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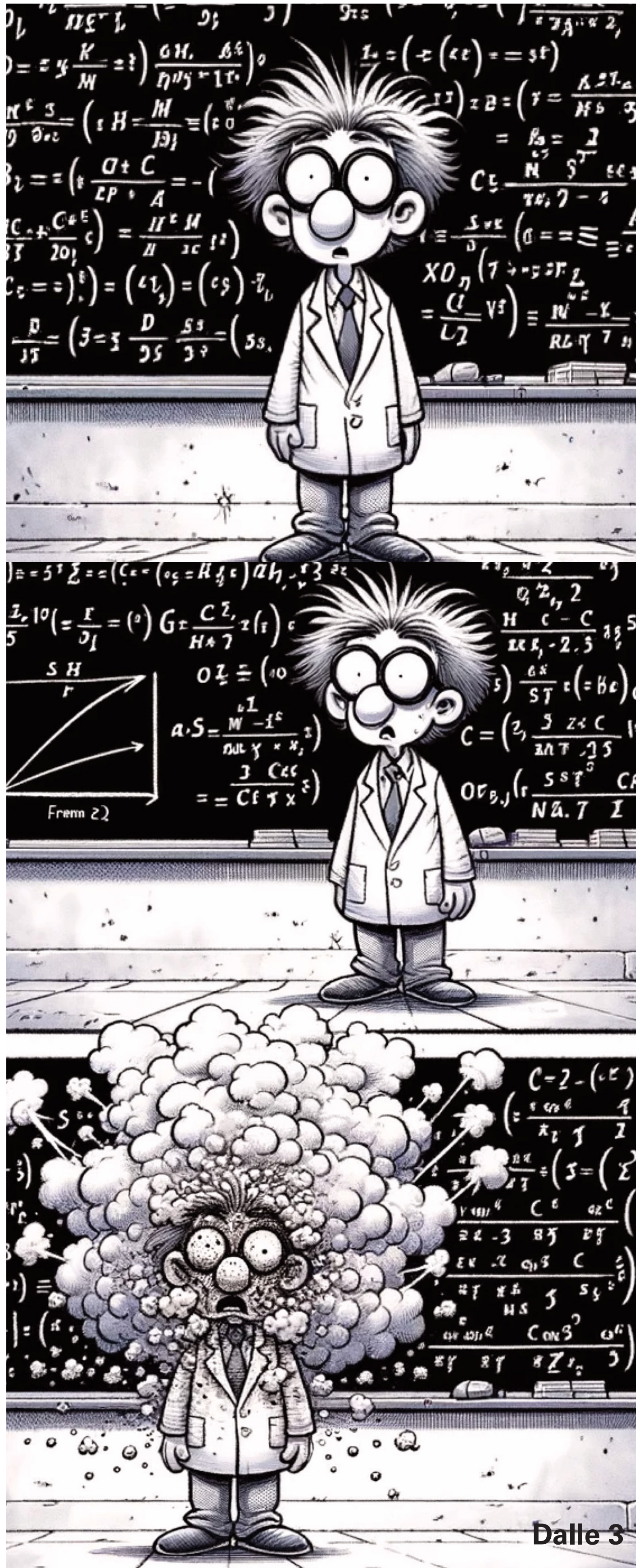

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The Colorado Engineer has been reporting on the "latest and greatest" from the engineering, science and technology community since 1904. We were there for the Model T, the jet engine, the IBM PC, the iPod — and we will continue to cover the future of human innovation. We publish the magazine biannually, with a readership of over 8,000 individuals, reaching students at the university, researchers, professors and alumni. If you would like to join our staff or have questions and comments, email us at cem@colorado.edu. Alternatively, check out our website at http://https://www.colorado.edu/studentgroups/colorado-engineer/. We always enjoy hearing our readers' feedback!

THE DEEP DIVE ISSUE

Dear readers,

My time working with the Colorado Engineer Magazine has given me a deep appreciation for something I only just learned the formal name for: lifelong learning.

That term, introduced in my senior capstone class as part of our professional development, is what I see reflected in all of our staff, who go well beyond treating knowledge as a means, and work so hard to share what they've learned through our publication.

Working for CEM certainly helps lay down a pattern for lifelong learning. This semester in particular, I saw the dedication of our writers, who did in-depth research on a topic of their choice. Each piece will take you on a deep dive into issues ranging from innovations in biotechnology and immunology, the design of coffee, to the problem of modeling human systems.

New to this issue in particular is our use of images and graphics produced by ChatGPT-4. This decision was made with the intent to use this publication to better understand AI through using it. We feel that approaching AI with a curiosity-first mindset allows us to use the emerging technology as a learning opportunity.

Thank you for joining us in the practice of lifelong learning, and I hope you enjoy reading these pieces as much as I have!

Sincerely,

Hannah Sanders
Editor-in-Chief

Our CEM Mission

As staff of the Colorado Engineer, our mission is to inform and educate our readers and reflect pride in CU's College of Engineering & Applied Science worldwide.

Our student-led magazine seeks to provide a voice for CU's engineering students while also carrying on the 119-year CEM tradition: by students for students.

NANOTECHNOLOGY IN PHARMACEUTICAL ENGINEERING :

How is nanotechnology impacting pharmaceutical engineering?

Malena Garcia

In 1959, American physicist and father of nanotechnology, Richard Feynman, introduced the concept of nanoscience at the California Institute of Technology. Fifteen years later, Japanese scientist Norio Taniguchi was the first to coin the term "nanotechnology" in 1974, defining it as "the processing of separation, consolidation and deformation of materials by one atom or one molecule." It is now defined as a branch of technology and engineering that deals with the manipulation of molecules and atoms with tolerances of less than 100 nanometers. Nanotechnology is used in everyday items such as computer motherboards, cosmetics, food, clothing, building materials, and renewable energy products. There are two distinct approaches to manufacturing and generating nanostructures. One method for developing nanotechnology, often referred to as the "top-down" approach, entails the gradual reduction of bulk materials until they attain nano-sized dimensions. This process is similar to a sculptor chiseling a massive block of stone to craft a small and intricately detailed sculpture. In the realm of nanotechnology, the "top-down" approach involves the disintegration of a substantial material chunk into exceedingly minute nanoparticles measuring between 1 and 100 nanometers in scale.The second, "bottom-up" approach involves the building and design of nanostructures starting with an atom-by-atom or molecule-by-molecule method. This approach is analogous to building a car, where screws and wires can be thought of as atoms that are combined to make a larger, functioning system. These two approaches have advanced rapidly in recent years and are used in various everyday applications, including sunscreen and medical devices. Apart from these everyday uses, another facet of nanotechnology has risen from advancements in nano-research called nanooncology. As defined by Hindawi Journals, it involves the application of nanomedicine to cancer diagnosis and treatment. Nanooncology uses nanotechnology to develop new methods for diagnosing and treating cancer. This cutting-edge sector of research has the potential to make an immense impact on cancer treatment.

What makes pharmaceutical nanotechnology so special?

Humans have been using items from their surroundings to treat symptoms and disease for thousands of years. The first officially marketed drug was morphine, first produced around 1800 by German pharmacist Friedrich Serturner, who isolated the narcotic opiate from the poppy plant. The pharmaceutical company Merck went on to market morphine commercially in 1827.

Traditional drug delivery methods like pills (via softgels and capsules) have made significant contributions to medicine; however, pharmaceutical nanotechnology is a new wave of medicine. It is a precise approach that can overcome limitations of conventional methods, particularly in terms of bioavailability.

Bioavailability, as defined by the Oxford Dictionary, is the proportion of a drug that enters the circulation when introduced into the body and is then capable of having an active effect. Essentially,

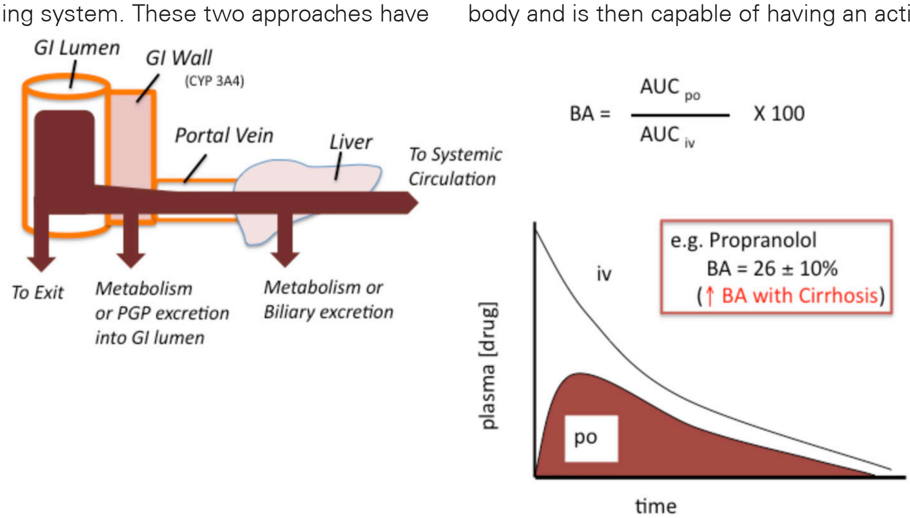
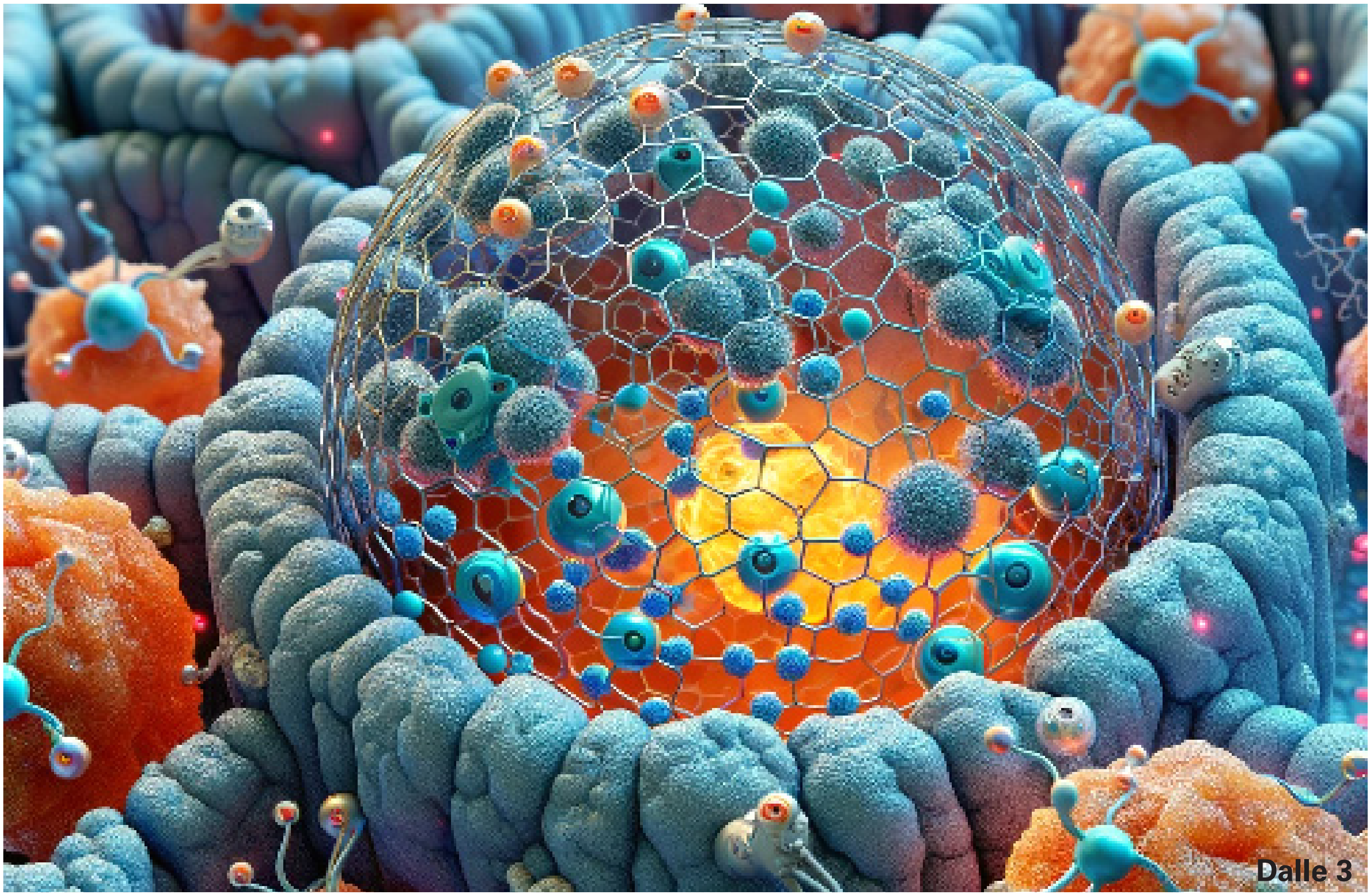


