zilly [5], who was facing sentence for stealing a lawn mower in 2013, the judge consulted COMPAS and imposed a sentence that would double Zilly's time in prison, all because of a single number. In 2016, ProPublica, an independent online newsroom, conducted their own research on the legitimacy and fairness of the COMPAS algorithm. When comparing the COMPAS scores of 7000 offenders in Florida to those who actually re-offended, they found that the algorithm was twice as likely to flag black defendants as false positives as white defendants. Race was never mentioned anywhere in the dataset fed into the algorithm.

Weapons

The second law suggests that robots should always listen to human orders unless it results in the harm of death of another human, but will warfare stop for morality?

'Slaughterbots' [6] is a short film released in 2017 in which the narrator makes the point that the 'artificial intelligence powered' weapons are able to target individual people and is a much more ethical way of eliminating your 'enemies' than traditional techniques such as using nuclear bombs. A terrorist organisation then gains control of these robots, and organises an attack on the US senate, killing eleven senators from the from the same party. As the film go on, TV pundits and officials start discussing purchasing a stockpile of these bots, to 'strike back' and 'seek revenge'. Chaos descends as more and more people gain control to slaughterbots, and the public begin shutting themselves in their homes, fearful that they may be next.

In the past, humanity have come together to stop the further development and even banning weapons such as napalm and agent orange, but what about autonomous robotics? In a complex war zone, who is to say that robotic soldiers have been trained on a data set that allows them to respond to any situation in a way that follows the second law? [7] Is it even possible to condense and manipulate the torment and the psychological horror of war in the painful memories of veterans into numbers and digits for a computer to read and make predictions from? Is it ethical to send millions of robots with perfect aim against a platoon of human soldiers, knowing the lives that will be lost, just to win a battle?

Conclusion

Robots do not have emotions, and they would never intend to put someone into prison for longer than they want to or murder soldiers and civilians in warfare. In reality the three laws are only broken via human interference - only through unconscious bias and knowingly cruel decisions do we arrive at a situation where emotionless lines of code break the laws of morality. Artificial intelligence and robotics, at least as of right now, is only a tool, and it is up to us to decide how we use it.

Edited by Jonathan Peter-Rajan

Machine Learning 101

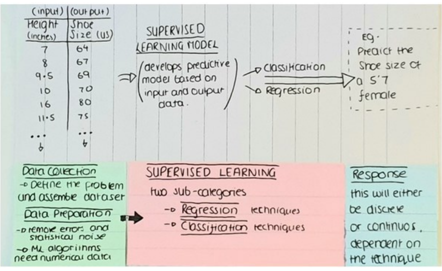
By Reyansh Sharma (Y12)

The recommendations engine, photo recognition, virtual assistants, and a whole plethora of features we use on a day-to-day basis relies on the principles of Machine Learning. As a subset of artificial intelligence, Machine Learning is at the forefront of development being used within medical diagnosis and speech recognition. But what is it?

Machine Learning: 'The use and development of computer systems that are able to learn and adapt without following explicit instructions, by using algorithms and statistical models to analyse and draw inferences from patterns in data.'

At its core Machine Learning (ML) seeks to extract information from data sets, using iterative methods whereby they can learn from data and recognise patterns thus adapting independently with minimal human intervention.

Within a supervised model we use training sets to 'teach' our models. We want this model to map an input to an output, based on our example input-output pairs. For example, let's take height and shoe size as our variables with the intention of getting our model to, say, predict the shoe size of someone who is 5'7. This kind of predictive modelling is often used in the financial industry- such as to measure market risk and fraud detection.



'Predict the shoe size of someone who is 5'7' - As our intended output will be a continuous variable (height) we would aim to find a target value (height) based on independent predictors – and so we would need find a relationship between the dependent and independent variables. This requires the use of Regression Models.

One of the most common forms of regression models include linear regression- extensions of which are multiple linear regression (a line of best fit) and polynomial regression (a curve of best fit).

Above, we once again have our training data which consists of our independent predictors and target values, much like our first example with height and shoe size. The decision tree consists of decision nodes and leaf nodes, where the decision nodes have two or more branches that test varying attributes and the leaf nodes consist of a decision on a numerical target value. Let's say our query is 'Predict the hours of hot rainy days', the model would go through our decision tree and return the target 27.5 hours.

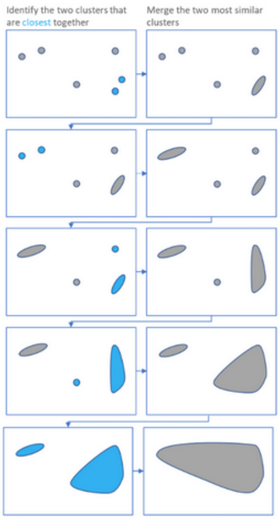
The principle behind classification is that classes (sometimes called groups of labels) tend to cluster together within a data set. A prevalent application of classification is in email filtering, where emails can be automatically filtered into spam and genuine emails, within our example we have a binary – our element or entry is either spam or not spam.

One classification method is K Nearest Neighbour, often referred to as KNN. As classification models return discrete responses, the output will be a class membership.

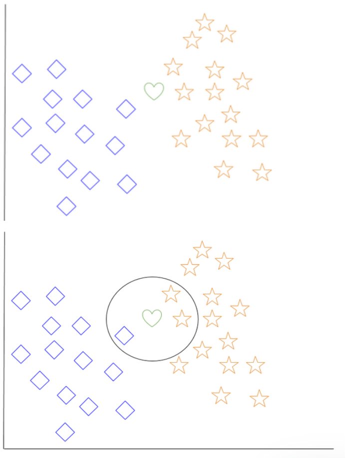
As with our other supervised learning models we have training sets, in this example our stars can be our genuine emails and our squares can be our spam emails. For this model, the features of our data that we may be looking for could be key phrases, such as 'Win A Free iPhone' or some other feature such as whether e-mails have been exchanged with the recipient and sender previously.

Let our new entry be the green heart, and our query is 'Does this email belong to the Spam Class?'. Knn would classify our object (green heart) based on a plurality vote between its k nearest neighbours where k would typically be a small integer- often odd to ensure a tiebreak. Let's let k=3 for this example:

Our Knn algorithm has found the three nearest neighbours of our object, and to classify the object we must take the modal or majority class (it doesn't matter which, as in this example as we only have two classes). In this new email, the majority of its k nearest neighbours



are stars – the genuine email class. Therefore, our classification model has concluded the new email is genuine, and so it would go to a spam folder. Unlike supervised learning, unsupervised learning is used to draw inferences and find patterns from input data without references to the labelled outcome- within our previous examples we had always given the algorithm test data that had been previously sorted, such as within the spam vs genuine email we had already fed examples of each, clearly identifying which data entries were real, or scam. Two main methods using unsupervised learning include clustering and dimensionality reduction. Unsupervised learning can simply be our aim, trying to find hidden pattern in data, or can be a means to feature learning (where the algorithm find its own way to recognise features and group this raw, unlabelled data.



Clustering is a way in which unsupervised learning can detect patterns within data and is used within a vast range of real-word applications, such as user-specific recommendation systems and general user analytics. Or simply put, your Netflix Recommendations, your YouTube recommendations, the way in which TikTok can feed you videos automatically based on what you've liked and what you've followed- it's the basis behind user retention and increasing revenue.

If we imagine the sorting of a different items in a supermarket as a physical example of clustering, where related items are grouped together, we can start to look at examples of clustering within machine learning. Let's say you're a youtuber looking to go through your user analytics, you have a lot of information on your subscribers, if the purpose of the machine learning algorithm is to find groups of similar subscribers in order to cater to them, you may run a clustering algorithm.

As we've already established, we don't need to tell the algorithm if a subscriber is in a certain group. We may know, for example, that 50% of the subscribers are within the UK and 25% are in the USA –and within this example we can use hierarchal clustering to subdivide our data into smaller and smaller groups (a process we've encountered before within the decision trees).

And so, our hierarchal clustering algorithm has transformed our raw data on the left to the 'dendrogram' (showing the hierarchal divisions between clusters) on the left, through the iterative process of creating these clusters we've been able to establish relationships and subgroups within our subscribers, all with no human intervention.

While at its core, machine learning is the process of fitting a model to data, ML has enabled us to tackle new problems that involve data with little to no structure – and created significant advancement in facial recognition, conversational AI, and autonomous vehicles. But at the end of the day the lucrative fields in which ML can be applied are not the reason they are special within AI's progression: it's the ability to change, and to adapt. ML's ability to iteratively learn, approximating and refining, is what makes it retain its status as at the forefront of technological innovation.

