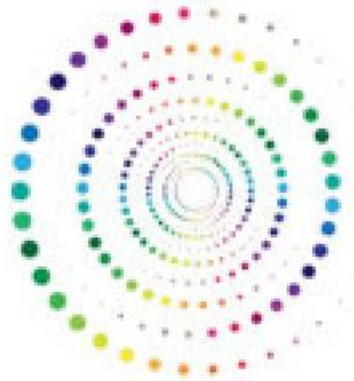


INNOVATIVE TECH VOL 2

INNOVATIVE



TECHNOLOGY

Dean Kamen Says Inventing Is Easy, but Innovating Is Hard

The legendary engineer says
innovation = idea + scale



Dean Kamen is trying to create a runway for startups that will revolutionize biomanufacturing.
FIRST ROBOTICS

[INVENTION](#) [DEAN KAMEN](#) [STARTUPS](#) [BIOENGINEERING](#) [TISSUE ENGINEERING](#)

This article is part of our [special report](#), “[Reinventing Invention: Stories from Innovation’s Edge](#).”

Over the past 20 years, technological advances have enabled inventors to go from strength to strength. And yet, according to the legendary inventor [Dean Kamen](#), innovation has stalled. [Kamen](#) made a name for himself with inventions including the first portable insulin pump for diabetics, an [advanced wheelchair](#) that can climb steps, and

the [Segway](#) mobility device. Here, he talks about his plan for enabling innovators.

How has inventing changed since you started in the 1990s?

Dean Kamen: Kids all over the world can now be inventing in the world of synthetic biology the way we played with Tinkertoys and Erector Sets and Lego. I used to put pins and smelly formaldehyde in frogs in high school. Today in high school, kids will do experiments that would have won you the Nobel Prize in Medicine 40 years ago. But none of those kids are likely in any short time to be on the market with a pharmaceutical that will have global impact. Today, while invention is getting easier and easier, I think there are some aspects of innovation that have gotten much more difficult.

Can you explain the difference?

Kamen: Most people think those two words mean the same thing. Invention is coming up with an idea or a thing or a process that has never been done that way before. [Thanks to] more access to technology and 3D printers and simulation programs and virtual ways to make things, the threshold to be able to create something new and different has dramatically lowered.

Historically, inventions were only the starting point to get to innovation. And I'll define an innovation as something that reached a scale where it impacted a piece of the world, or transformed it: the wheel, steam, electricity, [Internet](#). Getting an invention to the scale it needs to be to become an innovation has gotten easier—if it's software. But if it's sophisticated technology that requires mechanical or physical structure in a very competitive world? It's getting harder and harder to do due to competition, due to global regulatory environments.

[For example,] in proteomics [the study of proteins] and genomics and biomedical engineering, the invention part is, believe it or not, getting a little easier because we know so much, because there are development platforms now to do it. But getting a biotech product cleared by the Food and Drug Administration is getting more expensive and time consuming, and the risks involved are making the investment community much more likely to invest in the next version of [Angry Birds](#) than curing [cancer](#).

A lot of ink has been spilled about how AI is changing inventing. Why hasn't that helped?

Kamen: AI is an incredibly valuable tool. As long as the value you're looking for is to be able to collect massive amounts of

data and being able to process that data effectively. That's very different than what a lot of people believe, which is that AI is inventing and creating from whole cloth new and different ideas.

How are you using AI to help with innovation?

Kamen: Every medical school has incredibly brilliant professors and grad students with petri dishes. “Look, I can make nephrons. We can grow people a new kidney. They won't need dialysis.” But they only have petri dishes full of the stuff. And the scale they need is hundreds and hundreds of liters.

I started a not-for-profit called ARMI—the [Advanced Regenerative Manufacturing Institute](#)—to help make it practical to manufacture human cells, tissues, and organs. We are using [artificial intelligence](#) to speed up our development processes and eliminate going down frustratingly long and expensive [dead-end] paths. We figure out how to bring tissue manufacturing to scale. We build the bioreactors, sensor technologies, [robotics](#), and controls. We're going to put them together and [create an industry](#) that can manufacture hundreds of thousands of replacement kidneys, livers, pancreases, lungs, blood, bone, you name it.

So ARMI's purpose is to help would-be innovators?

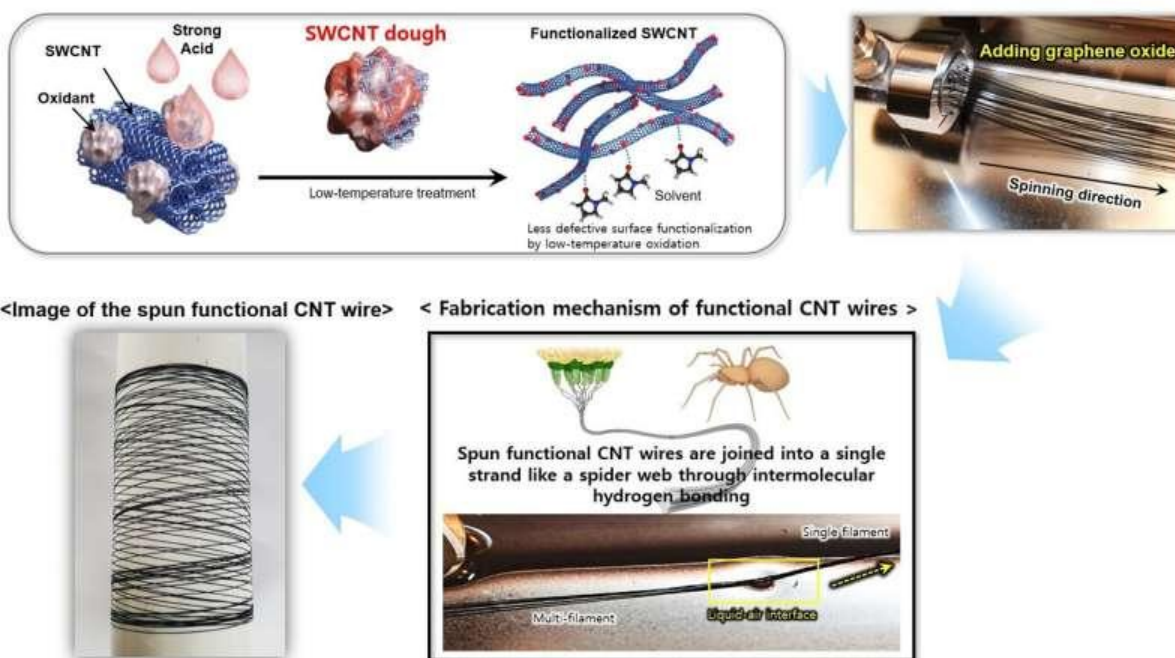
Kamen: We are not going to make a product. We're not even going to make a whole company. We're going to create baseline core technologies that will enable all sorts of products and companies to emerge to create an entire new industry. It will be an innovation in health care that will lower costs because cures are much cheaper than chronic treatments. We have to break down the barriers so that these fantastic inventions can become global innovations.

This article appears in the November 2024 print issue as "The Inventor's Inventor."

MARCH 19, 2025

Carbon nanotube wires for wearables can be crafted from existing fiber manufacturing process

by [National Research Council of Science and Technology](#)



The manufacturing process of CNT-based high-energy lightweight functional wires. Credit: Korea Electrotechnology Research Institute

Dr. Han Joong Tark's team at KERI's Nano Hybrid Technology Research Center has successfully fabricated "functional wires," which are the foundation of wearable electronic devices, by directly applying the existing synthetic fiber processing methods.

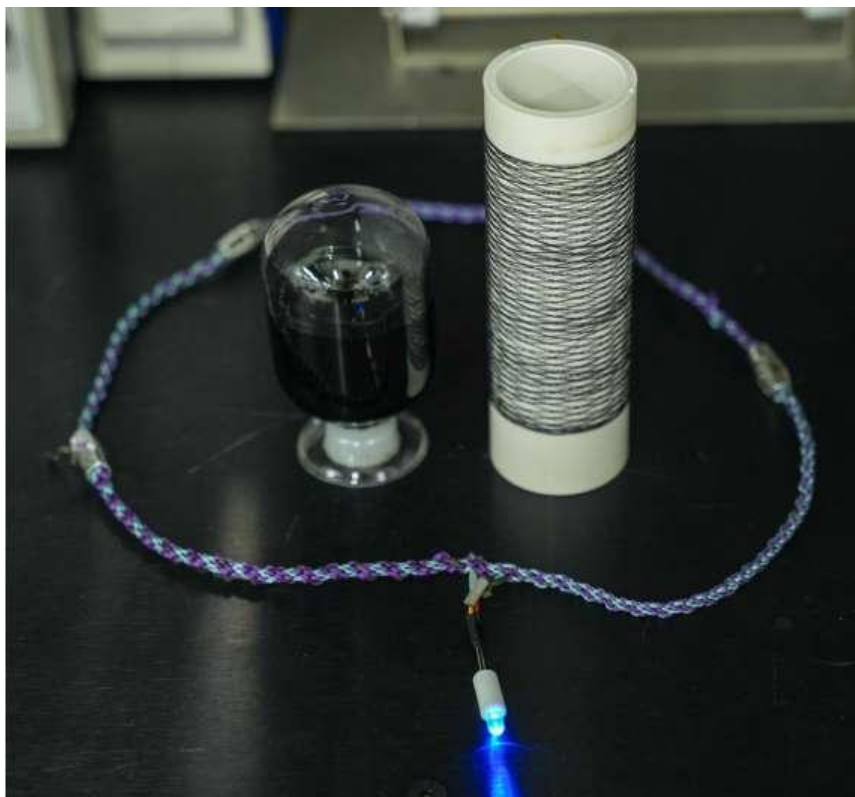
The paper is [published](#) in the journal *ACS Nano*.

Wearable electronic devices, which can be attached to or worn on the body, such as on the wrist, ear, or eyes, have long become a part of our daily lives in various forms, like smartwatches, glasses, and earphones. The key to these devices is that they must be lightweight while maintaining long-lasting performance.

While there have been various efforts to achieve this, one of the most important elements is the conductive functional wire, which is a crucial material.

KERI's achievement is a high-energy, lightweight wire made using [single-walled carbon nanotubes](#) (CNT). CNT is a new material that is 100 times stronger than steel and has [electrical conductivity](#) comparable to copper. The carbon atoms in CNT are connected in hexagonal rings, forming a long cylindrical shape, which also gives it excellent flexibility.

In particular, CNT has the advantage of significantly increasing [energy density](#) even with a small amount of addition, which allows for a substantial reduction in the amount of heavy copper used in electronic devices.



The CNT dope and lightweight CNT wires, along with the necklace-type supercapacitor fabricated by using functionalized CNT wires. Credit: Korea Electrotechnology Research Institute

However, CNT has a strong tendency to agglomerate, forming tangled structures and it is difficult to disperse CNTs using organic solvents and other methods. Therefore, applying CNT in the field of electronics and electrical devices requires highly advanced and sophisticated technology.

To address this, Dr. Han Joong Tark's team first introduced a small amount of strong acid and additives to the CNT powder to add oxygen functional groups onto the surface that are compatible with solvents.

They then kneaded the mixture and stored it at a low temperature (2°C) for a certain period. This method mimics the process used in making bread or noodles, where flour is mixed with water and additives to undergo maturation. By doing this, CNTs are highly functionalized with fewer defective structures on the surface, maximizing their performance.

In addition, [graphene oxide](#) with a size-controlled to around 100 nanometers (nm) was added, and then, following the same process as the conventional synthetic fiber manufacturing method, the CNT paste (dope) was spun through multiple small holes to form a multi-filament in a coagulation bath.

In this process, the size-controlled graphene oxide enhanced the dispersion of the CNT dope and significantly reduced the nozzle clogging during spinning. Finally, the CNTs with oxygen functional groups, after undergoing the spinning process, are bonded into a single strand through hydrogen bonding, forming functional wires like a spiderweb.



(From left to right) Dr. Han Joong Tark of KERI and Dr. Kim Taehoon of KIMS, along with their research teams, are posing while holding the CNT dope and wires, as well as necklace-type supercapacitors. Credit: Korea Electrotechnology Research Institute
KERI produced CNT wires in the form of textile supercapacitors through Dr. Kim Taehoon's team at the Korea Institute of Materials Science (KIMS) and evaluated their performance, confirming excellent energy storage capabilities. Additionally, through Professor Lee Wi Hyeong's research team at Konkuk University, it was confirmed that CNT wires with oxygen [functional groups](#) also exhibited excellent gas sensor performance for detecting the presence of harmful gases.

This functionality could be greatly applied in smart clothing, such as for firefighters' fire suppression efforts or in defense fields.

KERI's Dr. Han Joong Tark said, "This is the world's first achievement of dispersing functionalized CNTs in organic solvents for solution spinning. It will drive the development of lightweight and long-lasting wearable electronic devices.

"Through continuous research, this technology could replace copper wires in future mobility fields, such as electric vehicles and drones, greatly improving both lightweight design and energy efficiency."

More information: Jung Hoon Kim et al, Hydrogen Bond-Driven Hierarchical Assembly of Single-Walled Carbon Nanotubes for Ultrahigh Textile Capacity, *ACS Nano* (2025). DOI: [10.1021/acsnano.4c14761](https://doi.org/10.1021/acsnano.4c14761)

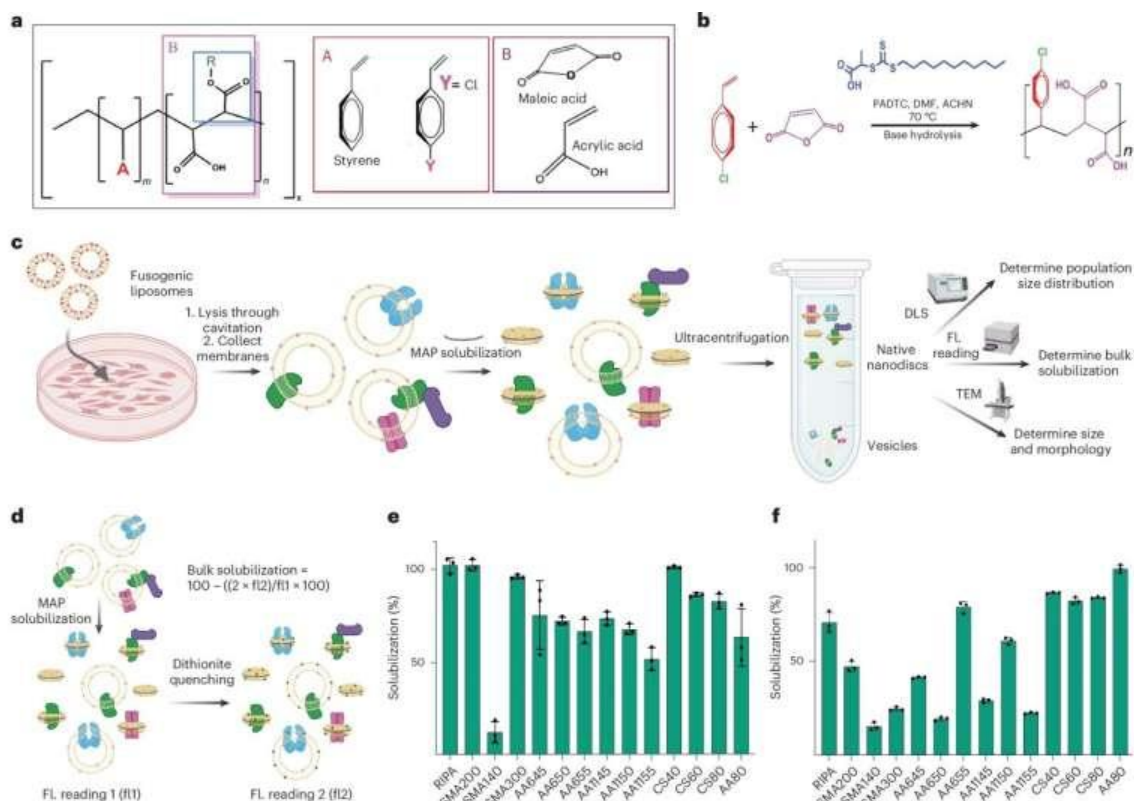
Journal information: [ACS Nano](#)

Provided by [National Research Council of Science and Technology](#)

MARCH 19, 2025

'Molecular library' opens up new frontier of biological space-time

by Jon Atherton, [Yale University](#)



Generation of MAP library and development of high-throughput bulk solubilization assay.

Credit: *Nature Methods* (2024). DOI: 10.1038/s41592-024-02517-x

In the search for solutions to diseases like cancer, scientists are pursuing a new frontier in biology—the spatial and temporal places where our cells live.

Where first generation drugs targeted [single molecules](#), over time evolving their own resistance, [new tools](#) and techniques are needed to keep ahead of resistant diseases by targeting the surrounding cellular space.

Much of this exploration is taking place at the surface of our cells—the protein-packed semi-permeable membranes that act as protectors and as signaling posts to other cells in the surrounding area.

Over 60% of current market drugs target our [membrane proteins](#), and this number is expected to increase with the help of a new, accessible molecular "library" developed by Yale's Kallol Gupta, an assistant professor of Cell Biology at the School of Medicine.

"There are all kinds of proteins congregating at the cellular membrane, and if we want to understand what a protein does, how it's regulated by its environment, and specifically how it triggers the spread of a disease, we need to understand what surrounds it," explained Gupta, whose lab is part of the Nanobiology Institute at Yale's West Campus.

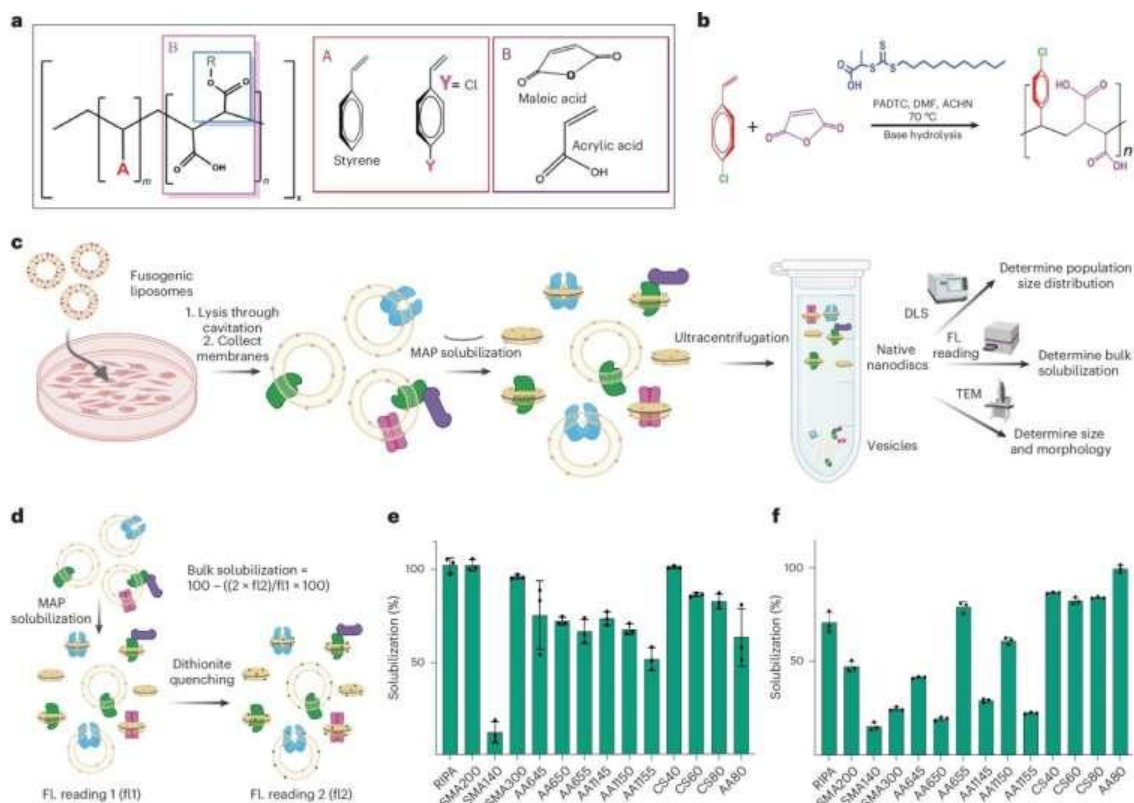
Lacking the spatial nanotechnology required to understand the molecular context of how membrane proteins are regulated in health and diseases, the scholars developed a novel

platform that provides access to around 2,000 membrane proteins as well as a chemical tool to examine areas that surround proteins of interest.

"We wanted to share these important tools to study membrane proteins and make them accessible to researchers anywhere in the world," said Caroline Brown, a graduate student in the Gupta lab and a co-first author of the study, which [appears](#) in *Nature Methods*. "There are thousands of proteins in our body, but which one should you look at relative to a specific [disease](#)?"

MARCH 19, 2025

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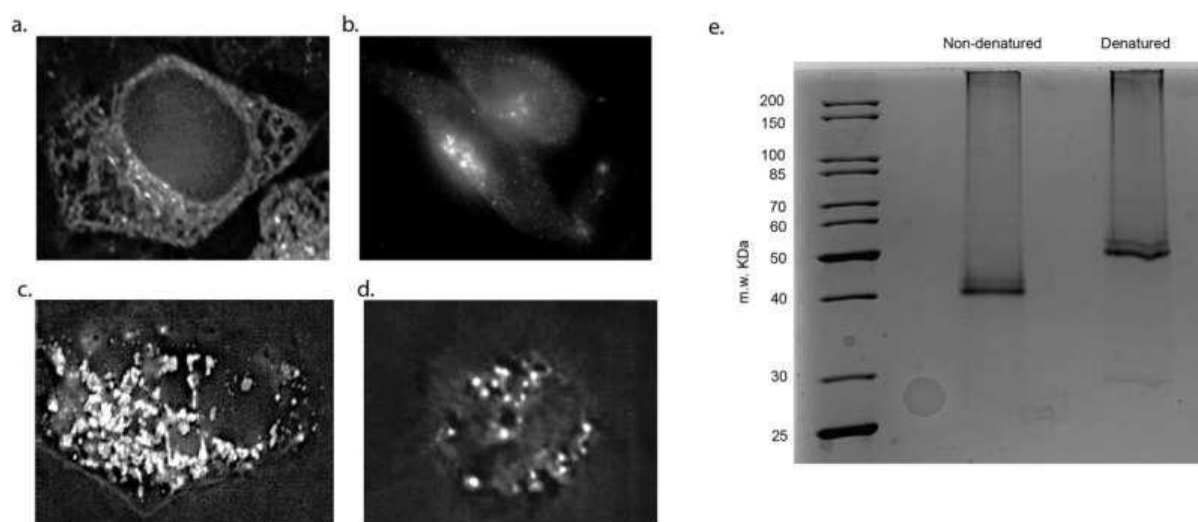
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Confirmation of organellar localization and KRas purification. Credit: *Nature Methods* (2024). DOI: 10.1038/s41592-024-02517-x

The new database is expected to save time by helping any researcher trying to find proteins that relate to a specific health problem.

Collaborating with adjacent labs at the West Campus, the scholars used on-site mass spectrometry to reveal a class of molecules known to be active in the [cell membrane](#).

With the "library" established, the scholars turned to developing a new tool that could make sense of the broader cellular space.

Typically measured at the micron level—or slightly thinner than a spider web—for the library to reveal events and associations driving protein signaling, resolutions of a thousand-fold higher would be needed.

"By modulating the chemistry of the molecules, we were able to change the diameter of the area of interest to create a new spatial resolution that helps us understand how the function of a protein is regulated by its surroundings," continued Gupta.

The result is what the scientists refer to as a programmable chemical "scoop" used to collect molecular information from a given nanoscale contextual area.

The technological landmark is expected to help more scientists understand how membrane proteins interact in association with other proteins, in turn revealing new drug targets to disrupt the spatial signals that drive different diseases.

More information: Caroline Brown et al, A proteome-wide quantitative platform for nanoscale spatially resolved extraction of membrane proteins into native nanodiscs, *Nature Methods* (2024). DOI: [10.1038/s41592-024-02517-x](https://doi.org/10.1038/s41592-024-02517-x)

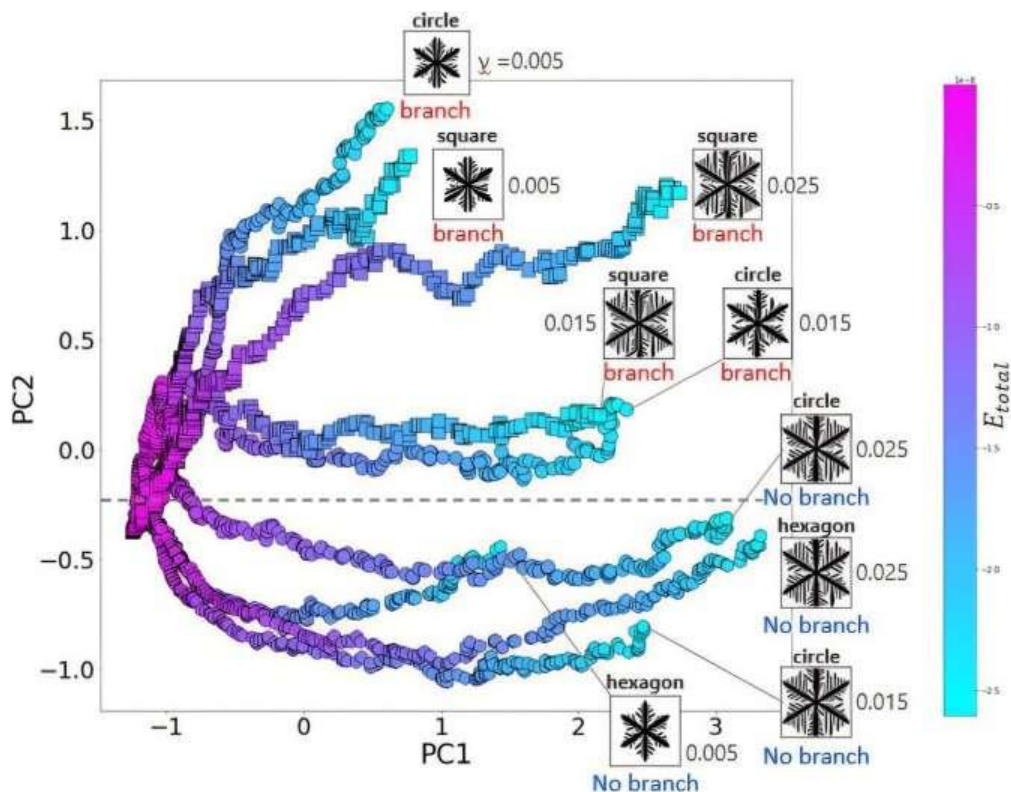
Journal information: [Nature Methods](#)

Provided by [Yale University](#)

MARCH 19, 2025

AI model reveals secrets of dendritic growth in thin films

by Tokyo University of Science



The PCA enabled the team to quantify the structural changes in dendrites and correlate these changes with Gibbs free energy. This relationship revealed the specific conditions and mechanisms that drive dendrite branching in thin films. Credit: Masato Kotsugi / Tokyo University of Science, Japan. Source link:

www.tandfonline.com/doi/full/10.1080/27660400.2025.2475735

Thin film devices, composed of layers of materials a few nanometers thick, play an important role in various technologies, from semiconductors to communication technologies. For instance, graphene and hexagonal-boron nitride (h-BN) multilayer thin films, deposited on copper substrates, are promising materials for next-generation high-speed communications systems.

Thin films are grown by depositing tiny layers of materials onto a substrate. The growth process conditions significantly influence the microstructure of these films, which in turn influences their function and performance.

Dendritic structures, or tree-like branching patterns that emerge during growth, pose a major challenge to large-area fabrication of thin-film devices, a key step toward commercial application. They are commonly observed in materials like copper, graphene, and borophene, particularly in the early growth stage and multilayer films.

Since the microstructure directly impacts device performance, reducing dendritic formation is, therefore, critical. However, methods for studying dendrites have largely relied on crude visual analysis and subjective interpretation. Understanding the conditions that drive

dendritic branching is essential for optimizing the thin-film growth process, but existing approaches often require considerable trial and error.

To address these challenges, a research team, led by Professor Masato Kotsugi from the Department of Material Science and Technology at Tokyo University of Science (TUS), Japan, developed an innovative explainable artificial intelligence (AI) model for analyzing dendritic structures.

Their study was published online in [Science and Technology of Advanced Materials: Methods](#).

The team included Misato Tone, also from TUS, and Ippei Obayashi from Okayama University. The team developed a novel method that bridges structure and process in dendritic growth by integrating persistent homology and machine learning with energy analysis.

"Our approach provides new insights into growth mechanisms and offers a powerful, data-driven pathway for optimizing thin-film fabrication," explains Prof. Kotsugi.

To analyze the morphology of dendrite structures, the team used a cutting-edge topology method called persistent homology (PH). PH enables multiscale analysis of holes and connections within geometric structures, capturing the complex topological features of the tree-like dendrite microstructures that conventional image processing techniques often overlook.