Diagram showing bioavailibility,the fraction absorbed into systemic circulation[1]

[1]**Image Citation:**Tulane University. Bioavailability_the_First_Pass_Effect [Pharmwiki]. bioavailability_the_first_pass_effect [TUSOM | Pharmwiki]. https://tmedweb.tulane.edu/pharmwiki/doku.php/bioavailability_the_first_pass_effect



it is how much of a medicine is actually absorbed in the body when taken. This is where nanotechnology plays a crucial role: the potential to enhance bioavailability, which holds great promise for more effective and precisely targeted drug therapies. Pharmaceutical nanotechnology offers compelling advantages over traditional delivery methods through precise engineering. Working at the scale of one billionth of a meter allows for meticulous control over drug delivery. Scientists can design nanoparticles to transport drugs with extraordinary accuracy to specific targets, such as cancer cells. This precision extends to enhancing bioavailability; by encapsulating drugs within nanoparticles, they are shielded from premature breakdown or excretion, ensuring a higher proportion of the drug reaches its intended destination. This approach additionally permits tailoring drug delivery systems to specific drugs and medical conditions. Companies like Nanoform (a Finnish pharmaceutical manufacturing company) excel in custom nanotechnology. This level of tailoring ensures the efficient and effective administration of drugs. The nanoscale also allows for reduced side effects, because tailored drug delivery minimizes impact on healthy tissues and allows lower medication doses while achieving the same or even superior therapeutic results. This is particularly significant for powerful painkillers and cancer treatments.

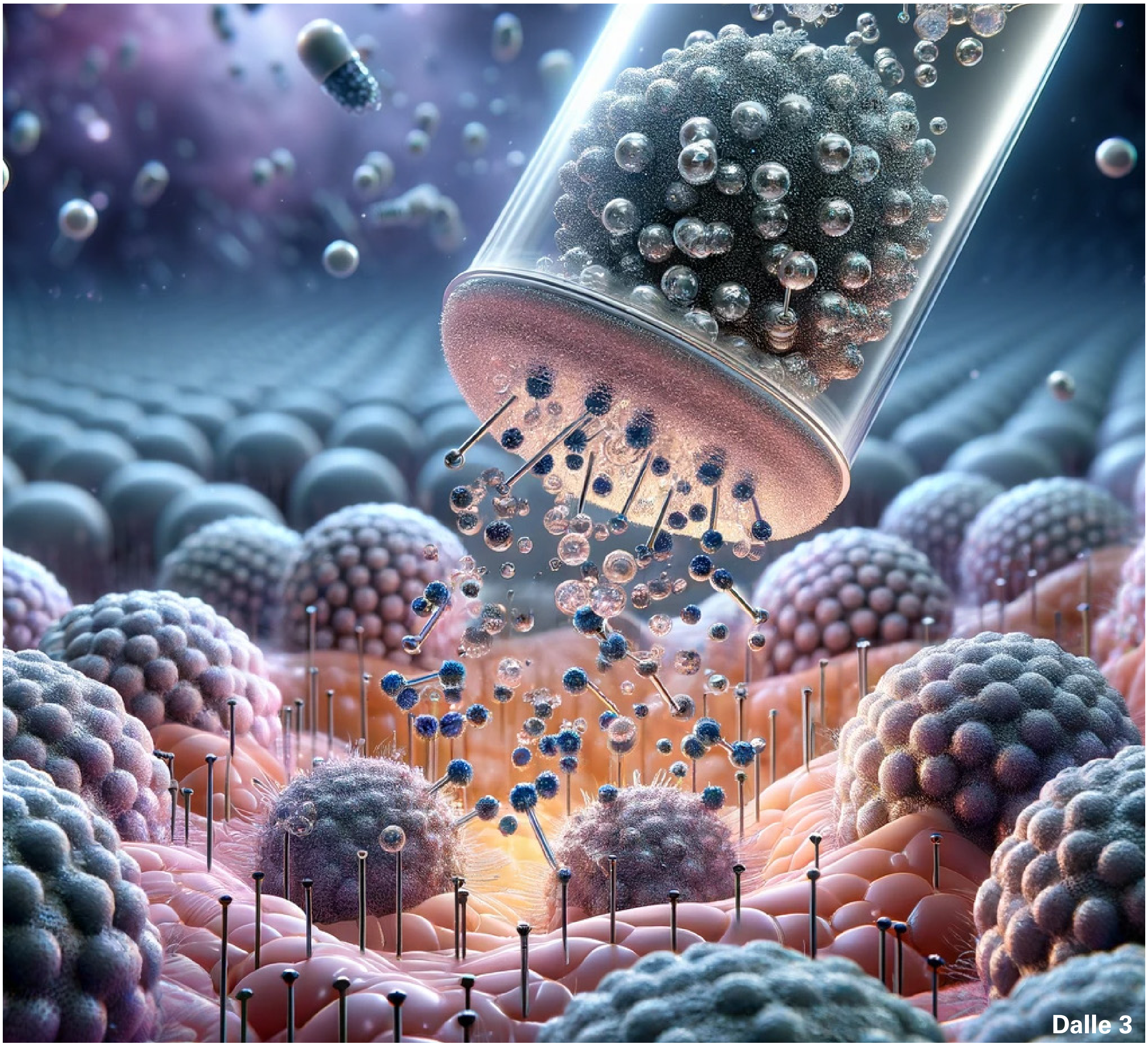
Nanotechnology also paves the way for innovative drug development forms that include the use of nanoparticles, liposomes and micelles which offer diverse ways to deliver drugs and expand treatment options. This opens up new avenues for drug administration, such as inhalation or topical application. As a result, nanotechnology can enhance drug solubility, facilitating passage of a drug through biological membranes and absorption by the body.

The Bioavailability problem:

As previously mentioned, bioavailability refers to how much and how quickly a substance gets absorbed and becomes available for the body to use. High bioavailability means most of it gets used, while low bioavailability means a lot of it goes to waste or passes through without being absorbed. According to ScienceDirect, pH and oxygenation levels in the body as well as other factors contribute to lowered bioavailability when consumed orally. Orally administered drugs must pass through the intestinal wall and circulate through the liver, both of which are sites of metabolism. These sites are where most of the drug gets absorbed before the drug completes whole-body circulation, resulting in a reduced concentration of the active drug. The National Center for Biotechnology defines this as the "first-pass effect." An example of a frequently prescribed medication with limited bioavailability is the powerful Schedule II painkiller morphine. The Drug Enforcement Administration defines Schedule II narcotics as "drug(s) with a high potential for abuse, with use potentially leading to severe psychological or physical dependence." When orally administered in a liquid or tablet form, morphine has a bioavailability of approximately 25%, which means only 25% of the administered dose is actually absorbed by the body. Consequently, the dose of oral morphine given is often 3-5 times more than a morphine injection, resulting in higher cost, an increased risk for addiction, and a harder impact on the body. This is particularly difficult for patients that are unable to consume the drug by other means. Morphine can be orally or intravenously administered, but if the patient is at high risk for a blood infection (e.g. sepsis), it is safer to administer the drug orally. This route is less risky because the stomach acid could kill any bacteria or viruses on it, although the bioavailability is lessened. This problem aligns with Nanoform's mission to solve the problem of bioavailability by using their technology to allow higher levels of the drug to be absorbed into the body. This difficulty is not exclusive to morphine. Chemotherapy drugs, critical in cancer treatment, confront a set of formidable impediments as well. One such impediment concerns the size and type of molecules involved. As noted in the Journal of Nanobiotechnology, chemotherapy drugs, often administered orally, tend to consist of large molecules. While oral drug delivery is suitable for small-molecule treatments, it proves less effective for chemotherapy drugs due to their substantial size. Additionally, solubility issues further complicate matters. Chemotherapy drugs exhibit low solubility, impeding their dissolution in the stomach or intestine. Furthermore, the biological barriers present within the digestive tract diminish the amount of drug that successfully enters the body. Enzymes and transporters in the body form yet another roadblock, due to their tendency of breaking down or obstructing the absorption of chemotherapy drugs, thereby further decreasing their bioavailability. These multifaceted challenges collectively underscore the pressing need for innovative solutions in drug delivery and formulation for the effective treatment of cancer. For perspective, a common pain reliever like Tylenol has a bioavailability of 79%. Chemotherapy drugs frequently have extremely low bioavailability, often between 0.1% and 1% of the given dose. Increasing the bioavailability of chemotherapy drugs could have monumental benefits. Patients could take less toxic drugs which would reduce side effects and the overall cost of treatment. The implementation of nanotechnology into these drugs could also improve the chances of patients recovering from cancer.

