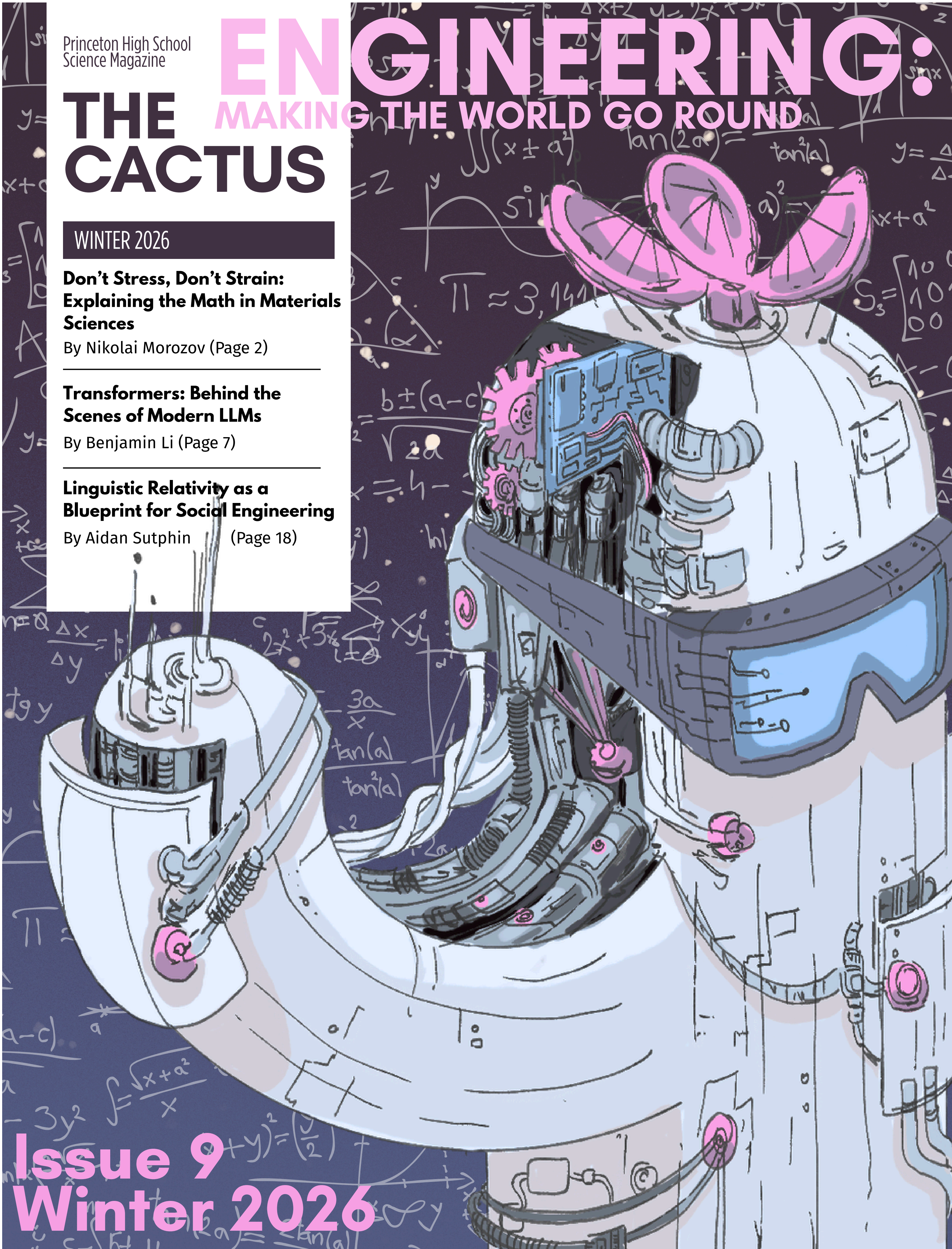
Princeton High School Science Magazine

THE CACTUS

ENGINEERING: MAKING THE WORLD GO ROUND

WINTER 2026



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THE CACTUS

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EDITORS' LETTER

We don't exaggerate when we say that engineering is found everywhere. Derived from the Latin roots *Ingenium* (cleverness) and *Ingeniare* (to devise), engineering forms the basis of everything: simple ramps, surgical tools, vaccines, hurricane-proof towns, and even the way we communicate through 5G networks.

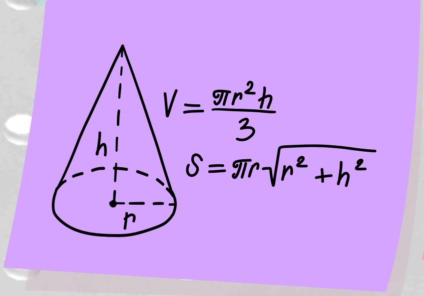
The *Ingenium* displayed by PHS students is inspiring. By questioning the mundane systems around us, we have discovered surprising insights that compel innovation.

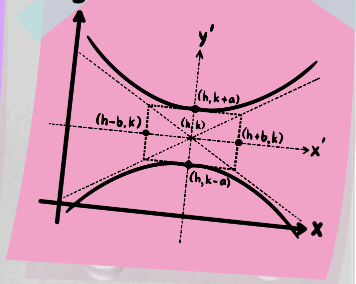
High school is often characterized as a time of self-exploration, which is driven by curiosity and inquiry. The basis of all innovation, of self and of technology, stems from the driven minds of our humanity, continuously asking "what if" and daring to search for answers.

In a way, the founding of the Cactus and its continued success was built on top of the strong foundational curiosity found within the PHS community. We are constantly surrounded by peers who dare to push their limits and challenge their minds that makes creations like the Cactus possible. As we approach the third anniversary of the Cactus and begin to think about long term goals—a change in staff, writers, leaders, and artists, and the vast field of possibilities our curiosities have yet to explore—we hope that this issue can remind us of our efforts and accomplishments that brought us to where we are today through an appreciation of past innovation.

To showcase humanity's ingenuity of engineering through the ingenuity of PHS students, we welcome our readers to the second issue of the 2025-2026 cycle, *Engineering: Making the World Go Round*.

Joanna & Hojung





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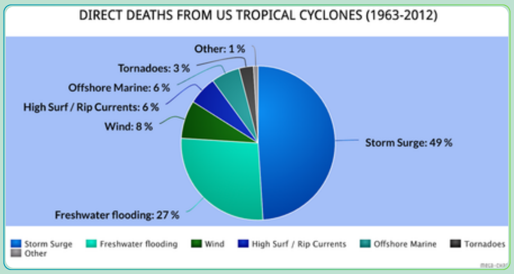
The Town That Can't be Drowned: How Babcock Ranch Re-engineered Resilience

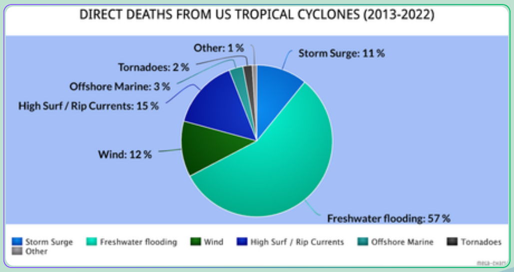
BY: FELIX YU

Every year, millions around the world are confronted by powerful tropical cyclones, forced to watch as wind and water erase homes, possessions, and entire communities. Many of their shelters, never designed to survive the modern climate, provide little protection against the ferocious storms raging around them. The U.S. Gulf Coast region, known for its stunning beaches and vibrant cultures, is no exception, having experienced 11 of the 15 costliest hurricanes in history. Collectively, these storms have taken thousands of lives and caused hundreds of billions of dollars in damage.

But what if things didn't have to be this way? What if we could build communities where lights stay on, houses remain intact, and essential services continue functioning even in the strongest of storms? This isn't a futuristic fantasy—it's a reality that already exists.

In recent years, one community in Southwest Florida has drawn attention to its incredible design, allowing it to withstand even the most powerful hurricanes: Babcock Ranch. Since construction began in 2015, this pioneering town has been battered by four powerful hurricanes—Irma, Ian, Helene, and Milton—yet each time, the town emerged virtually unscathed, even sheltering over 2,000 people from surrounding areas [1,3].





[2]; Image: Felix Yu

The first foundational defense is the town's location. The community is deliberately situated 20-30 miles from Florida's coast, which, in addition to the region's natural barrier islands, largely eliminates the devastating threat of coastal storm surge, the deadliest component of many tropical cyclones [2,5]. Additionally, all development is situated on lands approximately 30 feet above sea level, placing the entire community outside of major flood zones [5]. The town was also built in tandem with the surrounding wetlands, unlike typical Floridian developments that use grid-like plans to maximize land usage [7]. In many conventional neighborhoods, developers fill in natural protections, such as ditches and wetlands, in order to maximize sellable properties [7]. While efficient for real estate, these concrete grids disrupt the earth's natural drainage systems and water barriers, exacerbating flooding effects of hurricanes. In contrast, Babcock Ranch builds around natural flow-ways and wetlands, allowing the landscape to absorb and redirect floodwaters [5].

These wetlands are the basis of the community's water management system, absorbing massive amounts of rainfall and slowing the flow of water into the town. Designers also built a series of interconnected drainage bowls that water gets directed to. Ahead of powerful storms, these bowls can be drained to maximize their storage capacity [5]. In Babcock Ranch, even the roads are intentionally constructed lower than surrounding infrastructure: in the case of flooding, they are designed to serve as temporary drainage channels, directing excess water away from homes and essential structures before slowly releasing it [5]. This water is then routed into a natural drainage system the town was built on, slowly flowing into the nearby Caloosahatchee River, which eventually drains back into the Gulf of Mexico. By ensuring the gradual flow of water, Babcock Ranch reduces flooding risks for downstream communities [5].

However, hydrologic design is only one component of Babcock Ranch's broader resilience strategy. Similar to most of Florida, the majority of the town's buildings can withstand 150 mph winds, but essential buildings, such as grocery stores and designated shelters, adhere to even stricter regulations to ensure they stand during and after a storm [3]. For example, while homes are elevated by five feet, leaving them one foot above a theoretical 100 year storm event, offices and grocery stores are elevated by six feet, providing an additional safety margin of two feet [5]. The community is also entirely solar powered by an on-site solar farm, with all internet and power infrastructure being buried underground, ensuring that power stays on even during the strongest of storms [6].

Image: AP Photo/Wilfredo Lee

The true testament to Babcock Ranch's design came with Hurricanes Ian and Milton, two of the most powerful storms to hit the region. While many neighboring towns were left reeling following both storms, enduring weeks without power and utilities, the damage at Babcock Ranch was remarkably minor: a few fallen trees but not a single structural failure. Even more significantly, the town's designated shelter, the high school field house, sheltered thousands of residents from surrounding communities between the two storms [3].

Babcock Ranch is more than just a real estate development; it's a compelling demonstration of proactive planning and sustainable construction. It proves that the catastrophic cycle of clean-up and rebuilding, so often seen in vulnerable communities, is not something they must endure forever. By designing with nature, not against it, this small Florida town is offering a powerful vision for how communities can thrive - even in the face of an increasingly volatile climate [4].

Hurricane-proof

Image: Wall Street Journal

*Formatter: **Rebecca Zhang***

Don’t Stress, Don’t Strain: Explaining the Math in Materials Sciences

BY: NIKOLAI MOROZOV

A child of any age can identify texture, color, and shape. These are the basic, macroscopic properties of a material. When engineers consider materials for use, they take into account more than just these qualities [1]. This is because engineers constantly subject materials to extreme conditions. For example, in planes, the thermal properties of the materials that make up the rotors are extremely important, since a melting rotor cannot propel a plane. Therefore, engineers have devised four criteria for choosing materials to ensure that a material is up to par. They are (i) how easily it can be manufactured, (ii) if it can withstand its functional requirements, (iii) if it can withstand external conditions, and (iv), its price [2]. Under these parameters, there are a few broad groups, like metals, ceramics, and organic polymers, that are commonly used. Metals, for example, are classified by being good electrical conductors, are solid at room temperature, are at least somewhat malleable and ductile, and, finally, are lustrous when cut [2]. Though not perfect, criteria like these are typically satisfactory.

Engineers use quantitative measures of a material’s properties to better define these groups. Better defined categories make for better engineering. For example, the right materials must be chosen for large public projects like bridges, otherwise the people using them are at risk [3]. The materials bridges are made of must withstand constant stress and strain.

Stress and strain can be expressed in physics. Take the simple example of a spring. Strain refers to how far the spring is stretched, while stress is the tension in the spring (i.e. how hard you have to pull to keep it in place). Intuitively, increasing strain should mean increasing stress. This is indeed the case, and their relationship is shown in equation (1), a formula known as Hooke’s law describing an ideal spring.

(1) $F = -k\Delta x$, where k is the spring constant, and Δx is displacement.

This, however, is not general, since k is specific to each spring. Also, when looking at real materials, the stress-strain relationship is not linear, as Hooke’s law suggests.

There is still, however, a period of linearity, as seen in the figure to the right. The slope of this line is known as Young’s Modulus, and is defined as equation (2).

