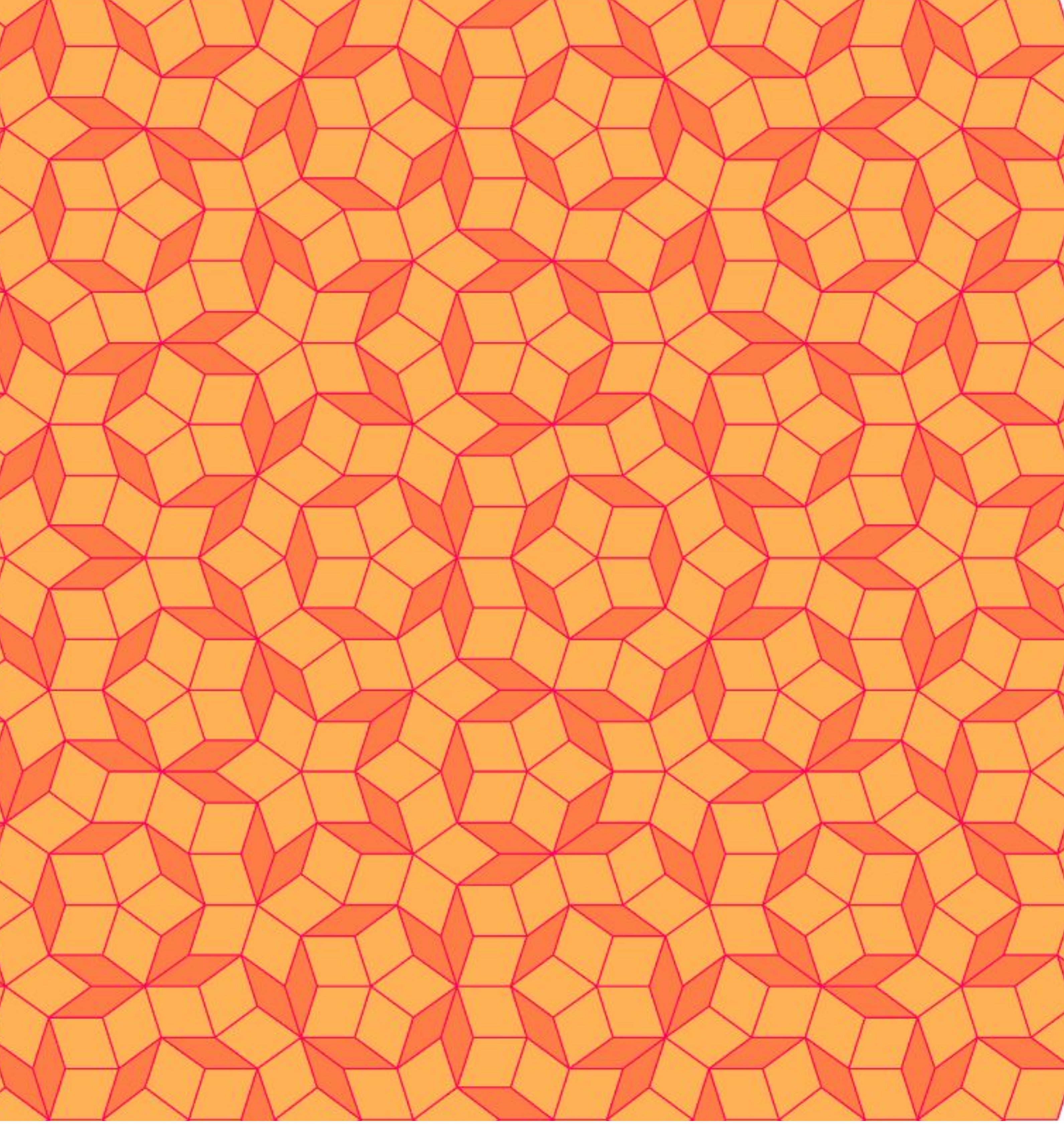

THE PENROSE MAGAZINE

STEM

Issue 5: Ambassador Issue, 24 Nov 2025

Welcome to the Fifth Issue of Penrose Magazine!

Penrose is a STEM magazine where we hope to establish a community of young people who are passionate about STEM and want to share with their peers and further their knowledge beyond the curriculum. This installment of the magazine features work from our ambassadors across a wide variety of topics from the science of rigor mortis to the technology behind Howitzer. We hope to continue fostering an environment where people are encouraged to push themselves to create meaningful work and support each other to grow.

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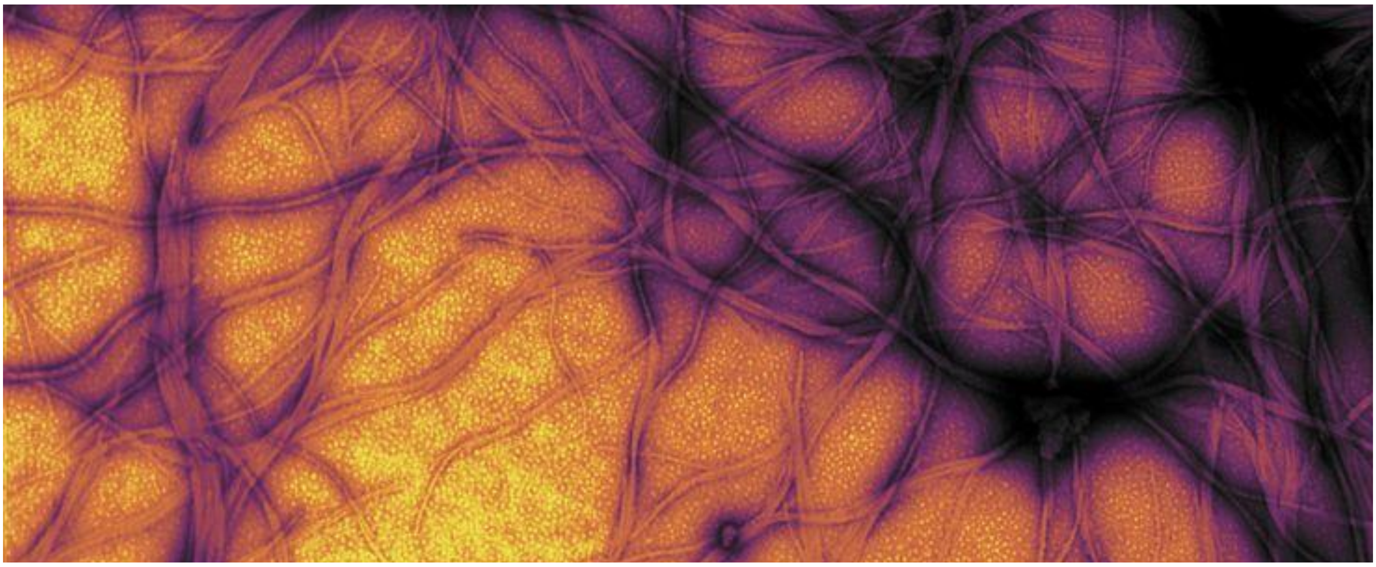

Prions: The Misfolded Proteins That Challenge Biology and Medicine

Prions are among the most unsettling biological entities to have ever been discovered. Unlike the common sickness-inducing mediums such as bacteria, viruses, and fungi, prions are not living organisms, nor do they contain any genetic material (DNA or RNA) [1].

Instead, they are infectious proteins: abnormal versions of naturally occurring proteins in the body that can cause other proteins to misfold in similar ways. This ability to spread their misfolded shape has placed prions at the center of several devastating neurological diseases and challenged our understanding of what it means to be "infectious."

An Overview on Prions

The word "prion" is the shortened form of "proteinaceous infectious particle." Prions are misfolded forms of a normal protein, typically found in the brain. The normal version of this protein, called PrP^{C}, plays a role in cell signaling and nervous system health. When PrP^{C} misfolds into a disease-causing shape, known as PrP^{Sc}, it becomes insoluble and resistant to degradation [2].

The misfolded prion protein can then "template" its abnormal shape onto healthy proteins, obliging them to adopt the same harmful structure. Over time, this chain reaction can lead to multiple misfolded proteins. This in turn causes clumps and leads to disruptions in normal cell function, resulting in cell death.

How Prions Spread and Prevention Methods

Prions can arise in three different ways. One way is sporadically, where proteins randomly misfold without any direct cause (e.g., sporadic Creutzfeldt-Jakob disease). Another way prions can form is genetically. Inherited mutations in the gene coding for PrP can increase the likelihood of misfolding. The third way, which is more prevalent than commonly thought, is by acquiring. The direct transmission between people and contaminated food, medical equipment, or tissues (e.g., variant Creutzfeldt-Jakob disease linked to "mad cow disease") is a main cause of prion formation [3].

Mad cow disease is transmitted from cows to humans. Mad cow disease refers to the progressive neurological disorder of cows, meaning it worsens over time. When a cow is diagnosed with mad cow disease, it shows symptoms such as trouble moving, changes in personality, and looking sicker than normal cows. People can get BSE (mad cow disease) by eating a cow with neurodegenerative disease, causing them to acquire the disease as well. Mad cow disease cannot be acquired from an infected person, so it is not contagious in the way other diseases and sicknesses are [4].

Though prions are not contagious in the general sense, they can be spread through ingestion. An example of this would be mad cow disease, and because of this, stricter regulations were put in place in terms of food origin, transportation, and preparation. Another way prions are contagious is through transfer via medical equipment. Medical facilities have to follow special precautions and sterilization methods of surgical tools used primarily in high-risk tissue, in order to ensure safety of everyone involved [5]. Even with these precautions in place, there is still so much we don't know about prion diseases. Many scientists hope to find a cure in the near future, but it is unlikely [6].

Symptoms of Prion Diseases

Because prion diseases actively deteriorate nerves and neurons in the brain, the symptoms are devastating. Traits include rapidly developing dementia, difficulty walking, changes in gait, jerking movements of the muscles, hallucinations, muscle stiffness, confusion, fatigue, and difficulty speaking [3].

The Dangers of Prions

Prions are a great threat to biology and medicine because they do not respond to normal methods of sterilization. Because they are not bacterial or viral—they lack nucleic acids—finding treatments is a difficult challenge. High temperature and chemical disinfectants were used, but ultimately did not work effectively enough to eliminate all prions. Once prions are initially introduced in the brain, they are nearly impossible to get rid of. They can also stay dormant with symptoms appearing after years, making early detection close to impossible.

The diseases known collectively as transmissible spongiform encephalopathies, or TSEs, are always fatal. Examples of this include CJD, Variant CJD, Variably protease-sensitive prionopathy (VPSPr), Gerstmann-Sträussler-Scheinker disease (GSS), Kuru, and Fatal Insomnia (FI) [3].

Current Research

Modern research on prions is mainly focused on understanding how a "simple" protein misfolding can lead to drastic outcomes. Scientists have also explored how prions may be related to other neurological disorders such as Alzheimer's and Parkinson's disease [8]. This connection leads to new breakthroughs in both prion diseases and Alzheimer's and Parkinson's disease.

Conclusion

To conclude, the existence of prions is still a confusing topic which challenges scientists across the globe. Prevention methods are in place, and while there is hope for a cure, there are many confusing aspects associated with prion disease. Prions have been classified by scientists as "not 'alive' in the classic sense but not exactly 'dead' either," representing the confusion surrounding prions, and the difficulty in treating them [9].

By Sasya Koneru '28

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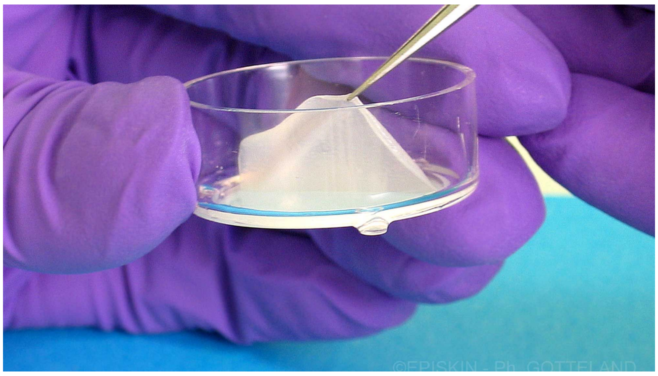

Advances in Bioprinting and Tissue Engineering: Opportunities, Challenges and Future Directions

Similar to how documents can be printed today, advancing technologies are enabling the printing of organs and bones, revolutionizing the field of medicine and healthcare. Bioprinting and tissue engineering are rapidly advancing fields in modern medicine, enabling the reconstruction of internal tissues and organs using cutting-edge technology. 3D bioprinting has further advanced the goals of tissue engineering, which initially focused on culturing replacement tissues using scaffolds and cells [5], [8]. Today, they envision life-saving treatments, personalized drugs tailored to individual patients, and solutions for organ shortages globally.

Bioprinting has already demonstrated several practical applications. For instance, researchers use printed tissues to screen drugs and model diseases, offering substitutes for animal models [3]. By printing tissues that closely mimic the structure and function of human organs, scientists can observe how cells respond to new drugs in a controlled environment. Similarly, disease-specific models can be created by incorporating patient-derived or genetically modified cells, allowing researchers to study disease progression and test potential treatments more accurately and efficiently. Printable skin grafts are being developed for burn victims to promote better healing and reduce scarring [4]. Cartilage, bone, and even vascular structures have been created through bioprinting, a process that uses layer-by-layer deposition of bioinks containing living cells and biomaterials to replicate the complex architecture of human tissues. By using patient-derived cells, bioprinting helps minimize immune rejection and advances the development of personalized medicine [2], [5]. Moreover, one of its most promising applications lies in addressing the global shortage of donor organs [4]. Thousands of individuals die every year while waiting for a transplant, and printed organs could provide a viable solution.

Pharmaceutical discovery also benefits from bioprinting, as testing on bio-printed tissue can accelerate drug development and reduce costs [3], [6]. Personalized therapies that utilize a patient's own cells enhance treatment effectiveness and reduce side effects [2], offering safer and more targeted medical interventions.

Despite progress, challenges remain. Cell survival in thick tissues is difficult without proper vascularization [2], [8]. Another challenge is high costs, along with the limited availability of specialized knowledge and printers. Achieving a balance between printability, mechanical stability, and biocompatibility in bio-inks continues to pose challenges [1], [6]. Printability ensures that the bio-ink can be precisely deposited to form complex tissue structures, while mechanical stability allows the printed construct to maintain its shape and withstand physical forces. At the same time, biocompatibility is crucial to support cell survival, growth, and proper tissue function, making it difficult to optimize all three properties simultaneously. Ethical considerations and the evolving regulatory framework make this field increasingly complex. For example, agencies such as the U.S. Food and Drug Administration (FDA) provide guidelines for the clinical use of bioprinted tissues, while the European Medicines Agency (EMA) regulates advanced therapy medicinal products, including bioprinted constructs. Despite these challenges, bioprinting nonetheless holds a highly promising future [1], [2]. 4D bioprinting, which enables tissues to change their shape or function over time, is currently under development [2], [7]. Artificial intelligence is also being included to optimize design and reproducibility [1]. Researchers are actively investigating space-based bioprinting, where it can aid in the healing of astronauts' injuries on long-duration missions. While the ability to print fully functional organs remains a distant goal, each advancement brings us closer to making this dream a reality [1], [7].

In conclusion, bioprinting and tissue engineering are two of the most leading edges of contemporary medicine and some of the most groundbreaking disciplines within biomedical science. Despite significant technical, financial, and ethical barriers that persist, the results achieved so far are highly commendable. With ongoing technological advancements and continued research, one day we may have the capacity to print fully functioning organs on demand, changing medicine and saving thousands of lives. With the power to print life, society holds the huge responsibility to finance, regulate, and steer this technology in a responsible manner, to guarantee that it is used in the best interest of everyone.

By Geetha Saravanan '26

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Electrogenesis in Electric Eels

Historically, the electric catfish *Malapterurus electricus*, was worshipped by the Ancient Egyptians as the "thunderer of the Nile" [1]. Its ability to biologically produce electric fields is seen across approximately 350 species of fish, including the three species of electric eel (*Electrophorus*) [2]. This ability is known as electrogenesis. Contrary to their name, electric eels are not related to true eels but instead are knifefish from the order *Gymnotiformes*; they are more closely related to catfish.

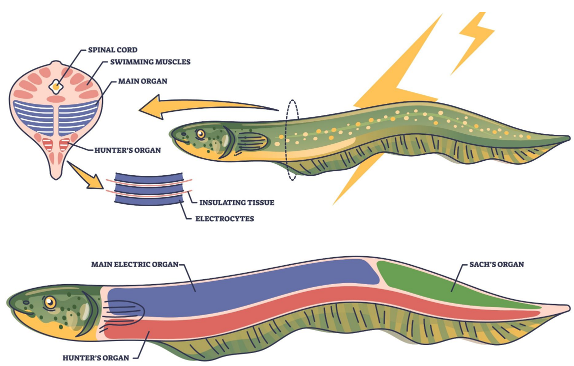
Electric eels possess three specialised electric organs (EO): the main organ, the Hunter's organ and the Sach's organ. These organs combined make up about 80% of its body. Their electrical function comes from disc-shaped electrocytes. These are arranged in parallel arrays, while individual cells are lined with ion gates. Electrocytes typically emit sodium and potassium ions to create a positive charge outside the cell and a negative charge inside.

When the eel's nervous system spots a predator or prey, it prompts the ion gates to open, allowing for mass flow of ions into the cells. This creates a polarity in charge across its membrane, with an alternating positive and negative charge on opposite sides of the cell, driving a current as a result. Each organ may contain thousands of electrocytes arranged in both series and parallel arrangements. Although individual cells produce a negligible voltage, the electrocytes in their totality can discharge up to 860 volts at peak currents of 1 ampere [3], [4].

Depending on situational needs, electric eels can produce two distinct electric organ discharges (EODs): low- and high-voltage.

The main organ is responsible for producing most of the high-voltage discharges, with the highest abundance of potassium ion gates. High-voltage EODs are used to overwhelm an organism's neuromuscular system by inducing spasms that immobilise it. They are generated by the main organ in several pulses and supported by the front end of the Hunter's organ to stun prey or to deter predators [5].

The Sach's organ, with the lowest abundance of potassium ion gates, generates low-voltage discharges in high-frequency pulses of around 10V; it is specialised for electrolocation and communication. These weak EODs are supported by the rear section of the Hunter's organ [5].



The Hunter's organ serves a dual purpose in electrogenesis, as it is able to generate both high- and low-voltage EODs. However, some studies indicate that the Hunter's organ contributes only to low-voltage EODs [6], [7]. Its function and evolutionary history is therefore unclear, even though it was discovered in 1775.

The purpose of electrogenesis in electric eels appears to be for navigation, hunting, and self-defence. In order to navigate and detect prey in murky waters, electric eels use active electrolocation. This involves a low-voltage EOD to generate a surrounding electric field. Objects or prey in the water distort the electric field based on their conductivity, and these distortions are then detected by the eel's electroreceptors buried in its skin. With this, the eel is able to map out or "see" its surroundings, regardless of the visibility of the water. This is especially important given that these eels are nocturnal in tandem with having poor eyesight.

Once an eel detects prey, it delivers high-voltage EODs to expose and immobilise it. This can include fish, crustaceans, insects, and small vertebrates. They often do so alone, however there is evidence to suggest that they take part in social predation by working in groups to herd prey into confined areas [8]. Combined with electrolocation, electric eels are able to accurately track and strike fast-moving prey even in darkness. They can also deliver powerful discharges to defend against predators such as caimans and jaguars by leaping out of the water and making direct contact to shock them [9].

In all, the electric eel's ability to generate electricity is a remarkable example of evolutionary innovation in adverse environmental conditions. They represent a unique class of electroreceptive organisms, containing electric organs that function similarly to a modern battery and providing a biological power source unlike most species in the animal kingdom. Beyond evolutionary intrigue, understanding its bioelectric capabilities would serve as a crucial step in informing bioengineering and energy research.

By Kingston Tew '26

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The Impact of Industry Funding on Clinical Research and Public Health

Introduction

Clinical research is the branch of scientific research concerned with "producing knowledge valuable for understanding human disease, preventing and treating illness, and promoting health" [1]. These aims underpin most research and have the potential to improve global health and our understanding of disease. However, real-world considerations mean this may not always be the case. Cost, research agendas, and the socio-political climate all have implications on research outcomes. The effects can span the social, political, and economic world, with research often influencing government policy and the operations of major industries [2]. Therefore, an observable tension exists between the imperative that research be conducted with neutrality, and the bias towards the confirmation of an agenda or promotion of a product.

The structure of clinical research

The standardisation of the scientific process means that there is a well-established procedure for carrying out research.

Each phase of the research system is complex and nuanced and provides a structure wherein scientists can investigate. The formulation of enquiry questions and a hypothesis form the foundation of the investigation and dictate its direction. A method to test the hypothesis is then developed. For reliable and accurate data to be collected, the methodology must ensure relevant variables are standardised, control groups are used, and biases are mitigated.

Double-blind trials are a common method employed to reduce biases. In such trials, participants are randomly assigned to a group that either receives a placebo (the control group), or receives the treatment being tested. The 'double-blind' in the method's name refers to the fact that neither the participants nor the doctors administering the treatments know which group each person has been placed in. Further variable standardisation methods also involve imposing stringent inclusion and exclusion criteria. This ensures that participants with desired characteristics (e.g. age range, a specific condition, or sex) are included in the study, while those with characteristics that may interfere with the trial (e.g. pre-existing conditions, concurrent medications, pregnancy, or breastfeeding) are excluded. Trial data is then analysed and statistical tests are used to draw scientific conclusions and answer the initial enquiry questions. Each section of the process is highly adaptable, lending itself to meet the needs of the research, but also creating room for external influence.

Traditionally, the final stage involves the submission of a manuscript for peer review before being published in a scientific journal. However, a changing publication landscape is seeing the peer review process be brought under scrutiny, with varying opinions on its efficacy for ensuring quality research outputs [3]. Some view bypassing the peer review process as a lack of 'quality control' for new publications, especially when considering the vulnerabilities to unscientific influence, whilst some argue the very nature of science requires ongoing post-publication review as our understanding develops [3]. Overall, this system grants uniformity, allowing each scientific paper to act as a brick in a growing wall of knowledge and a foundation for future research.

Research funding

There is a broad consensus on the importance and necessity for research. However, scientific investigation can be prohibitively expensive, meaning not all potential research projects can be carried out. The high cost associated with experimental research means scientists must turn to funding sources such as the government, public and private foundations, and industry. In modern academia, funding for research projects is limited and highly competitive, which arguably comes at a detriment to research quality [4]. Firstly, applying for grants and funding has become a time-consuming part of the research process, often requiring multiple applications to increase their chance of having one approved [4]. Secondly, it means researchers are obligated to comply with any conditions accompanying their funding, potentially requiring modifications to the study and shifting the study away from its original focus, ultimately curbing scientific freedom.