Applications of pharmaceutical nanotechnology: Oncology

Pharmaceutical nanotechnology, particularly within the realm of oncology, holds the promise of several remarkable advantages. One such benefit is the mitigation of systemic toxicity, achieved by employing nanoparticles for targeted delivery of cancer treatments. This precise targeting allows for the direct intervention of a drug at the tumor site, effectively minimizing the adverse side effects typically associated with chemotherapy. The use of nanoparticles also extends its advantages to surgical resection: the surgical removal of part or all of a tissue or organ. Surgeons can harness these minuscule carriers to enhance the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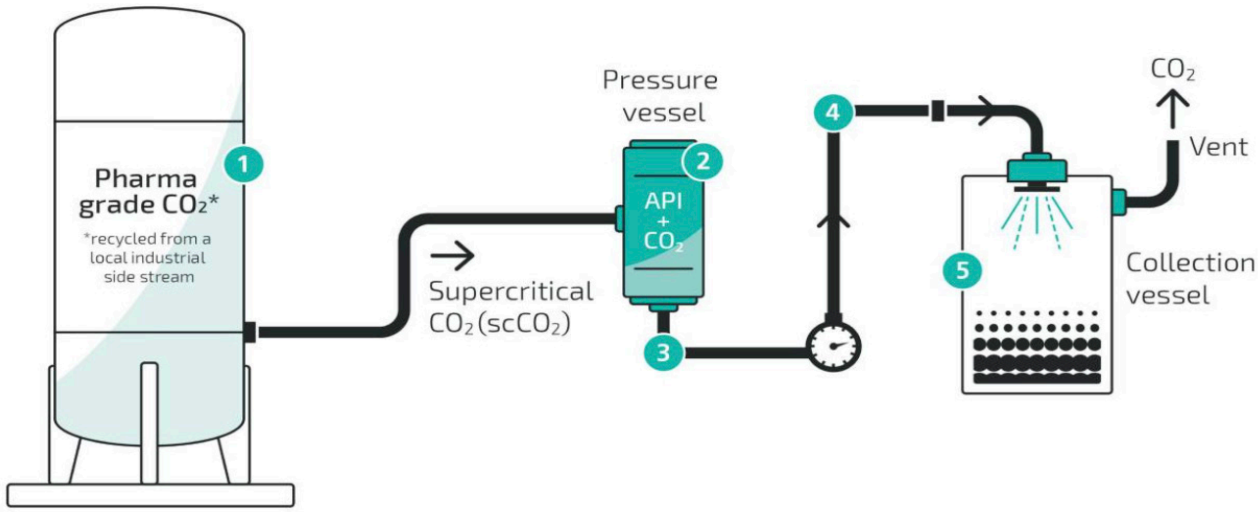


A graphic that shows the process behind Nanoform's CESS technology.[2]

precision of tumor localization and removal, consequently elevating the success rates of surgical procedures. Nanoparticles can also enhance the effectiveness of radiation-based treatments. They can be used to focus radiation on the tumor, sparing surrounding, healthy tissues while delivering its potency directly to the tumor. Nanotechnology in oncology also offers the advantage of a selective drug release mechanism. Facilitated by nanoparticles' size and specific targeting capabilities, the selective drug release enables controlled and localized drug administration at the tumor site, enhancing therapeutic effects while reducing the necessity for systemic drug delivery. Factors such as pH, heat, ultrasound, and specific chemicals can serve as triggers for drug release, guaranteeing that the right dosage is delivered precisely when and where it is needed, pioneering a new era of personalized and effective cancer treatment. Pharmaceutical nanotechnology in oncology offers a promising way to make cancer treatment more effective and less toxic to the patient's overall health. By harnessing the unique capabilities of nanoparticles, medical professionals can target tumors more precisely and deliver therapies in a way that minimizes damage to healthy tissues. This can lead to better outcomes for cancer patients while reducing the side effects commonly associated with chemotherapy. One such application in oncology is the use of nanoparticles to improve drug bioavailabilities.

Nanoform's CESS nanotechnology:

Nanoform, a Finnish company founded in 2006, has been conducting ground-breaking research in pharmaceutical manufacturing to ensure that every tiny particle and molecule in a drug formulation can be absorbed by the body. Their research opens up new delivery methods like nasal sprays or inhalation for drugs that weren't available before.

One notable breakthrough developed by Nanoform is the Controlled Expansion of Supercritical Solutions (CESS). CESS offers a range of advantages, including precise control over particle size, morphology (shape), and polymorphism (change of shape), effectively optimizing the form of a drug's active ingredient. This innovative formulation process not only addresses bioavailability issues, but also provides several other significant benefits. For instance, it results in reduced drug manufacturing requirements, as the drug becomes more efficiently absorbed, thus lowering production costs. On top of that, CESS also enables tailored drug release, ensuring that the drug is administered in a controlled manner for maximum effectiveness.

Moreover, Nanoform's technology can eliminate the "food effect," a phenomenon where some drugs exhibit varying effects depending on whether they are taken with or without food, thereby ensuring consistent performance. CESS also has the ability to create nanoclusters of drug particles with precise sizes, particularly valuable for medications like inhalers, where precise particle size is crucial for effective delivery. As Nanoform's CESS innovation addresses bioavailability challenges, it also revolutionizes drug manufacturing by reducing costs.

Nanoform's approach to the problem of low bioavailability is not only to improve the physiological impact of drugs in the body but also to offer economic and practical advantages that benefit both patients and the pharmaceutical industry.

Ultimately, the combination of nanotechnology and oncology presents a groundbreaking frontier in the realm of drug delivery and cancer treatment. From its conceptualization in 1950 to the present day, nanotechnology has given rise to a versatile field that finds applications in everyday products and medical advancements. This type of precise technology promises to alleviate bioavailability issues, minimize side effects, lower medication doses and open up new avenues for drug administration.

The emergence of pharmaceutical nanotechnology represents a revolutionary step forward, addressing age-old challenges in drug delivery and bioavailability. With continuous studies, developments and nanotechnological innovations like Nanoform's CESS technology, the pharmaceutical industry is on the cusp of a new era of drug delivery, one that holds great promise for both patients and the healthcare field.

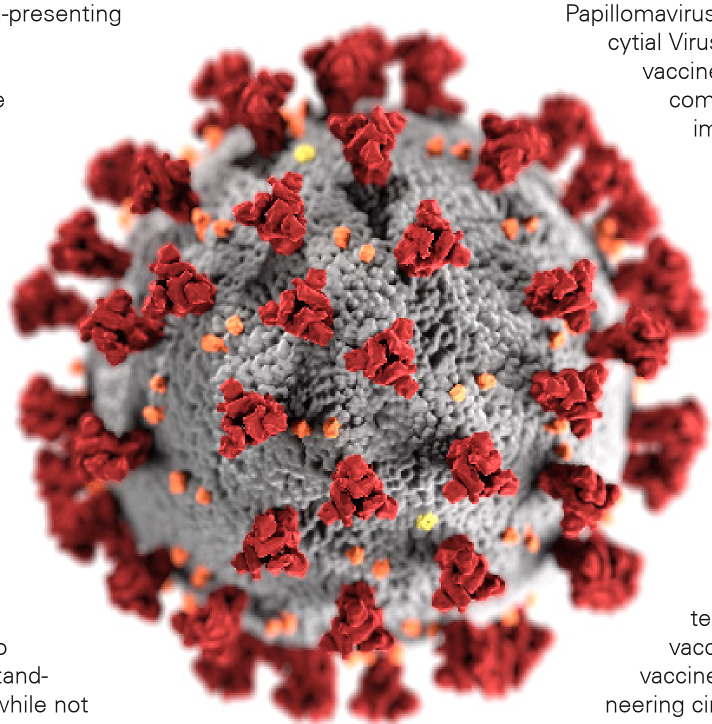
[2]**Image Citation:** Nanoform: Small is Powerful. (2023, July 25). Controlled expansion of Supercritical Solutions (CESS®) technology.

VACCINES AND HUMAN IMMUNOLOGY:

History, current trends, and future prospects

Aidan Magruder

Immunology, the study of human immune response to infection or allergens, has seen an increased level of attention through the COVID-19 pandemic. Like most other biological sciences, this field is a particularly young. Early immunology primarily focused on preventing diseases like cholera or diphtheria through hygienic practices and germ theory. While this approach helped save lives, the field did not find its footing in microbiology and molecular biology until the 1960s and 70s. The initial breakthrough in immunological research was the discovery of various types of cells in the body working together to generate an immune response. This discovery was later refined by the discovery of T-cells (thymus-produced cells), B-cells (bone marrow-produced cells), and antigen-presenting cells (APC).