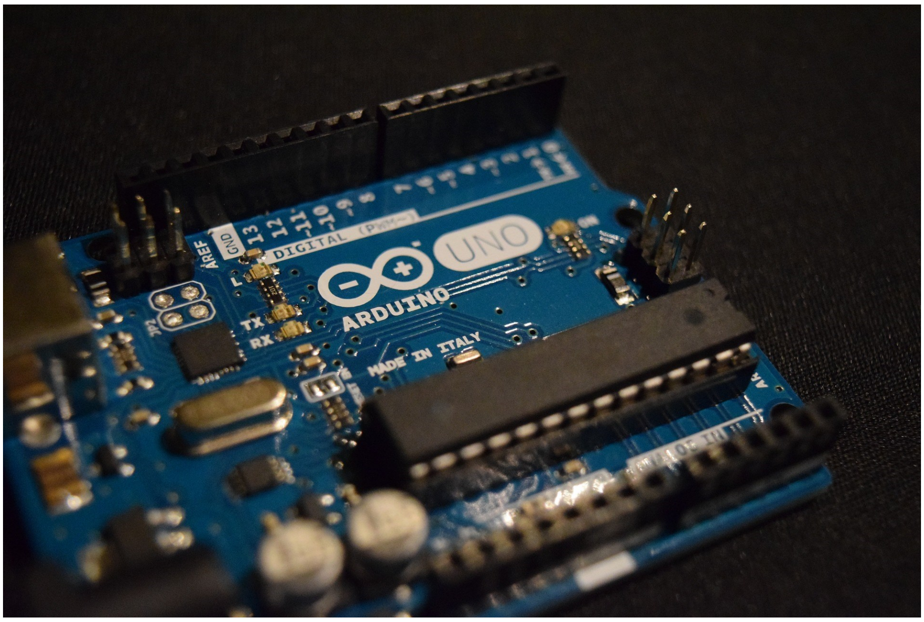
Edited by Jonathan Peter Rajan

IoT: The Technology for a Smarter World

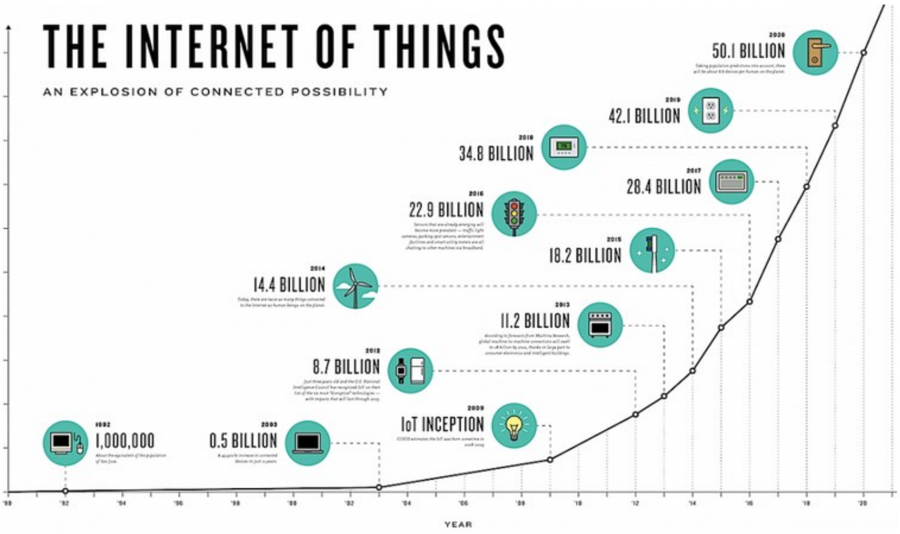
By Harish Venkat (Y13)

Imagine this, it's 6am and your alarm goes off. Automatically, the lights start slowly increasing in brightness to gently wake you up. The curtains start opening and the kettle starts boiling the water for your morning cup of tea. IoT is a digital ecosystem in which smart products that are connected to the internet communicate with one another without requiring human intervention. IoT is already prevalent and is starting to become more and more mainstream, for example, most people already own a type of smart home device such as Amazon's Echo.

The main goal of IoT is to decrease the time that humans spend on doing things that are meaningless like turning the lights on or off. Although this may only take you 5 seconds to do so, it can build up-35 seconds per week, 30 minutes per year. Saving this time may not seem significant but the compounding effect of these marginal gains prove to be very effective in the long run even for very basic tasks. By decreasing the time that humans spend on doing tasks that are "boring" and "repetitive", we can spend your attention on things that require human intellect such as your office work.



Not only can IoT save our time but it can also help save the planet. For example, turning the lights off in a room when you are not there will save electricity, decreasing the strain on fossil fuels. IoT is already being used in many industries including agriculture and manufacturing for this reason, such that it has been given the nickname as Industry 4.0. In manufacturing IoT does something called predictive maintenance[1] where machines can predict when they are going to have an error. This means that there is limited downtime since the company can take necessary precautions for the downtime of the machine and services can also be arranged prior. In the case of agriculture, smart irrigation monitors weather, soil conditions, rate of evaporation and how much water is needed by different types of plants to change the scheduling and amount of irrigation [2]. This makes sure that the plants are getting optimum levels of water whilst preventing water wastage.



IoT heavily revolves around monitors constantly collecting data in order to do their task to the best of their ability. For example, smart lights that turn on when you are in a room monitor your presence so the device knows where you are in the house or if you're not in the house at all! This is problematic if the data falls into the wrong hands. If a burglar gets hold of this information they can very easily rob your house knowing exactly when you are not at home. Furthermore, hackers can hack into devices that use IoT and will be able to extract the Wi-Fi password and even hack into other devices connected to that Wi-Fi such as a mobile phone or laptop and the data could be breached. This is why tech businesses should prioritise privacy whilst developing their products, keeping data encrypted so it is not vulnerable to hackers.

As it has always been in history, development in technology has always given rise to new problems. Development of the internet caused a whole host of "e-safety" issues to occur. So there will inevitably be problems caused by IoT. In order to minimise the frequency and the severity of these problems, privacy should be a fundamental necessity that the technology is developed around. What can the average consumer do? Firstly, you should have a strong Wi-Fi password. This may seem obvious however Kaspersky found out that 25% of Wi-Fi hotspots in the world are not encrypted or password protected [3]. Another way in which you could protect your data is by setting up a secondary network for all the smart devices you have at home. This means that all your smart devices will work normally but connecting your smartphone and laptop to the main network means that a data breach due to one of the smart devices will mean that your personal data is safe. So overall, IoT has many advantages and is undoubtedly a large part of the future of humanity. The technology will definitely improve over time and so security will hopefully improve as well. Despite the large number of data breaches we have seen in the recent years, tech companies are putting a greater emphasis on security so security can only improve from now. So there is less need to worry about your data being collected next time you ask Alexa to play you a song.

Edited by Jonathan Peter-Rajan

The Importance of AI

By Harish Rajkumar (Y13)

We have all seen the movies where some sentient computer marks humanity as a plague, and decides to wipe it out for the greater good, performing some technological coup in the process; however, in reality the threat posed by AI is of a different kind- financial and social. As of today, 44% of the world's working population is classified as low skilled labour [1], whether it be store clerks, cashiers or fast food workers. To put it crudely, they are replaceable. In fact, the AI takeover has already begun, with Jeff Bezos' Amazon Fresh[2] already implementing AI to make human interaction at stores redundant. Chatbots, search engine recommendations and voice assistants have become commonplace and well known tools to consumers. As implementing AI solutions continually gets cheaper [3] for businesses, it's making more and more sense to replace fragile and flawed people with more efficient machines.

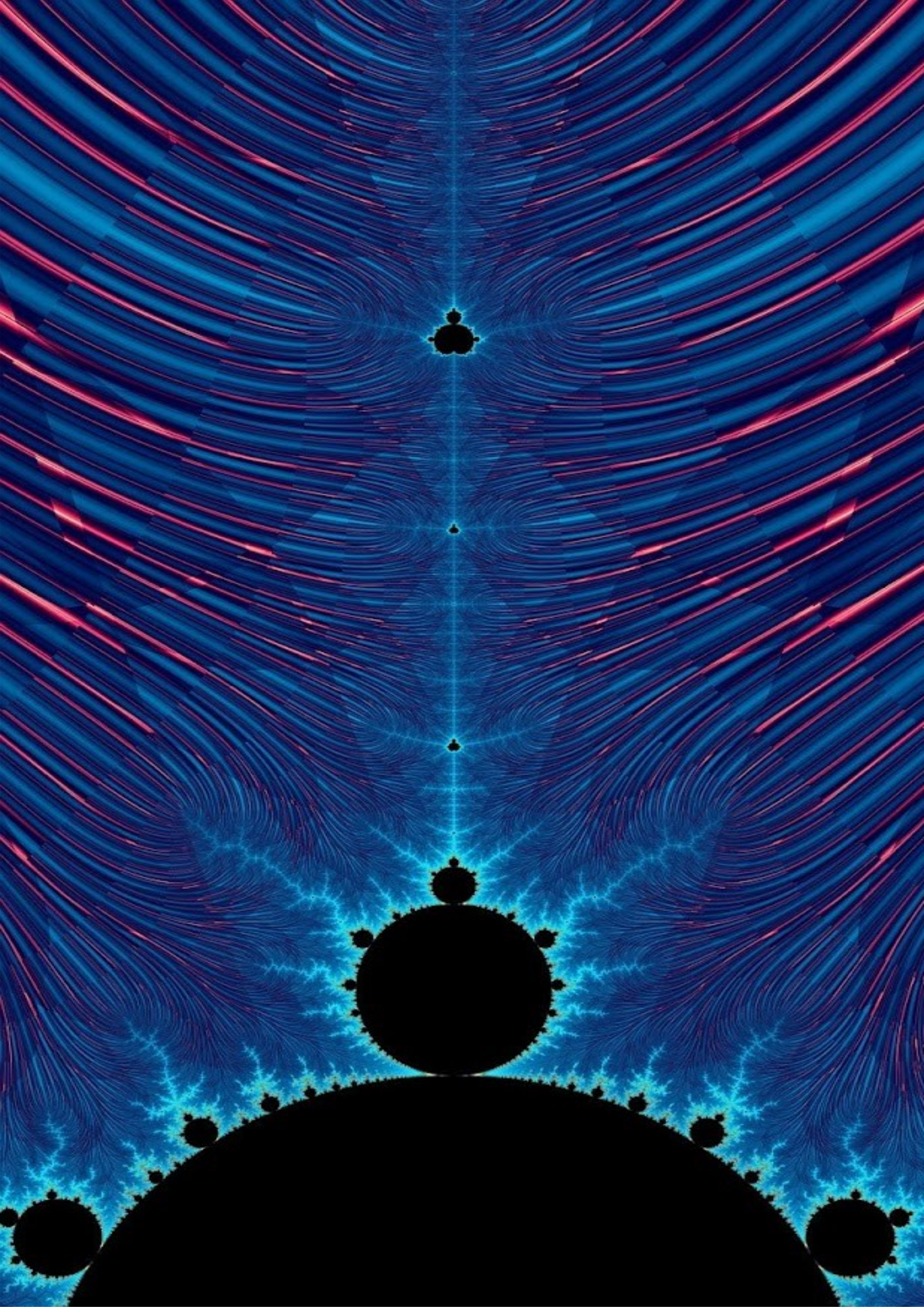
Today, even after more than half a century of research, AI is still in its infancy. Although the possibility for a machine to perform logical reasoning has been proven by Turing [4] more than 70 years ago, the perfect "electronic brain" is still out of our reach, as seen from the picture of the USA seen from orbit. By extending the workday into the night, it has boosted the productivity of economies around the world, enabling both local communities and whole nations to prosper.

