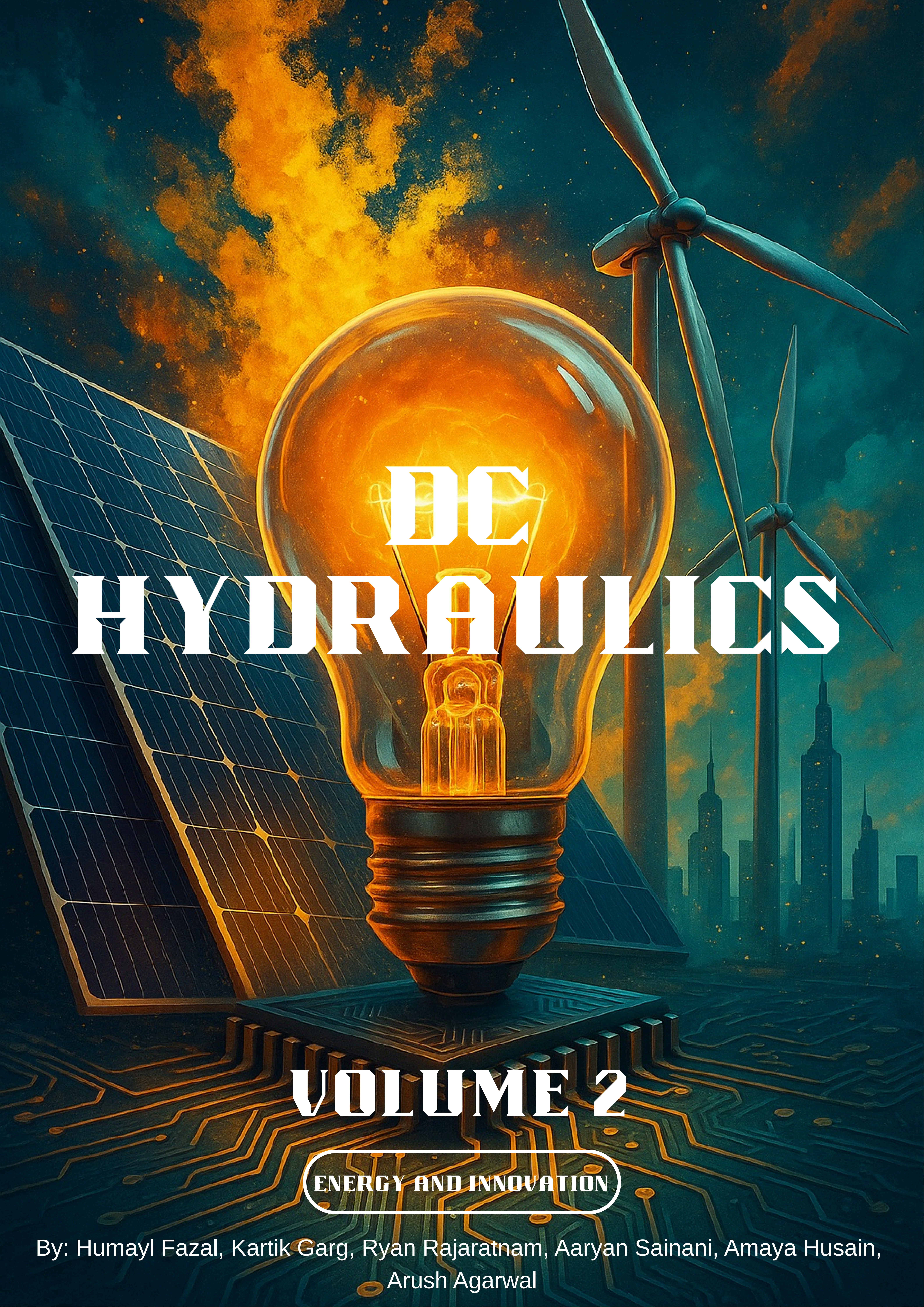


DC HYDRAULICS

VOLUME 2

ENERGY AND INNOVATION

By: Humayl Fazal, Kartik Garg, Ryan Rajaratnam, Aaryan Sainani, Amaya Husain, Arush Agarwal

CONTENTS

THE GRAPHENE REVOLUTION

As global energy demands surge and the need for better healthcare solutions grow more urgent, scientists and engineers worldwide are focused on improving efficiency and driving innovation. Be it excess greenhouse gas emissions from motor vehicles or outdated technologies in the healthcare sector, there is an urgent need to accelerate technological advancements. At the forefront of this effort is graphene - an allotrope that holds the promise to solve such challenges. Composed of a single layer of carbon atoms in a two-dimensional honeycomb structure, it's hailed for its extraordinary strength, electrical conductivity, and thermal properties.

Despite its immense potential, graphene's journey from laboratory research to practical applications remains riddled with obstacles, with many solutions still in the developmental phase. Yet, the stakes have never been higher, as we strive for sustainable energy solutions and more effective medical technologies.

This report explores how harnessing graphene's unique properties could drive groundbreaking progress in the healthcare and transportation sectors.

Graphene in fuel enhancement

One of the critical areas for application of graphene lies in its potential to make modern-day fuel more efficient. Using graphene additives in fuel for transportation has the ability to improve combustion rates and reduce emission of greenhouse gases.

A graphene-based additive in fuels, like petrol, can modify the fuel's surface tension properties, making it easier to break the fuel into smaller droplets. Surface tension is a key factor in how well the fuel atomises when it enters an engine's combustion chamber, directly affecting the efficiency of the burning process. When fuel is converted into finer molecules, a greater surface area is in contact with oxygen, allowing for more efficient energy release.

Additionally, graphene's exceptional heat conductivity enables heat to be distributed more evenly throughout the fuel, preventing temperature imbalances that could lead to inefficient burning.

Motor vehicles are notorious for emitting potent gases such as carbon monoxide, nitrogen oxides (NOx) and sulphur dioxide, which are produced by incomplete combustion and high, uncontrolled temperatures in the combustion chamber respectively. In these extreme conditions, nitrogen and sulphur react with oxygen, leading to the formation of these harmful pollutants.

Traditional fuel additives may not be effective, but graphene’s unique molecular structure allows it to interact with fuel molecules in a way that promotes finer atomisation, resulting in a much more complete energy release.

Graphene additives have the potential to mitigate the formation of such gases by better controlling combustion temperatures and promoting more efficient fuel utilisation. This leads to reduced emissions and more environmentally friendly vehicle performance.

Graphene papers in wearable technology

Graphene papers (GPs) are thin, lightweight, and flexible films made from stacked layers of graphene or its derivatives, such as graphene oxide and reduced graphene oxide. They are created through various fabrication techniques, including vacuum filtration, solution casting, and chemical vapour deposition.

Moreover, graphene-based polymers preserve many of graphene’s exceptional properties, including high mechanical strength, flexibility, and a large surface area, making them ideal for flexible technologies.

Currently, polymers like polyurethanes, polyethylenes, and polysiloxanes (silicone) are widely used in wearable technology due to their flexibility. However, they come with significant drawbacks, such as low mechanical strength, which makes them prone to tearing over time, and their tendency to absorb small hydrophobic molecules interferes with sensing applications.

The field of wearable technology stands to benefit significantly from GPs. Their exceptional electrical conductivity, 100 times greater than that of copper, enables efficient transfer of bioelectrical signals to computing units. More importantly, GPs are ultrathin and flexible, mimicking the properties of human skin while maintaining remarkable structural integrity and elastic strength, making them ideal for next-generation wearables.

The usage of graphene is currently being explored in technologies, such as wearable biosensors, Point of Control (POC) testing, and flexible circuits and transistors.

Graphene and neuroelectrics

Millions of people worldwide suffer from brain diseases such as epilepsy and Parkinson's, with many receiving ineffective treatments. Most doctors and hospitals rely on rigid electrodes made from hard metals like platinum to stimulate electrical impulses and manage these conditions. However, traditional electrodes often cause inflammation, tissue scarring, and show limited effectiveness. Graphene has the potential to revolutionise this field, offering a more biocompatible alternative that could significantly improve treatment outcomes.

Graphene's exceptional conductivity, flexibility, and biocompatibility make it an ideal material for brain implants. Unlike traditional rigid electrodes, such as platinum, graphene-based interfaces are softer and more flexible, allowing them to behave like electronic skin. This flexibility ensures perfect contact with the brain surface, reducing the risk of inflammation and improving signal collection. Additionally, graphene's ultrathin structure enables the creation of miniaturised brain sensors that are 40,000 times smaller than platinum-based sensors, allowing precise and localised monitoring of brain activity thanks to nanotechnological advancements.

Graphene-based implants also show promise in the field of adaptive neuromodulation, where AI algorithms adjust electrical stimulation based on real-time neural activity. For example, INBRAIN Neuroelectronics uses graphene to create implants that detect abnormal brain signals and deliver personalised stimulation, improving treatment outcomes and reducing side effects compared to traditional methods.

Using graphene, scientists are developing microchips that are working towards accurately mapping out the human brain, which can be used for further research and surgery.

Graphene's exceptional properties offer transformative potential across various industries, from enhancing fuel efficiency and reducing emissions to revolutionising medical devices. Its high conductivity, flexibility, biocompatibility, and impressive heat transfer capabilities make it ideal for cleaner energy solutions, advanced wearable technologies, and improved neuroelectrical treatments.

While these possibilities are promising, it is important to acknowledge that this miracle material is still undergoing extensive research, and many of these solutions remain in developmental stages. Future scientists must continue exploration and innovation in graphene technology, which holds the promise of a future where technological progress aligns with environmental and healthcare advancements.

Aadit Nag

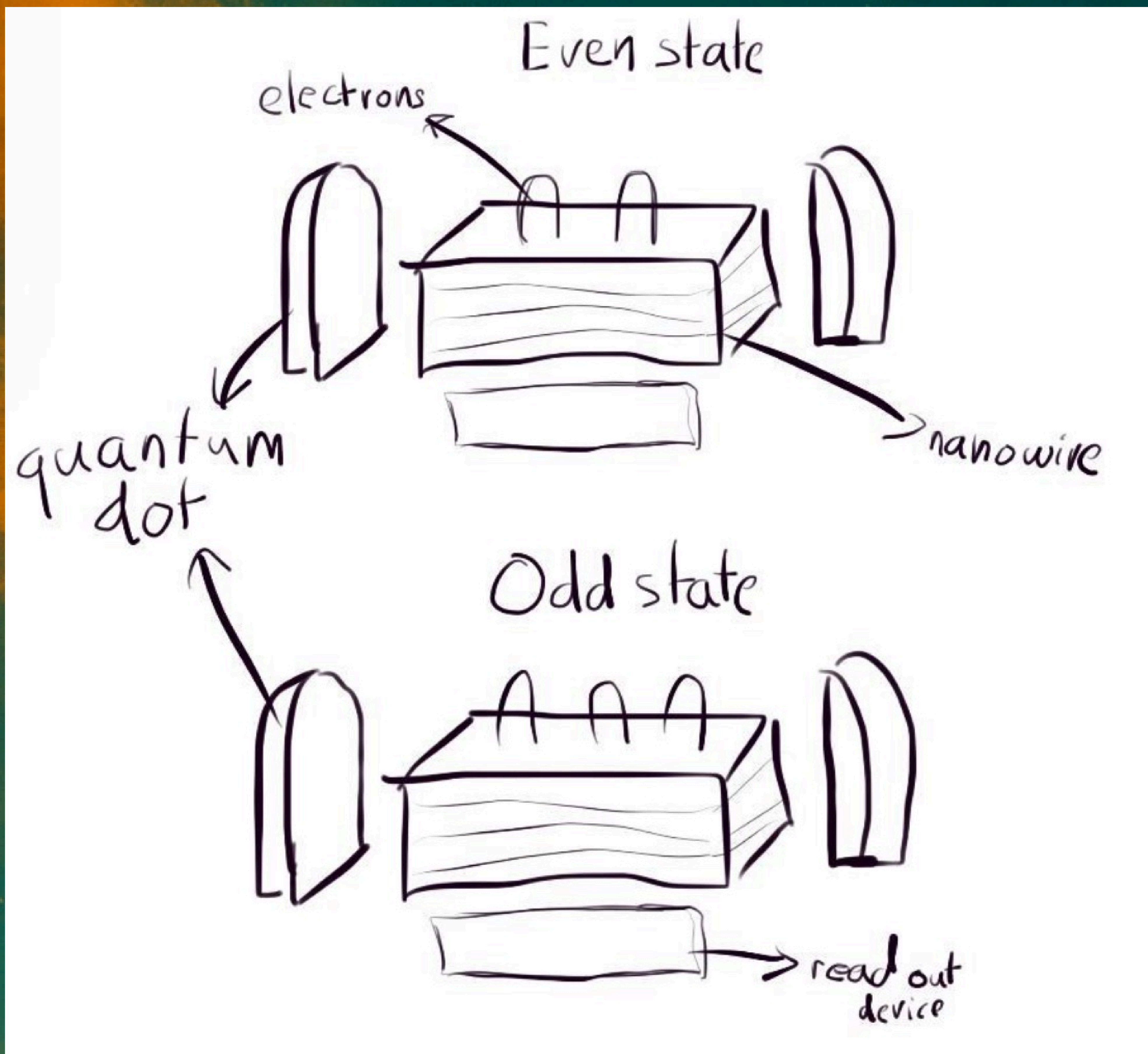
MAJORANA PARTICLE: THE NEW STATE OF MATTER AND QUANTUM COMPUTING

Ever since third grade, we’ve always been told there are four states of matter: solid, liquid, gas and plasma. This has always been an irrefutable fact, one that would be strange to question. Yet on the 19th of February this year, Microsoft announced an entirely new state of matter - the topological state - on their path to creating a quantum computer. Many people all over the world were confused. How could there be another state of matter? Questions flew about how the particles would be arranged, how this state would act in real life and, most importantly queries about where this topological state was before. In this article, we will delve into the topics of this new, controversial state of matter, quantum computing and what this means for our future.