Motivation and influence behind funding research

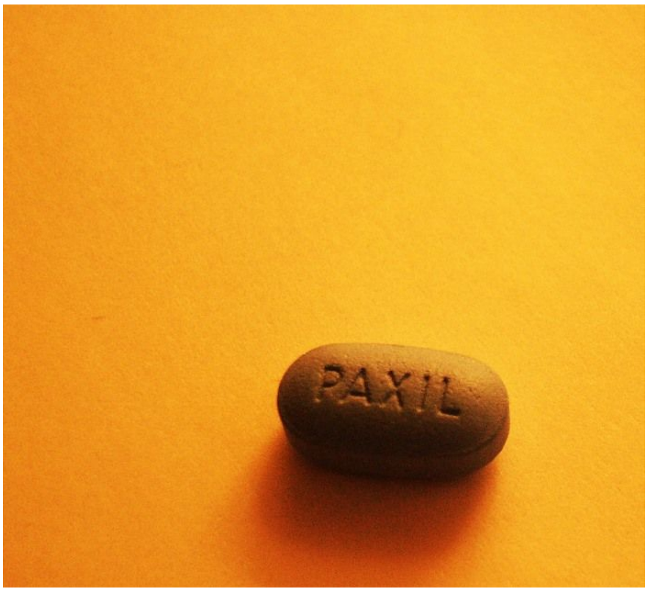
Each funding source has its own motivation. Governments, charities, and public bodies give grants to universities and researchers to either fund general scientific discovery or address specific issues they want to understand or tackle. The private sector's focus is normally related to developing and testing products for commercial purposes.

Most non-governmental sources of funding, i.e. industry and interest groups, have an incentive to support research that will produce favourable conclusions. Funding may be accompanied by expectations to publish or produce 'meaningful' results and often have conditions on how the money is spent. The expectations and conditions compromise scientific objectivity due to the influence they can have on the research and its outcomes.

In the case of governments and interest groups, this can be important in ensuring research focuses on pressing or otherwise unprofitable issues and therefore unlikely to receive private sector support. However, it may equally impose an expectation of providing a return on investment for the money spent. Consequently, researchers' scientific freedoms become limited, and their scope of action becomes narrowed to what is pressing (e.g. a disease outbreak) or profitable.

Additionally, the private sector can choose to fund and manipulate research to ensure that the conclusions or results from these experiments are aligned with their interests [5]. This is possible due to the susceptibility of research to influence at multiple stages in the process. Tactics used to achieve desired outcomes include: framing enquiry questions to elicit results favourable to the sponsor, steering studies towards commercial applications, and omitting or discrediting data not supportive of desired conclusions, among other practices [6]. These patterns of behaviour by industry have had significant effects on public health, noticeably with the promotion of products that are harmful to consumers.

Study 329 – A case study



Study 329 was carried out between 1994 and 1998 by SmithKline Beecham (a precursor of GlaxoSmithKline). The drug that was studied, a selective serotonin reuptake inhibitor (SSRI) marketed as Paroxetine (Seroxat in the UK), is commonly prescribed as an antidepressant to adults. The study, conducted across 12 hospitals in North America, sought to test the efficacy of the drug in adolescents between the ages of 12-18. The resultant paper, allegedly co-authored by 22 writers, was published in the Journal of the American Academy of Child and Adolescent Psychiatry (JAACAP) and claims that "paroxetine is beneficial in treating adolescents with major depression" [7]. However, it was later discovered that the paper was ghost-written by a medical communications company, with evidence of data manipulation by the firm in favour of the drug [8].

A review of the trial data by a team of researchers associated with the British Medical Journal's Restoring Invisible and Abandoned Trials (RIAT) initiative showed that the drug "was not statistically or clinically significantly different from placebo for any prespecified primary or secondary efficacy outcome" [9]. In reality, the drug increased suicidal and self-harm tendencies among the adolescents, the target group for the off-label use (the use of an approved drug for an unapproved effect) seeking to be authorised [9].

The study is an example of how industry sponsors may intercept multiple stages of the research process. In this case, we see how methodological malpractice, data manipulation, and results publication were altered for SmithKline Beecham's commercial benefit [8], [9]. The active influence of the corporation on the trial put the wellbeing of adolescents at risk. The study is not unique in its findings, with the RIAT initiative also bringing the unpublished "8-way" Bendectin Study under scrutiny and highlighting its apparent methodological shortcomings, despite it being used by the Food & Drug Administration (FDA) to justify the approval of the drug [10].

Analysis and Conclusion

Study 329 and the Bendectin study are clear examples of research manipulation by corporate sponsors. Influence was exerted at different stages in the research process, such as data analysis and the writing of the publication to ensure a favourable outcome. The evident threat posed to public health by scientific malpractice requires stronger and more rigorous safety nets. Examples of these include addressing the issues of the peer review process, providing open access to trial data, and mandatory publishing of results, allowing for better accountability by the scientific community. Given that industry funding is essential in sustaining many areas of research, the scientific community should learn to adapt and work with industry partners. Through the use of independent regulators and greater transparency measures, higher standards of scientific integrity can be achieved. This is particularly true in the context of current research climates in places such as the USA, where funding for research has been significantly cut by the government [11]. Fundamentally, the onus is on scientists to develop mechanisms to maintain a community of academic integrity and ensure our publications can be used as the stepping stones for future discovery.

By Samuel Betancourt Cortes '25

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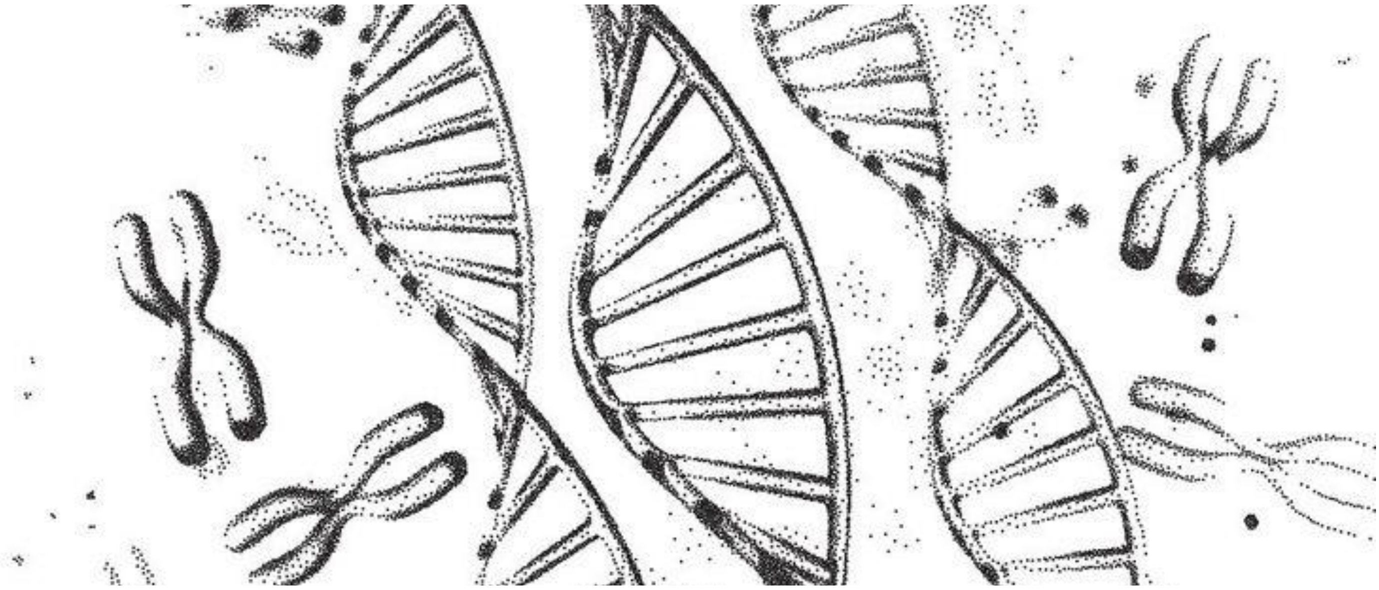

How Ancient Genomics is Shaping the Future

Ancient genomes are instrumental in understanding the past, giving insights into traits such as our physical characteristics, risk of diseases, and intellectual ability [1]. By analysing ancestral DNA, researchers have estimated that modern humans emerged around 111,000 to 300,000 years ago [2]. Using ancient genomics, we can explore the genetic diversity of Neanderthals and Denisovans [3].

Neanderthals and Denisovans Ancestries

Modern-day humans share a common ancestor with Neanderthals and Denisovans [4]. Around 600,000 years ago a group of early humans migrated out of Africa. They approximately diverged into Neanderthals in Europe and Denisovans in Asia [4]. These groups interbred with early-modern humans contributing DNA to the present day gene pool [5]. Most people outside of Africa typically carry 1-4% of Neanderthal ancestry. In comparison Denisovan ancestry is found in Asian populations ranging from 1-6% [6].

The genetic material from these early human groups contributes to vital traits. For example, some mutations provided ancient hominins with stronger immunity to survive in their environments.

Neanderthal and Denisovans passed down key immune-related genes including OAS and TLR1-TLR6-TLR10 that helps the modern human immune system recognise and respond to microbes [7]. However, these inherited traits also come at a cost. Certain Denisovan gene variants have been linked to a higher risk of inheriting coronary artery disease in East Asians. While Neanderthal alleles have an increased risk of coronary atherosclerosis in European descendants [8].

Beyond immunity, dietary habits also reflect on ancestral evolution. Ancient hominins possessed only a single copy of the AMY1 gene, which is essential for the breakdown of starch. In contrast, modern humans have multiple copies, suggesting an evolutionary shift towards a starch-rich diet and a rise in the agricultural lifestyle [9].

Ancient DNA and Its Effect on Skin Pigmentation

Ancient DNA reveals the environmental adaptations humans made, reflected through changes in skin pigmentation. In regions with reduced sunlight, exposure to lighter skin provided for more Vitamin D synthesis. While in sunnier areas, darker skin offered protection against folate degradation. These adaptations did not just affect appearance but also played a role in health and survival [10].

Investigating Ancient Pathogens

Insights into our past are not limited to ancient hominin DNA alone. Human specimens can also preserve disease-causing ancient pathogens. For example the bacterium *Yersinia Pestis* responsible for the black death has been found in specimens over 5,000 years old [11]. This highlights the longstanding evolutionary conflict between humans and bacteria.

By studying pathogens researchers can uncover the evolution and spread of infectious diseases over time. This includes endemic diseases such as malaria and tuberculosis and pandemic diseases such as the plague, which have left everlasting impacts on modern humans [12]. For an example scientists retrieved DNA from a 1,000-year-old South African mummy that contained mycobacterium tuberculosis. This sample was examined using spoligotyping [13], a PCR based method. It detects genetic variation between strains by analysing short DNA sequences known as spacers within the direct repeat locus of M. tuberculosis. Each strain has a unique combination of spacers [14] allowing scientists to distinguish between different bacteria species but also reveals how tuberculosis spread across different populations and time periods [13]. By looking into this we can get a better understanding of the epidemiology of ancient pathogens and also improve our reaction to modern outbreaks.

The Challenges of Extracting Ancient DNA

Extracting DNA from ancient hominin specimens is significantly difficult due to degradation over time. Environmental factors such as oxidative damage, hydrolysis, heat, pH levels and radiation exposure can affect DNA preservation. These conditions can also lead to contamination of the genetic material [16]. Traditional methods like PCR often produce an inadequate number of sequences with contaminants that make the result unreliable [15].

To estimate a sample's age, radiocarbon dating is used. This is a method utilising carbon isotope ratio (C^{12} and C^{14}) but can be inaccurate for contaminated specimens. To overcome this researchers have developed AI-based genomic dating models. One example is the TPS (temporal population structure) model, which estimates the age of ancient genomes by identifying TIM (time informative markers). TIM are allele frequencies that change over time.

AI analyses ancient and modern genomes to find temporal components which are DNA patterns that change over time. By learning how these patterns change, the TPS model can estimate when an individual has lived [17].

AI tools such as ARIADNA (artificial intelligence for ancient DNA) can differentiate SNV (single-nucleotide variants) from noise from DNA degradation. It can also outperform existing variant identification methods such as GATK and Antcaller to improve contaminant detection in ancient DNA samples [18].

Ancient DNA Relevance to Modern Healthcare

Ancient DNA research is fundamentally changing our approach to medicine especially on a genetic level. It also explains why certain populations are vulnerable to certain conditions by identifying ancient gene variants inherited [8]. Understanding this can initiate new treatment methods and even personalised medicine based on an individual's genetic background.

In summary, ancient DNA shows us how evolution, disease and environment shaped modern humans. Advances in AI allows scientists to extract and analyse ancient genomes with greater precision. Continued research into ancient genomics can pave the way to further improve modern-day healthcare.

By Thusshigka Thirukumaran '23

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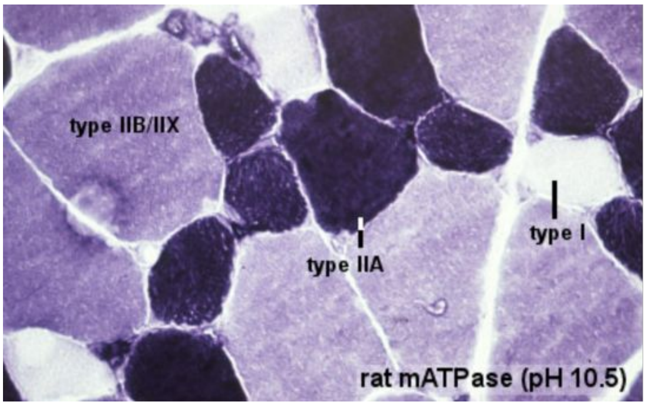
Frozen in Time: The Long-Debated Science of Rigor Mortis

Rigor mortis is the stiffening of muscles after death, caused by the loss of energy (adenosine triphosphate; ATP) and buildup of calcium in the muscles when breathing stops [1]. It typically starts in small muscles around the jaw and then continues to spread throughout the body [2]. Research shows that factors like muscle type, energy reserves, and physiological state at the time of death influence how rigor develops. Studies with rats have also found that the cause of death, such as asphyxiation or poisoning, can alter the timing and progression of rigor mortis [3]. Differences in muscle fiber type and size also play a role, meaning both the structure and metabolism of muscles impact the process [4]. Overall, rigor mortis develops based on a combination of biological and chemical factors.

A fundamental study of rat masticatory muscles, the muscles responsible for chewing, highlighted the influence of both fiber type and muscle volume on rigor development [4]. The results showed that white muscles, made up mostly of type IIB fibers, retain ATP longer after death than red muscles, which consist mainly of type I and IIA fibers. This difference occurs because white muscle fibers have more enzymes for breaking down sugar, which keeps ATP available for longer and delays rigor mortis. In contrast, red fibers rely on oxidative phosphorylation, the process by which cells use oxygen to produce energy, and tend to lose ATP more rapidly [4]. This study also proposed that larger muscles, which typically contain more glycogen, experience a slower decline in ATP. These findings suggest that both fiber type and muscle size play important roles in determining the sequence and timing of rigor mortis.



The relationship between muscle type and metabolic activity further explains why rigor mortis follows a descending pattern through the body. Small skeletal muscles in the head and neck often contain a higher proportion of fast-twitch (type II) fibers, which rely heavily on anaerobic metabolism and deplete ATP quickly [2]. Without sufficient ATP, muscle relaxation becomes impossible, and actin-myosin cross-bridges remain locked, resulting in rigidity [5]. In comparison, larger muscles such as those in the limbs and torso, which contain a greater concentration of slow-twitch (type I) fibers, rely on aerobic metabolism and retain ATP longer [2]. This physiological difference helps explain the sequential nature of rigor's progression. Given that rigor mortis progresses differently in various muscle fiber types, genetic factors that influence the distribution and characteristics of these fibers can also impact its development. Individuals naturally vary in their muscle fiber composition due to genetic differences, which affect muscle metabolism and energy utilization. These variations can alter the timing and severity of rigor mortis. Another key factor is the physical condition of the body prior to death. Intense muscular exertion, whether voluntary or induced by external substances, can lead to a rapid decrease in ATP, triggering an earlier onset of rigor mortis [6]. However, this accelerated onset of rigor does not always lead to a quicker resolution. For example, in cases of strychnine poisoning, characterized by intense convulsions, rigor sets in earlier and lasts longer due to substantial ATP depletion prior to death [3]. This observation suggests that factors beyond ATP alone, such as calcium ion buildup or systemic physiological stress, contribute to the regulation of rigor mortis.

Temperature plays an important role in the development of rigor mortis. In warmer conditions, increased enzymatic activity accelerates ATP breakdown, leading to a faster onset of muscle stiffness. In contrast, lower temperatures slow these enzymatic processes, causing a delay in both ATP depletion and the progression of rigor mortis [5]. Forensic researchers have noted that cooler environments not only postpone the initiation of rigor but can also prolong its duration. This variability highlights the importance of accounting for environmental factors when estimating the time of death in forensic investigations.

The cause of death can further complicate how rigor mortis develops. Animal studies have shown that the type of fatal event can significantly influence how rigor develops; for instance, Krompecher and colleagues observed that rats subjected to different causes of death, such as intoxication or suffocation, displayed clear differences in rigor mortis progression [3]. In contrast to cases involving intense pre-mortem muscle activity, such as strychnine poisoning, carbon monoxide poisoning has been shown to delay the progression of rigor, likely due to its effects on oxygen delivery and overall metabolism [3]. These variations reinforce the importance of considering cause of death when analyzing rigor mortis as a postmortem indicator.

One of the more practical challenges in rigor mortis analysis is ensuring accurate measurement. Relying solely on a single observation of muscle stiffness can be misleading, as the development of rigor varies with numerous internal and external factors. Krompecher's study emphasized the benefit of serial measurements over time, using objective methods such as torque rigidity, which gauges muscle resistance when twisted, to provide a more precise assessment of muscular stiffness [3]. This approach provides a clearer picture of rigor's development and allows for more accurate estimation of the postmortem interval.

Overall, rigor mortis develops through a complex mix of anatomical, biochemical, and environmental factors working together. ATP depletion remains the central biochemical trigger, but it interacts with fiber type, muscle volume, temperature, and cause of death in complex ways. Although rigor mortis continues to be widely used in forensic investigations, the inconsistencies introduced by external conditions and individual physiological variation emphasize the need for further research. Continued study of rigor mortis at the molecular and cellular levels may lead to more precise forensic tools and a deeper understanding of the postmortem timeline.

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The Rise Of Biodegradable Polymers

Plastics are an essential part of modern life, used in everything from packaging and electronics to medicine and transportation, largely due to their extensive durability and versatility. However, these perceived strengths have also created one of the most pressing environmental challenges of our time. Each year, millions of tons of plastic waste accumulate in landfills and oceans, where they remain for hundreds of years. As global awareness of plastic pollution grows, researchers are working to design sustainable materials that retain the versatility of conventional products while minimizing their environmental impact. In order to build a more sustainable planet, it is crucial to understand the science behind these materials and the challenges of using them, as well as their future potential in the daily lives of people worldwide.

Biodegradable polymers have emerged as one of the most promising innovations in this field. They are bio-based and derived from organic resources, such as plant starches, and can serve as alternatives to conventional plastics. They are designed to decompose under specific environmental conditions due to the action of naturally occurring microorganisms. However, the rate and completeness of this degradation can vary depending on the environment [1], [2].

The Science Behind Biodegradable Polymers

Polymers are large molecules made up of many repeating smaller units called monomers. These may be naturally occurring, like proteins or cellulose, or synthetic, like plastics or nylons. Biodegradable polymers are broken down differently from traditional plastics because of their unique chemical structures. While traditional plastics persist for centuries, breaking down into smaller and smaller microplastics that pollute the environment, biodegradable polymers are degraded by microorganisms into basic elements like water, carbon dioxide, and biomass, leaving behind no long-term waste. This process is also much quicker than the decomposition of traditional plastics.

PLAs and PHAs

Among the many different variations of biodegradable polymers, polylactic acid (PLA) and polyhydroxyalkanoates (PHA) are the most widely recognized and utilized because of their potential to replace petroleum-based plastics in commercial applications.

Biodegradable plastics are classified based on their sources and the properties that determine how they perform in different industries. They are divided into two main categories: biobased and petroleum-based [1]. Biobased plastics are made from renewable materials, such as plant starches, feedstocks, proteins, and microbial polyesters produced by microorganisms. In contrast, petroleum-based plastics are created from synthetic polyesters like aliphatic and aromatic [1]. PLAs and PHAs are both biobased polymers with a wide range of applications.

PLA is a biodegradable polyester often derived from cornstarch, and it is one of the most used bioplastics, utilized to create fermented sugars from crops like corn or sugarcane. It is strong, lightweight, transparent, and biocompatible, meaning it is not harmful to living tissue. However, it tends to lose strength at high temperatures [2]. Despite this weakness, PLAs are suitable for packaging, textiles, and especially biomedical fields, where their biodegradability and compatibility with human tissue make them ideal for use in tissue engineering and regenerative medicine [3]. PLAs are also FDA-approved for use in food and beverage packaging [1].

PHAs are naturally occurring biopolymers produced by bacteria that ferment sugars and lipids. More than 150 different PHA monomers have been identified, offering a wide range of properties. Because many PHA types are non-toxic and highly biodegradable, they are widely used in medical devices, drug delivery systems, biodegradable implants, and tissue engineering, as well as agricultural products, compostable bags, and packaging [1].

While both PHA and PLA are biodegradable polymers with similar medical applications, PLA typically degrades faster into lactic acid, which the body can metabolize, making it well-suited for rigid implants and shorter-term devices. On the other hand, PHA degrades more slowly and is more flexible, making it more useful for soft-tissue scaffolding, which supports tissue regrowth, as well as for longer-term implants [4].

Polymer Blending and Its Advantages

A growing strategy for improving biodegradable materials is the blending of different polymers. This approach helps overcome the limitations seen in single polymers, including weak mechanical performance, limited processability, or unsuitable degradation rates for specific applications. When two or more polymers are combined, the resulting product can be designed with tailored properties that balance the characteristics of each, improving functionality and environmental compatibility [3].

A key advantage of this method is that it allows for the fine-tuning of degradation behavior, as blending fast- and slow-degrading polymers produces materials that decompose at a rate appropriate for its intended use. This property is particularly valuable in fields like medicine and agriculture, where the lifespan of the material plays a critical role [3]. For instance, medical implants often require materials that remain stable for a defined period before requiring removal, and using blended biopolymers reduces the need for manual disposal, allowing the implants to naturally degrade instead [3].

Additionally, polymer blending allows for the improvement of mechanical and physical characteristics. PLA is a good example of this, as it is a widely used biodegradable polymer, valued for its mechanical strength and transparency. However, it also tends to be brittle and lacks flexibility [2]. The incorporation of more flexible polymers, such as PHAs, greatly expands the possible applications of this biopolymer, enhancing flexibility while maintaining PLA's strength and transparency [3].

Environmental and Economic Impact

The environmental benefits of biodegradable polymers are more than just reducing plastic pollution. Since they are derived from renewable sources, they release less greenhouse gas emissions and decrease fossil fuel dependency compared to petroleum-based products [1]. They play a large role in preventing waste accumulation and are able to contribute to environmental improvement while maintaining the balance of the biogeochemical cycle. They also save the nonrenewable natural resources typically used in the production of plastics.

From an economic standpoint, blended polymers offer a cost-effective and efficient way to tailor characteristics while keeping carbon footprints low. It allows researchers and manufacturers to modify polymer properties without needing to develop entirely new compounds, reducing both research expenses and production energy [5].

Large-scale production of bioplastics, however, remains about 20-30% more expensive than traditional plastics due to higher material and processing costs [5]. This is further exacerbated by limited recycling and composting infrastructure. Nevertheless, as research in polymer blending and microbial fermentation advances, costs continue to decrease and performance continues to improve. This trend is reflected in the significant increase in biodegradable plastic production over the last five years.