At present, AI is only capable of learning via trial and error, tweaking parameters in a set of instructions (having programmed by an engineer what a satisfactory result looks like) until the goal that the AI has been set to learn has been achieved. However, this cannot be defined as true intelligence since it merely employs the automation of statistical techniques rather than developing a heuristic by itself, created from past experiences as we humans do. Due to this fact, humans are currently irreplaceable in certain markets where creativity and emotions are vital for success such as architecture, literature, and healthcare.

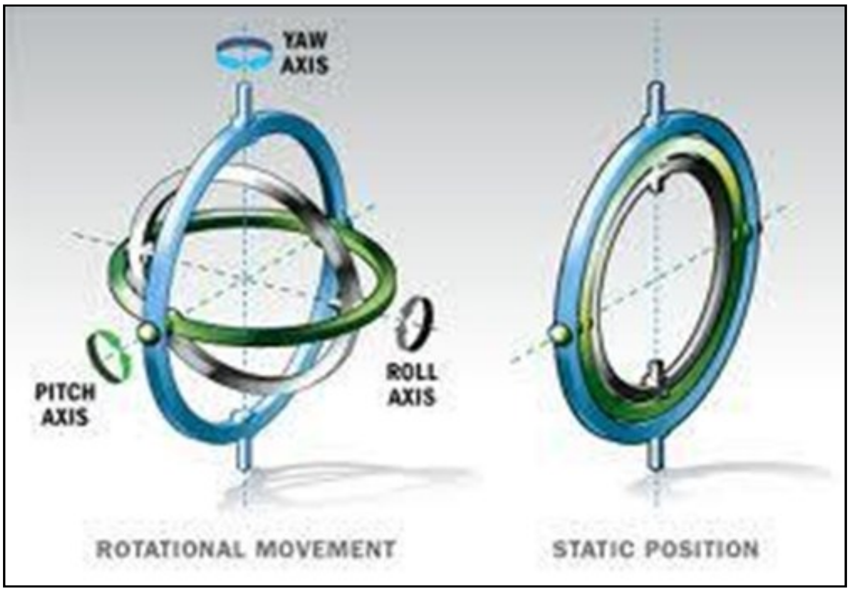
Such mentality is known as the AI effect [5], where each new development in the field is eventually normalized and becomes commonplace, hence is cited as not being "true intelligence", and so the development's status of being AI is stripped. Despite this, AI's growth in the past decade has been exponential, with 37% of all businesses utilizing AI in their workplace as of 2021.[6] While it is easy to get overwhelmed by the threat to jobs created by AI, it is also important to consider the opportunity presented by it. By 2025, 97 million jobs are expected to be created due to AI in the USA alone, compared to 85 million jobs lost because of it [7]. More importantly, the jobs being created are high skilled and high paying, in contrast to those being lost. As a result, the overall economic benefits of AI are expected to contribute $15.7 trillion dollars to the global economy by 2030 [8]. While one could argue the people affected by job loss are not those who gain the new opportunities, the net improvement to quality of life outweighs the negative impact caused by AI.

AI is beginning to move away from theories and more towards modern day, consumer-oriented applications, which provide immediate benefit to businesses. While we may never see the presence of a fully digitized thinking being, the impacts of AI will continue to grow in the future, improving the customer experience, and providing new opportunities to businesses around the world.

Edited by Jonathan Peter Rajan



Maths Section



Hamilton's Quaternions

By Ahesan Sivakumaran (Y13)

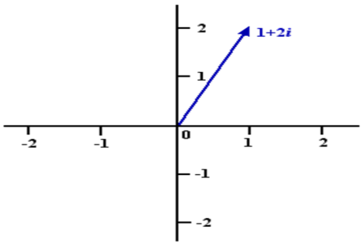
Consider the following equation: $x^2 = -1$.

Normally, you would say the equation has no solutions as you cannot square a negative number. However, if we define some imaginary number *i* to equal √-1, or:

$i^2=-1$

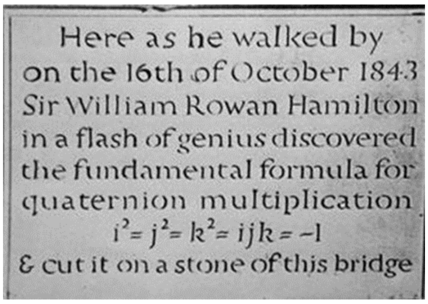
The solution would be $x=i$

This definition of *i* is powerful because it allows us to solve quadratic equations with a negative discriminant by finding its complex roots.



A complex number (z) simply consists of a real part and an imaginary part and can be written as:

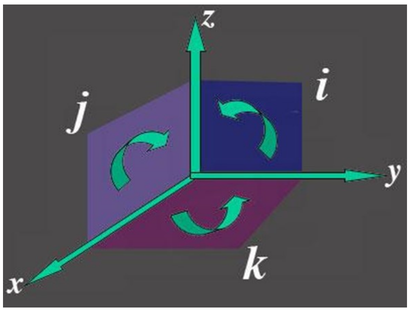
Z=a+bi, where a and b are real numbers and ***i*** is an imaginary number.



Here as he walked by
on the 16th of October 1843
Sir William Rowan Hamilton
in a flash of genius discovered
the fundamental formula for
quaternion multiplication
$i^2 = j^2 = k^2 = ijk = -1$
& cut it on a stone of this bridge

Complex numbers can be represented on an Argand diagram which is a useful tool which can be used to map the rotations of points in the complex plane, with a horizontal real axis and a vertical imaginary axis:

An extension of Complex Numbers:



What are Quaternions and where did they come from?

Quaternions are 4 dimensional complex numbers. They can be defined as:

$q = a_0 + a_1 i + a_{2} j + a_{3} k$ [1]

Where a_0, a_1, a_2 and a_3 are real numbers and ***i, j and k*** are imaginary numbers. This notation can help us see more clearly why quaternions are 4-dimensional, as they contain a real component, and 3 different imaginary components. It was Sir William Rowan Hamilton who devised this new concept in 1843, where On October 16, he and his wife took a walk along the Royal Canal in Dublin.

While they walked across Brougham Bridge (now Broom Bridge), an epiphany had struck him. By using three of the numbers in a quaternion as the points of a coordinate in space, Hamilton could represent points in space by his new system of numbers. He then carved the basic rules for multiplication into the bridge:

$i^2=j^2=k^2=ijk=-1$

Hamilton defined a quaternion as the quotient of two directed lines in a three-dimensional space i.e., the ratio of the 2 lines and dedicated the rest of his life investigating and teaching quaternions even further, pushing its development to have a significant effect in the modern era of technology even after his death.

Much like a simple Argand Diagram, quaternions can be geometrically represented by considering ***i, j and k*** to be elemental planes of 3-D space [2].

When we represent quaternions, or any complex number geometrically and in the complex plane, it allows us to more clearly see utility of quaternions and their unique properties. For instance, this diagram show that ***i, j and k*** can be represented as vectors in the complex plane, and also clearly shows how complex numbers behave in the exact same way 3D vectors do. It also shows that using these geometric representations, quaternions can be rotated around the axis. This diagram shows the distinction between 2 dimensional complex numbers and quaternions. In the first Argand Diagram, points in the complex plane can be rotated in 2-dimensional space, whereas in this diagram, the 3 elemental planes are designed so that the numbers (quaternions) can rotate in 3-dimensional space. It is interesting to note that 4 dimensions is required for a 3- dimensional rotation of a point about an axis. This could be explained by the analogy of a two-dimensional map of the earth, there is no way of mapping the surface of the earth without distorting either angles or areas. However, once the 2D map is wrapped round a 3D sphere it becomes linear, in a similar way the 3D space of rotations becomes linear when it is translated or “wrapped” around a 4D hypersphere, which in this case are the quaternions themselves [3].