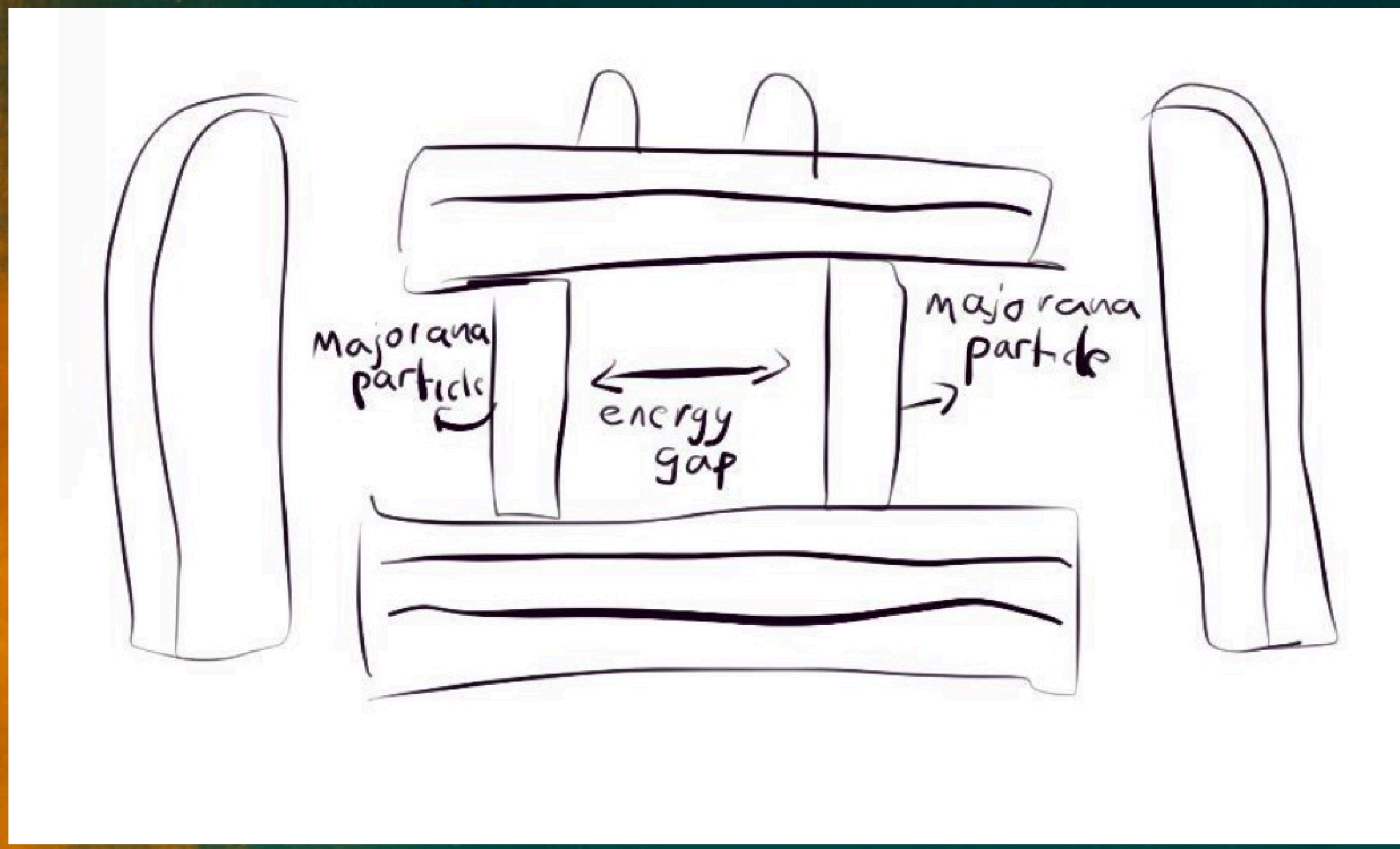
So, what is the topological state? Well, topology is defined as what properties of a thing stay the same when you change the shape of said thing. For example, the number of holes in an object: A mug and a donut both have the same number of holes in them, and technically, you can merge one into the other without changing this fact. The topological state is a special way of storing information using particles that are intertwined tightly together – like twists of a rope- which allows for the data stored to be more protected from “noise” or interference. Microsoft also detected and found means to control a particle that was theorised a hundred years ago- the Majorana particle, which is its own antiparticle. When these particles move around each other within the topological state, quantum information can be stored.

This all sounds very complicated, so let's try to simplify this by looking at what a qubit is and how Microsoft went about making one. To make a quantum computer, you need to make a tiny controllable quantum system called a qubit, which is the smallest fundamental part of information. These are like bits, but while bits can only ever hold the values 1 or 0, a qubit can be in a state of superposition. What this means is that when unobserved, a qubit can be a 0 or a 1 or something in between, but when observed while giving a value or 1 or 0. There have been numerous versions of qubits over the years, but what Microsoft are using is a qubit made of a topological quantity of a group of electrons working together, which is the Majorana particle.

Firstly, there is a nanowire as a base, which is made of many materials delicately stacked together. On each side of this nanowire are quantum dots, which are a type of gate which allow electrons to travel through the wire when open, and when closed, they trap electrons on the wire. We can use this structure to make a basic qubit where the state of the qubit is the number of electrons on the nanowire. An even number of electrons leads to the 0 state, and an odd number becomes the 1 state. The gates (quantum dots) also allow for this singular qubit to be isolated from the rest of the circuitry. Another device in front of the nanowire will read out the state of the qubit.



This design alone would be very susceptible to noise, leading to data loss. To amend this, Microsoft created a chip which can separate pairs of Majorana particles and place them in a layer of the nanowire. This creates an energy gap, which means that if noise came along and managed to disrupt one Majorana particle, the other one would still maintain the qubit and less data would be lost. This is what makes this model so unique- the increased strength to noise and disruption as in the past this has been one of the main hindrances to the process of making a quantum computer apart from qubit size and storage



The pursuit after the creation of a quantum computer has been followed by many firms even apart from Microsoft all over the world. Unlike a normal computer, a quantum computer unlocks a whole new realm of possibilities, harnessing the power to solve complex, previously unsolvable equations at a mere fraction of the time a supercomputer may take. To put this into perspective, while a supercomputer may take tens of thousands of years to complete a highly complex power(if put to the test in a hypothetical situation), the quantum computer would only take 3-4 minutes. This is because while a traditional computer tries each solution to a problem one at a time, a quantum computer has the ability to try numerous solutions at once, greatly reducing the time it takes.

This could mean great things for our society! For example, if a quantum computer is developed by Microsoft following Majorana 1, more complex situations may be simulated. Currently, the world's supercomputers are only able to simulate a few electrons, but a quantum computer has the potential to simulate the laws of nature and larger particles well(if developed much further). This could mean the development of special enzymes for sustainable food consumption, new medicines being created and many more life-altering beneficial scenarios!

Despite this newfound hope, this source of greatness could also lead to serious trouble. With this quantum development, hacking becomes much more efficient. As mentioned previously, while a traditional computer tries each solution to a password when being used by a hacker until it is correct (which may take years if the password is strong), a quantum computer simply tries all possibilities at once. The time taken for hacking is greatly reduced, and data safety is compromised, posing a grave cybersecurity threat worldwide.

This is still some time away, and quantum computing has a long way to go. Who knows what our future may look like and whether this invention could become the most influential creation since Artificial Intelligence?

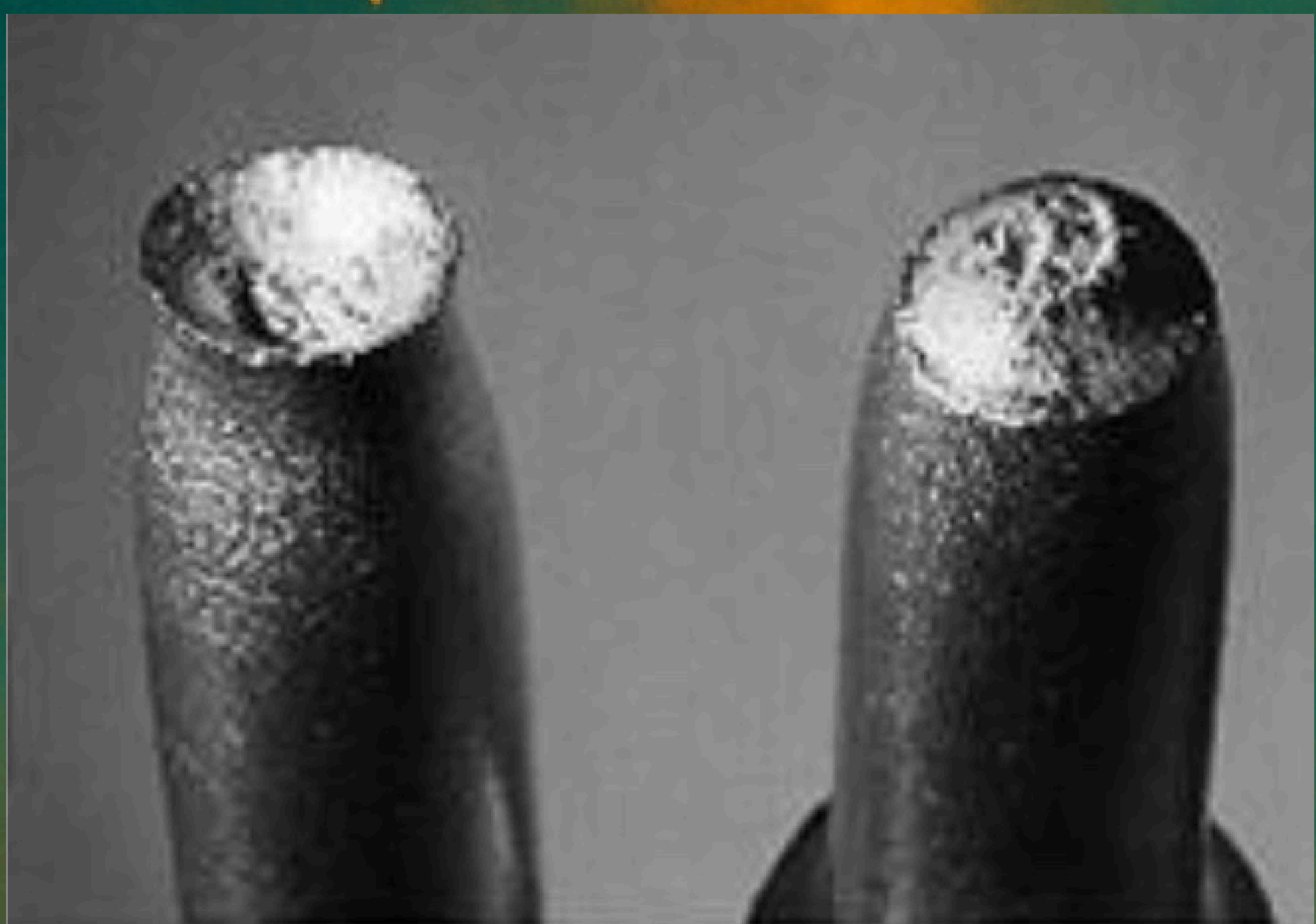
Sanaaya Patil

SELF-HEALING MATERIALS

Imagine if buildings could mend cracks, roads could seal potholes, and aircraft could repair damage mid-flight, just like living organisms heal wounds. In nature, skin regenerates, plants restore broken stems, and some animals even regrow whole body parts. Based on these biological processes, self-healing materials have been developed to automatically repair themselves without any human intervention. As the demand for more resilient materials with tailorable properties grows, these materials can prevent failure and reduce costs, with applications from biomedicine, infrastructure, and aeronautics.