The researchers combined PH with [principal component analysis](#) (PCA), a machine learning technique. Through PCA, the essential features of the dendrite morphology extracted via PH were reduced to a two-dimensional space. This enabled the team to quantify structural changes in dendrites and establish a relationship between these changes and Gibbs free energy, or the energy available in a material that influences how [dendrites](#) form during crystal growth.

By analyzing this relationship, they uncovered the specific conditions and hidden growth mechanisms that influence dendritic branching. Prof. Kotsugi explains, "Our framework quantitatively maps dendritic morphology to Gibbs free energy variations, revealing energy gradients that drive branching behavior."

To validate their approach, the researchers studied dendrite growth in a hexagonal copper substrate and compared their results with data from phase-field simulations.

"By integrating topology and free energy, our method offers a versatile approach to material analysis. Through this integration, we can establish a hierarchical connection between atomic-scale microstructures and macroscopic functionalities across a wide range of materials, paving the way for future advancements in material science," remarks Prof. Kotsugi.

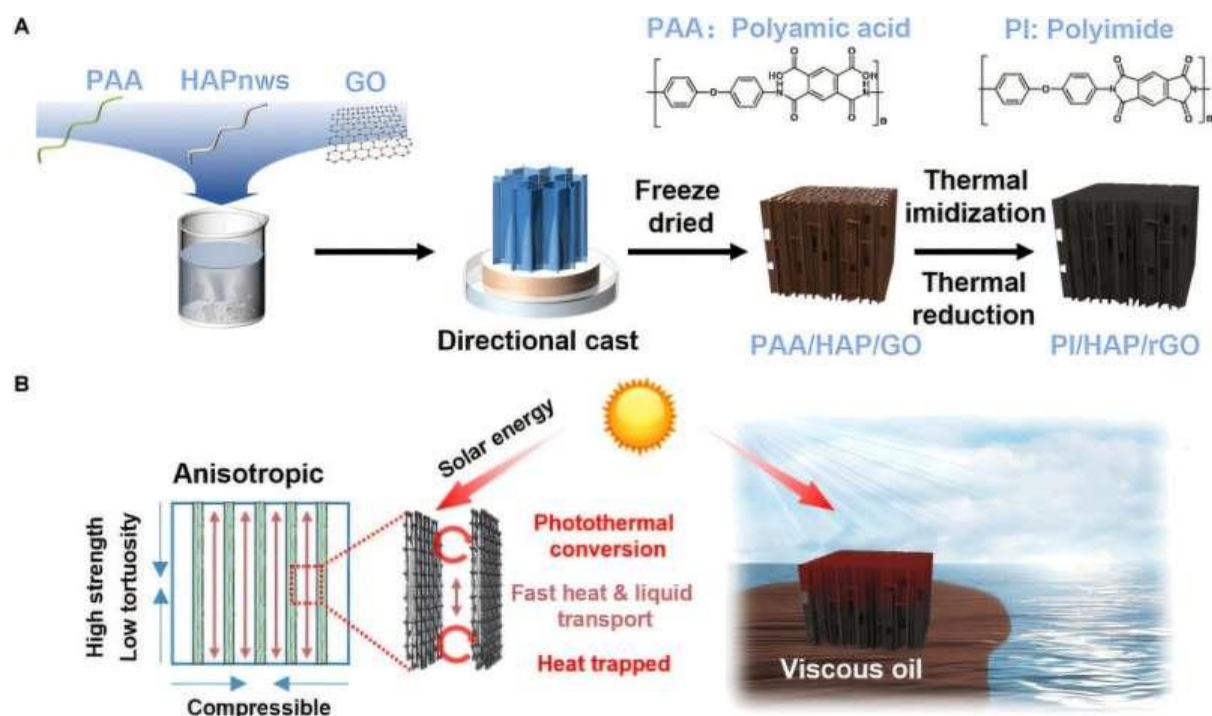
"Importantly, our method could lead to the development of high-quality thin-film devices leading to high-speed communication beyond 5G."

This study's framework could pave the way for breakthroughs in sensor technology, nonequilibrium physics, and high-performance materials by uncovering hidden structure-function relationships and advancing complex system analysis.

More information: Misato Tone et al, Linking structure and process in dendritic growth using persistent homology with energy analysis, *Science and Technology of Advanced Materials: Methods* (2025). DOI: [10.1080/27660400.2025.2475735](https://doi.org/10.1080/27660400.2025.2475735)
Provided by [Tokyo University of Science](#)

Aerogel provides enhanced oil adsorption through anisotropic structure

by Research



(A) Schematic of the synthesis route of the PI/HAP/rGO aerogel. (B) Illustration of the structure, properties, and application of the PI/HAP/rGO aerogel. Credit: *Research* (2024). DOI: 10.34133/research.0512

Oil contamination from various human activities (such as oil spills from production, transportation, shipping, and storage) and natural events (e.g., natural seepage) has caused significant environmental, ecological, and economic impacts. Enhancing the adsorption efficiency of adsorbent materials for high-viscosity oil remains a significant challenge for researchers.

A research team from the University of Alberta has developed a highly robust, compressible, anisotropic, and fire-retardant aerogel adsorbent composed of polyimide (PI), hydroxyapatite nanowires (HAPnws), and reduced [graphene oxide](#) (rGO). This innovative material leverages reduced flow tortuosity through its anisotropic structures and solar-assisted viscosity reduction via photothermal materials. The findings are [published](#) in the journal *Research*.

"It is challenging for most conventional porous adsorbent materials to efficiently adsorb viscous oils," said Hongbo Zeng, who led the research. "This is because randomly

distributed pores exert high resistance to oil flow, particularly for highly viscous oils, preventing the oil from penetrating the internal space of the adsorbent materials. This results in low adsorption capacity and slow adsorption rates."

Inspired by the aligned channels in wood, which facilitate rapid water transport, the authors believe that fabricating porous materials with aligned channels using directional freeze-casting can significantly enhance the adsorption efficiency for viscous oils. In addition, incorporating photothermal materials to reduce oil viscosity through photothermal effects is a promising strategy to improve the adsorption performance of porous adsorbents for viscous oils.

The anisotropic PI/HAP/rGO aerogel developed in this work features vertically aligned channels, enabling superior adsorption efficiency (with an adsorption coefficient K_s 0.37 Kg $m^{-1} s^{-1/2}$ for engine oil with a viscosity of 144.36 mPa·s) for oils of varying viscosities compared to aerogels with uniform pores, thanks to the significantly reduced flow tortuosity.

Meanwhile, the photothermal properties of rGO enhance the adsorption speed of PI/HAP/rGO under sunlight, even for ultra-high-viscosity crude oil. In addition, PI/HAP/rGO exhibits excellent fire resistance, allowing reusability via both adsorption-compression and [adsorption](#)-combustion cycles.

This study provides valuable insights into the design of porous adsorbents for highly viscous oils, with the PI/HAP/rGO aerogel showing great potential for the rapid cleaning and recovery of viscous [oil spills](#).

More information: Pan Huang et al, Highly Robust, Compressible, Anisotropic, and Fire-Retardant Polyimide/Hydroxyapatite Nanowires/Reduced Graphene Oxide Aerogel for Rapid Adsorption of Viscous Oil Assisted by Sunlight, *Research* (2024). DOI:

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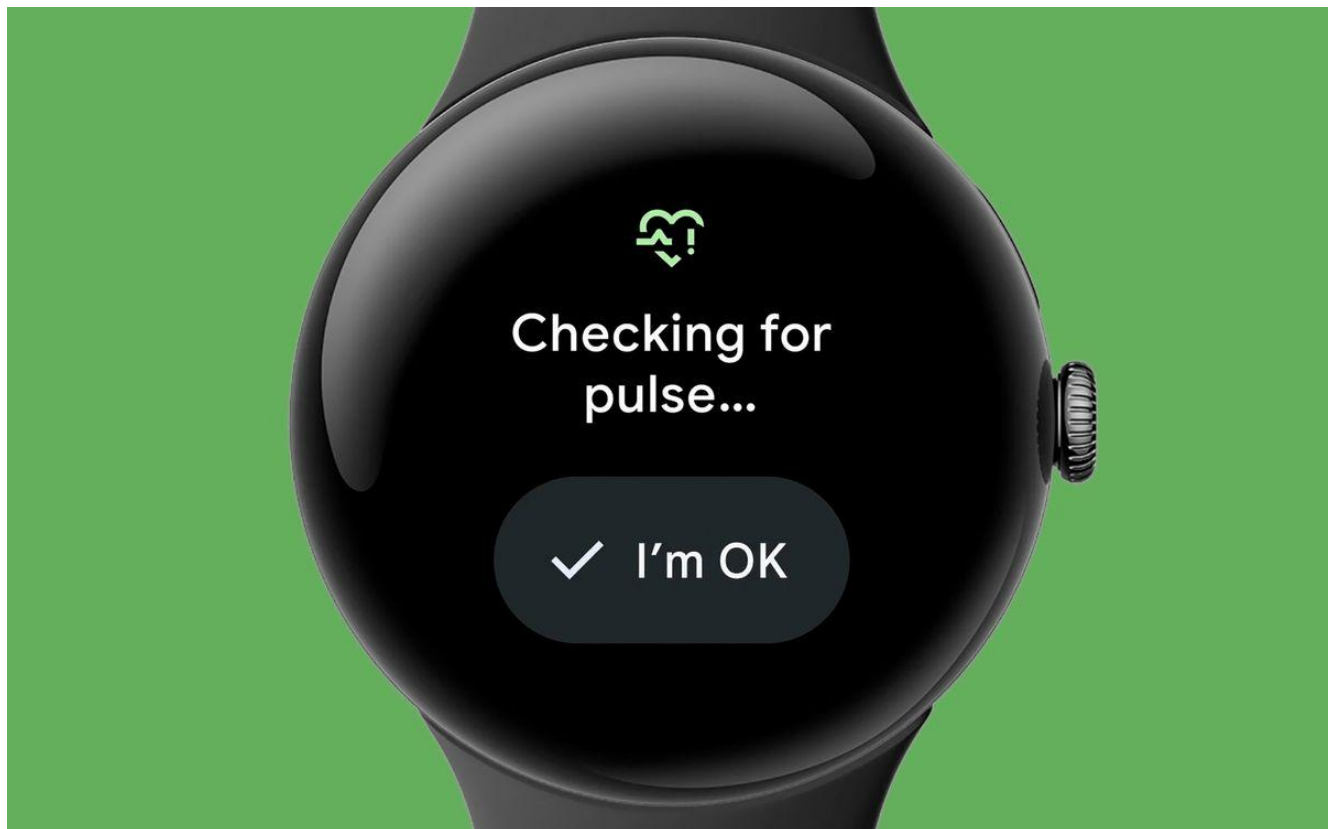
Journal information: [Research](#)

Provided by Research

Google's Pixel Watch Knows When Your Heart Stops Beating

The feature set to roll out in the U.S. this month will call 911 if you can't

ELISSA WELLE
11 MAR 2025



Later this month, [Google](#) is expected to roll out software on its Pixel Watch 3 in the [United States](#) that has the potential to correctly identify two-thirds of [out-of-hospital cardiac arrests](#) in people wearing the smartwatch. The feature uses AI to detect when the wearer no longer has a pulse, and it's meant to combat the quiet killer of cardiac events that occur at home when people are alone and unable to call for help.

A team of Google researchers and scientists at the University of Washington recently published a study testing the software, with the aim of balancing the need for a low number of false positives—when 911 might be called but not needed—with the desire to identify a loss of pulse in as many cases as possible.

“You can make this more sensitive, but it just comes at a cost,” says Google research scientist [Jake Sunshine](#) who led the study. An algorithm that “excessively” calls 911, Sunshine says, “can’t exist in the world like that.”

The study was released by the journal *Nature* as an [accelerated article preview](#) on 26 February, the day after the [FDA announced](#) premarket medical device approval of the loss of pulse feature on the Pixel for the company [Fitbit](#), which

was acquired by Google’s parent company Alphabet in 2021. The feature was approved in Europe last year, and is expected to become available to people in the U.S. this month.

Training Pixel’s AI

Data from three cohorts of Pixel Watch wearers was used to train the model. The first cohort included 100 patients with an implanted cardiac [defibrillator](#), which delivers [small pulses of electricity](#) to the heart when it detects irregular heartbeats. The patients wore a Pixel Watch when their heart temporarily stopped during a scheduled test of their defibrillator.

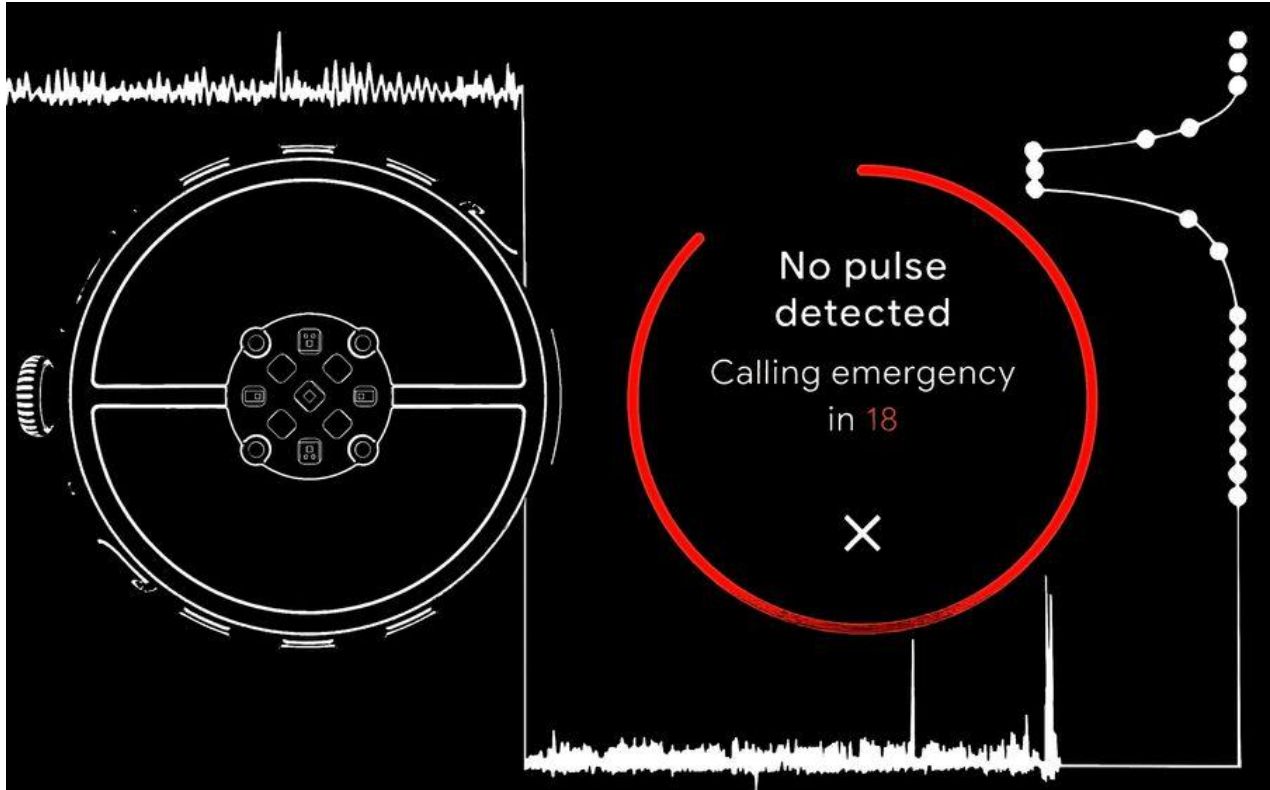
But that data was hard to get because the tests had to be done under medical supervision. “We can’t just take healthy volunteers and make their heart stop, and then send them on their way home, right?” Sunshine notes. So, the team turned to a second cohort of 99 participants who experienced a temporary loss of pulse when a tourniquet tightened on their arm. The two signals—or lack thereof—recorded on the wrist of defibrillator patients looked “indistinguishable” from the signals of people with a tourniquet wrapped around their arm. The third and largest cohort included nearly 1,000 Pixel Watch wearers living their daily lives.

The model was trained to identify the transition between a regular heart rhythm and loss of pulse. Part of the model processed the pulse signal to identify if the amplitude dropped and if the accelerometer detected any movement. Another part of the model used [neural networks](#) to quickly run through more than 500 signal features in order to confirm that a transition between pulse states took place.

But these signals can also occur when a wearer simply falls down or lies in an awkward position, Sunshine says. The model needed to proceed through additional checks before calling 911.

After identifying a possible loss of pulse, the watch turns on an [infrared light](#) that penetrates deeper into the skin than the standard green light that is always on to detect pulse. The watch searches for a pulse as the green and infrared lights flood the wrist. At the same time, another algorithm checks that the pulse detected, if there is one, matches the regularity of a beating heart.

Finally, a “quite annoying” haptic buzz with an irregular pattern is turned on, Sunshine says. If the wearer is still motionless after 35 seconds of buzzing, then 911 is called. The goal is for [classification](#) to occur in around one minute.



The [algorithms](#) in Google's Pixel Watch look for changes in pulse amplitude that might be a sign of cardiac arrest. GOOGLE

Specificity Over Sensitivity

After training the algorithm in these controlled settings, Sunshine and his colleagues tested the feature on 355 Pixel wearers outside the lab, yielding one errant call to 911. The team also tested the model back in the lab on a new set of participants using the tourniquet technique to temporarily pause their pulse. There, the model correctly identified a loss of pulse in 67 percent of the more than 1,000 sessions of tourniquet-induced pulselessness conducted in the lab by 156 participants (21 of

whom were professional stunt persons). This means that the algorithm did not catch around one third of cases where there was a loss of pulse.

The decision to maximize specificity over sensitivity is understandable to [Mahsa Khalili](#), a postdoctoral researcher at the University of [British Columbia](#), who studies out-of-hospital cardiac arrests and was not involved in this work. Similar to other models, this one will likely improve as more data comes in from the U.S.-based users who opt in to the feature, she says.

While many academic labs are limited by the number of participants willing to enroll in cardiac monitoring studies, Google is uniquely resourced and situated to reach many more end users, Khalili adds. The Google research team made the details about the participant numbers and [system architecture](#) were made available, but only published pseudo code of the model itself.

The opt-in feature is geared toward the general population. But like all [medical devices](#), it is not [for certain populations](#), such as people with severe cardiac disease, Sunshine says. He and the team expect to evaluate the real-world data as it comes in and disseminate the findings.

Loss of Pulse Detection: A first-of-its-kind feature on Pixel Watch 3

Aug 13, 2024

Many loss of pulse incidents happen when the person is alone, leaving them with effectively no chance of receiving resuscitation. Loss of Pulse Detection on Pixel Watch 3 can detect loss of pulse and automatically place a call to emergency services, potentially saving lives.

Loss of pulse occurs when the heart suddenly stops beating. It's a health emergency, where every minute matters. It can affect people of any age and be due to a wide range of problems inside or outside the heart, such as primary cardiac arrest, respiratory or circulatory failure, overdose or poisoning. ¹ [Pixel Watch 3](#) introduces a first-of-its-kind Loss of Pulse Detection feature to help people receive emergency care in these situations, even if they're alone and unable to make the call themselves. ²

Getting help from emergency medical services or other trained professionals quickly is critical, but that usually relies on a bystander to recognize the situation and provide or call for help. Unfortunately, many loss of pulse incidents happen when a person is alone, leaving them with effectively no chance of receiving help.

Loss of Pulse Detection on [Pixel Watch 3](#) is an opt-in feature that has the ability to detect loss of pulse and automatically place a call to emergency services if you are unresponsive to provide potentially life-saving care. ³ Here's why we created Pixel Watch 3's Loss of Pulse Detection feature to fill that gap, and how it works.

An animation of the Loss of Pulse Detection feature in action on Pixel Watch 3. First, the watchface shows text saying the watch is checking for a pulse, above a button the user can tap that says I'm OK. The watch then goes into a countdown before making an emergency call.

Example of the user flow for the Loss of Pulse Detection feature.

How our Loss of Pulse Detection feature works

Loss of Pulse Detection combines signals from Pixel Watch 3's sensors, AI and signal-processing algorithms to detect loss of pulse events, with a thoughtful design — built from user research — to limit false alarms. The feature uses signals from the Pixel Watch 3's existing Heart Rate sensor, which uses green light to check for a user's pulse.

If the feature detects signs of pulselessness, infrared and red lights also turn on, looking for additional signs of a pulse, while the motion sensor starts to look for movement. An AI-based algorithm brings together the pulse and movement signals to confirm a loss of pulse event, and if so, triggers a check-in to see if you respond.

The check-in asks if you're OK while also looking for motion. If you don't respond and no motion is detected, it escalates to an audio alarm and countdown. If you don't respond to the countdown, the LTE watch or phone your watch is connected to automatically places a call to emergency services, and shares an automated message that no pulse is detected along with your location.

Our goal is to make a difference and contribute towards saving lives. While Loss of Pulse Detection won't detect every loss of pulse event, we believe it can make a meaningful difference, providing help when it counts most to people and their loved ones.

Loss of Pulse Detection will be available on Pixel Watch 3 in September in various countries in Europe, including the U.K., France, Austria, Denmark, Ireland, the Netherlands, Norway, Sweden and Switzerland. We'll continue working with regulatory bodies to make the feature available in more countries.

How we developed and tested Loss of Pulse Detection

Our goal has been to build a potentially life-saving feature, and to develop it responsibly. Because loss of pulse events are timely but relatively rare emergencies, they can't easily be observed, reproduced and tested in real-world settings. We had to find other ways to collect enough data to develop the feature to detect true loss of pulse events.

An animation zooms into a black and white Pixel Watch 3 simulation to reveal different black and white charts, including one labeled accelerometer and another labeled inference probability. The animation ends by zooming out to show a Pixel Watch 3 making an emergency call.

Loss of Pulse Detection combines signals from Pixel Watch 3's sensors, AI and signal-processing algorithms to detect loss of pulse events. [Caption updated Aug 20]

The breakthrough came when we used AI and digital signal processing, together with data collected in clinical settings. We worked with cardiologists, gaining unique insights into how a loss of pulse manifests on the watch, that informed our AI algorithm that detects these time-sensitive events. We then tested the algorithm using hundreds of thousands of hours of real-life user data from a diverse group of people.

Finally, to validate that our technology could function in real-life emergency situations, we partnered with stunt actors to simulate real-world circumstances of loss of pulse. The actors wore tourniquets to artificially induce pulselessness, and then simulated the types of falls that would mimic a person suddenly losing their pulse.

Of course, creating a responsible solution goes beyond algorithms. We've also been working with emergency medical service providers, dispatchers, paramedics and other experts, getting feedback and ideas along the way to ensure what we're building is as helpful to our users and the wider emergency medical service ecosystem as possible.

Loss of Pulse Detection is part of our broader effort to make Pixel Watch a [guardian of your health and safety](#). It joins other features like [Irregular Heart Rhythm Notifications](#), which can check for signs of atrial fibrillation; [Safety Check](#), which allows you to set a timer on your device when you feel unsafe to then send your location to a loved one if you don't respond; and [Fall](#) and [Car Crash Detection](#), which can check in and call for help if you fall or are in an accident.

GM Already Has The Perfect Design To Save Buick

The General Motors Design Instagram account is a place where GM's designers can post the ideas and shapes that never really made it off the drawing board. Vehicles that were penned to help showcase new ideas, to try out changes in styling language, and, probably, just to blow off some of their creative energies before tackling the cupholder for the next [Equinox](#).

This latest is another great one: a look at a Buick crossover coupe that shows some definite connections with the SUV that would become the [Envista](#).

One Of GM's Top Designers Is Having Some Fun



Buick Design Concept (3)

The sketches are from Aaron Riggs, GM's lead exterior designer. He's been at GM since 2012 and has led the Buick Exterior Studio since 2018. We've seen his work before on models including the [Cadillac Escala concept](#) (which became the [Celestiq](#)) and a four-door Buick Electra.

This time around, we're looking at what appears to be a much more stylish [Envision](#)-sized crossover. The concept doesn't have a name, but it does have one heck of a shape.

A boat-like nose doesn't seem to have anywhere to put the headlights, but that's not unusual for a concept car. Someone else can figure that part out later. The model gets a fastback tail that is far more stylish than Buick's traditional upright crossovers.

It's a popular look these days, with BMW, Mercedes, and Audi all doing crossover-coupe models. Even in Buick's own league, the [Toyota Crown](#) delivers a similar experience as a high and curvy shape.

Buick Could Use A Fifth Model



2022 Buick Wildcat EV Concept Silver High Front Angled View

With Buick offering just four models, does this mean it is looking at expanding? Not likely, but there are some bits that could end up making it to one of the models Buick does ultimately produce. The chrome trim, for example, that runs from the base of the A-Pillar to the very rear of the car would work for Buick. The same goes for the lower door moldings and even the arc of the front of the hood, where [the Buick logo](#) resides.

So if you want to know what the next generation of Buicks could look like, this is your best place to find out. Again, don't expect this entire design to make it to production. Do expect it to give some cues to models that do - much like how Buick didn't build the [Wildcat EV concept](#) of 2022, but brought that car's nose to production in the form of the thin L-shaped accent lights and prominent overhanging nose of every Buick crossover launched or refreshed since then.

That's how many of these concept drawings shape a generation of actual vehicles.

New metamaterial stores 160x more energy, paving the way for smarter robots

Human progress has always depended on the ability to store and release energy efficiently.

Springs, buffers, and energy-damping materials power everything from industrial machines to futuristic robotic limbs.

Now, a breakthrough from scientists at the Karlsruhe Institute of Technology (KIT) is pushing energy storage technology to the next level.

They have developed a new class of mechanical metamaterials—artificially engineered structures that store and release elastic energy more efficiently than ever before.

This innovation could lead to major advancements in energy-efficient robotics, mechanical systems, and flexible structures that maximize energy use while maintaining strength and durability.

These materials use a unique structure of twisted rods that deform in a helical shape, allowing them to absorb and release large amounts of elastic energy.

By leveraging this novel design, researchers have created a material that combines high stiffness, high strength, and exceptional flexibility.

What are mechanical metamaterials?

Metamaterials are specially engineered materials designed to have properties that don't exist in nature.

They are made by arranging tiny structural elements in precise ways to create materials with enhanced mechanical behavior.

In this case, the KIT researchers developed a mechanical metamaterial built from rods that are tightly twisted and arranged in a specific pattern.

Normally, when a spring bends, stress builds up at its top and bottom surfaces, which can lead to breaking or permanent deformation.

However, twisting a rod instead of bending it spreads the stress more evenly across its surface. This means it can store more energy without damage.

Peter Gumbsch, Professor for Mechanics of Materials at KIT's Institute for Applied Materials (IAM), explained, "The difficulty is to combine conflicting properties: high stiffness, high strength and large recoverable strain."

By carefully arranging these twisted rods into a structured network, the scientists created a material that can store far more energy than traditional materials while remaining strong and stiff.

Designing a material with maximum elasticity

Gumbsch and his team, which includes researchers from China and the U.S., successfully translated this concept into a functional metamaterial.

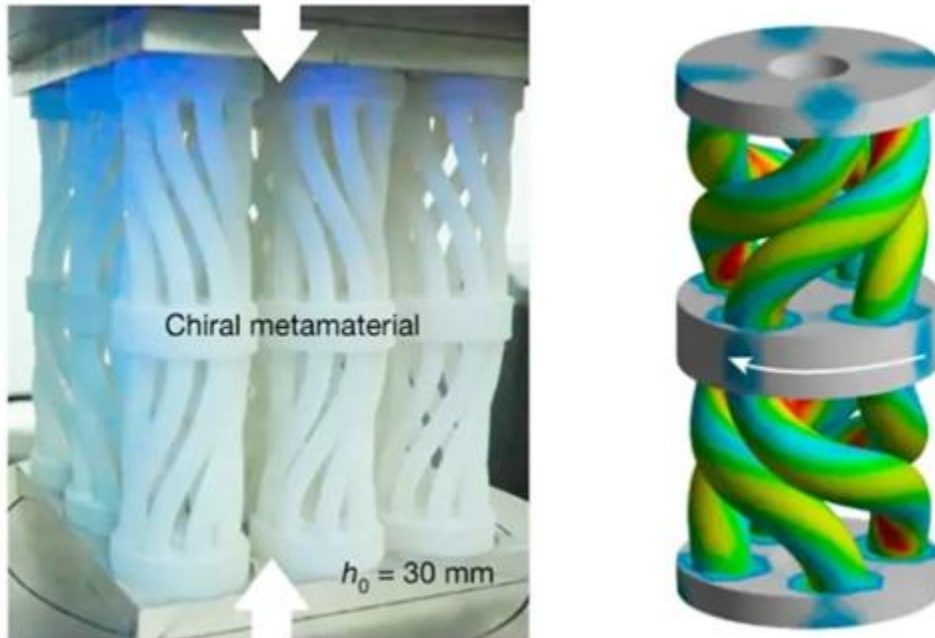
"At first, we detected a mechanism for storing a high amount of energy in a simple round rod without breaking it or deforming it permanently," said Gumbsch.

"By defining a clever arrangement of the rods, we then integrated this mechanism into a metamaterial."