How do we rotate Quaternions using Euler’s Formula?

Euler’s Formula states that:

The complex number e^{ix} can be written ***e^{ix} = cos x + i sin x***

But how do we prove that this is true?

We can use Taylor Series:

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \ldots$$

When we multiply the power series for **e^x** by ***i,*** we get the following series.

$$\begin{aligned}
e^{ix} &= 1 + ix + \frac{(ix)^2}{2!} + \frac{(ix)^3}{3!} + \frac{(ix)^4}{4!} + \frac{(ix)^5}{5!} + \frac{(ix)^6}{6!} + \frac{(ix)^7}{7!} + \frac{(ix)^8}{8!} + \cdots \\
&= 1 + ix - \frac{x^2}{2!} - \frac{ix^3}{3!} + \frac{x^4}{4!} + \frac{ix^5}{5!} - \frac{x^6}{6!} - \frac{ix^7}{7!} + \frac{x^8}{8!} + \cdots \\
&= \left(1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \frac{x^8}{8!} - \cdots\right) + i\left(x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \cdots\right) \\
&= \cos x + i \sin x,
\end{aligned}$$

By grouping the series into real and imaginary components, we can see that the real component represents the series for cos(x) and the imaginary component of the series represents sin(x)

Thus, returning us to the formula: [4]

$$e^{ix} = \cos x + i \sin x$$

How can this be applied to quaternion rotation?

If we want to mark the coordinates of a point **R** from rotation of a quaternion ***p* *by*** **π** radians about a specified axis of rotation ***q***, we would construct 2 quaternions [5] :

$$q_1 = \cos\frac{\pi}{2} + \sin\frac{\pi}{2}(a_1 i + a_{2j} + a_{3k}$$

$$q_1 = \cos\frac{\pi}{2} - \sin\frac{\pi}{2}(a_1 i + a_{2j} + a_{3k})$$

where ***a*** represents a real number and ***i, j and k*** are imaginary components of the quaternion that is the axis of rotation.

It should also be noted that q_1 is the inverse quaternion of q_2.

Then we find the new coordinates of p by multiplying the following quaternions in this specific order, as quaternion multiplication, unlike number multiplication is non-commutative, so the same quaternions multiplied in a different order would give a different point on the complex plane.

$R=q_1 . p . q_2$ [6]

But why did we divide the angle of rotation by 2?

Although seemingly arbitrary, if we were to multiply the quaternions together using $x= \pi$, we are actually rotating the point p around the axis of rotation by an angle of 2π, as we have multiplied the two inverse quaternions together, so have actually double-covered and over-compensated for the space of rotations. To counteract this, we have to divide the angle of rotation by 2 when using this equation. The modulus or magnitude of the new quaternion stays the same, it is just the angle that halves.

Practical Applications of Quaternions

There are many applications that quaternions extend to which allow for technological advancements. For example, quaternions can be used in astronautics, robotics, animation and special effects in animated films. Personally, the most appealing aspect of quaternions is their critical role in computer vision and games. Think of FPS, sandbox and any character-oriented game. The rotations of these 3-D characters we take advantage of could be efficiently controlled by quaternions. Matrix multiplication can be used for 3-D rotations, however, when two of the axes of rotation are parallel, the system loses a degree of freedom of movement because essentially there are now only two dimensions that can move. This is known as Gimbal Lock [7]. If 3-D rotation of characters used conventional matrix multiplication, they would encounter their character losing a degree of movement which would mean a character could get stuck in the same position. One efficient way to counteract Gimbal Lock is to use quaternions, because quaternions are four dimensional rather than 3-dimensional matrices, so adding another dimension to the system would prevent it from getting stuck in a position as the system bypasses Gimbal Lock, so can move without losing the degree of freedom. This helps smoothen character rotations and the overall gameplay experience.

Overall, quaternions are a unique and powerful mathematical concept that started out as an epiphany in 1843 and has branched out to boost technological advancements to this day.

Edited by Agustya Iyer

Sierpinski's Triangle

By Aarav Shivamanker (Y13)

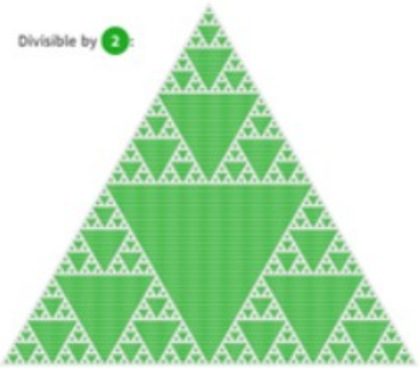
Wacław Sierpiński was a Polish mathematician who is well known for his extensive work in set theory and topology. His most famous discovery of topological spaces was the Sierpiński Triangle/Gasket, a self-similar fractal.

How is it formed?

Start by taking an equilateral triangle and dividing it into four smaller equilateral triangles using the original triangle's midpoints, and remove the middle triangle. Repeat this with the other three equilateral triangles, which will create four more (one of which you will remove), and keep continuing this. You will end up with the Sierpiński Triangle which looks like the image below.

Pascal's Triangle

Pascal's triangle can also be used to create patterns that resemble Sierpiński's Triangle. Pascal's Triangle is a number pyramid where every number is the sum of the two numbers above it (starting with 1 at the top). Pascal's triangle has many uses in mathematics, such as combinatorics and binomial expansion, but something interesting happens if we concern ourselves with multiples of different numbers. If we highlight all the even numbers in Pascal's triangle, we can see the Sierpiński Triangle:



This is because if two adjacent numbers are multiples of 2, then the number underneath, by following the rules of Pascal's triangle, must be even. This would mean that if a row had x even numbers, the row beneath would have x - 1, and after x - 1 rows, there would only be one even number, resulting in the formation of a triangle.

Another pattern worthy of mentioning occurs when we highlight multiples of prime numbers. Here, we can see the patterns formed using 13 and 19 respectively:

Chaos Game

The chaos game can also be used to create patterns that look like the Sierpiński Triangle and other fractals.

Start by plotting the three vertices of an equilateral triangle and plot any fourth point within the triangle. Then, pick a vertex at random and plot the midpoint between this vertex and the fourth plot. Continue this process of picking a random vertex of the original triangle and finding the midpoint between it and the last plot made. If we continue this process we will eventually see that the distribution of plots resembles the Sierpiński Triangle.

For example, the pentagonal snowflake

Other fractals can be seen if we use squares or pentagons as our starting shape, or if instead of plotting the midpoint between points, we choose a different ratio, such as Φ = **(1+√5)/2 - the golden ratio.**

Fractals and Dimensions

First introduced by Felix Hausdorff in 1918, fractals are geometric shapes, unlike 'standard' shapes, which have a fractional dimension. Fractal geometry has many uses inside and outside the mathematical world, for example, its uses stretch from statistical mechanics to modelling the behavior of the stock market as well its close links to patterns in nature.

In the case of the Sierpiński Triangle, it sits between being a one-dimensional and two-dimensional shape.

Formally, to decide how many dimensions a shape has, we use the following formula:

$$Number\ of\ dimensions = \frac{\log(number\ of\ self - similar\ pieces)}{\log(scale\ factor)}$$

For example, for an equilateral triangle, if we enlarge it by scale factor 2, we would observe four of the original triangles in the new triangle, so the dimensions of the object would be:

$$Dimensions = \frac{\log 4}{\log 2} = \frac{2\log 2}{\log\ 2} = 2$$

So, for the Sierpiński Triangle, if we enlarge it by a scale factor of 2, we would see three of the original triangles in the new shape, as we always remove the middle triangle:

$$Dimensions = \frac{\log 3}{\log 2} \approx 1.585$$

Even when enlarging it by a scale factor of 4, we see 9 of the original triangles:

$$Dimensions = \frac{\log 9}{\log 4} = \frac{\log 32}{\log 22} = \frac{2\log 3}{2\log\ 2} = \frac{\log 3}{\log 2}$$

Where do we see this?

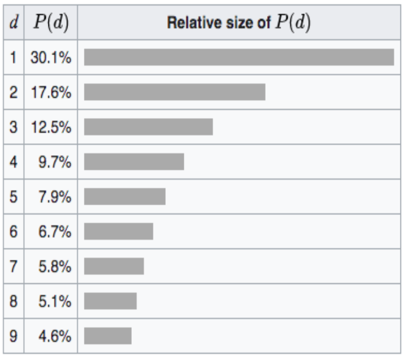
There are many variations of the Sierpiński Triangle such as the Sierpiński Pedal Triangle, Sierpiński Relatives, and Triangle Fractals, and many of these can be seen in ancient art, for example, floor tilings (mosaics) in Rome and Neolithic art.

Edited by Jonathan Peter Rajan

The Law that Detects Fraud

By Ugas Jeyakanth (Y13)

Grab a newspaper. Write down all the numbers in it. Then tally the frequencies of the first digit of each number. You would expect each digit to appear equally frequently, so around 11.1% for each digit from one to nine. While this may seem logical, I can tell you that one will be the first digit more often than two, which will be the first digit more often than three, and so on; you might be even more surprised to learn that the frequencies follow the table to the right, with one appearing almost a third of the time. This is Benford's Law. Although seemingly counter-intuitive, this law holds true with frightening accuracy for many numerical data sets (particularly those covering multiple orders of magnitude) [1].



d	$P(d)$	Relative size of $P(d)$
1	30.1%	
2	17.6%	
3	12.5%	
4	9.7%	
5	7.9%	
6	6.7%	
7	5.8%	
8	5.1%	
9	4.6%	

Probability, P(d), or leading digit, d, appearing [1]

Although it may be difficult to prove why Benford's Law is true for numerous data sets, and even more difficult to see how it has any usefulness outside of a party trick, it has many applications in the real world, most notably in law, which I will explore.