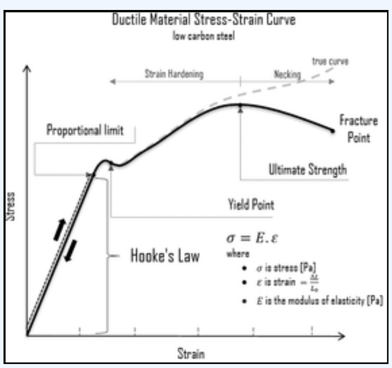


Image: Kakani, S. L., Kakani, Amit (2004)

(2) $E = \sigma/\varepsilon$, where σ = stress, and ε = strain.

Thus, Hooke’s law can be generalized to equation (3):

(3) $F = E\Delta x$

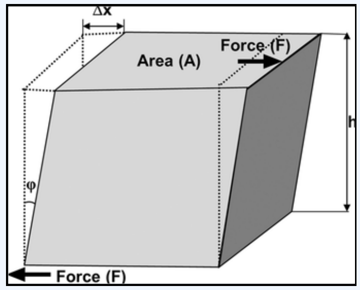


Fig. 1 - A block being put under shear strain. Image: Shuang Li (2022)

Equation (3) holds true only for tensile and compressive stresses. Shear stresses, which cut through a material in a non-parallel direction to the grain, are more complicated. The ratio of shear stress to shear strain is shown in the equation below, which is complemented by figure 1.

(4) $G = \tau_{xy}/\gamma_{xy}$, where $\tau_{xy} = F/A$ and $\gamma_{xy} = \varphi$ (shown in *Fig. 1*)

G is therefore a conversion constant and, given the angle to which a material is deformed, can give the strength of its resistance.

Past the linear region on a stress-strain graph, a material yields and becomes “plastic.” Once plastic, it can stretch and bend. Materials, however, have a limit to the extent to which they can be stretched before fracturing, also known as their ductility. As for the height of the graph, the maximum point on it is a measure of the strength of the material, since it is its maximum resistance. The combination of these two factors—strength and ductility—is known as toughness, and is a measure of the magnitude of stress a material can withstand before fracturing. Its equation, intuitively, is the area underneath the curve from the origin to the abscissa of the fracture point, εf. It has units of J/m3, since it is the amount of energy each unit of volume of a material can absorb before fracturing. Its formula is shown in equation (5) [5].

(5) $\int_0^{\varepsilon f} \sigma \, d\varepsilon$ = energy/volume

The way materials deform is intricately tied with their structure. In general, there are two forms of material: crystalline and amorphous. Crystalline patterns are repeating and regular, and therefore are stronger than amorphous materials [2, 6]. On a simple two dimensional plane, hexagons or squares can be the repeating unit; these are unit cells. In three dimensions, the story is much the same, just that there are more possible patterns [2].

Amorphous materials, in distinction with crystalline ones, are brittle and unstable. Because of their structure, stress builds up on some bonds, compromising them. As such, the microscopic structure of a material can manifest itself in application and in macroscopic tests [6].

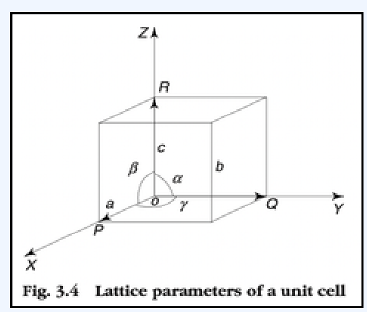


Fig. 3 - A unit cell in three dimensions. It can be described by 6 parameters: (1) the three vectors α, β, and c, and (2), the three angles and between them. Image: Kakani, S. L., Kakani, Amit (2004),

The future of material sciences is promising. Nanomaterials hold promise for their applications in technology, while superconductors could make transporting electricity infinitely more efficient. Once only theoretical, these materials have become tangible, with some now in our very homes.

Formatter: ***Emily Kim***

Engineering of Surgical Tools

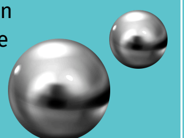
BY: EILEEN CHEONG

For centuries, the surgeon's kit was a collection of simple, single-function tools designed primarily for basic amputations and cuts. The first engineering advancement began during the 19th century with the introduction of anesthesia and antiseptic techniques, which demanded cleaner, more specialized implements. This change continued into the 20th century by blending careful craftsmanship with new material science, such as new steel alloys and plastics, leading to an explosion of new instruments for intracavity, visceral, invasive, resection, and excision procedures [1].

Materials Used For Surgical Tools

The process of designing a surgical tool begins with selecting the right material. The chosen material affects the strength, durability, magnetic properties, weight, and effectiveness of the surgical tools. The most common materials used are stainless steel, titanium, and polymers.

Stainless steel is an alloy, or mix, of iron, chromium, carbon, and sometimes nickel [2]. Carbon, which makes up at most 2.1% of steel, provides strength and hardness, while chromium makes it corrosion-resistant by oxidizing in air and in water and creating a protective layer that prevents further scratches and surface damages on the surgical tool [2]. Most surgical tools are made out of austenitic stainless steel, which contains 16%-30% chromium and 2%-20% nickel and is malleable when heated, allowing the alloy to be manipulated into certain tools more easily. Once it's cured and set, it is one of the strongest forms of metals, making it a preferable material for surgical tools [2]. Austenitic steel s pecifically is non-magnetic due to its nickel content, allowing tools to be used in highly magnetic MRI environments [2].



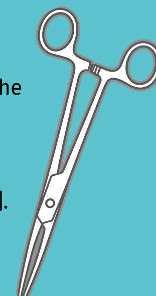
Titanium, another common tool material, is a transition metal significantly lighter than most metals while also being strong and durable [3]. Similar to steel, titanium is highly resistant to corrosion for the same reasons and has the ability to be shaped into complex forms. But, considering titanium's strength compared to its lower density makes it favorable for medical applications that need weight reduction [3]. Its ability to withstand continuous usage while being lightweight makes it most optimal for tools will be used for long operations.

Stainless steel and titanium are both materials that are able to withstand high temperatures. Steel has a melting point of 1370°C (2498°F) [2] while that of titanium is 1668°C (~3034°F) [3]. This is key when it comes to repeated sterilization using an auto-clave, machines that use steam under pressure to kill harmful bacteria, viruses, fungi, and spores [4].The moisture in the steam efficiently transfers heat to the surgical tools, destroying the protein structures of bacteria and thereby killing them to sterilize the tools [4]. With autoclave temperature ranges from 250°F (121°C) to 275°F (135°C) [4], the high melting points of materials like steel and titanium prevent them from degrading over time.

Polymers, medical grade plastics engineered to meet strict needs, are equally as important as metals in the medical field [5]. A variety of polymers are used: while polyethylene (PE) is commonly found in disposable IV bags and syringes, polypropylene (PP) is used for surgical masks, gowns, and test tubes. Equipment like oxygen masks are typically made from polyvinyl chloride (PVC), whereas anesthetic masks and incubators are made from acrylic (PMMA) [5]. Polymers are often used because of their biocompatibility, non-permeability, sterilization resistance, lightweightness, and durability [5].

Types of Surgical Tools

With these materials, we can make surgical tools used in almost any operation, such as forceps, clamps, scalpels, and scissors.



Forceps are one of the primary tools used in surgery, offering the ability to grasp, hold, and extract tissues or objects from the patient [6]. They come in various shapes, sizes, and designs, each suited to their specific surgical task. Some forceps have serrated jaws, where the tip is textured to offer better grip, while others have delicate tips for fine tissue manipulation [6]. Modern surgical forceps are typically made from high-quality stainless steel, alloy, or titanium [6].

Another important medical instrument, clamps are designed to temporarily close up blood vessels during operations [7]. They are mainly used to control bleeding, to prevent fluid leaks, and to decrease risk of injury when manipulating organs [7]. Clamps can be straight or curved depending on their usage. Straight clamps are generally used for clamping larger vessels while curved clamps are preferred for reaching deeper vessels [7]. Common clamp materials include stainless steel, titanium, and medical polymers [7].

Scalpels are one of the most essential tools as their primary function is to provide surgeons with the capability to perform high precise incisions [8]. The blade's geometry is either straight, curved, or angled, creating smooth and controlled incisions by maintaining precision. [8]. Having ergonomic gripped handles, the surgeon is able to maintain command over the instrument at all times and reduces fatigue during long procedures [8]. The materials of stainless steel, titanium, alloys, polymers, and ceramic coating all contribute to its sharpness and durability.

Also designed for cutting, surgical scissors come in many forms based on their operation. For example, bandage scissors are used to cut gauze and bandages [9]. Designed to have an angled and blunt bottom tip, they are able to cut thin fabric while protecting the skin [9]. Dissecting scissors provide more leverage than scalpels when making incisions, removing skin, tissue, and stitches; with their curved blade, they are able to protect incisions when probing [9]. Stitch scissors are designed with a hook-shaped tip to remove sutures, offering a firm grip on the suture before making the cut [9]. For all these scissors, the main materials used include stainless steel, titanium, and tungsten carbide [9].

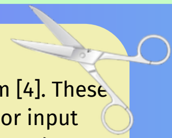
Ultimately, the advanced engineering of medical tools and equipment has made surgical procedures widely successful. By relying on the unique properties of titanium, medical-grade polymers, and alloys, engineers have done more than creating durable equipment; they have fundamentally improved patient outcomes, saving millions of lives in operations.

Formatter: ***Emily Kim***

Simple Machines

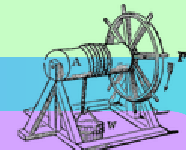
BY: JONINA HOU

Simple machines have been around for millennia. Having first been proposed by the Greek philosopher Archimedes, they have been used by ancient civilizations in building everything from pyramids to irrigation systems [1]. As defined by NASA, simple machines are devices that are used to help complete a task by changing the direction of motion or the amount of required force [2]. In doing this, they allow for less effort to overcome a larger load, gaining what we call mechanical advantage, which is the ratio of the power output to the power input [3]. Today, 'simple machine' refers to the six classical simple machines that were defined by scientists during the Renaissance.



Lever:

A lever consists of a rigid bar pivoting on a fixed point called the fulcrum [4]. These devices are grouped into three classes based on fulcrum location, effort or input force, and resistance, also known as the load. Levers with the fulcrum located between the effort and the resistance are categorized as Class I, and they allow the direction of the force to be changed, which is useful for a task that requires balancing and lifting. An example would be a seesaw, where the beam is balanced on a pivot point (fulcrum) that is between a person on each end (one side is effort, the other is resistance) [4]. Class II levers are those that have the resistance located between the effort and the fulcrum, such as a wheelbarrow, where the load (dirt, rocks, etc.) is positioned between the wheel's axle (fulcrum) and the handles (effort). Class II levers will always have a mechanical advantage and are helpful in lifting heavy objects easily. Levers in Class III have the effort located between the resistance and the fulcrum, one of which includes tongs, where the squeezing the arms (effort) is located between the pivot (fulcrum) and the food (load). These levers are good at achieving distance and generating velocity (sacrificing force for speed because of the location of the effort), which is good for quick movements [5]. Each type of lever has its own advantages, and one might be preferred over the other two to complete specific tasks [4].

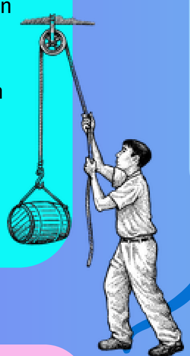


Wheel and Axle:

A wheel and axle consists of a wheel attached to a smaller axle where both parts rotate together [6]. This simple machine can also be seen as a version of a lever since a force is applied to the center of the wheel, the fulcrum, through the axle. Wheel and axles are used for tasks that involve transferring rotational force, or torque, to make things easier to roll by using mechanical advantage. One example of this is a car's steering wheel, where the force of the wheel rotating the smaller steering shaft (axle) is amplifying the driver's applied force, allowing the wheels to turn without much effort from the driver [7].

Pulley:

A pulley consists of a wheel on an axle with a taut cable that passes over the wheel and moves and changes its rotating direction, transferring power between it and the axle [8]. There are three different types of pulley systems: fixed, movable, and compound. The simplest one is a fixed pulley, which is secured to one spot and has the wheel rotating about the axle with the rope moving over the wheel. These types of pulley systems are useful in construction sites, assisting in lifting heavy objects and changing their direction with minimal effort from people [9]. Another type of pulley is the movable pulley. It does not remain fixed and is attached to the load, which is suitable for when the load is below the person lifting. They are essential in construction and are found in construction cranes that lift heavy loads with precise control [10]. Lastly, the compound pulley is a combination of the fixed and movable pulleys. The load is on a wheel of a movable pulley, which is then attached to the rope of a fixed pulley [11].

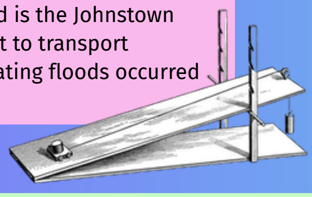


Wedge:

A wedge can be described as a triangular shape that starts thick at one end and tapers off to a thin sharp edge at the other side, and it consists of either one or two inclined planes put together [14]. There are two different types of wedges - single and double wedges. A single wedge only has one inclined plane, such as a chisel, while a double chisel has two inclined planes, such as an axe. The sharper and thinner the wedge is, the greater its mechanical advantage for splitting objects [15]. A wedge is used by applying force to the blunt end while lining up the sharp end perpendicular to the object's slope, allowing the wedge to split the object in half.