By aligning the rods in a precise way, the researchers created a material that could be stretched or compressed while still returning to its original shape.

Computer simulations predicted that this metamaterial would have high stiffness and could handle large forces.

Their tests confirmed that the material's energy storage capacity, or enthalpy, is between 2 and 160 times greater than other known metamaterials.



Helical deformation of the new metamaterial. – IAM, KIT / Collage: Anja Seifrin, KIT

Future applications in robotics and energy storage

The potential uses for this new type of material are vast. “Our new metamaterials with their high elastic energy storage capacity have the potential to be used in various areas in the future where both efficient energy storage and exceptional mechanical properties are required,” said Gumbsch.

Robots could become more flexible and durable, benefiting from the material’s ability to stretch and recover without breaking.

Additionally, energy-efficient [machines](#) could store and release energy more effectively, improving overall performance.

Another possibility is using the twisting mechanism within the metamaterials to create purely elastic joints, removing the need for traditional hinges and improving motion in [robotic](#) limbs and wearable exoskeletons.

With these advancements, mechanical metamaterials could pave the way for stronger, more efficient, and longer-lasting technology.

The study is published in the journal *Nature*

Scientists create super skin that self-heals 90% of cuts in 4 hours, fully repairs in 24



Scientists create super skin that self-heals 90% of cuts in 4 hours, fully repairs in 24

We come across different types of gels in our daily lives, such as in hair products, foods, and even in our bodies. However, human skin has unique properties that are difficult to replicate—it combines both strength and flexibility while also having the remarkable ability to heal itself within 24 hours after injury. Artificially synthesized gels have been able to achieve only one at a time.

Scientists from Aalto University and the University of Bayreuth have now crossed these boundaries. A major milestone in materials science has been achieved after the development of a self-healing, flexible, and strong hydrogel. This milestone opens a window to newer possibilities in the fields of wound healing, soft robotics, artificial skin, and drug delivery.

A breakthrough in hydrogel design

In order to achieve these features in the rigid hydrogel, the researchers used ultra-thin clay nanosheets. These sheets created a dense entangled network of polymers that strengthened hydrogels and stopped them from being too soft. They also increased the ability of the gel to self-repair.

The researchers mixed a powder of monomers with water that contains nanosheets. The mixture was then placed under a UV lamp. "The UV radiation from the lamp causes the individual molecules to bind together so that everything becomes an elastic solid – a gel," Chen Liang, one of the authors, explains.

The innovation in question relies heavily on subsequent interactions of the polymers. "Entanglement means that the thin polymer layers start to twist around each other like tiny wool yarns, but in a random order," adds Hang Zhang from Aalto University. "When the polymers are fully entangled, they are indistinguishable from each other. They are very dynamic and mobile at the molecular level, and when you cut them, they start to intertwine again."

The healing process is phenomenally fast. The [hydrogel](#) is 80-90% repaired within the first four hours of being cut and wholly restored after twenty-four hours. The hydrogel has around 10,000 layers of nanosheets in a sample that is one millimeter thick, allowing it to achieve stiffness akin to human skin while enabling it to stretch.

Nature-inspired materials with real-world potential

"This work is an exciting example of how biological materials inspire us to look for new combinations of properties for synthetic materials. Imagine robots with robust, self-healing skins or synthetic tissues that autonomously repair," says Olli Ikkala from Aalto University.

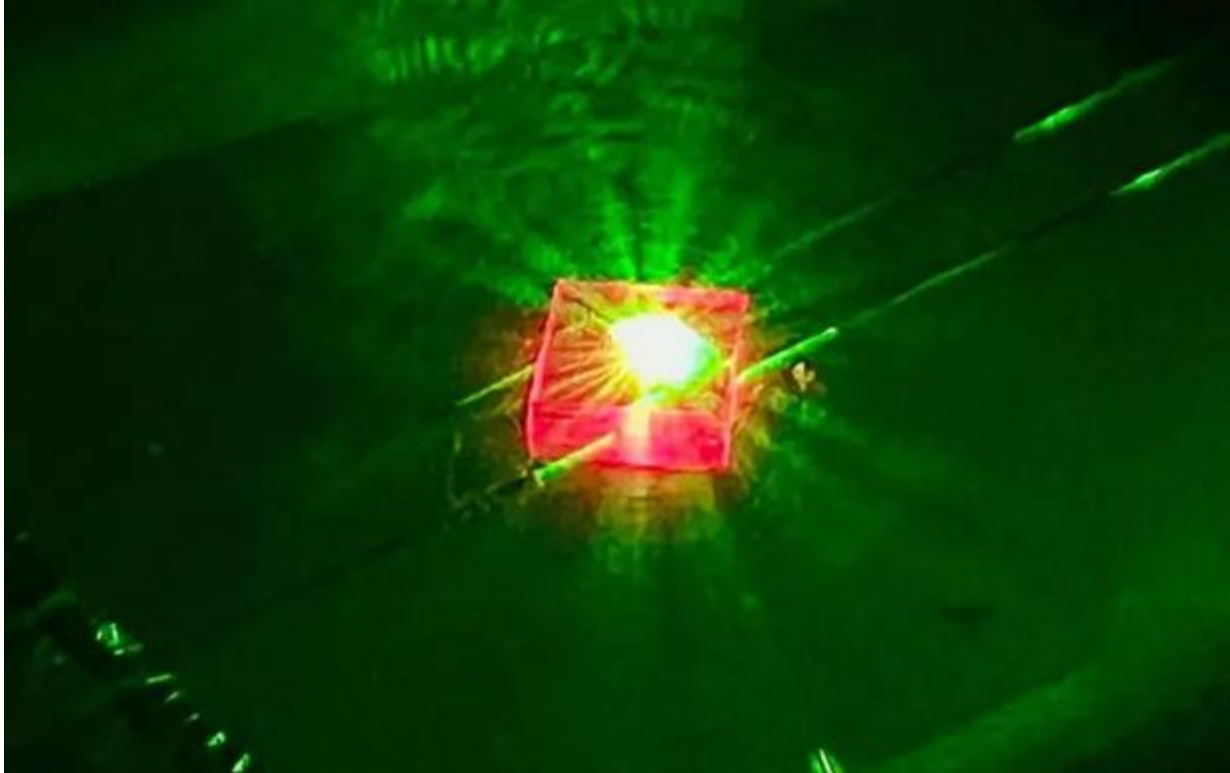
"It's the kind of fundamental discovery that could renew the rules of material design."

After further development and research for commercial purposes, self-healing synthetic tissues, flexible [robots](#) with protective outer layers, and medical materials that can autonomously repair damage stand to benefit from this study.

'Stiff, strong and self-healing [hydrogels](#) have long been a challenge. We have discovered a mechanism to strengthen the conventionally soft hydrogels. This could revolutionise the development of new materials with bio-inspired properties,' [concludes](#) Zhang.

The study has been published in [Nature Materials](#).

Researchers create a new type of “time crystal” inside a diamond



Washington University physicists shine a microwave laser into a chunk of diamond to create a time quasicrystal, a new phase of matter that repeats precise patterns in time and space. Image credits: Washington University.© ZME Science

Imagine repeatedly tapping a bell with two fingers at uneven rhythms — over time, a haunting pattern emerges. It’s not a simple beat, but something more elusive and eerie. Now imagine doing this not with sound, but with time itself. If your brain feels a bit funny, well, that’s more than understandable.

Yet, in a dazzling experiment, a group of physicists has done just that. They’ve created a new kind of temporal structure called a “discrete time quasicrystal” (DTQC), where the rhythms of quantum spins seem to defy both physics and geometry.

A What?!

[A crystal](#) is a material whose atoms or molecules are arranged in a repeating, orderly pattern in space. No matter what type of rock or how fancy it looks, all

crystals are basically just [ordered arrangements of molecules](#). The idea of time crystals, however, sounds like something straight out of science fiction.

A time crystal is a phase of matter that breaks [time-translation symmetry](#) — it exhibits a repeating pattern in time, even though the system is driven by a steady, periodic force. Unlike a ticking clock, where something moves because it's being pushed, a time crystal responds by oscillating at a slower rate than the periodic drive itself, creating a stable, self-organized rhythm that doesn't fade away. This concept is relevant because it reveals that quantum systems can organize not just in space, like regular crystals, but also in time.

"In theory, it should be able to go on forever," says [Chong Zu](#), assistant professor of physics, one of the study authors. In practice, time crystals are fragile and sensitive to the environment. "We were able to observe hundreds of cycles in our crystals before they broke down, which is impressive."

Time crystals were a radical idea proposed by Nobel laureate Frank Wilczek just over a decade ago. They [have since been demonstrated](#), but only under special conditions — when systems are kicked at regular intervals, like a kid on a swing pushed at perfect beats.

But what happens if you get a bit wild with your pushing rhythm?

A Different Timing

This is what researchers did in the new study. Instead of a simple, periodic tick-tock, the team behind this new discovery used *quasiperiodic* driving — two pulsing rhythms based on incommensurate frequencies. That means their ratio isn't a neat fraction. In this case, the scientists chose the [golden ratio](#) (approximately 1.618), a number that keeps popping up in nature.

Using these two frequencies, they zapped a cloud of quantum spins embedded in the diamond. These spins are essentially tiny defects in the crystal called [nitrogen-vacancy centers](#). They act like quantum compass needles, and they can be controlled with lasers and microwaves. When they applied their two-frequency pulses, the spins didn't go haywire. They can be locked into a new kind of rhythm. Not a simple one, but a rhythm nonetheless. The result?

"It's an entirely new phase of matter," Zu said.

Groundbreaking physics

The mere existence of time crystals and quasicrystals confirms some of the most ethereal hypotheses in quantum physics, so their existence is inherently useful. Time crystals and now time quasicrystals show that the realm of nonequilibrium quantum matter is far richer than we thought.

This experiment gives us a framework for understanding what can happen when energy is constantly pumped into a system, but instead of going chaotic, the system settles into a strange kind of harmony. It's a new way of being, and that's why Zu says it's a new phase of matter.

What's more, the robustness of these phases hints at real applications. Because time crystals can theoretically tick forever without losing energy, they could be useful for quantum computers. It's still early days, but the potential is enormous.

"They could store quantum memory over long periods of time, essentially like a quantum analog of RAM," Zu said. "We're a long way from that sort of technology. But creating a time quasicrystal is a crucial first step."

If you feel confused by this whole thing, well, you're not alone. Richard Feynman, the brilliant and irreverent physicist, once said, "If you think you understand quantum mechanics, you don't understand quantum mechanics." He'd probably say the same about time after reading this study.

Time, in our ordinary experience, is a straight line. It moves forward, evenly, like a metronome. But in the world of quantum spins, time can twist, flip, split, and organize itself into patterns that are neither random nor regular. They're something else entirely. Something new.

The research has been [published](#) in the journal *Physical Review X*.

How To Use Neuromarketing To Help Your Business

Neuromarketing is the application of [neuroscience](#) to marketing. The term neuromarketing was coined by [Professor Ale Smidts](#) in the early 2000s as part of his research into marketing psychology in the brain. As this field expanded, scientists were then able to use [fMRIs](#) and [EEGs](#) to analyze brain behavior when [exposed to various types of market research experiments](#).

By analyzing the brain imaging to watch neural circuits light up, market researchers were able to understand what products people are inclined to buy. Neuromarketing psychological concepts might have been new to the business world 20 years ago, but today even small business owners on a budget can use this market research to their advantage.

Here are some neuromarketing concepts that can help any entrepreneur.

The Framing Effect

The [framing principle](#) refers to the concept of how the wording, presentation, and framing of information influences how consumers interpret information. Understanding this effect will help an entrepreneur communicate what they need to say when advertising. Everything should be written in positive framing.

For statistics, use wording like “treatments are 99% successful,” or “get 50% off”.

The IKEA Effect

The [IKEA effect](#) refers to the concept that labor adds value to the product you’re selling. This is a psychological concept called “[effort justification](#).” You can see this concept in the longtime successes of products like instant cake mixes or boxed macaroni and cheese.

While people could buy the same food and desert already made, some prefer to do it themselves with the mixes. Customization is an asset you can add to any product. Consumers will pay on a free site for customization alone.

The Paradox Of Choice

The [paradox of choice](#) is the concept that too many choices for the consumer actually leads to more psychological stress and makes it harder to choose anything at all. While in theory we like to have choices, endless choices make it less likely for anything to be bought.

This can be seen with people browsing through thousands of clothes in the mall but leaving with nothing, or looking through endless options on 10 streaming sites, and ultimately picking nothing at all to watch. Sales will increase if you give your customer the right number of options to pick from.

The Anchoring Principle

The [anchoring principle](#) is the concept that individuals will rely heavily on the first piece of information they receive to make all future choices. In marketing, this means that the first piece of information on a page will influence the script of the rest of it.

If people see the price of a product at \$100 initially, they will continue to evaluate that product at \$100 no matter what else they hear. If you write that this product, a \$100 value, is now on sale at \$75, the customer won't pay attention to the fact that they are spending \$75, so much as the fact they are receiving the \$100 product at a lower price.

The Endowment Effect

The [endowment effect](#) is the concept that people will value things once they own or perceive ownership over products. This comes from a psychological effect called [loss aversion](#), where the pain of losing something is worse than the pleasure of winning or gaining something.

Once people have something, they'll be so attached to it they'll be upset if they lose it, even if they don't need it or weren't planning on buying it. In marketing, this is why it's beneficial for you to offer free trials, especially for subscription-based products. After being used to a month of a service, the client will be more likely to want to pay and keep it rather than lose something they now feel entitled to.

In summary, integrating neuromarketing concepts is essential for anyone entering the marketing and market research phases of business. Although creativity and informed assumptions continue to play critical roles in crafting effective marketing campaigns, the use of scientifically validated neuromarketing strategies significantly diminishes the level of guesswork. By relying on data-driven insights, businesses can make more informed decisions, tailor their strategies more precisely, and increase the likelihood of connecting meaningfully with their target audience.

MARCH 30, 2025

AI-powered drones track down fires in German forests

by Sebastien ASH



German technology company Dryad is creating AI-powered drones to track down and extinguish wildfires.

Inside a green orb planted in the German countryside is a high-tech aid to prevent wildfires that have grown more common and destructive with rising global temperatures.

The installation, resembling a giant golf ball covered in [solar panels](#), is the hangar for an AI-powered [drone](#) that its developer hopes one day will be able to sniff out and extinguish new blazes in minutes.

"Fires are spreading much faster and more aggressively than in the past. That also means we have to react more quickly," Carsten Brinkschulte, the CEO of the German firm Dryad, told AFP at a demonstration of the technology outside Berlin.

Once a rarity, the German capital has to get used to more wildfires. Flames ripped through a forest on the city's western edge in the midst of a 2022 heat wave that saw several wildfires spring up in Germany.

The sort of tinderbox conditions which promote blazes—where heat, drought and strong winds dry out the landscape—have increased with climate change.

Wildfires have reached the point where they were "basically unstoppable," said Lindon Pronto, senior wildfire management expert at the European Forest Institute.

That is why action is needed to develop tools to "address fire in the prevention phase, during the operational phase, and also post-fire," said Pronto.



Dryad eventually hopes the drones will put out fires using novel technology: a "sonic cannon" blasting low-frequency sound waves at the right pressure.

'Prevent a disaster'

Dryad is in the running with 29 other teams from around the globe for a multi-million-dollar prize to develop the ability to autonomously put out fires within 10 minutes.

During Dryad's demonstration on Thursday—the first for a computer-steered wildfire detection drone according to the company—chemicals in smoke from burning wood were picked up by sensors distributed in the forest.

The signal was relayed back to the company's platform which released the drone from the orb. The unit rose above the trees, charting a zig-zag course to track down the precise location and extent of the fire.

Firefighters using the information collected by the drone would be able "to respond much more efficiently and quickly and prevent a disaster," Brinkschulte said.

Dryad eventually hopes to have the drone descend below the canopy and put out the fire using a novel technology: a "sonic cannon" blasting low-frequency sound waves at the right pressure to suppress small fires.

An experimental acoustic suppression method, if it can be realized, would save the drone from carrying "large amounts of heavy water," making the unit more nimble and effective, according to Brinkschulte.



Technologies like Dryad's are a step towards putting out fires 'without putting people's lives in danger'

'Civilization meets nature'

Technologies like Dryad's are a step towards putting out fires "without putting people's lives in danger," said Pronto, a native of California, where recent wildfires have had a devastating impact.

Huge blazes in Los Angeles in January killed 29 people, razed more than 10,000 homes and caused some \$250 billion (231 billion euros) in damage, according to estimates by the private meteorological firm AccuWeather.

The greatest benefits of an autonomous fire prevention system would be in areas where "civilization meets nature," Brinkschulte said.

Such crossover zones are the most vulnerable to man-made [wildfires](#) and "where the risk to life and limb is naturally highest."

The company hopes to bring the drone to market in 2026, with the first deployment likely to be outside Europe.

"These systems still need to have the [regulatory framework](#) to be able to operate commercially," Brinkschulte said, adding that Dryad was aiming for deployment in Europe in the "coming years."

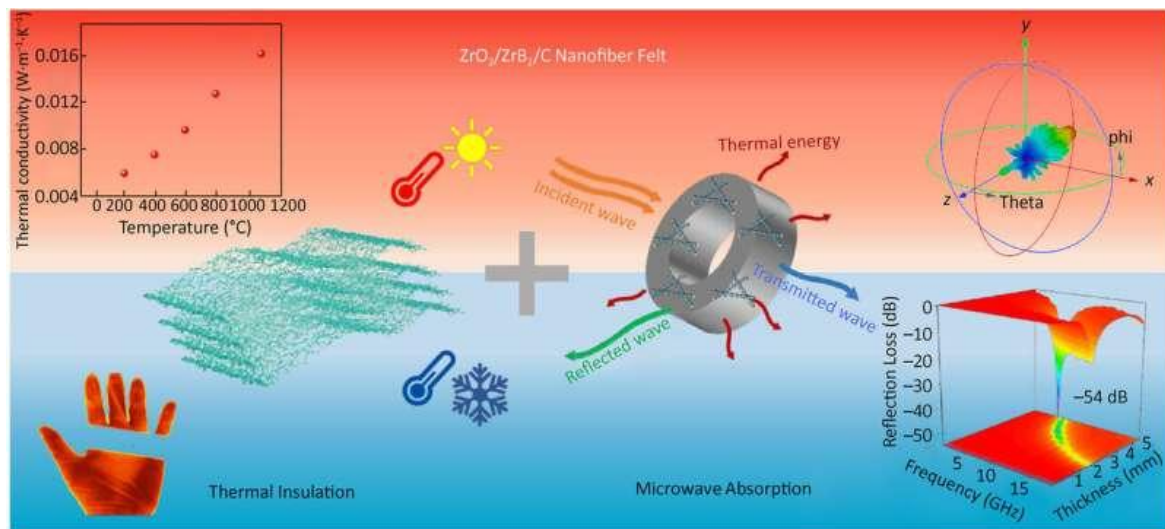
A couple of kinks need to be worked out before then, however. The first attempt to respond to the dummy fire on Thursday was held up by a faulty GPS signal.

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APRIL 1, 2025

New flexible nanofiber material combines strong microwave absorption with exceptional thermal insulation

by Zhao Weiwei, [Chinese Academy of Sciences](#)



Credit: *Journal of Materiomics* (2024). DOI: 10.1016/j.jmat.2024.100988

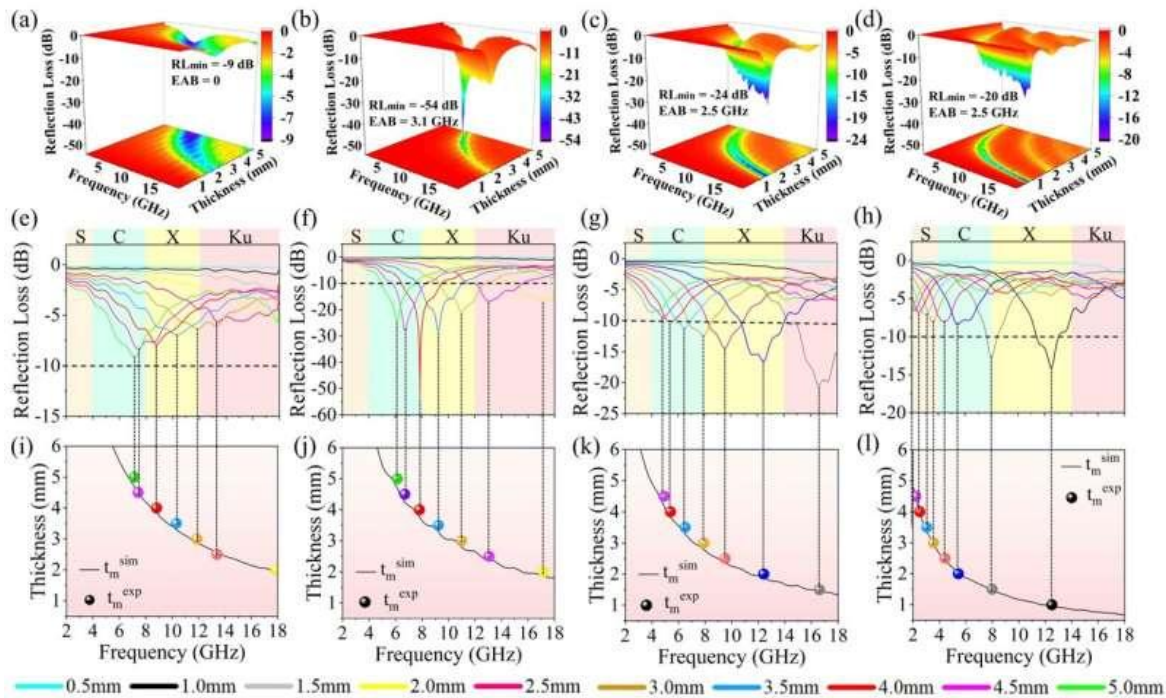
Recently, a research team led by Prof. Huang Zhulin from the Hefei Institutes of Physical Science of the Chinese Academy of Sciences successfully synthesized a flexible nanofiber felt with ultralow thermal conductivity and exceptional electromagnetic wave absorption properties.

The findings are [published](#) in the *Journal of Materiomics*.

With the rapid advancement of modern technologies, there is growing demand for materials that can efficiently absorb [electromagnetic waves](#) while also being lightweight, heat-resistant, and durable under [extreme conditions](#). However, current carbon-based materials, though widely used, often suffer from poor impedance matching and limited performance in [harsh environments](#).

To overcome these challenges, the researchers designed a novel $\text{ZrO}_2/\text{ZrB}_2/\text{C}$ (zirconia/zirconium diboride/carbon) nanofiber felt. By incorporating ZrO_2 and ZrB_2 into carbon fibers, they successfully addressed the issue of excessive electromagnetic wave reflection caused by the high conductivity of pure carbon. This multi-component composite structure greatly improved impedance matching and enhanced the material's ability to absorb electromagnetic waves across a broad frequency range.

The [new material](#) achieved a maximum reflection loss of -54 dB and a broad absorption bandwidth of 3.1 GHz, indicating excellent microwave absorption capabilities. In addition, [theoretical calculations](#) revealed that the $\text{ZrO}_2/\text{ZrB}_2$ components promote electron transfer at the interfaces, boosting interfacial polarization—key mechanisms for efficient electromagnetic wave attenuation.



Reflection loss diagrams for four sample groups with varying $\text{ZrO}_2/\text{ZrB}_2$ loading contents,

and correlations between simulated thickness and peak frequency for the four sample groups. Credit: Yang Chengwan

Further simulations also demonstrated the material's radar stealth capability, showing its ability to reduce radar wave scattering—an essential feature for stealth applications.

Beyond its electromagnetic performance, the material also showed exceptional thermal insulation properties. Its complex multi-interface structure acts as a barrier to heat flow while its surface properties enhance heat radiation dissipation. As a result, the material achieved an ultralow thermal conductivity of just $0.016 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ at $1,100^\circ\text{C}$, which is among the lowest reported for such materials.

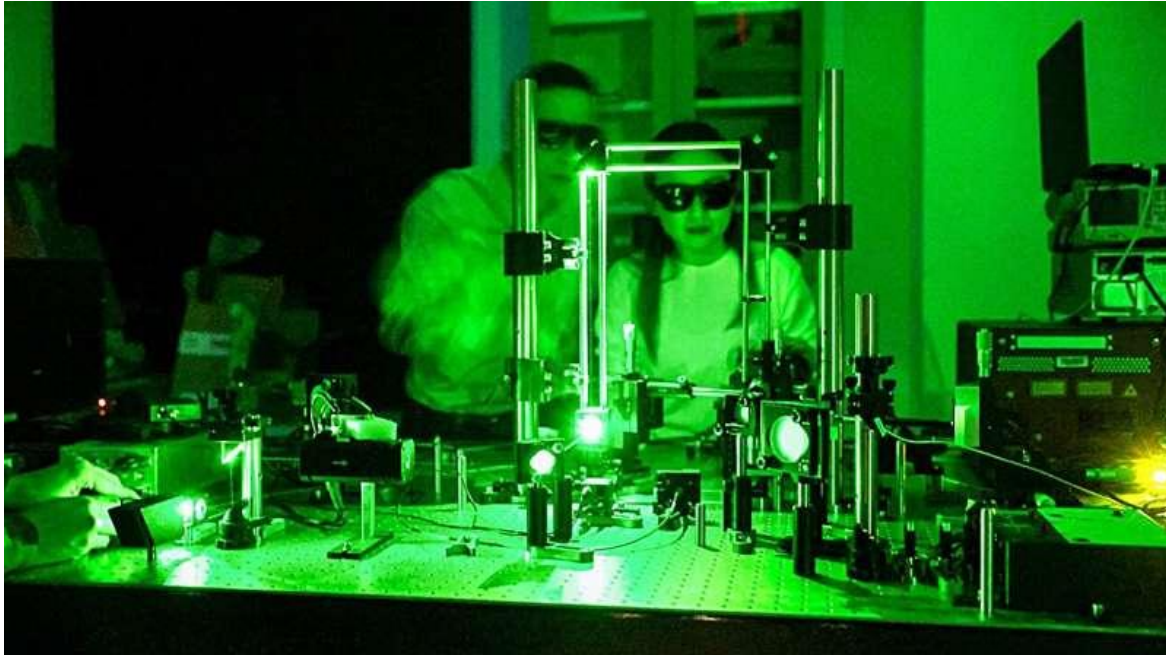
This study paves a novel pathway for designing multifunctional microwave-absorbing materials suitable for complex and extreme environments, according to the team.

More information: Chengwan Yang et al, Flexible $\text{ZrO}_2/\text{ZrB}_2/\text{C}$ nanofiber felt with enhanced microwave absorption and ultralow thermal conductivity, *Journal of Materiomics* (2024). DOI: [10.1016/j.jmat.2024.100988](https://doi.org/10.1016/j.jmat.2024.100988)
Provided by [Chinese Academy of Sciences](#)

APRIL 1, 2025

Supersonic speed limit for strong metal bonding revealed

by Syl Kacapyr, [Cornell University](#)



Assistant professor Mostafa Hassani (left) and doctoral student Qi Tang work with a custom-built laser optic platform to launch supersonic microprojectiles and study how high-speed metallic collisions form solid-state bonds. Credit: Cornell University

Faster isn't always better when it comes to high-speed materials science, according to new Cornell research showing that tiny metal particles bond best at a precise supersonic speed.

In industrial processes like cold spray coating and [additive manufacturing](#), tiny metal particles travel at extreme speeds and slam into a surface with such force that they fuse together, forming strong metallic bonds. This rapid, high-energy collision builds up layers of material, creating durable, high-performance components. Understanding how and why these bonds form, and sometimes fail, can help optimize manufacturing techniques and lead to stronger materials.

In a [study](#) published March 31 in the *Proceedings of the National Academy of Sciences*, Cornell scientists launched [aluminum particles](#), each about 20 micrometers in diameter, onto an aluminum surface at speeds of up to 1,337 meters per second—well beyond the speed of sound—and used high-speed cameras to record the impacts.

The results showed that bond strength increased steadily as impact velocity rose, but as velocity increased beyond 1,060 meters per second, the bond strength began to decline. By 1,337 meters per second, the particles barely adhered to the surface at all.

"It was a total surprise," said senior author Mostafa Hassani, assistant professor in the Sibley School of Mechanical and Aerospace Engineering and in the Department of Materials Science and Engineering, both in Cornell Engineering.

"The expectation was that as you go higher, you should get better bonding quality," Hassani said. "This study shows that, in fact, there is a peak in bond strength and higher speed doesn't necessarily lead to higher strengths."



A

microprojectile launch pad in the Hassani Group laboratory can shoot metal particles at supersonic speeds and capture the impact using high-speed cameras. Credit: Charissa King-O'Brien/Cornell Engineering

The researchers attribute this decline in [bond strength](#) to a phenomenon called intensified elastic recovery. At extremely high velocities, the surface material loses some of its ability to absorb energy through deformation and, instead, more energy is stored as elastic strain, causing the particles to snap back after impact. This rebound effect stretches and damages the interface, weakening the bond.