What is Benford's Law exactly?

Benford's Law can apply to many different data sets. You have already seen that random numbers from a newspaper, where there is no consistency with units or measurements, follows Benford's Law very accurately. There are many sequences in maths that follow the law as well, such as the doubling sequence, the tripling sequence, and the Fibonacci sequence. In terms of specific criteria, a set of numbers will satisfy Benford's Law if…

$P(d) = \log_{10}(d+1) - \log_{10}(d)$ where d is the leading digit.

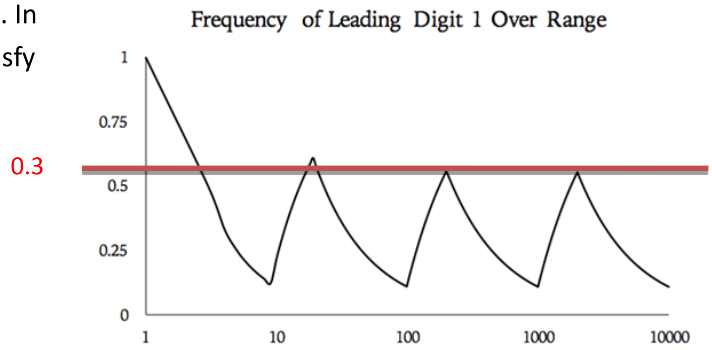
This can be simplified to give…

$P(d) = (1+1/d)$

How does Benford's Law work?

It is difficult to prove Benford's Law, and there isn't one method of firmly confirming it. One way of understanding why it works is by thinking about a raffle of numbers [2]. If you put numbers into the raffle in numerical order so start with one, the probability of a number starting with one winning is 100%. When you add two, that becomes 50%. With three, it becomes 33.3%, and it keeps on decreasing until you reach nine where the probability is 11.1%. However, when you reach ten, the probability starts to increase again, up to 20%, then 27.3% with eleven, and so on, reaching 57.9% at 19. But then it starts to decrease again as you keep adding more numbers, reaching the lowest probability of 11.1% again when you reach 99.

And then as you go through the 100s, it rises, then decreases through the 200s, 300s, 400s, etc., and starts to increase again through the 1000s, and so on. If you plot this on a graph, it will look like this:



The x-axis is the last number added to the raffle, and the y-axis is the probability of a number picked from the raffle having a leading digit of one [3].

The average of this graph is around 30%: this matches with Benford's Law.

Applications of Benford's Law

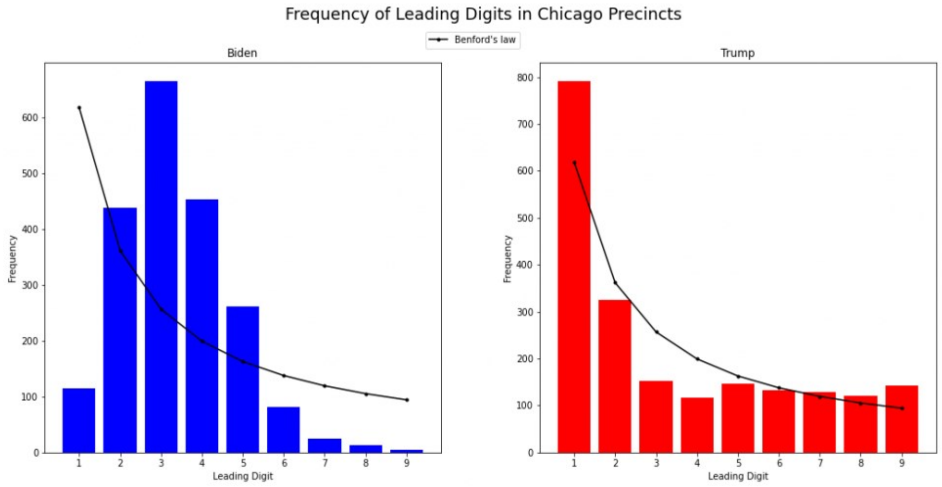
While Benford's Law may not seem to have any purpose, it has some interesting applications in real world scenarios. After learning about Benford's Law, the financial investigator, Darrell D. Dorrell, applied this knowledge to his work of detecting fraud: he would check the leading digits of bank accounts (financial data is spread over multiple orders of magnitude so should comply fairly closely with Benford's Law) and if they don't conform, he would analyse the data further to see if there is any clear evidence of fraud [4]. Of course, there may be several reasons why the data doesn't fit the law, such as a recurring purchase of a good priced item at £90 skewing the data, but it does flag any indication of malpractice which could prompt further investigation. In fact, Benford's Law is admissible in federal, state and local courts of law. Dorrell successfully managed to convict a local financial advisor, Wesley Rhodes, after he stole millions of dollars from investors; Rhodes' financial statements failed to pass the first-digit test, prompting Dorrell to investigate further and discover that the data was fake.

Benford's Law most notably came to light when conspiracists claimed that it proved Biden's election victory was rigged. The graphs show the results for the Chicago area, with Biden's in blue and Trump's in red, and a line representing what Benford's Law would look like with the data set. Clearly, Trump's data conforms with Benford's Law, and Biden's doesn't. This was clear evidence that the voting was rigged, so Biden should have been sent to jail and Trump should have served his second term. Not quite…

The problem with applying Benford's Law to district election data is that it doesn't span multiple orders or magnitude: precincts usually only register a three-digit number of votes. If a precinct registers between 400 and 900 votes, and the votes were split in some proportion between Biden and Trump, you expect the most frequent leading digits to be 2, 3, 4 and 5, as shown in Biden's diagram, instead of following Benford's Law [6]. So, the Trump supporters were wrong in using the law to claim rigging in this case. However, the 2009 Iranian elections also showed signs of electoral fraud when political scientist Walter Mebane analysed the ballot-by-ballot results using a version of Benford's Law that looks at the frequency of the second digit of numbers, and discovered that the winner, Mahmoud Ahmadinejad, had results that showed high discrepancies with the law. These accusations of rigging had a much greater impact than those against Biden, with millions of Iranians protesting around the world as part of the Iranian Green Movement [7]. It was never proven that the results were rigged, and Ahmadinejad served his second term as president. It is interesting that Benford's Law was able to spark such outrage.

Benford's Law is certainly one of the stranger mathematical theorems that exists, and the fact that there is little to no proof to explain it does put its reliability into question. But I hope that I have shown you how it has the capability of flagging fraud, especially on such a huge scale as a presidential election.

Edited by Shanjeev Mathialagan



2020 US presidential election data for the 2054 precincts in Chicago [5]

Physics Section

A Black Dwarf is the remnant of a once shining star that has now been crushed under such pressure that they will be about one million times denser than our Sun.

The End of the Universe: A Tragic or a Hopeful Finale?

By Thenutan Ravinthiran (Y12)

How will the Universe end? A question that has plagued many minds since the concept of a universe was known. Many theories have been proposed but the following three theories are the most prominent and all show different outcomes of our universe: The Big Bounce[1], The Big Freeze[2] and The Big Rip[3].

The Big Bounce (The Big Crunch)

The Big Bounce theorises that the universe goes between phases of contraction and expansion (i.e., The Big Crunch and The Big Bang). We have already experienced a Big Bang and the Universe will eventually undergo a Big Crunch, continuing the cycle. The Big Crunch is where the expansion of the universe reverses and the gravity overpowering the force that let the universe expand from The Big Bang.

It was hypothesised that the density of all matter in the universe is high enough that the gravitational attraction would overcome the expansion caused by the dark energy (dark energy and matter isn't a known substance but is predicted to exist by physicists as a way to explain the expansion of the universe). As the universe becomes increasingly small it also becomes much hotter. Hundreds of thousands of years before The Big Crunch, Cosmic Background Radiation (radiation released at the beginning of the universe during the Big Bang), which we ignore even though it surrounds us, will be hotter than the surfaces of most stars which would cook them from the outside. Minutes before the Crunch, the temperature would be so large that atoms and their nuclei would break apart and be sucked into black holes. These would coalesce into one supermassive black hole which holds the mass of the universe. In the last moments before the Crunch, it would devour the universe, including itself[4]. The Big Bounce expands on this theory and states this then leads to The Big Bang leading to cycles of the same universe.

Unfortunately, if you were hoping for this outcome, there is considerable evidence which shows that the universe is expanding at an accelerating rate. This contradicts the theory of The Big Crunch which, if true, would dictate that gravity would slow this expansion down, reducing the plausibility of this outcome[5].

The Big Rip

Perhaps the most spectacular of all the theories is The Big Rip which predicts that space, from galaxies to atoms, will be torn apart by the expansion of the universe until the distance between the individual particles becomes infinite. The Big Rip theorises that the expansion of the universe is accelerating, which has been supported by evidence which has given its finders the Nobel Prize (Saul Perlmutter, Brian Schmidt and Adam Riess). However, The Big Rip also hypothesises that this acceleration of the universe will increase with the density of dark energy (dark energy and matter isn't a known substance but is predicted to exist by physicists as a way to explain the expansion of the universe).