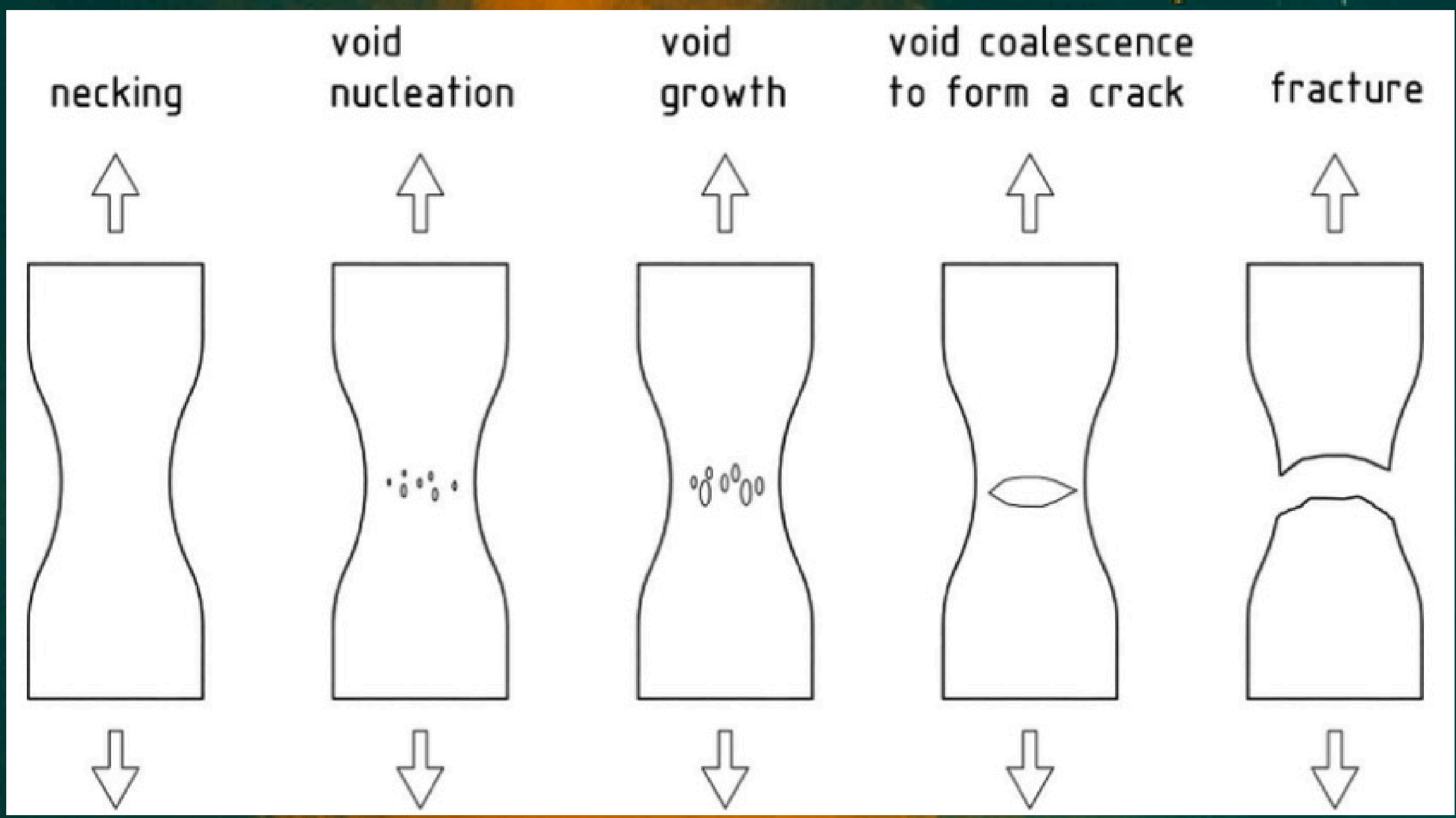
Why do materials break?

Before discussing how self-healing materials offer promising solutions to preventing catastrophic failure, it is essential to understand why materials break in the first place. Fracture occurs in all materials under stress. It is caused by the propagation of cracks throughout the material, eventually leading to the full separation. However, the mechanics of fracture vary for brittle and ductile materials.



Ductile Brittle Dayman, 2017

Brittle fracture occurs extremely rapidly, reaching several thousand meters a second. This type of failure can be commonly thought of as a dropped vase shattering instantaneously on impact. Because brittle materials undergo little to no plastic deformation before breaking, they absorb no energy. Typically, brittle fracture starts with a defect, such as an irregularity in crystal growth or a surface scratch. Under repeated stress, the crack grows longer, resulting in stress concentrating around its tip. Once the crack reaches a critical length, it rapidly spreads throughout the material as that is what is most energy favorable, resulting in sudden failure.



In comparison, ductile fracture occurs gradually as cracks propagate slowly with applied stress. Ductile materials deform extensively before breaking, which absorbs a lot of energy. The fracture mechanism begins with micro voids or cracks, which expand and merge until they form a crack; it grows longer until the material fractures.

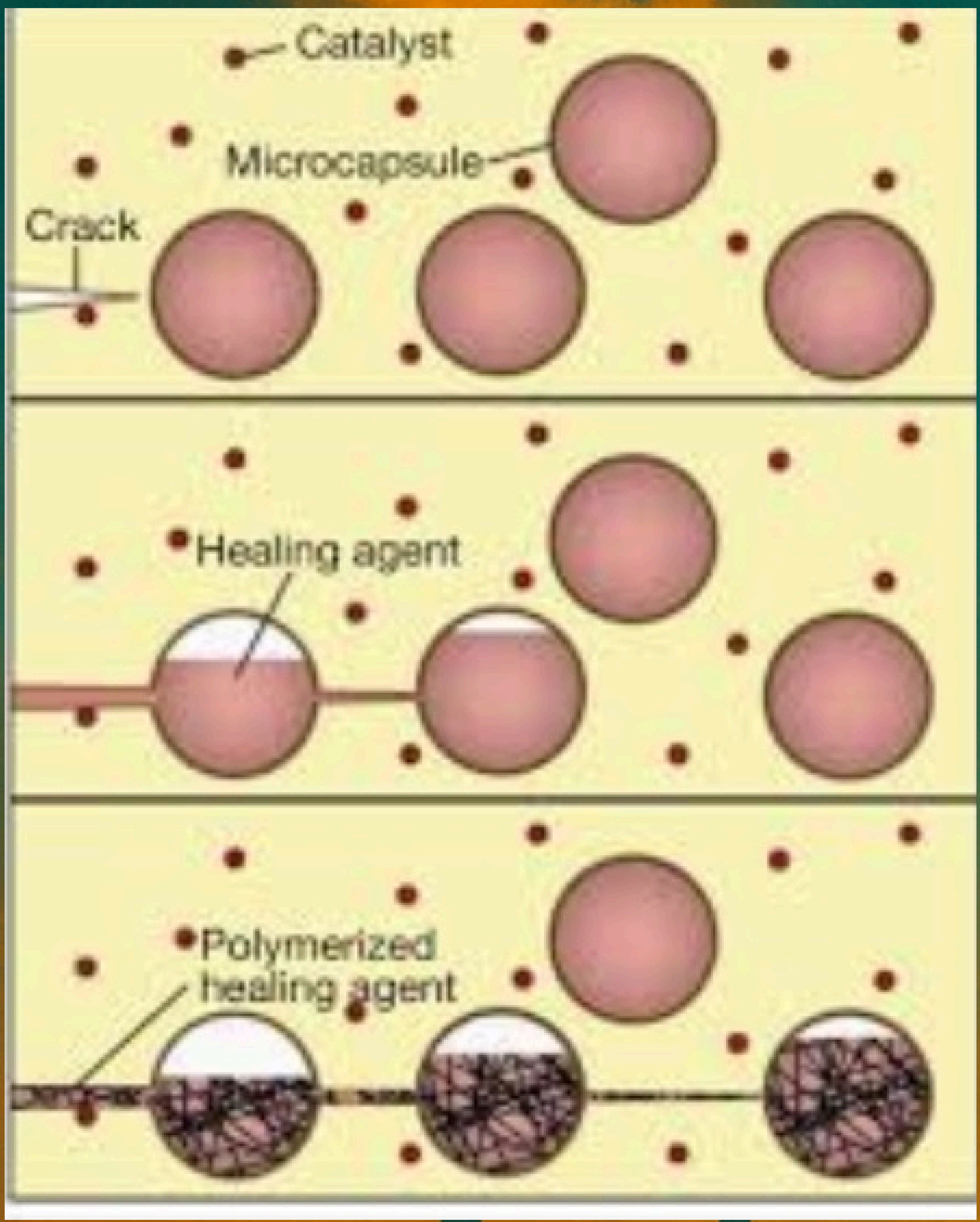
Fundamentally, all fracture occurs because of cracks propagating. Thus, to prevent fracture and to heal themselves, self-healing materials must prevent the growth of cracks as early as possible. By intervening at a microscopic level, these materials can halt or reverse damage before it becomes critical.

<u>How can materials selfheal?</u>

The earliest instance of a self-healing material is Roman concrete, which has withstood the testament of time for centuries. They used quicklime, which formed strains of brittle nanoparticles with a readily available calcium source. When micro-cracks appeared in the concrete structure during compression, they tended to form within these weaker regions. This allowed water to seep into those cracks and react with the calcium, solidifying as calcium carbonate to fill the gap or reacting further with surrounding material to strengthen it. Once healed, water could no longer flow through the concrete, effectively sealing it until further micro-cracks appeared.

This is one example of extrinsically healed materials, where a ‘healing agent’ is released upon a trigger, such as heat or hydration. Materials can also be intrinsically self-healing, which is usually achieved through reversible bonds in glasses and polymers. Typically, when heated, these materials can flow to fill the gaps and cracks within themselves. There are some elastomers, which have been shown to completely reform without heating or a catalyst by naturally being able to create covalent bonds at room temperature.

In modern times, self-healing concrete has been developed to have faster and more efficient healing rate. One method of doing this is through fiber reinforced concrete, where the fibers form a vascular network filled with self-repair fluid. Besides providing tensile strength to the material itself, when the brittle fibers eventually break due to microcracks, they release a chemical which fills them. Another method is bio-based healing, where the addition of bacteria to the concrete induces calcium carbonate precipitation. Unfortunately, the viability of the bacteria is not yet long term.



The principle of extrinsic healing by releasing a self-repair fluid was taken further with capsule based healing in polymers. A polymer matrix with capsules of a solvent and a catalyst is created. When the catalyst and solvent meet, their reaction fuses and strengthens the polymer. This is typically very favorable, as this method of encapsulation can be tailored to many different polymers requiring different reactions. However, one of the major drawbacks of this method is that an area can only be self-healed a limited number of times as eventually all the capsules in the vicinity will be used up.

Another material group with a need for self-healing are ceramics. Although ceramics are far stronger than metals at hot temperature, they are prone to sudden brittle failure, diminishing their uses in engineering. Ceramics, as brittle materials, are also sensitive to flaws and slight surface imperfections, which significantly reduce their strength over time. However, some ceramics can intrinsically heal microcracks instantaneously by filling it with solid product upon oxidation. This typically occurs at extremely high temperatures, where the particles exposed to heat, and oxygen react and fill the gaps through volume expansion.

Self-healing ceramics, due to the requirement of heat and oxygen for them to repair damage, are particularly suited to applications in high stress situations. Ceramics of low weight have high potential in aircraft, as turbine blades. This could allow the engines to run hotter than with their metallic counterparts due to the superior strength of ceramic when heated, allowing the engines to run more efficiently. Ceramics can also have wider uses as coatings, repairing microscopic damage which still would have led to degradation and corrosion yet would have been costly to repair. The coatings may also act as heat shields in space applications.

Hydrogels, which are loosely linked polymers saturated with water, also have high self-healing capabilities. They can mend themselves instantaneously through the reforming of dynamic covalent and non-covalent bonds. This significantly improves their uses in biomedical engineering, allowing them to easily be injected, deliver drugs, heal tumors and aid with wound recovery. They have also shown promise in the world of soft body robotics, allowing robots to self-heal without heat.

Self-healing materials can transform engineering by enhancing durability, sustainability, and efficiency across industries. From Roman concrete to modern polymers, ceramics, and hydrogels, these materials prevent failure by repairing damage autonomously. While challenges remain in scalability and long-term performance, research is driving advancements toward smarter, more resilient materials.

Darya Mostovaya

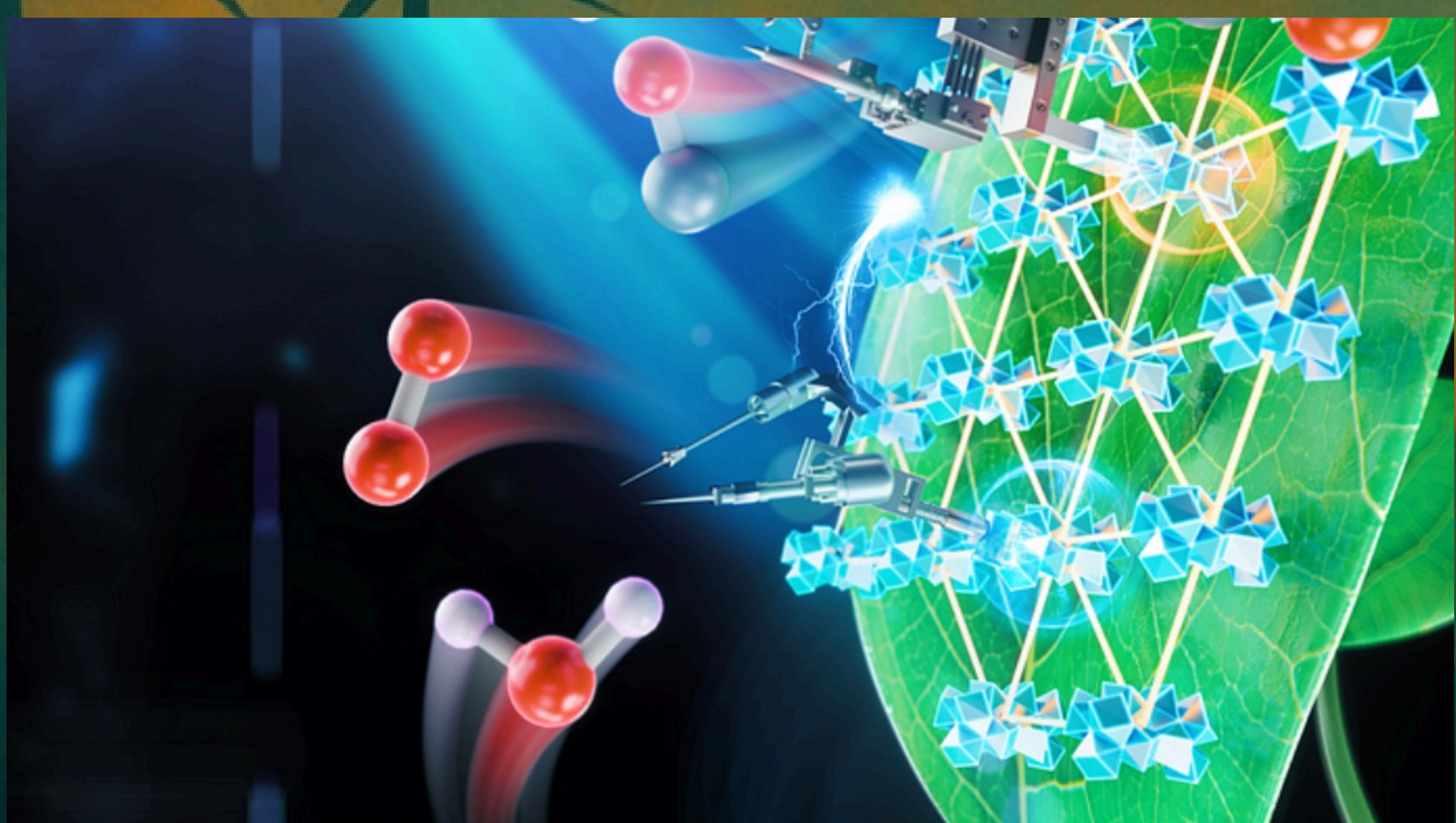
FUELLING TOMORROW: CAN ARTIFICIAL PHOTOSYNTHESIS TURN SUNLIGHT INTO THE POWER WE NEED?