In some industrial processes, extremely high velocities can erode or even melt the surface, preventing proper bonding. Qi Tang, doctoral student and lead author of the study, said the new findings can help optimize manufacturing processes by providing insight into why erosion occurs.

"Previously, people in industry may have speculated that erosion is caused by fast-moving particles plowing through the substrate surface or by melting at the interface," Tang said. "But now we see that when you give a super-high velocity to a particle, the increased rebounding tendency can cause a previously bonded particle to detach, preventing material buildup."

While the study focused on aluminum, the researchers said the mechanism responsible for peak bonding velocity is likely universal across all metals and alloys. Subsequent studies will investigate how [particle size](#) influences the results and explore potential ways to engineer both the particles and the substrate surface to maximize bonding strength.

More information: Qi Tang et al, Microparticle impact–induced bond strength in metals peaks with velocity, *Proceedings of the National Academy of Sciences* (2025). DOI: [10.1073/pnas.2424355122](https://doi.org/10.1073/pnas.2424355122)

Journal information: [Proceedings of the National Academy of Sciences](#)

APRIL 1, 2025

Charging electric vehicles 5x faster in subfreezing temps

by Jim Lynch, [University of Michigan](#)



Engineering student Chloe Acosta plugs in an EV for charging in snowy weather on the University of Michigan's North Campus. EV charging becomes less efficient in colder weather, but a new strategy for manufacturing battery electrodes could enable charging in 10 minutes in temperatures as cold as -10C. Credit: Marcin Szczepanski, Michigan Engineering

A modified manufacturing process for electric vehicle batteries, developed by University of Michigan engineers, could enable high ranges and fast charging in cold weather, solving problems that are turning potential EV buyers away.

"We envision this approach as something that EV battery manufacturers could adopt without major changes to existing factories," said Neil Dasgupta, U-M associate professor of mechanical engineering and [materials science](#) and engineering, and corresponding author of the study [published](#) in *Joule*.

"For the first time, we've shown a pathway to simultaneously achieve extreme fast charging at [low temperatures](#), without sacrificing the energy density of the lithium-ion battery."

Lithium-ion EV batteries made this way can charge 500% faster at temperatures as low as 14 °F (-10 °C). The structure and coating demonstrated by the team prevented the formation of performance-hindering lithium plating on the battery's electrodes. As a result, batteries with these modifications keep 97% of their capacity even after being fast-charged 100 times at very cold temperatures.

Current EV batteries store and release power through the movement of lithium ions back and forth between electrodes via a liquid electrolyte. In cold temperatures, this movement of the ions slows, reducing both [battery power](#) as well as the charging rate.

To extend range, automakers have increased the thickness of the electrodes they use in battery cells. While that has allowed them to promise longer drives between charges, it

makes some of the lithium hard to access, resulting in slower charging and less power for a given battery weight.

Previously, Dasgupta's team improved battery charging capability by creating pathways—roughly 40 microns in size—in the anode, the electrode that receives lithium ions during charging. Drilling through the graphite by blasting it with lasers enabled the lithium ions to find places to lodge faster, even deep within the electrode, ensuring more uniform charging.

This sped up room-temperature charging significantly, but cold charging was still inefficient. The team identified the problem: the chemical layer that forms on the surface of the electrode from reacting with the electrolyte. Dasgupta compares this behavior to butter: you can get a knife through it whether it's warm or cold, but it's a lot harder when it's cold. If you try to fast charge through that layer, lithium metal will build up on the anode like a traffic jam.

"That plating prevents the entire electrode from being charged, once again reducing the battery's energy capacity," Manoj Jangid, U-M senior research fellow in mechanical engineering, and co-author of the study.

The team needed to prevent that surface layer from forming. They did this by coating the battery with a glassy material made of lithium borate-carbonate, approximately 20 nanometers thick. The addition of this coating sped up cold charging significantly, and when combined with the channels, the team's test cells were 500% faster to charge in subfreezing temperatures.

"By the synergy between the 3D architectures and artificial interface, this work can simultaneously address the trilemma of fast charging at low temperature for long-range driving," said Tae Cho, a recent Ph.D. graduate in mechanical engineering and first author of the study.

In the past two decades, EVs have become more commonplace on roadways as consumers look for better environmental options, but AAA survey results showed that the momentum is hard to maintain. From 2023 to 2024, the number of U.S. adults who would be "likely" or "very likely" to buy a new or used EV dropped from 23% to 18%.

And 63% said they would be "unlikely" or "very unlikely" to make an EV their next vehicle purchase. Part of the concerns are range drops over the winter, combined with slower charging, which was widely reported during the January 2024 cold snap.

"Charging an EV battery takes 30 to 40 minutes even for aggressive fast charging, and that time increases to over an hour in the winter. This is the pain point we want to address," Dasgupta said.

The devices were built in the U-M Battery Lab and studied at the Michigan Center for Materials Characterization.

The team has applied for [patent protection](#) with the assistance of U-M Innovation Partnerships. Arbor Battery Innovations has licensed and is working to commercialize the channel technology.

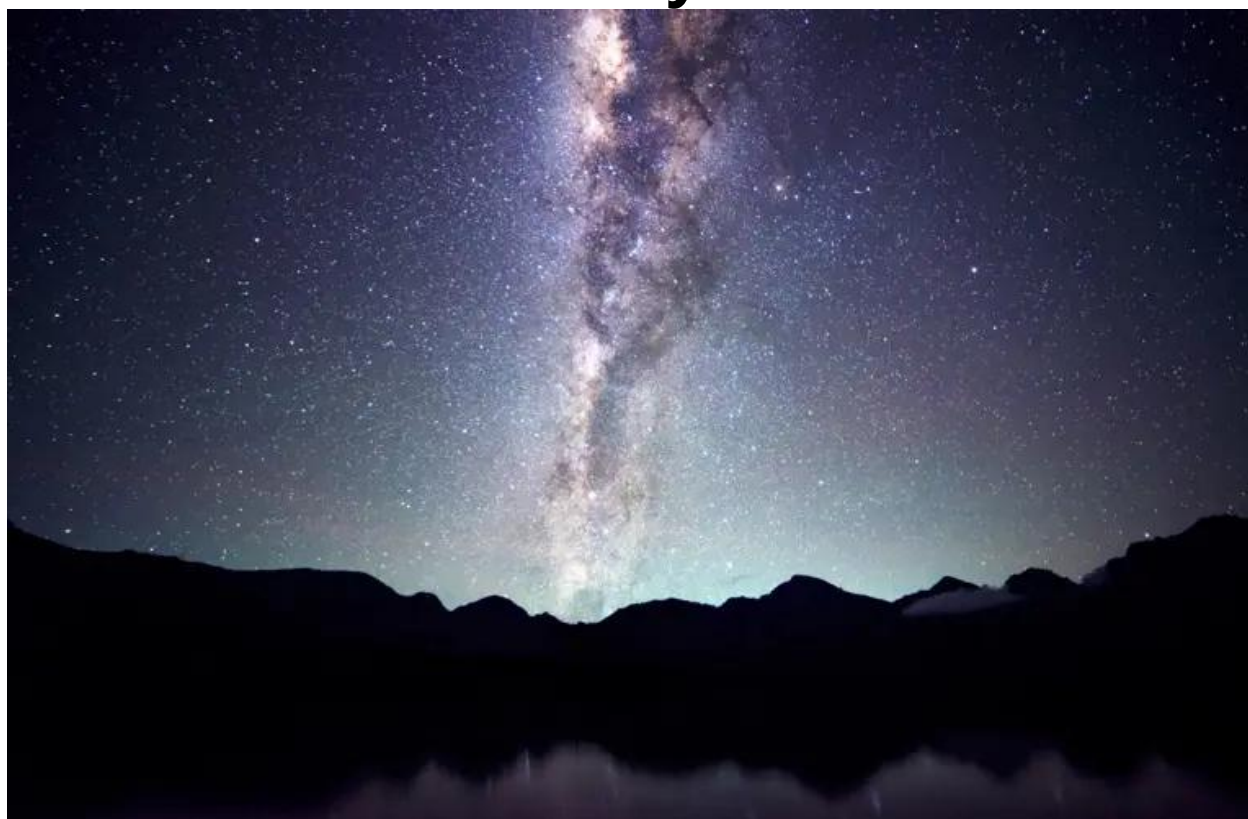
More information: Tae H. Cho et al, Enabling 6C fast charging of Li-ion batteries at sub-zero temperatures via interface engineering and 3D architectures, *Joule* (2025). DOI:

[10.1016/j.joule.2025.101881](https://doi.org/10.1016/j.joule.2025.101881)

Journal information: [Joule](#)

Provided by [University of Michigan](#)

Discovering oxygen in a distant galaxy rewrites cosmic history



The cosmos holds many secrets, and recent discoveries continue to astound even seasoned experts. Scientists have detected oxygen in the most distant known galaxy, JADES-GS-z14-0. Two independent research teams achieved this remarkable finding using the Atacama Large Millimeter/submillimeter Array (ALMA). "It is like finding an adolescent where you would only expect babies," said one of the researchers.

This groundbreaking discovery of oxygen in JADES-GS-z14-0 compels scientists to rethink existing theories about the pace of galaxy evolution. By using the

Atacama Large Millimeter/submillimeter Array (ALMA), two independent research teams confirmed the presence of oxygen, leading to significant theoretical reconsiderations.

A new look at galaxy evolution

The European Southern Observatory (ESO) reports that two independent teams of astronomers have detected oxygen in the most distant of known galaxies, JADES-GS-z14-0. Situated 13.4 billion light-years from Earth, we observe it as it appeared when the universe was just 300 million years old. The presence of oxygen suggests that its chemical composition evolved faster than current models predicted.

"It is like finding an adolescent where you would only expect babies," said Sander Schouws from the Leiden Observatory, the lead author of a paper to be published in "The Astrophysical Journal." The findings show that **the galaxy formed and matured rapidly**, contributing to the evidence for faster-than-expected galaxy formation.

"The galaxy is already mature in the infant universe"

ESO experts explain that galaxies usually begin as regions filled with young stars, primarily composed of light elements such as hydrogen and helium. As stars evolve, they create heavier elements, including oxygen, which spread throughout the galaxy after a star's lifecycle ends.

Previous assumptions held that at 300 million years old, the universe was too young for galaxies rich in heavy elements. However, recent studies indicate that JADES-GS-z14-0 contains about 10 times more heavy elements than expected.

"I was astonished by the unexpected results because they opened a new view on the first phases of galaxy evolution," said Stefano Carniani from the Scuola Normale Superiore di Pisa, the lead author of an article accepted for publication in "Astronomy & Astrophysics." **"The evidence that a galaxy is already mature in the infant universe raises questions about when and how galaxies formed."**

Distance of the galaxy from earth

The oxygen detection also allowed for a precise measurement of the galaxy's distance from Earth with an accuracy of 0.005%. "This level of precision – analogous to being accurate within 5 cm over a distance of 1 km – helps refine our understanding of distant galaxy properties," stated Eleonora Parlanti, co-author of the publication in "Astronomy & Astrophysics."

The JADES-GS-z14-0 galaxy was initially spotted by the James Webb Space Telescope (JWST), but it was ALMA that confirmed and precisely determined its vast distance.

This highlights the remarkable collaboration between ALMA and JWST in revealing the formation and development of the earliest galaxies, points out Prof. Rychard Bouwens from the Leiden Observatory.

APRIL 4, 2025

Report: Energy leaders present six big ideas to help avoid US electricity crisis

by [Stanford University](#)



Professor Sally Benson opened the roundtable meeting by presenting an overview of rising U.S. electricity demand, difficulties in expanding the capacity of America's grid, and some examples of how the inadequacies have already been seen in some regions of the country. Credit: Erik Zarazua/Precourt Institute for Energy

After about 20 years of scant growth, U.S. electricity demand is expected to grow about 15-20% in the next decade and double by 2050, according to the Department of Energy. In light of these predictions, more than 80 U.S. energy experts met at Stanford in February to discuss how to avoid the U.S. electricity grid being overwhelmed by rising demand. This meeting, which was organized by the Stanford Doerr School of Sustainability's Precourt Institute for Energy, has resulted in [a report](#) focused on six big ideas for federal and state energy policymakers to consider.

Artificial intelligence processing, the renewal of domestic manufacturing, and electrification of transportation are among the drivers of electricity demand. While this growth is good news, the U.S. power system lacks the capacity to handle it, meeting participants agreed. Expanding the U.S. [grid](#) and optimizing its current capabilities, while controlling costs and system reliability, faces several barriers, which the readout report may help to overcome.

"Energy experts across the board realize that this is a pivotal moment and that we all must work urgently to secure America's energy future," said Arun Majumdar, dean of the Stanford Doerr School of Sustainability, which includes the Precourt Institute. At the meeting, Majumdar moderated a discussion between Condoleezza Rice, director of Stanford's Hoover Institution and secretary of state during President George W. Bush's administration, and Jennifer Granholm, who was secretary of energy during President Joe Biden's administration.

The readout report was drafted primarily by Stanford participants in the [Feb. 12 meeting](#) and reviewed by 12 participants working in the energy, finance, IT, consulting, government, and non-profit sectors. For each idea, the report presents a brief explanation of the problem and several policy options.

Six big ideas

The six ideas are not consensus solutions from the all-day meeting. The participants have different political perspectives and work across the private sector, government, academia, and non-profit organizations. Instead, the report's ideas synthesize the conversations to provide starting points for addressing grid inadequacies already seen in some regions of the country.

1. Ensure American security

National security depends on meeting rising electricity demand, especially in the race to develop and implement AI technologies, which the U.S. and its competitors already use for gathering intelligence, law enforcement, and military operations. Also, the grid is vulnerable to cyber and physical attacks. Policymaking opportunities include negotiating trade agreements to strengthen supply chains, pursuing international partnerships to commercialize technologies like next-generation [nuclear energy](#), and investing to reduce grid vulnerabilities.

2. A true "all-of-the-above" energy strategy

Too often, people supporting an all-of-the-above energy supply policy add "except ...". Market-driven production from all available electricity resources through mid-century—including renewable energy, nuclear power, natural gas, and energy storage—could control costs and keep the grid reliable. Conducting energy portfolio planning with the short-, medium-, and long-term in mind could also help ensure affordability. Policy options include pairing [natural gas](#) with carbon capture, and continuing technology-agnostic tax credits for [renewable energy projects](#).

3. Create a federal and state grid investment fund

The U.S. electricity system consists of six regional grids with limited interconnection. The ability to transfer more electricity between regions could help mitigate the intermittency of

wind and solar power and reduce costs. Policy opportunities include creating publicly backed financing to build out a national transmission system, granting federal regulators the authority to facilitate such a system, and replacing key existing transmission lines with higher-capacity cables.

4. Streamline permitting

Permit timelines for new transmission lines, electricity generation, and energy storage projects have significantly lengthened in the past two decades. Process modernization could get such projects permitted more quickly and inexpensively without sacrificing environmental goals. Policy openings include prioritizing the most advanced projects, implementing permitting "shot clocks," and using AI and machine learning to accelerate environmental reviews.

5. Make grid policies more flexible

The delay in bringing power generation and storage projects online also stems from requirements to determine both the infrastructure needed to connect new projects to the grid and grid adjustments needed to manage a new generation source at the outset. Policy ideas include regional grids adopting a connect and manage approach used successfully elsewhere, and improving the integration of distributed energy resources, such as commercial and residential electricity storage.

6. Modernize utility operations and business models

Utility incentives prioritize large, capital-intensive projects over those aligned with intended goals, like smart grid technologies to control costs and better resilience to severe weather. Policy opportunities include transitioning from capital-based to performance-based consumer rates, incentivizing transmission line capacity increases, and putting more transmission lines underground.

Advancing ideas at every level

U.S. economic growth and technological eminence could falter if the U.S. electricity system cannot modernize and expand quickly, meeting participants agreed. The federal government, state and local regulators, utilities, financial institutions, and large IT companies must collaborate on solutions, the report emphasizes.

"Expanding an affordable, reliable, and secure grid is not a partisan issue. It is an American one," William Chueh, director of Stanford's Precourt Institute for Energy, and Karen Skelton, a visiting scholar and the project's leader, write in the report. Skelton was a senior advisor to Granholm and White House Climate Diplomat John Podesta during the Biden administration.

"We urge policymakers and leaders across the country to consider, test, and build on these ideas swiftly—because this is no longer some far-off challenge. America's energy future has begun," the two write.

While all stakeholders are needed to rescue the grid, the federal government may have the unique opportunity to lead the development of a strong, interconnected national grid system. President Donald J. Trump's administration and the 119th Congress inherited this challenge, which is also an opportunity to advance critical, practical reforms quickly, according to the report.

"President Trump has been clear that he wants American energy to be the foundation for our economic growth. Our group's proposals are practical solutions to make that vision a reality," said meeting speaker and reviewer of the report, Pat Wood III, CEO of Hunt Energy Network. Wood was the Federal Energy Regulatory Commission chairman who inherited the western U.S. energy crisis of the early 2000s when appointed by President George W. Bush in 2001.

"None of these fixes are technically hard," continued Woods, "but they will only happen with committed leadership."

More information: Meeting 21st Century U.S. Electricity Demand, [drive.google.com/file/d/1akisK ... _KsHN1CeadaH06S/view](https://drive.google.com/file/d/1akisK..._KsHN1CeadaH06S/view)
Provided by [Stanford University](#)

Quantum computer set to untangle math knots beyond supercomputer's superpower

Quantum computing is still in the early stages of development, but it has proven to be an extremely powerful tool for various applications.

While most demonstrations of their efficiency are limited to theoretical work, researchers have now made strides to bridge the gap between theory and practical applications.

Researchers from Quantinuum have now developed an [end-to-end quantum algorithm](#) capable of solving a prominent problem in knot theory—a branch of mathematics for studying closed loops in 3D space, i.e., *knots*.

Knot theory is widely used across several scientific disciplines. Most notably, it's used in molecular biology to study instances where DNA can sometimes form supercoils and knots during replication.

The study marks a potential milestone toward practical quantum advantage. This is the point where a quantum computer can solve a problem that a classical computer can't in a viable amount of time.

Previous studies have claimed to [achieve quantum advantage](#), but none have any practical use case. While the researchers at Quantinuum haven't yet demonstrated this advantage, they present the exact calculations that show that it is achievable with their upcoming 96-qubit Helios quantum processor.

Knot theory and Jones polynomial

Knot theory belongs to the larger field of topology that deals with the properties of spaces when they undergo continuous deformations like twisting, bending, or stretching.

Determining if two knots are identical is nuanced and not simply based on their appearance. This is similar to how a mug and a donut are topologically equivalent because they have one hole, but might not look similar in appearance.

To distinguish between knots, researchers often depend on the Jones polynomial, which acts like a fingerprint. If two knots have different Jones polynomials, it means that they are definitely not topologically equivalent. However, if they have the same Jones polynomial, they may or may not be topologically equivalent.

As knots become more complex—more crossings or overlaps—the Jones polynomial becomes challenging to compute. However, it is an important parameter to distinguish between knots.

Developing a quantum solution

The researchers at Quantinuum came up with an end-to-end [quantum algorithm](#) for evaluating the Jones polynomial. This means the algorithm can

handle all aspects of solving for the Jones polynomial without any additional processes.

They additionally developed novel error mitigation methods to handle present quantum computers, which are extremely noisy. In other words, they wanted to minimize the errors due to different factors, including the environment.

Their implementation significantly reduced the number of operations needed to calculate the Jones polynomial compared to previous studies. They ended up using 15 times fewer quantum gates!

The algorithm was successfully demonstrated on Quantinuum's H2 quantum processor, calculating the Jones polynomial for a knot with 15 strands and 104 crossings.

However, their calculations had an error rate of 43% with respect to the true value of the Jones polynomial, even after using their error mitigation methods.

Through calculations, the researchers were able to estimate that a quantum computer with [approximately 85 qubits](#) (compared to the 56 qubit H2 processor) is needed for quantum advantage in this problem. Their upcoming Helios, which has 96 qubits, meets this threshold.

Additionally, Helios is expected to have a 99.95% fidelity for quantum operations, meaning the calculations will be 99.95% accurate. This is close to the 99.99% fidelity required—according to their calculations—for quantum advantage.

The current approach is adaptable to similar problems that are [quantum-easy](#) but classically difficult. Further, it has implications for several fields that make use of knot theory, including cryptography, statistical mechanics, and magnetohydrodynamics—to name a few.

US firm unveils light-powered computer to tackle energy-hungry AI problems

This invention signals a new era of faster, greener AI as silicon tech nears its limits.

Apr 10, 2025

Complex software in artificial intelligence makes connection speeds a significant concern.

[Lightmatter](#)

Silicon Valley startup Lightmatter has developed a novel computer chip that can speed up artificial intelligence processes and save electricity in the process. The company focuses on using beams of light to move data between computers rather than using electric signals.

Connection speeds are a great matter of concern when it comes to artificial intelligence due to its complex software. This complexity requires the software to be spread over many computers.

Currently valued at \$4.4 billion after a venture capital round of \$850 million, [Lightmatter is confident](#) that it can use beams of light to process the computation itself. The company focused on this idea in a paper it published in the scientific journal Nature on Wednesday.

Conventional computers use transistors that are similar to tiny on-off electrical switches. If the transistors are small, they generally gain more computing power.

An overview of the recent past

The chip industry hasn't seen exactly 'memorable moments' with its struggle in shrinking the size of these transistors. Lightmatter's chip avoids those challenges by using precisely calibrated beams of light, which it directs to interact with each other. The outcomes are measured using an integrated chip package manufactured in partnership with GlobalFoundries.

Previously, photonic computers faced issues with precise computation. If the outcome of a computation was a very small number, the chip would report the answer as zero. Lightmatter solved the issue by grouping extremely large and small numbers before

sending them through the photonic circuits, ensuring that the very small numbers aren't lost in the process.

Lightmatter CEO Nick Harris shed light on the company's latest findings regarding this chip while [talking to Reuters](#) on April 8. He said that the chip can work on some current AI problems with the same precision as conventional chips but it will likely take a decade before the technology goes mainstream.

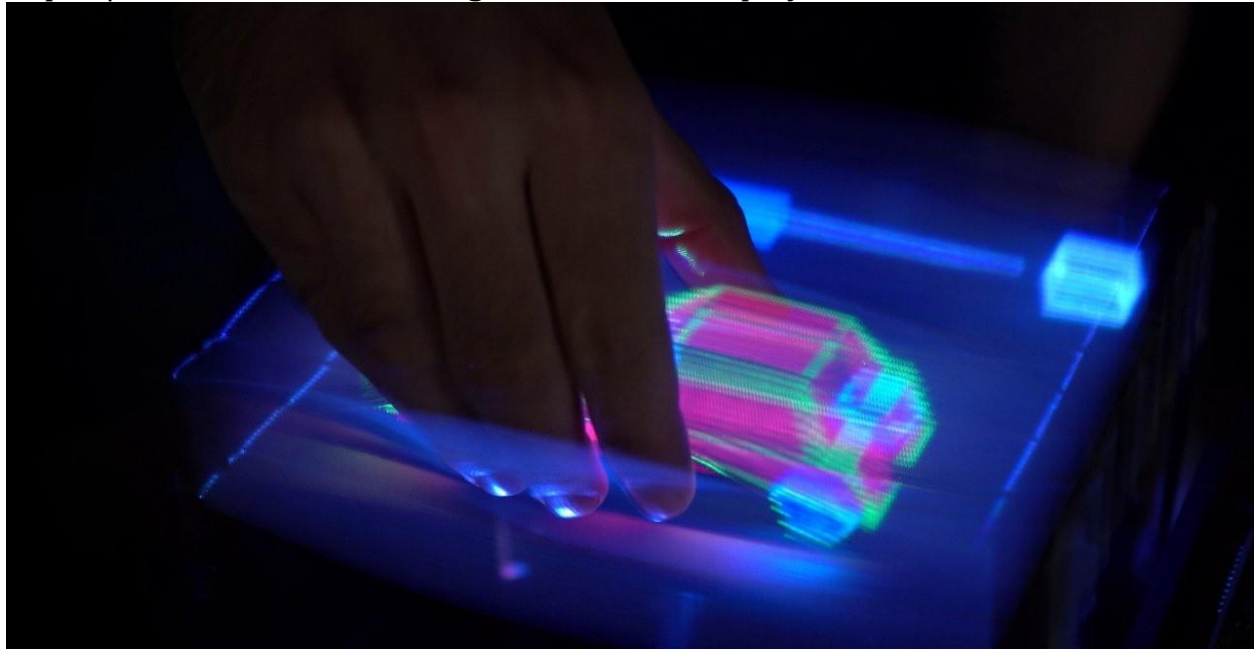
"What we're doing is looking at the future of where processors can go. We fundamentally care about computers, and this is one of the alternative paths. There's trillions of dollars of economic value that's behind the idea that computers will keep getting better," Harris said.

What's in the design?

The chip's hybrid design—photonic cores working alongside traditional electronic control and memory systems—means it can be programmed using standard machine learning frameworks like PyTorch and TensorFlow. This compatibility hints that developers can integrate photonic processors into existing infrastructure, much like GPUs were in their early days.

In a first, breakthrough 3D holograms can be touched, grabbed and poked

Futuristic holograms you can manipulate have become a reality sooner than we thought, thanks to breakthrough display.



[Holograms](#) that can be physically manipulated have [made their way out of science fiction](#) and into real life thanks to a breakthrough in mixed reality technology.

In a new study uploaded March 6 to the [HAL open archive](#), scientists explored how three-dimensional holograms could be grabbed and poked using elastic materials as a key component of volumetric displays.

This innovation means 3D graphics can be interacted with — for example, grasping and moving a virtual cube with your hand — without damaging a holographic system. The research has not yet been peer-reviewed, although the scientists demonstrated their findings in a [video showcasing the technology](#).

"We are used to direct interaction with our phones, where we tap a button or drag a document directly with our finger on the screen — it is natural and intuitive for humans. This project enables us to use this natural interaction with 3D graphics to leverage our innate abilities of 3D vision and manipulation," study lead author [Asier Marzo](#), a professor of computer science at the Public University of Navarra, said in a statement.

The researchers will present their findings at the CHI conference on Human Factors in Computing Systems in Japan, which runs between April 26 and May 1.

Holographic hype

While holograms are nothing new in the present day — augmenting public exhibitions or sitting at the heart of smart glasses, for example — the ability to physically interact with them has been consigned to the realm of science fiction, in movies like Marvel's "Iron Man."

The new research is the first time 3D graphics can be manipulated in mid-air with human hands. But to achieve this, the researchers needed to dig deep into how holography works in the first place.

At the heart of the volumetric displays that support holograms is a diffuser. This is a fast-oscillating, usually rigid, sheet onto which thousands of images are synchronously projected at different heights to form 3D graphics. This is known as the hologram.

However, the rigid nature of the oscillator means that if it comes into contact with a human hand while oscillating, it could break or cause an injury. The solution was to use a flexible material — which the researchers haven't shared the details of yet — that can be touched without damaging the oscillator or causing the image to deteriorate.

From there, this enabled people to manipulate the holographic image, although the researchers also needed to overcome the challenge of the elastic material deforming when being touched. To get around that problem, the researchers implemented image correction to ensure the hologram was projected correctly.

While this breakthrough is still in the experimental stage, there are plenty of potential ways it could be used if commercialized.

"Displays such as screens and mobile devices are present in our lives for working, learning, or entertainment. Having three-dimensional graphics that can be directly manipulated has applications in education — for instance, visualizing and assembling the parts of an engine," the researchers said in the statement.

"Moreover, multiple users can interact collaboratively without the need for virtual reality headsets. These displays could be particularly useful in museums, for example, where visitors can simply approach and interact with the content."

Scientists turn light into a 'supersolid' for the 1st time ever: What that means, and why it matters

published March 13, 2025

For the first time, researchers transformed light into a quantum crystalline structure to create a "supersolid" that's both solid and liquid at the same time. Here's what that means, and why it's such a big step forward.

For the first time, researchers have transformed light into a "supersolid" — a strange state of matter that is both solid and liquid at the same time.

Although scientists have made supersolids out of atoms before, this is the first instance of coupling light and matter to create a supersolid and it opens new doors for studying condensed-matter physics, researchers explained in a paper published March 5 in journal [Nature](#).

But what exactly is a supersolid, and why is this new development so exciting? Here's everything you need to know.

What is a supersolid?

Supersolids are a strange [state of matter](#) defined by [quantum mechanics](#) where particles condense into an orderly, crystalline solid but also move like a liquid that has no viscosity. (Viscosity refers to a substance's internal friction, governing how smoothly it flows).

Usually, solids don't move on their own, but supersolids change direction and density depending on particle interactions while maintaining an organized lattice structure.

Why are supersolids so cold?

Supersolids require extremely low temperatures to form — usually very close to [absolute zero](#) (minus 459.67 degrees Fahrenheit, or minus 273.15 degrees Celsius). Most of the particles have to occupy the lowest energy state available, and heat makes particles jump up and down like excitable toddlers in a ball pit.

If a material is cold enough, the temperature no longer obscures how the particles interact with each other. Instead, the tiny effects of quantum mechanics become the defining factors in how the material behaves.