To see if this is true, it depends on one key equation - the Equation of State[6]: $w = P / \rho$

This is the ratio between the dark energy's pressure (P) and its density (ρ) and is characterised by the w. Note that this is the simplest form of the equation where we assume that we are measuring a fluid of some sort, the universe obviously contains more than just fluid, but to measure that the equation will become more complex. In addition, is nothing more than a placeholder for the value of pressure over density, in this case for dark energy. If the equation of state of dark energy is anything smaller than –1, so if , then this is phantom dark energy and its density increases as the universe expands, which would lead to this phantom dark energy overpowering gravity and leading to the Big Rip. However, if , then there will be no phantom dark energy and the dark energy would dissipate over time, leading to no Big Rip[7]. Fortunately, observations of large galaxy clusters by the Chandra X-ray observatory suggests that w is approximately -0.991 so The Big Rip is unlikely to happen[8].

The Big Freeze

The Big Freeze, unlike The Big Bounce, predicts that dark energy, which produces the force of expansion, will win the war between itself and gravity, proposing the idea that the universe is infinite[9]. The theory considers the expansion of the universe and suggests that energy dissipates in space, eventually leading to the universe having its energy so spread out that it will be too cold to support life.

The space amongst it however continues to expand and the distance between planets gets larger and larger. This means that eventually no work will take place (i.e., no events take place) and is put eloquently by Professor Brian Cox as - "nothing happens, and it keeps not happening"[10]. Even though the universe continues expanding, it would eventually reach stagnation as nothing happens.

As the universe expands and energy is dispersed, the temperature of the universe will fall, and the last stars will become black dwarfs - the remnants of once shining stars now crushed under such pressure that they will be about one million times denser than our Sun. Note that these stars are purely theoretical as they take longer to form than the current age of the Universe. The last matter inside black dwarfs will evaporate away into radiation[10] and eventually black holes will also "fizzle" out due to Hawking Radiation, thermal radiation that is theorised to be emitted by black holes. The only thing left will be photons approaching temperatures of absolute zero as the universe continues its expansion.

Conclusion

The most probable end to our universe as far as we know is The Big Freeze however, we are not certain that The Big Freeze will definitely happen as the value of dark energy's w is proving difficult to measure accurately as well as not knowing how dark energy could change and, if it is any comfort, we will be long gone before we get remotely close to the end of the universe.

Edited by Shanjeev Mathialagan

Special and General Relativity

By Tejas Gadkari (Y12)

Einstein is probably the most famous theoretical physicist of all time. He developed theories that were controversial and some scientists didn't even understand his work until they were proven after his death in 1955. Referred to as the founder of modern physics his work provided new ways of thinking of space, time and gravity and included the famous equation $E = mc^2$.

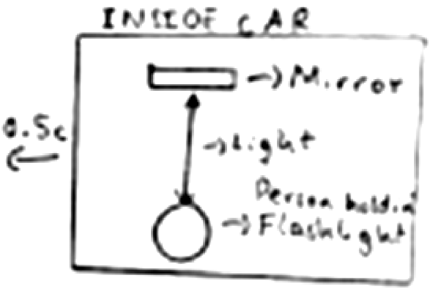
Special Relativity

He published his theory of special relativity in 1905. It is called special relativity because it only applies to situations where the different frames of reference aren't accelerating. It explains behaviour of things that move at near the speed of light, where Newton's laws don't always apply. A key aspect of this theory is the principle of relative motion. We normally measure velocity compared to an observer standing still on earth's surface. But, imagine a car on a road travelling at 50km/h on a straight road. Its velocity is 50km/h north. Now imagine a second car on the same road, with a velocity of 20km/h in the same direction. To an observer in the first car, the second car is appearing to be going backwards. Its relative velocity is 30km/h south.

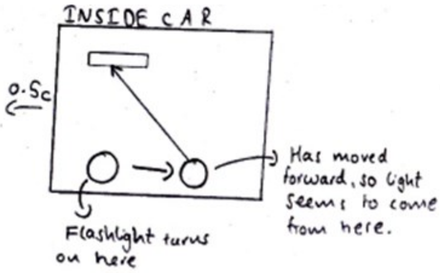
Time Dilation

Time dilation occurs when another reference frame is moving relative to you, so time appears to slows down in that reference frame.

The speed of light is written simply as the letter c, which is about 300 million meters per second.



Imagine a person in a car, moving at half the speed of light and has a mirror next to them. They shine a flashlight at the mirror. The light will enter their eye at the speed of light and will look like this:



The light will leave the flashlight, hit the mirror and reflect back to the person.

Now imagine you are standing on the side of the road and you can see the person shining the flashlight. You will see this:

As the person is moving so fast the light leaves the flashlight, and the person moves forward, so the event has happened in the past.

The mirror is moving relative to your spot on the platform. When the light has reflected off the mirror the person is still in front of the mirror, so the light travels diagonally to reach the person.

Special Relativity tells us that the speed of light is still exactly c, even though it travelled a greater distance.

Speed = Distance / Time

Therefore the time must have also increased to lead to the same speed. This is time dilation. From your perspective on the platform time has slowed down for the person in the car.

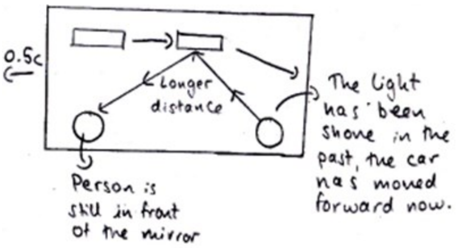
Length Contraction

Length contraction is also linked to the speed of objects moving very fast.

Say you measured the length of the car before it started moving and it was 5m long.

We know that Distance = Speed x Time.

The speed is constant (0.5c) and the time has slowed down for you compared to the person on the car. Because you have measured a shorter time than the person in the car the distance must have decreased.



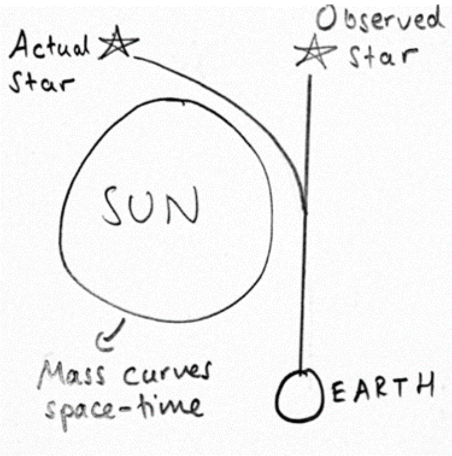
Both Time dilation and length contraction happen at regular speeds. For example a car moving at 150km/h will decrease in length by 1/100th the length of a hydrogen atom, so is too short for us to notice.

General Relativity

Einstein was dissatisfied with the theory of special relativity because it doesn't apply to accelerating reference frames, only objects moving at a fixed speed in a straight line. He began thinking of general relativity soon after special relativity. In 1907 he had a very important thought experiment called the principle of equivalence. Here is how he explained it.

Imagine you are a window cleaner and you fall off a tall building. Without the effects of air resistance, the only force acting on your body is gravity and you would be accelerating at $9.8m/s^2$. You would feel weightless as the ground is not pushing up against your body. You would be in free fall. This is the same as being weightless in space. Therefore you cannot tell the difference between the effects of gravity and the effects of acceleration.

This was a very key step. Einstein also wondered if there was a way to tell the difference between gravity and acceleration. He now imagined himself in a spaceship travelling at $9.8m/s^2$. If he had a flashlight and shone it onto a wall he would be able to measure the fact that the light would bend from the point it left the flashlight to the point it hits the wall because the spaceship is moving up at ever increasing speeds. The light beam would appear to curve downward.



He now imagined himself on earth and also shining a flashlight onto a wall. You may think that the light would be travelling in a straight line. However Einstein thought that this cannot be the case because this would violate the principle of equivalence. The effects of acceleration should be no different to the effects of gravity.

This made him realise that light must bend in the presence of a gravitational field. Light always takes the shortest part between two objects, so Einstein realised that the shortest part is actually a curved line. He hypothesised that gravity somehow causes the curvature of space itself. But to prove this it requires very complex mathematical equations and Einstein took the help of Marcel Grossman, a talented mathematician to work out the geometry of curved space-time. This is the basis of General Relativity.

Evidence of General relativity came in 1919, during a total solar eclipse. He went on an expedition to Guinea to photograph the eclipse. The photographs proved that distant stars had appeared to change position by the exact amount he predicted, finally proving general relativity.

To show the curving of space time a trampoline analogy is often used. But bodies do not sit on top of space time, they are embedded into it. A more accurate representation of this is this three dimensional model of space shown.

Space-time also has a fourth dimension of time, but we cannot comprehend this as we live in a three dimensional world.

Time dilation and length contraction also occur in general relativity and apply in similar ways to special relativity.

John Wheeler later summarised General relativity in a few words:

"Space-time tells matter how to move. Matter tells space-time how to curve."

To conclude, special and general relativity are extremely astounding feats by a very famous theoretical physicist. The work of Einstein will always be important for us in our understanding of space-time and we hope that there will be discoveries into things we do not yet know.