By replacing conventional plastics with these biodegradable alternatives, industries can lessen their long-term environmental damage and open opportunities for more sustainable production systems that reduce waste and carbon emissions globally.

Future Potential and Conclusion

The development of biodegradable polymers continues to evolve as researchers find ways to overcome the material and production challenges that stop biopolymers from becoming widely adopted. One major area of focus is improving the mechanical strength and thermal stability of bioplastics, like PLA, so they can become a more viable competitor for traditional polymers in terms of durability and versatility. Scientists are also exploring how to use advanced enzyme-based and microbial degradation techniques to accelerate decomposition and make these materials more practical in the day-to-day lives of people in diverse environments [1], [3]. Additionally, innovations in feedstock sourcing, used in the development of PLAs, aim to reduce both production costs and competition with food resources [1].

The global shift towards sustainability is represented in the rapid expansion of the bioplastics industry [5]. The ability to customize mechanical properties and degradation behavior through polymer blending is a significant step in the direction of greener material innovation, providing a solution that merges environmental responsibility with practicality. Looking ahead, collaboration between scientists, industries, and policymakers will be crucial to building the infrastructure and economic incentives needed for large-scale adoption and production. As polymers become more efficient and accessible through advances in biotechnology, they offer a realistic path toward a more sustainable future.

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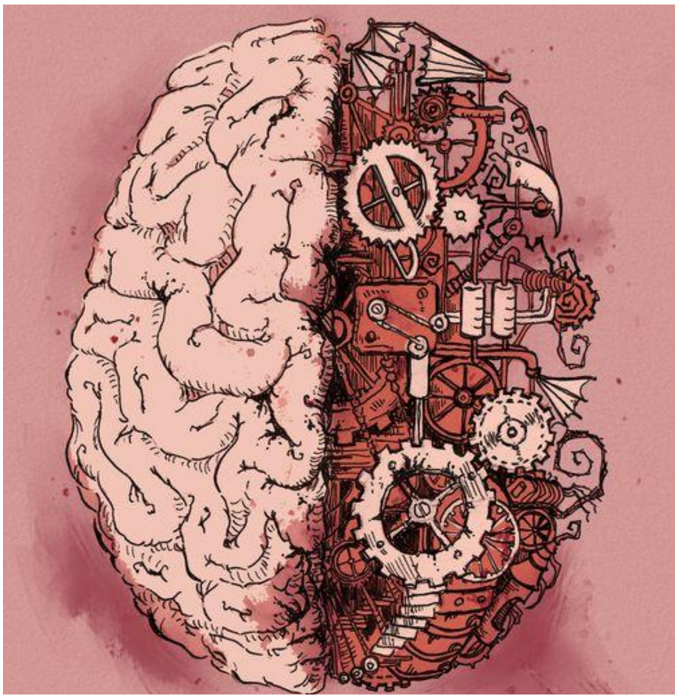

Engineering the Human Mind: Neuromodulation and Brain-Machine Interfaces Advances

Introduction

Biomedical engineering is a rapidly advancing field that integrates medicine and technology that creates transformative innovation. The integration of engineering principles, neuroscience, and clinical practice,have allowed for the development of groundbreaking tools that are transforming our understanding of treatment for the enhancement of the human brain. Among the most sensational advances are neuromodulation technologies like deep brain stimulation (DBS) and noninvasive stimulation methods.

Through the exploration of engineering concepts, clinical applications, and ethical implications of DBS, medicine is experiencing a transformational change. Biomedical engineering is transforming modern neurosurgery and neuroscience to usher in medicine and technology that will merge as a cohesive whole.

Deep Brain Stimulation and Its Clinical Applications

Deep brain stimulation was first cleared by the U.S. Food and Drug Administration (FDA) in the late 1990s as Parkinson's disease management. The treatment involves surgically implanting electrodes into specific regions of the brain and stimulating them with electrical impulses to regulate neuronal activity. Through adjustment of aberrant neural circuits, DBS provides relief from motor symptoms such as tremor, rigidity, and bradykinesia [1].

Unlike pharmacologic therapies, which taper off in efficacy over time, DBS is a long-term, tunable treatment that is tailored to fit each patient. Clinicians can modulate stimulation parameters in real time, a feature that makes DBS flexible compared to fixed drug treatments.

The uses of DBS are not limited to movement disorders. Clinical trials and treatment studies have been effective in obsessive-compulsive disorder, major depressive disorder, epilepsy, and Tourette syndrome [2]. Advances in engineering have been the principal drivers for this development. As an example, the development of closed-loop systems, which adjust stimulation autonomously on the basis of neural feedback, helps DBS in decreasing side effects and improving therapeutic accuracy [3]. Such progress underscores how biomedical engineering is transforming neurosurgical practice.

New Noninvasive Neuromodulation Methods

While DBS requires invasive neurosurgical implantation, noninvasive neuromodulation methods are becoming increasingly clinically relevant. Of these, transcranial magnetic stimulation (TMS) has appeared as a common FDA-approved and employed treatment for depression that is resistant to medication. TMS applies targeted magnetic fields to create electric currents in cortical neurons, modulating brain circuits without surgical enhancements [4].

A second promising approach is transcranial direct current stimulation (tDCS), which applies weak electrical currents transmitted through the scalp to modulate neuronal excitability. Initial studies indicate potential benefits for cognitive enhancement, stroke rehabilitation, and pain management. These methods present formidable engineering challenges, including maximizing current delivery through the skull, increasing spatial resolution, and ensuring patient safety [5].

New electrode designs and computational models of current distribution are being developed to break down the barriers. By enhancing stimulation accuracy, biomedical engineers are making way for noninvasive neuromodulation to more populations. The promise to democratize brain-based treatments enhances the fundamental role of engineering in expanding healthcare equity.

Brain-Machine Interfaces: Restoring Function and Beyond

Long-term vision for BMIs exceeds rehabilitation. As technology continues to evolve, scientists are looking towards applications in cognitive enlargement, memory enhancement, and human-computer symbiosis. Such opportunities extend beyond medicine to philosophy and ethics and raise basic questions about the future of human identity and autonomy.

Brain-machine interfaces represent a major sector of engineering, neuroscience, and clinical medicine, forming the foundation for many of the emerging applications previously mentioned. BMIs unscramble neural messages and translate them into external instructions, enabling individuals with paralysis or loss of limbs to operate robotic body parts, enter virtual environments, and become exoskeletons [6].

Groundbreaking research has already shown tetraplegic patients controlling prosthetic limbs directly through their thoughts. A situation facilitated by advancements in recent years through neural sensors, machine-learning algorithms, and real-time signal processing [6]. More recently, BMI-assisted neuromodulation has enabled patients of spinal cord injury to regain voluntary limb control, a revolution in rehabilitation [7].

Advances in engineering have been behind such breakthroughs. Improvements in wireless communication have brought an end to tethered systems, while device miniaturization is paving the way for use outside research settings. Recent discoveries are aimed at the creation of fully implantable, long-term, and biocompatible BMI systems that are added into the nervous system.

Ethical and Societal Issues

While neuromodulation and BMI technologies are replete with unprecedented promise, their rapid progress necessitates serious ethical consideration. Key concerns include risks of cognitive augmentation, informed consent for vulnerable patient groups, long-term safety of the implanted devices, and the psychological effects of brain-based augmentation.

Equity of access is another key question. Without deliberate policy and engineering intervention, cutting-edge treatments risk being accessible only to privileged groups, widening current disparities in neurological care. Biomedical engineers and clinicians share a responsibility to demand that innovation come with inclusivity. This requires designing cost-effective tools, advocating for equitable healthcare delivery, and engaging in cross-disciplinary conversations that incorporate ethics, law, and social science.

Conclusion

The convergence of engineering and medicine via neuromodulation and brain-machine interfaces are rapidly evolving and changing the treatments available for neurological disorders.

Deep brain stimulation has expanded from Parkinson's disease to psychiatric and neurological disorders, and noninvasive neuromodulation offers safer and more accessible options. Meanwhile, brain-machine interfaces are revolutionizing rehabilitation and redefining the division between humans and technology.

Biomedical engineers are on the cutting edge of these advances, combining technical expertise with clinical experience to engineer treatments that are tailored, adaptive, and transformative. As progression continues, BMIs promise not just to restore function but to expand the range of human thought and interaction with technology. The future of medicine will be distinguished by systems that are not only more personalized but more integrative—technologies that do not only repair the brain but transform it.

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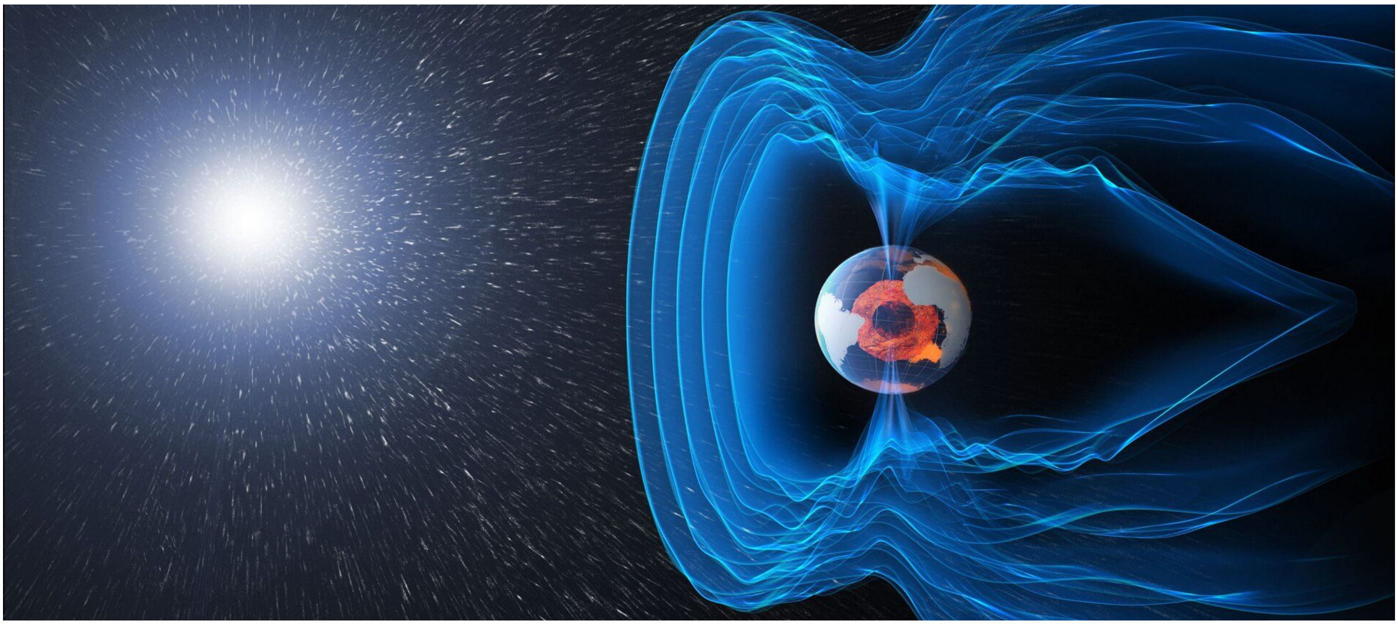


Effect of Cosmic Radiation on Human DNA

Introduction

Cosmic radiation refers to streams of high energy charged particles that originate from galactic, solar and interstellar sources. These particles constantly travel through space and can penetrate biological tissue, posing significant risks to astronauts and other individuals. Understanding the threats of cosmic radiation on human DNA is a key concern in the fields of radiation physics, space medicine and biology.

Nature and Sources of Cosmic Radiation

Cosmic radiation is a steady reminder that life survives only under the protection of Earth's atmosphere and magnetic field. Cosmic radiation refers to high-energy, charged particles produced in space. These particles travel through the universe at nearly the speed of light [1]. Cosmic radiation originates from energetic particles emitted by the Sun and distant astrophysical sources such as supernovae and black holes. When these charged particles, which are mainly protons, heavy ions, and high energy electrons, enter Earth's atmosphere they are absorbed by the Earth's atmospheric layers. However, outside Earth's protective shield beyond low Earth orbit, which is 160 to 2,000 kilometers above the planet, astronauts are directly exposed to these high linear energy transfer (LET) particles [2]. These are typically large, charged particles like alpha particles and neutrons, which cause dense ionization and significant, localized biological damage.

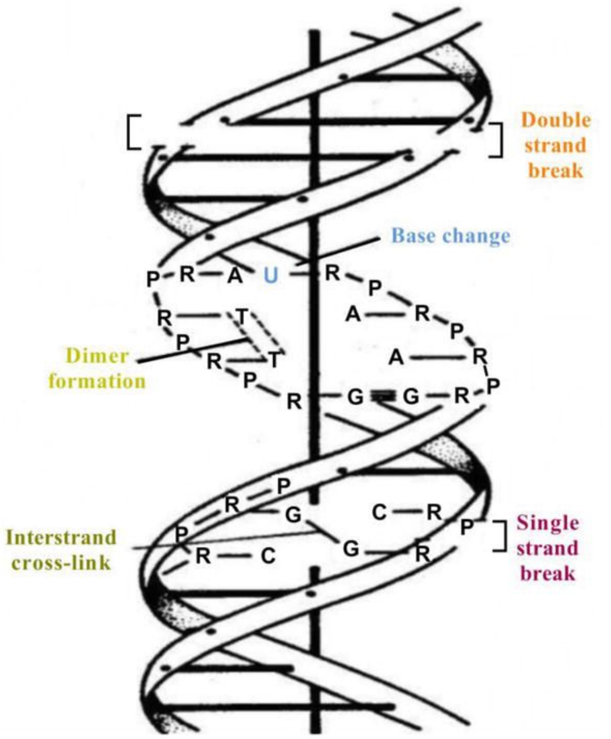
Classification of Cosmic Radiation

Cosmic rays are generally classified into three primary types based on their origin, namely, Galactic Cosmic Rays (GCRs), Solar Energetic Particles (SEPs), and Anomalous Cosmic Rays (ACRs).

GCRs emanate from outside our solar system, likely from supernova explosions, black holes and other high-energy astrophysical phenomena in the Milky Way. These rays consist of protons, helium, and heavy ions, with high energy. In contrast, SEPs have moderate to high energy. They originate from the Sun, especially during solar flares and coronal mass ejections. These rays are made up of protons, alpha particles, and electrons. Whereas, ACRs emerge from within the solar system from neutral interstellar atoms that become ionized and are accelerated at the heliospheric boundary. The heliospheric boundary is the region where the Sun's solar wind meets and is pushed back by the interstellar medium. This boundary is not a solid surface but an invisible, dynamic bubble of plasma. ACRs are made up of He, N, O, Ne ions and have low to moderate energy.

Energy Characteristics and Ionizing Nature of Cosmic Radiation

The range of energy contained in cosmic radiation is tremendous, spanning from 10^7 eV to 10^{20} eV [3]. They are a form of ionizing radiation. This indicates that they have high energy such that they are capable of displacing electrons from atoms in biological tissues. There are two common mechanisms by which cosmic radiations induce harm to human DNA.



Direct ionization is a process when a charged particle has sufficient kinetic energy to directly remove an electron from an atom or a molecule through collision.

In direct ionization the radiation particles strike the human DNA directly and break chemical bonds. This leads to single strand breaks (SSBs) and double strand breaks (DSBs). Indirect ionization is a process when an uncharged particle deposits its energy in a material to create a charged particle that then causes ionization. The radiation interacts with water molecules that make up approximately 70% of cells. This generates unstable molecules called reactive oxygen species (ROS), such as hydroxyl radicals (•OH), which readily react with cellular components and can damage DNA.

DNA Damage Detection and Repair Pathways

Specialized proteins constantly scan DNA for irregularities. When damage such as single strand breaks (SSBs) and double strand breaks (DSBs) occur, sensor proteins like Ataxia-Telangiectasia mutated (ATM) and Ataxia Telangiectasia and Rad3-related proteins (ATR) recognize the break sites. Once damage is detected, these sensors trigger a signaling cascade that activates checkpoint kinases (CHK1, CHK2) and transcription factors like p53. This halts the cell cycle to prevent the cell from dividing before the damage is fixed. Damages induced by cosmic rays are difficult to repair as they overwhelm cellular repair mechanisms. The repairing process can either be slow, error-prone or can even cause mutations.

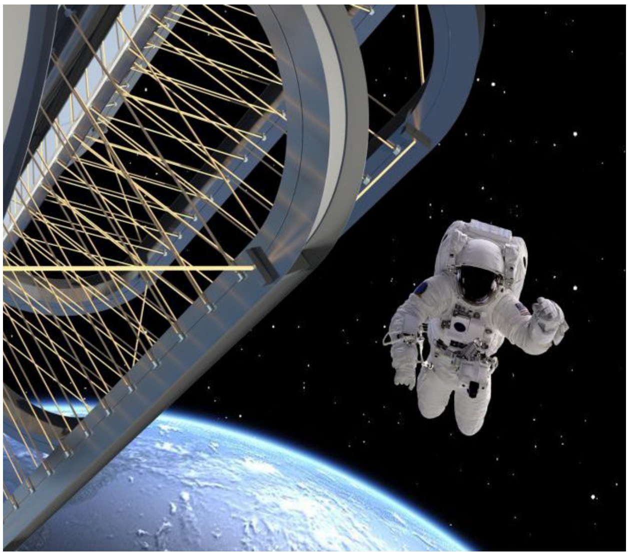
Biological Impacts

Charged particles containing high-energy, such as protons and heavy ions, present in GCRs induce direct ionization by colliding with atoms and molecules within biological tissues. Therefore, they displace electrons and break chemical bonds. This mechanism can cause immediate molecular disruption, including clustered DNA strand breaks along the ionization track. When these high-energy particles interact with intracellular water molecules, they generate secondary radiation and ROS deriving indirect ionization. The ROS formed, including hydroxyl radicals and hydrogen peroxide, further react with DNA bases and the sugar-phosphate backbone, amplifying cellular damage. Thus, the combined action of direct and indirect ionization makes cosmic radiation uniquely dynamic in inducing complex biological effects compared to most radiation sources.

High Linear Energy Transfer particles, such as heavy ions found in the GCRs are extremely damaging as they create dense ionization tracks that result in clustered DNA damage. This is a combination of single and double strand breaks that are difficult for cellular repairing mechanisms to correct. For instance, studies conducted on astronauts aboard the International Space Station (ISS) have shown increased chromosomal aberrations, including deletions, translocations, and aneuploidies, due to prolonged exposure to space radiation [4]. Such DNA damage, if misrepaired, can lead to mutations, carcinogenesis (specifically lung carcinogenesis) or degenerative diseases over time, posing a major barrier to safe long-term spaceflight [5].

Health Risks and Overall Conclusions

Beyond DNA damage, radiation also affects other biological systems, leading to immune suppression and cognitive decline during long-duration missions. In spite of advances in understanding these mechanisms, predicting the extent of long-term genetic damage remains complicated due to the variable composition and energy of cosmic radiation. To reduce the risks, agencies are developing radiation shielding materials and optimized spacecraft designs. Current research continues to focus on genomic repair mechanisms, biomarker detection, and artificial magnetic shielding to mimic



Earth's natural protection. Understanding and mitigating the effects of cosmic radiation are therefore critical for ensuring astronaut health and the long-term feasibility of human deep-space travel. Continued interdisciplinary research in radiation physics, space medicine, and molecular biology remains essential to meet the challenges of living and working safely beyond our planet.

By Rimsha Dharwar '28

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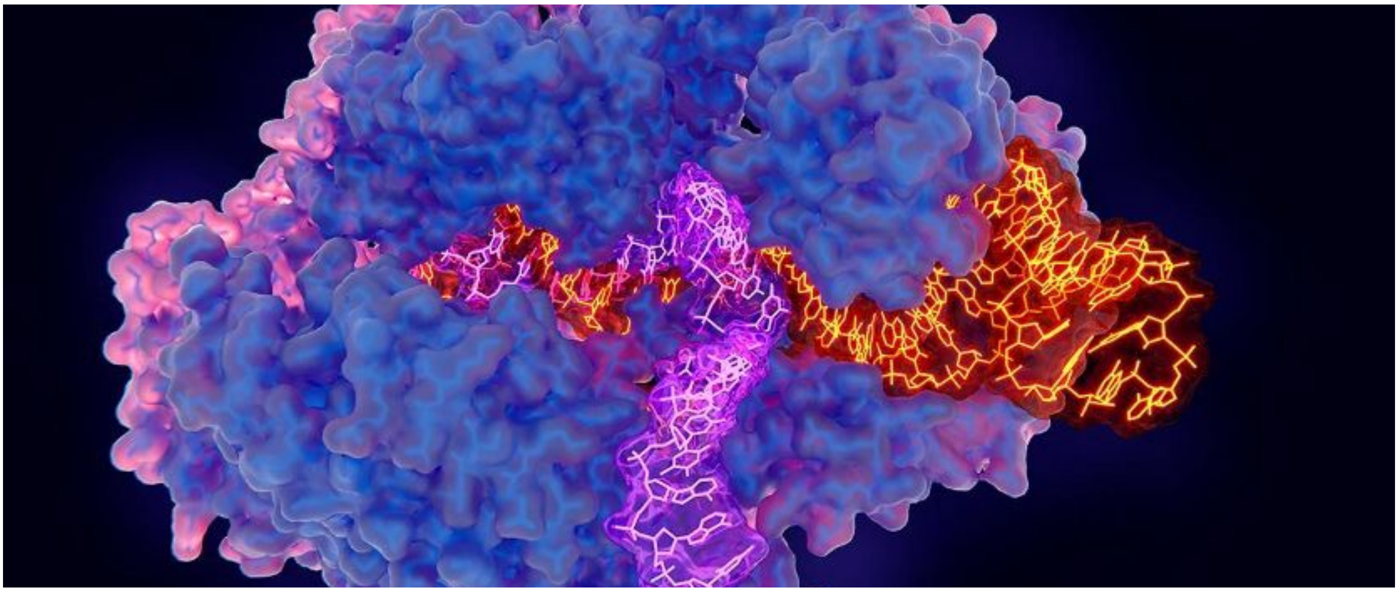


CRISPR Gene Editing: Bridging Science, Medicine, and Ethics

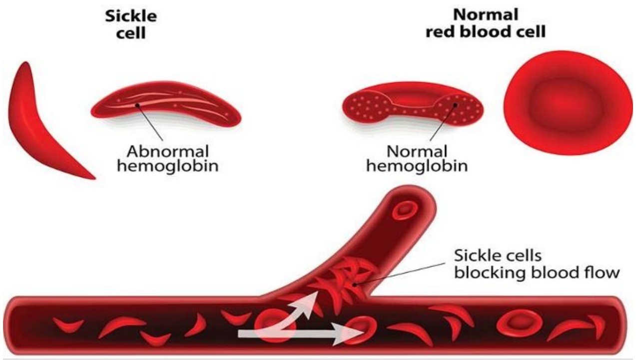
CRISPR gene editing has become a frequent topic of discussion in scientific and public circles. CRISPR, short for clustered regularly interspaced short palindromic repeats, is one of the most revolutionary tools in modern biomedicine. Although CRISPR is widely discussed, most information is either highly technical, targeted at advanced biochemists, or overly simplified for the general public. This discussion bridges that gap, making CRISPR accessible to those seeking a digestible, scientifically accurate explanation. Beginning by introducing the CRISPR mechanism and exploring how humans can use it to edit genes. Then, examining the medical implications of CRISPR in humans, with a particular focus in the treatment of sickle cell anemia, and lastly, considering the ethical implications of gene editing associated with CRISPR.