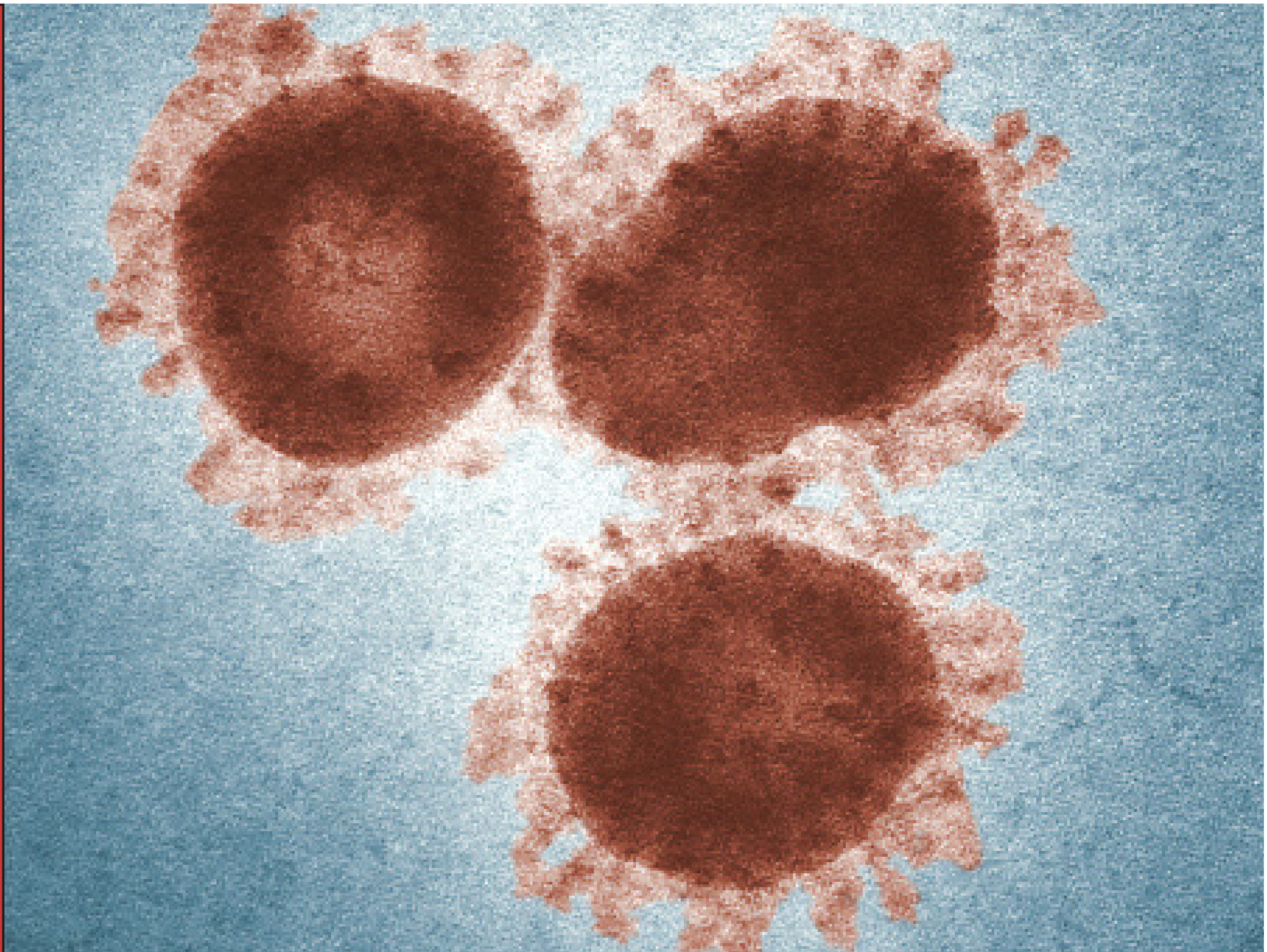
These cells form the backbone of the human immune response through their production of antibodies, as well as their ability to attack infectious bacteria or viruses directly. More recent developments in immunology have come from a deeper understanding of molecular biology. These developments included techniques for cloning and reproducing important antibody-forming cells (AFCs), separating immune cells for research use, and isolation of complementary DNA, or DNA that corresponds to specific proteins found within antibodies. These developments have pushed the field of immunological science to the place we see today. Our understanding of the human immune system, while not complete, allows us to fight diseases that affect people from the smallest to largest populations.

This development of immunological science is deeply interlinked with the development of vaccines. The primary goal of early immunologists, such as Edward Jenner and Louis Pasteur, was to create various means of preventing disease through immunization of humans and animals using live virulent or bacterial factors. The first vaccines, and most vaccines up until recent history, use a modified or similar, less harmful, viral/bacterial vector to build an immune response to the more harmful form of the disease. Vaccine development found its footing near the middle of the 20th century. During this time, demand to eliminate diseases that had been harming millions of people each year was high, thus scientists began to develop modified vectors to immunize people against them. This type of vaccination led to the elimination of diseases like smallpox, as well as the near elimination of polio.

Near the beginning of the 21st century, the development of polysaccharide and DNA-recombinant vaccines marked a major breakthrough in fighting preventable diseases such as Human Papillomavirus (HPV) and Respiratory Syncytial Virus (RSV). The polysaccharide vaccine, developed before the DNA-recombinant vaccine, trains the immune system by introducing specific types of sugars found on the cell coating of the bacteria the patient is being treated for. This introduces the AFCs, T-cells, and B-cells, to a specific part of the bacteria, so that the immune system can seek and destroy the bacteria when it enters the body. This type of vaccination provides robust protection against the bacteria the vaccine mimics.

This differs from the technique the DNA-recombinant vaccine utilizes. DNA-recombinant vaccines involve genetically engineering circular pieces of DNA called plasmids, which infiltrate the human cell and cause an immune response through the production of bacterial or viral proteins. The proteins are used by the T-cells and B-cells to create antibodies marked by the specific proteins to provide a more complete immune response to the diseases. This provides especially effective protection against slowly mutating DNA viruses and bacteria.

Aaron Eli Glatt, MD, chair of medicine at Mount Sinai South Nassau in New York, said these results demonstrate that SARS-CoV-2 is "clearly capable" of contaminating bathroom sinks and toilets.



Digitally colorized electron microscope image of four human coronavirus 229E, members of the Coronaviridae family. The characteristic corona envelope, derived from the cells of the hosts, can clearly be seen in this image. [3]

However, as globalization advances and the risk of pandemic becomes greater and greater, DNA-recombinant vaccines have proven less useful as rapidly mutating RNA viruses, such as COVID-19, become the prominent concern for rapid global spread. This made the development of mRNA vaccines more prevalent and in higher demand. MRNA technology utilizes messenger RNA, a single-stranded genetic material, to infiltrate human cells which then produce identifiable proteins of the virus being immunized. These proteins are then released from the cell into the bloodstream where the immune response begins to recognize and attack those proteins. This places the protein and thus the virus into the memory of the immune system, which then fights the virus more effectively when the virus infects the immunized person. MRNA vaccines do not guarantee immunity like other types of vaccines, but they do provide a large amount of protection against damaging side effects of the viruses they immunize against.

COVID-19 had a profound impact on commercial vaccine research. The novel virus set major pharmaceutical companies on an accelerated path toward a solution for the drastic health and economic outcomes. While major pharmaceuticals focused on the global pandemic, many public laboratories, especially those at universities, restarted their work on various methods to develop new and more effective vaccines to combat highly mutable viruses such as HIV. The Rationally Designed Immunotherapeutics & Interfaces (RDI) group here at CU Boulder was one such lab. Headed by Dr. Kayla Sprenger, the RDI group focuses on developing technology to best combat highly mutable viruses by analyzing machine-learning models of antibody evolution when responding to specific infections. Through this research, the group also aims to develop a greater understanding of human antibodies and the processes that take place when dealing with virulent diseases. Focusing on HIV, a disease that is incredibly hard to treat due to its mutable nature, brings challenges to creating a vaccine that is able to prevent HIV from embedding itself in the DNA of its host. Because the body is not very adept at recognizing HIV,it can take a long time for an immune response to occur, which is why modeling proteins and antibodies to detect HIV is such an important step for vaccine development.

As the RDI group continues its work, it joins a great number of academic research groups in the search for new vaccine technologies to better prepare our human immune systems to face the growing world of diseases. Our grasp of human immunology and how to integrate new biotechnologies to fight disease continues to grow each day, thanks to incredible breakthroughs.

[3]**Image citation:** Centers for Disease Control and PRevention, Murphy, F. & Whitfield, S. (1975). Public Health Image Library ID 15523

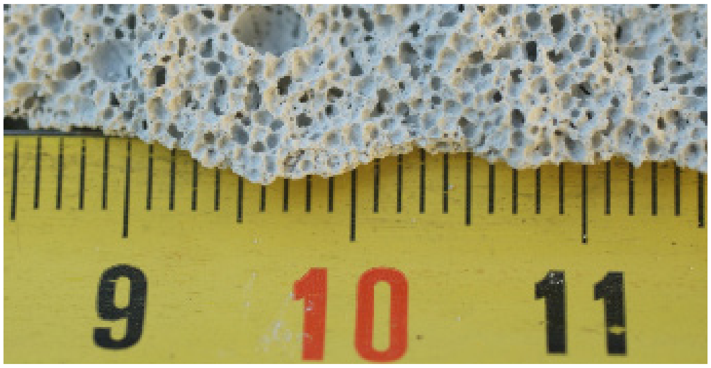
WHEN CONCRETE GOES WRONG:

The RAAC crisis and why it is failing

David Brennan

From the Coliseum of ancient Rome to the skyscrapers of today, concrete has been a staple of the great constructions engineers have made possible for thousands of years. While exact compositions vary, this mixture of cement, sand, gravel, water, and air is so ubiquitous that it has become the most widely used construction material worldwide with more than 2.2 billion tons of it produced annually. The material is so ingrained in our lives and our modern world that it has even entered our lexicon, referring to something that is real and dependable. The buildings we live and work in and the roads we travel on are typically made of concrete. In the vast majority of cases, concrete has proven itself to be a reliable and trustworthy material, and in the hands of the right engineer it can be used to create something breathtaking. However, in the rare instance it fails, the impacts are catastrophic.

Over the thousands of years that concrete has been in use, the formula has been altered and reevaluated, with new kinds being introduced for different purposes. One particular kind of concrete is called reinforced autoclaved aerated concrete, or RAAC. RAAC was first invented in Sweden in the 1930s, and gained popularity in the 1950s. It is made by creating a slurry or mixture of cement, lime, finely ground sand, fly ash, and water. Aluminum powder is then added to the slurry, which acts as an expansion agent, and the slurry is allowed to set. As it sets, the slurry reacts with the aluminum powder, expanding the material and creating air bubbles. After it is done setting, the mixture is baked in a machine called an autoclave. The resultant concrete is 80% air, making it lightweight and cheaper to produce than traditional concrete. Additionally, it has significant fire-resistant properties and is an excellent insulator.



A close up of reinforced auoclaved aerated concrete[4]

One may ask why an architect would choose anything other than RAAC. After all, a cost effective material that offers the same structural integrity as regular concrete seems like a no-brainer for a responsible and efficient engineer. And in many cases, it was. Beginning in the 1950s, RAAC gained immense popularity as a cheap and effective concrete for a variety of constructions. Its flame-resistance and light weight made it ideal for things like roofs and walls, as it reduced the total load on the structure and made it safer in case of emergency. It was particularly in vogue in the United Kingdom where it was commonly used to construct roofs, floors, and walls up until the 1990s. It was particularly popular in the public sector, and used in the construction of buildings like schools and hospitals. For a while, it seemed like a great addition to the structural engineer's toolbox.

However, before long, some cracks began to appear. In 1996, the British government issued a report about excessive deflection and cracking in RAAC roof planks that were installed before 1980. The report stated that there wasn't yet enough evidence to say that there was a significant safety hazard in buildings with RAAC, but it did recommend that RAAC be phased out of use in new constructions. This was followed by a report in 1999 by the British government's Standing Committee on Structural Safety, which recommended that buildings with RAAC roofs that were installed before 1980 schedule inspections, but also stated that "generally the deterioration of RAAC planks may not jeopardise structural safety". Discussion over the safety of RAAC began to die down, as it wasn't being used in any new constructions and the available information at the time suggested to communities that the concrete was of no real concern. It was not until 2018 that things came crashing down.