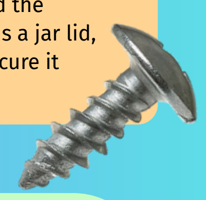
Inclined plane:

An inclined plane consists of a sloping surface without any moving parts [12]. They are used to raise heavy objects against gravity without requiring them to directly go up vertically. An example of an inclined plane is a ramp, which can help to transport carts or other wheeled objects between two surfaces on different levels. The steepest vehicular incline in the world is the Johnstown Inclined Plane, located in Pennsylvania and originally built to transport residents up a hill with a grade of 70.9% whenever devastating floods occurred [13].



Screw:

A screw consists of a twisted inclined plane that is wrapped around a cylinder with ridges in between [16]. Most have a sharp tip at the end to help the screw drill into tough materials like wood and plastic. However, some screws, called bolts, have smooth ends and use a nut to hold the pieces together. An example of a screw is a jar lid, where the ridges (incline plane) help secure it onto the jar.



Simple machines are crucial to society by making work easier with mechanical advantage, enabling people and nations all over the world to accomplish their own monumental feats that would later become signs of their wealth and influence. Originating from basic sticks and stones, simple machines have come to affect varying fields of study and equipment with their efficiency and amplification of forces. They form the foundation of modern engineering and will continue to evolve to be incorporated into modern technology.

Formatter: ***Rebecca Zhang***

5G – Now a Reality

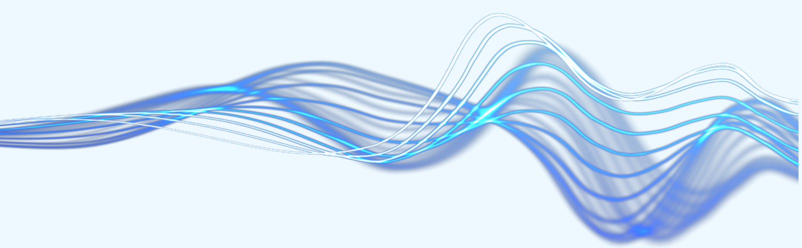
BY: SUNNY CUI

We encounter 5G in our everyday lives—whether it be when we scroll on our phones and brain rot or do productive work, it stays as a little icon on the top right corner of screens. But what exactly is it scientifically? And how does it work?

5G stands for the fifth generation of cellular network technology. In comparison to its predecessors—1G through 4G—it improves in three major aspects: faster data speeds, lower latency, and higher connection capacity. Behind these advancements are a whole world of electrical engineering, a field that works with electricity, electronics, and electromagnetic waves to build real systems such as tiny microchips and massive power grids.

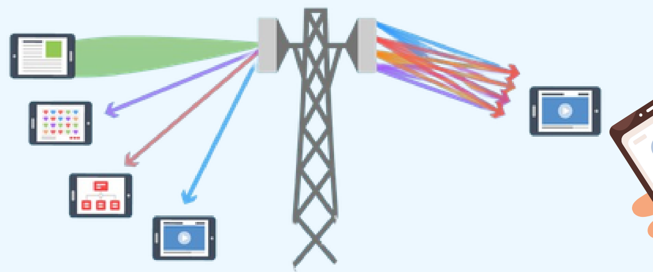
Faster data speeds are one of the most visible improvements introduced by 5G. At its core, the transferred wireless signals rely on and are carried by radio waves. Like visible light, radio waves travel at the speed of light in a vacuum but are comparably much less defined, characterized by their lower frequencies and longer wavelengths [1, 2]. Wavelength is the distance between successive waves, while frequency is the number of wave cycles per second, typically measured in hertz. Wavelength and frequency have an inverse relationship: higher-frequency waves have shorter wavelengths, while lower-frequency waves have longer wavelengths.

With these basic concepts in mind, let's consider two factors that are key to electrical engineers in building 5G: coverage and data carriage. Short wavelengths cause the wave to be more easily absorbed, scattered, and blocked as they interact more intensely with atoms and molecules encountered. Therefore, low frequency waves correspond to larger coverage, and high frequency waves correspond to smaller coverage. However, high-frequency also means greater data carriage or higher bandwidth [3]. As the waves oscillate faster with increased frequency, more signal changes (or number of cycles) occur every second, which translates to more bits (0s and 1s) of information being packed into the given time frame. In balancing these two factors to achieve high speeds, 5G uses a wider spectrum of radio waves, including higher frequencies that were not utilized in earlier generations, and carefully modeled wave behavior in real life to design a robust 5G network [3].



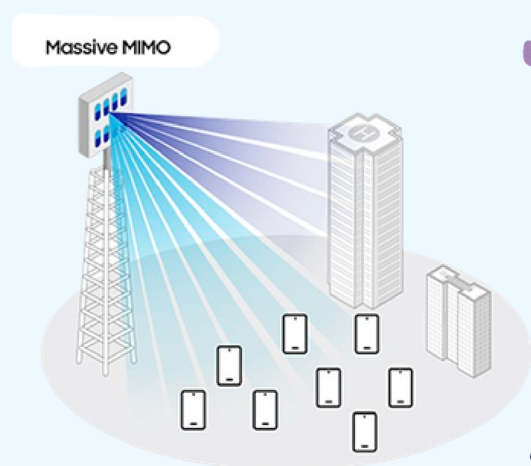
High capacity allows many devices to be connected simultaneously to the network. As the number of smart devices grew, earlier generations struggled in this aspect. 5G electrical engineers addressed this challenge by introducing the Massive Multiple-Input Multiple-Output (MIMO) [4]. In previous generations, each base station used only a few antennas to transmit and receive data [4]. Massive MIMO, on the other hand, packs dozens, and sometimes hundreds, of tiny antennas into a single unit, transmitting multiple data streams in parallel for different users [4]. As the result, speed, capacity, and efficiency were boosted significantly.

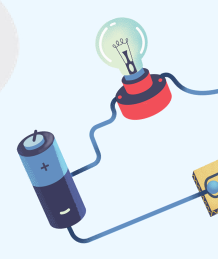
Latency refers to the delay between sending and receiving information, and 5G greatly reduced it. In addition to scaling up the number of antennas in Massive MIMO, a signal processing algorithm called beamforming is also incorporated [5]. Instead of blasting wireless signals everywhere, the base stations precisely control the phase and timing of the signals across each antenna, creating a narrow beam aimed at one user [5]. Different directed beams can be formed for different users simultaneously—thanks to the increased number of antennas—reducing interference, improving signal quality, and ensuring data packets arrive more quickly [5]. Low latency is especially important for uses that require real-time feedback, such as video calls and remote control systems.



5G heavily relies on other advanced electronics and circuits as well, and we will introduce a few here. In every 5G phone and base station, integrated circuits [6], commonly known as chips, do heavy computing. Electrical engineers design these to be compact, energy-efficient, and fast at handling huge amounts of data with little delay. Each device also has Printed Circuit Boards that connect all the chips and electronic components. 5G uses specialized, low-loss materials and a well-thought layout to keep the signals clean and strong and facilitate heat dissipation [7]. Electrical engineers are very careful with power distribution and heat control inside the device to maximize battery life.

5G, as we can now see, depends heavily on electrical engineering for its design, implementation, and functionality. In addition to the daily benefits of more efficient networks and sustainable advancements, 5G networks have also enabled new, transformative applications such as remote surgery and autonomous vehicles, and made simultaneous breakthroughs in fields including healthcare and computer science [8]. It isn't just a number switch from 4 to 5, but a vast scientific project requiring innovations at every layer.





Formatter: **Sunny Cui**

Transformers: Behind the Scenes of Modern LLMS

BY: BEN LI

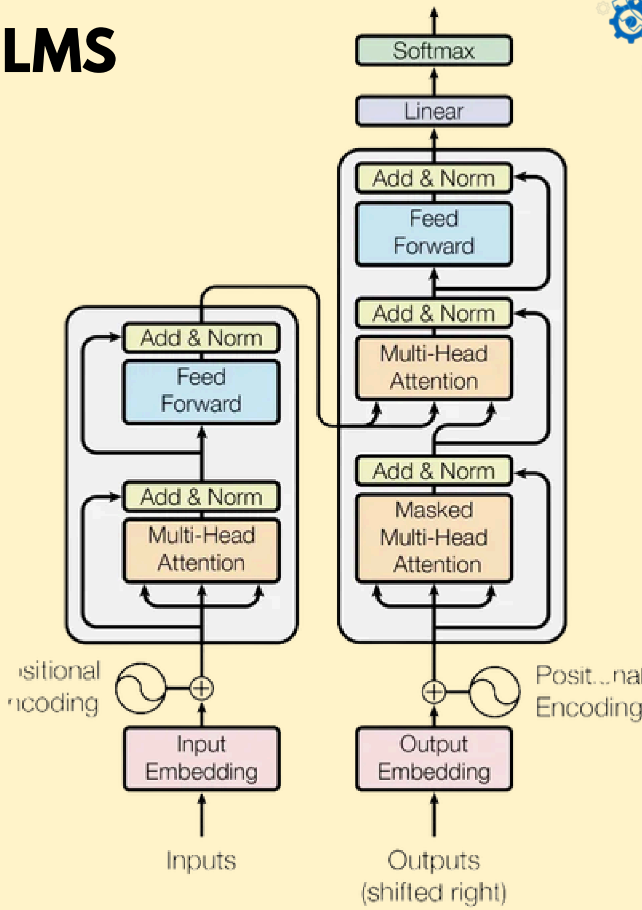


Image: Vaswani, A., Shazeer, N., Parmar, N., Uszkoreit, J., Jones, L., N.Gomez, A., Kaiser, L., & Polosukhin, I. (2025). Attention is all you need. In arXiv [cs.CL].

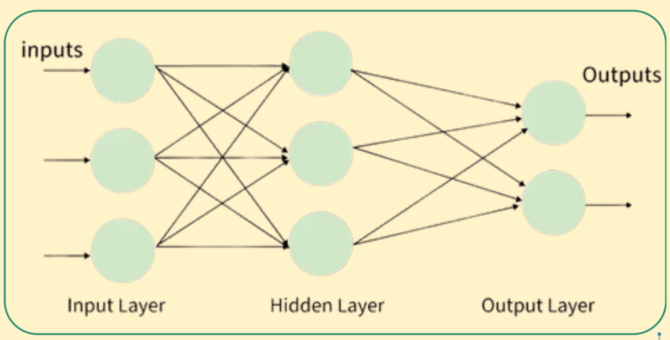
While people use generative AI for various tasks such as creating customized study materials, brainstorming ideas, or coding, few understand the inner workings of these models. The architecture behind tools like ChatGPT is a powerful model known as the transformer. Transformers were first introduced in 2017 in a research paper titled Attention is All You Need [1]. At the time, the most effective AI language models were recurrent neural networks (RNNs) and long-short term memory networks (LSTMs). However, these models were incredibly inefficient, unable to capture nuances in language, and difficult to scale as datasets increased in size. While people use generative AI for various tasks such as creating customized study materials, brainstorming ideas, or coding, few understand the inner workings of these models. The architecture behind tools like ChatGPT is a powerful model known as the transformer. Transformers were first introduced in 2017 in a research paper titled Attention is All You Need [1]. At the time, the most effective AI language models were recurrent neural networks (RNNs) and long-short term memory networks (LSTMs). However, these models were incredibly inefficient, unable to capture nuances in language, and difficult to scale as datasets increased in size.

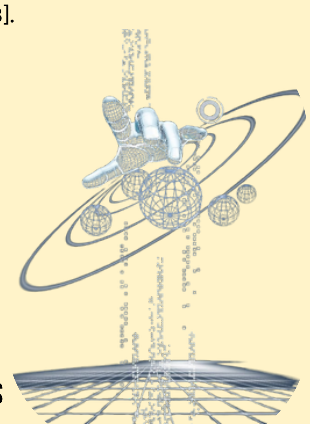
On the other hand, transformers rely on a different approach where, instead of processing text sequentially, they take in large chunks of text using the self-attention mechanism to connect words across a large sequence of text. By using parallel processing, transformers overcame the computational cost limitations that came with traditional neural networks. These design innovations allowed transformers to scale to billions of parameters, significantly improving natural language comprehension and the robustness of new language models [1, 2]. As transformers became more adaptable, scalable, and context-aware, modern Large Language Models (LLMs) that we use day-to-day such as ChatGPT, Claude, and DeepSeek have become more prominent. In addition to self-attention and parallel processing, other essential components of the transformer architecture include tokenization, embeddings, multi-head attention block, MLP layer, and the output probabilities.

The goal of a transformer is to predict the next word given a sequence of text. LLMs such as ChatGPT generate text by constantly estimating probabilities of next words. They then select one that best fits the context of the text sequence, similar to how phones generate suggested words while texting. LLMs seem "human" in their responses because they are trained on vast datasets that contain examples of text from the internet, a process in which they "learn" the nuances of human language. Although seemingly simple, the process of transformers predicting the next word in a response requires a deep understanding of probability, statistics, and linear algebra. However, in this article we will understand the transformer on a fundamental and intuitive level without the complex math behind the scenes [3].