The Science Behind CRISPR

Genome editing refers to the deliberate modification of DNA at a target site [1]. In humans, gene editing can be used to produce new favourable traits, remove unfavourable traits, or inactivate harmful genes. CRISPR-Cas is a favourable editing tool because it is straightforward, inexpensive, performs well, is repeatable, and operates in fast cycles. CRISPR is an immune system in microorganisms [2], such as E. coli and S. pyogenes [3]. CRISPR-Cas 9 works naturally as an adaptive immune response in bacteria where it keeps some of the viral DNA of past infections as a memory. This DNA will be used by CRISPR to make a guide RNA sequence [2], which enables the bacteria to react quickly and effectively during the next exposure [3]. The significance of CRISPR was underscored in 2020 when Emmanuelle Charpentier and Jennifer A. Doudna won the Nobel Prize in Chemistry for discovering that CRISPR-Cas 9 can be used as a gene editing tool [4].

CRISPR In Medicine: The Case of Sickle Cell Anemia

CRISPR-Cas 9 has excited researchers due to its potential in curing human diseases. Sickle cell anemia is an inherited disease which results from a gene mutation causing the red blood cells to become "sickle"-shaped rather than their normal disk shape [5]. Sickled red blood cells are unable to move efficiently and can inhibit blood flow throughout the body. This disease persists for life which can result in serious health complications such as chronic pain or stroke.



Sickle cell anemia is a relatively simple disease usually caused by a single mutation [1], making it a good target for CRISPR therapy. In 2023, the FDA approved the first CRISPR-based therapy for sickle cell anemia [6]. This therapy can boost fetal hemoglobin production to prevent red blood cells from sickling. There have been several clinical trials testing this, and while many are still ongoing, the CTX001 (Casgevy) trial has been successfully completed. In addition to genome editing, scientists have been using CRISPR as a tool to create animal models and cell models, which has allowed for researching diseases such as mental illness and even cancer [7].

Ethical Considerations

Although CRISPR offers extraordinary promise, ethical questions have been raised. Gene editing requires careful consideration of risk versus benefit [8]. Firstly, there are worries regarding safety and potential errors. CRISPR gene editing is a new tool, and with that comes a level of uncertainty such as unpredictable side effects. Next, CRISPR gene editing may impact biodiversity, which is the diversity of species and a variety of genes within the species. Biodiversity is important because it allows species to adapt to changes.

CRISPR has also raised concerns about inequalities. Genomic treatments cost around $2 million per patient and are often not covered by health insurance. These treatments have the potential to deepen the inequalities in healthcare access. Additionally, treatments such as CRISPR can leave vulnerable populations at risk. Concerns of discussions of eugenics or promoting discrimination against race, sex, gender and disabilities is a possible risk. Further ethical questions arise when considering diverse religious and cultural beliefs. For some, CRISPR may be an overreach of human power. Views on this issue vary widely across individuals and cultures.

Conclusion

To conclude, CRISPR gene editing represents one of the most significant breakthroughs in biomedicine. CRISPR has the potential to cure diseases such as sickle cell anemia. However, this new technology has created important discussion around the ethical implications of gene editing in humans. Balancing innovation with responsibility will be essential to ensuring that CRISPR benefits humanity.

By Sydney Kozera ‘24

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The role of metformin in the treatment of Alzheimer's

Alzheimer's disease (AD) is the most common cause of dementia, affecting an estimated 55 million people worldwide [1]. This number is expected to double by 2025 due to the growing ageing population, emphasising the need for new treatments. AD is characterised by progressive memory loss and cognitive decline in abilities such as learning and decision-making. These characteristics are associated with the accumulation of amyloid-beta plaque (abnormal protein clumps), tau tangles (twisted fibres of a protein that disrupt nerve function) and chronic neuroinflammation (long-term activation of the immune system). The enzyme AMP-activated protein kinase (AMPK) is an important molecular pathway linked to AD progression. In healthy patients, AMPK is activated during low-energy states where it stimulates glucose uptake and fat burning. However, the role of AMPK is disregulated in patients with AD.

Despite decades of research and costly trials, only one novel treatment has been approved. However, it has been linked to severe side effects such as brain swelling and haemorrhage. These limitations have channelled an interest in drug repurposing, which is the process of identifying new applications for existing medicines. Repurposing drugs has many benefits including quicker development time, lower costs and established safety profiles [2]. An example of this is Metformin, which lowers blood glucose and is the most common first-line oral therapy for type 2 diabetes [3].

Experimental evidence from mouse models

For the experiment shown in Figure 1, researchers injected a widely used transgenic model (APP/PS1 mice) and wild-type mice with brain extracts containing tau protein clumps at nine months of age. The mice were then given metformin diluted in drinking water for two months before their brains were analysed. The brains of the APP/PS1 mice showed several changes. They had reduced amyloid-beta plaque buildup and fewer tau tangles, which indicates there is a potential slowing of Alzheimer's pathology. Additionally, the mice showed an increased number of neuroprotective microglia which are resident immune cells found in the central nervous system. These microglia cluster around amyloid-beta plaques and enhance clearance mechanisms in the brain, making it more neuroprotective

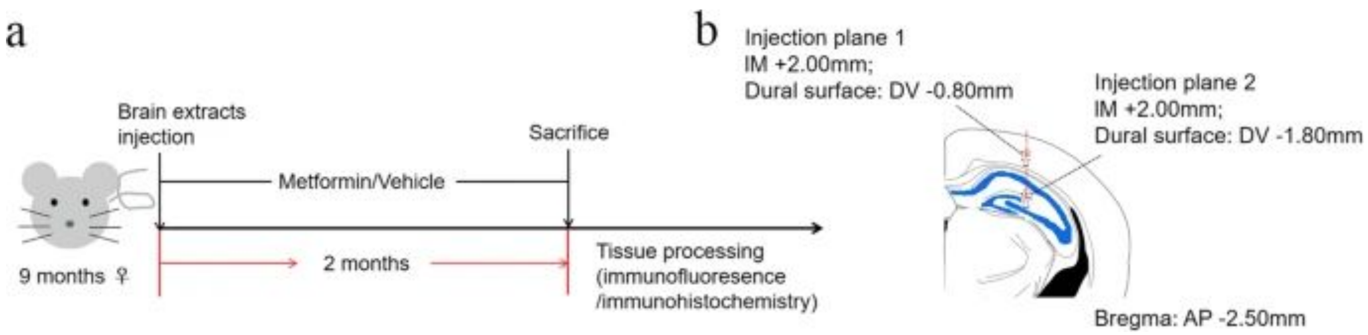

Figure 1 shows the study design, including the timeline against nerve damage. In relation to the activation of the AMPK pathway, metformin treatment in the APP/PS1 mice showed reduced amyloid-beta production, promoted aggregation clearance and decreased oxidative stress. Furthermore, insulin signalling balance was restored and hyperphosphorylated tau was reduced, thereby inhibiting tau tangle formation [4].

Limitations to animal models

However, a limitation of this study is the use of rodent models. Many therapies effective in mice have failed in human trials, further emphasising the complexity of AD. To address this, researchers are utilising non-rodent genetic models, such as zebrafish, Drosophila, and Caenorhabditis elegans [5]. Nevertheless, no animal system can fully replicate human AD progression. Complex disorders like AD are artificially induced in animals and don't progress naturally like humans due to many reasons, like differences in genetics and physiology. This makes animal models poor predictors of AD in humans.

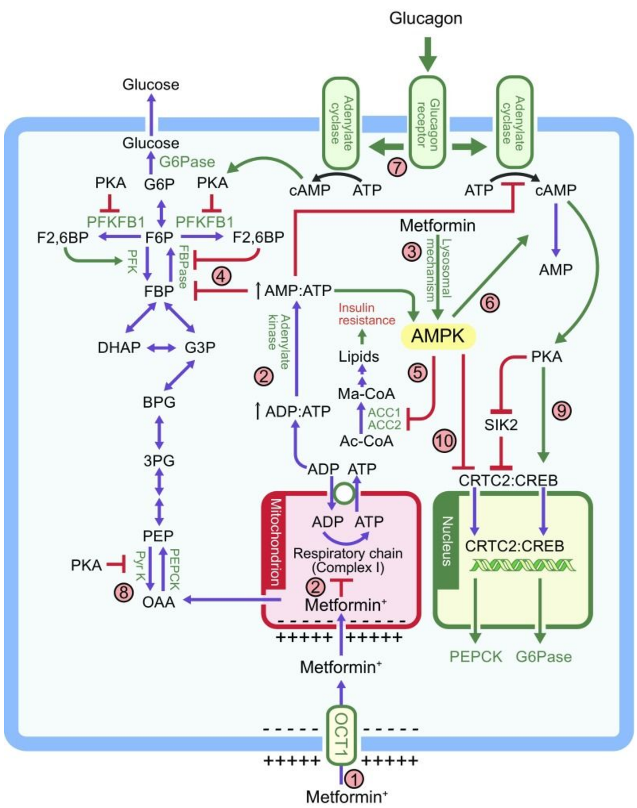

Figure 2 shows the multiple mechanisms that affect glucose metabolism in the liver. It shows mechanisms that regulate glucose metabolism under the actions of metformin.

Mechanisms of Metformin

Figure 2 shows the mechanism by which metformin activates AMPK. Metformin inhibits mitochondrial complex I which causes an increase in cellular AMP levels. This triggers AMPK activation, leading to many beneficial outcomes. AMPK activation can reduce glucose production in the liver and increase glucose uptake in muscle and fat tissue, whilst also reducing oxidative stress. In neurons, these effects improve insulin sensitivity and limit the production of reactive oxygen species by removing tau proteins [3], [6].

Moreover, Metformin increases the activity of insulin-degrading enzyme (IDE), resulting in a greater breakdown of insulin and amyloid-beta. IDE activity supports metformin amyloid-beta clearance and alters microglial phenotypes, which favours the production of neuroprotective immune cells to help reduce inflammation [7].

Neuroinflammation plays an important role in AD progression, where overactive microglia release pro-inflammatory cytokines and reactive oxygen species, causing damage to neurons and accelerating disease progression [1]. Metformin has been proven to shift microglia towards less inflammatory states, thereby limiting neuronal injury and slowing pathological progression.

Risks and Limitations of Metformin

However, despite these findings, there are several limitations. A well-known side effect of metformin is vitamin B12 deficiency, particularly when used at high doses [8]. The drug reduces B12 absorption by changing the function of intrinsic factor, affecting the transport and calcium-dependent uptake. This B12 deficiency is linked to cognitive impairment, including memory loss and slower processing speed, which could worsen outcomes in AD. This suggests the need to monitor nutritional needs during long-term treatment.

Patient diversity further complicates outcomes as genetic and metabolic differences can alter drug efficacy, meaning that not all patients would respond similarly to the drug. Indeed, some epidemiological studies have shown increased amyloid-beta accumulation with metformin. However, other studies suggest that alternative drugs such as pioglitazone may be more effective [9].

Conclusion

In conclusion, metformin demonstrates promise as a viable therapeutic strategy against AD. Preclinical trials show that metformin can reduce amyloid-beta and tau pathology, regulate neuroinflammation and enhance neural activity through mitochondrial and insulin-related pathways.

However, it cannot be considered a cure; side effects such as B12 deficiency, patient variability and inconsistent findings across studies limit metformin's ability to become a cure. The future role for metformin may be as a multi-target, disease-modifying therapy that could be used with other drug treatments to slow AD progression. More large-scale clinical research is essential before it can be used as a therapeutic. This highlights the importance of drug repurposing and offers new hope in tackling neurodegenerative diseases.

By Thussharaka Thirukumaran '23

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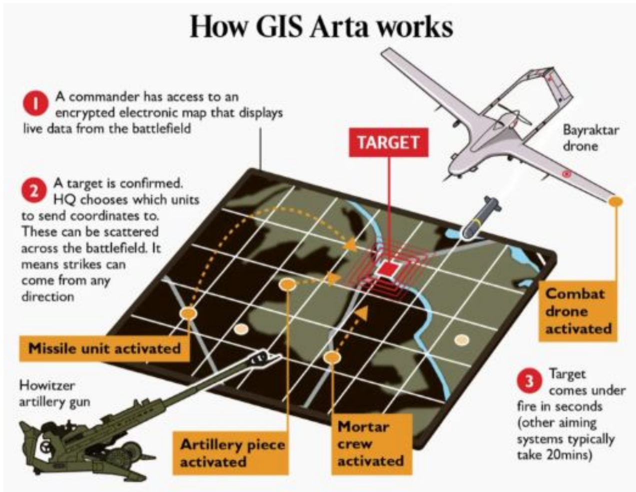
Uber for Howitzers

The recent Russia-Ukraine war has shown great advancements for the world of digital warfare, showing the future of military warfare. Examples of this include the increased reliance on drones, satellites, and the use of software. The Geographic Information System Art for Artillery (GIS Arta), also nicknamed “Uber for Howitzer” and “Uber for Artillery” refers to Ukrainian military software, and is a prevalent example of software developments in warfare. It uses real-time data to identify targets and then automatically assigns artillery units to strike them. GIS Arta demonstrates how these types of software also hold great potential to adapt into day-to-day life, and is already emerging in fields like finance.

GIS Arta was developed in response to the events that commenced the Russo-Ukrainian conflicts in February of 2014. Unidentified military figures, later confirmed to be Russian, surrounded airports in Crimea in Ukraine [1]. The nation had found that some of the main reasons that the invasion was successful were due to the unreliable geographical intelligence and limited artillery availability. GIS Arta technology was then integrated into the army in May of 2014. In 2017, The League of Defense Enterprises of Ukraine was then assembled with the aim of coordinating 75 private manufacturers, defense contractors, and technology firms. The group then listed their projects, one of them being the Android app GIS Arta LLC. Its concept was based upon a rideshare app, and was created in order to produce more targeting information [2]. When a target is identified and confirmed by the software, it deploys artillery units based on availability and distance [3]. The artillery then arrives and commences fire in under a minute. The system includes built-in GPS receivers for the given area, providing accurate models of a given terrain; additionally, it includes high-precision aerial and space photographs to aid it [4].



These targets are identified via different forms of data inputting, including the use of satellites, specifically Elon Musk’s Starlink. This constellation is one that is highly resilient to any attempts at jamming. This maintains a greater data security. This is also amplified due to its user-to-user encryption and lack of vulnerable on-land infrastructure [5], [6]. The GIS Arta app is able to gain information about drones and general enemy movement using GPS systems meaning that the locations provided are exact, and the data would be in real-time. There are also manual data inputting options available on the application. For example, there is a space for the manual relaying of any target locations and information. This data is necessary for target confirmation, which is also aided through the integration of intelligence from NATO countries, providing the app with enhanced algorithmic analysis. Once a target is identified, its raw information is translated into accurate coordinates suitable for the artillery and drone systems, which are mapped out on the GIS Arta software. This means that the closest artillery to the target can easily be identified, and the machinery that would be the fastest in completing the task would be chosen, and automatically dispatched. Each of the weapons used is equipped with a DFCS (Digital Fire Control System), which includes onboard navigation. This means that it is able to identify the weapon’s exact location and orientation, allowing it to aim and fire with great precision and with easy transport.. The built-in gun laying capability allows the weaponry to fire automatically, and allows the artillery to fire within two metres of the coordinates given [7].

The high precision of GIS Arta software allows its efficiency to be greatly increased. It reduced the time taken to translate the coordinates and fire the weapon from twenty minutes to as little as thirty seconds. The twenty minutes is also not including the verification of the target or ensuring minimal risk of collateral damage [5]. Uber for Howitzer also takes this collateral damage into consideration via the 'shoot and scoot' method that it provides - the artillery batteries are set up to fire and then are quickly relocated to prevent any further damage to the artillery systems [3]. This is hugely important as it allows the reduction of costs regarding the maintenance of the military equipment. These economical aspects are also furthered by the fact that it is extremely easy to use, requiring less highly-paid professionals to be hired. This is allowed due to the embedding of the technology into the military's system, meaning that minimal maintenance and input from the professionals would be necessary for GIS Arta to be functional [8].

This does also mean that the implementation of Uber for Howitzer would require large volumes of high-quality data. Inadequate collection or use of it would run the risk of flawed results or loss of precision. Additionally, any high-value data being stored within the GIS Arta system runs the risk of security breaches from other military offices. However, these worries are being diminished through the great advances in the built-in security systems of these kinds of applications [9].

GIS Arta will always be vulnerable to cyber threats, but the decentralised design of its security system means that it has great resilience when being attacked. This method means that data is disturbed across the application's network, eliminating any singular points of failure. This is crucial as it would reduce the likelihood of having any vulnerabilities in the code which would allow an easy hacking pathway [6]. Accordant with any other software with built-in security systems, GIS Arta also maintains continuous updates to protect against any new vulnerabilities that may arise [3].

GIS Arta has revolutionized warfare, but it also remains applicable to other fields. It offers a wide range of functional uses including mapping, analysis, and modeling. That means that the software could be slightly modified to adhere to the needs of urban planning [10]. For example cities' infrastructure can be optimised via resource and regulation management, which are barriers that people like contractors might find difficult to adhere to.

Another application of the GIS Atra software is in business intelligence. GIS Arta can be modified to collect data on different markets and demographics. This would allow it to understand different customer demographics through the analysis of trends within the markets. Advances like this would allow many within banking to be able to identify unique potential within the market, that they may not have been able to discover prior.

GIS Arta is a significant turning point within technology. No other Western artillery system would be able to compare to GIS Arta's capabilities or accuracy; but the software doesn't only stop there. It has been able to spread across many fields, and it will, undoubtedly, evolve into a component of the workforce that us humans will end up relying on or opting for to increase efficiency within the workforce.

By Rosalia Bialek '27

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Science Behind Decision Making

Decision-making is prevalent in day-to-day life. Traditionally, decision-making has been perceived as a rational process. It is assumed that the decision-maker has complete and factual information, clear objectives, and that they always select the choice that will maximise benefit for themselves. However, modern studies show that decision-making is a complex process which integrates numerous factors including neurotransmitters, prefrontal cortex systems, and the environment people are raised in.

The developing brain of a child is highly susceptible to being influenced by the environment around them. This means that early childhood experiences shape neural architecture, directly affecting future decision-making skills. Humans often use value-based decision-making, which is primarily controlled by the orbitofrontal cortex. Value based decision-making refers to recognising the value behind a cue – whether it indicates potential dangers or safety. This is shown when someone may instinctively apologise to another person who has furrowed their eyebrow - as facial expressions can serve as social cues [1].

When raised in a stressful environment, children's ability to use value-based decision-making is detrimentally impacted. This has been proven by neuroimaging studies which show that these children have a reduced orbitofrontal cortex volume [2]. This is because stressful environments are associated with unpredictability. In this situation, it is difficult to predict which events lead to reward and which to punishment. Therefore, these environments often result in adults who avoid any risk when making decisions as it allows them to eliminate any possibility of "danger". This contradicts traditional decision-making views because it means that people do not always select the choice that leads to the most optimal outcome.

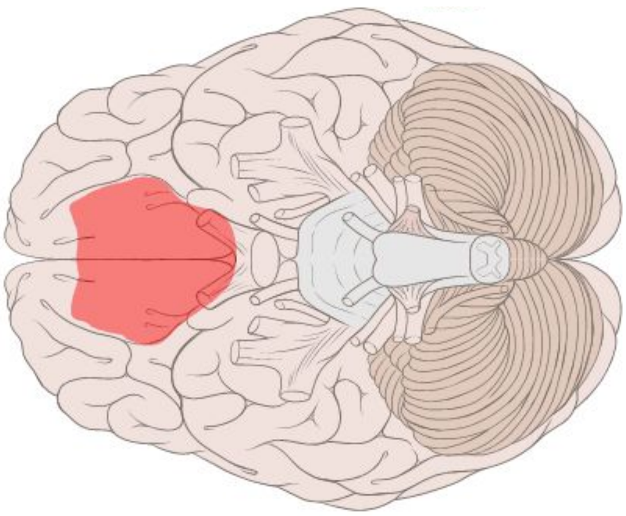
Similarly, dopamine is also used to predict events. Dopamine is a neurotransmitter which works by transmitting signals between brain cells. When the result of a decision exceeds expectations, dopamine surges - this reinforces the behaviour that led to the positive outcome, motivating people to repeat this choice again. Conversely, when the result is disappointing, dopamine dips below average, signalling that similar actions should be discouraged [3]. When there are sudden dopamine surges, such as from consuming social media content or gambling, the brain can become confused because this overrides the logical dopamine surges that aid in predicting events. This is because dopamine is not an indicator of happiness itself; it functions as a learning signal that is used to improve accuracy when predicting outcome.

Mental diseases can alter how dopamine is received and sent. For example, depression. This can be characterised by reduced dopamine activity, as common symptoms include decreased sensitivity to rewards and higher sensitivity to punishment [4]. For this reason, those who suffer from depression are often stuck in a cycle of risk-avoidant decisions and decreased motivation because potential rewards do not provide enough dopamine to encourage similar behaviour.

The ventromedial prefrontal cortex, located in the frontal lobe, plays a major role when integrating emotional signals with logical reasoning to guide decision-making [5]. This region of the brain links previous experiences to the emotions felt during them. This means that when a negative experience has occurred, the ventromedial prefrontal cortex labels the memory of it with warning signals so that if a similar situation arises, these "warning signals" emerge as gut feelings to help guide decision-making.

The importance of emotional guidance for decision-making was shown when an iron rod pierced Phineas Gage's ventromedial prefrontal cortex in 1848. Gage successfully retained his intelligence, memory, and language abilities. But without the emotional reassurance from the ventromedial prefrontal cortex, Gage lacked the ability to recognise factors that would usually drive people away from making a choice. As a result, he consistently made suboptimal choices, demonstrating that emotion provides essential guidance that is necessary when decision-making [6].

Decisions are made through combining life experiences and neurological architecture. This contributes to why people often



struggle to understand the thought process behind others' decisions - humans have all experienced different situations that may have altered neurological architecture, leading to differences in decision-making. By understanding factors that influence decision-making and the reasoning behind them, future policies and case studies can become more efficient.

By Chloe Chen '26

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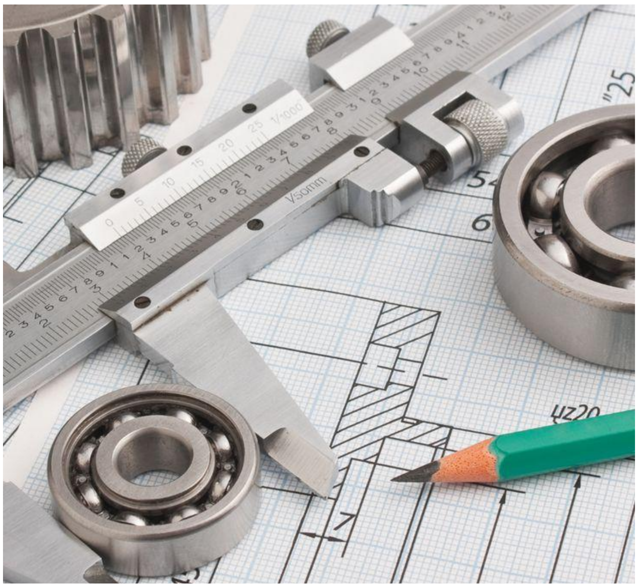

Where Engineering Meets Intuition: The Science of Everyday Design

Technical excellence alone does not ensure a product's success, as evidenced by numerous everyday design failures. A design may exhibit mechanical robustness and efficiency yet still fail if users are unable to comprehend or operate it effectively. The most successful products integrate engineering precision with human-centred principles, resulting in designs that appear intuitive, coherent and effortless in their use.