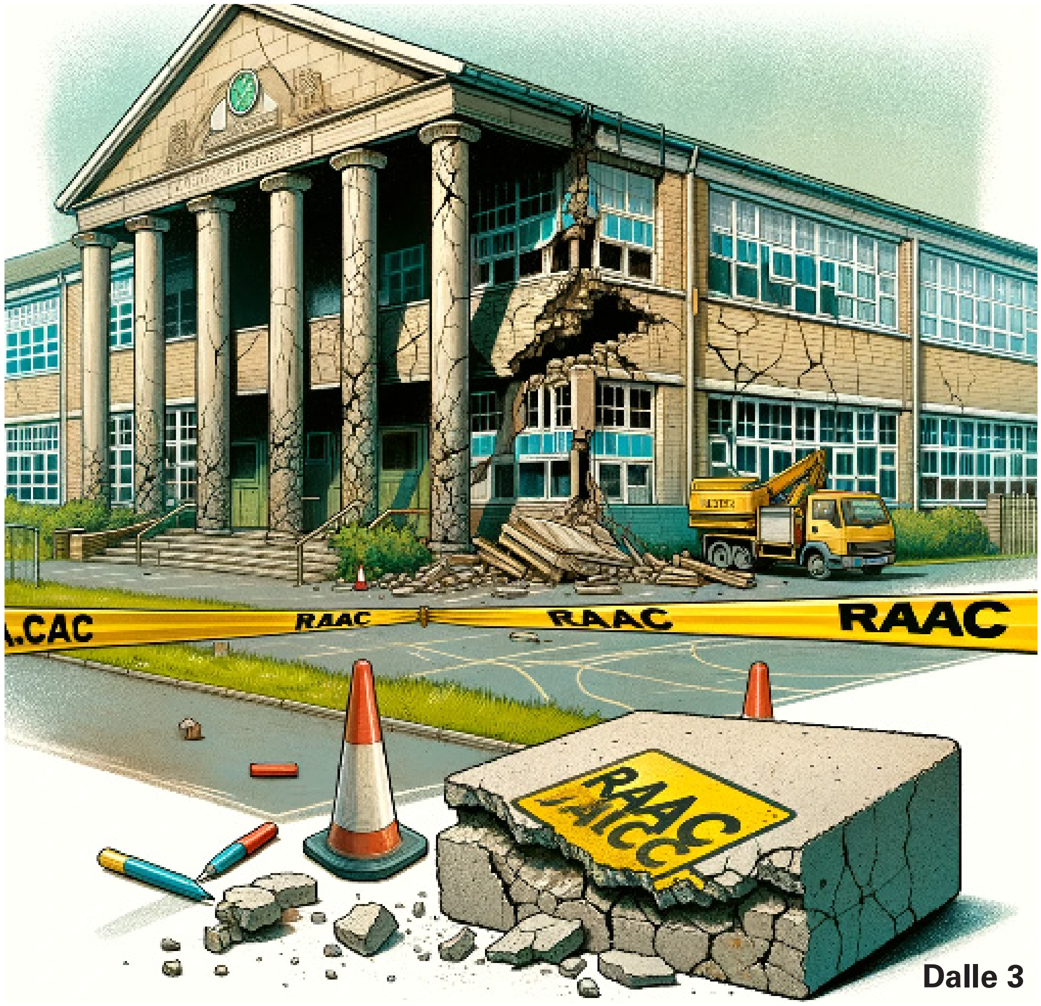
In June of 2018, the roof of a primary school in Gravesend, Kent, partially collapsed. Thankfully it was a Saturday, and nobody was injured or killed, but the potential danger of a collapsing roof is obvious. What made this collapse especially concerning was what happened before the collapse. Typically, a roof that is failing will show signs of that failure long before an actual collapse occurs. In this case, there was almost no warning of structural insecurity, with the only signs of stress appearing the day before the building collapsed. The structure went from appearing completely sound to collapsing over the span of a single day, something that is not supposed to happen with concrete. With standard concrete, one can expect to see cracks, unevening, and a weathered appearance well before failure, all of which will increase in severity as the concrete weakens. This school's roof had none of those signs. The roof that collapsed was found to have been made out of RAAC that was installed in 1979, and it showed that RAAC would fail without any warning. Although engineers were aware of flaws of the concrete that led to deflection and deterioration, they were under the working assumption that structures made with RAAC would show signs of deterioration so that they could be repaired before catastrophic failure could occur. This was not the case, and it meant that any building made out of RAAC could fail without any warning.

There are several reasons why RAAC was not as strong and durable as it once seemed. One is its response to moisture. The inside of the concrete is mostly made up of air bubbles, which makes it easier for water to get into and corrode the interior.

[4]**Image Citation:** Bernardini, M. (2009). Macro detail of aerated auoclaved concrete. CC By-SA 3.0

Another issue has to do with the composition of the concrete, specifically the lack of coarse aggregates such as gravel or other materials made of larger particles. RAAC is composed of fine aggregates, like the finely ground sand, which makes the bond between the actual concrete and the rebar used to reinforce it much weaker. The most important issue has to do with the material's elasticity. While concrete is generally a brittle material, there is a range to how brittle it actually is. Standard concrete will visibly deflect before it fails, allowing it to be fixed, but RAAC is so brittle that even when it is under great stress and it is near failure, it will appear as if it were perfectly sound.

Despite the collapse in 2018, concern over RAAC was still relatively limited. One collapse could just be a fluke. However, it was quickly proven that the collapse was no fluke. In November of 2021, a roof collapsed on 15 students and a teacher in South London, all of whom were injured. Another roof collapsed in July of 2023. All of these collapses had little to no warning.



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Once it was revealed that RAAC would fail without warning, an immense public safety hazard became clear. In August of 2023, the UK Government's Health and Safety Executive announced that "RAAC is now life-expired. It is liable to collapse with little or no notice". This concrete, which was nearing its life span, was present in hundreds of buildings, often public buildings like schools and hospitals, all of which could be at risk of imminent collapse. In September of this year, hundreds of schools were confirmed to have RAAC, and over fifty of them were deemed to be in danger of a sudden collapse. Thousands of more schools are yet to be checked. At least seven hospitals containing RAAC need to and have yet to be rebuilt. It has even been found in the Houses of Parliament. The true number of buildings containing RAAC is impossible to know, but it is likely in the many thousands, and many of them are at risk of collapse.

Although this is still a developing crisis, measures have been taken to try and prevent disaster. The buildings that have been deemed to be at the highest risk of collapse have been closed. In the case of school closures, students are being taught at alternate locations or remotely. In many cases, sections of buildings that are at a higher risk of collapse are closed off, while the rest of the building stays open. Around £700 million ($860 million) has been allocated to the UK's National Health Service to be put towards remediation and failsafe measures in public health buildings affected by RAAC. Costs to fix, replace, and strengthen schools with RAAC will come out of the UK's Department of Education budget. Private owners of buildings have been encouraged to inspect their buildings for RAAC and to take adequate measures to ensure the stability of their property. While the danger is still present, significant measures have been taken to prevent any more collapses that could cause injury or loss of life.

This entire crisis, however, raises an interesting question: why is this concrete—and seemingly all modern concrete—failing relatively quickly, when there are concrete buildings built thousands of years ago that still stand today? Indeed, the Romans, perhaps the greatest innovators in the history of concrete, built many structures out of concrete that are still standing out in the open thousands of years later. In fact, implementing aspects of the Romans' concrete may help us avoid crises like the RAAC crises we are facing now.

The key to what made Roman concrete so strong is volcanic ash. While modern concrete also uses lime, the Romans mixed theirs with volcanic ash. The ash contains aluminosilicates, which reacts with the lime to create a calcium aluminosilicate material which binds the concrete together. This makes the concrete stronger. What is especially interesting about this volcanic ash, however, is that it also allows the concrete to repair itself. When moisture enters the concrete, water dissolves some of the remaining ash, which then crystallizes. These crystallizations fill in the cracks that are left by the water, essentially healing the concrete. Modern engineers have been attempting to use this phenomenon and apply it to modern concrete. One interesting possibility is using bacteria to regrow concrete that has been cracked by moisture. By placing dried-out bacterial spores in concrete, the bacteria could lay dormant within the interior of the concrete until moisture reaches the bacteria, at which point it germinates and generates the material that will fill the crack. By looking back at the innovations of the engineers that came before us, we can make sure that our knowledge doesn't set and solidify, allowing us to better solve the problems of today and create a better future.

THE PERFECT CUP OF COFFEE :

An educational journey where students discover the art of merging engineering and artisanal craftsmanship to get the perfect cup of coffee

Skylar Edwards

For countless students, coffee is not just a beverage; it's their daily savior. Whether you brew it at home or make a trip to your favorite coffee shop, all it takes is your preferred coffee bean blend, perhaps a touch of milk and sugar, and you're ready to conquer the day.

What some may not realize is that there's a science behind crafting the perfect cup of coffee. In fact, you might be surprised to learn that making the perfect cup involves a delicate balance of art and engineering principles.

For those with a passion for both coffee and engineering, an exciting opportunity awaits in MCEN 4228/5228: Design of Coffee, taught by Professor Carmen Pacheco-Borden. This unique class is exclusively available to mechanical engineering students at the junior, senior, and graduate levels at CU Boulder. It draws inspiration from a program initiated at UC Davis, enabling students to apply their existing engineering expertise to challenges beyond the conventional engineering realm, such as the art of roasting and brewing coffee.

Sam Gluskoter, a former student and now a teaching assistant for the class, shares his perspective:

> **"I first heard about the 'Design of Coffee' class through students talking, and I was intrigued. I wasn't quite sure what 'design of coffee' meant, but I was astounded by the complexity that goes into crafting a single cup of coffee. It made me appreciate the engineering side of food, especially the meticulous process of coffee preparation."**

In this class, engineering principles are at the heart of coffee design, optimizing the brewing process. Students apply principles like heat transfer, mass transfer, thermodynamics, materials science, sustainability, water quality, biomedical engineering, and device design evaluation to perfect their coffee-making process. It's an opportunity to blend the love of coffee with the precision of engineering, creating a brew that's not only delicious but also sustainable.

Each week begins with a lecture delving into distinct engineering principles, exploring their intertwining with the world of coffee production. The semester commences with a study of coffee production, encompassing global sourcing, farming practices, and the science behind coffee production. There are also weekly


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hands-on lab components that allow students to experiment with these principles and the coffee brewing process. They explore various roasting methods, including using popcorn makers, and investigate different brewing options such as French presses, drippers, and AeroPress machines, all of which impact the flavor and potency of the coffee. Along with that, there are more engineering skill techniques that delve into thermal management, water flow control, material science, and more. And yes, you get to taste the results of your experiments.

In addition, students have the opportunity to visit local companies and hear from guest speakers who are experts in both coffee and engineering. Sam says,

> **"Some of the most memorable moments have included guest lectures, visits to a Denver roastery where we observed the art of roasting, and the revelation of the coffee taster's flavor wheel. Additionally, conducting particle analysis on coffee grounds opened my eyes to the scientific precision involved in coffee brewing. It made me wonder about the feasibility of creating a coffee-making machine from scratch."**

The course currently also collaborates with local coffee shops like OZO Coffee, where they get pre-roasted coffee beans. This is a great experience as students witness the roasting and brewing process, learning industry best practices.