Image: GeeksforGeeks

In order for a transformer to predict the next word in a sequence, the input sequence in human language must be converted into something that it can interpret, similar to how computers use binary code to understand human commands. In the transformer architecture, the input embedding block is responsible for the conversion task. For ChatGPT, the input text is converted into tokens through tokenization, which breaks down the word sequence into singular words or subwords [4]. For simplicity, it can be assumed that each token is a word, but in reality words are broken down into smaller units depending on its length, which includes common prefixes, roots, and suffixes.





Formatter: ***Rebecca Zhang***

Each token is then encoded into a separate high dimensional vector or embedding that stores the meaning of the word it represents [5]. These vector embeddings can go up to thousands of dimensions and are impossible to visualize. However, researchers are able to visualize these embeddings by reducing their size to a two or three dimensional space. In this space, words with similar semantics are positioned close together. For example, the word “man” and “king” would be pointed in a very similar direction since they both denote a male human being. When processing a group of words, determining a word's semantic meaning also depends on its relationship to other words or context. As a result, input token embeddings have an additional positional encoding vector added to them, where each is provided information strictly about its location in text sequence [5, 6]. This allows transformers to have a deeper understanding of the meaning of the token since a word could mean different things in differing contexts. Through intricate embeddings of words and positional encodings, transformers are able to process and understand text.

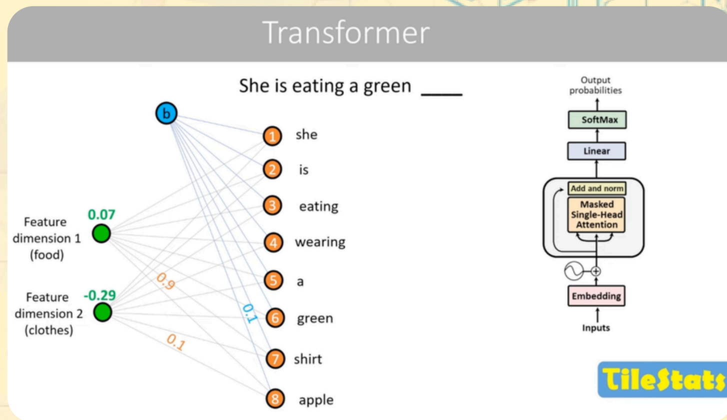


image: TileStats

The embeddings of the input then enters the multi-head attention block of the transformer, where the mechanism of self-attention enables the model to understand the relationship and semantics between words in a sequence [1]. Prior to the transformer, RNNs and LSTMs were only able to contextualize small amounts of tokens. Now, the transformer's self-attention capability allows for a word to be contextualized given a much larger sequence of tokens. Each word’s linguistic components – meaning, syntax, and relationships– are determined based on weighing the relevance of its surrounding words to itself [7]. To interpret self-attention more intuitively, in the sentence, “The young boy adopted a fluffy gray cat”, the word “young” specifies the description of boy, similar to how “fluffy” and “gray” both affect the meaning of cat. On the other hand, words like “the” or “a” have less importance in determining semantics. Essentially, each word determines which other words in the sentence influence its meaning; if a word is significant, its embedding is added to the word, creating an embedding that holds greater semantics.

In the transformer block, multi-head attention runs self-attention in parallel across many tokens, which not only improves the model’s efficiency in understanding text, but also allows the model to focus on different parts of the input simultaneously. In fact, these multiple “heads” can each examine relationships between tokens from different perspectives. For example, one may consider syntax while another might examine semantics [8]. The learned meanings of each token are then applied to the original embedding of the token, transforming the embedding into capturing a more contextualized version of that word. Because each token now contains a much deeper and richer meaning, the transformer model is able to generate text with the knowledge of the relationship between tokens in the input, allowing for significantly more context-aware and coherent responses [2, 8]. The self-attention mechanism gives modern LLMs the ability to understand complex natural language and generate a relevant and effective response in various contexts.

In addition to the multi-head attention block, further refinements for each token’s representation are made through the Multilayer Perceptron (MLP) layer. Instead of each token interacting with other tokens in the sequence like in the self-attention block, in the MLP layer, each embedded representation of a token is separately passed through for adjustments. In this block, each token is essentially examined through answering various questions that clarify its meaning [8]. These changes are then applied to the embedding, enhancing its overall representation of the token’s meaning and syntax.

The input doesn’t go through the transformer block and the MLP layer once. Instead, these two components are stacked many times, allowing each token in the sequence to gradually encapsulate more meaning and complexities. Although this process seems long, transformers take up to fractions of a second to predict the next word, which is why ChatGPT can produce long texts in a few seconds. After passing through all transformer operations, the model focuses on the last embedding or word in the text and applies a mathematical operation known as the softmax function to it, creating a probability distribution over next possible words [1, 8]. The final embedding of a text sequence is similar to the last word in a fill in the blank question. After reading a chunk of text and you are tasked to predict the next word, you wouldn’t just consider the last word alone because it could have an infinitely many meanings. Instead, you would consider the context and the relationship of the relevant words in the text before predicting the next word.

The development of the transformer model has propelled the field of AI to today, where models are able to understand and produce text at a high level of sophistication. Early after the transformer’s establishment, different transformer architectures such as BERT and GPT were created which allowed for even deeper understanding of text and efficient generation of it [9]. Although the transformer was initially designed for natural language, it was later applied to image generation, computer vision, and audio processing. Today, transformer models have been applied across a wide range of fields such as chatbots for customer service, protein folding predictors in healthcare, and consumer LLM tools used everyday. Even though these models have yet to obtain human consciousness, their ability to learn and produce across various fields makes the transformer a core component of progress. As research continues, the transformer continues to be the foundation of artificial intelligence and set the stage for more advancements to be made in the field [10].

From Hit to Hero: The Role of Lead Optimization in Drug Development

BY: GAVIN MACATANGAY & JOSHUA HUANG

Drugs act as a common form of medication, serving as an accessible means of fighting sickness worldwide. As a result of rigorous testing and searching, however, drug development is an arduous process that takes billions of dollars and can often last over ten years [1]. The process of drug production can be split into two components: discovery and development.

Discovery is the process of identifying the target of the drug until its optimization, while development revolves around the testing and refinement of the discovered drug to ensure its effectiveness in the market [2]. Notably, lead optimization acts as the transition between in vitro and in vivo experimentation [3]. In vitro, meaning “in glass” in Latin, implies experimentation within a controlled environment, often a test tube. On the other hand, in vivo, meaning “in life” in Latin, suggests research conducted in organisms, which are more complex than their aforementioned counterpart. In short, lead optimization is the process in drug development where “hit” compounds, identified compounds likely to produce the best results, are tested and optimized with various compounds to optimize them into “leads” that are then tested in vivo.

Lead optimization works by seeking to optimize different categories of the prospective drug, such as efficacy, potency and selectivity [4]. First, potency is the correlation between drug dose and the strength of the effect. Efficacy describes the maximum possible effect when given to an organism. This differs from potency as several factors can turn a high potency drug into something with low efficacy; an example is how the body processes these drugs, where high metabolism in the body can make it hard for a given drug to have enough time to fully affect the body. Selectivity concerns the unwanted side effects a drug causes, with a low selectivity generally resulting in more side effects [5].

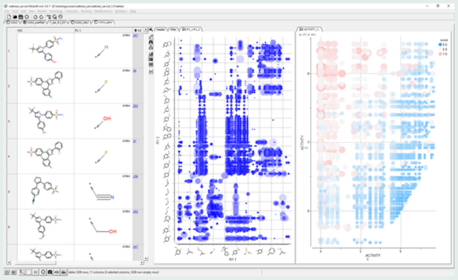


Image: SAR Analysis from molsoft

With these categories in mind, leads are optimized through a variety of ways. For instance, one key way leads are optimized is through structure-activity relationship (SAR) analysis. SAR analysis seeks to find the relationships between the structure of the lead and the assigned function [6]. Thus, by identifying the specific parts of the structure that result in the given activities, those parts could be optimized to have a higher efficacy, higher potency, or lower selectivity. For example, assume an important part of a drug binds to a ligand. SAR analysis would be able to identify this part and connect it to its activity of binding to the said ligand. Then, this part could be optimized to only bind to that specific ligand, which could increase the selectivity of the drug in this case.

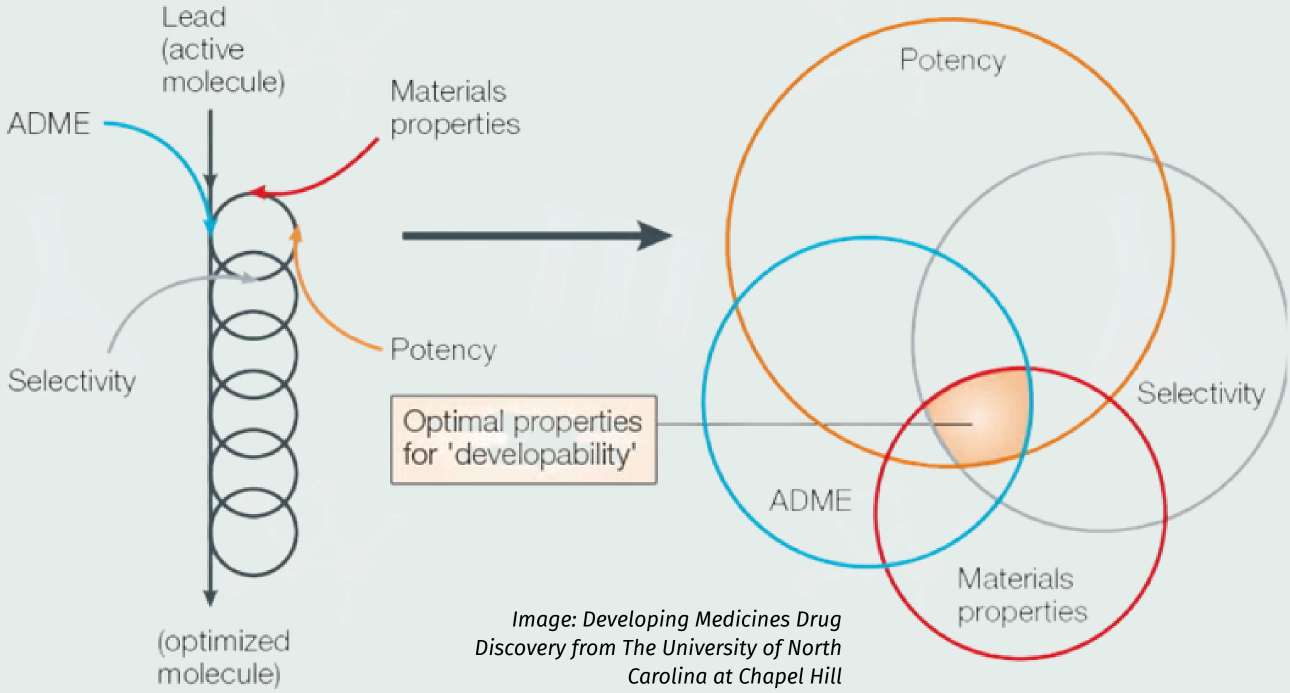


Image: Developing Medicines Drug Discovery from The University of North Carolina at Chapel Hill

Formatter: ***Aleena Zhang***

One way this technique is utilized is for the creation of a me-too or me-better drug, which is a drug based off of an already existing one that was just optimized in certain ways [1]. One prime example of a me-too drug is atorvastatin, a cholesterol drug, which is based on lovastatin [7]. Atorvastatin has a higher efficacy than lovastatin, as, through SAR analysis, scientists were able to engineer it to more efficiently decrease different types of cholesterol than lovastatin. Additionally, similar SAR analysis processes can identify parts of a drug's structure that decrease its overall performance, leading to scientists being able to mitigate these unwanted effects.

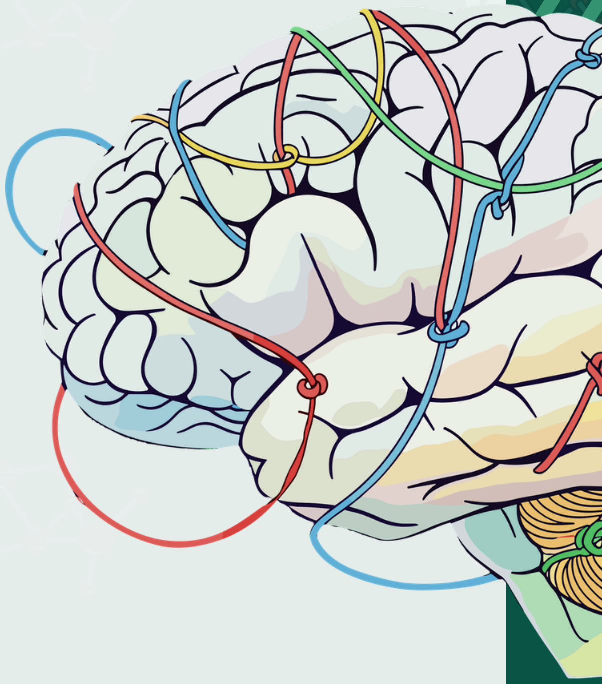
Another way leads are optimized is through more in vivo testing to see if the optimizations made in previous steps had worked out [8]. Lead optimization as a whole is an iterative process that works as a cycle of testing and optimizing until the aforementioned categories—efficacy, potency, and selectivity— are at the drug's fullest potential. Thus, this makes the process as a whole quite tedious.