The backbone of function

Engineering precision underpins a product's basic performance. For example, the thermal performance of a kettle is calculated by $Q = mc\Delta T$, which determines the energy required to heat a given mass of water. Engineers can then optimise the design of the heating element to maximise surface area and thermal conductivity. Material selection focuses on minimising heat loss while sustaining repeated thermal cycling, thereby balancing efficiency with durability. Thermal cycling refers to the repeated heating and cooling or materials during regular use, which can cause expansion, contraction and eventual material fatigue. Consideration of factors like this are imperative to good design and a long product lifespan [1].

Structural design likewise depends on deep analysis. Chairs that appear simple are designed using stress distribution concepts and safety factors to prevent failure. Material stiffness, characterised by Young's Modulus, is chosen to provide comfort and resilience. Modern designers employ computational tools such as finite element analysis (FEA) to predict stress concentrations before a prototype is built. These methods optimise durability, strength and energy use, but technical optimisation alone does not guarantee suitability for users [2].

Usability depends on perceptible cues and feedback as much as on mechanical function. Affordances, the visual and tactile signals that suggest how an object should be used, guide users' expectations and actions. When affordances and design contradict one another, operation becomes error-prone and frustrating. Clear feedback, such as an audible click or haptic response, confirms user actions and reduces uncertainty. Without it, technologically advanced systems may appear unresponsive or confusing [3].

Simplicity contributes to both aesthetic appeal and functional clarity. When a design communicates its purpose unambiguously, it becomes easier to use and more readily accepted by users. This principle emphasises restraint and clarity in the interface between user and product [4].

When engineering ignores the user

Historical examples illustrate how engineering innovation can be compromised when social, ergonomic or contextual are overlooked. The Segway (2001) exemplified sophisticated dynamic stabilisation and sensor control; however, its large size, social awkwardness in crowded spaces and limited practicality for everyday tasks hindered widespread adoption [5]. Similarly, Google Glass (2013) achieved impressive miniaturisation and seamless connectivity, yet social resistance and ergonomic shortcomings stopped it from becoming mainstream [6]. Even Apple's Butterfly keyboard (2015-2019) demonstrates this pattern: the design reduced laptop thickness through mechanical innovation, however persistent issues with key reliability and typing experience, necessitated product revisions and eventual discontinuation. The design failure cost Apple considerable revenue from development to production, overall a lesson in the importance of human centred design thinking and testing [7].

These examples highlight the necessity of integrating anthropometric data, ergonomic principles and human factors analysis into the design process. Anthropometrics, the study of human body measurements and variations, provide critical data that allows products to accommodate the full range of human sizes, strengths and abilities. Using this information supports inclusive and diverse design, ensuring usability across different genders, ages and physical conditions. For example, handle shape for common tools should be informed by hand-span and grip-force distributions to optimised comfort and control, while medical devices require interfaces that minimise operator error through clear displays, intuitive alarms and redundant safeguards [8]-[9].

Equations and Empathy in Design Engineering

Technical and human-centred considerations are inseparable in practice. In a tool such a screwdriver, torque transfer is described by $t = F \times r$, material selection must prevent torsional failure while the tip resists wear. Equally important are handle diameter, surface texture and balance. Factors such as friction and grip strength guide material and geometry choices, ensuring comfort and reliable performance in various conditions [1]-[9].

Disciplines, such as human factors engineering and ergonomics, combine principles of physics, material science and psychology. Designers consult anthropometric databases, simulate load paths, energy transfer and iteratively test prototypes with representative users to achieve both technical robustness and intuitive usability.

Conclusion: Seamless Operation as a Mask of Success

The most successful everyday designs become effectively invisible because they require no conscious thought from users. Such designs unite stress analysis, heat transfer and mechanical optimisation with clear affordances, feedback and human-centred simplicity. When engineering meets intuition, products are both mathematically sound and immediately usable, delivering value through unobtrusive and reliable interaction.

As Norman emphasises, good design makes objects understandable, while Soetsu highlights that simplicity itself is a form of beauty. Taken together, these perspectives define the aims of design engineering, to make complex technology accessible, safe and satisfying in daily life [3]-[4].

By Elodie Levesque '26

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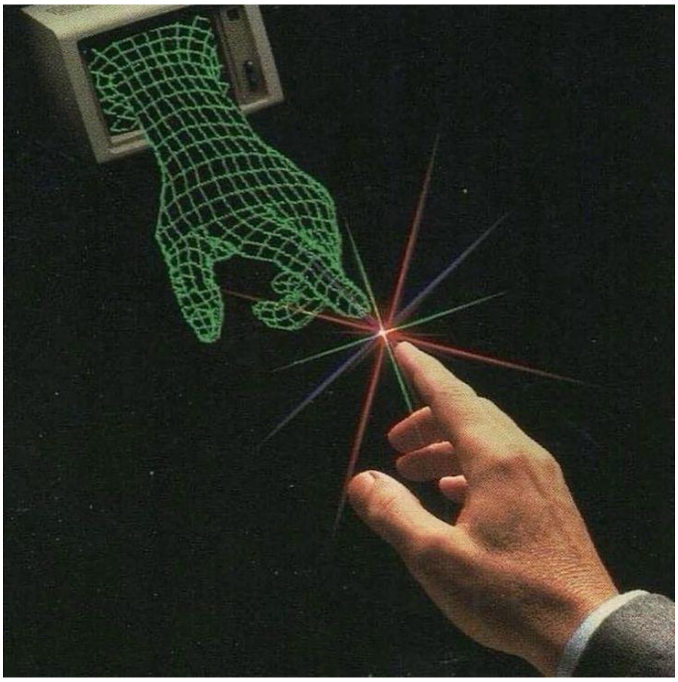


How wearable technology works

Wearable technology is an electronic device designed to be worn on the user's body. These devices can come in many types of forms including jewellery, accessories, medical devices, and clothing or elements of clothing. Most wearable technology contains microprocessors, batteries, sensors and internet connectivity such as syncing data [1].

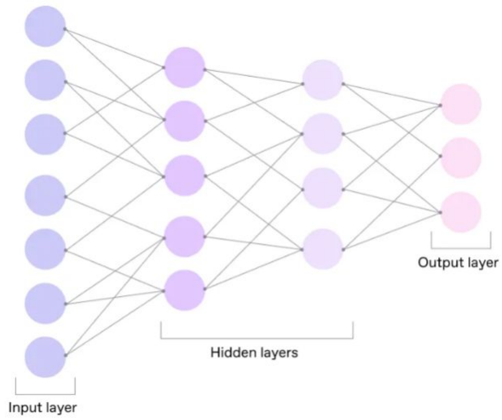
The devices contain multiple types of sensors, such as biometric, light, accelerometers and magnetic sensors. These are all important in aiding the function of a wearable device [1].

Biometric Sensors are a feature of electronic technology which captures biometric data. It does this by storing the data digitally so that it can be turned into a biometric template [2]. Which is a mathematical representation of features or characteristics from the inputted data. For example, fingerprint scan, facial image, or voice recording. The input data can be analysed with a quality evaluation algorithm [3]. A quality evaluation algorithm is used to access facial images for biometric matching, which has been proven to be highly effective [4].

Biometric scanners use face matching (liveness detection) and advanced AI techniques compare the biometric template against the user that is asserting their identity to determine if it is a real person [2].

Liveness detection algorithms are powered by neural networks. Trained on hundreds of thousands of face images with various backgrounds, they can recognize synthetic traits in photos submitted by users.

A neural network consists of many algorithms inspired by the structure of the human brain. It analyses large amounts of data to find patterns, learn from them, and then apply what it has learned to predict the output for similar queries. A neural network consists of layers of interconnected nodes ("neurons") that process information in parallel. The first layer is called the input layer, and the last one is called the output layer. The layers in between are called hidden, although they perform most of the computation [6]



These technologies also align with passive and active liveness checks. A passive approach often relies on 2D facial map generation. This results in a single user's selfie being sufficient to retrieve all the data the neural network needs for analysis.

However 3D liveness is frequently implemented with active flow. This can be done by prompting a user to perform specific spatial movements such as smiling or rotating their head. 2D technology is considered faster, while 3D is more secure. This is why 3D liveness is recommended for use at critical points [5].

Certain types of biometric sensors require more specialized hardware than others. For example, face biometrics only require a device with a user-facing camera. Other types, such as fingerprint biometrics, require specialist technology like fingerprint readers. Which is only available to those with certain hardware or specific smartphone, tablet, or laptop models.

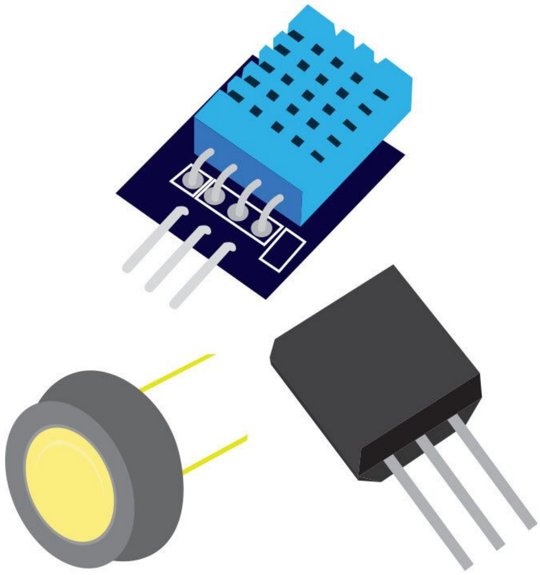
The light sensors typically used in biometric sensors work via the photoelectric effect. When a photon (light) hits the metal surface of the light sensor, the energy of the light is absorbed by the electrons. Their kinetic energy and allowing them to be emitted from the material. This movement of electrons, and therefore charge, is electrical current [7]. Light sensors are a type of photodetector (also called photosensors) that detect light. Common types of light sensors are photodiodes, photoresistors, phototransistors, and photovoltaic light sensors. These types of light sensors can be used in wearable technology.

Light sensors can be used in different ways when it comes to wearable technology. It can be used for Automatic Brightness Adjustment which is a light sensor used to ensure optimal screen brightness based on ambient light conditions, enhancing usability and reducing eye strain, it can also be used for proximity sensing. When the light intensity is outside of a certain parameter, then a certain function will be completed, for example for the screen to temporarily turn off. Finally, the light sensors can also be used for facial recognition which incorporates aspects of biometric functionality. It uses advanced light sensors to secure unlocking and user authentication [8].

Magnetic sensors are typically used to convert the magnitude and variations of a magnetic field into electric signals. Magnetic sensors have multiple variations, such as coils, reed switches, and MR sensors.

Magnetic sensors contain coils. When a magnetic field is brought close to the field it will increase the magnetic flux density in the coil. The increase of magnetic flux density in the coil will also generate opposing forces in the form of induced electromotive force and induced current. A reed switch consists of a glass tube encapsulating two reeds.

The reeds are made of nickel or other magnetic material and are separated by a gap. The glass tube is filled with nitrogen or another gas to prevent the activation (deterioration) of the contacts. The reed switch is usually open, but when both ends of the magnetic material are exposed to a magnetic field it causes the magnetic material to be magnetized. The contacts are attracted to each other closing the circuit (conduction state).



An MR sensor element is a type of magnetic sensor . There are a few MR sensor types using different operating principles. When electrons move through a ferromagnetic material (a material with a certain level of magnetism) and the spinning of the electrons fluctuates within the magnetized material rises and falls. This is what causes the MR effect [9].

Magnetic sensors can detect the geomagnetic field so that it can be used when finding directions such as navigation and can also accurately measure the positional relationship between the sensor and a flexible permanent magnet [10]. They hold immense potential for wearable electronics, offering a range of advantages such as comfort, real-time health monitoring, motion sensing, durability, and seamless integration with other sensors [11].

Accelerometers can be considered an additional feature of wearable technology.

Accelerometers can detect changes in acceleration often up to 1000Hz, giving us 1000 data points every second. Due to the specific demands of much of our wearable technology, accelerometers are supported by other devices within the system [12].

Accelerometery data can be used to derive velocity and displacement information by integrating data with respect to time. Some accelerometers can respond to gravity to provide tilt sensing with respect to reference planes when they rotate with. The resulting inclination data can be used to classify body postures (orientations). With these characteristics, accelerometery can provide sufficient information for measuring PA and a range of human activities [13].

Overall, these sensors can be used to help create wearable technology; the sensors offer transformative and real-time monitoring as well as improved functions/devices, such as allowing medical wearable devices to be created, devices such as fitbits/smart watches.

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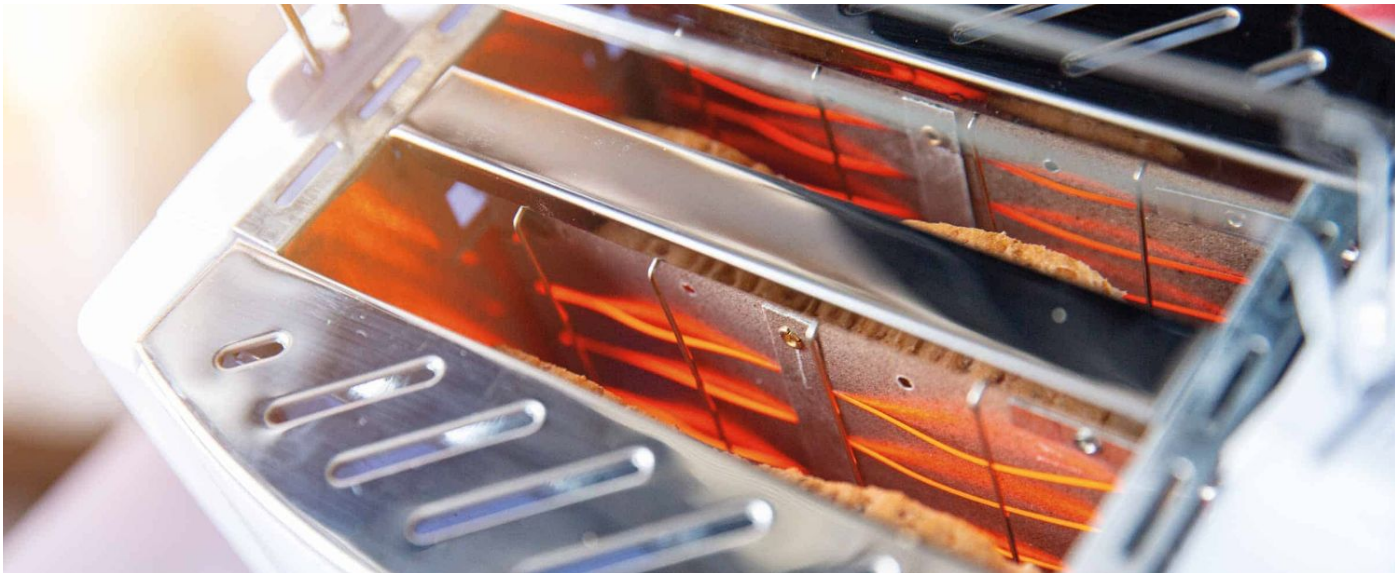
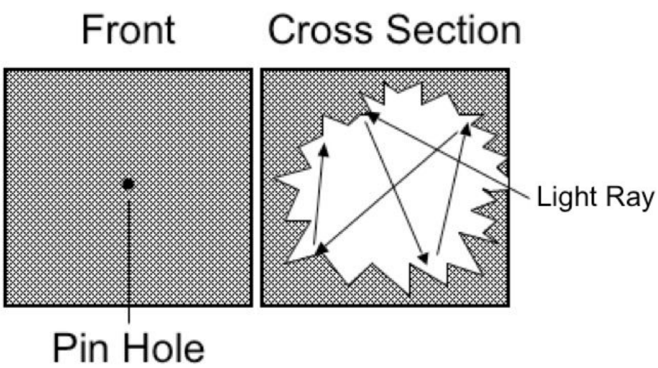


Quantum Physics and Its Application in the Toaster

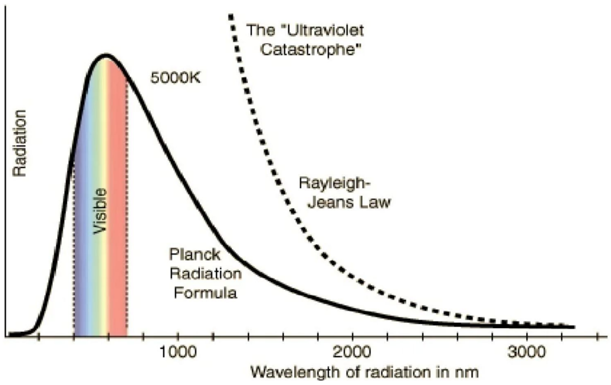
Quantum physics, to someone unfamiliar, may appear out of reach and theoretical. Most of the information presented to the public tends to focus on remote black holes and elusive particles, concepts that feel abstract and disconnected from an individual's daily life [1]. Other sciences like chemistry, biology, and astronomy are often seen as more directly impactful and easier to understand due to their observable effects. What many people do not realize is that the simple act of making toast, because it requires heating an appliance to toast the bread, involves one of the most foundational phenomena in quantum physics [2].

Scientists observed that when matter is heated, it emits thermal radiation that changes color with temperature [2]. At low temperatures, it glows red, then transitions to yellow, and eventually to white as the temperature increases [2]. This event, known as blackbody radiation, occurs independently of the material or heating method, provided the object reaches a sufficiently high temperature [1], [3]. As temperature increases, the peak wavelength of emitted radiation shifts toward shorter wavelengths in the visible spectrum, resulting in higher-energy visible light, also known as color [1], [3]. This contradicts classical physics, which describes light as a wave with energy dependent on amplitude rather than frequency [4]. A clear example of this is the metal heating elements in toasters, which act as blackbodies [5]. A blackbody, best represented by a box with a small hole, is an object or surface that absorbs and emits all frequencies of light [4].



model showing what a blackbody is

Physicists originally made incorrect predictions based on the box model and classical equations. If their hypothesis were true, heating elements like those in a toaster would continue to get hotter and emit progressively higher-frequency radiation, ultimately leading to an unrealistic prediction of infinite energy output [5]. Eventually, X-rays and gamma rays would be emitted, which are forms of hazardous, potentially lethal high-energy radiation [4]. Physicists of the time were deeply puzzled by the discrepancy between theoretical predictions and experimental results, a dilemma that came to be known as the “Ultraviolet Catastrophe” [1].



Comparison of the spectrum depicted by Planck's formula versus that of the Ultraviolet Catastrophe.

Later, physicist Max Planck, often referred to as the father of quantum physics, developed an empirical formula that matched the observed distribution of electromagnetic radiation from a blackbody [5]. This distribution became known as the blackbody spectrum [5]. He validated his equation using a radical assumption, paving the way for modern quantum physics [5]. This mathematical adjustment to Planck's formula implied that the interaction of the atoms and the light field was somehow quantized, into what he termed quanta [4, 6]. The idea was that each quantum has a fixed amount of energy dependent on the frequency, but the stacking of multiple quantum increases the total energy present [5].

Planck's Quantum Hypothesis works because, at any given temperature, all available thermal energy is shared evenly across all the possible wave patterns, also known as modes inside the blackbody [5]. This continues until the "cost" of one quantum is higher than the available thermal energy [5]. As a result, radiation created by short wavelengths is reduced, creating a spectrum that rises, peaks, and then sharply falls [5]. This also explains the appearance of the long-wavelength tail in the spectrum graph, where fewer available modes cause a shift toward longer wavelengths [5]. This indicates that hotter objects, which are comprised of shorter wavelengths, release more light and radiation [8].

Therefore, quantum physics is an active part of everyday life as it works to decode the relationship between energy and matter [6]. While pioneering thinkers like Albert Einstein advanced quantum physics, its principles aren't confined to high-level theory but are embedded in everyday technology [5]. Even simple devices, like your toaster, rely on quantum mechanics to function, demonstrating how deeply this science influences modern life.

By November Bombard '28

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The Science Behind Personalized Content: Exploring Recommendation Algorithms

Today's world is filled with a vast array of media, which can make it challenging for people to find content that they are interested in. In the wake of such an issue, a solution was created: recommendation systems.

Recommendation systems are tools that are made to help predict what media a user may want to consume based on prior watch history and other factors. One subsect of recommendation algorithms falls under the topic of AI and data science, which is the preferred method for many entertainment companies today.

Such algorithms are used by many different companies to ensure that their users are able to quickly procure and view content that they enjoy. These companies include Spotify, Amazon, YouTube, and Netflix.

The Basics of Recommendation Systems

The intended use of recommendation algorithms is to analyze user behavior in order to output a likely next choice for that specific user to select. IBM explains it as a system that relies on massive datasets that contain inputs such as user preference, item attributes ,such as director, artist, and price range, and past interactions to make a decision [1].

There are three major types of recommendation algorithms: content-based filtering, collaborative filtering, and hybrid models. All of them focus on a different facet of recommendations. Content-based ones focus on the attributes of the items, such as the director, genre, and length of a movie, while collaborative focuses on patterns that it is able to identify between users.

When given limited user data, collaborative models are unable to draw patterns between users, leading to what is called a cold-start problem. This is when the model is unable to draw any inferences from the user data, therefore stalling its ability to provide accurate recommendations.

Hybrid models on the other hand adopt the functionality of both content-based and collaborative models, which help them provide the most accurate recommendations [2].

The user-item ratings, represented by R, can be approximated when two-lower-dimensional matrices, U and V, are multiplied. This relationship can be represented by the equation $R = UV^T$. When viewing this equation through the lens of recommendation systems, U represents latent, or hidden, user feature vectors, while V represents latent item feature vectors. These hidden features capture latent patterns in data. In other words, patterns that do not directly correspond to attributes such as genre or length can still be factored into the recommendation using this formula. The *T* represents taking the transpose of V.

To take the transpose of something means to take a matrix and switch its columns and rows. So this:

$$A = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix}$$

Would turn into this:

$$A^T = \begin{bmatrix} 1 & 4 \\ 2 & 5 \\ 3 & 6 \end{bmatrix}$$

Transposing is done so that the math lines up when combining information where rows equal users, and columns equal latent features. Each user is represented as a vector in matrix U, while each item is

represented as a vector in matrix V where rows equal items, and columns equal latent features.

The dot product, which is created when two equal-length lists , otherwise known as vectors, are combined, is what is used when deciding what a good recommendation is. The higher the dot product of the user and item vector, the better the recommendation it is [3].

Netflix Case Study

An example of such a system being operated at a large scale is Netflix. The platform is able to service its audience of hundreds of millions with a recommendation system being operated at a massive scale.

Since Netflix utilizes both collaborative and content-based filtering, it includes attributes such as time of day, the month, and even the time of year when making decisions.

This effective use of mathematics based modeling displays how such models can translate into a satisfactory personalized user-experience, and help users traverse such a vast library of content [4].