As the need to find an alternative to fossil fuels becomes increasingly more urgent, the race to harness a sustainable energy source intensifies. Hydrogen had been identified as a promising contender for ‘the fuel of the future’ however, sourcing it sustainably to be used as a fuel proved to be too difficult of a challenge to overcome. Until now.

Imagine a world where sunlight, the life-giver to all things green, is harnessed not just for plants but to power our lives. Picture sunlight cascading down, its golden rays splitting water, breathing life into clean fuels—fuels that could one day drive our cars, heat our homes, and power our industries without polluting our skies. This is the dream of **artificial photosynthesis**, a revolutionary approach that aims to replicate what nature perfected over billions of years.

The idea of recreating nature's most efficient process to address humanity's energy needs feels almost poetic. The biggest opportunity lies in coupling artificial photosynthesis with carbon capture technologies. This not only addresses climate change but also creates a dual-purpose system that mitigates emissions while producing clean fuel.

At its heart, artificial photosynthesis is about capturing sunlight's magic, splitting water to release hydrogen, while simultaneously transforming carbon dioxide, that notorious greenhouse gas, into something more than just a villain in the story of climate change [3]. With the help of cleverly designed catalysts, researchers are attempting to tame this unruly gas, turning it into fuels like ethylene or methanol—fuels that can feed our hungry energy grid. But how feasible is it in practice?



To understand artificial photosynthesis, it is helpful to look at its natural counterpart. Photosynthesis is an elegant process where plants absorb sunlight using chlorophyll, the energy is then used to split water molecules (H_2O) into oxygen (O_2), protons (H^+) and electrons. Energy stored in molecules like ATP and NADPH is used to convert CO_2, O_2 and H^+ into glucose ($C_6H_{12}O_6$) using enzymes through a series of steps called the Calvin Cycle. Scientists aim to replicate this process using precisely engineered systems that produce solar fuels, like hydrogen, ethylene or methane, to be used for energy production or as industrial feedstocks, instead of glucose.

The process of typical artificial photosynthesis systems can be broken down into 4 key parts.

Capturing sunlight with photocatalysts

Photocatalysts are materials that absorb light and convert it to chemical or electrical energy, the chlorophyll of this system. Semiconductors like titanium oxide (TiO_2), Gallium Nitride (GaN), or metal organic frameworks (MOFs) are commonly used photocatalysts in artificial photosynthesis [4].

When the photocatalyst absorbs sunlight, electrons are excited to higher energy levels which leave behind positively charged holes. This separation of charges creates the potential for the chemical reactions required to produce H_2 and O_2 from H_2O molecules.

Splitting H_2O molecules

- Splitting water into O_2, H^+ and electrons is crucial as it produces hydrogen, and the electrons required to reduce CO_2.
- Excited electrons from the photocatalysts reduce H_2O molecules to produce H_2 gas, while the positively charged holes oxidise water to produce O_2.
- This reaction can be summarised as **$2H_2O$ +** *Sunlight* **-> $2H_2 + O_2$**

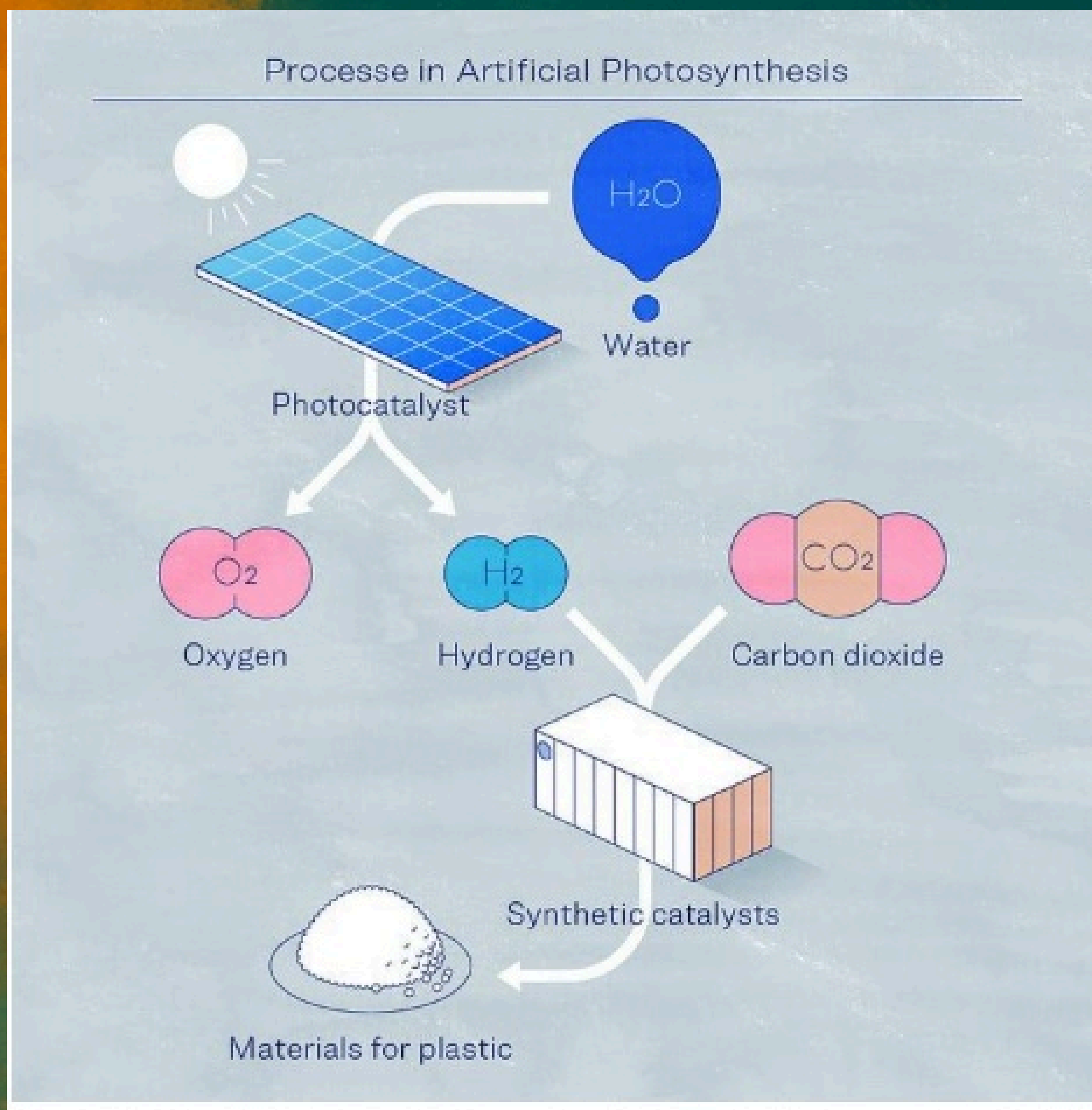
CO_2 Reduction

- After the water is split, the system directs electrons toward converting CO_2 into another form of fuel. This step is the ‘Calvin Cycle’ of the process, producing energy-dense compounds such as methane (CH_4), ethylene (C_2H_4), or methanol (CH_3OH).
- Specialised catalysts are used to achieve this reaction. For example, recent advancements have involved using MOFs combined with amino acids to increase efficiency. [1]

- However, the fuels produced from the reaction have significant CO2 emissions when burned therefore, they are mainly used as chemical feedstock for producing other materials instead.

Storage and utilization of fuels

- Artificial photosynthesis differs significantly from natural in the end-product fuel, while natural photosynthesis produces glucose to be stored in the plant for later use, the hydrogen produced in artificial is directly used in a hydrogen fuel cell to produce electricity.
- There are methods to store hydrogen, for example compressed gas or a liquid, however, they are extremely energy intensive, leading to major loss of energy for power



Despite the significant efforts being made globally, the process faces technical hurdles. The first being efficiency. In current systems, only 1-2% of the energy from sunlight is converted to usable energy. For reference, most residential solar panels have an efficiency of 20%. For the process to be commercially viable, efficiency must increase drastically.

Cost is also a major setback for feasibility as the materials used as photocatalysts are typically very expensive. This raises the cost of energy production significantly, ranging from $10 to $20 per kg of hydrogen produced. For context, grey hydrogen produced from traditional steam methane costs $1 to $2 and green hydrogen from electrolysis costs $4 to $6 per kg of hydrogen.

We don’t know if the vision of hydrogen powered cars, carbon neutral industries and self-reliant homes that artificial photosynthesis holds will ever come true. Artificial photosynthesis is still in its infancy, a seedling nurtured by breakthroughs from institutions like the University of Michigan, where researchers have achieved conversion efficiencies as high as 61% [2]. Yet, this budding technology faces significant challenges before it can bloom on a global scale. Its current efficiency, a mere 1-2% compared to the 20% of solar panels, and the high cost of materials like titanium dioxide and gallium nitride, are hurdles that need overcoming. Scaling these systems is like trying to grow a delicate plant in barren soil—it requires precision, innovation, and patience. However, with advancements such as more resilient catalysts and systems running over 100 hours without faltering, the roots of progress are spreading. If nurtured with continued investment and ingenuity, artificial photosynthesis could one day flourish into a transformative solution for our energy needs.

So, we stand on the brink, looking forward to a future where sunlight can be more than just a source of light and warmth. It could become our ticket to a world free of fossil fuels, where we extract energy not from the depths of the Earth but from the skies above. As researchers toil away, perfecting their artificial leaves and sun-harvesting systems, the question remains: Can we turn sunlight into the fuel that powers our future, or will we forever be chasing the sun?

In the words of the great explorers before us, we’ve set sail into unknown waters, seeking new ways to power our lives sustainably. Whether artificial photosynthesis can deliver on its promise is yet to be seen, but the pursuit itself embodies humanity's endless curiosity and our undying hope for a better, cleaner world.

Aaryan Sainani

THE FUTURE OF RENEWABLE ENERGY

Imagine a world where every rooftop, every highway, and even every window in your home generates clean energy. A world where the wind and sun provide enough power to light up entire cities, and nuclear energy no longer carries the risks of the past. This future isn't just a dream—it's one that engineers around the world are actively building today. With groundbreaking innovations in solar, wind, and nuclear power, we are inching closer to a sustainable energy revolution that could change how we live, work, and power our planet.

Solar Energy

Solar energy has long been considered one of the most promising clean energy sources, yet traditional silicon-based solar panels come with challenges—efficiency limitations, high costs, and space constraints. But engineers are rewriting the rules of solar power. Imagine solar cells made from a material called perovskite, which are not only cheaper to produce but also capable of absorbing sunlight more efficiently (1). In labs, some of these perovskite-silicon tandem cells have reached over 30% efficiency, meaning they can generate more energy from the same amount of sunlight. Then there are bifacial solar panels, which soak up light from both the front and the back, increasing output (2). Picture massive floating solar farms on lakes and reservoirs, which not only generate power but also reduce water evaporation, preserving precious resources in dry regions. This is possible.

Wind Energy

Wind energy has its own set of challenges. Turbines are massive, expensive, and only work well when the wind is blowing just right. But engineers are finding ways to make them more efficient and adaptable. Vertical-axis wind turbines (VAWTs) can generate power regardless of wind direction, making them ideal for urban spaces where traditional turbines wouldn't work. (3) Offshore wind farms are going deeper into the ocean with floating wind turbines, tapping into stronger, more consistent winds that were previously unreachable. Taller turbines, built with carbon fiber composite blades, are harnessing wind power at new heights, capturing more energy than ever before. Additionally, Artificial intelligence is also stepping in, analyzing wind patterns and adjusting turbine positions in real time to maximize efficiency. These advancements are making wind power not just viable, but a dominant force in the energy sector.

Nuclear Energy

Nuclear energy, often a controversial topic due to its dangers, is also undergoing a transformation. Traditional nuclear reactors have been criticized for their safety risks and high costs, but modern innovations are changing the game. Small modular reactors (SMRs) are a new breed of reactors that can be built in factories and transported to remote locations, offering safer and more flexible power solutions (4). Molten salt reactors (MSRs) use liquid fuel instead of conventional water cooling, making them not only safer but also more efficient (5). Some reactors are even exploring the use of thorium, a more abundant fuel source than uranium. And then there's nuclear fusion—the holy grail of clean energy. Recent breakthroughs, where scientists have achieved net energy gains in fusion experiments (6), hint at a future where we can harness the same energy that powers the sun, providing nearly limitless, clean electricity.