Modern applications of AI into lead optimization could not only provide a more efficient process but also give valuable insight through new methods. Particularly, AI helps speed up the lead optimization process by being able to find both hits and leads much quicker than humans. Computer-aided drug design (CADD), for example, is effective in streamlining this identification process, ultimately reducing cost as well [1]. As for the optimization process itself, AI is able to optimize lead by splitting it into four different sub-tasks: scaffold hopping, linker design, fragment replacement, and side-chain decoration. This is necessary for AI-aided drug discovery (AIDD) because the depth of knowledge necessary to perform optimizations in one task would otherwise be greater than currently possible. Thus, these sub-tasks help the AI optimize through lead optimization.

Generative AI in Drug Discovery

Generative AI has broadened the possibilities for AI use in drug discovery. Most of the development within AIDD has come through de novo, meaning "from new", generative models [1]. These models visualize molecular generations as a graph generation problem. Under a set of constraints, the model connects a set of nodes with each other in the most optimal way. For example, assume that each house within a neighborhood can be represented as a node, and the streets are the constraints for the AI to maneuver around. Thus, the problem would entail something along the lines of finding the most optimal path from one house to another. This can end up creating new structures that lead optimization wouldn't be able to make. The aforementioned models also don't have a strong need for excessive background information, allowing them to be able to generate new structures quicker than the lead optimization AI models.

However, a restriction of AI models within lead optimization is the lack of data [1]. Training models in general require lots of data to build. Since the technology is still novel, there isn't sufficient data to be able to make a hyper-accurate model for lead optimization. However, as data becomes increasingly available and accessible, a world where the lead-optimization process fully utilizes AI becomes more and more possible. This could lead to huge benefits for the pharmacology industry as this would rapidly speed up the time it takes for new drugs to be made [1].



In conclusion, lead optimization plays a vital role in the development of drugs by crafting a careful balance in three aspects: potency, efficacy, and selectivity. More specifically, it functions as the bridge between discovery and development. Furthermore, recent developments in the industry, particularly those that work with AI, expedite a process that could otherwise be extremely costly in both time and finances. These innovations can also be applied more broadly in the field such as in other phases of the drug development process, such as the creation of hit compounds and data review. Moreover, these changes in the development process also offer indirect benefits to the average consumer—enabling personalized medication, accelerating the development of a certain drug, etc. At the end of the day, lead optimization proves to be a fascinating process crucial to the proper functioning of any drug [2].

Genetic Engineering: A Pathway to a More Perfect Being

BY: YUNSHENG XU

What if you could change how organisms express themselves, giving them completely new characteristics? Or perhaps fight off diseases that have long plagued humans?

That is precisely what genetic engineering does; scientists use a variety of methods to modify the tiny instructions that give a living organism its characteristics and functions. For billions of years, DNA, the code for organisms, could only be slowly modified over millions of years, giving organisms specific traits through evolution and natural selection. However, scientists are now able to precisely rewrite an organism's genetic code, changing its features much faster than evolution would. Genetic engineering isn't just a theory; it's happening right now. It's how scientists are curing diseases, fighting climate change, and making agriculture more efficient.

Genetic engineering may involve deleting a region of DNA, or adding a new segment of DNA [1] to the organism's genetic code, thereby changing its features. One method that scientists use to accomplish these alterations of DNA is through CRISPR (also known as Clustered Regularly Interspaced Short Palindromic Repeats). Interestingly, CRISPR isn't a tool that scientists invented from scratch; it's actually a natural defense method found in bacteria that help them fight off viruses. When a bacterium is attacked by a virus, it stores a part of the virus' DNA in its own genome. That way, if the bacterium is infected by the same virus again, it can recognize and easily eliminate the threat, like how vaccines work for our own bodies [2].

Looking further into the CRISPR system, scientists discovered a DNA-cutting protein called Cas9. They then realized that they could edit the genomes of plant and animal cells using "guide RNA," essentially a GPS for Cas9. The guide RNA tells the Cas9 protein where to go, cutting out specific regions of DNA under a scientist's guidance [3]. This way, harmful molecules can be removed from organisms, allowing for the organism to heal themselves. Alternatively, scientists may even introduce different DNA to replace the cut-out DNA region.

In addition to deleting unwanted DNA, scientists can also use recombinant DNA to "grow" and introduce new DNA to an organism. In this process, DNA of interest is taken and combined (or spliced) into a plasmid, a type of circular DNA found in bacterial cells. Restriction enzymes cleave DNA at specific locations, while DNA ligase acts as a glue and joins the new DNA to the plasmid. In the next step, the plasmid is introduced into bacterial cells. This "recombinant" DNA is then replicated over and over again as the bacterium reproduces, copying the engineered DNA as well as itself [4,5]. With a whole batch of DNA-containing bacteria, scientists then select and screen for the transformed cells.

But how do scientists actually deliver the DNA into other organisms? This is where viruses come in. Ordinarily, contracting a virus sounds like a bad thing. However, scientists actually genetically modify viruses to contain helpful, therapeutic genes, leveraging the viruses' natural ability to infect cells. One of the most effective gene delivery vehicles, modified viruses, can efficiently target genes to enhance immune response or correct genetic defects [6].

With precise and effective tools to edit an organism's characteristics, scientists have already used genetic engineering to innovate in many different fields. For example, in cancer research, researchers use CRISPR to change genes linked to cancer, then closely track the individual cells that form [2]. CRISPR has also been applied in the agriculture industry, modifying crops to have better quality, disease-resistance, and even yield [2]. Recombinant DNA has been used in the healthcare industry, producing recombinant proteins for therapeutic purposes. Notably, recombinant technology was used to create human growth hormones to treat growth hormone deficiency in children, as well as produce insulin to treat diabetes without the use of cattle and pigs—which could cause allergic reactions [5].

While the benefits of genetic engineering are apparent and already applied in several different fields, there are also risks that need to be considered. The most likely problem is unexpected allergenicity. If allergenic proteins are transferred between foods through recombinant technology, it can cause unanticipated allergic reactions in people who ate it. Another possible problem is the activation of unknown, nonfunctional genes that are harmful toward humans and animals. By randomly inserting transgenes into an organism, scientists may inadvertently activate previously inactive genes in the target genome, possibly producing harmful compounds [7].

Apart from damage to humans, genetic engineering may also hurt the environment. If environmentally advantageous genes are transferred to crops, then those crops may become weeds. For example, tolerance of high-salt environments is a desirable trait for many crops. However, the addition of advantageous genes may allow the crop-weed hybrids to displace other naturally occurring salt-tolerant species. Another risk could be the adaptation of pests as the pests grow more used to a resistant gene. Historically, the use of a widespread resistant gene in domesticated species has led to adaptation in the pest population, as the pests grow more used to the resistant gene. Recombinant technology may accelerate this, as the resistant gene will most likely be used over large areas due to the immediate economic benefits that a grower or producer can obtain [7].

While genetic engineering is a route to quick genome editing in organisms and therefore its characteristics, it still is a very new technology, whose effects have not been thoroughly studied yet. The benefits are clear, but scientists should explore the possible risks of genetic engineering before using it extensively.

Formatter: ***Aleena Zhang***

Must Have Been the Wind

BY: LUKE TAYLOR

Wind energy is crucial to this day as a natural and renewable source of power that helps reduce pollution and need for fossil fuels. Wind turbines are machines that use the force of wind to create electricity. Evolved from a simple tool, wind turbines have become crucial to creating clean-energy.

The earliest windmills were engineered in Persia and China in 500-900 AD, where it was mostly used to grind grain and pump water for farming [1]. These simple designs demonstrated how early machines could replace human labor.

Over time, windmills spread to Europe, where Dutch designs focused on improving water management. The later innovation of tower mills proposed a design where the top to rotate with the wind. Eventually, windmill technology advanced to the point where it was able to generate electricity, leading to the modern design of wind turbines.

A windmill has many parts to it, such as the blades that catch the wind, making it spin. The rotor connects the blades to the main shaft such that the wind's kinetic energy can be made into electricity. The shaft then carries this motion through into the machine, where the gears are able to increase the rotational speed allowing a more increased power output and to become as efficient as possible. After this, the generator converts this mechanical energy into electrical energy [2].

The kinetic energy from wind flows across the large turbine blades allowing it to rotate the rotor where this motion creates mechanical energy within the shaft. The shaft spins the rotor within the generator allowing the mechanical energy to be turned to electric currents. Through cables, the electricity is sent to the power grid for the use of the world.

Likewise, an older model of wind turbines is the Vertical Axis Turbine. It is set up such that wind can be captured from all directions by the blades rotating around the turbine, unlike the Horizontal Axis [4]. This type of wind turbine is best for environments where the wind directions change frequently. The reason for the VAWT becoming less common to this day is due to its low efficiency at creating electricity. From a larger range to capture wind, it came at the cost of the speed of the blades becoming lower, causing less output.

The advantages of wind energy is that it is renewable, as it will never run out as long as there's wind. The operation cost is also low aside from the cost of building the wind turbine [5]. These machines are able to create energy throughout the day and night as long as there is wind blowing continuously.

One of the main challenges of wind energy is that it is less efficient and reliable in areas without consistent wind. They also require large amounts of land, especially for wind farms [6]. Moreover, it can also impact the creatures that fly such as birds, however, most newer designs are attempting to reduce this problem by slowing down the windmill with cameras able to detect creatures nearby [7].

Wind energy is important as it uses natural wind to create energy without any pollution to the world. Over time, they evolve and become more efficient to fit the needs of the problems rising, demonstrated through pumping water at first then being able to create electricity. This is a key energy source in the future, as it helps solve many issues globally.

Formatter: ***Aleena Zhang***

WHAT A-BOT BOTS?

BY: ELIZABETH WONG

INTRO

In recent years, the global rise of artificial intelligence and robotics has captured public imagination and sparked heated debate. Robots are increasingly present in everyday life, creating both excitement and concern. Some fear robots may lead to over-dependence on machines or even replace humans entirely. These concerns often overlook how robots can complement human abilities rather than diminish them. To start, robots are suited to perform dangerous, repetitive, or high-precision tasks that challenge human capabilities. These tasks include repetitive laboratory pipetting, handling dangerous chemicals, or detailed assembly jobs. Rather than eliminating human involvement, robots can free up time scientists and technicians can use to focus on higher level problem solving and analysis, maximizing overall productivity. For example, in 2015, Asea Brown Boveri (ABB) introduced YuMi, a robot that adds flexibility to assembly processes. YuMi allows for collaboration between humans and robots by adapting to changes presented to them, meaning that people and robots can work side by side on the same task. [1]

DESIGN AND DEVELOPING ROBOTS

Robotics engineering is a multidisciplinary field that combines elements of mechanical, electrical, and computer engineering to conceptualize, design, build and operate robotic systems [2]. This process begins with mechanical design, where engineers determine the physical structure and the capabilities of a robot. This is often inspired by biological systems, leading to adaptive and flexible robot forms such as soft robots.

Soft robots use biological systems as a source of inspiration for the structure or function of the robot. For example, soft robots are made of materials that resemble the stiffness of skin, which allows them to hold and maneuver irregular or fragile objects. This allows them to work in tight spaces or environments that require precision, like medical applications [3].

HARDWARE

A robot's effectiveness depends heavily on its hardware, which enables movement, perception, and interaction with its environment. Robotic hardware integrates mechanical and electronic components that work together to translate digital commands into real-world actions. [4]

Sensors allow robots to perceive their surroundings by collecting data like temperature, pressure, light, motion, and more. In laboratory and medical settings, sensors are critical for precision and safety, enabling robots to respond to environmental changes rather than following pre-set instructions [5].

Actuators convert signals into physical movement in order to control a robot's joints and limbs. There are many types of actuators, such as electric motors, pneumatic actuators, and hydraulic actuators.

Electric Actuators

Image: Linak-US

Hydraulic Actuators

Image: Kurvalf Vana

Pneumatic Actuators

Image: Alloy Valves and Control

Different types of actuators use different methods to generate movement. Electric actuators have motors that can convert electricity taken from a power source into linear or rotary motions to open, close, or adjust a corresponding valve [6].

Pneumatic actuators use compressed air or pressurised gas to create movement. The pressure from the gas forces a piston to move, generating linear or rotary motion that can be controlled for precise movement [7].

Hydraulic actuators use the idea of fluid compression to generate motion. There are two types of hydraulic actuators, single action units and double acting units. Simple action units only apply pressure to one side of the piston and double acting units apply pressure to both sides of the piston.