Ethics

While recommendation systems are able to enhance the user experience, they raise multiple ethical concerns. These systems can reinforce certain biases presented in training data, creating what is known as filter-bubbles. This phenomenon essentially means that the system, due to inherent biases within the dataset, continues to promote only certain types of content, preventing the distribution of more diverse media.

Another large issue is privacy. While the collection of user data may be detailed in the service's terms and conditions, the user may have a poor understanding of the extent to which this data is collected and used.

A lot of this data may be sensitive, such as behavioral data and personal information. Developers of these algorithms must ensure that while personalization is important, they still prioritize data privacy and security to make sure that no users are put at risk.

A few solutions to this have been created, such as explainable AI and fairness-aware algorithms. These algorithms help to mitigate the risks recommendation algorithms bring with them, but also allow for recommendations that are true to the wants of the user [4].

Conclusion

Recommendation systems can transform massive datasets into a satisfactory user experience. They combine math, machine learning, and deep data analysis to achieve this. Platforms such as Netflix, TikTok, and YouTube demonstrate the effectiveness of such algorithms. As these algorithms grow and change, companies and developers have to be vigilant in their responsibility of ensuring their users' data privacy and security. Developers have to make sure that their models are trained on bias-free datasets to ensure ethical recommendations.

By Sreehaasini Jakkaraju '27

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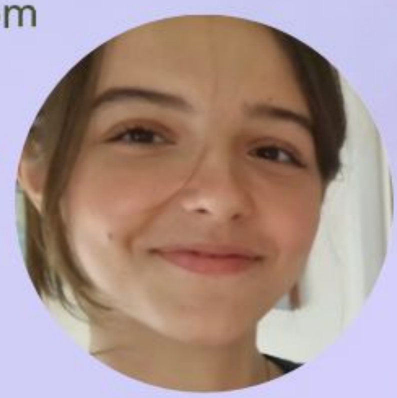

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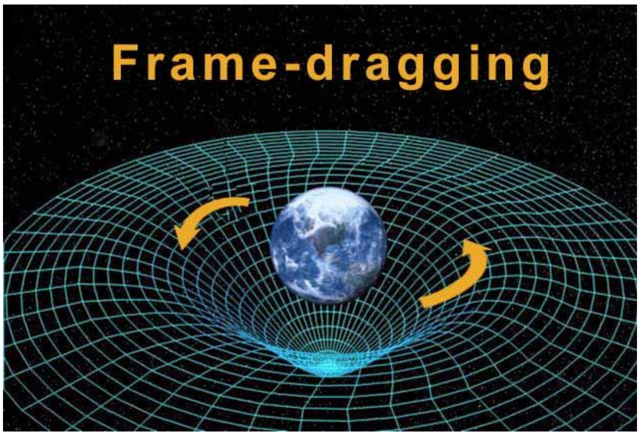
Theories of Time Travel

Time travel is a concept that has been used in countless movies and books, fascinating authors and scientists alike, but it is usually regarded purely as science fiction rather than a true scientific prospect. Substantial evidence proves that time travel is an unachievable concept due to the numerous paradoxes and problems it creates. As Hawking said, "If time travel is possible, where are the tourists from the future?" [1]. However, ongoing research points to theoretical models that could make time travel probable in the future, using scientific concepts such as relativity and the frame-dragging effect to prove their feasibility.

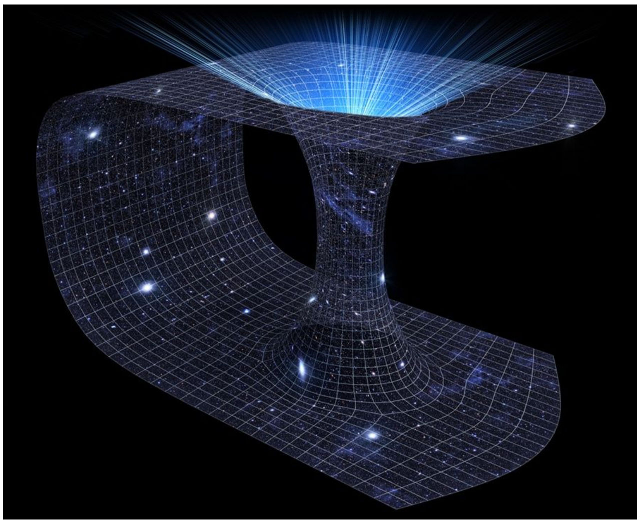
Most of these ideas rely heavily on Einstein's theory of special and general relativity. In 1905, Einstein published his paper "On the Electrodynamics of Moving Bodies", which explained the concept of special relativity. This suggested that time was relative based on speed, meaning that time could be experienced differently by people travelling at different speeds. This idea was termed "time dilation", and is often explained through the thought experiment of lightning on a train track. In this scenario, two lightning bolts strike beside a person at equal distances on either side of them. Due to the constant speed of light, the person will see the two bolts strike at the same time. However, a person in a train moving towards one bolt and away from the other will observe the bolt closer to them earlier. The exact difference in time experienced varies based on the object's speed in comparison to the speed of light. For example, astronauts traveling at 99% of light speed would age only one year while around seven years passed on Earth.

The concept of time dilation is further observed in various phenomena in the universe, such as the Muon Paradox [2]. Muons are unstable, subatomic particles that are created when cosmic rays strike atoms in the upper atmosphere. These particles are observed despite their average lifespan of approximately 2.2 microseconds, which should make them impossible to detect. However, due to their extremely high speed of almost 99.99% of light speed, they experience time much slower. Theoretically, if a person could move at such high speeds, this could lead to the possibility of time travel to the future. In this situation, the person would return to Earth years later, while only a short time had passed for them. A similar effect was observed by NASA during the "Twin Study" [3], where the effects of the environment in space on the human body was studied, testing for factors such as body mass, cognition and gene expression. After the study, it was found that due to his time in space, Scott Kelly experienced time differently, leading to him aging slower than his brother Mark, who remained on Earth. These studies provide scientific evidence for the concept of special relativity, and suggest a method for human travel to the future. Nevertheless, these ideas are highly experimental, and it is unlikely that there would be sufficient technological advancements in the near future to create spacecraft that can travel at such extreme speeds.

However, in 1949, Kurt Gödel proved that the existence of a rotating universe allowing backwards time travel was scientifically possible. He presented an exact solution to Einstein's field equations with matter and a cosmological constant. The solution is known as the "Gödel metric" [4], and among other surprising properties includes closed timelike curves. These are paths in spacetime that distort and start to curve backwards, theoretically allowing a person to move backwards to a point in their past. Despite this possibility, the universe doesn't match this model; the entire cosmos doesn't rotate. Even so, it proves that mathematically, relativity permits time loops if spacetime rotates sufficiently to a point in the past, creating the concept of time loops.



The idea of closed timelike curves inspired Ronald Mallett, who proposed a framework for backwards time travel using powerful lasers circulating in a continuous loop [5]. Hypothetically, spacetime could be warped enough through the lasers to allow an object to return to its past. This theory relied on Einstein's general relativity, published in 1905. This proved that just as high speeds can slow the passage of time, strong gravitational fields can do the same. Stronger gravitational fields cause time to pass slower in comparison to weaker fields. It also shows that mass, such as a planet or celestial body, can cause spacetime to curve. If the mass rotates, it can drag spacetime with it. This idea is called the "frame-dragging effect", and is used for Mallet's theory of time travel. Mallet suggested that because light carries energy, a loop of circulating light could, in theory, create a frame-dragging effect [5]. If the laser is strong enough, this could bend time into a loop, allowing subatomic particles or information to be sent to an earlier point in time. However, most scientists consider this unfeasible, both because of the impossibly high laser power required and because, even if it worked, it would only permit travel back to the moment the machine was first activated.



This is related to wormholes, another potential method of time travel, one that is often featured in science fiction. Like Mallet's ideas, this method also relies on Einstein's general relativity, which could allow spacetime to bend enough to create hypothetical tunnels connecting two distant points in space or time. If one end of this tunnel accelerates close enough to the speed of light, or sits in a strong gravitational field such as in close proximity to a black hole, it experiences time dilation. This suggests that travelling through it may allow movement from one point in time to another [6]. However, to keep these tunnels open, a large quantity of negative energy would be needed to counteract the extreme gravitational forces. Negative energy is a state of less energy than empty space, causing objects to accelerate opposite to the applied force. It can be found in exotic matter, which is not made of regular subatomic particles such as protons and neutrons. This causes them to exhibit strange properties, including negative energy density, mass and pressure. While some forms of exotic matter have been created in laboratories (like superfluid helium), many exotic matter concepts are still theoretical, including exotic matter with negative energy. Unfortunately, this makes the concept of human travel highly speculative and unachievable at current times.

However, while it may be impossible to transport humans, quantum mechanics suggests that it may be feasible to send information through time, as particles are connected through different time periods. This may happen through quantum superposition, where particles can exist in multiple states at once until observed. These particles can be linked together through quantum entanglement, so measuring one particle's state causes the other to be instantly determined, despite their physical distance [7]. This leads to ideas of retrocausality, which suggests that future measurements can affect past experiments if particles are linked between time. This is best explained by the delayed-choice quantum eraser, a scientific experiment where the choice to erase or store the information of the path the proton travels affects the results obtained. This could be interpreted as the future decision affecting the past experiment, meaning information must have traveled through time to change it.

Despite the possibilities time travel may bring, there are various paradoxes that must be considered, such as the commonly known Grandfather Paradox, or the Bootstrap Paradox. Many physicists have suggested solutions. For example, Hawking's Chronology Protection Conjecture states that time travel would cause quantum effects such as vacuum fluctuations, shutting down potential loops before they form. Other scientists, such as Novikov, claim that the universe "self-corrects", making the past unchangeable. Another notable theory is Everett's Multiverse theory, which states that multiple parallel universes form every nanosecond based on choices made, so paradoxes are impossible.

While time travel remains unproven, scientific possibilities ranging from relativity to quantum mechanics suggest the idea is consistent with the laws of physics in limited ways. In the future, this may change from speculation to reality, making it possible to travel through time.

By Ishita Chowdhury '27

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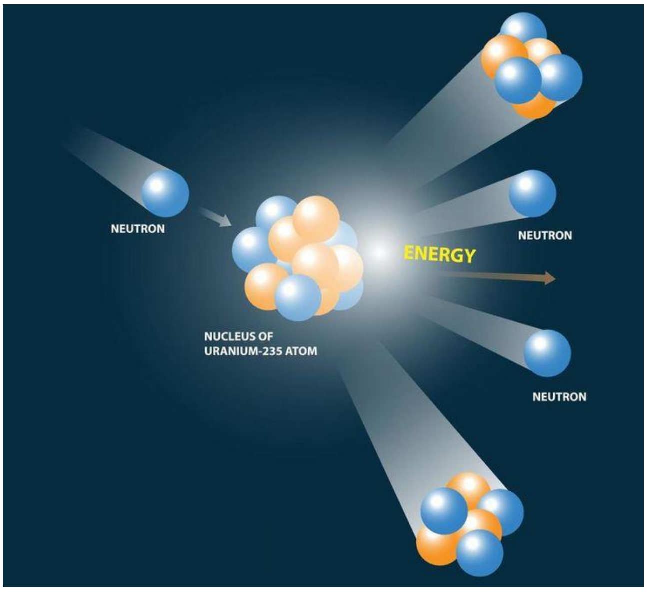
Nuclear Power: Benefits, Risks, and Public Perception

Typically, the negative viewpoint we, as individuals, might form on nuclear energy is influenced by our distrust of the energy source, frequently caused by inaccurate portrayals within the media. It has often been displayed as a weapon, capable of destroying the planet. Dissimilar to the media's portrayals, nuclear energy, in truth, is considerably one of the safest and most reliable energy sources available to us for power production.

The process which takes place in nuclear power plants is called fission, where we bombard heavy atomic nuclei with neutrons, causing them to split and release energy. If we were to bombard the nuclei of Uranium-235 with neutrons, they would briefly turn into Uranium-236 before fission takes place [1]. During the fission event, the U-235 nuclei split into smaller nuclei, such as Barium-139, Krypton-94, and 3 neutrons, while releasing energy in the process. As a result of this energy release, the sum of the fission products' masses is less than that of uranium-236, and this can be explained through Einstein's mass-energy equivalence equation:

$$E = mc^2$$

The conversion of mass into energy occurs within the nucleus [1], as a portion of it is converted into binding energy. For example, consider a nucleon, a particle within the nucleus, to have a mass of *m*. If we were to have 56 of those nucleons, their combined mass would be 56*m*. However, this is not the case in an iron-56 nucleus, as it would be lower than 56m. This mass defect allows us to calculate the binding energy released when the components of the nucleus combine to form a stable system.



The fission products of uranium-235 have a higher binding energy per nucleon than the uranium-235 nucleus itself, meaning that these products are far more stable. The outcome is that a significant amount of energy is released during the fission process, either in the form of kinetic energy of the fission products or as gamma rays.

While the energy released from one fission event is small, the amount released from multiple nuclei is far more than that which is released through chemical reactions [1]. For instance, 1 kg of coal corresponds to a value specified as 7,000 kilocalories, while the complete fission of 1 kg of uranium-235 results in the release of 19 billion kilocalories [2].

The thermal energy released during the fission process is turned into electricity, using the heat to create high-pressure steam, which spins a turbine connected to an electrical generator. The gas we see coming from nuclear power plants is primarily water vapor from the condensation process used to cool the steam, and poses no environmental risk. Nuclear power plants do not emit greenhouse gases during operation, therefore they hardly contribute to global warming. Fossil fuel power plants, on the other hand, do contribute to the amplification of the greenhouse gas effect during operation.

When sun rays hit the earth, 70% of the energy is absorbed by various objects such as land and oceans, and is eventually radiated out. On the other hand, the remaining 30% is reflected back into space by reflective surfaces [3]. While some of this heat makes it to outer space, the rest is absorbed by greenhouse gases in the atmosphere, leading to a warmer climate on Earth.

As a result of the industrial revolution, human beings have been releasing greenhouse gases, such as carbon dioxide, into our atmosphere, leading to an amplified greenhouse gas effect. Through the combustion of fossil fuels, we contribute to the increase in concentrations of carbon dioxide within the atmosphere. Thus, by increasing the amount of infrared rays absorbed, we contribute to the rise in global temperatures. In truth, fossil fuels account for 68% of global greenhouse gas emissions, and nearly 90% of all carbon dioxide emissions [4].

An explicit advantage to nuclear power is that, with its use, the percentage of greenhouse gas emissions released through power production would decrease.

A further advantage to nuclear power is its safety during the electricity production process. It is certain that nuclear and renewables are far safer than fossil fuels, which is evident in the data of death rates per unit of electricity production. It has been shown that the use of coal for power production results in 24.62 deaths per terawatt-hour [5]. Other sources such as hydropower result in 1.3 deaths per terawatt-hour, and oil results in 18.43 deaths per terawatt-hour. However, the nuclear death rate per unit of electricity production is only 0.03 per terawatt-hour [5].

Furthermore, the main contributors to the statistics for nuclear power are the large-scale incidents of Fukushima and Chernobyl. It was clear that Chernobyl had profound defects in reactor design [6], including unstable control rods, and its nuclear operators lacked training. This allowed a catastrophic nuclear accident to occur, as a reactor exploded and released large amounts of radioactive material into the atmosphere.

The other significant nuclear incident, Fukushima, occurred when a 9.0 earthquake and a 15-meter-high tsunami hit Japan [6]. This resulted in a loss of electricity supplied to the nuclear power plant in Fukushima for cooling, ultimately ending in a nuclear meltdown. This disaster was a consequence of the assumption that nuclear power plants were far too safe for a disaster of this scale to occur [6].

While the events that occurred in Fukushima and Chernobyl were devastating for many, both incidents serve as lessons for future use of nuclear energy. Modern reactors now feature containment structures and more robust fail safe mechanisms that prevent explosion and radiation release. Additionally, nuclear operators receive significantly better training, and safety procedures have been established to prevent such an incident from reoccurring. These procedures include the continuous cooling of the reactors, automatic shutdown systems, and so forth.

Moreover, a NASA science brief claims that nuclear power prevented around 1.8 million deaths worldwide between 1971 and 2009. Other sources such as fossil fuels with higher pollution mortality rates would have been used in its place if it were not used [6].

In addition to this, nuclear energy is a reliable energy source that provides baseload energy, which is the minimum level of electricity demand on a grid that is constant over a period of time. While renewables such as solar or wind depend on their environment for electricity production, nuclear and fossil fuels do not, making them significantly easier to depend on.

The land efficiency of nuclear power is also highly beneficial. This helps reduce ecosystem fragmentation, the process of breaking up a continuous habitat into isolated patches, while also preserving natural habitats. Nuclear energy requires 50 times less land compared to coal, and 18-27 times less than on-ground solar PV [7]. Nuclear power plants could also considerably be far more land-efficient than wind farms, however, the land used between the turbines can be used for farming, making it difficult to determine its true land-efficiency [7].

No matter the advantages of nuclear power, the choice of whether the government should invest in nuclear technology often depends on public perception. It has been found that since the 1970s, a negative image of nuclear energy has been often portrayed within the media. For example, "Red Alert", a 1977 film, portrays a scenario where every nuclear power plant in the United States explodes simultaneously [8]. Additionally, there was an increased fear of the energy source following the accident in Chernobyl, along with the incident at Three Mile Island in 1979. There have been major efforts made to persuade the public that nuclear energy is a beneficial energy source.

However, it is unlikely that our society will ever fully accept nuclear energy without fearing the possible consequences of its use.

Another significant disadvantage to nuclear energy is the high costs associated with its use. While operation costs are relatively low, capital costs can be immense. Currently, the costs of nuclear energy are increasing, possibly due to developments such as regulatory requirements [9]. The EIA calculated that the overnight cost of a nuclear power plant built in the USA increased from $1500/kWe in the early 1960s to $4000/kWe in the mid 1970s due to these developments [9].

Nuclear energy has a range of advantages, yet similarly to our other energy sources, it does not come without its disadvantages. Regardless, it is impossible to not admire how we, as macro-beings, have managed to harness energy from something as small as an atomic nucleus.

By Eve Williams '28

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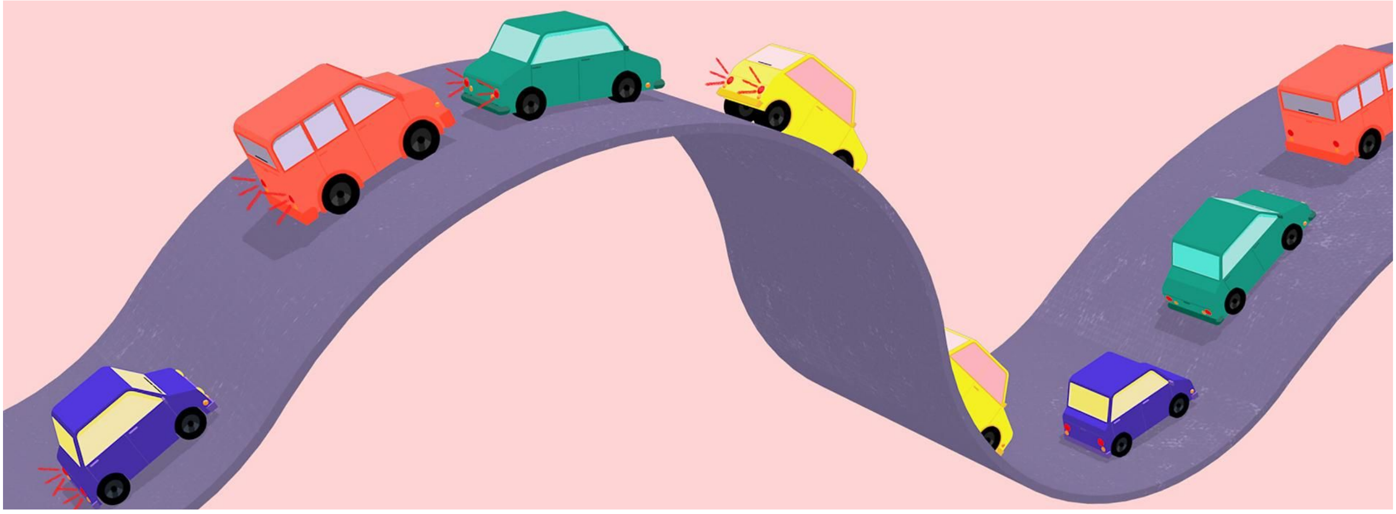


The physics of traffic optimisation

Traffic is deemed an annoyance by most members of the public, so one may wonder why we still have it on our roads. In truth, traffic is a complex situation in which scientists and engineers alike struggle to combat. Traffic optimisation is the method by which the time spent stopped in road traffic (traffic jams) is reduced. The physics of traffic optimisation was theorised by treating traffic as a fluid. This means that fluid dynamics, a strain of physics which studies the movement of liquids and gases, can be used to understand and in turn, further increase traffic optimisation.

Fundamentally, traffic optimisation is based on the equation:

$$q=vk$$

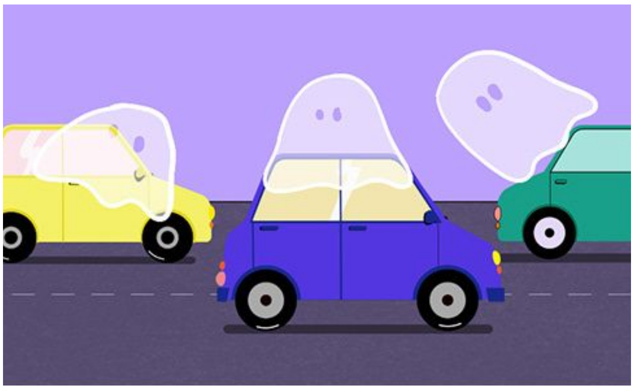
Within this equation, q represents traffic flow, v represents velocity of the cars and k represents the density of cars (number per unit length). This means that initially increasing density increases the traffic flow, but traffic flow will then decrease when the density exceeds the optimum point. This is because velocity begins to drop once the optimum capacity is reached on the road, therefore reducing traffic flow [1].

Traffic optimisation aims to maintain a balance between traffic flow, minimal congestion, and the ideal number of cars; however, this can be difficult due to two things: traffic jams and Braess' paradox.

Traffic jams are created by sudden changes in the rate at which cars are moving down a road. Cars can meet a 'kink', causing them to move at a different velocity. This 'kink' is the jam, and it typically moves backwards impacting the other cars which follow [1]. Traffic waves, one type of traffic jam, are moving disturbances in the distribution of cars. The waves can move with or against the traffic, relative to a fixed point, or even remain stationary if the cars are moving with an equal speed in the opposite direction to the traffic wave [2].Traffic waves work similarly to a longitudinal wave, as such that they have areas of compression and rarefaction.

Another type of traffic jam is a phantom jam. A phantom jam is a traffic jam which appears unexpectedly and thus has earned its name as a phantom. They occur due to the braking of a singular car which causes the car behind it to brake and so on. This creates a chain reaction similar to those in chemistry, such as nuclear fission. Each successive driver must brake harder to reduce their speed due to the shortened distance and thus a wave of braking is created which results in a traffic jam. Luckily, these are far less likely to occur on smaller roads as the braking of one driver impacts the next significantly less due to the variable environment [3].