Energy Storage

Of course, all of this progress would be meaningless without the ability to store and distribute energy effectively. Renewable energy sources like solar and wind are naturally inconsistent, so energy production is difficult when the sun isn't shining with a high enough intensity, or wind speed isn't high enough Engineers are solving this issue with cutting-edge energy storage solutions. New battery technologies, including solid-state batteries and flow batteries, are allowing for longer, more efficient energy storage. Hydrogen energy storage, where excess renewable energy is used to produce green hydrogen that can be stored and later converted back into electricity, is another promising development. AI-powered smart grids are also revolutionizing how energy is distributed, automatically adjusting supply and demand to minimize waste. Even electric vehicles (EVs) are playing a role, with vehicle-to-grid (V2G) technology allowing them to act as mobile energy storage units, feeding power back into the grid when needed.

Final Thoughts

The transition to renewable energy isn't just a technological shift—it's a human one. Every breakthrough represents the work of scientists, engineers, and visionaries who believe in a cleaner, more sustainable future. The choices we make today—whether as policymakers, business leaders, or individuals—will determine the speed and success of this transition. Renewable energy is no longer just an option; it's becoming the backbone of our global energy system. With each new advancement, we are building a world that is not just powered by nature but in harmony with it. The next decade promises to be a defining era of energy innovation—one that could reshape our planet for generations to come.

THE SANDWICH INSIDE OUR SOLAR PANELS

In a world where most of our electricity is generated via electromagnetic induction, an unmoving system like solar panels might seem impossible! In less fancy terms, usually, we spin things to generate electricity, and we do not spin solar panels. So how do they really work? A cleverly made sandwich, weirdly enough.

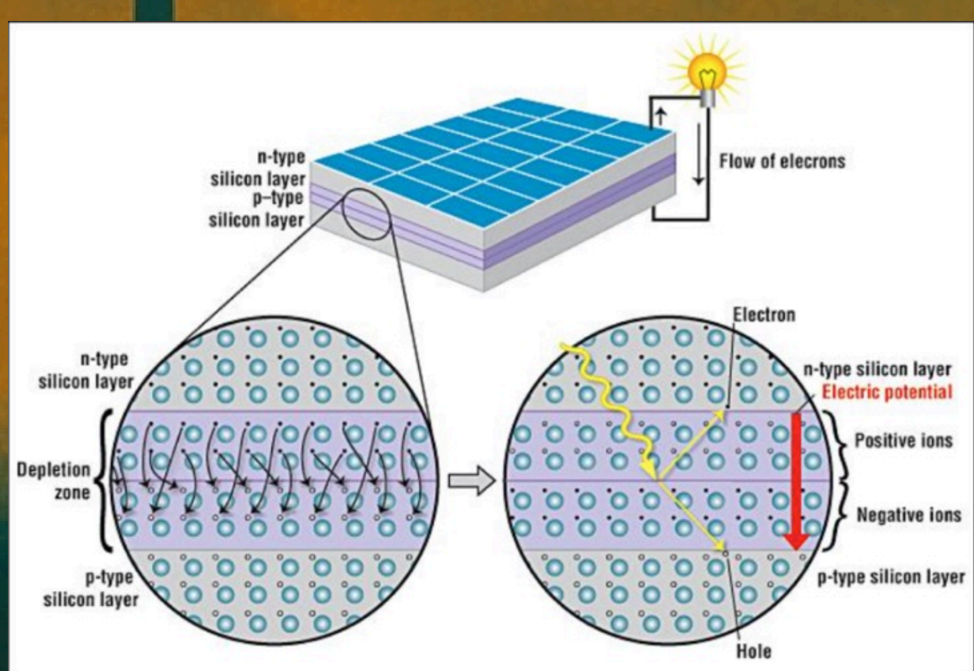
Let’s zoom into a single solar cell…

The Structure

Firstly, we need a hearty filling: silicon. Silicon is a semiconductor, meaning it’s non-conductive, unless combined with other elements. We use silicon to create compounds with either too many electrons, or too few electrons to fill the outer shells.

In solar panels, we use 2 silicon compounds. N-type silicon contains elements with more electrons in the outer shell than needed to bond with silicon, like gallium or phosphorus. This means there is one extra delocalized electron per bond. Additionally, we use P-type silicon, usually containing boron, leaving one positively charged ‘hole’ that there aren’t enough electrons to fill. Just to note, the compounds themselves are not charged (there is an equal number of protons and electrons in each compound right now)! These compounds each form the filling of the solar cell sandwich, with a layer of n-silicon sitting on top of p-silicon.

Now, we have a layer with loads of free-moving electrons, and a layer with lots of empty holes to fill, which connect at the ‘p-n junction.’ This results in electrons in the n-layer jumping into nearby holes in the p-layer, forming what is called the depletion layer, where there are no holes or electrons. So, there is a little sliver in the p-layer with a negative charge, and vice versa in the n-layer. Importantly- not ALL the electrons jump into ALL the holes, as when the layer is formed, the potential difference between the charged parts creates an electric field ‘barrier’ where electrons further from the junction can’t fill other holes.



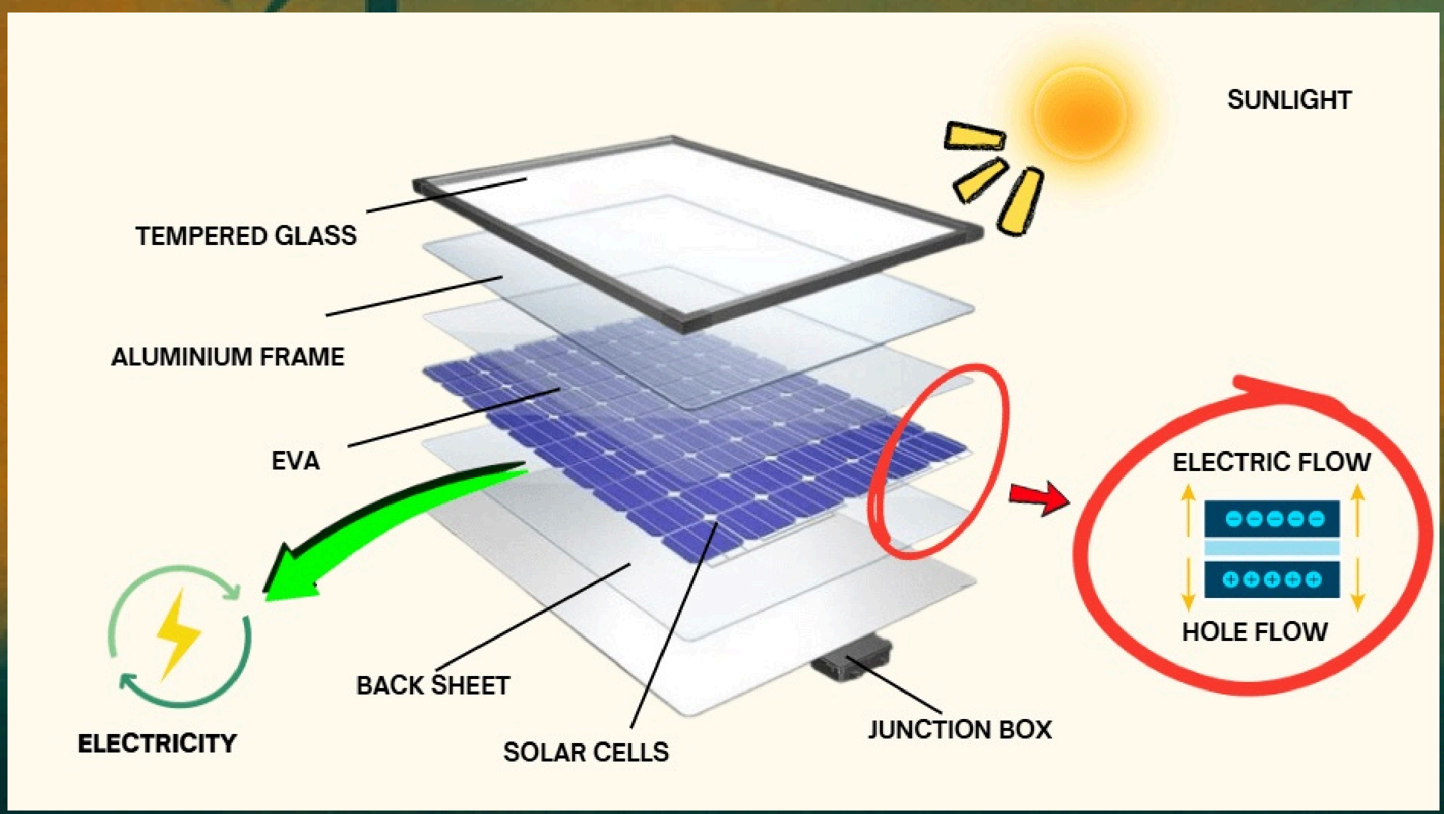
So, the sandwich filling is ready: A p-silicon layer; the depletion layer; and the n-silicon layer. As for the bread, we use 2 pieces of conductive material (each with layers of various metals). As with ideal bread, there are plenty of gaps in the top layer, that is just a thin grid of sorts. This creates the iconic dark blue (silicon) with the square outlines on it (metal). It is now when I realise the sandwich metaphor is falling apart, like a poorly made sandwich itself. Let's lose the analogy now.

The grid lines form channels for electrons to be sent through, known as 'fingers', which are all connected to a thicker 'bus bar.' The grid on top is called the 'negative electrode', and the metal on the bottom (not a grid) is the 'positive electrode.'

How does it works?

Now, let's see how light is converted into electricity. First, let's imagine light as not waves, but little particles called 'photons.' The sun shines, making billions of photons meet the cell. Now, some of those photons have enough energy to 'kick out' an electron from the depletion zone, causing the ejected electron to move up through the n-type silicon layer to the negative electrode. This leaves a hole in the depletion zone. So, a nearby electron in the p-type layer moves to fill it, creating another hole as a result. This causes a flow of electrons as they move to fill holes which the others have created, causing the hole to move down to the positive electrode.

Now, we have positive holes at one electrode, and negative electrons at the other. Naturally, the electrons will be attracted to these holes, so we need to create a channel for them to move through. This allows the electrons to be 'collected' at the fingers, move to the buses, and move through the complete circuit to the positive electrode. THIS is our circuit, and we can place anything we want to power between those two electrodes, like a light, or a rechargeable battery. Basically, the current is the constant movement of electrons trying to 'fill' the holes which light has created. It's truly a feat of engineering and is such a useful step in renewable energy. We can combine loads of these solar cells to form our solar panels, which can be placed in sunny areas to generate power!



Downsides

So why don’t we use solar cells EVERYWHERE? Well, there are some unfortunate flaws to the model. Firstly, Solar cells are REALLY inefficient, because photons can be reflected off the cell, rather than be absorbed. Even if they make it through the top layer, they likely will not have the energy to knock out an electron with enough force, to make sure the electron doesn’t just go back into the hole it made. We can try to prevent this through using anti-reflective coating, but this minimizes rather than solves the issue. Secondly, solar panels are expensive: the best ones are made from monocrystalline silicon, which is defect free, and allows for the easiest electron flow (even then, with only 20% efficiency). AND the transfer of energy from the photons to the electrons does cause the dissipation of some energy into useless heat, which unfortunately also just increases the temperature of solar panels. You just need a lot of light to make this work, which also means a large area dedicated to many solar panels to be effective.

But solar panels don’t necessarily need to be one size fits all, because we can just use them where they’d be most effective. For example, they are really growing in popularity in the UAE, which can afford the upfront and maintenance costs, and gets so much sunlight that it is worth it. Let’s hope that as time goes on, this incredible invention becomes even more efficient and can become a staple in our lives for a more sustainable future.

Shreya Kopuri

SOLAR TECHNOLOGIES: HARNESSING THE SUN'S POWER

Abstract

Solar technology represents one of humanity's most promising solutions for sustainable energy. By converting sunlight into usable electricity, it offers a clean, renewable alternative to fossil fuels, helping to combat climate change and meet growing global energy demands. This article explores what solar technology is, delves into the technical mechanisms behind its operation- focusing primarily on photovoltaic (PV) systems and concludes with what it enables us to achieve in today's world. Drawing from recent research, including detailed insights into perovskite solar cells (PSCs) and a broader review of PV technologies, we'll uncover how these systems work at their core.

What is Solar Technology?

Solar technology harnesses energy from the sun, an abundant and inexhaustible resource, to produce electricity or heat. The most prominent form, solar photovoltaic (PV) technology, uses semiconductor materials to convert sunlight directly into electrical energy through the photovoltaic effect. This process, discovered in the 19th century by Alexandre-Edmond Becquerel, has evolved from rudimentary experiments to sophisticated systems powering homes, industries, and even spacecraft [1]. Solar PV technologies are categorized into generations: first-generation wafer-based cells (e.g. monocrystalline and polycrystalline silicon), second-generation thin-film cells (e.g. amorphous silicon, CdTe, CIGS), and third-generation emerging technologies (e.g. perovskite, dye-sensitized, and polymer cells) [2].

Each type has unique characteristics, efficiencies, and applications. For instance, monocrystalline silicon cells, made from a single crystal structure, boast efficiencies up to 26.7% due to their purity, while thin-film CdTe cells offer lower costs at 21% efficiency [2]. Emerging technologies like perovskite solar cells (PSCs) have surged from 3.8% efficiency in 2009 to over 26% by 2024, rivalling traditional silicon cells while promising cheaper production [3]. Solar technology, therefore, is not a monolith but a diverse field, continually advancing to optimize performance and accessibility.