As the semester draws to a close, the course culminates in an exciting competition. Student teams compete to craft the most delicious coffee while minimizing energy consumption, fine-tuning the brewing process. There is a lot of thought that goes into the making of coffee: selecting coffee beans that meet specific taste and quality criteria, considering factors like origin and processing, choosing roasting methods to highlight the bean's unique characteristics, and tailoring brewing techniques to bring out the best flavors, balancing factors like grind size, water temperature, and brewing time. It's a thrilling challenge that combines the art and science of coffee making with engineering innovation, and the results are often as invigorating as that first sip of morning brew. The judging process is done through a blind taste test.

The class has seen remarkable growth in recent years, becoming increasingly popular among students. Sam says, "The multidisciplinary nature of the course has broadened my perspective on food and engineering in general." To meet the growing demand, the university has expanded the number of sections available, enabling more students to participate. Furthermore, the success of this class has sparked the creation of additional food engineering courses, offering students a broader array of opportunities to explore the captivating intersection of engineering and culinary arts. This course opens the doors for more than just learning how to make the best cup of coffee but also to think about the food world from a different perspective—an engineering perspective and a greater appreciation.

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EDUCATING ETHICAL ENGINEERS:

Dr. Finelli's ethics modules reshape engineering education

Hannah Sanders

The Herbst Program held their third Moulakis lecture series in October, bringing Dr. Cynthia Finelli of the University of Michigan to speak on her work in Engineering Education UResearch. The lecture series, aimed at inspiring students to understand the unique opportunity engineers today have to shape a better world, allows students to hear from experts in engineering ethics and engage in meaningful dialogue through a Q&A session after the lecture.

Dr. Finelli described through her lecture a new approach of teaching engineering ethics through modules integrated into a circuits class. The first module, which teaches students about capacitors, includes information about Tantalum, the primary material used to make capacitors today. The tantalum used in electronics is primarily mined in the Democratic Republic of the Congo. Tantalum is one of many so-called "conflict minerals", because the demand for them incites or worsens conflicts in the countries where they are being extracted. For electrical engineers, it is easy to get lost in the details of how to build a circuit, but by tying it back to the material make-up of capacitors, students are pushed to consider the role their design choices have in the unethical sourcing of minerals.

Another module developed by Dr. Finelli and her colleagues introduce students to the concept of a circular economy through a lesson plan about voltage dividers. In simple circuits, including a voltage divider reduces battery life. By making the connection between the design of circuits and the life cycle of design components, students go deeper to consider how their work can negatively impact the environment.

These modules developed by Finelli's work are a successful approach because they are seamlessly integrated into core engineering curriculum, and require no additional training for the faculty teaching the course. Making ethics curriculum easy to teach means that it won't get neglected in case of lack of resources or staff. Further, this approach is better for students, who often have their humanities learning outsourced to another department.

"We have found in our research that a standalone humanities program, or any kind of stand alone course where you send your students in engineering to someplace else to learn the material… the students see that it's a separate piece. So by being embedded, students see that it's important, and that it has equal stature to engineering," said Finelli.

The module approach turns this problem into a solution: if the existing engineering curriculum prioritizes technical courses, then by inserting ethics conversations into foundational coursework, students see that ethics is not a course requirement, but touches everything they do.

This approach to ethics education is more important now than ever. Engineers today must learn how to design for a world with challenges like infrastructure resiliency in the face of increasing frequency and strength of natural disasters, and develop AI technology that has the potential to devastate job markets and human infrastructure. AI specifically presents an interesting dynamic in engineering education. On one hand, the ease of use and applicability to coursework makes it harder to hold students accountable for doing the work of learning important material. On the other hand, students going through their education with AI at their fingertips will grapple with ethics on a more frequent basis to develop a more complex understanding of what it means to do the right thing, and what constitutes adding intellectual value.

As the final assignment in the Dr. Finelli's modules, students write an Op-Ed about an ethical issue they are concerned about and ultimately make a call to action. Writing an Op-Ed emphasizes to students the agency they have. This type of reflection in undergraduate education reminds students that upon entering the workforce, the responsibility lies squarely in their hands.

This feeling of agency, and of feeling prepared to address ethical dilemmas as they come up is what Finelli hopes students ultimately get out of their education.


EXIT

BAND-AIDS REIMAGINED:

Smart bandages use AI to expedite chronic wound healing

Shreeya Roy

When you fall during a hike or get a paper cut, you probably don't think much of it. Blood rushes to the site of the wound, and begins to clot. Then, during the inflammatory stage, white blood cells and enzymes actively work to eliminate bacteria and debris from the wound. Then, collagen production increases, and new tissue is created to completely heal the injury. The healing of wounds is a complicated process, but we typically slap on a bandage and carry on with our day-to-day life, knowing that our body's natural response to the injury will help the wound heal in a few days.

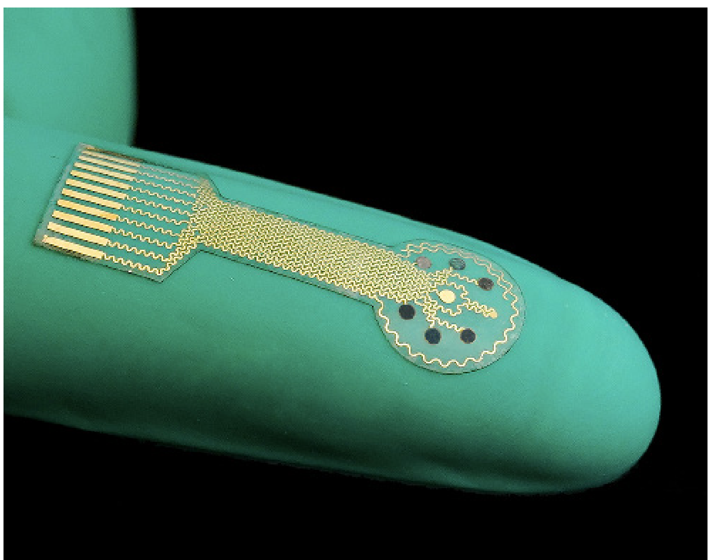

Photo of the smart bandage tested by Gao and his group.[5]

However, some wounds such as deep burns, certain infections, and significant trauma to the skin are slow to heal. Such wounds are called chronic wounds, some of which may need surgery to treat. In fact, up to 30% of untreated chronic wounds can lead to amputations. Current research on this topic suggests that chronic wounds get "stuck" in the second phase of wound healing: the inflammatory phase. Although more research is needed to understand how to expedite wound healing, in the meantime, this problem has inspired scientists to work on a device that can help alleviate this issue: bandages combined with AI.

The concept is a bandage incorporated with electronics that can monitor and aid the healing of chronic wounds. These devices have the potential to send alerts to the patient and the doctor, notifying them of a wound that needs attention. Sensors that can detect variations of inflammatory markers, temperature, and pH, can track the healing progress of a chronic wound. The benefits of an upgrade are straightforward: a chronic wound in need of attention will not be left unattended. A doctor or other medical professional will be notified when the wound needs attention or is not healing at the ideal pace. They could ensure that the patient's wound promptly receives necessary care .

Another type of AI bandage that is being developed are called "closed-loop" bandages because they are sufficient to care for the wound.The closed loop bandage monitors the status of the wound and releases medication and electrical pulses to help supplement wound healing without the intervention of a medical personnel. Similar to insulin pumps, which automatically release insulin into a diabetic's bloodstream, a closed-loop bandage can provide an electrical pulse or antibacterial medicine to encourage healing. While medication protects the wound from infection, electrical pulses enhance wound healing by directing cell migration to the site of injury.

Wei Gao and a team of researchers tested wearable bandages and their impact on healing wounds in a rodent model. The "bio-electronic" system they discuss includes features such as being biocompatible, stretchable, and adhesive to skin. Gao's study found that smart patches were able to accurately detect changes in the rodent's wounds. This patch releases both medication and electrical pulses for a highly efficient smart patch.
A diagram showing how concentration of HDF cells increases near the wound when the wound is exposed to Electrical Simulation (ES)

The study found that HDF cells (human dermal fibroblasts, a type of cell that plays a critical role in wound closure) migrated quickly and consistently to the wound that received an electrical impulse. The bandage's double pronged healing approach, involving both medication and electrical pulses, supported the complete healing of some wounds in 2 weeks. All wounds with patches achieved at least partial healing in that time.

While smart bandages don't exist yet, many scientists are actively working on this convergence of medical biology and AI. Smart bandages could be revolutionary for many people across the world. Patients with chronic wounds, severe burn wounds, or surgical incisions could use smart bandages to accelerate the wound healing process through simulation via electricity. Additionally, the periodic release of medication and constant monitoring of the wound can prevent infection.

[5] **Image Citation:** Gao, W., et al. (2023). A stretchable wireless wearable bioelectronic system for multiplexed monitoring and combination treatment of infected chronic wounds. Science Advances, 9(12). https://doi.org/10.1126/sciadv.adf7388

HUMAN SYSTEMS AND COMPLEXITY:

Exploration of mathematical models to explain human systems

Conor Rowan

We often speak of individuals and groups as being acted on by external ``forces." I suspect we use the word force, borrowed from the language of physics, to illustrate that environmental factors such as technology, work, and politics appear to produce certain responses in people. Just as mechanical forces act on physical systems, there are forces which act on ``human systems"--this is simply a logic of cause and effect. In helping make sense of how humans respond in different situations, these intuitive models are used to aid in decision making.

Whether these decisions are political (introducing a new policy) or personal (choosing how to spend your time), we use informal mental models of the world to assess the consequences of taking certain actions. In physics and engineering, models are used to avoid costly experiments. Similarly, people use mental models to avoid a trial and error--we can experiment with different possible worlds in our imaginations, and take the actions which seem likely to lead to the best outcomes. A force applied to a mass-spring-damper system causes the system to change state via motion of the mass. Analogously, we will consider a changing environment as a force which causes human systems to change "state." Unlike the mechanical system, it is not clear what a good measure of the state of a human system is. But the notion of a state, however vague, is supported by our intuitions about these complex systems. It is obvious that changes in the environment cause *some* change in people, even if it is hard to pinpoint or quantify what precisely is changing. Do occurrences like the advent of large language models, war in Ukraine, or starting/finishing college affect you? If so, then you have already have some notion of a state. *As an experiment, what if we take this analogy even further?* Perhaps we might write:

$$s(t) = G\Big(f(t)\Big)$$

This relation is intended to mean "the state of a person in time *s(t)* is a function *G(·)* of time-varying external forces *f(t)*." [6] Again, we do not necessarily need to have clear understanding of how a state *s(t)* is measured, and certainly not precise knowledge of the function *G(·)* which relates the human state to external forces. Forces are perhaps easier to understand, as they are conceptualized as things in the environment which may have an influence on individuals or groups. At this point, the idea is to cast an existing qualitative way of thinking about human systems into a general mathematical framework and see where it takes us.[7] It is often interesting and useful to model the time dependent response of a system in physics or engineering, so we do the same here. The time dependence of our hypothetical model suggests that we care about the human response to a dynamic environment. For example, our technological environment is constantly changing and being disrupted–the present and future effects of this innovation are the subject of many books, articles, and discussions. Informal models of how society will respond in time to these emerging technologies are used in thinking through these questions. Thus, time dependent forces and states seem to be a reasonable framework for our model.