Edited by Matteo Cascini

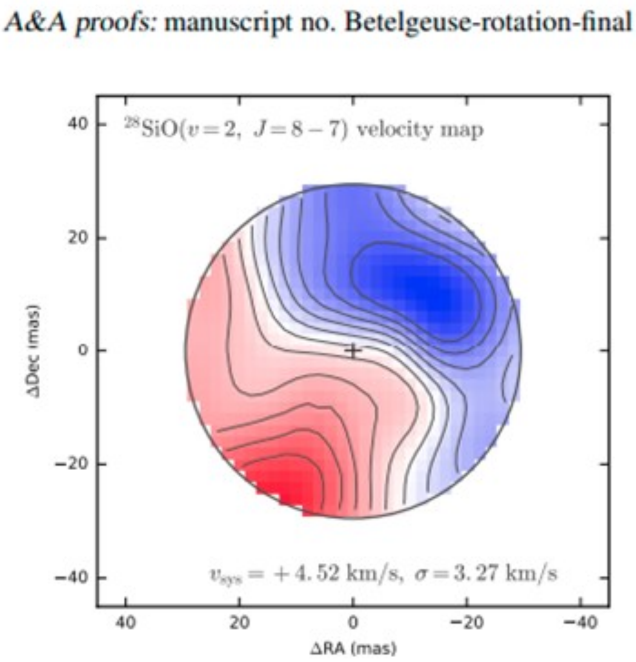
DIY Astronomy: Astronomical Spectrometry

By Leo Kavanagh (Y13)

If you look up on a winter's night it's hard to miss the constellation of Orion, with its iconic belt of three stars, and the bright red star of Betelgeuse. At Orion's foot the brightest star in the night sky visible – Sirius, the Dogstar. It glows a palish blue as it shimmers in the sky, twice as brightly as the next brightest star. The colours of these two stars can tell us a great deal about them – their composition, their age, even how and when they will die. Betelgeuse is a red supergiant, a massive and unstable dying star that could explode at any moment. Sirius is a bright young main sequence star, only 200-300 million years old – our sun is five billion years old.

Clearly, analysing colour is a useful tool for astronomers, however it is highly subjective – the colour of Sirius has actually caused some controversy during the history of its observation, with some ancient observers seeing it as red or orange. Luckily, there is a technique that allows us to make the visual observation of stars (and any other object that happens to emit visible light) far more objective – spectrometry.

The concept of spectrometry is fairly simple and has been in use for some time. All that it involves is splitting light from the target of observation into its constituent colours (for example by using a prism) and then looking at the strength of different colours in the resulting output (spectrum). This means that we can analyse the strength of different frequencies within the light that reaches the observer, which can tell us a number of useful things. One such thing is the chemical composition of the target – different elements and compounds emit and absorb different wavelengths, leading to a distinctive "signature" left behind by different substances. For example, if you use a prism to split up light from the sun, you will be able to see several dark bands in the resulting spectrum. These are caused by the sunlight from the sun being absorbed by different gases in the Earth's atmosphere – water vapour, carbon dioxide and ozone cause some of the most prominent of these. We can use the intensity of these absorption bands to work out how much of each gas is present in the atmosphere, and this technique isn't limited to Earth's atmosphere – we have been able to successfully use it

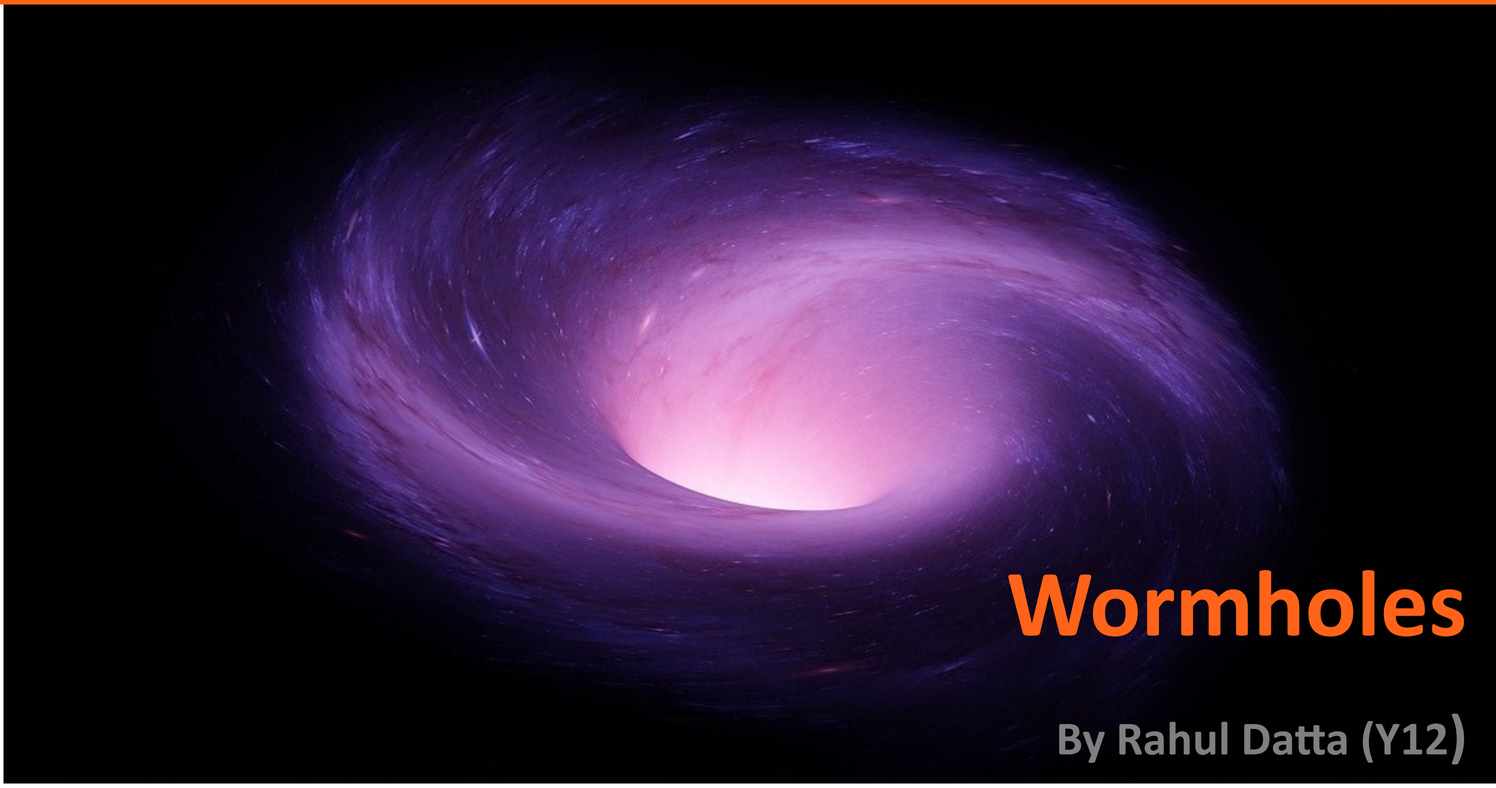

A&A *proofs:* manuscript no. Betelgeuse-rotation-final

to measure the atmospheric contents of all the planets in the solar system, as well as some outside it, making it an extremely useful tool.

We can also use this knowledge of specific frequencies to measure the motion of different objects due to the Doppler effect. This is the phenomenon where if an object emitting some form of wave moves away from the observer, that wave will be stretched out – or compressed if the object moves towards the observer. This means that the frequency of this wave will be lower if the object is moving away from the observer, and higher if it is moving towards the observer. This means that the light from a star moving towards the Earth will increase in frequency, and we can measure this using spectrometry. In particular, if we look at peaks in the frequency that we know will be there, such as the peak caused by light emitted by hydrogen and compare the frequency that we observe it at to where it would normally be, we can see what the frequency shift is. We can then use this to work out the velocity of the star. Recently astronomers were able to do this with Betelgeuse, not just measuring the velocity at one point but at multiple across the star, creating a map of the stars rotation – you can see in the image created that half of the star is moving towards us, and half is moving away, indicating rotation.

This way, we can describe the composition and motion of virtually any astronomical object in the night sky just from the light it emits, making spectrometry one of, if not the most useful technique available to astronomers.

Edited by Matteo Cascini



Wormholes

By Rahul Datta (Y12)

'Interstellar'; 'Thor: Ragnarök'; 'Synchronicity'. Three movies – all box office hits – yet their plots contrast starkly. However, there is one concept that they all have in common, and that is the idea of a wormhole. A connection between two separated places of space-time. Wormholes do sound very sci-fi, which explains their popularity in movies. Travelling from one universe to another seems unfathomable. Time warps are impractical and sliding across one region to another in a tunnel faster than the speed of light sounds preposterous. All this points to wormholes being no more than an unsolvable enigma but there is evidence to suggest that they are rather an unexplored phenomenon. Do wormholes exist?

There is no point of talking about wormholes if there is not a way to create one. Einstein and Nathan Rosen discussed the possibility of there being connections between space-time, which could act as shortcuts, greatly reducing the time and distance humans would need to reach that location. Think of hiking up and down a mountain as a normal route and a tunnel that goes through the mountain as the wormhole, but on a cosmic scale [1].

As for how we make it, Einstein visualised the universe as a single sheet and using his theory of relativity, he states that the things on the sheet, such as planets and suns, can affect the shape of the sheet, which stretch and distort it. His visualisation of the universe would indeed make wormholes mathematically possible; it could make two distant locations connect via a tunnel or bridge that people could travel across at insane speeds, faster than the speed of light. This sounds very hypothetical, but not impossible [2].