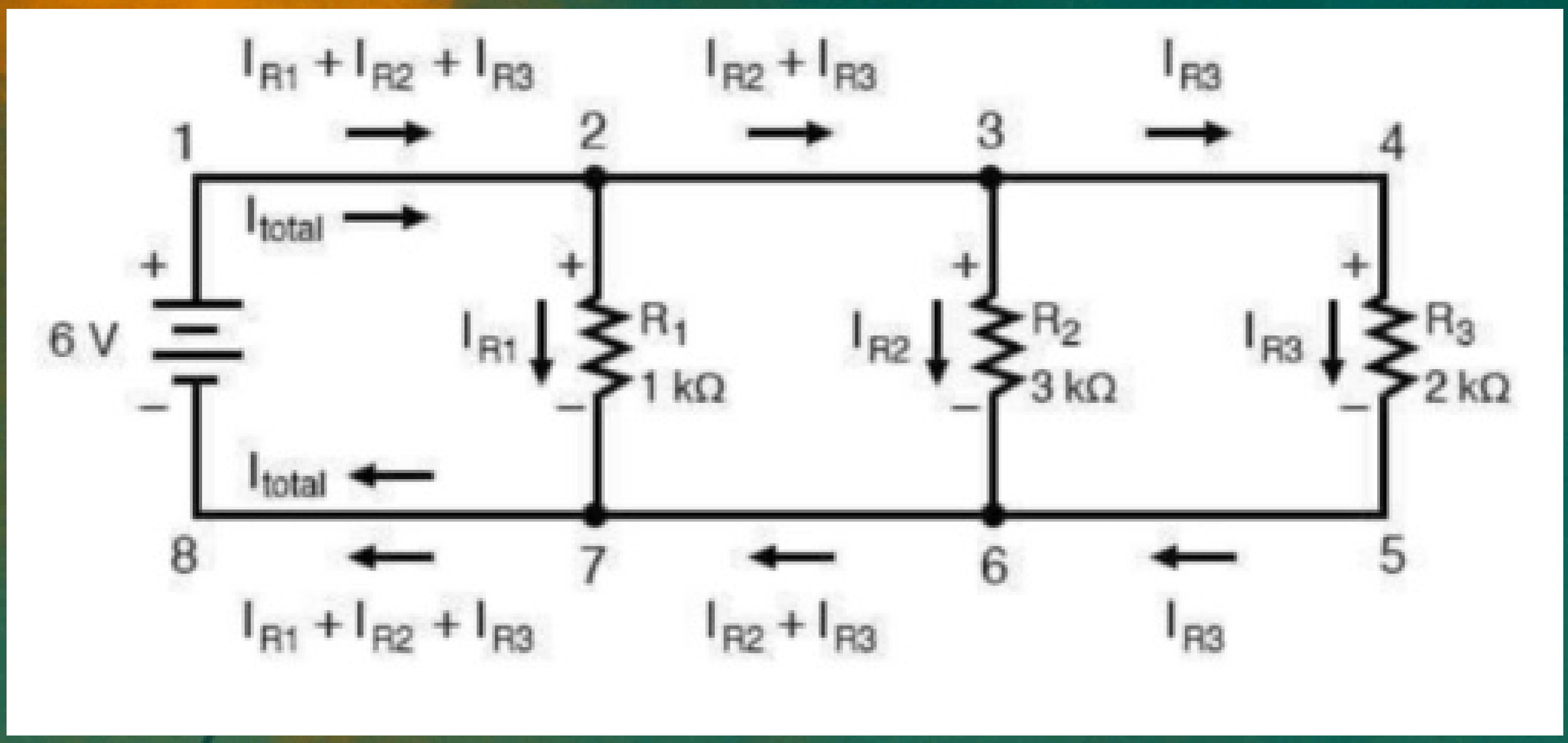
How Solar Technologies Work

At the heart of solar PV technology lies the photovoltaic effect, where sunlight excites electrons in a semiconductor material, generating an electric current. Let's break this down, focusing on the mechanisms of a typical solar cell and spotlighting the cutting-edge perovskite variant.

The Basics of a Solar Cell

A standard solar cell, such as those made from crystalline silicon, consists of a p-n junction—a boundary between a p-type (positive) and n-type (negative) semiconductor layer. When sunlight strikes the cell, photons with sufficient energy dislodge electrons from their atoms, creating electron-hole pairs. The p-n junction's internal electric field separates these charges: electrons move toward the n-type layer, and holes toward the p-type layer. Electrodes on either side— often made of conductive materials like indium-tin-oxide (ITO) or metal— collect these charges, channelling them into an external circuit as electricity [2].

Mathematically, the current output is described by Kirchhoff's Current Law, and can be represented by the following diagram:



Perovskite Solar Cells: A Deeper Dive

Perovskite solar cells (PSCs) exemplify modern innovation in this field. Named for their ABX3 crystal structure-where A is a cation (e.g. methylammonium, MA1), B is a metal ion (e.g. Pb2+), and X is a halogen (e.g. I^-)—PSCs offer exceptional light absorption and charge mobility [3]. Their operation mirrors traditional cells but with unique twists.

In a PSC, sunlight hits the perovskite layer, exciting electrons into the conduction band and leaving holes in the valence band. The material's crystal structure enhances charge separation, driving electrons and holes apart efficiently. An electron transport layer (ETL), often titanium dioxide (TiO2), and a hole transport layer (HTL), such as spiro-MeOTAD, guide these charges to electrodes [3].

Recent advancements have boosted PSC efficiency. For example, Tsinghua University's team achieved 26.41% efficiency using vacuum evaporation and new HTL materials, leveraging the perovskite's adjustable bandgap to capture a broader sunlight spectrum [3]. Another breakthrough by Park et al. in 2023 introduced a self-assembled monolayer (SAM) of phosphonic acid molecules on textured substrates, reducing recombination losses and achieving a certified 24.8% efficiency [3]. These cells retained 95% performance after 1000 hours of stress testing, highlighting improved stability—a critical hurdle for commercialization [3].

Fabrication and Optimization

Fabrication techniques vary across technologies. Silicon cells rely on the Czochralski process or molten silicon cooling, while PSCs use spin-coating or vapor deposition, enabling flexibility and scalability [3]. Innovations like triple- cation perovskites (Cs/FA/MA) or ionic coupling in HTLs further enhance stability and efficiency, pushing PSCs toward practical use [3]. These technical refinements underscore how material science and engineering converge to make solar cells more effective.

What Solar Technology Enables Us to Do

Solar technology's technical prowess translates into transformative real-world impacts. It powers millions of homes, reduces carbon emissions, and drives energy independence. First-generation silicon cells dominate with 80% market share, thanks to their reliability and efficiency, while PSCs promise a future of lightweight, flexible panels for diverse applications—think solar windows or wearable devices [2, 3]. Globally, China leads PV production, followed by Europe and North America, reflecting a shift toward renewables [2].

Emerging PSCs, despite lead toxicity concerns, offer a path to affordable, scalable energy, potentially decarbonizing economies if stability and safety challenges are resolved [3]. From powering remote villages to supporting space missions, solar technology illuminates a cleaner, more equitable energy future.

Conclusion

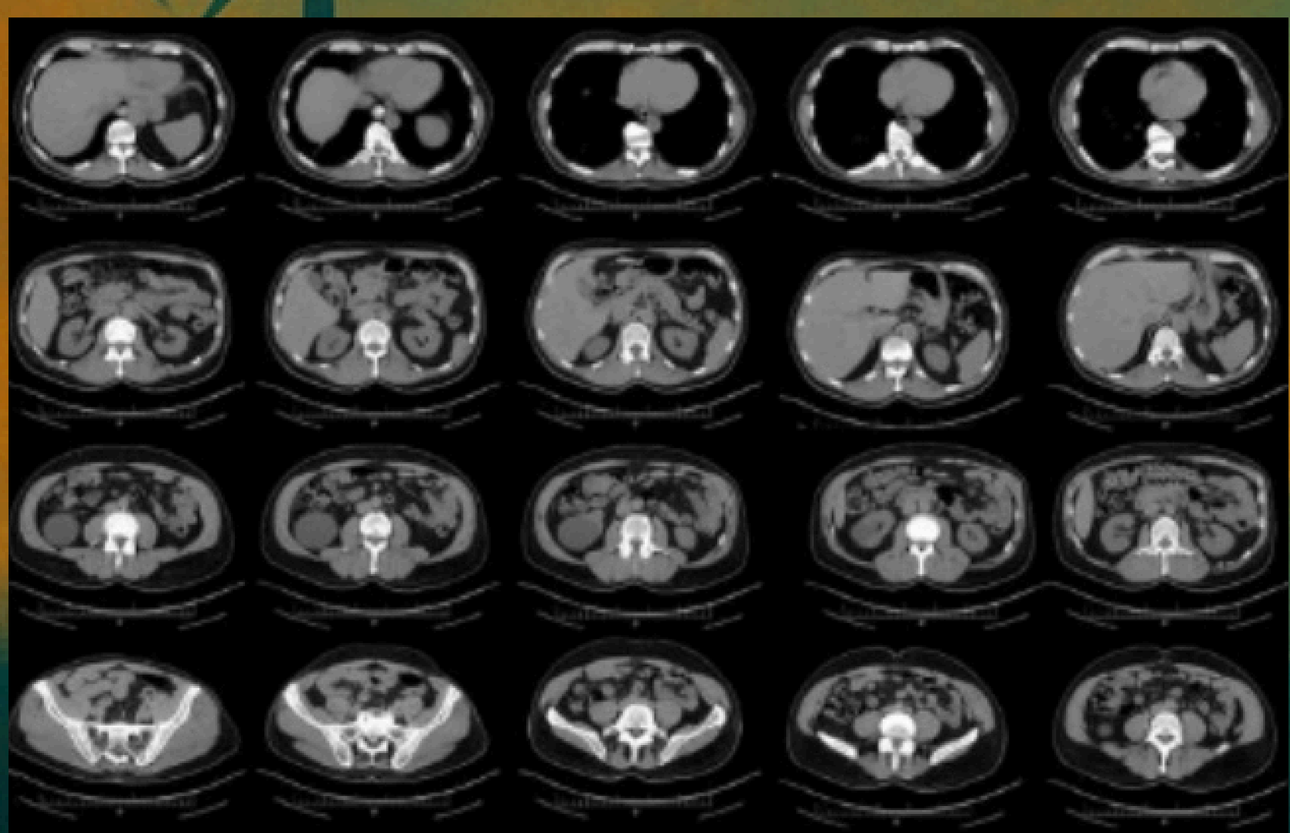
Solar technologies exemplify human ingenuity in tapping the sun's vast potential. At their core, they transform photons into electrons through intricate semiconductor physics, refined by decades of research. As efficiencies climb beyond 26% and stability improves, they enable us to power our world sustainably, echoing the promise of renewable energy envisioned long ago. The technological revolution continues, with both technical leaps and failures bringing us closer to a sun-powered planet.

Syed Ahmad Azim

IMAGING THE INVISIBLE: HOW CT SCANS ARE TRANSFORMING PANCREATIC CANCER DIAGNOSIS

Pancreatic cancer is known as the ‘silent killer’ *[1]* and is notorious for its aggressive and fatal nature. Due to its absence of early symptoms, pancreatic cancer is often diagnosed at an advanced stage, with up to 80% of cases identified in later, difficult-to-treat stages, and only 12% of patients surviving for five years after diagnosis *[2]*. In 2020, pancreatic cancer was found to be the fourth leading cause of cancer-related deaths in the United States (US) for all ages, and the third highest for those aged 50-79. In 2023, there was an estimated 64,050 new cases and 50,550 deaths of pancreatic cancer in the US alone *[3]*. Hopkins Medicine conducted a groundbreaking experiment which further confirmed the dangers of late detection. In 2022, an experiment was conducted where 1,461 high-pancreatic-cancer-risk individuals were enrolled into a programme which included annual pancreatic imaging tests. The results of this experiment showed that patients under surveillance who were diagnosed with pancreatic cancer had a five-year survival rate of 73.3% and a median survival of around 9.8 years, meanwhile those diagnosed with pancreatic cancer outside of surveillance had a median survival of only 1.5 years. This experiment highlights the significant impact that early detection can have on survival rates, and to further improve these outcomes, it is crucial to invest in higher-quality diagnostic machines *[4]*.

Pancreatic cancer is most commonly diagnosed by using a computed tomography (CT) scan. A CT scan is a radiological imaging study which captures accurate images of different parts of the human body including bones, muscles, organs, and blood vessels *[5]*. The machine works by directing narrow, uniform x-ray beams which are rapidly rotated around the body of the patient. These signals are detected by the detectors and computerised to generate cross-sectional images (also known as slices) which can be stacked together to form a three-dimensional image of the patient *[6]*.



The technology of CT scans has significantly evolved over four generations. The first generation consisted of a narrow “pencil” beam with a single detector, which had to be rotated 1 degree after each projection. This generation was very time-consuming and poor resolution. The second generation significantly reduced scanning time by angularly adding detectors so that several projections could be detected. The third generation introduced a rotating anode x-ray tube with a wide fan-shaped beam and arc-shaped detectors. The fourth generation eliminated translate-rotate motion by using a stationary ring of detectors, however this made it more susceptible to scatter artifacts *[7]*.