Imagine the toddlers have gone home and the ball pit has settled into a calm state. Now we can study in peace how the individual components of the ball pit interact with each other to define its characteristics.

How can a fluid have no viscosity?

Viscosity is a measure of how easily a fluid changes its shape. A fluid with a higher viscosity tends to stick to itself more and, therefore, resist movement, like how syrup moves more sluggishly when poured from a container compared with how water streams from a tap. All fluids, except superfluids and supersolids, have some amount of viscosity.

The best-known example of a fluid with no viscosity is helium cooled to temperatures within a few degrees of absolute zero. Particles aren't completely still at absolute zero; — they wiggle around a little due to [the uncertainty principle](#). In the case of the helium-4 isotope, they wiggle around a lot — enough to make it impossible for a sample of helium-4 to become solid at absolute zero, unless there are about 25 atmospheres' worth of pressure applied to really squish the particles together.

Helium-4's wiggling at absolute zero and other quantum phenomena cause some drastic changes in how the fluid acts. It stops having friction (and, therefore, has no viscosity) and can quickly siphon itself out of containers, among other things.

How can we make light into a solid?

Supersolids have been [made from atomic gases](#) before. However, the new research used a novel mechanism that relies on the properties of "polariton" systems.

Polaritons are formed by coupling photons (light) and quasiparticles like excitons through strong electromagnetic interactions. Their properties allow them to condense to the lowest possible energy state in a similar way to some atomic gases. In other words, light is coupled with matter, and together, they can be condensed into a supersolid.

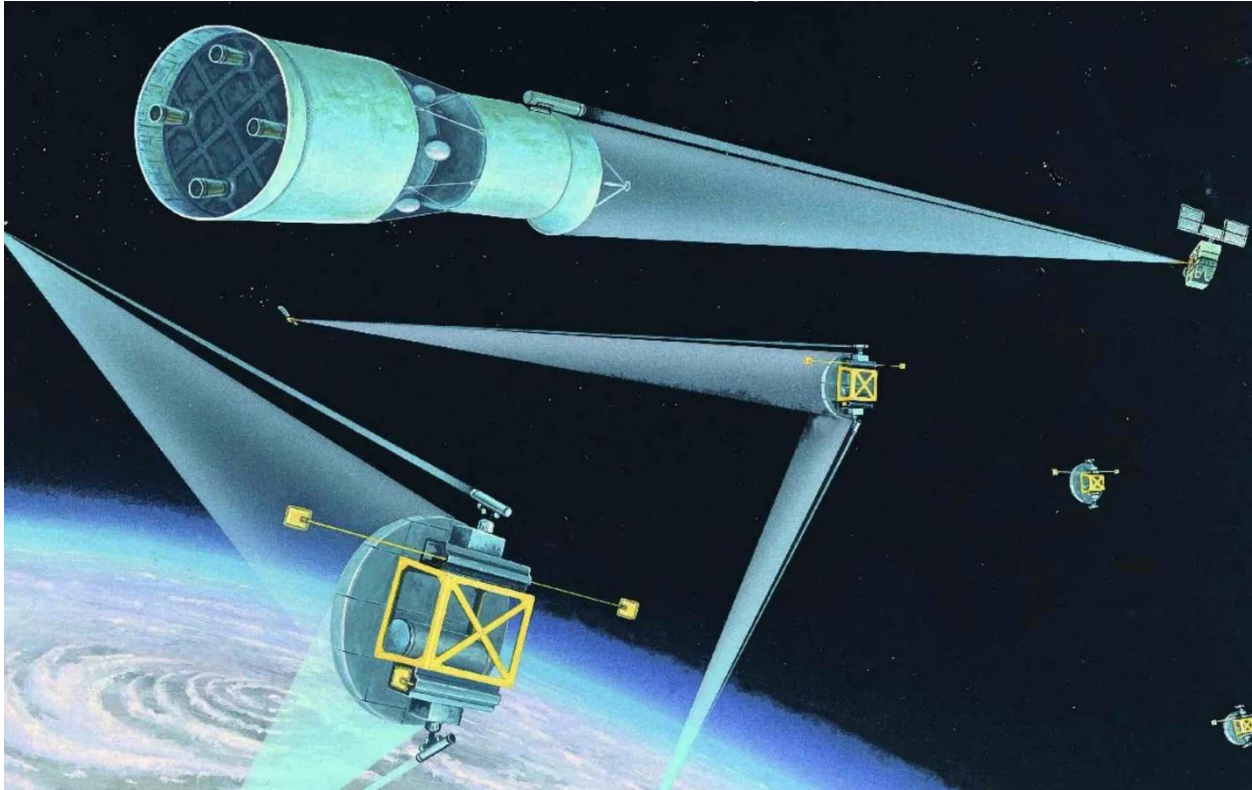
Why are supersolids useful?

Supersolids are important to study because they show the effects of tiny, quantum interactions between particles without temperature getting in the way. When we map out the behavior and characteristics of supersolids, we're really looking at how atoms and particles are put together. This teaches us about the world we live in at a fundamental level.

With more research and development, supersolids could be used for [quantum computing](#), [superconductors](#), frictionless lubricants, and applications we haven't even begun to think of yet. There are so many possibilities we have yet to discover — and making a supersolid out of light is a big step forward.

“It’s time that we can clearly say that we need space fires and we need weapon systems.”

– Gen. Stephen N. Whiting, U.S. Space Force



U.S. Officials Are Concerned Over Adversaries' space Weapons

U.S. officials are expressing concern about aggressive efforts by adversary nations to develop offensive capabilities in space, with a potential arms race in orbit looming that could present new challenges for U.S. satellites and military assets.

Speaking this week at the Space Symposium in Colorado Springs, U.S. Space Force (USSF) Gen. Stephen Whiting [said](#) America has reached a “time that we can clearly say that we need space fires and we need weapon systems.”

“We need orbital interceptors,” Whiting said at the event. “And what do we call these? We call these weapons, and we need them to deter a space conflict and to be successful if we end up in such a fight.”

In recent weeks, maneuvers undertaken by China and Russia have heightened concerns about the prospect of space becoming a future battleground, with U.S. Space Force intelligence suggesting that both nations have undertaken training for combat scenarios in orbit.

The training includes potential satellite attack drills, as well as co-orbital weapons systems exercises. Additionally, some information pointing to the possibility of experiments with new anti-satellite technologies—potentially capable of crippling American strategic defense systems—has also been discussed.

Attack and Defend Maneuvers

Last month, one U.S. official [told CNN](#) that Russian satellites were believed to be engaged in attack and defend maneuvers, displaying capabilities that are of growing concern to the Pentagon.

The concerning revelation comes amid ongoing suspicions that Russia is pursuing the placement of an anti-satellite nuclear weapon in space. Last year, it was learned that a Russian satellite, [Cosmos 2553](#), is operating in a rare, high-altitude low Earth orbit (LEO). Two of the most likely reasons for the satellite's unusual position in orbit include surveillance using synthetic aperture radar (SAR), or the potential use in testing deployment strategies for a future orbital nuclear weapon.

The satellite, launched in February 2022, orbits at an altitude that places it largely out of the way of other active spacecraft—an uncongested orbit that may provide an ideal proving ground for experiments free of U.S. interference or detection. The satellite's orbital position may also serve a strategic purpose, which would be ideally suited for any spacecraft housing a potentially hazardous payload that its operators would want to keep out of the way of potential collision risks.

Despite Cosmos 2553's careful placement in orbit, the U.S. defense official who spoke with CNN in March warned that "Russia wants to take away our advantages in space," adding that Moscow "[doesn't] care about collateral damage."

Speaking last month at the Air & Space Forces Association Warfare Symposium, [USSF Gen. Chance Saltzman](#) also expressed concerns over reports of Russia's purported tests involving orbital nuclear weapons.

"We must simultaneously be ready to defend American spacepower as well as to protect our forces against hostile spacepower," Saltzman said at the event.

Moscow's Space Warfare Capabilities

Concerns involving Moscow's intentions in space are nothing new. Four years ago, a test involving a Russian anti-satellite missile destroyed one of the country's defunct satellites,

resulting in dangerous debris that added to [the growing amount of clutter in Earth orbit](#). It was also revealed in 2023 that Moscow's efforts to build a space-based electromagnetic pulse (EMP) weapon capable of disabling vast numbers of orbital satellites.

Along with Russia's pursuit of orbital weapons, China has displayed similar ambitions. Last December, Chinese satellites performed a series of [close-proximity maneuvers](#) using "advanced patrols and attack approaches" based on U.S. assessments, indicating their ability to physically strike and potentially disable nearby satellites.

China Makes Surprising Leaps with space weapons

China's leap in space capabilities may have caught many in the U.S. by surprise, although like Russia's progress in recent years, it isn't new. As of late 2024, China reportedly had over 1,060 satellites in orbit, placing it second only to the United States. Last year, the country conducted 66 successful launches that carried 67 intelligence, surveillance, and reconnaissance (ISR) satellites into orbit.

Like the U.S., Beijing views space as critical for ensuring battlefield dominance according to China's military doctrine. Presently, the U.S. Space Force is prioritizing developing defensive and offensive capabilities to deter or counter a surprise attack—what officials warn could amount to a "blitzkrieg" in space.

U.S. Still in the Lead... And Hopes to Stay There

Despite such concerning scenarios, officials maintain that the U.S. retains an advantage in space. While a fair degree of the recent saber rattling over space warfare capabilities aims to drive concerns that will likely bolster future budgets, China and Russia are indeed rapidly closing the gap on the U.S. and its orbital capabilities.

Despite being signatories of the 1967 Outer Space Treaty—which prohibits placing weapons of mass destruction in orbit—Russia and China's recent behavior also signals a shift away from diplomatic restraint. Namely, Russia's veto of a 2024 UN resolution reaffirming the treaty's principles only helped to deepen international concerns that the agreement is becoming obsolete.

"Weapons in space used to be considered inconceivable, but now space-based interceptors are a key component of how we win," General Whiting said at the Space Symposium in Colorado this week.

“We are a combatant command, and like all other combatant commands, we must be dominant at warfighting and war winning,” he added. “Dominant warfighting in space requires credible, acknowledged, kinetic and non-kinetic capabilities, fires and weapons.”



(Image: U.S. Air Force photo by Andy Morataya)

THREAT OF WAR IN SPACE RISES AS U.S. GENERAL OUTLINES PLANS TO “MILITARIZE” LOW EARTH ORBIT

APRIL 4, 2025

The threat of [the world's first war in space](#) appears to be rising following comments from General Chance Saltzman, the United States Space Force's chief of space operations, regarding American plans to militarize space assets in response to increasing attempts by adversary nations to weaponize low Earth orbit.

During a presentation at the [Air & Space Forces Association Warfare Symposium](#) last month, Saltzman said that America's efforts to counter [China](#) and [Russia's](#) development of space domain weapons,

including reports of [Russia's orbital nuclear weapons platforms](#), are already falling behind. The General also said catching up and passing our adversaries is critical to maintaining “space superiority” in any potential conflict.

“We must simultaneously be ready to defend American spacepower as well as to protect our forces against hostile spacepower,” Saltzman told conference attendees.

Few details of the exact systems were made available. However, the Space Force Chief discussed several categories of space warfare systems that are likely under consideration.

THE FIRST WAR IN SPACE WILL LIKELY FEATURE THESE WEAPONS

Since the end of World War II, several weapon platforms and systems designed to weaponize low Earth orbit for a potential war in space have been proposed. The first and only weapon fired in space occurred on January 24, 1975, when the Soviet Union test-fired a modified aircraft cannon from the ALMAZ/Salyut 3/OPS-2 space station.

During the 1980s, U.S. President proposed the Strategic Defense Initiative. Nicknamed “Star Wars,” the program, which many believed violated [national law governing the weaponization of space](#), outlined various potential weapons designed to arm America for the first war in space.

Saltzman highlighted many of those same categories, including employing “kinetic and non-kinetic means to affect adversary capabilities through disruption, degradation, and even destruction, if necessary.”

“It includes things like orbital warfare and electromagnetic (EM) warfare, and its counterspace operations can be employed for both offensive and [defensive purposes](#) at the direction of combatant commands,” the chief explained.



The amphibious transport dock ship USS Portland (LPD 27) conducts a high-energy laser weapon system demonstration on a static surface training target, Dec. 14, while sailing in the Gulf of Aden (Credit: U.S. Navy photo illustration by Mass Communication Specialist 2nd Class Devin Kates).

A report from ArsTechnica indicated that Saltzman told reporters in a separate meeting that combat [lasers](#) and several other directed-energy weapons were also under consideration. While no specific [combat laser](#) contractor or platform was mentioned by name, *The Debrief* has covered several potential [EM, kinetic, microwave, and laser space warfare weapons](#) already in development, including some [currently viable](#) and some more [far-out concepts from the Defense Advanced Research Projects Agency](#) (DARPA).



The Air Force Research Laboratory's Tactical High Power Operational Responder (THOR) was developed for airbase defense. Photo credit: AFRL Directed Energy Directorate

The Air Force recently tested a device, called Thor's Hammer, which uses microwaves to fry the electronics of drones and missiles. Contractor Lockheed-Martin is developing two different microwave-based weapons designed to counter the electronic systems of enemy platforms. Defense contractor BAE Systems recently bet over \$5 billion on the prospect of a future war in space when it acquired Ball Aerospace.

ORBITAL CARRIER COULD BE A "GAME-CHANGER"

One space-based weapon platform already receiving funding from the Space Force is an "orbital carrier" capable of launching and retrieving

automated satellites and weapons like a sea-based aircraft carrier. According to Colin Doughan, the CEO of the \$60 million award recipient SpaceWERX, their orbital carrier offers several advantages currently unavailable to military forces.

“The Orbital Carrier is a game-changer, acting as a pre-positioned launch pad in space,” Doughan said at the time of the award. “It bypasses traditional launch constraints, enabling space vehicle operators to rapidly select a deployment orbit on demand.”



Rendering of an Orbital Carrier. Image Credit: Gravitics.

“We’re honored to partner with the U.S. Space Force on this critical initiative,” Colin Doughan added.

Although many other potential weapons systems in development could factor into the first-ever war in space, General Saltzman noted that “we’re not pursuing all of those yet.” However, the general warned that China and Russia are “pursuing all of those.”

Whatever systems are ultimately chosen to arm the U.S. for a potential war in space, the General noted that it is merely the Space Force’s duty and honor. It is also what separates them from a scientific organization or private corporation.

“Space Superiority is the fundamental difference between a civil space agency and a warfighting space service,” the chief explained. “It is the distinction between a company’s employees operating commercial satellites and Guardians conducting combat operations to achieve joint objectives.”

APRIL 10, 2025

Race isn't a 'biological reality,' contrary to recent political claims



In the recent flurry of executive orders from President Donald Trump, one warned of "[a distorted narrative](#)" about race "driven by ideology rather than truth." It singled out a current exhibition at the [Smithsonian American Art Museum](#) titled "[The Shape of Power: Stories of Race and American Sculpture](#)" as an example. The exhibit displays over two centuries of sculptures that show how art has produced and reproduced racial attitudes and ideologies.

The executive order condemns the exhibition because it "promotes the view that [race](#) is not a biological reality but a social construct, stating "Race is a human invention."

The executive order apparently objects to sentiments such as this: "Although a person's genetics influences their [phenotypic characteristics](#), and self-identified race might be

influenced by physical appearance, race itself is a social construct." But those words are not from the Smithsonian; they are from the [American Society of Human Genetics](#).

[Scientists reject the idea that race is biologically real](#). The claim that race is a "biological reality" cuts against modern scientific knowledge.

[I'm a historian](#) who specializes in the scientific study of race. The executive order places "social construct" in opposition to "biological reality." The history of both concepts reveals how [modern science](#) landed at the idea that race was invented by people, not nature.

Race exists, but what is it?

At the turn of the 20th century, scientists believed humans could be divided into distinct races based on physical features. According to this idea, a scientist could identify physical differences in groups of people, and if those differences were passed on to succeeding generations, the scientist had correctly identified a racial "[type](#)."

The results of this "[typological](#)" method were chaotic. A frustrated Charles Darwin in 1871 [listed 13 scientists](#) who identified anywhere between two and 63 races, a [confusion that persisted](#) for the [next six decades](#). There were almost as many racial classifications as racial classifiers because no two scientists could seem to agree on what physical characteristics were best to measure, or how to measure them.

One intractable problem with racial classifications was that the differences in human physical traits were tiny, so scientists struggled to use them to differentiate between groups. The pioneering African American scholar [W.E.B. Du Bois](#) [noted in 1906](#), "It is impossible to draw a color line between black and other races ... in all physical characteristics the Negro race cannot be set off by itself."

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But scientists tried. In an 1899 anthropological study, [William Ripley](#) classified people using head shape, hair type, pigmentation and stature. In 1926, Harvard anthropologist [Earnest Hooton](#), the leading racial typologist in the world, listed 24 anatomical traits, such as "the presence or absence of a postglenoid tubercle and a pharyngeal fossa or tubercle" and "the degree of bowing of the radius and ulna" while admitting "this list is not, of course, exhaustive."

All this confusion was the opposite of how science should operate: As the tools improved and as measurements became more precise, the object of study—race—became more and more muddled.

When sculptor [Malvina Hoffman's "Races of Mankind"](#) exhibit [opened at Chicago's Field Museum in 1933](#), it characterized race as a biological reality, despite its elusive definition.

World-renowned anthropologist [Sir Arthur Keith](#) wrote the [introduction to the exhibition's catalog](#).

Keith dismissed science as the surest method to distinguish race; one knows a person's race because "a single glance, picks out the racial features more certainly than could a band of trained anthropologists." Keith's view perfectly captured the view that race must be real, for he saw it all around him, even though science could never establish that reality.

In the scientific study of race, however, things were about to change.

Turning to culture to explain difference

By 1933, the rise of Nazism had added urgency to the scientific study of race. As anthropologist [Sherwood Washburn](#) wrote in 1944, "If we are to discuss racial matters with the Nazis, [we had better be right](#)."

In the late 1930s and early 1940s, two new scientific ideas came to fruition. First, scientists began looking to culture rather than biology as the driver of differences among groups of people. Second, the rise of population genetics challenged the biological reality of race.

In 1943, anthropologists [Ruth Benedict](#) and [Gene Weltfish](#) wrote a [short work also titled The Races of Mankind](#). Writing for a popular audience, they argued that people are far more alike than different, and our differences owe to culture and learning, not biology. An animated cartoon short later gave these ideas wider circulation.

Benedict and Weltfish argued that while people did, indeed, differ physically, those differences were meaningless in that all races could learn and all were capable. "Progress in civilization is not the monopoly of one race or subrace," [they wrote](#). "Negroes made iron tools and wove fine cloth for their clothing when fair-skinned Europeans wore skins and knew nothing of iron." The cultural explanation for different human lifestyles was more robust than confused appeals to an elusive biological race.

The turn to culture was consistent with a deep change in biological knowledge.

A tool to understand evolution

Theodosius Dobzhansky was a [preeminent biologist of the 20th century](#). He and other biologists were [interested in evolutionary changes](#). Races, which supposedly didn't change over time, were therefore useless for understanding how organisms evolved.

A new tool, what scientists called a "genetic population," was much more valuable. The geneticist, Dobzhansky held, identified a population based on the genes it shared in order to study change in organisms. Over time natural selection would shape how the population evolved. But if that population didn't shed light on [natural selection](#), the geneticist must

abandon it and work with a new population based on a different set of shared genes. The important point is that, whatever population the geneticist chose, it was changing over time. No population was a fixed and stable entity, as human races were supposed to be.

Sherwood Washburn, who happened to be [Dobzhansky's close friend](#), brought those ideas into anthropology. He recognized that the point of genetics was not classifying people into fixed groups. The point was to understand the process of human evolution. This change reversed everything taught by Hooton, his old teacher.

[Writing in 1951, Washburn argued](#), "There is no way to justify the division of a ... population into a series of racial types" because doing so would be pointless. Presuming any group to be unchanging stood in the way of understanding evolutionary changes. A genetic population was not "real"; it was an invention of the scientist using it as a lens to understand organic change.

A good way to understand this profound difference relates to roller coasters.

Anyone who's been to an amusement park has seen signs that precisely define who is tall enough to ride a given roller coaster. But no one would say they define a "real" category of "tall" or "short" people, as another roller coaster might have a different height requirement. The signs define who is tall enough only for riding this particular roller coaster, and that's all. It's a tool for keeping people safe, not a category defining who is "really" tall.

Similarly, geneticists use genetic populations as "an important tool for [inferring the evolutionary history of modern humans](#)" or because they have "fundamental implications for [understanding the genetic basis of diseases](#)."

Anyone trying to pound a nail with a screwdriver soon realizes that tools are good for tasks they were designed for and useless for anything else. Genetic populations are tools for specific biological uses, not for classifying people into "real" groups by race.

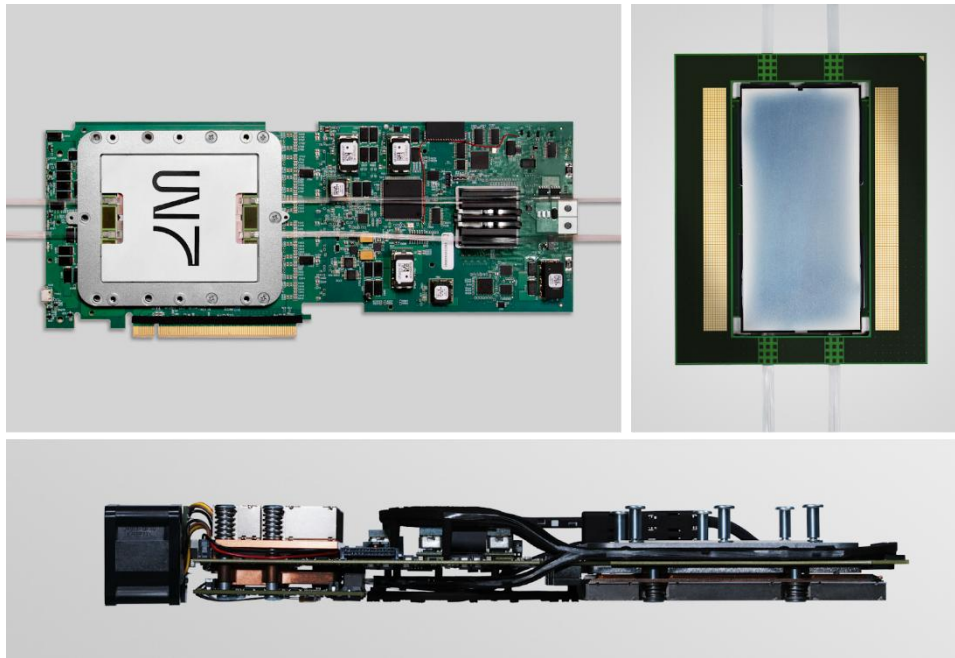
Whoever wanted to classify people, Washburn argued, must give the "[important reasons for subdividing our whole species](#)."

The Smithsonian's exhibit shows how racialized sculpture was "[both a tool of oppression and domination and one of liberation and empowerment](#)." Science agrees with its claim that race is a human invention and not a biological reality.

[Lightmatter has developed a quadcore photonic processor that uses light to power the computer chip, tackling complex computing tasks that were previously out of reach for photonic systems¹. The chip is part of a 'wafer-scale' programmable chip interconnect fabric that boosts performance while reducing energy usage².](#)

A New Kind of Computer

Foreword: This blog post outlines our breakthrough photonic AI acceleration research. This body of work is essential for the future of computing and as a look-ahead at what may come tomorrow. Today, the problem to solve is interconnecting millions of chips, and at Lightmatter, we're fully committed to addressing that challenge for our customers.



Computing stands at an inflection point unlike anything we've seen since the transistor was invented. Artificial intelligence workloads are driving computational demands beyond what traditional scaling laws—Moore's Law, Dennard scaling, and memory scaling—can deliver. All three have effectively stalled, particularly on a per-silicon-area basis.

To double the performance of a chip package in your next generation, you double the silicon area in the package. To double chip memory, double the number of DRAM chips in the chip package. This is mostly great news for silicon foundries. While the approach of doubling silicon area is reasonable in the near term, it has a major side effect—exponential cost. Soon, you will not

be able to afford your computer. Consumer GPUs are already prohibitively expensive.

It wasn't like this in the past. The fundamental units of compute (and memory) were shrinking and reducing their energy consumption commensurate with the density improvements.

Zooming out, the future of computing requires breakthroughs in three critical areas: memory, interconnect, and compute. Developing a scalable, DRAM-like memory solution remains a significant and unresolved challenge without clear practical solutions. For interconnect, there is growing awareness of Lightmatter's groundbreaking [Passage](#) photonic interconnect and advanced packaging technology. Today, we're excited to unveil our latest achievement in the area of compute—a revolutionary photonic processor detailed in our publication in [Nature](#).

A FUNDAMENTAL DEPARTURE

Over the past decade, accelerated matrix computations have become foundational to advances in artificial intelligence (AI) and deep learning, driving demand for improved energy efficiency and computational performance. Photonics has emerged as a compelling alternative to traditional electronics by offering inherent advantages such as high bandwidth, low latency, color-enabled parallelism, and the potential for [superior energy efficiency](#) through light-based computation. Recent developments, including photonic accelerators utilizing interleaved time-wavelength modulation and photoelectric multiplication, have demonstrated significant progress toward practical photonic processors for AI tasks. However, substantial challenges remain, particularly in achieving the necessary computational precision, scalability, seamless system integration, and compatibility with modern AI architectures. Addressing these hurdles is crucial for photonic processors to become competitive with electronic accelerators, unlocking the potential for substantial enhancements in computational speed and efficiency.

Interestingly, the evolution of AI computing has continually reduced computational precision requirements from 32-bit floating-point down to as

low as 4-bit operations today. Given that photonic computation's energy cost scales exponentially (and super-exponentially in some cases) with increased precision demands, this reduction in precision requirements presents a significant opportunity. Nonetheless, no photonic chip has yet achieved the precision required for practical AI applications, and previous demonstrations have been limited to simplified benchmark tasks.

Today, we introduce a photonic processor capable of executing advanced AI models such as ResNet, BERT, and the Atari deep reinforcement learning algorithm pioneered by DeepMind. To our knowledge, this represents the first photonic processor capable of accurately executing state-of-the-art neural networks—including transformers, convolutional network classification and segmentation tasks, and reinforcement learning algorithms—without modifications. Critically, this processor achieves accuracies approaching those of conventional 32-bit floating-point digital systems “out-of-the-box,” without relying on advanced methods such as fine-tuning or quantization-aware training. This breakthrough validates the computational robustness of photonic processing, marking a significant milestone for photonic computing as it competes with established electronic AI accelerators and moves closer to realizing post-transistor computing technologies.

The processor integrates six chips within a single package, employing high-speed interconnects between vertically aligned photonic tensor cores and control dies, delivering exceptional efficiency and scalability in AI computations. Despite several hardware non-idealities discussed in supplemental materials, the processor performs 65.5 trillion Adaptive Block Floating-Point 16-bit (ABFP) operations per second, consuming only 78 watts of electrical power and 1.6 watts of optical power. This integration level represents the highest yet achieved in photonic processing. The 3D packaging involved is a technological marvel—50 billion transistors spanning 6 chips with 1 million photonic components. This level of integration has not been achieved to date.

BEYOND THE LABORATORY

To fully appreciate the significance of this breakthrough, let's consider how it differs from other alternative computing technologies that researchers have pursued for decades. Various non-traditional computing methods have aimed to address limitations inherent to transistor-based architectures:

- Quantum computing promises exponential speedups for certain problems but currently struggles with error correction, scalability, and maintaining coherence. It's also hard to create new algorithms for quantum computers that are provably more efficient than algorithms that can be executed on classical computers.
- DNA computing leverages molecular-scale parallelism but faces significant practical barriers, including slow operational speeds and difficulties in interfacing with conventional computing systems.
- Neuromorphic and analog computing methods provide unique ways of processing information inspired by biological neural networks but often lack flexibility, general-purpose applicability, and compatibility with existing algorithms.
- Carbon nanotube-based processors aim to replace silicon transistors, yet remain fundamentally limited by the energy and time costs associated with charging and discharging the electrical wires interconnecting nanotube compute elements. As a result, these processors may only offer a 2x improvement in computational efficiency over traditional transistor-based systems, since interconnects consume approximately half the total energy. It's important to note that this theoretic maximum efficiency gain improvement only applies to the computational energy budget and not to data movement or memory access.
- Earlier generations of photonic and optical computing have shown theoretical potential, yet consistently failed to evolve beyond proof-of-concept demonstrations in controlled environments.

Our advancement stands out because it transcends these limitations, crossing the crucial threshold from theoretical promise to practical reality. Unlike previous photonic computing efforts, our photonic processor isn't merely a lab prototype; it's a fully operational system capable of running advanced neural network models actively used in production today.

For the first time in computing history, we've demonstrated a non-transistor-based technology capable of running complex, real-world workloads with accuracy and efficiency comparable to existing electronic systems. This shift from theoretical possibility to practical implementation signals a new chapter in computing, validating photonics as a viable solution that can significantly impact the future of AI processing.