Both types of traffic jams, traffic waves and phantom jams, have similar properties as both are moving jams and caused by waves. However, congestion jams are not due to this. Congestion jams are a blatantly obvious impact of the high reliance on cars nowadays. They are created by the density of cars on a road exceeding the optimum capacity, thus cars come to a standstill as they have no room in front of them to enter. This is why traffic jams mainly occur during rush hour as there is simply not enough space on the road for all the cars and thus, the traffic flow decreases eventually leading to a jam [4].



To solve this, one may argue that more roads should be built. However, this is where Braess' paradox takes effect. Braess' paradox is the observation that adding one or more roads into a road network can slow the overall traffic flow through it [5]. This is because in a Nash equilibrium ,where no person can benefit from changing route, nobody has the incentive to change route. However, if the system is not in a Nash equilibrium, then selfish drivers are able to improve their individual running time by changing route. This seems like it should improve journey times, but this process of switching routes will continue until a Nash equilibrium is reached, and thus in the case of Braess' paradox, the overall running time will increase [6]. Braess' paradox has been seen in real life, for example in Seoul, where a new highway was built in the 1990s. Engineers believed this would reduce traffic congestion, but it only got worse [7]. Therefore, if solely the physics of Braess' paradox was used to create a road system, the ideal situation may be to reduce the number of roads, as this would imply that a Nash equilibrium is met quicker, thus overall running times would be reduced.

The challenge of traffic optimisation is the number of components which need to be accounted for. Although reducing the number of roads would limit the ability to change routes, it could still increase the number of traffic jams due to a reduced optimum capacity of the roads.

Smart motorways, motorways designed to ease traffic flow by using technology, have been introduced in the UK which help to prevent the formation of traffic jams, specifically phantom jams. They do this by using cameras to see when traffic begins to slow down and thus reduce the speed limit further back on the motorway. This has improved some of the travel times, but the expansion of the scheme has been halted due to crashes which have been blamed on the new style of road. This is due to the removal of the hard shoulder, an emergency lane, on some smart motorways. This means that there is a limited number of safe places to stop for broken down vehicles, resulting in crashes.

Therefore, our road systems still have a long way to go before they are perfect, but until flying cars are made available, we will have to remain in traffic jams on the odd occasion.

By Lara Dee '27

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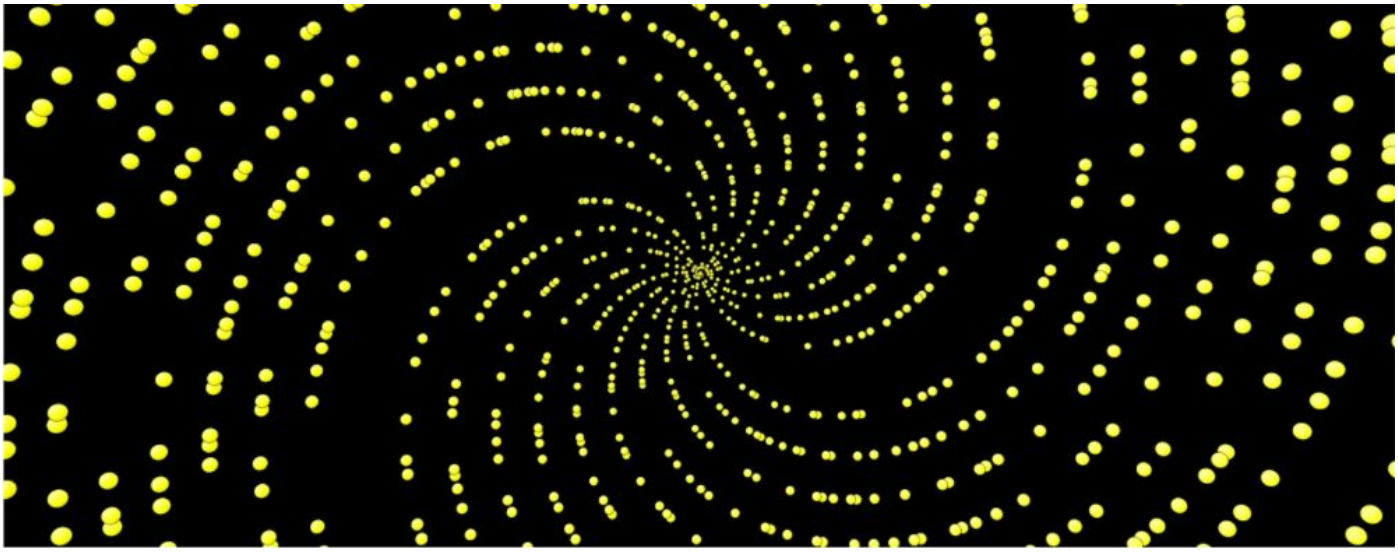


Chasing primes: The numbers that outsmart supercomputers

Prime numbers have been the fascination of mathematicians since 1550 BC [1]. Despite mathematicians working on prime related problems for centuries, a quick way to identify a prime, is yet to be discovered.

Prime numbers are the building blocks of the number system, as they cannot be formed by multiplying two smaller numbers and therefore cannot be broken down further. Furthermore, these whole numbers have exactly two distinct factors: 1 and the number itself [2].

For example, 5 can be tested. The only factors are 5 and 1. Therefore, 5 is prime. From this a new goal can be formed - to spot patterns in primes, in order to make identification of them quicker.

This calls for the testing of further numbers. The next number to be examined is 4, which fails to meet the definition of a prime, as it has factors 1, 2, and 4. Therefore it is a composite number - any integer with more than 2 distinct factors. In fact, it can be seen that all even numbers except 2, are composite, as they all have the additional factor of 2. Using the current method to find the factors of a number, all the numbers less than it, are being checked.

However, this method becomes flawed when larger and larger numbers are being checked. For an odd number with just 6 digits, at a minimum, 100,000 numbers are being tested. Looking for a faster method to do by hand is now the new goal.

Recognizing patterns in the factors of a number may serve as an initial step in refining the method. For instance, the number 4 is equal to 2×2, where 2 is prime. From this, it can be noted that 4 can be represented as the product of primes.

Extending this test to additional composite numbers confirms that each can be expressed as a product of prime factors. The hypothesis, now known as 'The Fundamental Theorem Of Arithmetic' [3], was originally discovered by Euclides. The proposition was later formalised by Kamāl al-Dīn al-Fārisī and rigorously proved by Gauss [4].

Rewording the theorem, it is now known that if a number is composite, it will have a prime factor. Hence, when checking if a number is prime, the only potential factors needing to be tested are the primes less than the target. This reduces the sample size of the numbers being checked, improving the efficiency of the primality test (a test used to check if a number is prime). This method was formalised 2000 years ago, and is namely 'The Sieve of Eratosthenes' [3].

This algorithm was kept organized using a grid, so that numbers are checked sequentially. The grid in Figure 1 has been completed up to 89.

To check 89's primality each of the highlighted numbers (primes below 89) are tested as divisors of 89: 2, 3, 5, 7 … 83.

And every time there is a remainder. Therefore, 89 is a prime and is also highlighted.

	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100

Figure 1 – Number grid with primes highlighted demonstrating the Sieve of Eratosthenes

To check 90, the process is repeated. In this case, 2 immediately divides 90 with no remainder, so 90 is not prime. A benefit of this method can be done by hand, as well as coded, as seen in figure 2.

```
#Python
import math
n = 30
#generates all primes less than or equal to n
prime = [True for _ in range(n + 1)]
prime[0], prime[1] = False, False

    #sieve of eratosthenes
for p in range(2, int(math.sqrt(n)) + 1):
#sqrt(n) is the biggest number that needs to
# be checked (Proof left as exercise to reader
# or check lemma 1.11.2 of ref [3])
    if prime[p]:
        for i in range(p * p, n + 1, p):
            prime[i] = False

for i in range(2, n + 1):
    if prime[i]:
        print(i, end=" ")
```

Figure 2 – Python code for Sieve of Eratosthenes

In Figure 2, it can also be seen that only primes up to $\sqrt{n}$ are checked. This was originally demonstrated by Euclid in his book - The Elements [5]: where he showed that for any composite number, at least one of its factors (other than 1) is always less than $\sqrt{n}$ [6].

In practice, primes of up to 100 digits are needed. A 100-digit number has a magnitude of roughly 10^{99}, making $\sqrt{n} \approx 10^{50}$. Even if one number was checked every millisecond, testing all 10^{50} candidates would take about 10^{37} centuries [7].

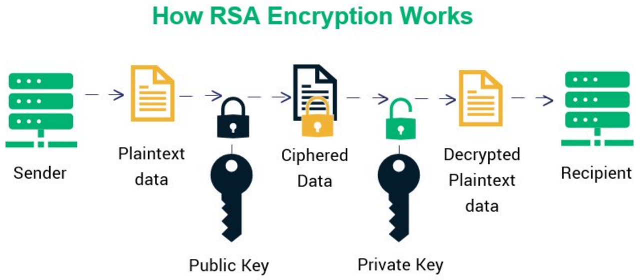
Instead, modern algorithms like the Miller-Rabin primality test are used. This test is primarily used in RSA encryption, where these 100-digit primes are desired.

The Miller-Rabin test is unique compared to the previous tests, because rather than doing singular divisibility tests, it combines other behaviours of the primes [8]. For instance, it uses Fermat's Little Theorem to check if these enormous numbers are composite [9]. No prime numbers fail the test, however some composite numbers - known as the Carmichael numbers - pass the test. So, a fail of this test can ensure a number is composite, but a pass does not ensure the number is prime.

Other tests are combined into the Miller-Rabin test to improve the chance of the test being correct. Furthermore, the test is run multiple times to decrease the probability of failure to almost 0, so the chances of it being wrong are unrealistically low, making it trustworthy. This technique, albeit more complex, is much faster and can be run in a realistic amount of time making it invaluable. A key application of this test is RSA encryption, where primes are actively used for security.

Messages, bank account details, and other pieces of confidential information are constantly being sent across the internet. This data is kept safe by being encrypted - a message is made into unreadable text, that can only become readable again with a key. The most common method used is RSA encryption [10], and it is at the heart of our society. RSA encryption uses 2 large prime numbers and multiplies them to create 2 keys: a public key and a private key. The public key only encrypts the message, and it can be seen by anyone.

RSA encryption is thus asymmetrical, as it requires the 2nd key - the private key- to decrypt it.



If a hacker was able to determine the two original prime factors, they could reconstruct the private key and access sensitive information. Such decryption could be exploited for malicious purposes. Consequently, the security of encrypted messages relies on the infeasibility of efficiently factoring large numbers, as this is the method of creating the private key. In fact, it is believed such an algorithm does not exist as the problem is believed to be NP-intermediate, meaning any algorithm for it would not run in a realistic amount of time by classical computers. The proof that this truly is the case, is yet to be solved and is part of a bigger problem - The P vs NP problem [11].

Primes are at the centre of our society. They protect the way we communicate, and further insight would only improve efficiency in our technologies. However, it is a balancing act. If we are to learn of better methods to prime factorise numbers, the foundations of cybersecurity from messages to crypto transactions will fail. Despite this, active research by mathematicians continues, with new properties of primes being explored. This expands into the field of number theory and analysis, where the focus is less on the application of primes, and more on the patterns that can be found. In just the recent 2022, James Maynard was awarded the field medal for his work on prime gaps [12]. Therefore, it can be seen that primes will continue to be a pivotal part of our lives.

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Harmony in Numbers: Exploring the Mathematics of Music

Music is an artform that combines harmony and rhythm in a way in which it can express sentiments. A commonly overlooked aspect is the hidden science behind those sounds. Every beat, melody, and chord is built on mathematical patterns and geometric sequences, the very same ones that shape our universe and govern the natural world.

When two notes are played together and sound harmonious, the combination follows simple numerical ratios. This idea dates to Pythagoras, who discovered that if you pluck a string and then pluck another that is exactly half the length, the two notes sound good together [1]. This interval is known as an octave. It appeals to the ear because the two notes vibrate at frequencies in a 1:2 ratio — a simple and naturally pleasing mathematical relationship. Building on Pythagoras's discoveries, researchers and musicians across different eras have examined how mathematics shapes musical harmony. Figures such as Aristoxenus in Ancient Greece, Mozart, Bach, and Beethoven , as well as modern acousticians, have demonstrated that simpler ratios between notes produce more consonant sounds [2]. This principle forms the backbone of most musical chords, scales, and compositions we hear today.

However, not every combination of notes is pleasant to hear. In some cases,playing two notes simultaneously produces harsh sounds. This phenomenon is governed by the mathematical relationships between their frequencies.This effect is known as dissonance. In these cases, the ratio between the two frequencies is more complicated. For example, a ratio of 42:33 produces interference patterns that the auditory system perceives as roughness.The ear transduces sound waves into neural signals,and the brain interprets those signals and assigns perceptual qualities such as unpleasantness [3]. Despite this , composers and musicians often use dissonance to build tension, then "resolve" it by returning to a simpler ratio. This resolution is what gives music its emotional depth [4].

The use of dissonance is still central to modern Western music. Most songs across genres are built on major or minor chords, including more complex variations . These chords are usually the first thing a beginner learns when picking up an instrument. They form the basis of the harmonious, balanced sounds we instinctively enjoy. For example, if you play C, E, and G together on a piano, you get a C major chord. These notes have frequencies of about 264 Hz (C), 330 Hz (E), and 396 Hz (G), placing them in an almost perfect 4:5:6 proportion . This connects to physics and neuroscience through the way we perceive and process these frequencies. When sound waves align and reinforce each other, the brain recognizes this regularity and interprets it as pleasant, happy, and melodious [5]. This simple bit of math is why the chord sounds stable to the ear. A major chord is essentially a structured "stacking" of simple ratios: a root note, a major third (5:4), and a perfect fifth (3:2) [4]. Interestingly, minor chords are made up of more complicated but still simple ratios, e.g. 10:12:15 which is why they sound melancholy or slightly tense. In other words, music's emotional power is partly our brain reacting to mathematical order (or disorder) in sound waves [5].

From a more mathematical standpoint, notes and chords aren't the only thing governed by math. Entire symphonies often follow larger, hidden patterns, and this is where fractals come in. Fractals, a mathematical concept often used to explain patterns in nature, are essentially "patterns within patterns" — shapes that retain their form no matter how closely you zoom in or out [6].This property is called self-similarity, and it creates a sense of balance and unity. A very famous fractal is the Mandelbrot set, defined by the iteration $z_{n+1} = z_n^2 + c$. In music, fractals are not usually expressed through complex equations. However, they can be represented using simpler transformations such as $f(x)=F(kx)$, where k stretches or compresses a melody.This preserves the original pattern while changing its frequency or timing, making the music more complex [7].

There are two main ways fractals appear in music. Melodic fractals occur when a short motif is repeated at higher and lower pitches, forming a pattern that spans the entire piece. Rhythmic fractals, on the other hand, involve a rhythm that is repeated faster or slower, creating multiple layers that remain connected [7].

Researchers K. J. Hsü and A. Hsü (1990) studied this idea in their paper Fractal Geometry of Music and found that pieces by composers like Bach often follow a 1/f noise distribution — also known as pink noise [7]. In simple terms, this is a statistical pattern where the power of a signal decreases as the frequency increases. Although it doesn't have a single defining equation, it is described as its power spectral density being proportional to the 1/f ,where f denotes frequency [7].

Hsü & Hsü analyzed not just pitch, but also rhythm across 1,788 pieces by many composers. They discovered that both pitch intervals and rhythms have fractal geometry: they look similar whether you "zoom in" on a few notes or "zoom out" to look at whole sections. On a log–log plot of power versus frequency, musical patterns appear as straight lines with a negative slope. This demonstrates that rapid, high-frequency variations carry less power than slower, broader patterns, while still maintaining a predictable structural relationship [7].

The very predictability of the pattern is what makes it sound harmonious to us.The music is mathematically organised enough for our brains to recognise patterns but still varied enough to avoid becoming boring [6], [7].

Scientists also note that 1/f noise appears in nature, from heartbeats to the rhythm of waves [8]. This may explain why we find it mentally and emotionally satisfying — the music feels organic rather than mechanical.Composers like Bach did not know about power spectra, but they instinctively wrote music that struck this perfect balance [7].

Of course, music is a vast spectrum. A "successful" song does not always follow these mathematical rules, at least, not in a neat or obvious way.

Mathematics is the study of patterns, and music is full of them. Even in apparent disorder, songs have hidden structures in chords, rhythms, and fractals. Music shows how maths and physics shape sound, proving that the two are deeply connected. Understanding these patterns helps both composers and listeners appreciate why music works.

By Yoana Evgenieva Rekarska '27

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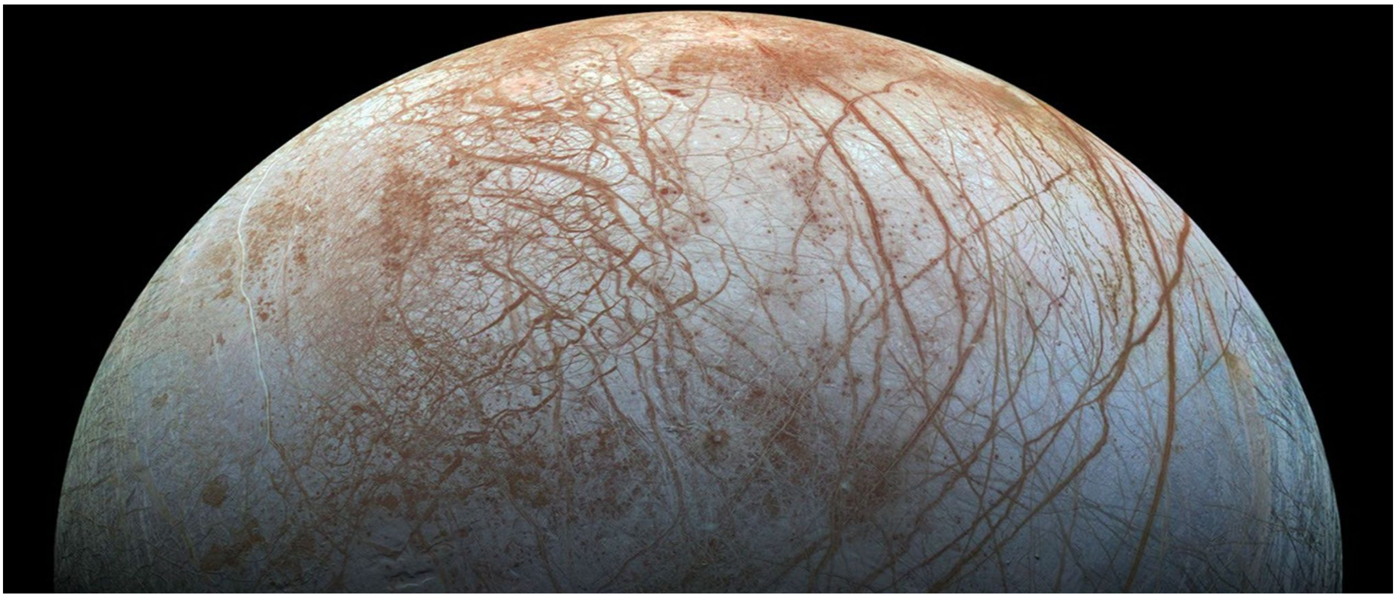


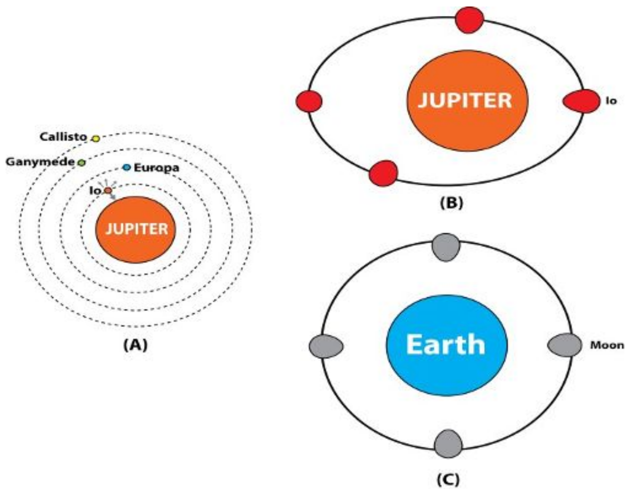
Tidal Heating in Icy Moons: A New Order

We inhabit an era that fosters an unpredictable age where the possibility of life and inhabitants elsewhere verges on the horizon. Though our eyes rest upon the prospect of Mars to be the answer to all our queries, my own belief is that we look to the moons of giant planets to represent an alternative to the classical portrait of habitable worlds. As they rely on a marvel coined Tidal Heating. If we observe Jupiter's largest moon Io, which possesses the most volcanically active site in our solar system, possesses a surface that is constantly reshaped by tidal forces. And Europa, Jupiter's icy moon, not yet frozen over, due to the same process.

A request to relinquish the mind of all preconceptions of space and life in space and enter with a fresh headspace. To justify the ambition of such a statement is to define why tidal heating is an answer, a glistening star partially obscured by a sea of jet black. In a simple notion, it is the breakdown of an object, in response to an external time-varying force, like car brakes or vibrating guitar strings. This response generates frictional energy which heats up the object's interior. This is a direct effect of the friction [1]. When we consider a time-varying force we first observe that its magnitude fluctuates, whereby the strength of its force can increase or decrease over the course of time. The force is affected by speed and distance as well as the change in direction. The process of tidal heating is natural for satellites, whose driving force is the gravitational pull of the planet they are orbiting as well as other planets. If we observe the moon's gravitational force, it may be understood that it causes the earth's water to bulge out on the side, closest to the Moon, as well as on the other side, further away from it. The work done by the gravitational force is dissipated into the oceans, thus producing a prominent contribution to the Earth's heating [1].

Make no error in judgement: this is not just technical curiosity. It is the one sole idea with the ability to revolutionize humanity's homes and habitats, and everything beyond this planet, humanity inhabits. Originally, we placed ourselves into a safe sanctuary, by believing that anything habitable had to orbit near a star, within the distance from which liquid water can thrive, to exist on a planet's surface. If we go beyond this range - the water will freeze. If we shorten this distance, the water will boil. But then came forth this new age, coined Tidal Heating, where scientific boundaries were nudged and physics challenged the cosmological comfort zone that science had secluded itself in. This is demonstrated with the example of Europa and Enceladus, two moons orbiting far beyond the sun's warmth, which astoundingly display signs of liquid oceans under the moon surface – a direct result of Tidal heating. This is not powered by starlight but by the force of the gravitational pull [1]. It is without a doubt that this endeavour proves unsuccessful and science refrains from further utilising this process as a means of colonization. Nevertheless, tidal heating poses a second possibility in the prospects of space colonisation. It provides research of the process with the key notion; that habitable zones are longer about distance but energy.

As mentioned previously, in the case of a satellite and its eccentric orbit, the distance and direction to the primary is constantly changing. This continuous deformation generates heat [2]. By eccentric orbit we refer to a value possessing no dimension, and to communicate that the orbit of the object deviates from a perfect circle.