The quality and precision of actuators determine how smoothly and accurately a robot can perform tasks such as surgical movements or delicate sample handling [4]. Advanced robots often use multiple actuators to mimic human or animal movements.

Robots require reliable power sources to operate effectively. Depending on the application, robots may use batteries, wired power supplies, or energy-efficient systems [5]. Power efficiency is especially important in mobile robots and medical nanorobots, where limited energy availability can restrict operational time and effectiveness.

At the core of robotic hardware is the processing unit, which controls the robot's body and manages communication between sensors and actuators. This system must be fast, energy efficient, and robust, especially in hospitals or labs where failure could pose safety risks. The integration of specialised processors allows robots to handle complex computations, including real-time feedback and decision making.

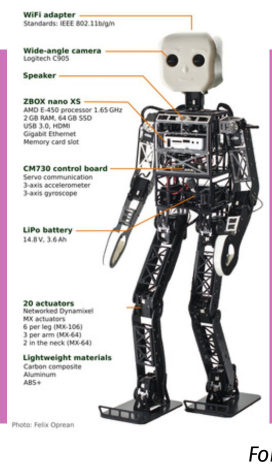


Image: Felix Oprean

Formatter: ***Emily Kim***

SOFTWARE

The software in robots allows it to interpret sensory input, make decisions and execute actions. Robotic engineers use programming languages such as Python, C++, and Java, and frameworks like the Robot Operating System (ROS), to coordinate tasks and manage complex behaviors [8]. Developers continually test and debug robot code to ensure safe and efficient operation. This includes tuning control algorithms and responding to unexpected behavior during trials.

Effective robotic design depends on seamless integration between hardware and software. Sensors provide data, processors interpret it, and actuators execute the response. Any mismatch between these components can result in errors or inefficiencies. For this reason, engineers often test hardware and software together in iterative cycles, refining both physical design and code to improve performance and reliability.

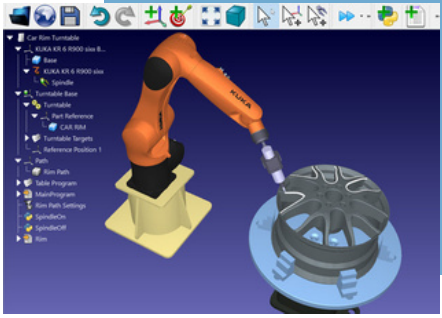


Image: RoboDK

ETHICAL CONSIDERATIONS

The increasing use of robots raises significant ethical concerns that must be addressed alongside technological advancements. One major issue is human dependence on machines; over-reliance on robots could erode essential skills and decision-making abilities. Additionally, accountability becomes complex when autonomous robots make decisions or perform actions independently, leaving questions about who is responsible for errors or accidents. In healthcare and research settings, the deployment of robots must consider patient safety, informed consent and equitable access to advanced technologies, ensuring that benefits are available fairly across populations. Furthermore, the integration of robots into workplaces may exacerbate social inequalities if certain groups are disproportionately affected by automation or excluded from opportunities to work with these systems. Addressing these ethical challenges requires collaboration between developers, policymakers and society to create frameworks that balance innovation with responsibility, safety, and human well-being [9,10].

REAL-WORLD APPLICATIONS

Medicine and healthcare:

Robots have become vital tools in modern healthcare. Robotic assisted surgical systems enable procedures that improve precision and reduce recovery times [11]. However, these systems raise ethical concerns regarding informed consent, training requirements, and equitable access to advanced care [12]. Researchers also stress that robotics in healthcare must adhere to ethical principles like “beneficence, non-maleficience, and respect for (patient) autonomy” [13].

Another aspect of robot healthcare is nanomedicine. Nanorobots are designed to navigate the human body to deliver drugs to targeted cells and precise manipulation of cells which could revolutionise treatment by targeting disease at the cellular level. Nanorobots have the potential to transform healthcare by enabling accurate diagnosis, precise medicine administration, and less invasive surgical procedures [14].

Chem and Bio research:

In laboratory settings that involve hazardous compounds, robots can safely handle toxins, pathogens, and radiation, reducing risk to human researchers and improving experimental consistency. This capability is especially valuable in high-risk environments where precision and repeatability are paramount.

FUTURE POTENTIAL

As robotic technology continues to advance, its future potential lies in deeper integration with AI, allowing robots to become more adaptive, autonomous, and collaborative. Rather than relying solely on pre-programmed instructions, future robots should be able to learn from data, experience, and provide real-time feedback. This shift will enable robots to operate effectively in unpredictable, real-world environments such as hospitals and research laboratories.

A major area of growth is AI-driven perception and decision-making. With improved machine learning algorithms and advanced sensor systems, robots may be able to recognise patterns, predict outcomes, and adjust their actions accordingly. For example, in healthcare, robots could assist doctors by identifying early signs of disease through medical data like imaging or patient data analysis. [9]

Another promising development is the expansion of collaborative robots, or “cobots.” Unlike traditional industrial robots that operate separately from humans, cobots are designed to work safely alongside people. These robots could take on physically demanding or repetitive tasks while humans handle supervision, creativity, and ethical decision making [5].

Despite these advancements, the future of robotics depends heavily on ethical regulation and responsible design. As robots gain more autonomy, guidelines must be put into place to address accountability, safety, data privacy, and equitable access. Ensuring that humans remain in control of critical decisions will be essential to maintaining trust in robotic systems.

CONCLUSION

From hardware design and software programming to real-world applications in science and medicine, robots are reshaping our world. While ethical challenges accompany these innovations, robots ultimately have the potential to improve safety, enhance human skill, and expand what is already possible across industries. By combining human creativity with robot consistency and precision, the future of work and research can be safer, more efficient, and more innovative.

Formatter: **Emily Kim**

Synthesizing the Fibers and Fabrics of Tomorrow

BY: ALEX GU

From fabrics in clothing to the materials used for sports equipment, medical supplies, and industrial uses, almost everything we touch and interact with in our daily lives contains synthetic materials designed to serve a specific purpose where natural materials fall short. Synthetic fibers and polymers are key components of material engineering, a field that seeks to understand the fundamentals of material behavior to optimize existing products and invent new materials [1]. By manipulating chemical bonds and structure, material engineers can create materials that are stronger, more durable, and more flexible than traditional fibers. Through these processes, synthetic fibers and materials can be adapted and utilized in many different fields, expanding the horizons of innovation.

What exactly are synthetic fibers and polymers? To start, polymers are the building blocks of fibers at the molecular level. They are defined as large molecules composed of repeating units called monomers. These monomers bond together through chemical reactions, such as chain-growth, addition, stepwise, and condensation polymerization, forming polymers with distinct properties [2]. Compared to some naturally occurring polymers, such as cellulose in plants, synthetic polymers are created through controlled industrial processes in which material engineers can adjust factors such as molecular structure, chain length, and bond strength to customize a material's properties through synthesis using chemical and physical methods[3]. Engineers select specific polymer types and processing conditions, like temperature, to maximize performance. For example, the material Kevlar, with extreme tensile strength, is developed by preparing intermediates, synthesizing high-molecular-weight aromatic polyamides, dissolving the polyamides in a solvent, spinning the solution into fibers, and then using high heat to set the fiber's structure [4]. Once synthesized, the polymers are processed into fibers by combining them into a thick liquid and forcing them through a small device with precisely shaped holes called a "spinneret" to form thread, allowing them to be woven or molded into the shape of the final product [5].

Before the development of synthetic materials, people relied entirely on natural fibers like cotton, wool, and silk. While these natural resources were effective, they were often expensive and limited in supply. As a result, people began seeking alternatives. The first semi-synthetic polymer, celluloid, was invented in 1869 by John Wesley Hyatt, who sought an affordable alternative to ivory for billiard balls [6]. Through Hyatt's breakthrough, manufacturing was no longer restricted by nature, and the discovery gave the world a glimpse at the power of artificial manufacturing. In 1907, Leo Baekeland invented the first fully synthetic plastic, Bakelite, as a substitute for shellac, a natural resin, as an electrical insulator. Decades later, WWII required an expansion of plastics in the U.S. to strengthen the military and reduce reliance on imports from foreign nations. Wallace Carother, a chemist at the company DuPont, invented Nylon, a synthetic silk, which became crucial for producing parachutes, ropes, body armor, helmet liners, and more. After the war, DuPont created a family of fibers, including Dacron (polyester), Orlon (acrylic), and Lycra (spandex), transforming industries such as textiles, manufacturing, and consumer goods. Today, synthetic fibers and polymers are foundational to modern material engineering as ongoing innovations continue to focus on performance, efficiency, and sustainability.

Synthetic fibers and polymers are used across a wide range of industries due to their versatility and ability to be modified for specific applications. In the textile and fashion industry, materials such as polyester, nylon, and spandex are used for their durability and stretch. In engineering and manufacturing, synthetic polymers are crucial for producing ropes, insulation, and protective materials. The medical field relies on polymers for tools such as prostheses, sutures, and implants, which require strength and biocompatibility. Furthermore, synthetic materials play a key role in sports equipment, packaging, and electronics, highlighting their broad impact across diverse industries [7].

The primary purpose of developing synthetic fibers and polymers is to meet the modern standards that natural materials struggle to fulfill. As industries and global consumption expand, the superior durability, low cost, availability, and functional properties such as waterproofing and heat resistance of synthetic materials have become essential. However, synthetic materials also carry their own disadvantages, mainly surrounding their sustainability. In the 1960s, plastic debris was observed as Americans grew increasingly concerned about environmental problems, raising concerns about pollution[6]. Microfibres, or tiny plastic threads, are commonly found in the environment because they are shed by manmade materials during washing, drying, or manufacturing. They do not dissolve easily in water and can absorb other substances that then leak into nature [8]. Despite efforts to manage waste and recycle, limited biodegradability and microplastic pollution have become more pressing issues than ever.

Despite their ecological consequences, synthetic materials are critical to modern engineering. As mentioned previously, they allowed for the development of the items we use and interact with daily. To resolve the issues surrounding these synthetic materials, scientists have developed biodegradable polymers and bio-based synthetic fibers. Innovators are also actively searching for ways to make recycling more efficient, with one goal being to create a process that converts plastics back into fossil fuels [6]. Together, these efforts give a positive glimpse into the future of material engineering by improving sustainability and adapting to societies' constantly changing demands.

Formatter: **Emily Kim**

The Building Blocks for the Pyramid of Engineering

BY: SANYA BHATT & LILY CAO

Engineering shapes every part of our daily lives; from the water that flows from your faucet to the smartphone you carry around, the modern world runs on innovations and allows us to live the way we do. Today, engineering branches into more individualized categories, including civil engineering, chemical engineering, and countless others. However, these varieties of engineering would not be possible without the centuries of problem-solving and development from the past.

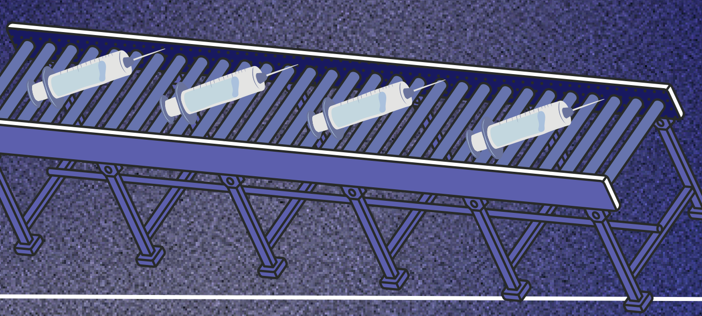
Jumping back to 2600 BCE, Imhotep [1], an ancient Egyptian architect, made history when tasked to build a tomb. Refusing to follow the conventional route of building a rectangular one, he decided to stack these structures on top of one another, creating the famous step pyramid. His creation paved the way for similar pyramids, notably the pyramids of Giza, to be built - and they still stand the same today and impress architects with their precision and durability. This period marks the early introduction to civil engineering, the foundation of what we define today as the "built environment" - roads, buildings, bridges, and dams [2]. More than 2000 years later, the ancient Roman empire further developed civil engineering with many ingenious innovations [3]. With the invention of Roman concrete, they designed and built more than 50,000 miles of roads and aqueducts that transported goods and water vast distances. Their architectural achievements, such as the construction of the esteemed Colosseum and Pantheon, further redefined the usage of arches and concrete in structures [2].

Mechanical engineering first appeared through inventions such as boats and windmills, but truly accelerated in Europe with breakthroughs such as the printing press, textile machines, and ideas of human flight. This surge of development called for rapid technological growth, especially from the 1800s to the innovation we still observe to this day [4]. The Industrial Revolution marked the beginning of modern engineering by shifting from manual labor to mechanical labor with steam power to fuel engines and factories. This period also introduced electrical technology to the world, as inventions such as the telephone and the lightbulb emerged. This opened the path for the widespread use of electronic devices and gadgets today. Shortly after, a revolution in chemical engineering surfaced, using chemical reactions to transform everything, from creating life-saving drugs to lithium batteries and biofuels.