BEHIND THE SCENES

Running large AI models demands high numerical precision, a significant challenge for analog processors like our photonic chip. Standard fixed-point numbers, often used in analog systems, struggle with the vast range of values encountered in deep neural networks, leading to potential accuracy loss. To overcome this, we utilized and refined the ABFP numerical format mentioned earlier. The core idea is to group numbers (like segments of weight or activation vectors) into blocks. Instead of assigning an exponent to every single number (like standard floating-point), ABFP assigns a single, shared exponent (or scale factor) to the entire block, determined by the largest absolute value within that block. These vectors are normalized using their respective scales, quantized to fixed-point format for the analog computation, and the result is then rescaled using the appropriate block exponents. This adaptive scaling, applied independently to input and weight blocks feeding into each computation tile, drastically reduces quantization errors compared to simpler fixed-point or non-adaptive block schemes, preserving crucial information even with limited bit precision.

A key innovation in our work was combining [ABFP](#) with analog gain control. When performing matrix multiplication in analog, summing many terms (determined by the tile size, N) increases the potential range of the output signal. If the analog-to-digital converter (ADC) has fixed precision, this larger range means the smallest variations (the least significant bits) can get lost. We introduced a technique where the analog signal resulting from the computation is physically amplified by a gain factor, G , before it hits the ADC. Mathematically, the quantized output y_{ijq} becomes $Q(G \cdot w_{ijq} \cdot x_{jq}; \dots)$. This gain boosts the lower-order bits, allowing the ADC to capture them, effectively

increasing precision without needing a higher-resolution (and more power-hungry) ADC. The gain is then divided out digitally ($y_i = \sum(\dots) s_{ij} y / G$). While this risks saturating the largest values, careful management allows a net gain in representational accuracy, proving critical for achieving the precision needed for complex AI models on our photonic hardware.

Photonic components are inherently sensitive to environmental factors like temperature – a trait valuable for sensors, but a formidable obstacle for stable computing. Achieving the high precision needed for AI calculations meant actively controlling and stabilizing every single one of the roughly one million photonic elements in our processor using dedicated mixed-signal circuits.

EVOLUTION RATHER THAN REVOLUTION

Our approach doesn't require abandoning existing infrastructure and algorithms. Our processor leverages a hybrid photonic-electronic design, integrating photonic tensor cores with conventional electronic control and memory systems. The system is programmed using standard AI frameworks like PyTorch and TensorFlow, making adoption straightforward for developers.

This pragmatic approach mirrors how other transformative technologies gained traction. Early GPUs didn't replace CPUs but complemented them for graphics processing before expanding to general computation. Similarly, photonic processors may initially serve as specialized accelerators for AI workloads before potentially expanding to broader applications.

The integration of photonic technology also offers a promising roadmap for continued improvement. Techniques such as quantization-aware training have already shown significant accuracy improvements. Additionally, wavelength division multiplexing could dramatically increase computational density without proportional increases in size or power.

A NEW COMPUTING PATHWAY

Today, memory access and data movement dominate the energy consumption and execution time of AI workloads as much as—or more than—the

computation itself. Even if computational units consumed nearly zero energy, overall efficiency would still be constrained by data-transfer overhead. Lightmatter's breakthrough photonic interconnect technology, Passage™, addresses this critical bottleneck by dramatically reducing energy spent on data movement and by providing ultra-high bandwidth for today's cutting-edge AI computing infrastructure. Our publication highlights that continued innovation in compute technology remains critically valuable: we've introduced a photonic processor that unveils a path towards commercially viable alternative processors (especially with modern workloads executing with 4 bits of precision). These advances in interconnect and compute are the first major steps towards fundamentally reshaping how computers work.

Make no mistake—this work represents a historic moment in computing. For the first time, a non-transistor-based technology can execute complex, real-world workloads with accuracy comparable to traditional digital electronics. As we approach the end of fundamental electronic scaling improvements, our work demonstrates a viable path forward that doesn't depend solely on transistor scaling. This doesn't mean electronic computing will vanish; rather, we're entering an era where multiple computing paradigms coexist, each optimized for specific tasks.

The invention of the integrated circuit, the microprocessor, or the transistor itself—none of these innovations immediately replaced their predecessors, but each fundamentally changed what was achievable. At Lightmatter, we've demonstrated that computing's next chapter need not remain bound by transistor limitations. For an industry accustomed to continual reinvention, photonics represents an exciting and necessary new frontier.

Humanity must innovate at the fundamental level of computing technology or risk approaching a computational cost singularity.

Nick Harris, Ph.D.

Founder and CEO

Over the past decade, photonics research has explored accelerated tensor operations, foundational to artificial intelligence (AI) and deep learning, as a path towards enhanced energy efficiency and performance. The field is centrally motivated by finding alternative technologies to extend computational progress in a post-Moore's law and Dennard scaling era. Despite these

advances, no photonic chip has achieved the precision necessary for practical AI applications, and demonstrations have been limited to simplified benchmark tasks. Here we introduce a photonic AI processor that executes advanced AI models, including ResNet and BERT, along with the Atari deep reinforcement learning algorithm originally demonstrated by DeepMind. This processor achieves near-electronic precision for many workloads, marking a notable entry for photonic computing into competition with established electronic AI accelerators and an essential step towards developing post-transistor computing technologies.



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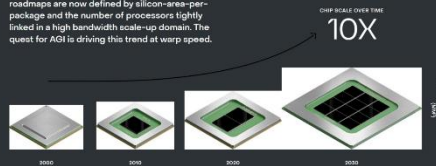
PHOTONIC CHIPS FOR AI



LIGHTMATTER INTERCONNECT LAUNCH EVENT AT OFC 2025

Lightmatter Founder and CEO Nick Harris Unveils Passage
L200 3D Co-Packaged Optics and Passage M1000 3D
Photonic Superchip

Chips are becoming physically larger and more power hungry due to fundamental physical limitations of transistors. Compute performance roadmaps are now defined by silicon-area-per-package and the number of processors tightly linked in a high bandwidth scale-up domain. The quest for AGI is driving this trend at warp speed.



A BRIGHT FOUNDATION FOR BIG CHIPS

We enable the silicon-area-per-package scaling roadmap, shatter the concept of "beachfront" and bring networking radices to new highs with our breakthrough interconnect and packaging technology platform—Passage. We sell the photonic chips that will make building AGI possible (and the lasers that power them). From single reticle to wafer-scale, the world's fastest (and first) 3D-stacked photonic chips.



DRIVING PHOTONICS STANDARDIZATION

ACCELERATING AI THROUGH INDUSTRY COLLABORATION

Lightmatter is at the forefront of silicon photonics innovation, fostering collaboration through partnerships with leading industry organizations like the Global Semiconductor Alliance (GSA) and Optica to facilitate adoption and unlock the full potential of AI.



A WELL REGULATED UAP INDUSTRY: WHY ‘THE UAP REGISTRATION ACT’ IS A BETTER PATH TO DISCLOSURE

•APRIL 27, 2025

In this op-ed, Sean Munger, an attorney and former Marine Corps intelligence analyst, introduces the Unidentified Anomalous Phenomena Registration Act (UAPRA). This forward-thinking legislative proposal addresses two urgent needs: 1) It provides a path to responsibly manage breakthrough scientific discoveries, especially those held by commercial entities, that may originate from non-human intelligence (NHI), and 2) it brings the alleged unregulated UAP industry into a transparent, accountable, and efficient legal structure.

As disclosure efforts move from speculation to active efforts involving legislation, ‘The UAP Registration Act’ proposed herein provides a balanced, proactive approach that respects property rights, promotes public trust, and safeguards national security. It is a necessary step

toward building the legal and institutional infrastructure needed for the next chapter of engagement involving unidentified anomalous phenomena (UAP) and the potential existence of non-human intelligence (NHI).

This op-ed aims to re-energize legislative efforts to tackle this subject, promote productive debate, and help to bring about seamless disclosure that uses existing infrastructures and enforcement mechanisms. An initial draft of the proposed UAP Registration Act can be found at the end of this article.

BRIEF REVIEW OF REGULATION & INDUSTRY

The federal government has a long history of providing a regulatory framework for industries handling sensitive and potentially hazardous materials. One notable example is the Atomic Energy Commission (AEC), established in 1946 to oversee nuclear energy and weapons. The AEC was created to ensure nuclear materials were used safely and responsibly, balancing national security with public safety and environmental protections. This regulatory approach brought a previously secretive and dangerous industry under strict government oversight, establishing protocols, safety standards, and transparency.

Similarly, other sectors, such as pharmaceuticals, aviation, and telecommunications, are governed by robust regulatory bodies such as the FDA, FAA, and FCC. These agencies enforce compliance, ensure safety, and maintain public trust through clear regulations and oversight mechanisms.

By applying a regulatory framework comparable to that of the UAP industry, we can address the current lack of oversight and ensure that activities related to NHI technology and biological evidence are conducted responsibly and transparently. The UAP Registration Act aims to be a crucial step towards achieving this, aligning the UAP sector with established practices in other regulated industries to protect national interests and public welfare.

WHAT WENT WRONG WITH THE UAP DISCLOSURE ACT (UAPDA)

Despite receiving bipartisan support, the Unidentified Anomalous Phenomena Disclosure Act (UAPDA), introduced by Senators Mike Rounds and Charles Schumer, has failed twice to become law in its intended form. What began as a promising effort to compel disclosure of UAP-related information has been watered down due to behind-the-scenes political maneuvering, resulting in a bureaucratic framework that reinforces the status quo.

I argue that the current form of the UAP Disclosure Act (UAPDA) risks impeding disclosure by introducing complex oversight mechanisms, such as a nine-person review board appointed entirely by the Executive Branch. This review board would have unprecedented control over the flow or cessation of UAP disclosure. There are no guarantees that the review board would not become opaque, unaccountable, and susceptible to political influence. Instead of empowering independent inquiry or asserting real congressional oversight, the UAPDA centralizes control of UAP materials and intelligence within the same institutions that have historically concealed them. This structure doesn't move us closer to transparency; it risks locking the door indefinitely.

The UAPDA, as drafted, could delay meaningful public engagement and transparency by entrenching the executive branch's grip on UAP-related programs. Therefore, I propose the UAP Registration Act.

HOW THE UAP REGISTRATION ACT SOLVES THE PROBLEM

PREPARING FOR SCIENTIFIC BREAKTHROUGHS AND COMMERCIAL DISCOVERIES

First, the UAPRA is forward-thinking. As humanity stands on the threshold of transformative advancements in fields like artificial intelligence, quantum computing, and commercial space exploration, the possibility that private companies could encounter technologies or biological evidence of non-human intelligence (NHI) is no longer purely speculative. With commercial space firms pushing further into deep space and scientific frontiers rapidly advancing, we must be prepared for the legal and regulatory challenges such discoveries could pose.

The UAP Registration Act anticipates this scenario by creating a structured process for reporting, registering, and overseeing such materials. This ensures that any future breakthroughs of extraordinary origin are handled with transparency, accountability, and the public interest in mind.

THE UAP LEGACY PROGRAM ALLEGATIONS

For decades, it has been alleged that an unregulated UAP industry has been operating under the radar, reportedly sanctioned by [Executive Order](#). Government insiders have argued in recent years that private and government entities may possess and back-engineer NHI technology, and potentially even hold biological evidence.

Should these allegations be factual, this clandestine sector lacks oversight and transparency, raising significant national security and public trust concerns.

PRESERVES PROPERTY RIGHTS AND ENCOURAGES COOPERATION

Unlike eminent domain, which involves government seizure of private property, the Registration Act respects property rights; under this proposed legislation, private and government entities must register and allow inspection of their NHI materials. Eminent domain remains an option if necessary, but it should not be the starting point. This will help foster a cooperative relationship between private organizations

and the government, encouraging voluntary compliance and open disclosure.

ENHANCED TRANSPARENCY AND ACCOUNTABILITY

The Registration Act introduces a means of providing a public record, fostering transparency on a subject that has been suppressed for too long. Public knowledge of holdings will relieve stigma, allowing the science and academic community to study the phenomena without ridicule. The Act will allow the public and oversight bodies access information about NHI materials, ensuring activities related to UAP are conducted responsibly.

AVOIDS BUREAUCRATIC PITFALLS

Unlike the UAPDA, a nine-person review board appointed by the Executive Branch and confirmed by the Senate risks politicization and bureaucratic inefficiency. The Registration Act, by contrast, embeds oversight within existing, well-established structures for a streamlined, impartial process. Furthermore, the Registration Act eliminates the risk of obstruction because it requires a statutory public record.

BALANCE OF NATIONAL SECURITY AND PUBLIC INTEREST

The Registration Act will balance the need for national security with the public's right to know the truth. Though certain sensitive information may be withheld to prevent harm to national security, the transparency established by the simple disclosure of "NHI Technology" or "Biological Materials" in possession of a private or government entity will, in and of itself, bring about the "Disclosure" to the public.

ECONOMIC BENEFITS THROUGH TAXATION

Regulating the UAP industry provides the government with the ability to tax the sector, similar to other regulated industries. The Registration Act will bring UAP under federal oversight, which can be subject to taxation. This will generate revenue that can be reinvested into public services and future research. The economic benefit adds another layer of public interest to the regulatory approaches outlined within the Registration Act.

The time for speculation is over. If there is already an unregulated UAP industry, as whistleblowers and insiders claim, Congress must act. The UAP Registration Act provides the tools to do so responsibly, using the same regulatory logic applied to other sensitive industries. It offers public accountability without sacrificing national security. It respects property rights while encouraging transparency. It also provides a realistic, legally sound alternative to the bureaucratic dead-end of the UAPDA.

Disclosure should no longer be a question of if but of how. The UAP Registration Act is the proper foundation for follow-up regulations of this publicly emerging industry.

Vibrate Viruses to Death!

Destroying Viruses with Resonance - A New Hope for Healing ?

What if we could destroy harmful viruses or Tumors without drugs , just using the power of vibration?

That's exactly what Royal Rife discovered almost 100 years ago! He built super-powerful microscopes that could see tiny viruses and bacteria that normal microscopes couldn't. What he found was amazing: by using specific electrical vibrations (resonance frequencies), he could shake these tiny germs so much that they broke apart and died — without harming healthy human cells!

Key Points:

- **Everything vibrates**, including viruses and bacteria.

***Vibrate Viruses to Death!** □*

A New Natural Approach to Health ?

Everything in the Body Vibrates Viruses, bacteria, and even healthy cells have their own natural "resonance frequency" — their own special vibration.

- Using the **right frequency**, you can cause them to **break apart naturally**.

- *The Secret: Match the Frequency* Scientists can use a specific vibration to match the natural vibration of a virus.

- *Vibration Creates Stress* When the right frequency is applied, the virus begins to shake violently — just like how a singer can break a glass with a high note!

- *Virus Breaks Apart* The virus's outer shell (full of sharp spikes) gets torn apart — destroying it safely without harming your healthy cells.

● **No drugs or surgery needed** — just energy!

● This method has been reported to help with tough viruses like the ones causing pandemics.

Scientists now understand how this works: viruses have tiny spikes on their surfaces, and the right kind of vibration causes these spikes to move so much that the virus coating rips apart — like popping a balloon.

● This method is being re-explored today because it could be a powerful, natural way to fight infections etc without side effects.

The paper discusses how using specific electrical frequencies can break apart viruses by targeting their natural vibration (resonance). This idea was first explored by Royal Rife and is gaining interest again. Scientists now know viruses have surface spikes that can be shaken violently at the right frequencies, causing the virus to break without harming human cells. This method could offer new ways to fight viruses naturally and safely, without drugs.

● **Step 1: Everything Has a Natural Vibration**

Viruses, cells, bacteria — they all naturally "vibrate" at certain frequencies.

● **Step 2: Find the Right Frequency**

Rife tools and Scientific experimentation use energy waves tuned to the same vibration as the virus.

● **Step 3: Vibrations Cause Stress**

The virus begins to wobble and shake violently because of resonance.

● **Step 4: Virus Breaks Apart**

The virus shell (with its spikes) rips open — like a balloon popping — but healthy human cells are not harmed.

● **Step 5: Body Cleans It Up**

The immune system removes the broken virus pieces naturally. (Drink lots of water:)

● Your Body Finishes the Job Once the virus is broken, your immune system naturally clears out the junk.

- Why This Matters:
 - No drugs needed
 - No harsh chemicals
 - Natural, energy-based healing
- **Resonance and Tumor Cells: A New Frontier**

Recent studies, inspired by Royal Rife's work, suggest that specific frequencies can also impact tumor cells. When targeted with the right resonance, tumor cells may undergo stress and break down, much like viruses. Early experiments show that applying oscillating frequencies can damage tumor structures without harming healthy tissue.

● **What This Means:**

Potential new, gentle Tumor support therapies for humans and Pets
 Non-invasive energy-based treatments
 Helping the body restore balance naturally

● **FAQ: Resonance Healing**

Q: How does resonance destroy viruses and tumors?

A: Specific frequencies cause viruses and tumor cells to vibrate excessively, leading them to break apart naturally.

Q: Does this harm healthy cells?

A: No. Healthy cells have different resonance frequencies, so they remain unaffected.

Q: Is this proven science?

A: Early studies and historical experiments show promising results. Research is ongoing.

Q: Can this be used with traditional treatments?

A: a very powerful complementary therapy .

Q: Is this method safe?

A: Current studies show it to be non-invasive and gentle on the body.

Deeper Reflection: Healing the Mind and Body

Ancient wisdom and Quantum physics now remind us that, at our core, we are vibrations, and energy.

True healing comes not only from treating the body, but from harmonizing the mind, dissolving false divisions, and remembering that imbalance is often an illusion created by fear, anger, and discrimination.

By combining science, nature, and mindful awareness, we can often return to our natural state of harmony — body, mind, and spirit aligned. [The Rife pro](#) is designed [for all three, in a very easy to use software and hardware package.](#)

Shattering Viruses, Parasites and Tumors with resonant frequencies:?

[Know the Truth](#) about Rife machines

[Royal Rife built 5 different Rife machines, Rife Ray \(Beamray\) # 1,2, 3, 4 and 5.](#)

Rife Ray # (Beamray) 1-4 were designed by Royal Rife and [John Crane](#).. Rife Ray # 5 which was the most popular Rife machine amongst [doctors and practitioners](#) Designed and built by Philip Hoyland and Royal Rife. This was by far the most popular and effective Rife machine ever built. If you look near the bottom of this page, you will see the Rife Pro options 2H to 7H The "H" stands for Hoyland, These are the only units in the world that include the functions of the Rife Ray # 1,2, 3, 4, and recognise and use the [Rife Ray # 5](#), a **Combination** of Royal Rife and Philip Hoylands pure genius..

Dr. Johnson clearly points out in this letter that this was done with a new [Rife Ray #5 Clinical instrument]. Dr. Johnson had been using the Rife Ray #4 since the fall of 1935 on his patients but here he points out that

they were using a new Rife Ray #5 machine and that it was clinically more effective than the Rife Ray #4 machine he had been using up until this time. In the Beam Ray Trial documents Philip Hoyland stated that he had built a new Rife Ray #5 Clinical instrument in the summer of 1936: (Beam Ray Trial Transcript #956)" Source Rife videos .com"
More on the hoyland system Rife Ray #5

Shattering cancer with resonant frequencies: A **Holland** at TEDxSkidmoreCollege

Anthony Holland:(not to be mixed up with A **Hoyland**)Associate Professor, Director of Music Technology, Skidmore College. DMA, MM, MM, BM; President: Novobiotronics Inc. [a nonprofit 501(c)(3) charitable and educational company]. Discovered the ability of Oscillating Pulsed Electric Fields (OPEF) to destroy cancer cells and MRSA in laboratory experiments.

Expert in custom digital electronic signal design, synthesis and analysis for biological effects. Member: Bioelectromagnetics Society (BEMS), European Bioelectromagnetics Association (EBEA). Postdoctoral work: Center for Computer Research in Music and Acoustics (CCRMA) Stanford University. Advanced Digital Synthesis and Analysis studies with: Max Mathews (the ' Father of Computer Music'), John Chowning (founding Director of CCRMA, Electronic Composer and Inventor (famed FM Synthesis Patent); Jean-Claude Risset (Electronic Composer and founding Director of the Digital Synthesis Division of the internationally renowned IRCAM center, Paris, France); John Pierce: former Director of Sound Division: Bell Laboratories.

"In 1920 Royal Rife first identified the human cancer virus using the world's most powerful microscope. After identifying and isolating the virus, he decided to culture it on salted pork. At the time this was a very good method for culturing a virus.

*Many clients have asked for information on the frequencies for Spike proteins. We found approx 50. 3 were in the low hz range and the rest were a set of frequencies that ramped from 31-37 megahertz MHZ(very high frequencies) The Hoyland system in our RifePro packages will allow you to Ramp all these frequencies Automatically [listen to this mp3](#).no adjustments needed **Notes on SPs Spike proteins***

He then took the culture and injected it into 400 rats which as you might expect, created cancer in all 400 rats very quickly. The next step for Rife is where things took an interesting turn. He later found a frequency of electromagnetic energy that would cause the cancer virus to diminish completely when entered into the energy field. The great discovery led Rife to create a device that could be tuned to output the frequency that would destroy the cancer. "

Royal Rife was a researcher who studied the effect of frequencies on viruses and bacteria. By using the principle that every molecule vibrates at a unique frequency, Rife discovered that when applying frequency (like the singer smashing the wine glass)at which a microbe resonates, it disintegrates from structural stresses. Through his research, he was able to discover [Rife Frequencies](#). [Rife Frequencies](#) are the mortal oscillatory rates for many viruses. Rife designed a frequency generating device named the Rife Machine based on his observations on frequencies and harmonics.

Royal Rife Frequency kills Paramecium

This page contains some personal accounts of medical doctors who used Dr. Rife's machine on their patients.

"Dr Milbank Johnson, MD, was born in 1871. In the early 1930s Johnson became interested in the "Universal Microscope", and later the "Rife Ray" machine, both invented by Royal Rife of San Diego. Studies done at Northwestern Medical School by Edward Rosenow, MD, were published showing the effectiveness of the Rife Microscope over conventional light microscopes. Later, a culture medium invented by Arthur I. Kendall, Ph.D. of Northwestern Medical School (and a Dean of the school years earlier) was found to be effective for culturing cancer cells for microscopic study. In 1933 Johnson became interested in the success of the Rife Ray machine, a radio transmitter driving a plasma lamp device, in disabling or killing a number of bacterial organisms, as well as what appeared to be a form of cancer cell. Johnson's first wife had died of cancer in 1920, and in 1934, two years before his retirement, and using on the "Rife Ray" machines, he setup and ran what has become known as the "1934 Cancer Clinic" at a Scripps facility in La Jolla, Calif. near San Diego."

"I can assure you that no one, not even myself, could help but be astounded at the results we are now obtaining with the assistance of our new machines and our new band of MOR's. (Mortal oscillatory rate)" (Letter from Dr. Johnson to Dr. Gruner (copy sent to Dr. Rife) dated, November 4, 1936."

"Johnson set up two more clinics, the first in Los Angeles in 1935 focussing on various diseases, and the last in 1936-37 in Altadena, California, at the Scripps Home for the Aged. This clinic was focussed on [treatment for cataracts](#), and Dr. Johnson writes that the results were excellent, with total restoration of vision in 29 out of 30 patients. Johnson quarreled with Royal Rife in 1938 (Johnson had gotten USC to offer Royal Rife an honorary

Doctorate in 1935 or 1936, which Rife refused to have anything to do with) and by 1938 dropped his interest in Rife, although he stayed very active in the National and the California Taxpayer's Associations. He died of an apparent heart attack in 1944, but it was later discovered that he had been fatally poisoned. He died hours before a press conference where he was to announce to the world that Rife's electronic therapy had cured every patient (16 out of 16) in that medical study supervised by the University of Southern California. First thought to be accidental death, the poison was discovered years later by federal investigators when Dr. Johnson's body was exhumed" [Source](#)

[Can a Rife Machine Help?](#)

Enter in a problem/illness see if there is a known frequency

"Dr. Johnson and Philip Hoyland were looking for the frequencies for two organisms which were connected to cancer. In order for them to find these frequencies it was necessary for them to sweep the dial of the instrument through the various frequencies. They made the modifications to the Clinical instrument so that this new band of frequencies would be included in it. They also found that this instrument could not be used in the laboratory because every time they used it they would kill all the microorganisms in the laboratory."

"Dr. Johnson: "My dear Dr. Schram...the clinic was opened and run by me to satisfy me personally whether the Rife Ray would destroy pathogenic organisms in vivo as well as in vitro. The latter we had repeatedly demonstrated in the laboratory. I had to have this information conclusively positive before I could recommend to my friends to get in behind the work to carry it on to a logical conclusion."

[Cataracts](#)

Mainstream Science Validates Rife and Hulda Clark

"None of Dr. Rife's previous instruments ever had the capability that this new Rife-Hoyland instrument had.

Even though this new Rife Ray #5 Clinical instrument was useless in the laboratory for finding individual frequencies for organisms, it was ideal for using clinically. Dr. Johnson pointed this fact out in his letter. **"The major difference between this new Rife Ray #5 Clinical instrument and Dr. Rife's previous instruments is the fact that this new instrument could produce over one hundred harmonic side bands simultaneously.** It was this new harmonic sideband capability in this Beam Ray Clinical instrument which makes this sweep we are discussing on this page possible."

"However, our experience has forced us to do all of our experimenting with the new ray [Rife Ray #5 Clinical instrument] completely outside of our laboratory building or abandon all form of bacteriological experiments, because it instantly kills them all." (Letter from Dr. Johnson to Dr. Gruner (copy sent to Dr. Rife) dated, November 4, 1936. Page 1, Page 2).

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"We will now explain the significance of 3.10- 3.30 MHz (Megahertz) sweep and how it can be used to produce all of Dr. Rife's frequencies, both known and unknown. Not only can it be used to produce Dr. Rife's frequencies, both known and unknown, but this sweep can produce the frequencies for many organisms that we do not have the frequencies for. This makes this sweep very advantageous to use. Almost all of Dr. Rife's frequencies that he found which would devitalize the various micro-organisms ranged from 139,200 Hertz to 1,607,450 Hertz. Philip Hoyland found with his Clinical instrument that he could cover this entire frequency range using a fixed 3.10 - 3.30 Megahertz (MHz) carrier frequency modulated (combined) with audio frequencies. Through the use of these audio frequencies which were modulated onto this 3.10 - 3.30 MHz carrier frequency, high frequency harmonic sidebands were created. " [mp3 File](#)

"Philip Hoyland was able to produce all of Dr. Rife's frequencies, through harmonic sideband frequencies, using these audio frequencies because he found that Dr. Rife was correct when he said that many of his frequencies were harmonics (actually Dr. Rife meant sub-harmonics of higher frequencies). When Philip Hoyland tested this concept out in the laboratory in the summer of 1936 with Dr. Milbank Johnson, M.D., he found that Dr. Rife was correct that his frequencies were sub-harmonics of higher frequencies. What Philip Hoyland did was verify and prove that every harmonic of Dr. Rife's frequencies can be used to devitalize the organisms "

Oscillating pulsed electric field is literally shattering
targeted cancer cells like crystal glass

Using Plasma type tubes

*Another thing that should be kept in mind
is the fact that Dr. Rife found that X-Ray
can cause cancer to become virulent or*

very aggressive. This fact has been proven over the many years that radiation therapy has been used. Dr. Rife, on the Marsh Rife audio CD's, talks about how X-Ray creates a resonance in the cancer cell which makes it more difficult for the frequencies to work. John Marsh in one of his papers gives us more information about what Dr. Rife found regarding X-Ray:

We only use Pulsed Magnetic fields and Direct body contact like Hand held or tens pads to get the frequencies into the body...

Dr. Rife found 54 frequencies for many organism. We only have 18 of these 54 frequencies because the rest were lost. We may not know what those frequencies are but if this sweep is used every one of these organism's frequencies could be hit during this sweep. Besides these 54 frequencies there are many organism's which we do not know the frequencies for that may be in this same frequency range. If this sweep is done over a period of many hours starting with 1 Hertz and going to 40,000 Hertz it would be on an organism's window of vulnerability for about three minutes. Because the Clinical instrument can produce nearly one hundred harmonic sidebands it could hit each organism's frequency over 20 times during this sweep.