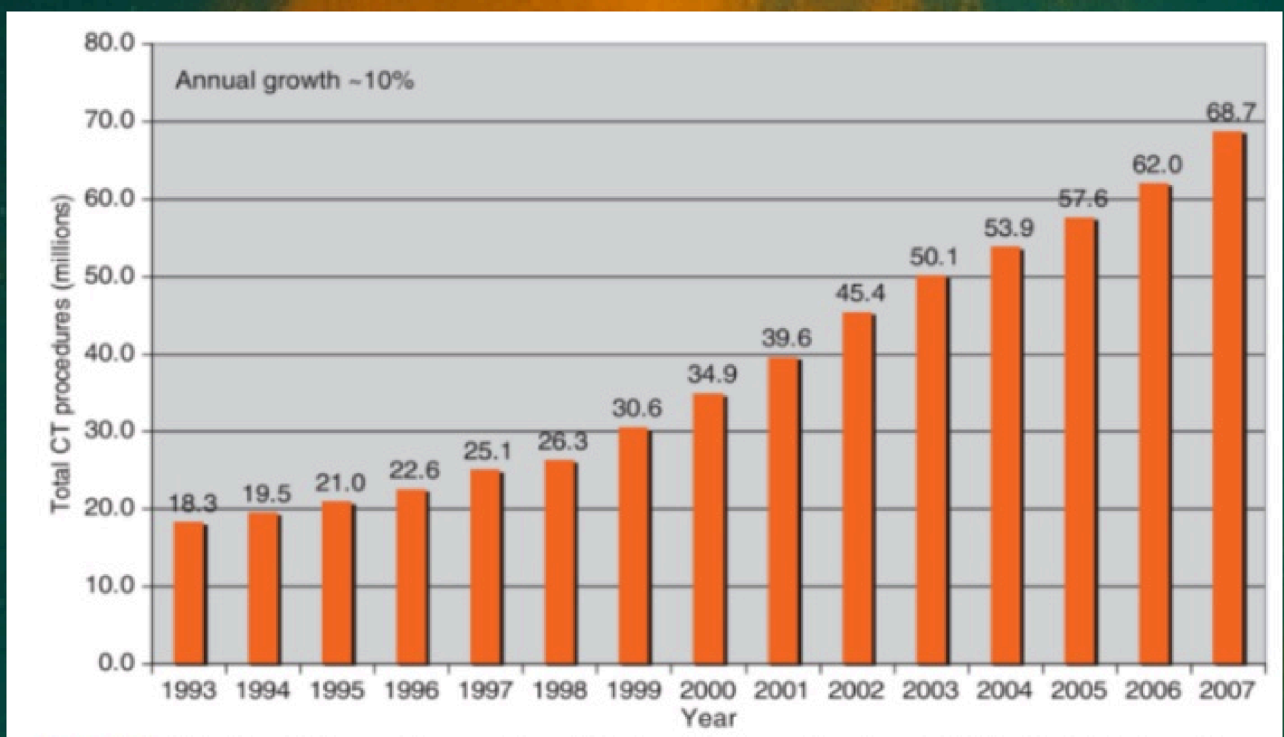
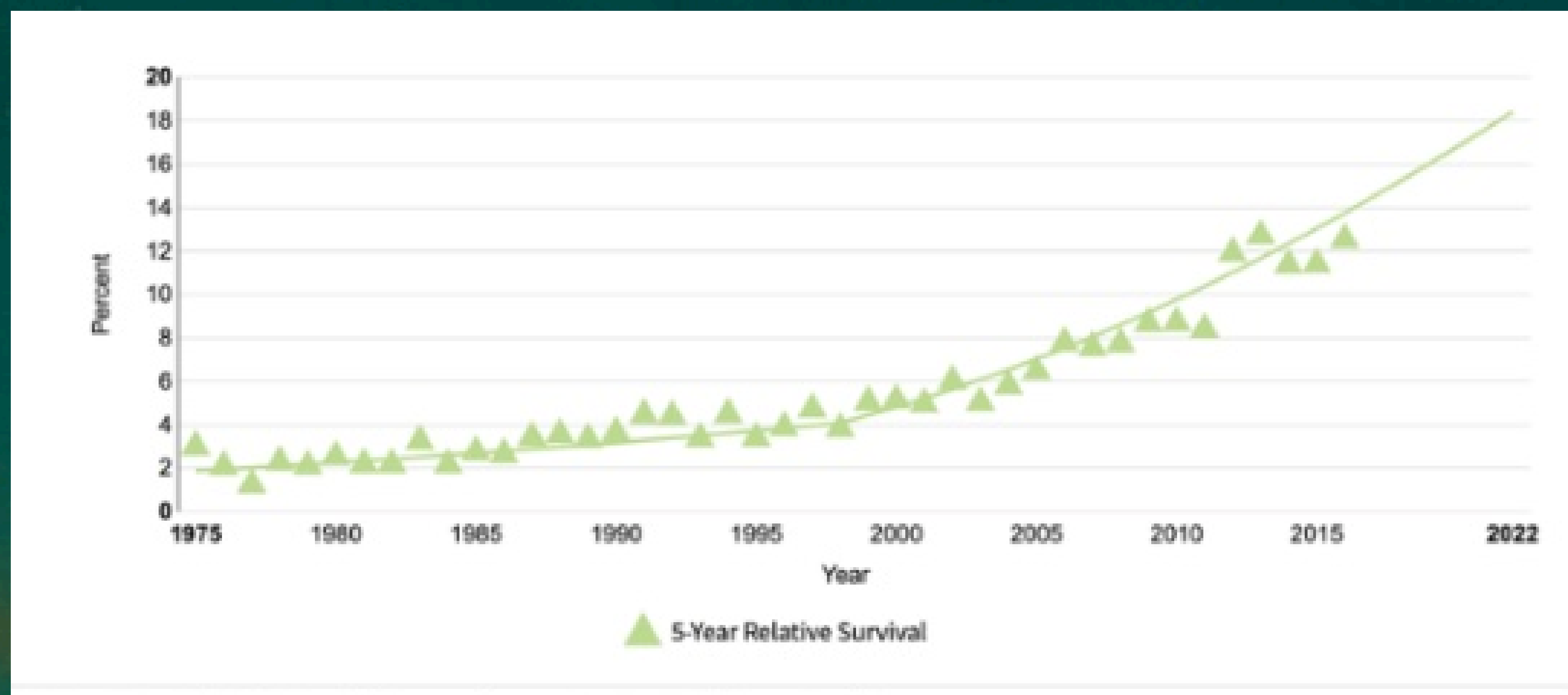


Figure 1.1. Number of CT procedures performed in the United States for the period of 1993–2007. Annual growth is approximately 10%.



SEER 8 5-Year Relative Survival Percent from 1975–2016, All Races, Both Sexes.
Modeled trend lines were calculated from the underlying rates using the Joinpoint Survival Model Software.

Both Figure 1 and Figure 2 show an exponential growth, suggesting that as the number of CT procedures in the US increased, the relative survival percentage of individuals with pancreatic cancer has also increased, indicating a potential positive correlation. The introduction of CT scans in the 1970s marked the beginning of this trend, and the noticeable delay in the improvement of survival percentage of individuals with pancreatic cancer reflects the time lag effect, where advancements in CT technology gradually contributed to better outcomes. As the total number of CT procedures began to increase in 1993, the gradient of the curve in figure 2 also increased, suggesting that after CT procedures in hospitals became more common, more individuals were being diagnosed with pancreatic cancer at its earlier stages, leading to higher survival rates.

Normally, traditional CT scanners rely on a two-step principle of x-ray scintillation (known as energy-integrating detectors), which involves using ceramic scintillators which generate a light impulse when exposed to x-rays.

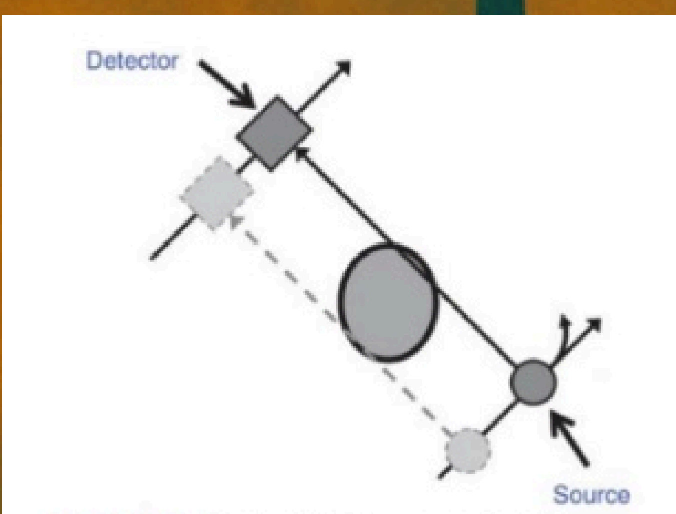


Figure 2.6. Sketch of the first-generation CT scanner that used parallel x-ray beam with translate-rotate motion to acquire data. (From Mahesh M. Search for isotropic resolution in CT from conventional through multiple-row detector. *RadioGraphics* 2002;22:949–962, with permission.)

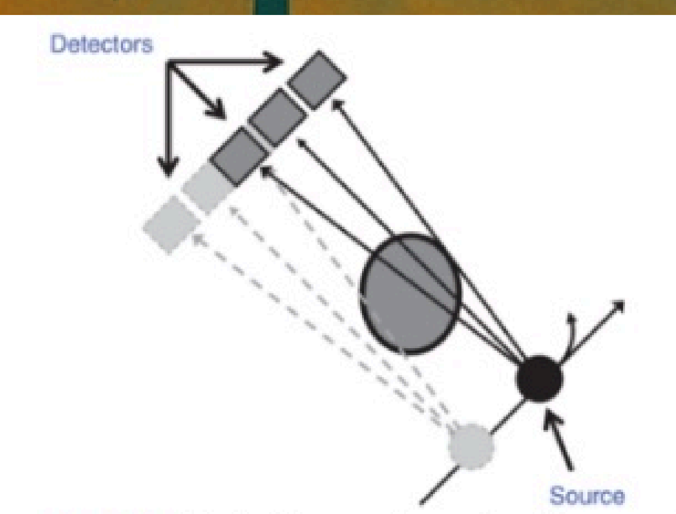


Figure 2.8. Sketch of the second-generation CT scanner with translate-rotation motion to acquire data. From Mahesh M. Search for isotropic resolution in CT from conventional through multiple-row detector. *RadioGraphics* 2002;22:949–962, with permission.)

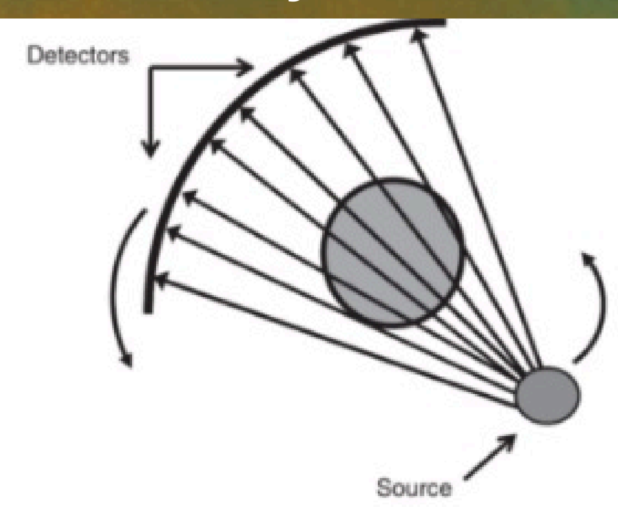


Figure 2.9. Schematic representation of the third-generation CT scanner, which acquires data by rotating both the x-ray source with a wide fan beam geometry and detectors around the patient and, hence, the geometry is called *rotate–rotate* motion. From Mahesh M. Search for isotropic resolution in CT from conventional through multiple-row detector. *RadioGraphics* 2002;22:949–962, with permission.)

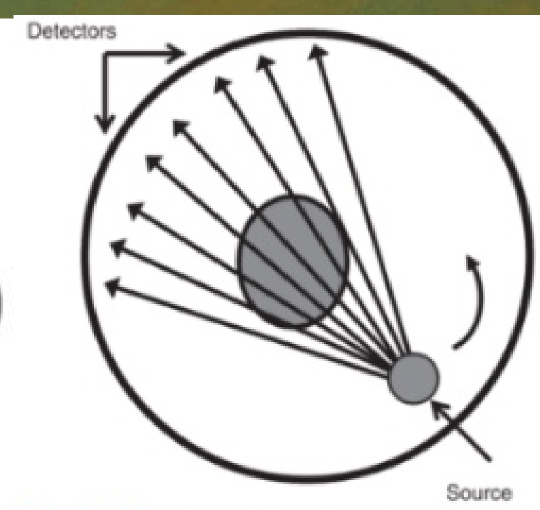


Figure 2.10. Schematic representation of the fourth-generation CT scanner; which uses a stationary ring of detectors positioned around the patient. Only the x-ray source rotates, using wide fan beam geometry, whereas the detectors are stationary and hence called *rotate-stationary* motion. From Mahesh M. Search for isotropic resolution in CT from conventional through multiple-row detector. *RadioGraphics* 2002;22:949–962, with permission.)

However, this requires the light generated to be controlled, to prevent the image from blurring (making it less precise and accurate) and so, to combat this, the detector is split up into separate sections to control the light. By doing so, dead spaces are created within the detector, leading to inefficiencies, resulting in higher doses of radiation being required. This is why photon counting CT has been introduced as a solution - it captures detailed images with greater accuracy, less noise, and lower doses of radiation. Photon counting CT scans work by using cadmium telluride crystal (CdTe) (a crystal semiconductor) in the detector, which directly generates an electric charge, rather than creating light first, enabling increased measurement speed and avoiding the creation of dead spaces as x-rays do not need to be converted to light. As a result of this recent innovation, more detailed images can be produced, allowing tumours to be detected at earlier stages when they are still very small [9].