Although the ancient origins of engineering may sound primitive or uninspiring, the engineering process of the Great Pyramids still stumps historians and archaeologists to this day. Historians believed that they were inspired by the "stepped" mastabas in Nubia, a tomb that greatly resembled the shape of a pyramid and contained underground burial chambers [5]. However, the large scale of the pyramids still causes historians to be unsure exactly how they were built, but some theories are more widely accepted than others. It is believed that the Egyptians moved the massive stone blocks that make up the pyramids by utilizing large ramps and sleds to drag these blocks up the ramps. However, there is still controversy if the ramps used were exterior ramps that either zig-zagged or spiraled around each pyramid, or internal ramps. Most experts agree that both ramps were used, and the exterior ramp would be removed after construction finished [6]. Most of the large stone blocks used on the outside were limestone, however the internal walls used granite. The outer layer of the pyramid was encased in a fine limestone that was polished, giving the great pyramids a spectacular white appearance. Egyptians also used the force of gravity and a weighted string to measure and create perfectly vertical surfaces [7]. Overall, the creation of the great pyramids is still a phenomenal engineering feat that continues to impress historians and inspire the scale and potential of the engineering of the future.

As our societal needs shift and rise, the future of engineering is subject to change and expansion in conjunction with many other fields. Future directions of engineering include utilizing artificial intelligence and machine learning to make specific processes and tasks more efficient, sustainable design and the creation of renewable energy, and cybersecurity to maintain data safety and privacy. Although the field of engineering has evolved from its beginnings and the first inventor Imhotep, the goal of engineering has always stayed the same: to solve and create efficient solutions to the problems we observe around us.

Formatter: ***Emily Kim***



Immunity on an Assembly Line: Vaccine Engineering

BY: ATHARVA DESAI AND YATHARTH MAKWANA

For many years, humanity's approach to combatting infectious disease was similar to that of building a wall made with blocks of inactivated pathogens. These were the key materials of early vaccines, which worked by providing a weakened version of the pathogens, safely allowing the body to arm itself for when it encountered the actual disease. However, this slowly-built wall was often penetrated by newly evolving pathogens and failed to provide foolproof protection. Here, modern vaccine engineering emerged, providing a strengthened guard protecting the body. Vaccine engineering has yielded an improved way to arm the body, not by providing a weakened version of the disease, but by providing a simple instruction manual for combat.

Now, vaccines save 5 million lives every year; this number is only expected to grow in the future with further development [1]. From the initial variolation concept in Asia to Edward Jenner's first small-pox vaccine, then to Pasteur's lab methods, vaccination has now reached a new peak in development: vaccine engineering. With the emergence of genetic engineering in the 20th century, vaccine development has been revolutionized, creating new approaches to synthesize antigens (such as in the hepatitis B vaccine) and to create safer live bacterial vaccines by removing particular dangerous genes. This revolution has led to contemporary vaccine engineering, where innovations such as mRNA technology and virus-like particles are the solid way to disease prevention, also allowing for the efficient accelerated manufacturing of vaccines [2].

As part of the new approach to vaccine development, the content inside vaccines has changed significantly. As mentioned above, vaccines used to work by exposing the human body to weakened or killed versions of a pathogen, so that the immune system could learn to recognize and fight it. Although this method was effective against diseases like polio, measles, and smallpox, it was a time-consuming process of growing and then inactivating a virus, in turn posing a greater risk for people with a weak immune system. Nowadays, many vaccines no longer rely on pathogens. Many modern vaccines utilize mRNA technology. Messenger ribonucleic acid, or mRNA, is a molecule in cells that copies instructions from DNA to the ribosomes to be made into proteins [3]. Vaccines with mRNA carry the instructions for creating specific parts of the pathogen, allowing the body to create a recognizable part of the pathogen and identify it as an invader. The body can then produce antibodies to fight off the infection more efficiently the next time it detects that same protein.

An equally important transformation has been large-scale production of vaccines. This increase in production can be attributed to new technology, such as computer modeling tools and synthetic DNA creation. Computer models are used by scientists to predict which parts of a pathogen may be recognized by the immune system and its complex line of defense; they help scientists choose which parts of a pathogen to include in vaccines that will spark the body's immune response [4]. To continue, synthetic DNA creation for vaccines allows for rapid, cell free production with no need for live pathogens. These developments allow factories to manufacture larger numbers of vaccine dosages in shorter amounts of time. During the COVID-19 pandemic, production of vaccines skyrocketed from 0 to 11.2 billion doses in just one year, allowing countries to launch the vaccines earlier than expected and protecting people across the world from the spread of the disease [5].

New developments for engineered vaccines offer more effective and efficient solutions to the previous methods. Paired with advancements in manufacturing and production, vaccines now have a much greater impact on global human health, exemplified through the role of vaccines in combating and overcoming the recent COVID-19 pandemic. With a current shift into AI-driven formula optimization and antigen identification, scientists are taking great steps to ensure a future of improved public health and safety.

Formatter: ***Emily Kim***

Prosthetics and Biocompatible Materials

BY: ISABELLA GUSTUS AND GRACE CHEN

Recently, new and more advanced solutions have been developed to restore mobility in missing and non-functioning body parts, changing lives. These artificial technological implants of joints and even entire limbs are called prosthetics [1]. However, the effectiveness of these devices is heavily reliant on the materials used to create them, specifically biocompatible materials that can contact the body safely. Biomedical engineers and prosthetic designers use these anti-inflammatory materials to design prosthetics that are both comfortable and practical. In recent years, prosthetics have become increasingly user-friendly and responsive

Scientists go to great lengths to make sure prosthetics are safe for daily contact. This can be done using biocompatible materials, which are substances that will not cause toxic reactions, inflammation, or immune rejection [2][3]. This is important in fields like prosthetic creation because these devices are made to be used for periods of time in contact with or inside the body. Biocompatibility will vary from person to person. Specific measures must be taken to see if the individual is able to successfully produce a protein layer between the blood cells and material through a process called protein adsorption. This process allows the human cells to recognize the material as its own and develop the correct tissue or bone to add it to the body more permanently. The type of material used has a direct effect on how quickly and sufficiently the first protein layer develops. If protein adsorption is insufficient or fails altogether, the prosthetic can either not correctly attach to the body or will be encased by a fibrous material produced by the body rather than tissue, ultimately causing instability and pain [4]. In addition, it is important that the patient has no allergic reactions causing inflammation. However, even after these personal factors are considered, not all other materials can be used.

Deciding what materials to use for prosthetics, especially implants, becomes complicated when biocompatibility is taken into consideration. Scientists need to choose materials that are both non-decaying and prevent all negative side effects. These materials commonly include: metals like titanium and cobalt-chromium alloys, which are strong wear-resistant; ceramics like alumina and hydroxyapatite, which are low-friction and bioactive or positively affecting; and polymers like polypropylene and polyethylene, which are flexible and provide cushioning. Engineers use many processes to further improve biocompatibility. Despite the frequent use of metals, they can sometimes release unwanted particles into surrounding tissues. Because of this, ceramic and polymer compounds have been created. Surface coating and texturing are used because it can encourage surrounding tissue to grow and bond with implants in addition to the preliminary protein adsorption. Techniques like material polishing and chemical treatments are also used to prevent other reactions inside the body. Before a biomaterial is introduced in a medical device, it will go through copious amounts of testing. Typically, it involves vitro testing, analytical chemistry, and vivo testing. Vitro testing refers to test tube experiments in which the materials being tested are placed in mimicked environments in the human body. Often, this data will be used in analytics chemistry, which is when material chemical make-up and toxicity are taken into account to predict possible reactions in the use of that material. Vivo testing is usually the last and most controversial step, testing how a material would integrate and be processed by an organism through tests on animals[5].

Once material compatibility has been achieved, prosthetic fabrication involves patient physical compatibility. After an initial consultation has occurred discussing goals and measurements, prosthetists begin to analyze patient movement to determine the necessary mechanics and shape for a prosthetic. Then, once the prosthetic goes into production, a process of fittings and adjustments begins to fine tune the device. Eventually, once the instrument is completed, intermittent follow up appointments are held to ensure that the prosthetic is functioning properly. [6]

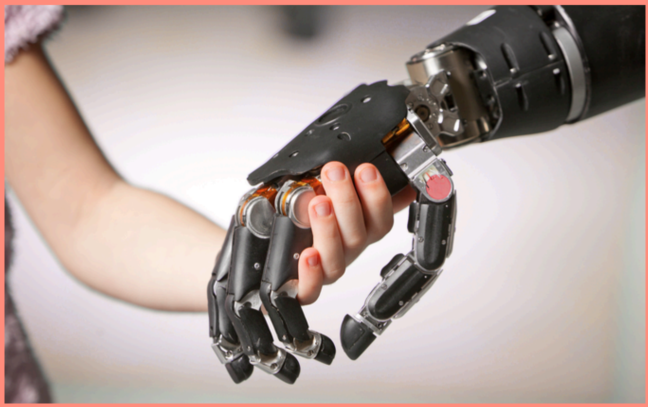


Image: Johns Hopkins Applied Physics Lab

In recent years, there have been significant advancements in prosthetic manufacturing. Some of these developments allow prosthetics limbs to mimic human movements more naturally and to replace manual movements with reactive movements that respond to the individual. One such innovation is myoelectric prosthetics, which uses neurological signals sent to the muscle to control movement automatically when sensed by the electrodes in the prosthetic. Another example is biomimetic prosthetics, which are engineered to replicate natural human movements as closely as possible through algorithms encoding it. These algorithms are usually used in addition to myoelectric functions. Biomimicry could reduce physical usage and improve coordination. Since prosthetics are often permanent, it's especially important for them to work efficiently and effectively. Researchers are also looking to integrate better neural control and AI into prosthetic creation. Neurally controlled prosthetics are connected directly to the nervous system through implanted electrodes, allowing users to control limbs with their thoughts. The incorporation of artificial intelligence into prosthetics will help prosthetics learn and adapt to behavior of the user over time. Pliable materials and touch sensors are also being developed to better prosthetic experiences [7]. Although prosthetics offer many benefits, at this moment, they are extremely expensive. In response to these costs 3D printed prosthetics are slowly being introduced, which will potentially decrease costs and increase the speed of device generation. As it stands, durability and biocompatible, printable materials are still issues in this area of prosthetic modernization [8].

Prosthetics and biocompatible materials are essential parts of biomedical engineering. Through careful material selection and designs, scientists are able to create devices that restore function while also ensuring patient safety and comfort. Technological advancements like neural control, AI integration, and 3D printing will further help restore function. These developments are important because they are not only advancements in science, but they also return autonomy and a sense of normalcy to patients who have lost function of their limbs.

Formatter: ***Claire Hua***

Linguistic Relativity as a Blueprint for Social Engineering

BY: AIDAN SUTPHIN

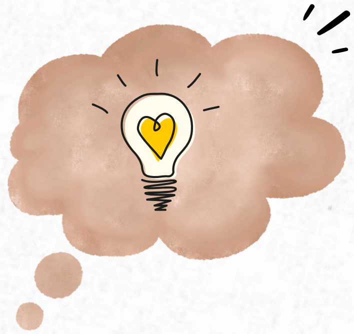
In 1984, George Orwell's renowned novel on totalitarianism, the government of Oceania controls citizen thought using an altered version of English. The state accomplishes this through "Newspeak," which has been altered to avoid thought in opposition to the government, which includes removing words such as justice and democracy [1]. However, just how plausible is it to expect such a language to be successful in its aim of hindering certain thought?

One significant and somewhat controversial principle within the field of cognitive linguistics is the Sapir-Whorf hypothesis, or linguistic relativity, named for linguists Edward Sapir and Benjamin Whorf. It posits that the language that someone speaks influences their perception of the world [2]. This theoretically could appear in a manner such as Newspeak, where removing vocabulary changes thought, or as a different perception of time, colour, etc. Linguistic relativity is often divided into a "weak" form, that language only influences thought, and a "strong" form, also called linguistic determinism, in which concepts not found within the language are practically impossible to conceive of [3]. For example, Whorf described the broad term of snow in English as being "almost unthinkable" to Inuit populations, who "would say that falling snow, slushy snow, and so on, are sensuously and operationally different [4]." Lexical gaps, where one term has a more specific meaning than another (such as specific words for light and dark blue in Russian), could also impact thought. For example, a Russian speaker may therefore be more able to differentiate between light and dark blues.

Much of Whorf's evidence for the theory of linguistic relativity, especially for linguistic determinism, came from his studies of Native American populations, specifically in the Southwest, and most significantly from the Hopi tribe. He understood the Hopi to have a different, cyclical conception of time [4, 5]. Thus, Whorf believed that the Hopi were unable to consider time as linear, as they couldn't express such a thought in their language. In 1983, however, German-American linguist Ekkehart Malotki published Hopi Time, which called this theory into question by suggesting that the language had a distinction between non-future and future [6]. A language's conception of time can be expressed through a variety of means, including metaphors and gesticulation [7]. For the Hopi in particular, this could include metaphors about the cycle of life if Whorf is to be believed, or about the lack of certainty about the future as opposed to the past if Malotki is correct. Malotki presents many metaphors supporting his point in Hopi Time [6], though Whorf was not alive to respond to such claims. The Hopi system of time continues to be disputed in the linguistic community.