Cure for ALL VIRUSES Dr Royal Rife In His Own Words

"Up to this point we have talked about how to use this sweep using a 3.30 MHz carrier frequency. We will now explain in more detail why we can use the same type of sweep using other carrier frequencies. We know that Philip Hoyland used two different carrier frequencies. These were 3.30 MHz and 3.80 MHz. **Because we now know how this instrument worked we can use the**

mathematical calculations to show that 3.10 MHz (3,100,000 Hertz) is actually a better carrier frequency to use with this sweep. This is because 3.10 MHz makes it so the harmonic sideband frequencies are closer to the frequencies that devitalize the organisms. In simple terms at 3.10 MHz there is more power in the sidebands that hit the frequencies which devitalize the organisms. In reality the more power the better they should work"

DR. JOHNSON: "I can assure you that no one, not even myself, could help but be astounded at the results we are now obtaining with the assistance of our new machines and our new band of MOR's." (Letter from Dr. Johnson to Dr. Gruner (copy sent to Dr. Rife) dated, November 4, 1936. Page 1, Page 2). Source Rife videos .com

DR. JOHNSON: "We are having a great time out here. I have opened a clinic in the Pasadena Home for the Aged and am having excellent luck. Of course, what I am trying to do is to experiment with the effect of the Rife Ray on bacteria in vivo. Our laboratory work has demonstrated pretty conclusively what it will do in vitro. The clinic is held three mornings a week, Tuesday, Thursday and Saturday. Yesterday I had eighteen patients. Among them were two cases of pulmonary tuberculosis, three cases of carcinoma, two cases of old chronic varicose ulcers of the leg, and sundry other cases of more or less definite infectious origins...I certainly wish that you were here to work with me because I am afraid that even you, who know what we are trying to do, will not believe some of the yarns that I would have to tell you as to what is occurring in the clinic without actually seeing them for yourself." (Letter from Dr. Johnson to Dr. Gruner (copy sent to Dr. Rife) dated, November 4, 1936. Page 1, Page 2). [Source](#)

Introducing our latest Hoyland type ADD on for your RifePro Rife Machine

"Dr. Johnson and Philip Hoyland were looking for the frequencies for two organisms which were connected to cancer. In order for them to find these frequencies it was necessary for them to sweep the dial of the instrument through the various frequencies. They made the modifications to the Clinical instrument so that this new band of frequencies would be included in it. They also found that this instrument could not be used in the laboratory because every time they used it they would kill all the microorganisms in the laboratory."

"Dr. Johnson: "My dear Dr. Schram...the clinic was opened and run by me to satisfy me personally whether the Rife Ray would destroy pathogenic organisms in vivo as well as in vitro. The latter we had repeatedly demonstrated in the laboratory. I had to have this information conclusively positive before I could recommend to my friends to get in behind the work to carry it on to a logical conclusion."

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Understanding Rife

Rife machines and [Multiwave oscillators](#) are claimed to complement each other based on the principle that life forms absorb energy. A multiwave Oscillator uses this principle to strengthen cells within the body to resist disease while a Rife machine uses this principle to destroy microorganisms with an overdose of frequency energy.

Amplitude-modulated electromagnetic fields for the treatment of cancer:
Discovery of tumor-specific frequencies and assessment of a novel therapeutic approach

Conclusion

Cancer-related frequencies appear to be tumor-specific and treatment with tumor-specific frequencies is feasible, well tolerated and may have biological efficacy in patients with advanced cancer.

Virus Destruction by Resonance

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Abstract

Viruses and other microbes can be inactivated in a selective way by subjecting them to an oscillating electric field of adequate frequency. Royal R. Rife discovered this method already about 100 years ago. He proved its efficiency by means of high resolution microscopes and in 1934, by controlled clinically tests. However, these results seemed to be unbelievable, since the underlying mechanism was not yet understood. Actually, we are faced with three problems: 1) the functioning of Rife's supermicroscopes, 2) his observation that bacteria can undergo size reduction, and 3) the decisive resonance phenomenon. We explain the high magnification and resolving power of Rife's microscopes and show that new discoveries confirm that the postulate of invariable forms of bacteria has to be abandoned. Then we prove that forced oscillations of virus spikes lead to a peculiar resonance, because of nonlinear effects. It causes total destruction of the virus by rupture of its coating. The same theory applies to bacteria and nanobacteria, because of their pili. The worldwide coronavirus pandemic, the constant threat of unpredictable mutations and the now available explanations should make it obvious that biophysical methods cannot be neglected anymore.

Keywords

[Rife](#), [Microscope](#), [Virus](#), [Pleomorphism](#), [Cantilever](#), [Resonance](#)

1. Introduction

Royal Raymond Rife (1888-1971) was an outstanding scientific inventor, who wanted to help humanity by discovering and fighting still unknown causes of sickness and death. His achievements and the opposition that he encountered were described in the remarkable book of Barry Lynes [1]. In his youth, Rife had been impressed by the discoveries of Louis Pasteur and Robert Koch during the second half of the 19th century. They used microscopes to see lethal microbes. They could then isolate and culture them. When the resulting entities caused always the same sickness after repeated cycles, the next step was to find specific vaccines to help their recognition by our immune system. Rife suspected that cancer does also result from microbes, but that they are too small to be seen by means of standard optical microscopes.

This limitation results from the wave nature of light. It leads to interference effects. The physicist Ernst Abbe, working for the Carl Zeiss Company, established even in 1873 a relation between the best possible resolving power of optical microscopes and the wavelength of light. It is at best of about $\lambda/3$, where λ is the wave length for visible light. The limit is thus about 180 nm, but for ultra violet light, $\lambda < 400$ nm. The Carl Zeiss Company developed therefore UV fluorescence microscopes. The light source was an intense electric arc lamp and the UV light was concentrated on the specimen by means of quartz lenses. Since the specimen converted this light by fluorescence into visible light, the objective and ocular were glass lenses. In 1913, the Carl Zeiss Company was ready to sell this new type of microscopes [2].

Rife started in 1917 to construct himself a better microscope for visible light and finished it in 1922 [1]. It magnified up to 17,000 times, while the best standard optical

microscopes could only reach 2000 - 2500 times. Moreover, the images were well-contrasted, with unprecedented high resolution. How this was achieved remained an unsolved puzzle. Rife constructed even more powerful optical microscopes. His second one was finished in 1929 and the third one in 1933. He called it a "universal microscope", because of its great adaptability. It could even magnify up to 60,000 times.

These supermicroscopes allowed him to make extraordinary discoveries, but they contradicted the beliefs of medical authorities. Using only conventional microscopes, they were unable to observe what Rife saw by means of his supermicroscopes. Moreover, Rife discovered the cancer microbe, although it was generally assumed that cancer is not an infectious sickness. Science progresses, of course, by discovering previously unknown facts and by explaining them, but that may require correcting previous assumptions. Unfortunately, it is very difficult to modify deeply rooted ideas. One objective of this article is to illustrate this fact by analyzing Rife's discoveries and achievements, to show the complementarity of experimental and theoretical methods. It has been claimed [3], for instance, that it is impossible to reach the high resolution of Rife's microscope, by repeating the standard theory. It is also incorrect to believe that Rife did suppress the interference effects [4]. The Nobel Prize in Chemistry of 2014 was actually awarded for the development of *super-resolved microscopy* [5]. This was achieved by using powerful lasers, while Rife succeeded with purely classical means. Nevertheless, his name has been wiped out from official medical and scientific literature.

Fortunately, some documents were preserved and their analysis did help us to uncover the secret that escaped attention. Moreover, they provide first-hand information about the discoveries that Rife made with his new microscope. The first one concerned the existence of "nanobacteria", resulting from size-reduction of known bacteria. They are more virulent, but Rife discovered also a method to destroy them, by resonance. To observe both phenomena very clearly, he constructed the more powerful microscopes. The size of typical bacteria is of the order of 1000 nm. For viruses, it ranges from about 400 to 20 nm, but their existence had already been established at about 1900 by means of porcelain filters with very narrow pores. The filtrate contained no bacteria, but remained virulent. This fact justified Rife's conviction that these mysterious entities should be observable by means of better microscopes.

A description of his universal microscope was published in 1944 by a scientific journal [6]. It mentioned also other new optical microscopes and compared them with electron microscopes, developed in the 1930th. Their magnification is greater and allows for instance to determine the size of the polio virus. It is merely 30 nm. The diameter of the spherical core of the Covid-19 virus is 85 nm and it carries 20 nm long spikes. However, electron microscopes can only yield images of dead microbes. The article of 1944 insisted thus on the "great interest" of the new type of optical microscopes, since they allow scientists to penetrate the unseen world of the minute and disease-causing organism when they are still living and active.

This was essential for Rife, but how did he acquire the competence for his apparently impossible achievements? We know that he began medical studies in 1905 at John Hopkins University in Maryland, but he broke them off. His aim was to construct as soon as possible a better microscope and to find the cancer microbe. It has been reported [7] that he married in 1912 and moved then to San Diego, California. Speaking German, he travelled often before WWI to Germany for the US Navy. Rife provided himself reliable information in 1960, by answering 137 questions of the lawyer of his collaborator John Crane [8]. He was on trial, since the powerful American Medical

Association (AMA) had decided to abolish the Rife/Crane cancer therapy. It was declared to be bogus, even without examining Rife's methods and results. After Rife's trial, orchestrated already in 1939 by AMA, he was forced to stop his research. He was bankrupt and desperate. His laboratory had been raided. His microscopes were made unusable and documents were stolen. They included also movies of the behavior of the tiny living beings that Rife made visible. He took refuge in Mexico. Even his written answers of 1960 were not allowed to appear in court during Crane's trial in 1961, but they were conserved.

Rife's answered (to question Q.38) that he acquired his expertise in optics by working for 6 years with Hans Lukel, who was Carl Zeiss's scientist in the USA. Rife mentions there also that he made "all the photomicrographs for the Atlas of Parasites which was done at the University of Heidelberg". This book was published in 1914 and contained more than thirteen hundred colored lithographs [9]. Our inquiries at the archives of the universities of Heidelberg and Gießen, as well as at the Carl Zeiss History Support in Jena revealed no recorded or easily accessible traces. The authors of the book did only thank their academic colleagues. Anyway, it took nine years before Rife felt ready to begin his own research (Q.39). The link [8] provides photographs of his microscopes and the copy of a certificate, where the Institute for Scientific Research of the Andean Anthropological Expedition recognized Rife's "outstanding contributions to science" and the attribution of a Research Fellowship in biochemistry. Rife confirmed this (Q.135-137) and added that he studied *bacteriology* at John Hopkins University (Q.56). He acquired there a PhD diploma, since he signed a scientific paper [10] with this title and was often called Dr. Rife.

When he was running out of financial resources, he took a job as chauffeur of the multi-millionaire Henry Timken. He manufactured ball bearings and Rife provided a way to control their quality by constructing an X-ray machine. Timken valued his creativity and technical abilities, demonstrated in various ways. Impressed by Rife's competence and his strong motivation to construct better microscopes for identifying the cancer microbe, Timken offered him a laboratory at Point Loma, California, with full equipment and financial support.

Rife constructed there his microscopes and the basement provided facilities for 1000 animals with precisely controlled air-conditioning (Q.10). There were about 800 albino rats, but also Guinea pigs and rabbits (Q.59). In 1929, a local newspaper published an article about Rife's extraordinary microscope and his fascinating discoveries [11]. The journalist praised his competence in bacteriology, chemistry, metallurgy and engineering. Rife had developed methods to observe and document previously unobservable living entities. He found even a technique to destroy harmful microbes, but "refuses to make money from it". He is concerned with pure science and wants to free humanity from cancer and other dreadful sicknesses.

In his interview [8], Rife provides important details concerning his research and the difficulties that he encountered. He did use cancer tissues and prepared over 15,000 slides, since he was convinced that his microscope should allow him to see the microbe that causes cancer, but it remained hidden. He tried numerous molecules for staining and this lasted over 10 years, to no avail (Q.22). Eventually, he thought that chemical substances might destroy the mini-microbes and started therefore to exploit other capabilities of his microscope. Although this was time-consuming, it allowed him to select a color that made microbes visible by their own luminescence, without having to add some staining substance. It was also necessary to discover a method for multiplying the microbes that he expected to be present in cancer tissue. He found that they had to be cultured in the "K medium", developed by the microbiologist Arthur

Kendall. This medium is protein based, but poor in peptones (polypeptides and amino acids). It was superior to all other ones (Q.29 and 30). Nevertheless, the decisive breakthrough was quasi-accidental [12].

"After many long procedures and unsuccessful attempts", Rife had fortuitously placed a test tube near an argon discharge tube. It ionizes air and produces O-2O2- ions, becoming ozone. Rife noted some cloudiness, but the microscope revealed nothing special. After incubation during 24 hours at 37.5° on K-medium, the solution was "teeming with cancer virus". These entities were very small and motile, but easily discernable by means of their purplish fluorescence. Their proliferation resulted from subjecting bacteria to stress. Since Rife had been searching these mysterious entities during many years, he called them X-bacteria or simply "BX". To verify if they did really cause cancer, he inoculated albino rats with a solution, derived from human breast cancer tissue. In almost 3 to 4 days there appeared a lesion at the point of inoculation in the mammary gland of these rats. Pathological examination disclosed typical malignancy. Rife mentioned that the same procedure was repeated 411 times with identical results (Q. 24). He wanted to be absolutely sure.

The culprit of cancer or at least a new possible cause had thus been uncovered. It was a tiny ovoid particle, about 50 nm large and 70 nm long. Its motility indicated that it was flagellated [10]. Rife observed also with his supermicroscope that these BX entities could be transformed again into bacteria or fungi, according to the medium where they were living. In their reduced form, they could not be destroyed by UV radiation or X-rays, but they were killed after two days at 42°C. The newspaper article [11] attracted the attention of Dr. Arthur Kendall, who had developed the K medium. He was professor and head of the department of bacteriology at the Northwestern University in Chicago and wanted to check the reality of these amazing claims.

He invited Rife in 1931 to bring his microscope to his institution, where he used a type of bacteria that he had cultured himself. In their "filterable state", they appeared in Rife's scope as tiny, motile granules of turquoise-blue color. These observations were so astonishing, that the whole procedure was repeated eight times. In 1931, Prof. Dr. Kendall published with Rife an article [10] that described these experiments and their results. Kendall was then invited to speak in 1932 at a meeting of the Association of American Physicians. Dr. Thomas Rivers, virologist at the Rockefeller Foundation, tried to get Kendall's talk cancelled. This was not accepted, but Rivers went immediately to the podium after his talk to express fierce opposition. He impressed the audience by daring to address Dr. Kendall as if he were a liar.

Dr. Rivers and Dr. Zinser, bacteriologist at Harvard, had tried to reproduce Kendall's results. They did use the K-medium, but their observations were made with conventional optical microscopes. Without Rife's supermicroscope and his method to provoke luminescence, they were unable to see the relevant nanoparticles. Moreover, they believed in *monomorphism*, advocated by Louis Pasteur. He had attributed infectious diseases to bacteria of specific size and form. A similar postulate is used for classifications in botany and zoology, but metamorphosis is not impossible. Since Rife and Kendall were facing *ideology*, Dr. Edward Rosenow, who was heading the Mayo Foundation's Experimental Bacteriology program at Rochester, Minnesota, wanted to check the facts. He spent 3 days at Kendall's laboratory where Rife's microscope was still installed and reported his observations in Science [13]. He wrote: "there can be no question of the existence of filterable turquoise blue bodies". They appear in large numbers in filtrates of cultures of infected tissues and constitute a "stage in the development of microorganisms."

Rife mentioned in his interview [8] that the BX entities are actively moving around (Q. 51), but that he found a method to “devitalize all microorganisms as desired” (Q.19). It required EM waves of particular frequency, depending on the kind of microbes. This frequency was determined by observing the microbes with his microscope (Q.76). Some types did then “explode or disintegrate” and other types did aggregate (Q.80). This happened for various types of bacteria (Q.78), but they were never affected by inadequate frequencies (Q.118). This observation led to the development of the “ray machine”. Its production was continued by John Crane when Rife fled to Mexico, but Crane was prosecuted. AMA accused him, though it refused to test his system (Q.131). The American Cancer Society was interested, until they found out that Crane and Rife were not medical doctors (Q.127).

However, Dr. Milbank Johnson, Professor of Physiology and Clinical Medicine at the University of Southern California, gathered in 1934 a Research Committee to test the clinical efficiency of Rife’s cancer therapy. Sixteen terminally ill patients with different types of malignancies were selected and treated with the instrument that produced an oscillating electric field of the required frequency for deactivating the BX entities. The sessions lasted only *3 minutes, every third day*. The patients felt neither pain nor any other sensation, but “the virus or bacteria is destroyed and the body then recovers itself” [1]. The interval between treatments was needed to eliminate the toxic debris. “After 3 months, 14 of these hopeless cases were signed off as clinically cured by the staff of five medical doctors”. Other ones participated in overseeing this test and the pathologist of the group, Dr. Foord, certified the healing. The two other patients were cured after 20 more days [7]. The first cancer clinic that used the Rife technology was opened in 1934 and the Rife Beam Ray Company was operating in 1938. That was intolerable for the powerful AMA. The capitalistic pharma industry wanted also to prevent the development of alternative forms of medical treatments, of course, but had merely to encourage AMA’s request of legal prohibition and its use of other methods of coercion. This procedure has been analyzed in the context of social anthropology, related to science and technology [14]. It is necessary, indeed, to realize that it was profoundly unjust, unscientific and even harmful, by preventing possible cure.

The structure of this article results from the need to solve three basic problems. *Section 2* describes Rife’s supermicroscope and explains its functioning. *Section 3* justifies the concept of pleomorphism. *Section 4* provides a detailed scientific explanation of the physical mechanism of targeted microbe destruction by resonance. This part illustrates also the usefulness of physical reasoning for solving scientific riddles, even in medicine. *Section 5* presents conclusions and some recommendations.

2. Optical Supermicroscopes

2.1. Rife’s Universal Microscope

The basic principles of microscopy result from the laws of geometrical optics. All light rays that emerge from a point A and pass through a lens L do converge at the point A' . To determine its position, it is sufficient to consider two rays, as shown in [Figure 1](#). The ray that passes through the center of a thin lens is not deviated, while the ray passing through the focal point F is refracted by the lens to become parallel to its symmetry axis. This applies even to combinations of thin lenses. The position of the image A' of A is determined by 5 parameters: their distances D and d from the plane of the lens, their heights H and h above and below the symmetry axis, as well as the focal length f of the lens L . Indeed,

$$1f = 1d + 1D \quad 1f = 1d + 1D \quad \text{and} \quad Hh = DdHh = Dd(1)$$

Analogous relations apply to the second lens L' . Since the rays that emerge from A' and pass through this lens are refracted as if they did emerge from I , this is a virtual image. The global magnification is the product of the magnifications provided by the objective and ocular lenses.

Rife modified this system to get a much greater magnification by increasing the distance D . He did that by intercalating many prisms as indicated in Figure 2. We represent there only a narrow bundle of rays, forming a beam that would coincide with the symmetry axis if it were not deviated. Rife stated in his description [15] that the beam was subjected to "21 light bends". There are only 20

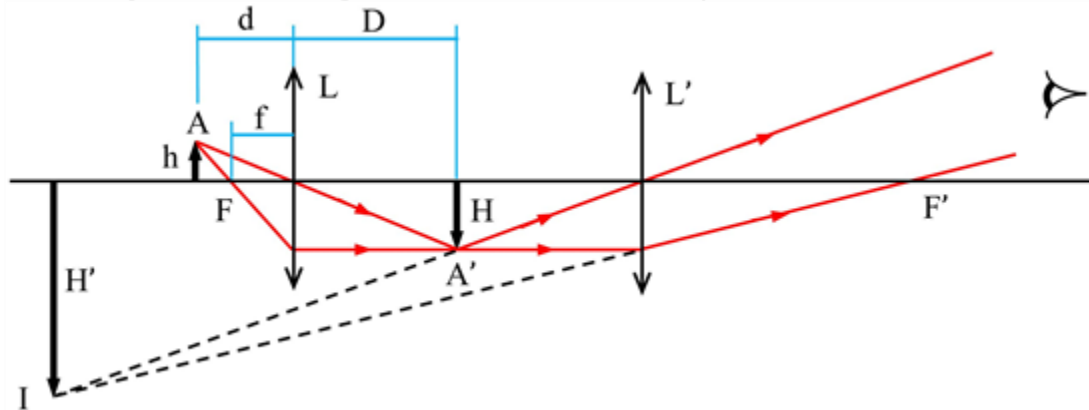


Figure 1. Successive formation of two images A' and I of the point A in optical microscopes.

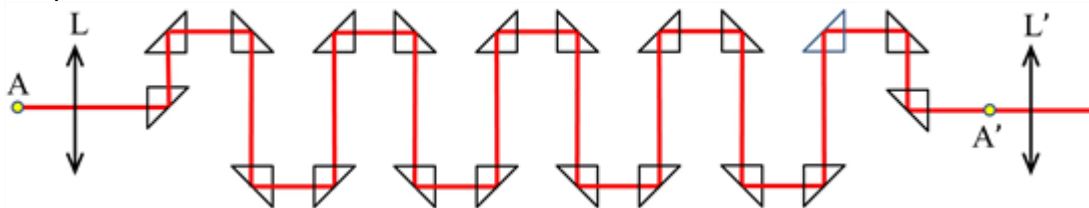


Figure 2. Rife achieved great magnification by increasing the distance D between the lens L and A' .

prisms, but the image A' does also produce a deviation to yield the image I . Rife insisted that the rays of light have to remain *nearly parallel*, although the rays emerging from the lens L are converging. The 90° prisms did thus not simply act like mirrors. One of their faces was slightly concave. Every time before the rays would tend to meet, they were thus made less convergent. This stratagem required extremely high precision, since the total deviation from the ideal one could not exceed one wavelength. The distance that light rays traveled zigzag fashion was 449 mm, while the length of the barrel was only 229 mm. For usual microscopes it is 160 - 190 mm. All prisms and lenses were made of block-crystal quartz. The barrel and screws were made of "magnalium". This Al/Mg alloy was very expensive, but it has the same thermal dilatation coefficient as quartz. Figure 1 shows that both focal distances f and f' should be as small as possible. Rife opted thus for a pair of identical, high-quality objectives with quartz lenses, developed by Zeiss. Why did Rife not follow the contemporary trend to improve resolution by using UV light? It would not be converted everywhere into visual light when it passes through the specimen, but is dangerous for visual

observation. Though it could be eliminated by a filter, Rife preferred to use a normal light source, since his initial intention was to use chemical staining.

Rife knew that molecular fluorescence results from processes that are represented in Figure 3(a). The curves show how the energy E depends for the ground state and the first excited state on the structure parameter s . Photons of blue or near ultraviolet light can thus excite an electron from the most probable ground state to another possible state. The molecule modifies then its configuration before emitting a photon of lower energy. Since absorption and emission of a photon are instantaneous processes, they are represented by vertical transitions. There are also vibrational states, leading to spectral bands instead of lines, but we can simplify the graph, since the essential point is that molecules, which can rapidly lose any excess energy. However, it was necessary that the light source could provide light of any required color to elicit optimal fluorescence.

An electric arc is a very intense light source, but there are spectral lines. Rife preferred thus an incandescent filament. It yields a continuous spectrum and Rife did use a special filter to select the adequate color. It had been invented in 1889 by the ophthalmologist Risley and is represented in Figure 3(b). Indeed,

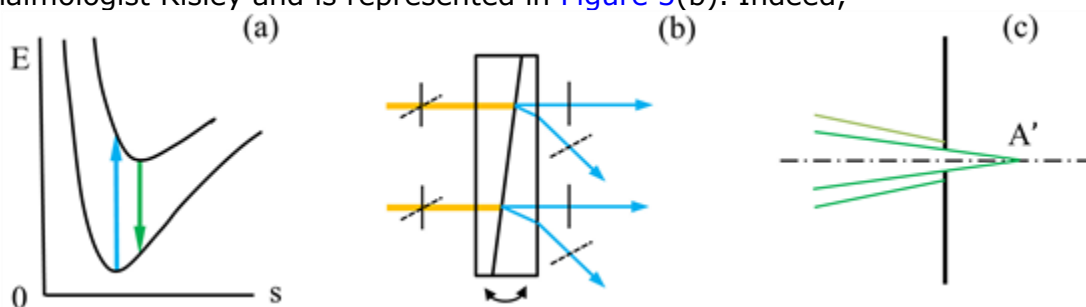


Figure 3. (a) Molecular luminescence is optimal when it is excited by light of a particular color. (b) It was selected by a Risley filter. (c) Rife's secret was a pinpoint filter near A' .

two identical 90° prisms can be rotated with respect to one another, while their oblique faces remain in contact. At normal incidence light is only refracted at the interface. This leads to dispersion, but by rotating the prisms with respect to one another, we get only light of a particular color that leaves the second prism at normal incidence. Since quartz is birefringent, the angle of refraction depends not only on the color, but also on the polarization of light waves. Rife could thus produce polarized light of any desired color. This is useful for mineralogy, since thin slices reveal then colored parts.

Figure 3(c) represents the pinpoint filter that Rife did place before the first image A' , but he did not mention it in his dialogue with Crane [16]. He stated there (#43) that the universal microscope has "a resolution of 31,000 times and a magnification of 60,000 times". These values have often been repeated, without explaining how they were determined, but Rife mentioned that he used a Zeiss silver coated slide, carrying 800 lines per mm with perfect definition. They were thus separated by $1.25 \mu\text{m}$. Under a standard microscope, there appeared 40 - 60 of these lines with distortions, due to spherical aberration of the lenses. "Under the universal microscope, we see only 1 - 3 lines and they are perfectly parallel through the entire field" (#44 and 45). The greater magnification kept only the central part of usual images. Rife claimed that "the resolution is 31,000 times", which is unusual, but he considered that the sharpness of the image reached at least half the separation of the lines.

The high resolution remained very puzzling, since Feynman noted in his famous lectures on physics (I, 27-7) that we might build a “system of lenses that magnifies 10,000 diameters, but we still could not see two points that are too close together.” We mentioned already that the resolving power of optical microscopes is limited by interference effects. However, Rife answered only to Cranes question concerning this limit (#43) that the lack of sharpness is due to “factors of error that come into the field of optics by the illumination and things of all sort.” The use of a pinpoint filter just before the first image was not mentioned. Even in the article of 1944, Rife noted merely [6] that “if one pierces a black strip of paper or cardboard with the point of a needle and then brings the card up close to the eye so that the hole is in the optic axis, a small brilliantly lighted object will appear larger and clearer, revealing more fine detail.” This hint has not been perceived, but Rife’s method is equivalent to a recent discovery [5], that deserved even a Nobel prize.

2.2. Modern High-Resolution Microscopes and Diffraction

Stephan Hell, who pioneered the use of lasers for high resolution optical microscopy, explained the basic idea in his Nobel lecture [16]. He began with underlining the advantage of minimally invasive optical microscopy with respect to electronic microscopy. However, the resolution of optical microscopes is limited and “scientists believed throughout the 20th century” that this barrier cannot be overcome”. Knowledge of Rife’s achievement had been wiped out, but Hell thought that “so much new phenomena were discovered” that higher resolution of optical microscopes should be realizable. He was teaching biophysical chemistry in Göttingen and attributed the difficulty to the fact that light is emitted by *different molecules* inside a small volume of the specimen. They are excited together and emit light by the molecular processes that were depicted in Figure 3(a). Since it is impossible to excite only a very small group of molecules, he tried to find out if we can “manage to keep some molecules dark”. Searching an answer to this question, he found that physics knows about *stimulated emission* of radiation. Einstein discovered this phenomenon in 1917 by proving that it accounts for Planck’s spectrum of EM radiation in an oven or any cavity at sufficiently high temperature. With lasers, it is possible to silence excited molecules by “stimulated emission depletion” (STED). This process is represented in a simplified way in Figure 4(a). Blue laser light (1) of moderate intensity is absorbed by a molecule. An electron is there raised from the ground state S_0 to the first excited state S_1 . The molecule relaxes, by changing its configuration. The interrupted line represents this loss of energy, since it is sufficient to represent the initial and final excited state to account for Figure 3(a). Light emission result from the transition (2) in Figure 4(a), but stimulated emission (2’) can be caused by intense laser light of the adequate frequency. The excited state is then constantly emptied and normal light emission is quenched.

Figure 4(b) represents the spatial domains of illumination by means of the two lasers. These light distributions cannot be point-like, but it is possible to produce a blob of blue light (1) and to superpose a ring of very intense green light (2’). It abolishes light emission in this ring and leaves only the small central spot where light emission (2) is still possible.

Once the spell was broken, other scientists did tackle the same problem during the two last decades and discovered various methods to solve it. They were reviewed in a comprehensive and interesting way [17]. The basic technique consisted always in separating light emission in space or time. How could Rife succeed already in the 1920th to reach high resolution without lasers? To understand this fact, it is useful to return to basics.

Grimaldi's careful observation in 1660 of the shadow cast by a rod revealed that it cannot be explained by geometrical optics, unless light rays that pass close to obstacles are divided (at least) in two rays. This led to the concept of "diffraction".

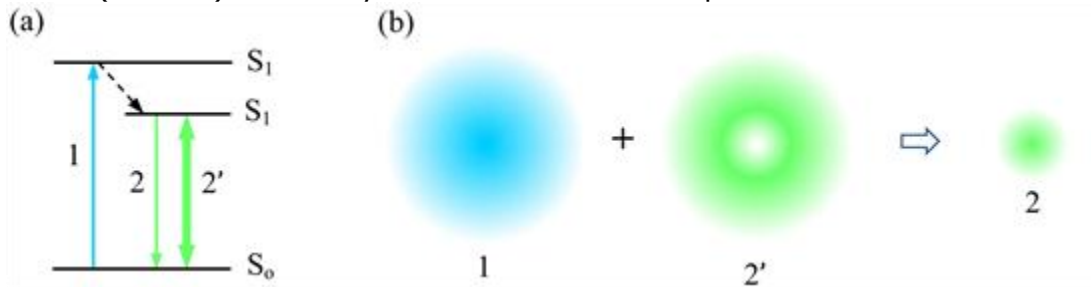


Figure 4. (a) Transitions between energy levels, used for high-resolution microscopy by the method of stimulated emission depletion (STEP). (b) Superposed illuminations and the resulting emission.