Exploring the Model

Now that we have established a general framework, we can use intuition about how we as individuals respond to influences from our environment to see what kind of properties the model should have. The first question we will ask of our hypothetical model is :

for an arbitrary constant *c*. In words, this is asking: if we know

$$\text{if } s_1(t) = G\Big(f(t)\Big) \quad \text{and} \quad s_2(t) = G\Big(cf(t)\Big)$$

$$s_2(t) \stackrel{?}{=} cs_1(t)$$

the state produced by environmental influence *f(t)*, does multiplying that environmental influence multiply the output state in the same way? We are investigating scaling properties of the model. Let's consider an example: if the force *f* is a measure of technology use, and the state *s* is a measure of anxiety, does doubling the amount of technology use double anxiety? I would argue not necessarily. Intuitively, we might think that at low levels of technology, increasing technology use does not increase anxiety at all. Looking to the distant past, transitioning from the use of hand tools to simple machines might lower anxiety through facilitating manual labor. But when technology is more prevalent, doubling technology use might have a very different effect, possibly leading to a dramatic increase in anxiety. This is perhaps the case in an era of widespread digital technologies, where an hour or so of daily social media use may have no mental health impact, but multiple hours spent online each day may be psychologically harmful. Increasing technology use in the case of hand tools reduces anxiety, but in the case of digital technology, it increases. We have come up with a plausible counterexample to show that the scaling property should not hold in general. Thus, we can say the following:

Without specifying precisely what *G(.)* is, we have learned

$$G\Big(cf(t)\Big) \neq cG\Big(f(t)\Big)$$

[6] *G(.)* is technically an operator as it maps from one space of functions to another.

[7] Economics is the field most interested in developing mathematical models of social systems. Some specific social phenomena of interest are: disease spread, rumor circulation, population growth, casualty in warfare, migration from one political party to another, and economic effects of climate change.

something about its properties. It is interesting to note that we can establish some properties essentially by common sense. Now, as before, we will use existing intuition about human systems to ask another question of the model. We want to investigate the following:

In words, we want to determine if the combined effect of

$$\text{if} \quad s_1 = G\Big(f_1(t)\Big) \quad \text{and} \quad s_2 = G\Big(f_2(t)\Big)$$

$$G\Big(f_1(t) + f_2(t)\Big) \stackrel{?}{=} s_1 + s_2$$

two forces is the sum of the responses to each force individually. Here, we are investigating *interaction* properties of the model. Again, we will try to think of a counterexample to demonstrate this property should not hold in general. This is a bit trickier than the scaling property. If f_1 measures the force associated with digital technologies, and f_2 that of political polarization, there is good reason to believe that an individual's response to these two forces is NOT simply the sum of the response to each force separately. In other words, digital technology and political polarization interact in some way to produce a new effect which cannot be decomposed into two distinct contributions.[8] This is equivalent to saying that the response to the influence of digital technology depends on the level of political polarization, and conversely, the response to political polarization depends on the amount of digital technology. This seems fair to say in a world where the creation of and reaction to polarization is intimately intertwined with online media platforms. Thus, we can say that:

Our model of the human response to environmental forces

$$G\Big(f_1(t) + f_2(t)\Big) \neq s_1 + s_2$$

should account for the fact that these forces frequently interact with each other in meaningful ways. We cannot look at a human system's response to individual forces in isolation and expect to get the full picture.

It will perhaps be familiar to engineers that by investigating these scaling and interaction properties, we have shown that the the model *G(·)* is non linear. Based on these simple thought experiments, it is clear that any model which seeks to capture human responses to external stimuli must be non-linear in order to be realistic. Whether or not such models can be built is not clear. All I claim is the following: *if a good model of this sort were built, it would have to be non-linear. Though it is not yet clear, we will see that this essentially guarantees these systems are highly complex.*[9]

A Particular Non-linear System

Having argued that any realistic model of a human system must be non-linear in order to capture two intuitive properties, we can now explore the behavior of a particular model. I have invented this model as a potential description of the time evolution of anxiety *a(t)* and sense of meaning *m(t)* driven by changes in the level of physical comfort *f(t)*. Positive values of these two state variables indicate high anxiety and a "large" sense of meaning respectively. Anxiety has its everyday definition, and meaning describes a sense of purpose, direction, or understanding in life. Physical comfort alludes to access to food, shelter, medicine, health, etc. These variables have been chosen because intuitively, they are related in some way. A sense of meaning acts to decrease anxiety, but persistent anxiety may also decrease meaning. On top of these effects, one could argue that the anxious person interprets the world through a lens of anxiety, which creates more apparent stressors. This indicates that anxiety is self-perpetuating. As basic survival becomes a guarantee and people need to find new and more abstract goals in life, physical comfort may reduce meaning. But, reliable access to basic comforts also acts to reduce anxiety.

You are completely free to, and probably justified in, contesting the relationships I am proposing. However, the goal of this informal model is to be reasonable, not rigorous. It is simply a candidate framework for this anxiety-meaning comfort human system which is grounded in apparently plausible assumptions about how these variables are related. Whether this model is understood on the individual or societal level is not important–we are interested in getting a qualitative sense of the dynamics of this model. *In other words, we want to investigate how predictable the system's behavior is.*

As is common in physics and engineering, differential equations are the natural framework for modeling the time evolution of interrelated state variables. Be cause we model the interaction of the two quantities anxiety *(a(t))* and meaning *(m(t))*, this will be a system of differential equations.[10] And finally, remember that for this system to even have a chance of reproducing intuitive features of the human system, it must be non-linear! One possible non-linear system which reflects the qualitative sketch of the relationships between these variables is the following:

To solve for how anxiety and meaning evolve over time, we

$$\begin{cases} \frac{da}{dt} = a^3 - m^{\frac{3}{7}} - f^2(t) \\ \frac{dm}{dt} = -a^5 - f(t) \end{cases}$$

must specify a time history of comfort (force) for our toy human system and initial conditions *a(0)* and *m(0)*. These initial conditions are interpreted as the baseline states of anxiety and meaning before we observe the effect of changing physical comfort perturbing the system. They are starting points. The time trajectory of comfort we will experiment with is a "saturating" exponential:

This represents a fast initial increase of comfort which

$$f(t) = c_0\big(1 - e^{-rt}\big)$$

eventually levels off. The parameters c_0 and r respectively determine the final value of comfort and the rate at which change takes place. Note that a generic non-linear system of differential equations will diverge to ±∞ unless carefully tuned. To avoid this, additional terms can be introduced to the system which discourage the state variables *a(t)* and *m(t)* from exceeding specified limits.[11] In some sense, this can be given a real world interpretation–in a well-functioning society, there are often restoring forces which tend to keep human systems from taking on extreme states. We will arbitrarily set the limits on the anxiety and meaning state variables at ±1 for simplicity. See Figure 1 for interpretation of the governing equations of the system.

We now have a candidate mathematical model of the system. It is non-linear in order to reproduce the richness of human responses. It is motivated by a qualitative understanding of how

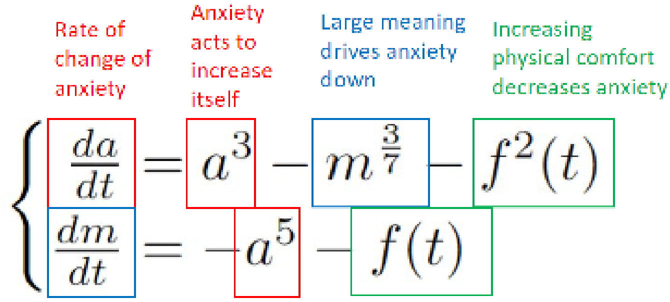

Figure 1 : A non-linear system of differential equations representing the anxiety-meaning-comfort system. The restoring force terms are approximately zero unless the limits are approached, and are not shown here.

anxiety, meaning and physical comfort might interact, but cast in a somewhat arbitrary quantitative form. Furthermore, we have chosen the limits on the system states arbitrarily. The parameters c_0 and r do not have clear physical meaning–what does an initial value of physical comfort $f(0) = 3$ (for example) correspond to in real life? Is the rate parameter r shifting a time scale of hours, weeks, months, or years? These questions are not important for our purposes. We are less concerned with the precise quantitative predictions of the system. *What we want to investigate is how predictable its qualitative behavior is. Do anxiety and meaning oscillate? Does one go up and the other go down? Are these responses sensitive to initial conditions? Are they sensitive to magnitude and rate of the changes in physical comfort?* To answer these questions, we can solve the system over given time intervals for different initial conditions and parameters of the forcing function. MATLAB's built-in differential equation solver

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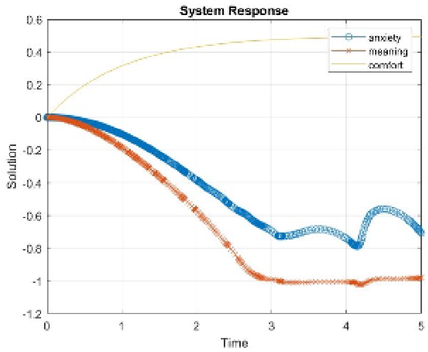
8 In making this argument, we are not being careful to consider the meaning of the time dependence of f_1 and f_2. To be more precise, we can think of these as measuring the evolution of digital technology and polarization in time. The full argument states that the human response in time cannot be decomposed into separate parts from the respective histories of polarization and digital technology.

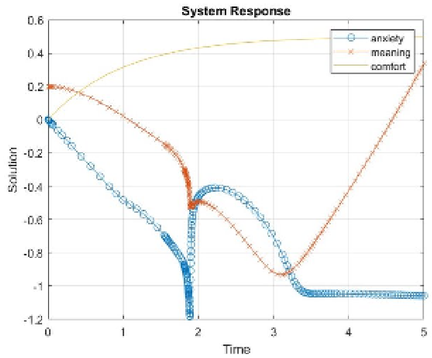
9 The study of "complex systems" has its own body of literature within which complexity is given a technical definition. For example, a complex system is distinguished from a complicated one by not being decomposable into a sum of its parts. Here, I use the term in a more colloquial way to indicate a system which is very unpredictable.