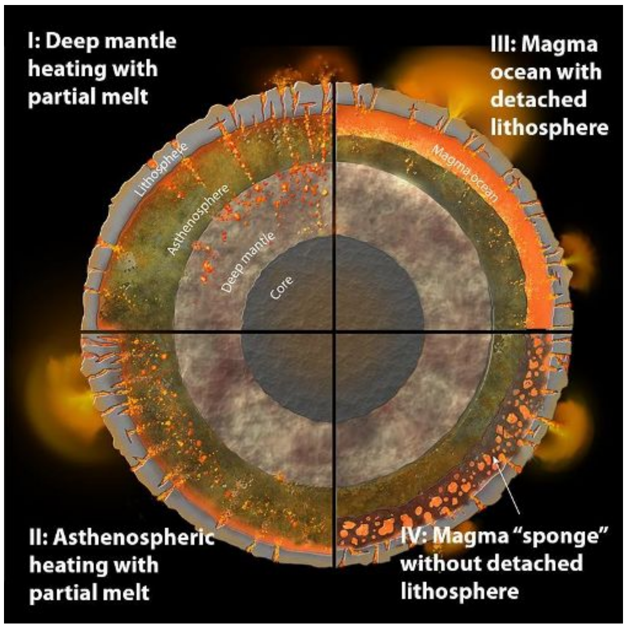
We can express this rate of heat production on the terms that the eccentricity is small, and that the satellite spin and period of orbit, are synchronized to each other, with the equation -

$$E = \frac{21}{2}\frac{n^5 R_s^5}{G} e^2 \frac{k_{2s}}{Q_s} = 15GW \frac{k_{2s}/Q_s}{0.01}$$

A composite equation, but when unpicked it reveals its components: *n,* the mean motion; *R*, the satellite radius; *G,* the gravitational constant; e, the orbital eccentricity and *k2,* the so-called tidal love number of the satellite [2]. The formula itself matters less than its implications. It reveals that tidal heating depends primarily on e – the orbital eccentricity - where even the tiniest eccentricities can generate mass heating, emulating the process of tidal heating [3]. A closer orbital distance amplifies this effect, and a subsequently larger planetary mass generates more heating. Yet the internal properties of the moon – expressed by *K2* and *Q* - ultimately determine how efficiently that energy is converted into heat, ensuring the accuracy and validity of the equation [3].

Tidal heating is occurring at this very moment. The most famous example of the process occurs on Io; a volcanic moon, housing hundreds of volcanoes that erupt constantly. The volcanic activity on Io is powered by tidal heating in its extreme form, which is caused by the orbital resonance from its neighboring moons – Europa and Ganymede. The surface of this moon is completely covered in sulfur, as well as the continuous flow of silicate lava [4]. Justifying the fiery sphere captured through NASA spacecraft. Experts estimate this heat flux to measure at ~100 trillion watts. This is more than enough to continuously melt the interior of this moon. Lo evidently undergoes extreme tidal heating; Ipso facto, its physical state is that of a volcanic furnace.

De facto, the heating mechanisms circulating within the moon, provide scientists with an explanation as to how the moon is geologically alive while most others are frozen [3].



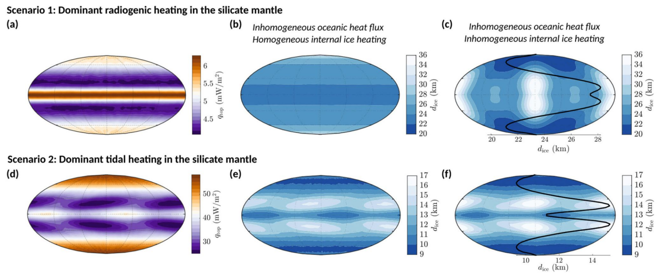
Lo and the possibility of a magma ocean

Lo is a testament to all motions, opposing the theory of tidal heating. The negative impacts of tidal heating on Io, consist of the moon having an absence of liquid water. However, this does not aid to the argument that life can be harbored on these moons. Which explains why most research into Io paused, and shifted to center on Europa.

Europa is an icy moon with the potential to host life if the presumption is that life does not already exist there [6]. This is due to the warmth present on the icy giant due to the direct influence of tidal heating. This is primarily caused by the gravitational interactions between Jupiter and other moons like Lo and Ganymede [5]. Europa orbits Jupiter in a slightly elliptical orbit – a direct consequence of the gravitational pull from other planets. Which results in the change of distance over time between Jupiter and its fellow moon [6].

When Europa is closer to Jupiter, the strong gravity of the gas planet exerts a powerful force that causes the shape of the Europa moon to flex and deform repeatedly [5]. It is like the stretching of a rubber band, which causes tension. This constant flexing occurs on Europa and creates mechanical stress on the planet which generates this internal friction. This same friction produces heat which is known to us now as tidal heating. The heat generated in this process is not weak, in that the planet remains frozen, but powerful enough to prevent the subsurface of the liquid oceans from freezing. Observe that the heat generated is also not powerful enough to become volcanic like Io. In essence, Europa has freezing temperatures, but the warmth of the tidal heating allows the ocean to remain in a liquid state.

In simple terms, tidal heating converts GPE – Gravitational Potential Energy into thermal energy.



Europa's ocean interior with the effects of tidal heating.

It can be argued that the rocky core of Europa can also contribute energy, but it has lesser impact than tidal heating. Heat from tidal forces warrants chemical interactions between the rocky mantle and the Moon's oceans [6]. This interaction possesses the potential to cycle nutrient and energy. To demonstrate that moons such as Europa may offer another path for humanity's expansion—or, at the very least, a chance to discover life beyond our own world. Tidal heating shapes Europa's geology and is thus vital for its potential to even host life.

By Zahra Aziz '27

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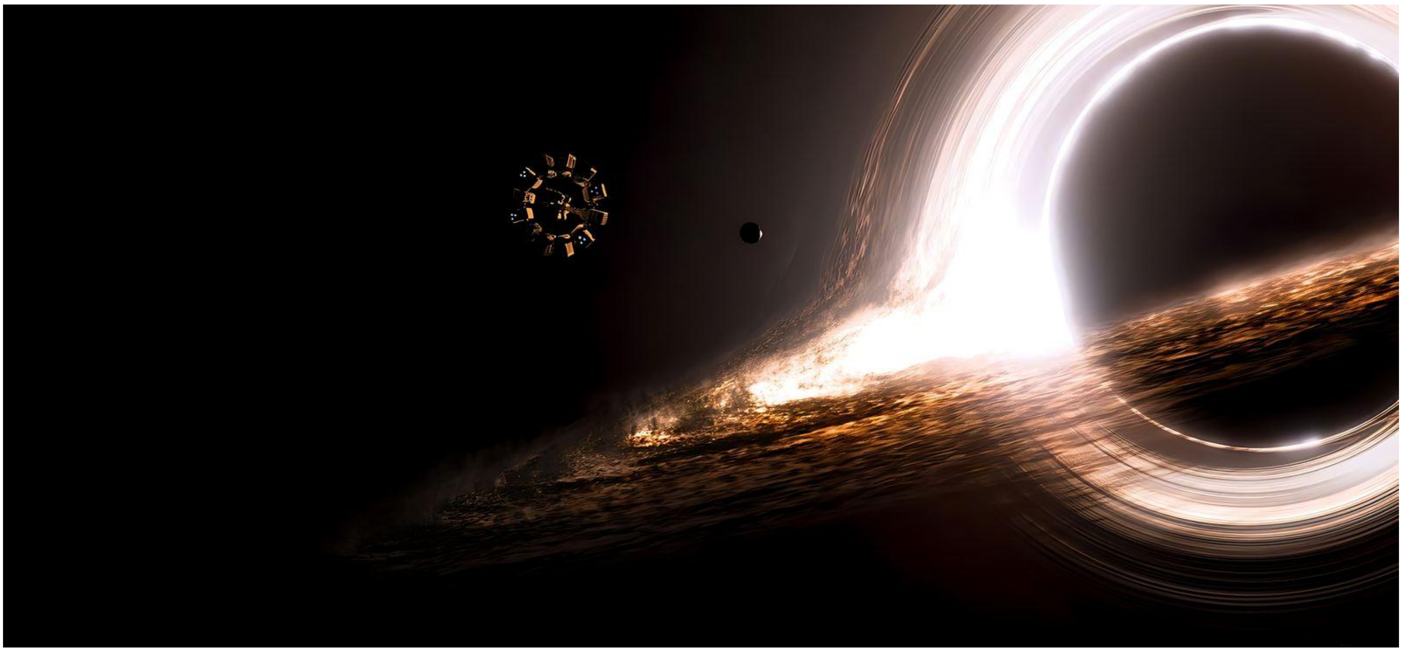

The Mesmerizing Special Effects of Interstellar

"Interstellar" is one of the most significant scientific accomplishments in film history. It is a science fiction movie that was released on the big screen in 2014 and since then it has transformed the way people understand science and technology behind space and interstellar travel. It has not merely offered a cinematic experience, it was a source of inspiration for millions of viewers worldwide, introducing them to the magic of the universe through impressive special effects.

This production not only won the audience's heart, but also attracted the interest of the wider scientific community, earning the admiration of many specialists and researchers. This is a remarkably singular aspect, because some sci-fi movies are characterized by bending theories and scientific inaccuracies.

Furthermore, screenwriter of "*Interstellar*", Christopher Nolan, cooperated with project's originator, Kip Thorne, a foremost authenticity in the field of general relativity. He has dealt extensively with wormholes and black holes, and has collaborated with, among others, the legend Stephen Hawking.

Kip Thorne has mentioned before that he wish to participate in a space movie about black holes and also wormholes. So, he not only investigated the science behind Nolan's ideas, but contributed drastically to their representation after advising and overseeing scientific accuracy [1].

Beyond the film's creator, prominent scientists highlighted the film's importance within the discipline. The well-known astrophysicist Neil deGrasse Tyson, director of the Hayden Planetarium in New York, publicly praised the scientific accuracy of the film. Despite his lack of involvement in the development, he commended the accurate representation of phenomena such as the curvature of spacetime and the temporal flow in proximity to gravitational entities [2]. Similarly, Michio Kaku, a theoretical physicist and author, praised "Interstellar" as a unique example of sci-fi that can serve as a model for the genre due to its scientific grounding [3]. Finally, Jean-Pierre Luminet, a well-known astronomer who was the first to simulate what a black hole would look like, was impressed by how the movie depicted gravitational distortions around the black hole. They occur because its immense mass bends spacetime, warping light paths, slowing time, and creating effects like gravitational lensing and time dilation near the event horizon [4].

Observing the scientists' comments, it is evident that they all highlight the significant special effects of the film. They not only allow viewers to travel with their imagination alongside Astronaut Cooper but also show that the details of “Gargantua”, a key scene in the work, almost perfectly reflect the real phenomenon that actually exists in the universe [5].

The black hole in “*Interstellar”* is more than just a captivating special effect. Since it is based on genuine physical models of general relativity, it is the outcome of a rare connection between science and technology. The scene of the black hole was not created entirely with artistic means; instead, it was developed using complex mathematical equations that reveal how light shifts around such an intense gravitational field. The scientific information was supplied by Mr. Thorne and the Double Negative group developed new software that could simulate millions of light rays to calculate how they would appear to an observer near a black hole. The most pivotal technical problem was the exact representation of relativistic phenomena, such as gravitational light bending and time dilation.

Additionally, the speeds around the “Gargantua’s” disk are so intense that they cause phenomena such as the Doppler shift and the optical distortion due to motion. Achieving a balance between scientific precision and accessible visualization was essential, allowing the audience to engage with the experience without being distracted by easily misinterpreted concepts. Achieving a balance between scientific precision and accessible visualization was essential, allowing the audience to engage with the experience without being distracted by overly complex technical details. The visual effects result was so realistic, that the scenes were used in scientific articles and presentations. The film proved to doubters that it is not only a space fiction movie, but also a useful tool for the global scientific community [6].

The special effects were so breathtaking that felt like someone was truly travelling through the wormhole and around “Gargantua”. This movie is a major inspiration for lots of people around the world and made them realize how fascinating space exploration is. So, to conclude, ''*Interstellar*'' is a must watch movie anyone can experience the magic of the universe with their own eyes.

By Archontia Chamilothori ‘26

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How Motorsport Has Cut Down On Carbon Emissions

Formula 1 is known for its high-speed cars, glamorous lifestyle, legendary races, and groundbreaking technological advances. Traditionally, this comes with conventionally high carbon emissions. Due to the growing global demand for sustainability in sports, Formula 1 is dedicated to creating a plan to help serve the environment better while simultaneously adding more tracks to the race calendar. Despite its rapid growth in races, attendance, and global popularity, Formula 1 has reduced emissions by 26% since 2018, and remains on track to achieve net zero by 2030 [1]. The aim by 2030 is to balance emissions created with those removed from the atmosphere, resulting in a net zero increase.

Only seven years ago, F1 was emitting 228,793tCO2e into the atmosphere. Since then, the sport has added 3 more races to the race calendar (from 21 to 24), race attendance grew from 4 million to 6.5 million, and the global fanbase of over 826 million people continues to grow [2]. Despite all of this, carbon emissions have decreased by over 60,000 tonnes of CO_2 as of the end of 2024, marking a significant reduction over the span of 6 years [1]. Considerable progress has been accomplished by focusing on 4 key emission sources: factories and facilities, travel, logistics, and event operations.

Due to the increased use of renewable energy sources such as solar panels and biofuels, carbon emissions from factories and facilities have decreased by 59% [2]. Furthermore, 80% of race promoters are powering aspects of their events using alternative energy sources with a proposal for the remainder to start similar plans in the coming years [3].

Travel-related emissions were reduced by almost 20,000tCO2e compared to 2018, a 25% reduction [1]. This was made possible by the rollout of remote broadcasting, investments in Sustainable Aviation Fuel (SAF), and race calendar optimization [4]. The remote broadcasting hubs have 140 employees working there each race, eliminating unnecessary travel. SAF is an alternative fuel for aircraft that reduces emissions by an estimated 80% per flight compared to regular fuel [5]. SAF is crafted from renewable energy sources such as agricultural biomass and used cooking oil. This formula can be blended with traditional fuel and used in existing aircraft without requiring any changes. Moreover, the Formula 1 race calendar faced optimization in order to minimize unnecessary freight emissions by grouping races by geographic location, saving thousands of tonnes of emissions. For example, the Azerbaijan Grand Prix was aligned with Singapore to create the Asia-Pacific segment, while the Qatar Grand Prix and the Abu Dhabi Grand Prix are successive on the race calendar, resulting in the Middle Eastern segment. Similarly, the Monaco Grand Prix got moved to June to start off the European leg of the season, and the Canadian Grand Prix was moved to May in order for direct freight from Miami to Montreal to be possible. This is projected to save thousands of tonnes of emissions by avoiding an extra transatlantic trip [6].

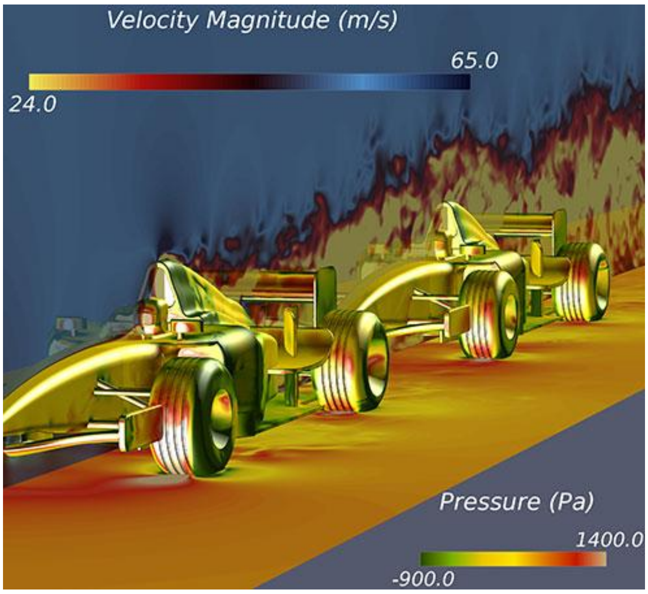
Furthermore, logistics has faced a 9% emission reduction through a variety of changes. F1 introduced new freight containers resulting in efficient Boeing 777 use. The sport invested into SAF investments for freight flights, and increased the use of biofuel trucks in Europe. Regarding overseas transport, F1 switched to sea freight. [1], [3]. Regional hubs have been in discussion and now are in the planning stage. These hubs will allow vital equipment to stay in the region to reduce the amount of travel required [6].

Event operations saw a 12% reduction per-race. Through its partnership with Aggreko, the sport has implemented low-carbon energy generation systems using renewable resources such as hydrotreated vegetable oil (HVO), solar, and batteries. This initiative resulted in a 90% reduction of event-energy emissions all over Europe [3]. F1's partner and tire producer, Pirelli, works alongside the Forest Stewardship Council to create FSC-approved tires to be used in all aspects of F1 racing [7], [8]. In fact, Pirelli was the world's first tyre manufacturer to obtain the FSC certification, meaning the natural rubber in the tyre complies with the FSC standards for sustainable forestry. All the tires brought to the track during a Grand Prix are transformed into secondary raw materials after their use. The electrical energy used to create the tires is derived exclusively from 100% renewable sources, and the use of virtual design technology reduces development time and cuts down on materials used [7].

Although significant progress has been made, Formula 1 still has a long way to go to achieve Net Zero, with further plans already in place. Starting from 2026, F1 will make history by being the first in motorsport to use 100% sustainable fuel across the entire grid, contrasting the 10% mixed fuels in use right now [9]. Formula 2 and 3 are already trialing sustainable fuel blends (55% in 2024) and the FIA medical and safety cars operated with a 40% blend in preparation for a full transition [2].

Additionally, F1 is bringing in new hybrid engines in 2026 with a 50/50 split between electric and combustion power, making them more efficient. These engines will cut fuel from 160 kg per race in 2013 to as little as 70kg by 2026 [9]. The inclusion of batteries allows the cars to deliver power more efficiently by enhancing acceleration out of corners, and contributing to overall performance improvements. This hybrid engine will include the Motor Generator Unit-Kinetic (MGU-K) and the Motor Generator Unit-Heat (MGU-H). The MGU-H uses heat energy from the exhaust to increase the engine power. Meanwhile, the MGU-K converts kinetic energy from braking into electrical energy stored in the battery, boosting acceleration and speed. The sport is committed to increase power output from the MGU-K from 120kW to 350kW, nearly tripling it [9]. This change will increase the energy efficiency to harvest braking energy. These fuels and engines have a great impact beyond racing, as they can also power road cars, offering every-day sustainability.

Since logistics and freight are F1's biggest emission source, producing about 45% of total emissions, the sport is bringing future changes such as more reliance on sea freight rather than air. F1 is putting resources into establishing regional hubs in order to avoid constant intercontinental transport, wider adoption and investments of SAF in freight, and new freight calendar adjustments to eliminate unnecessary transatlantic trips [6]. Formula 1 aims to reduce travel by expanding their remote broadcast system, which already has 140 staff working there remotely per race. The sport will continue the rollout of SAF for personal travel and aims to cut thousands more tonnes of travel emissions annually [4],



[5], furthering F1’s commitment to a more sustainable future.

The innovative sport of Formula 1 has continued to prove that sustainability and growth can coexist in the same matter. The progress seen throughout the sport, from emitting thousands of tonnes of CO2e absentmindedly to being halfway to Net Zero shows that change *is* possible. Reaching F1’s big sustainability goal will require continued work, determination, and innovation. Not only does this research benefit the motorsport community and our planet, but it is a testing ground for tech that can benefit society globally.

By Jessica Bokyo ‘27

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The Neuroscience of Rhythm: Music's Impact on Brain Activity

Neuroscientists have long been intrigued by the ways in which music influences the brain, not only through the emotions it elicits, but also through measurable electrical activity [1]. According to Harvard neurologist Andrew Budson, MD, "Music lights up nearly all of the brain". There are many different types of brain waves that play essential roles in sleep, memory, focus, and creativity. By examining the interaction among delta, theta, alpha, beta, and gamma waves, the relationship between music and neural activity becomes more clearly understood. Music interacts with each category of brain waves, guiding neural activity in ways that mirror its rhythmic structure. Even in moments of stillness, the brain remains active with complex electrical patterns. These patterns come in different speeds, called brain waves.

Brain waves are typically categorized into five main types, each associated with distinct mental states and functions. Delta waves (1–4 Hz) are the slowest and are primarily linked to deep, restorative sleep. Theta waves (4–8 Hz) appear during light sleep, daydreaming, and moments of imagination. Alpha waves (8–13 Hz) are most prominent when a person is awake yet relaxed, such as when resting with closed eyes. Beta waves (13–30 Hz) are connected to active thinking, concentration, and problem-solving. Finally, gamma waves (30+ Hz) are the fastest and are believed to help the brain integrate information, forming a cohesive understanding of complex ideas.

Neuroscientist György Buzáki describes how brain waves are a kind of "neural syntax", meaning they give structure to our thoughts the same way grammar gives structure to language [2]. Since music operates through rhythm and pattern, it easily resonates with the brain's own rhythmic activity. One of the most significant discoveries is that the brain can be entrained to music. Entraining means brain waves line up with the rhythm of the sounds we hear. This explains why a strong rhythm can compel movement, while soothing music promotes relaxation. Research shows that the brain is especially good at synching beats in the 0.5-4 Hz range, which is a typical song's beat [3]. Research from 2018 revealed that listening to real music modifies the interaction between different brainwave frequencies, rather than affecting only one type; for example, delta waves can influence beta waves [4]. As neurologist Oliver Sacks once said [5], "Our auditory systems, our nervous systems are tuned for music. Perhaps we are a musical species no less than a linguistic one."

Music is not merely an external experience; as we listen, our brains engage in their own rhythmic dance. Delta and theta waves connect music to memory and emotion, alpha brings calm, beta keeps us moving and focused, and gamma helps us put the whole experience together. Although science has more to uncover, one fact stands out clearly [6]. The rhythms of music and the rhythms of the brain are deeply connected. Thus, when music evokes a strong emotional or cognitive response, it reflects the brain's active participation rather than passive perception.

When considering various musical examples, clear connections emerge between their qualities and the research findings. Clairo's *"Bags"* seems to align with theta wave activity. The song is slow, emotional, and deeply nostalgic, evoking memories and reflection. In contrast, ROLE MODEL's *"Sally When the Wine Runs Out"* embodies more of a beta energy, marked by its upbeat tempo and sharp focus that easily engages the mind in rhythm. Taylor Swift's *"...Ready For It?"* introduces yet another dynamic, with its driving bass and layered production that demand attention from multiple directions while the brain integrates it all seamlessly. Music, therefore, is far more than background noise, it is a spark that synchronizes with the brain's most intricate rhythms. Whether it's a mellow Clairo track, an energetic ROLE MODEL song, or a high-intensity Taylor Swift anthem, the brain remains fully engaged, processing and responding to every beat.

In conclusion, music is far more than an art form. It is a neurological phenomenon that bridges emotion, memory, and cognition through the language of rhythm. Each beat and melody interacts with our brain's electrical patterns, shaping how we think, feel, and even move. From the slow waves of relaxation to the rapid bursts of focus and insight, music activates nearly every region of the brain, uniting science and art in a shared rhythm. As research continues to uncover these connections, it becomes increasingly clear that our brains are not passive listeners, but active participants. They are dancing, adapting, and harmonizing with the soundscapes that shape our inner worlds.

By Lexi Dalley '27

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Thank You!

This concludes the fifth issue of the Penrose Magazine. Thank you so much for reading and we hope you enjoyed!

Finally, we would like to thank our ambassadors for taking the time to write the articles, as this magazine would not have been possible without them.

If you would like to write for the next issue of the Penrose Magazine, please check out our website or socials:

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