There are other possibilities for wormholes as well. In fact, people have theorised that black holes could be wormholes in disguise. There could be a parallel universe on the other side where you get sucked in by a black hole and spewed out by what is called a white hole. However, the fact is that it would take an infinite amount of time to travel between two galaxies and the overwhelming gravity in black holes means any organism that dares to enter would quickly end up being stretched like spaghetti and dead, which rules out this theory [3].

There could also be the possibility of humans making wormholes – sounds impossible, but mathematicians have devised equations on how to create one. Though, the big issue is that humans do not have the sufficient materials in order to make and sustain a wormhole. Since gravity would always look to close or collapse the wormhole, we need something that repels gravity. And that can only mean something not having zero mass, but negative mass, since that would repel gravity instead of attracting it. This is called exotic mass – a concept which is only hypothetical since there is no evidence of its existence in the universe. So far, that is [4].

So, as you can see, humans have been much closer to making wormholes a reality than most people think. The maths is all there, but as mentioned previously, we need substances that are literally out of this world to create and sustain a wormhole. So, the question is not if they exist, but when will they exist?

The Pandora's Box: Dark Energy

By Bhuvan Challa (Y12)

Challenges have barred the knowledge available to humans on countless occasions, but curiosity has propelled our race further and forced us to question reality itself. Dark energy is one such phenomenon that opened a greater playing field for us apes. So how did dark energy challenge the fabric of the universe? In the initial months of 1998, two leading groups of Physicists discovered that the expansion of the Universe is speeding up. This discovery uncovered one of the greatest secrets of the cosmos, the so-called normal matter is only a fraction of reality. It is so rare in fact that it only makes up five percent of the Universe. Undetectable dark matter makes up 24 per cent while everything else is an enigmatic substance titled dark energy. [1] [2] [3]

At the start of the twentieth century scientists assumed that the rate of expansion of the Universe was slowing down. It seemed only fitting that gravity would overpower any other force in the Universe and eventually pull all matter together in a calamitous Big Crunch. However, one other possibility suggested that the Universe doesn't have enough matter to stop the expansion of the universe which means it would continue slowing down but never stop. This would lead to the heat death where the Universe cools down until the last star dies and none are born anymore leaving the aether in a state of darkness for eternity.[4] The only part of the puzzle left for scientists was measurements of the Universe's expansion to foretell the end of the Universe.

In the mid 1990s multiple programmes were underway to measure the rate of expansion of the Universe such as the Supernova Cosmology Project lead by Saul Perlmutter and many other scientists from across the world collaborating together. [5] The missions focused on obtaining the spectra of a 1a supernova which is a standard candle (an object of known and constant brightness) to view the redshift. The luminance, magnitude and redshift were used to pinpoint the explosion in space and measure how fast it moved away from us. Exactly at what velocity these supernovae moved at could determine the fate of the Universe as it could conclude if there was enough matter to cause the Big Crunch.[6] Astonishingly, both teams found that the expansion was not slowing down but speeding up when they looked beyond 5 billion light years. These results were at first thought of as an error, but further theoretical backing solidified the concept. Adam Riess had found out that the Universe appeared to have a negative mass by using Einstein's field equations or in other words a force that works against gravity permeates throughout space-time. This source of energy was dubbed dark energy. [7]

Dark energy has proven to be an indicator of how much we still need to learn about the universe as it is not as homogenous as we previously thought. It could also be showing Einstein's theory of gravity incorrect to an extent. However, dark energy could have been the cosmological constant that Einstein used to make the Universe static but later called it "the greatest mistake" in his life. The value for the cosmological constant was assumed to be zero – the energy that was contained in space. However, quantum theory predicts the existence of 'virtual particles' even in an empty vacuum for a Plank time (10^-43 seconds) and then they disappear again. Dark energy closely matches this idea – energy which stems from space-time itself and has more profound impacts as more space is created. This could suggest a revised cosmological constant, one which describes the quantum state of space and therefore not zero [8]. We cannot be sure of what dark energy definitely is until we exercise our curiosity further and push mankind into a new era of discoveries. But one thing is certain no other force will dethrone dark energy's influence on the Universe, which will inevitably lead to the Big Rip tearing apart space-time and if powerful enough creating a singularity – the next Big Bang.

Edited by Agustya Iyer

Noether: Ingenious and Injustice

By Shuayb Mohammed (Y12)

Amalie Emmy Noether, born in 1882 to Ida Kaufmann and mathematician Max Noether, made great contributions to the foundation of modern theoretical physics and helped to revolutionise the burgeoning field of abstract algebra. As a Jewish woman in early twentieth century Germany, Noether's resilience in the face of discrimination and adversity is an inspiring story for any young scientist. After her tragic death in 1935 from an ovarian cyst, Einstein praised her as "the most significant creative mathematical genius thus far produced since the higher education of women began" [1]. This view of Noether as an incredible mathematician was shared by some of her contemporaries, such as eminent mathematicians David Hilbert and Felix Klein; in 1915 they invited her to join them at the University of Göttingen to study the implications of Einstein's new theory of general relativity[2].

Noether the Physicist

The key issue was reconciling the law of conservation of energy with Einstein's field equations, from which they did not appear to be a necessary consequence. In studying this, she was very successful - Hilbert wrote a letter, commending Noether as his "most successful collaborator" in developing Einstein's gravitational theory[3]. In the letter he argued, much to the dismay of Göttingen's philosophical faculty[4], for Noether's "habilitation", which would permit her to become a professor, or *Privatdozentin*. Noether was finally able to achieve habilitation in 1919 after publishing Noether's First Theorem in 1918, which provided a tool to analyse a system of physical laws and derive from them a conserved property called a *Noether charge*, under the condition that these laws are unchanged under a certain change of coordinate system (meaning that the laws have some form of symmetry). This helped resolve the issues of Einstein's field equations by deriving the conservation of momentum from their symmetry in coordinate transformations of space, and by deriving the conservation of energy from their symmetry under transformations of time[2]. This theorem remains significant and has other surprising applications, such as calculating the entropy of black holes (this is a measure of the different possible internal states the black hole can occupy, or, roughly, the disorder of the system)[5].

Discrimination

Before forging connections with Hilbert and other at the University of Göttingen, Noether faced many challenges. From 1900 to 1902, she was barred from attending university because of her sex, instead informally attending classes in mathematics and languages for no credit as one of two women among the 986 students at the University of Erlangen, where her father lectured[6]. In 1903, women were finally allowed to enrol at Erlangen and Noether began her formal education. Later, in 1907, there was some debate on whether women should be allowed to teach at Prussian universities, but this was overwhelmingly opposed, and the Prussian Ministry of Education maintained the exclusion of women from professorship. In

1915, Hilbert fought, adamantly and unsuccessfully, for Noether's exemption from this rule, famously declaring that "we're a university, not a bathing establishment"[7]. This setback did not stop Noether. In the winter of 1916, Hilbert announced a series of courses that he would teach "with the support of Fraulein Noether", which were, in fact, taught by her alone.

From 1920, even before receiving a paid position, she became a leading figure in abstract algebra, which was the focus of her later research, and for which she is better known among mathematicians. In 1921, for example, she proved the Lasker-Noether theorem, a generalisation of the Fundamental Theorem of Arithmetic to more abstract algebraic structures. The Fundamental Theorem of Arithmetic states that every integer greater than one can be uniquely factorised as a product of prime numbers.

Noether, building on the work of Emanuel Lasker, studied this notion with respect to rings, which follow similar laws to the numbers with which we are familiar, except that multiplication need not be *commutative* (i.e., $a \times b$ need not equal $b \times a$) and numbers need not have multiplicative inverses (i.e., for some or all numbers x, there may or may not be elements denoted x^{-1} such that $x \times x^{-1} = 1$).

She was denied pay for a further four years after her habilitation, and in 1932, when Hermann Weyl, a colleague and successor of Hilbert, proposed Noether's election to the Göttingen Academy of Sciences, it faced near unanimous rejection despite that her papers had been presented at the Academy by members such as Felix Klein. Weyl wrote that he regretted the decision of the Academy to "forgo the collaboration of such a strong productive force for reasons which seem to [him] to be besides the point and not cogent"[4]. The situation only grew more dire in 1933 when Hitler became Chancellor. One of the first antisemitic laws to be passed in Nazi Germany was the "Law for the Restoration of the Professional Civil Service, which prohibited Jews and other ethnic minorities from many occupations, including teaching. The looming threat of antisemitism in Germany meant that Noether and many of her colleagues, such as Einstein and Weyl, whose wife was Jewish, sought positions in other countries where they could be safe. Noether found refuge in the USA, where she taught at Bryn Mawr College in Pennsylvania for a few years before her unfortunate passing.

> ***"In the midst of the terrible struggle, destruction and upheaval that was going on around us in all factions, in a sea of hate and violence, of fear and desperation and dejection - you went your own way, pondering the challenges of mathematics with the same industriousness as before." – Hermann Weyl, 1935*** [8]

But maybe this sad story does have a silver lining. Despite everything that she faced in her lifetime, she is now much better recognised within the fields of mathematics and physics as one of the greatest minds of her era, and she deserves to be known as such.

Edited by Shanjeev Mathialagan

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