10 In this context, $G(.)$ is conceptualized abstractly as the solution to the system of equations for a given force and set of initial conditions.

11 To accomplish this, I add a penalty term to each time derivative of the form $-x^n tanh(p(|x|-l))+1$, where x is the state variable, l is the specified limit, n controls the strength of penalty, and p is a positive number. As the limit l is approached, this term becomes large and pushes the state variable bak to zero. Plot this fcuntion to see how it works!



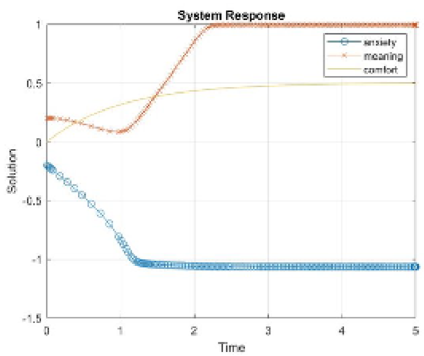
c_0=0.5, r=1, a(0)=0, m(0)=0



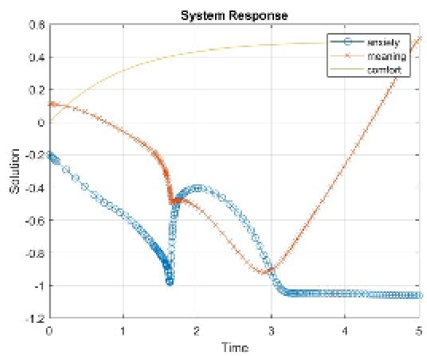
c_0=0.5, r=1, a(0)=0, m(0)=0.2

Figure 2

For a given force f(t) small changes in initial conditions lead to different final states. On the left, anxiety and meaning start at the same level and both approach their lower bound. On the right, meaning starts at a slightly higher initial value, decreases at first, then approaches its upper bound. This demonstrates the final states of the system are sensitive to initial conditions.



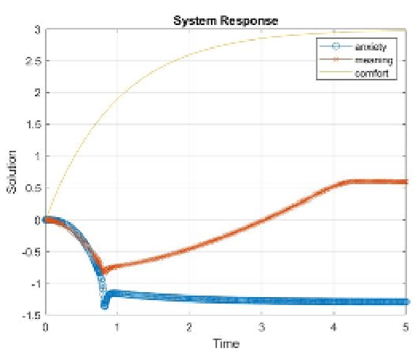
c_0=0.5, r=1, a(0)=-0.2, m(0)=0.2



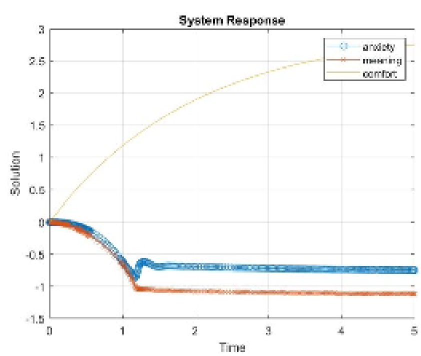
c_0=0.5, r=1, a(0)=-0.2, m(0)=0.1

Figure 3

For given force f(t), small changes in initial conditions can lead to the system approaching the same final state in very different ways. On the left, meaning approaches its upper bound and anxiety its lower bound. On the right, a small decrease in the starting value of meaning leads to a large initial decrease in meaning, which eventually is reversed. This is another indication of sensitivity to initial conditions.



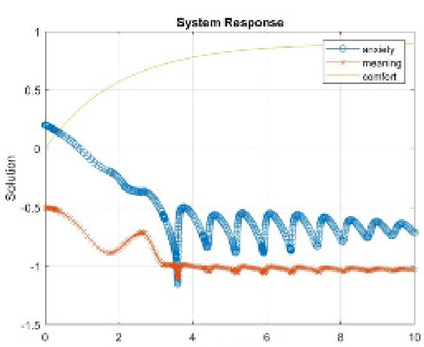
c_0=3, r=1, a(0)=0, m(0)=0



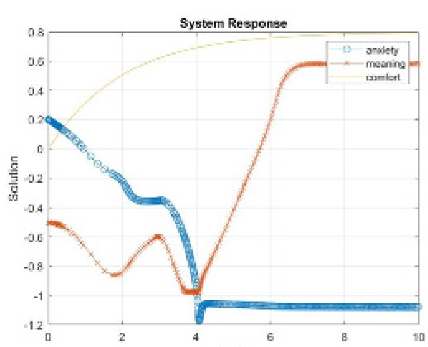
c_0=3, r=0.5, a(0)=0, m(0)=0

Figure 4

For given initial conditions and final value of comfort, the system is sensitive to rate at which change takes place. On the left, comfort changes more quickly. Meaning approaches its upper bound whereas anxiety tends towards its lower bound. On the right, changes in comfort happen slowly and both variables approach their lower bound. This demonstrates that the final value of comfort does not determine the final state of the system.



c_0=0.9, r=0.5, a(0)=0.2, m(0)=-0.5



c_0=0.8, r=0.5, a(0)=0.2, m(0)=-0.5

Figure 5

For given initial conditions and rate of change of comfort, the system is sensitive to the final value of comfort. On the left, anxiety and meaning approach their lower bound with significant oscillations in anxiety. On the right, a small change in the final value of comfort has meaning attaining its upper bound and anxiety its lower bound. This demonstrates that the system response does not scale with the input force.

"ODE45" is used to solve the non-linear system. See Figures 2-5 for an exploration of some of the properties of the anxiety-meaning comfort system.

Results

Figure 2 shows that the final state of the system is very sensitive to the initial conditions. Figure 3 shows that the manner in which the same final state is approached can also be very sensitive to the initial conditions. Figure 4 demonstrates that the character of the system response depends on how the final value of comfort is approached. Finally, Figure 5 shows that the nature of the system response also depends on what the final state of comfort is. Remembering that these features should apply to generic human systems, this should be troubling and counter-intuitive.[12] We do not expect that the dynamics of these systems depend chaotically on the minutia of environmental forces. We tend to assume that big effects must be the result of big causes. Yet, in the grand scheme of things, this is an extremely simple system: the two variables of anxiety and meaning are interrelated and change in time according to the state of physical comfort. We have made an attempt to capture these dynamics with differential equations, which we know must be non-linear to be realistic, and for which there are straightforward mathematical techniques to solve. It should be apparent that this model is a gross simplification and not to be taken too seriously. The point is not that this model tells us anything credible about the dynamics of anxiety and meaning in our lives. I hope you will agree that real human systems, depending on vast networks of interconnected "variables" and the vagaries of human will, are strictly more complex than our toy model here. *Yet, this toy model is already so complex as to defy intuition. Through extreme sensitivity to small changes in inputs and initial conditions, it exhibits chaotic behavior which makes even qualitative features of the response very difficult to predict.* And in general, increasing the complexity of a model will only serve to exaggerate its unpredictability.

Conclusion

If you accept my argument about the scaling and interaction properties of any candidate model of human behavior, you will accept that models of human systems must be non-linear. And if you also accept that toy models in the form of systems of ordinary differential equations are strictly simpler than real human systems, *you have placed a serious restriction on how predictable you can expect human systems to be.* Even the simplest non-linear ODE's exhibit chaos to the point of being totally baffling. You may argue that this is a particular non-linear system, and that other non-linear models should not be this chaotic. I would encourage you to experiment with some others to test this hypothesis! The properties we have shown here should be expected of a generic non-linear model. Furthermore, you may argue that human systems cannot or should not be modeled mathematically, a point which deserves serious consideration.

But here, I claim not that math is a good model for human behavior, but that in their inherent non-linearity, high-dimensional structure[13], and aversion to formalization, human systems are strictly more complex (and therefore less predictable) than these toy mathematical systems. And these simple systems already exceed the abilities of our intuitive reasoning! Given that effective personal and political decision making requires informal models of how the world responds to potential interventions, this is a rather troubling conclusion. If human systems are so complex as to resist mathematical formulation, and even simple mathematical systems surpass the capabilities of intuition, how can we have any faith in the decisions we make in the world? Can we have confidence that our visions for change and progress are beneficial if we cannot understand or predict how the world responds to such changes? We often encounter claims of apparent certainty about *what should be done* in social and political contexts. Implicitly, this a claim that given causes will produce a particular set of effects. The purpose of the admittedly clunky anxiety-meaning-comfort system was not to solve a particular problem, but to raise the general question: *is it ever fair claim certainty about cause-and-effect where human systems are concerned?*

Though mathematics may never be the *lingua franca* of personal and political decision making, it can give us insight into why these problems remain hard even after hundreds of years of scientific and technological advancement. If nothing else, this thought experiment should be humbling–next time you find yourself saying *if X then Y* without a well-defined mathematical model in hand, consider that you may be claiming to have intuition about a high-dimensional, non-linear system. In some situations, the tools to solve problems of this sort exist. Predictive models are powerful tools for simple and low-stakes experimentation with cause-and-effect relations. They tell us something about how possible actions map onto possible outcomes. This is the domain of computational science–from aerodynamics to drug discovery, high-dimensional non-linear systems are mined daily in industry and academia to much avail. But rarely do these explicit mathematical models exist for human systems.

In the absence of these quantitative models, we rely on tools such as intuition to make sense of the world. But, as we have seen, intuition is not a trustworthy guide in making precise predictions about non-linear phenomena. This is a deliberately disturbing conclusion–I interpret this to mean that in spite of all our technological and scientific sophistication, we operate essentially in the dark with regards to many important social and political questions. We simply do not know what the consequences of taking certain actions in the world will be. How are decisions made about complex problems then? I would argue values are one answer to this apparent bind.

Values are first-principle commitments which are to some extent outcome-independent. An act can be viewed as *inherently* right or wrong, thus ignoring uncertain downstream effects. Values such as freedom, justice, equality, compassion, etc. can be used as filters to constrain action and make some sense of what should be done. As I see it, it is an act of faith to believe that adherence to values leads straightforwardly to desirable personal and social outcomes. Yet I think we do this unconsciously: we do not demand exact predictive models as prerequisites to making decisions, rather we subject possible actions to the test of values. People successfully take action and the world is not entirely unpredictable, at least most of the time. There must be some hidden epistemic trick at work, wrangling the chaos of life's various non-linearities.

So I think the bottom line is this: when a system is too complex to model mathematically or make sense of intuitively, there may be no alternative but to lean more heavily on values as guides to shepherd decision making. And in realizing that we make decisions constantly despite the unreliability of our mental models, I think there is benefit in reflecting more seriously on what values drive these decision making processes.

[12] The idea of the "butterly effect," which states that a butterfly flapping its wings in one continent could cause a hurricane in another, comes from these properties of non-linear systems. This is another example of a troubling consequency of non-linearity.

[13] This just means that there are many interrelated variables needed to describe the state of the system.

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