Currently, AI is revolutionising the field of cancer diagnosis by accelerating the analysis of medical images, and enabling faster, more accurate results. AI algorithms can recognise anomalies and patterns which may have been overlooked by the human eye, enhancing diagnostic accuracy and reducing chances of misdiagnosis. Furthermore, AI has the capability of analysing historical data and identifying any trends or risk factors, meaning that personalised treatment plans can be tailored to each patient, enhancing the personalisation of healthcare [10]. One key development in AI is the emergence of deep learning (DL). DL is a type of AI that uses multiple layers of processing to understand the data in complex ways and can be used to automate tasks that typically require human intelligence [11]. When DL algorithms were first introduced into this field in 2012, the error rate was significantly reduced from 0.258 to 0.153 within only a year [12] – showcasing their potential to revolutionise cancer detection.

The advancements in CT scan technology have revolutionised pancreatic cancer diagnosis, allowing for earlier detection and significantly improving patient outcomes. As technology continues to evolve, integrating these developments into routine healthcare is crucial in further improving survival rates. By investing in higher-quality diagnostic machines and AI-powered tools, we can continue to push the boundaries of medical imaging, ensuring that more pancreatic cancer patients survive.

Dana Shater

THE RISE OF 4D PRINTING

Introduction

The field of additive manufacturing, commonly known as 3D printing, has revolutionized various industries, from healthcare and aerospace to construction and consumer goods. However, a new frontier has emerged within this domain: 4D printing. This advancement integrates time as the fourth dimension, allowing printed materials to undergo transformations in response to external stimuli such as heat, light, moisture, or magnetic fields. This essay explores the principles behind 4D printing, its applications, potential benefits, and the challenges associated with its widespread adoption.

Understanding 4D Printing

4D printing builds upon the foundation of 3D printing by incorporating smart materials that can change their shape or properties over time. The term was first coined by Skylar Tibbits, a researcher at the Massachusetts Institute of Technology (MIT), who envisioned a world where printed objects could self-assemble, adapt, and respond to environmental changes (Tibbits, 2014). The process involves the use of stimuli-responsive materials, including shape-memory polymers (SMPs), hydrogels, and liquid crystal elastomers, which enable these transformations.

Unlike traditional static 3D-printed objects, 4D-printed structures are dynamic and can perform mechanical functions without the need for complex electronic components. This characteristic opens new avenues for innovation across multiple industries.

Applications of 4D Printing

The versatility of 4D printing extends to a wide range of applications, particularly in the medical field, aerospace and automotive engineering, construction and architecture, as well as textiles and wearable technology. In medicine, 4D printing holds great promise in the development of customized implants, stents, and drug delivery systems. Self-expanding stents made from shape-memory alloys can be inserted into arteries in a compressed state and expand once inside the body, reducing the need for invasive procedures (Momeni et al., 2017). Similarly, bioprinting of tissues that can adapt to changing physiological conditions could revolutionize regenerative medicine.

In the aerospace industry, 4D printing is being explored for its ability to create lightweight, self-healing components. Shape-changing materials could help aircraft and spacecraft adjust their aerodynamic properties mid-flight, enhancing efficiency and performance (Ge et al., 2016). In the automotive sector, researchers are investigating the development of adaptive tires that respond to road conditions, increasing safety and durability.

Within the construction industry, 4D printing is being studied for its potential to create self-assembling structures and materials that adapt to environmental conditions. Researchers are developing materials that expand or contract in response to temperature fluctuations, reducing the need for heating and cooling systems in buildings (Tibbits, 2014). This innovation could lead to more sustainable and energy-efficient construction methods.

The fashion industry is also beginning to experiment with 4D printing to create garments that change shape, texture, or breathability based on external conditions. This advancement could result in adaptive clothing that responds to temperature changes or athletic wear that enhances performance through dynamic fit adjustments (Ionov, 2013).

Advantages of 4D Printing

The introduction of 4D printing brings several advantages over traditional manufacturing techniques. One of the most significant benefits is its ability to create self-assembling structures, reducing assembly costs and labor. This capability is particularly valuable in space exploration, where sending fully assembled structures is costly and logistically challenging. Another key advantage of 4D printing is its material efficiency, as it minimizes wastage compared to conventional subtractive manufacturing processes. By utilizing smart materials that morph into their final forms, this technology reduces environmental impact.

Beyond material efficiency, 4D printing enables new functionalities that were previously unattainable. The ability of printed materials to change properties in response to stimuli enhances performance across industries such as healthcare, aerospace, and consumer goods. Additionally, the durability and longevity of smart materials, many of which exhibit self-healing properties, contribute to reduced maintenance and longer product lifespans. This feature is particularly advantageous in applications such as medical implants and aerospace components.

Challenges and Limitations

Despite its promise, 4D printing faces several challenges that must be addressed before widespread adoption can occur. The success of this technology relies heavily on the availability of advanced stimuli-responsive materials. Research is ongoing to develop materials with enhanced durability, responsiveness, and biocompatibility, but significant progress is still needed. Another major challenge lies in the complexity of the manufacturing process. Achieving precise control over the printing process and external stimuli is crucial to obtaining the desired transformations, making large-scale manufacturing difficult and costly.

High costs also pose a barrier to accessibility, as the expense of smart materials and specialized 4D printers limits the adoption of this technology by small businesses and researchers. Lowering costs through material innovations and improved manufacturing techniques will be essential for broader implementation. Additionally, the introduction of shape-changing medical implants and self-assembling structures raises ethical and regulatory concerns. Ensuring safety, reliability, and compliance with existing regulations will be crucial for integrating 4D-printed products into everyday applications.

Future Prospects of 4D Printing

The future of 4D printing is promising, with ongoing research focused on enhancing material properties, refining manufacturing techniques, and exploring new applications. As material science advances, the development of multi-functional materials that respond to multiple stimuli simultaneously will likely become a reality. Collaborations between researchers, industry leaders, and policymakers will be critical in overcoming the current limitations of 4D printing.

Emerging technologies such as artificial intelligence (AI) and machine learning could further optimize the design and functionality of 4D-printed structures, leading to even more sophisticated applications. Additionally, as costs decrease and accessibility improves, 4D printing could become a mainstream manufacturing technique, transforming industries worldwide.

Conclusion

4D printing represents a groundbreaking evolution in additive manufacturing, offering dynamic, responsive materials that adapt and transform over time. From medical applications and aerospace engineering to construction and textiles, the potential uses of this technology are vast and revolutionary. However, significant challenges remain, including material development, manufacturing complexities, and regulatory hurdles. As research continues and technological advancements emerge, 4D printing is poised to redefine the future of engineering and material science, ushering in a new era of intelligent, self-assembling structures.

Kartik Garg

THE ENGINEERING BEHIND PARTICLE ACCELERATORS

The Importance of Particle Accelerators

Particle accelerators are one of the most advanced scientific marvels ever built, requiring complex engineering, cutting-edge materials and extreme precision in their construction. These machines accelerate charged particles, such as protons and electrons, to very high speeds, close to that of the speed of light. In fact, the Fermi Laboratory accelerates the particles to 99.997% of the speed of light. Scientists can study the particles and the force around them, as well as observe the result of collisions between these particles.

Therefore, particle accelerators play a huge role in research. For example, researchers at the Large Hadron Collider (the largest particle accelerator in the world), use the collision of heavy ions to recreate the conditions that existed after the Big Bang, allowing scientists to understand the formation of our world. Beyond research, particle accelerators are used in various other fields such as health, aerospace technologies and environmental monitoring.

Accelerating and Guiding Particles

Accelerating particles is crucial. When particles have enough energy, something almost unimaginable happens. The energy of the collision is converted into new matter in the form of particles, seemingly defying the laws of conservation of matter. However, this phenomenon is explained by Einstein's famous equation, $E=mc^2$, which suggests that matter and energy are interchangeable. Additionally, the higher the energy the particles have, the shorter their De Broglie wavelength, since the momentum and wavelength of the particles show an inverse relationship ($\lambda = h/mv$). This means that greater detail can be observed.

The engineering of the accelerator plays a key role in allowing this phenomenon to occur. Particle accelerators use electromagnetic fields to accelerate and guide the charged particles. The charged particles gain velocity when exposed to oscillating electric fields in structures called radiofrequency (RF) cavities. The basic principle of an accelerator is that the charged particle accelerates due to the potential difference (caused by the oscillating electric fields). In this scenario, the Energy Supplied = Charge x Potential Difference ($E=qV$).

As particles approach the speed of light, classical mechanics no longer accurately describe their motion. Instead, special relativity must be used, where the energy of the particles is given by: E=γmc^2. Where E is the energy, m is the rest mass of the particle, c is speed of light, and γ is the Lorentz factor:

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \Rightarrow E = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}}$$

Once the particles start to accelerate, magnets are used to guide and focus the particles along a predetermined path.

Key Components in a Particle Accelerator

Vacuum Systems

One of the key components of any particle accelerator is the vacuum system. To avoid collisions with gas molecules within the accelerator, the beams of particles must travel in a vacuum as empty as outer space. Interestingly, CERN's Large Hadron Collider (LHC) features 3 vacuums: one for the aforementioned purpose and two act as a thermal insulator, to keep the parts that need to be cooled at 1.9K. The LHC's vacuum system is the largest in the world, spanning 104 kilometres of piping. The system required around 250,000 welded joints and 18,000 vacuum seals, resulting in an in-pipe pressure between 10^-9 to 10^-10 kPa.

Radiofrequency (RF) Cavities

The RF cavities are metallic chambers which generate the electromagnetic field. LHC contains 16 RF cavities in cylinder-shaped refrigerators called cryomodules, which allow the cavities to function as a superconductor. Each cavity contains a klystron, a tube of electrons. These electron beams oscillate at 400 MHz, which allows for a maximum voltage of 2 megavolts per cavity.

The particles are injected with energy of 405 GeV, and the cavity increases the energy of these particles to 6.5 TeV, an increase of approximately 14 times. The timing of the arrival of the particles is important, since the field oscillates at a specific frequency. Within a beam of particles, the energy of each individual particle may vary. To overcome this, protons are sorted into groups. Ones with the correct energy are not accelerated, whilst others with lower or higher energies are accelerated or decelerated, to ensure that they stay close to the desired energy.

Superconducting Magnets

Superconducting magnets play a crucial role in particle accelerators. Without them, the particles would drift away from each other, and their momentum would mean they only travel linearly. In the LHC, the electromagnets generate 8.3 Tesla magnetic fields. For context, this is 100,000 times more powerful than the natural magnetic field of Earth. To allow high currents to flow through, a superconducting coil is used. Additionally, these magnets are cooled with liquid helium to nearly absolute zero, which allows the generation of these magnetic fields without excessive power consumption.

There are various kinds of magnets used. Lattice magnets are responsible for ensuring that the beam is stable. Dipole magnets bend the trajectory of the particles. When the particles are closer together, there is a greater chance for collisions, therefore quadrupole magnets are used to ensure that particles remain in a tight beam.

Magnets also play a key role in observing the nature of the particles. For example, physicists can analyse the deflection and momentum to gain an understanding of the types of particles present in the detector. The radius of curvature of a charged particle in a magnetic field is given by the following equation:

$r=mvqB$, where r is the radius, m is the mass, q is the charge and v is the velocity of the particle and B is the strength of the magnetic field.

Types of Particle Accelerators

Linear

Linear particle accelerators, also known as LINAC, are used in medical applications such as radiation therapy, and as injectors for large accelerators. The key feature of this type of accelerator is that the particles only pass through each of the accelerating cavities once. The advantages of this type of accelerator include the fact that the magnets don’t need to produce a centripetal force, therefore it is often cheaper and easier to build. Additionally, the likelihood of collisions is greater for a linear accelerator in a fixed target experiment. However, the key drawback is that there is limited acceleration of particles, since the particles only pass through the electric fields once.

Cyclotrons

Cyclotrons use magnetic fields to provide a centripetal force, allowing particles to move in a circular path, which means that they can pass through the electric field multiple times. Higher energies can therefore be achieved using the same voltage, but the actual accelerator does not need to occupy as large of space as linear accelerators. Additionally, oppositely charged particles would circle in opposite directions, which allow opportunities for collisions.

However, the cost for the magnets which provide the centripetal force is high. Additionally, if two particles with opposite charges but equal masses collide, the total momentum before the collision is zero, therefore there will be no energy left over for the creation of new particles.

The centripetal force is a key feature of a cyclotron. This force is provided since there is a changing magnetic field and a charged particle in that magnetic field. The centripetal force is determined by the following equation: F=Bqvsinx, where q is the charge and v is the velocity and B is the magnetic flux density.

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Fuelling Tomorrow: Can Artificial Photosynthesis Turn Sunlight into the Power We Need?

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NOTES FROM EDITORS

The calibre of articles received in this volume of the DC Hydraulics magazine was outstanding. We are very thankful to all the contributors for the enthusiasm and passion they brought to their work. The quality of writing, analysis, and research have been truly impressive. It is clear that each piece was crafted with care and expertise.

We also extend our appreciation to our readers for taking the time to engage with this volume. Whether you flipped through a few pages or read cover to cover, your support means everything.

We look forward to welcoming you back for our next volume.

DC HYDRAULICS

This magazine is volume 2 of DC Hydraulics and consists of articles related to energy and innovation written by you. Topics of articles range from solar panels and a new way to produce green hydrogen to 4D printing and particle accelerators. Explore a wide variety of engineering articles inside, we hope you enjoy and learn something new

-The editors

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