Many recent studies have been conducted to test the predictive accuracy of the hypothesis, offering mixed results. For example, number-based tests were conducted with the Pirahã people of Brazil, whose language has no terms for exact quantities. When conducting matching tests with a certain number of objects, researchers found that even despite not having precise numerical terms, they were able to match exact amounts when they were able to compare directly. However, when they were made to remember the number of objects, the results were significantly less accurate. The Pirahã were able to complete tasks like the first with near 100% accuracy, even without exact descriptive language. However, they struggled to remember exact quantities in tests of the second variety, evidence that suggests a weaker Whorfian hypothesis over a stronger variety [8,9].

[Linguistic Relativity] posits that the language that someone speaks influences their perception of the world [2].

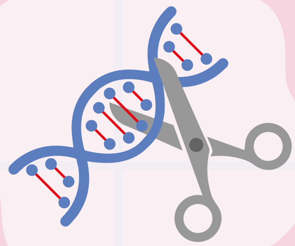


Interesting as the basis behind Newspeak may be, Orwell's language has little empirical grounding. The linguistic determinism the language is based on would not truly hold up in real life, though it is possible it could slightly change the connotations of terms regarding anti-governmental thought.

Formatter: ***Aleena Zhang***

Genetic Engineering in Dental Health

BY: HANNAH CHANG



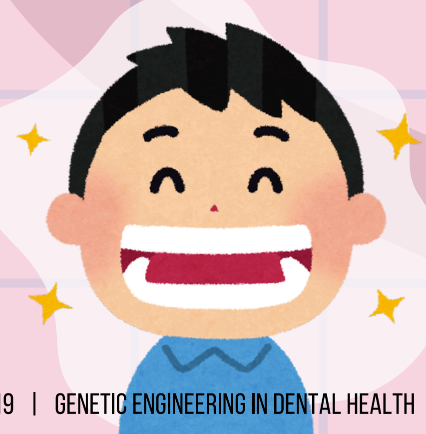
Everyone has genes, which have been passed down from their great-great-great-great grandfather and beyond. Genes, made of DNA, contribute to the unique physical features of each individual, and determine the very way a body functions [1]. Genes influence valued traits such as eye color, body composition, height, etc, but also unwanted traits like diseases [2]. Hence, in the 1960s-70s, Theodore Friedmann and Richard Roblin began their research in gene therapy and engineering to ameliorate genetic diseases [2]. Today, genetic engineering, a process that uses laboratory-based technologies to alter the DNA makeup of an organism, assists in saving lives and serves as a mollifier to health issues. One area where genetic engineering has become increasingly popular in is oral health and dentistry due to recent advancements in diagnostics and preventative innovations [3]. This paves the path for a possible future where expensive surgeries and certain medicines can be avoided entirely [4].

Genetic makeup is a significant factor in determining one's vulnerability to being infected by certain oral diseases [5]. By understanding conditions which are likely to occur in patients with certain genetics, healthcare and dental hygienists are given a key to assist in the prevention of problems through early detection, and resources to facilitate the process.

Cavities, or simply put, tooth decay, are permanent holes in teeth caused by bacteria from the mouth feeding of sugars and starches. These bacteria produce sticky acids called plaque that wear down tooth enamel and damage the gums [6]. People often associate tooth decay with poor oral hygiene and environmental influences, which to a certain degree, is true [5]. For instance, through the practice of brushing teeth twice a day with fluoride, or limiting the amount of sugary foods consumed, one can have a greater chance of protecting their teeth from an overproduction of harmful acidic byproducts made by the bacteria in the mouth [6]. Fluoride can assist in the repair of enamel and minerals, helping prevent tooth decay early on. However, as stated previously, it has been concluded that genes play a critical role in both how susceptible someone is to oral problems, as well as the aesthetics of their teeth and jaw [5]. Diseases like dental caries become a more severe issue for those who have abnormal tooth structure or weak tissue makeup, leading researchers to seek solutions in genetic engineering.

Gene therapy is a type of genetic engineering that can cure genetic dental diseases by targeting the genes responsible for heredity disorders. For example, gene therapy can help correct defects in the KLK4 gene that causes amelogenesis imperfecta, a genetic disorder causing defective tooth enamel formation [3]. Similarly, suicide gene therapy, where a gene encoding a toxin or enzyme is introduced to diseased cells, is used to target oral cancers. In this method, genes like HSV-TK, which convert inactive prodrugs into cytotoxic substances, destroy the DNA of cancer cells. This method is effective due to its format—a precise injection into the tumor or surgical area—as well as the way it performs the bystander effect, killing nearby cancer cells without causing harm to healthy tissue.
Another method of genetic engineering in dental care is regeneration. Regeneration is primarily used to grow the jaw/alveolar bone, since teeth are unable to naturally repair themselves due to their enamel and dentin makeup. Ex vivo or in vivo techniques are often used for patients who suffer from irregular jawbone growth. These include synthetic jawbone transplants or the injection of genetic material to instruct cells to build bone. Dental pulp has a natural ability to regenerate dentin and tooth injuries, but it can be enhanced through gene therapy and stem-cell applications [4].

Although genetic engineering in dentistry indisputably offers hope for beneficial outcomes in dental care and other fields, it is essential to understand its limitations. For instance, ONYX-015, an engineered adenovirus used for the treatment of head and neck cancers, showed limited efficacy in destroying p-53 deficient cancer cells when administered alone [4]. While it did cause cell death within tumors, the effect of it could not be connected in any way to the patient's p-53 genetic mutations, as was expected, implying that a more sufficient design would be needed [4]. Additionally, despite the interests in using gene therapy, bioengineering, and cell sciences for improving dentistry, it is still not practical, as there are a lack of studies on gum disease treatment and repairment. Therefore, future research is still needed to make these approaches more common and reliable therapeutic treatments.



Today, various forms of gene therapy are continuing to improve as researchers explore more ways to integrate it into oral healthcare whilst maintaining ethicality [5]. For instance, not only is suicide gene therapy being practiced in killing cancer cells, researchers are attempting to expand its effectiveness in treating orofacial/chronic oral pain, dry mouth, and even jawbone regeneration [4]. Nanorobotics also holds great potential, as nanorobots could offer even more accurate and efficient solutions to dental problems, as they are primarily used for plaque removal and bacteria destruction as of today [3].

Ultimately, bioengineering in oral health provides great potential to expand beyond just traditional treatments, offering a hopeful future of oral health.

Formatter: ***Emily Kim***

The Mechanics of Oil Extraction

BY: CLAIRE HUA

A steel tower rises from the ocean, surrounded by nothing but billowing waves and sky. Beneath it, a drill cuts through layers of rock that have been sealed underground for millions of years. Oil rigs are not just industrial structures, they are some of the most extreme examples of human engineering, designed to operate under intense pressure and unpredictable conditions. An oil rig is a large structure or vessel used to drill wells, extract crude oil, and harvest natural gas from beneath Earth's surface. Its purpose is to access and draw up oil and gas from reservoirs, processing it through continuous extraction, playing a critical role in providing global energy and supporting economies. By combining physics, mechanical engineering, and fluid science, oil rigs make it possible to safely reach resources buried deep beneath the earth's surface [1].

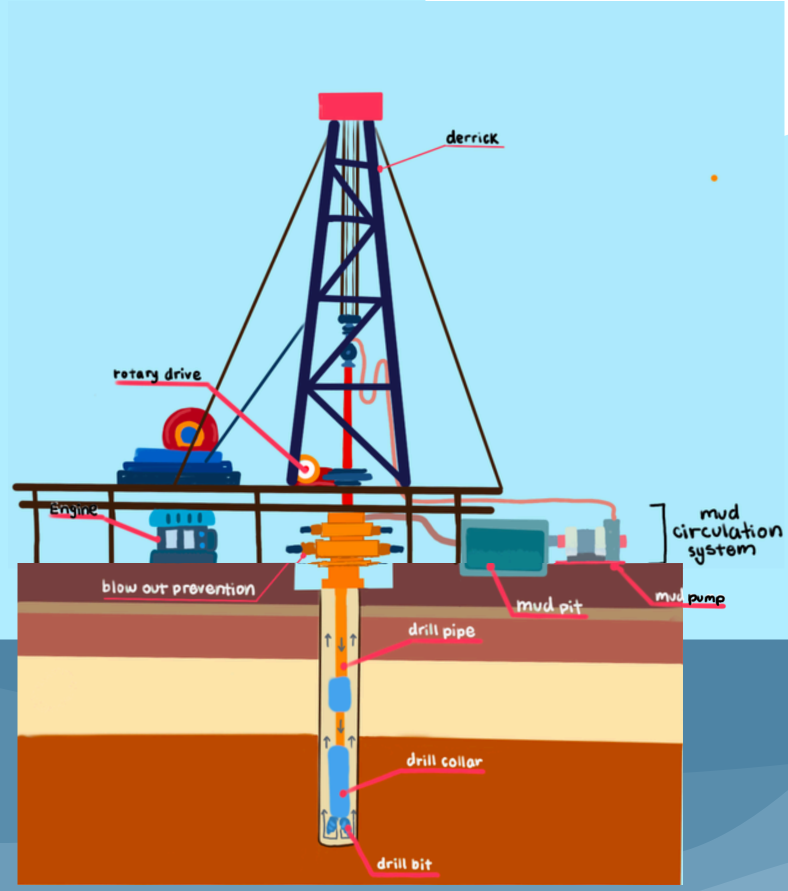
Modern oil drilling began in the mid 1800s when the first successful commercial oil well was drilled by Edwin Drake in Pennsylvania [2]. Since that first well, oil drilling technology has evolved dramatically, transforming simple land based rigs into complex offshore systems capable of operating thousands of feet below the surface. Understanding how these systems work requires examining the major engineering components that allow drilling to occur safely and efficiently.

The most recognizable part of an oil rig is the **derrick**, the tall steel tower above the drilling platform. While it may appear to be the drilling mechanism itself, the derrick's role is to provide vertical support for the drilling equipment. It acts as a rigid steel frame that holds the weight of thousands of feet of steel while guiding machinery in and out of the well. From an engineering standpoint, the derrick works like a specialized crane, using pulleys, cables, and motors to move extremely heavy loads [3]. Some drill strings can weigh hundreds of tons, so the derrick must be strong enough to withstand both the weight of the pipe and the constant motion caused by the drilling and the ocean waves.

The **drill string and drill bit** work together as the principal mechanical system that actually creates the well. The drill string is a long column of connected steel pipes that extends from the rig down into the Earth. It physically links the equipment at the surface to the underground oil and gas reservoirs. Its primary purpose is to transmit rotational force downward from the rig to the drill bit. At the very bottom is the drill bit, which cuts through layers of rock to create the well. Drill bits are engineered to withstand intense heat and pressures over thousands of feet, and typically use rotating cutters or industrial diamonds to break rock apart [4,5].

One of the most important scientific systems of an oil rig is the drilling **mud circulation system**. Drilling mud is a specially designed fluid pumped down through the drill string and back up the well. This system functions as a continuous loop, pumping drilling mud down though the drill string, across the drill bit, and back up the well to the surface. The mud serves several purposes: it cools and lubricates the drill bit, carries broken rock fragments to the surface, and, most importantly, controls pressure inside the well. By applying hydrostatic pressure, the pressure exerted by a fluid at rest due to the force of gravity, increasing proportionally with depth, the mud prevents oil and gas from escaping uncontrollably, which could lead to dangerous blowouts [6].

Similarly, the **blowout preventer (BOP)** is a crucial safety device installed at the top of the well. Its job is to seal the well if pressure becomes too high. The BOP uses powerful hydraulic systems that can clamp around the drill pipe or in some cases even cut through it entirely to stop the flow of oil and gas [6]. This system is essential for preventing accidents and protecting both workers and the environment.



Offshore oil rigs must remain stable in harsh ocean conditions. Engineers use principles of buoyancy, anchoring, and structural balance to keep rigs steady against waves and wind. For example, floating rigs rely on carefully distributed weight and submerged structures to reduce motion, while anchored systems secure the rig to the seabed. At the same time, onboard power systems – usually diesel engines or gas turbines – generate electricity to run pumps, motors, and control systems. Without the crucial support of continuous power, drilling operations would not be possible [7].

Oil rigs function not as isolated machines but many integrated engineering systems in which each component continuously affects the others. The hoisting system positions the drill string while the rotary system applies controlled force to break the rock, but neither can operate independently. As drilling deepens, the circulating system must immediately adjust to the changes in pressure and temperature, while the well control system remains ready to respond promptly to any unstable conditions. All of these operations depend on the rig's power system, which converts chemical energy from the fuel into electrical and mechanical energy that drives motors, pumps, sensors, and control equipment across the entire system. They're also constantly monitored, allowing engineers to respond in real time to changing conditions. Through real time data from sensors throughout the rig, engineers monitor pressure, rotation speed, and mud flow, making constant adjustments to keep the system balanced. Their decisions link mechanical design with human judgment to ensure drilling remains efficient with minimal risk. Together, these interconnected parts enable oil rigs to drill safely, efficiently, and reliably in some of the most extreme environments on Earth.

Formatter: ***Claire Hua***

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