Grimaldi thought already that light may not be constituted of particles that are moving along straight lines in any homogeneous medium. Young's famous double slit experiment of 1801 proved that light is propagating *like* waves. It was then generally believed that there are "light waves", but Planck discovered in 1900 that there are grains of light energy and Einstein proved in 1905 that they are particles. These photons do not always move along a single well-defined trajectory, but do also allow for interference.

In 1815, Fraunhofer discovered spectral lines in sunlight by improving the quality of lenses and prisms, but he did also use gratings with many equidistant narrow slits. The resulting interference decomposes white light in different colors. Fraunhofer found that a single slit produces also a set of closely spaced interference fringes. Even when light encounters a screen with a small circular hole of radius r , as shown in Figure 5(a), it does produce a brilliant spot of light that is surrounded by fainter rings. Fresnel explained this fact in 1819 by considering that all points inside this hole emit spherical light waves, but on the symmetry axis, they do always interfere constructively with one another. Figure 5(b) shows that for the angle θ with respect to the symmetry axis, light emitted by any pair of points that are radially separated by the distance r interferes destructively for monochromatic light of given wavelength λ , when

$$r \sin \theta = \lambda / 2$$

For other angles the wave amplitudes are not opposite to one another. Fresnel calculated the resulting variation of the light intensity and found that it varies as indicated in Figure 5(c). It is even the square of a Bessel function. The arrows define the width of the central spot, resulting from relation (2).

Distant stars are point-like light sources, but for telescopes, their image is a spot of light that is surrounded by rings of decreasing intensity. This was proven in 1835 and led to the term "Airy disc". It is represented in Figure 6(a), when light intensities are represented in black/white inversion. Figure 6(b) recalls that all light rays that emerge from the point A and pass through the lens L will converge at the point A'. Ernst Abbe realized in 1873 that a microscope is thus equivalent to a circular hole of radius

$$r = 0.61 \lambda / 2 \text{NA} \quad \text{where } \text{NA} = n \sin \theta$$

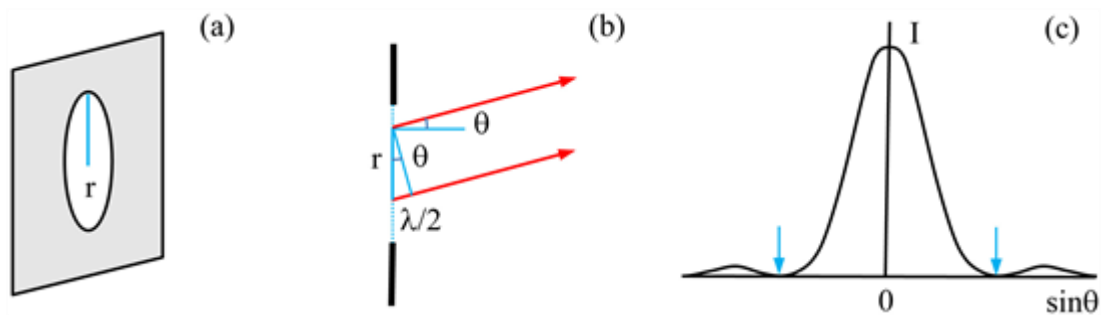


Figure 5. (a) Light passing through a small circular opening leads to interference. (b) It is always destructive for a particular angle θ . (c) The angular distribution of the resulting light intensity I yields a central blob, surrounded by fainter luminous rings.

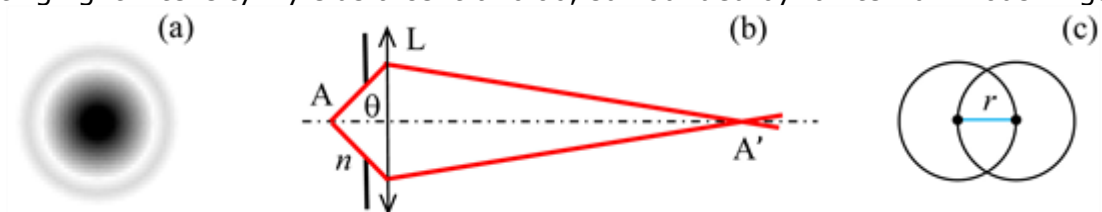


Figure 6. (a) Black/white image of an Airy disc. (b) Formation of the first image in a microscope. (c) The resolving power r defines the smallest distance between separable point-like sources.

The value of r results from (2) and the fact that light rays are refracted by the lens. NA is called the “numerical aperture” of the lens system, since it depends on the angular opening θ of the diaphragm and the index of refraction n of the medium between the specimen and the lens. It refracts light wave, but on the other side of the lens L there is air, where $n = 1$. Figure 6(c) shows that the blurred image of two points near A can only be separated when their separation is greater than r . The *resolving power* of microscopes is thus defined by (3). Abbe concluded that the resolution of optical microscopes can be improved by filling the space between the sample and the lens with a transparent fluid, where $n \approx 1.5$. Immersion does thus reduce r from $\lambda/2$ to $\lambda/3$.

2.3. Rife’s Method and Other Supermicroscopes

It has been asserted [3] that Rife could not overcome the diffraction barrier and that he did suppress it by applying the principle of reversibility [4]. Sorry, this principle is only valid in geometrical optics, since it implies that the direction of propagation of light is irrelevant for light rays. Diffraction of light that passes through a small circular hole or a narrow slit results from interference and cannot be eliminated, but Figure 4 showed that the difficulty can be bypassed. How could Rife also do that without lasers?

Rife’s contact with the Zeiss Company and his own observations made him aware of diffraction phenomena, but he found a very simple way to reduce their effects. He combined very high magnification with a pinpoint filter, which reduces the size of the Airy disc at A' , as shown in Figure 3(c). Probably, Rife did not mention this filter to protect his invention. It is even impossible to verify that he did use a pinhole filter, since his microscopes were dismantled. Rife constructed in 1932 a supermicroscope for a friend, who was a watchmaker and may have given advice for high precision tooling.

This instrument was sold on auction in 2009, but the objective and ocular lens systems were missing, as well as the pinpoint filter [18].

It is very remarkable that *Gaston Naessens* (1924-2018) developed in 1949 another type of optical supermicroscopes with specialists of the Leitz Company in Wetzlar, Germany. This instrument reached a magnification of 30,000 and a sufficiently high resolution to see very small living entities. Naessens called them "somatides" and his microscope a "somatoscope". He observed that these somatides resulted from changes of size and form of normal bacteria. They could pass through a simple or a complex life-cycle [19]. This is demonstrated in a short and very interesting video [20]. His microscope was also based on bioluminescence, but the exciting radiation was very intense UV and blue light of fixed wavelengths, respectively of 185 nm and 330 nm. Since excitation like that of Figure 3(a) requires a specific color, this was achieved by means of magnetic and electric fields, modifying molecular spectra in an adaptable way. Since we ignore if he did also use a pinhole filter to achieve very high resolution, we wonder if other methods might have been used. This is conceivable, since Figure 7(a) accounts for excitation by means of UV light that allows for transitions (1) between the ground state S_0 and a higher excited state S_2 . The energy is then reduced, by modifying the configuration parameter s of the molecule. However, the curve $S_2(s)$ cuts the curve $S_1(s)$. The excited electron goes then over to the lower energy state, which allows for immediate light emission (2), called *fluorescence*. However, the excited electron can also go over from S_1 to another state T . It is a triplet state, since the spin of the excited electron has been reversed. We get thus an electron pair, where the total spin is 1 instead of 0 for singlet S states and the transition $T \rightarrow S_0$ is forbidden. The electron is thus trapped until it is thermally excited to reach again the level S_1 . This allows for retarded light emission, known as *phosphorescence*. Since there is no fixed phase relation anymore with the exciting light, the emitted light waves are incoherent and cannot interfere.

Another method consists in placing a pinpoint filter precisely at the point A' , as shown in Figure 7(b). This has mainly the advantage of improving depth sharpness, since light emerging from other planes than at A will not be focalized in the image plane A' . This type of *confocal microscopy* was invented and patented in the 1950th [21]. It allowed for laser scanning. Optical microscopy made thus remarkable progress, but the pioneers, Rife and Naessens were unjustly discarded from the list of honorable scientists.

They did use their microscopes for observing that bacteria can reduce their size and developed then methods for fighting sicknesses. Rife did this by resonance and Naessens by discovering drugs that he could observe to be efficient, but he was prosecuted for illegal exercise of medicine [22]. Rife and Naessens did not belong to the required corporation or caste. This mentality is akin to *racism*, since it was not even deemed necessary to check if their observations were correct and if their treatments were helpful or not.

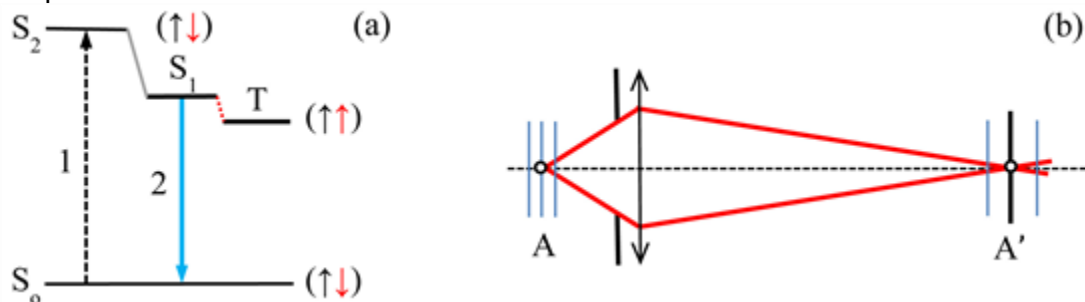


Figure 7. (a) Excitation of fluorescence and phosphorescence. (b) Confocal microscopy.

3. Biological Discoveries and Medical Applications

3.1. Pleomorphism Revisited

Antoine Béchamp, a compatriot of Pasteur, proved already by extensive experimentation that the size and form of bacteria can be modified [23]. He introduced the term *pleomorphism*, meaning more possible forms. He found that the smaller entities survive in chalk, but can reacquire their usual size and even become fungi. In 1886, Béchamp described “microzymas” (small ferments) that subsist as living entities after the death of organs, although it was believed that nothing can survive. These microzymas can also be present in living beings, where they cause diseases, but Pasteur did fiercely defend his conviction that all infectious diseases are only due to microbes of external origin. Béchamp was doctor of pharmacy and professor of chemistry. He became a medical doctor and then professor of medicine. He was a member of the French Academy, like Louis Pasteur, who was a chemist. Pasteur made very important discoveries, but was quite intolerant. He had even a feud with Robert Koch [24] and reacted so aggressively against Béchamp that monomorphism prevailed by docile consent of colleagues.

Nevertheless, Mrs. Henri of the Pasteur Institute in Paris observed in 1914 that anthrax bacilli change their form when they are subjected to ultraviolet light [25].

Monomorphism was also contested by the Swedish Biologist Ernest Almquist [26]. He wrote in 1922: “Nobody can pretend to know the complete life cycle and all the varieties of even a single bacterial species. It would be an assumption to think so.”

Rife was not aware of these controversies or not interested. His aim was to observe the tiny microbes that he expected to exist. He succeeded and found even that “any alteration of artificial media (for culturing bacteria) or slight metabolic variation in tissues will induce an organism of one group to change over into any other organism included in that same group”. These transformations are reversible, but the *bacillus typhosus* yields always turquoise-blue luminescent entities. For the *bacillus coli* it has a mahogany color, for *tuberculosis* it is emerald green and for the BX purplish-red. Rife found that inoffensive bacteria become virulent when their size is reduced. He thought therefore that bacteria do not produce themselves diseases, but the microorganisms that result from their transformation. “If the metabolism of the human body is perfectly balanced or poised, it is susceptible to no disease”. Rife added nine years later [12]: “with a pure culture of bacillus coli, by altering the media as little as two parts per million by volume, we can change that organism in 36 hours”. In the initial medium, the micro-organism becomes again a bacillus coli. Continued microscopic study and stop motion photography confirmed the reversibility and revealed that the BX allows for “many changes and cycles.”

In experimental animals, the BX produces “a typical tumor with all the pathology of true neoplastic tissue, from which we can again recover the BX micro-organism”. They are even abundantly present. To be absolutely sure of this astounding result, Rife repeated these observations several hundred times. It should be noted that he tended to use the term “virus” for any type of filterable microbes, since the specific mode of virus reproduction was not yet known. The biologist Gaston Naessens observed pleomorphism in more detail. He presented clear evidence in a video [27] that the somatid found in blood can have a simple lifecycle or one with 16 different stages. Can these facts simply be negated, since they are not observable with standard optical

microscopes? The books of Lynes [1] and Bird [23] denounce the enormous lack of scientific honesty in regard to the discoveries of Rife and Naessens.

Fortunately, it is possible to rediscover what is happening in Nature. Emmy Klieneberger-Nobel published in 1951 a thorough study of filterable forms of bacteria. She used a phase-contrast microscope, developed in 1942. It converts subtle phase changes of light waves passing through the specimen into amplitude modifications. They are made perceptible by reducing the amplitude of the background waves. This method made it possible to discover reversible changes of various types of bacteria, resulting from modifications of their environment [28]. According to her long list of references, she was not aware of the discoveries of Rife and Naessens, but the reality of pleomorphism was confirmed.

Kurath and Morita demonstrated in 1983 that marine bacteria are able to adapt themselves for survival under conditions of nutrient starvation [29]. The geologist Robert Folk discovered in the early 90th that precipitation of carbonates in hot springs of central Italy is due to modified bacteria. He studied them by scanning electron microscopy (SEM), proving that their average size was 200 nm. In 1994, Folk attributed the observed carbonate precipitation to negatively charged cell walls. They attract Ca^{++} ions, neutralized by CO_3 ions, which yields chalk (CaCO_3) [30].

Kajander and Ciftcioglu proved in 1998 that blood can contain nanobacteria, associated with Ca^{++} , CO_3 and PO_4 [31]. Nanobacteria act then as crystallization centers that lead to the formation of kidney stones. The calcified envelope seems to provide a shelter for survival, since SEM micrographs revealed that they are still able of division. It appeared also that these nanobacteria are covered with a "hairy layer". Transmission electron microscopy (TEM) confirmed the existence of this coat of mineralized whiskers.

However, the existence of nanobacteria raised controversies, since it was generally believed that bacteria have to be big enough to accommodate DNA or RNA, as well as the required enzymes for autonomous replication. The opposition to the concept of pleomorphism resurged, but now because of molecular genetics. Ciftcioglu, Kajander *et al.* responded in 2006 by more facts: pathological calcification caused by nanobacteria does also account for gallstones, arterial heart disease, prostatitis, cancer and Alzheimer's disease [32]. They stated that research in this area has been "paralyzed for decades by attributing the calcifications to insignificant, passive, degenerative processes of aging".

The dermatologist Milton Wainwright published already in 1990 a book [33], where he presented important results concerning microbiological causes of cancer. He discovered that *scleroderma*, a rare form of cancer that leads to hardening of the skin and inevitably to death, is caused by microbes. Other outstanding physicians and medical research scientists had also demonstrated in the meantime that various forms of cancer result from nanobacteria, but the medical establishment did recklessly reject all proofs that contradicted the standard dogma. Wainwright's book of 2005 provides ample proof of this kind of "medical politics" [34].

Milton Wainwright recalled the battle between pleomorphism and monomorphism [35], since it is still going on. By dismissing this possibility, "we may be missing something of fundamental importance". A review [36] concluded in 2011 that "the evidence that nanobacteria exist in the human body and are closely associated with many kinds of diseases is now overwhelming". Nevertheless, it came still in 2011 to a categorical denial [37]. It refereed unjustly to a study of Ciftcioglu and McKay [38]. It was much more careful and mentioned that calcifying nanoparticles "do not fit the typical definition of life", but it could be too restrictive. Smaller forms have detrimental effects on human health and should be the "focus of future effort."

Cantwell insisted again in 2014 on existing evidence that cancer is caused by pleomorphic bacteria [39]. More and more justifications of the relevance of modified forms of bacteria in human pathologies have been published. Russian scientists presented in 2012 a review [40] where coccoid nanobacteria were reported to appear in sea water, soil, sedimentary and granite rocks, the Greenland ice sheet, glaciers and permafrost soils, as well as in humans and insects, for instance. Their size can be reduced to about 150 nm. This article contains several micrographs showing that ultramicrobacteria can make contact with one another by means of hair-like appendices. Banfield's team at the University of California, Berkeley, collected nanobacteria by filtering acetate-amended ground water [41]. These cells were immediately deep-frozen to prevent deterioration and brought to the laboratory, where they were analyzed by CryoTEM. It appeared that these nanobacteria are even quite common and well-adapted for survival under adverse conditions. A widely published micrograph [42] shows a coated spherical particle. Its diameter is close to 300 nm and its surface is covered with numerous *pili*, radiating outwards. Their length is about 50 nm. Their presence attracted our attention and will turn out to be very important. Lida Mattman was an outstanding microbiologist. She confirmed pleomorphism and described the life cycle of various bacteria. Her textbook [43] concentrated on "cell wall deficient forms". They could result from an adaptation to increase protection against natural antibiotics, but they remained hidden in blood, though they are damaging. "Current bacteriology holds the belief that each cell species has only one simple form and retains it by reproduction". Nevertheless, they are able to "pass through stages with markedly different morphologies".

Dennis Claessen and his group at the Institute of Biology in Leiden discovered filamentous bacteria that are present in soils. He called them "actinomycetes". In response to stress, they can become cell wall deficient [44]. This may be a transient state, but also a lasting one. Pr. Claessen commented in an interview: "It gives a whole new understanding of the flexibility of microorganisms under stress and their ability to adapt to their environment." He published an article in 2019, where he reviewed recent progress concerning *stress induced* wall deficiency and pleomorphism [45]. He concluded that during the last decade, it became increasingly clear that "cells have a wide range of defense mechanisms to cope with various stresses." This is also clinically relevant, since morphological plasticity can cause reinfections.

It is particularly noteworthy that Rife discovered that deadly nanobacteria did thrive in tissues that had been treated by α , β and γ radiation or cobalt 60 gamma rays [46]. The idea that cancer results only from mutations, due to radiation damage and some chemical substances, needs revision, since we were not aware of pleomorphism, caused by stress.

3.2. Rife's Method for Producing EM Waves

His aim was not only to see small microbes, causing sicknesses and death, but also to destroy them. He suspected already 1915 that this might be possible by subjecting them to oscillating electric fields. He declared [8] that systematic experimentation started in 1920. At that time radio amateurs were very active. The carrier wave for radio frequencies had initially been produced by means of a sequence of sparks (in German: Funken, meaning also radio-emission). The sparks result from high tension, obtained by means of a Ruhmkorf induction coil and an interrupter. The electric field accelerates some stray electrons that become then able to ionize air molecules. This produces more free electrons in avalanche fashion, but recombination processes lead to a spark and rapid discharge. This is also relevant for lightning.

When it was realized that electrons can be emitted by a hot filament, it became possible to fabricate luminous diodes. However, Lee De Forest used a vacuum tube and invented the triode, where the amplified electron flux can be controlled. This “audion” could thus modulate a high frequency carrier wave at audio frequencies and was patented in 1908. Public broadcasting began in 1922 from the Eiffel tower in Paris and in 1926, NBC started radio emissions in the USA, but Dr. Rife wanted only to produce radio waves of limited range. Their frequency should be adaptable and stable to allow for selective action on particular microbes. Being technically gifted and very creative, he did that by combining two existing inventions.

On one hand, the German physicist and glassblower Geissler had created in 1857 a *gas discharge tube*, still used today as a source of colored light. It consists of a sealed glass vessel that contains a noble gas at low pressure and two electrodes. There is no hot filament, but a constant high potential difference is applied to these electrodes. The resulting field accelerates free electrons that will then ionize atoms. At low pressure, they are diffused by collisions before emitting light. The whole tube becomes thus luminous and the color depends on the chosen gas.

On the other hand, Coolidge invented in 1913 an *X-ray tube* that was a glass sphere. A hot filament emitted electrons, bundled and accelerated in high vacuum by a strong electric field to impact the other electrode at high velocity. They were there suddenly decelerated, but basic laws of electromagnetism predict that when the velocity of electrically charged particles is reduced, they emit *braking* radiation (Bremsstrahlung). Deceleration of high velocity electrons produces X-rays. Their frequency spectrum is continuous, but there are also superposed narrow peaks, resulting from excitation of strongly bound electrons inside atoms of the anode. They return to their normal state by emitting photons of particular energy. These processes yield a beam of X-rays that is emitted at 90° when the flat anode is inclined at 45° with respect to the electron beam. Rife created a new system, represented in [Figure 8\(a\)](#).

Actually, he replaced Geissler’s tube by a hand-sized glass sphere and the hot filament of the Coolidge sphere by a cold metal plate. When the applied potential difference between the two electrodes exceeds a particular value, there appears a glow discharge. It results from the fact that a local space charge is created near the negative electrode and pushes some ions towards the cathode. It emits then electrons that are accelerated and ionize atoms of the noble gas. Its pressure is such that diffusion of excited atoms is limited, but the accelerated electrons are constantly slowed down and hit the anode at moderate energy. Being suddenly stopped, they produce braking radiation, but the energy of the emitted photons is lower than for Coolidge’s X-ray tubes. The resulting *beam of radio waves* is also perpendicular to the electron beam and represented by points in [Figure 8\(a\)](#). The lateral divergence of this beam is greater than for X-rays, because of the longer wave length.

The gas that surrounds the beam becomes luminous and such a diode is called a “phanotron”. Rife tried different noble gases. He found that helium is preferable, since the impact of the lighter He^+ ions on the cathode increases its lifetime. [Figure 8\(b\)](#) indicates in a schematic way that the electric tension can be applied by modulating a signal of high-frequency F with rectangular pulses of lower

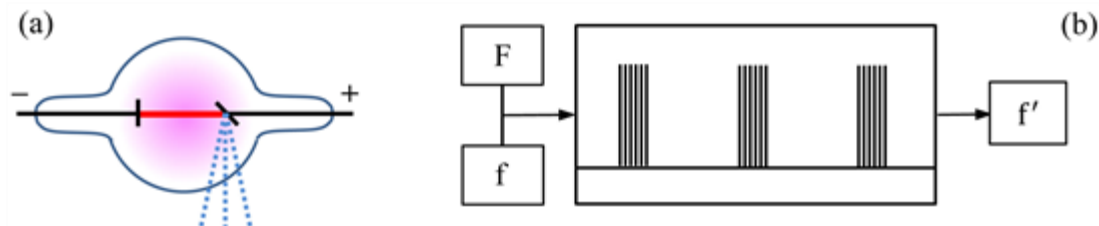


Figure 8. (a) Rife's *phanotron* is a gas-discharge diode, where an electron beam produces at 90° a beam of EM waves. (b) An electric signal of fixed high frequency F is combined with pulses at a particular audio-frequency f to produce sinusoidal oscillations of desired frequencies f' . frequency f . Since avalanche phenomena distort these signals, the resulting EM wave is equivalent to a superposition of sinusoidal waves of various frequencies f' by Fourier transformation.

3.3. The Rife Frequencies and Evidence of Exploding Microbes

The history of the development of Rife's machine has been reconstructed in detail [47]. The report contains many photographs and includes new measurements. They were performed on rediscovered instruments or reconstructed ones, according to original schemes. This study was essentially concerned with engineering problems, but for us it is important that this system could produce electric fields that oscillate at any desired frequency f' . Rife provided a list of *resonance frequencies* for different types of microbes by observing their reaction with his microscope. Since they were definitively inactivated, he called them "mortal oscillatory rates".

He communicated his initial list in 1935 to the electronic engineer Philip Hoyland. He had been hired by Dr. Milbank Johnson who operated a "cancer clinic" that used Rife's method. Hoyland's mission was to construct a more compact version of Rife's machine. Electronics was constantly progressing, indeed. He determined also the resonance frequencies with Rife's microscope and Rife did control his measurements. He agreed with the fine-trimmed values of 1936. Table 1 provides the carefully established list. It appears in the report (p.103), but is rearranged here for increasing frequencies instead of the names the pathologies in alphabetic order.

To produce these frequencies, Rife bought commercially available equipment of top quality. He needed a sinusoidal carrier wave of authorized frequency and was allowed to emit at $F = 3,300,000$ Hz. This signal, modulated by rectangular pulses, was fed to the phanotron. The pulses were distorted by avalanche effects and possible frequencies were then determined by

$$F + nf = n'f'F + nf = n'f'(4)$$

The numbers n and n' can be $1, \pm 2, \pm 3, \dots$. The sidebands have decreasing intensities for greater values of these numbers. Table 1 tells us that the resonance

Frequency	against	549.07 kHz	Staphylococcus Albus
139.20 kHz	Anthrax	759.45 kHz	Typhoid Fever (rod)
191.80 kHz	Streptothrix	719.15 kHz	Streptococcus Pyrogen.
233.00 kHz	Gonorrhea	769.000 kHz	Tuberculosis (filterable)
234.00 kHz	Tetanus	769.035 kHz	Coli (filterable)

369.43 kHz	Tuberculosis (rod)	788.70 kHz	Syphilis
416.51 kHz	Coli (rod)	1.4452 MHz	Typhoid Fever (filterable)
426.86 kHz	Spinal Meningitis	1.52952 MHz	Cancer Sarcoma (BY)
477.66 kHz	Staphylococcus Aureus	1.60745 MHz	Cancer Sarcoma (BX)

Table 1. The Rife-Hoyland list of resonance frequencies for different pathologies. frequency for BX is 1607.45 kHz. It was thus produced by choosing $f = 21.275$ kHz, while $n = -4$ and $n' = 2$. This procedure is quite complicated, but similar to normal practice for broadcasting. It did also protect Rife's invention, without requiring patenting, since it was not easy to find the adequate value of f .

When Hoyland passed away, Verne Thomson became Rife's new engineer. He built several ray machines and verified that the fine trimmed resonance frequencies of [Table 1](#) are correct. We see there that the resonance frequencies are different, but *unique* for any particular type of microbes. Rife attributed this fact to their "chemical constitution" (p. 20 of the report). It was not yet possible to be more explicit, but the empirical result was already very important.

Today, it is possible to use frequency generators and hand-held electrodes. We were surprised when we examined a system, promoted in a book (Frequenz Therapie, German Edition, 2014). It contains an enormous list of resonance frequencies, without explaining how they were determined. It states for instance that they are 21,275 Hz for the BX carcinoma and 20,080 Hz for the BY sarcoma. These values differ from those of [Table 1](#). Moreover, the book preconizes for instance 11 frequencies against "lack of appetite". They are very low, since even 10 of them are situated between 20 and 1865 Hz, while 63 frequencies were listed to treat hepatitis C. This contradicts Rife's result: there is *only one* resonance frequency for every type of microbes. Another list of frequencies, claimed to be Rife frequencies [\[48\]](#) provides also many relatively low frequencies, without any detailed justification. Only 4 of the 11 frequencies of the previous list are given here for lack of appetite, but 52 frequencies are provided for cancer. They range between 120 Hz and 795.6 kHz. It is prudently stated that these frequencies are "only for experiments", but "you can see if they work for you". Anyway, the apparatus is sold with much publicity.

We are afraid, of course, that this kind of business can constitute a serious obstacle to scientific recognition of Rife's method and have to conclude that objective control and authorizations are needed, as for most professions and technical equipment. The biomedical engineer Marcello Allegretti reviewed medical applications of EM waves in several books, to make them understandable in general terms [\[49\]](#). However, we never found an explanation of targeted destruction of microbes by resonance. It has to be possible for any real phenomenon.

Our first task was therefore to verify if there are visual proofs of the efficiency of Rife's method. In addition to the trustable test for curing cancer patients, Rife made numerous microphotographs and movies to document his observations [\[50\]](#), but nearly all of them were stolen or destroyed. Nevertheless, some proofs were saved. We recommend two easily available videos [\[51\]](#) to see with our own eyes what happens. The video "Royal Rife-in his own words" shows instruments, procedures and (at minute 6:58) the turquoise-blue nanobacteria that he discovered. "The Royal Rife story" shows several times bursting bacteria (6:45, 6:59, 7:12, 8:37 and 9:07). Other videos [\[52\]](#) provide more background information.

John Crane presents in “Dr. Royal Rife’s 1939 lab film” the working place and equipment, used by Rife. The first pictures of the BX (14:33) were taken with Rife’s microscope of 1922. Bacteria are much larger and could already be observed with standard optical microscopes, even when they exploded (34:25, 34:45 and 35:15). The longer version of “Rife in his own words” displays turquoise-blue nanobacteria (7:39) and green ones (8:53). Drawings of the BX and the BY entities (15:23, 16:23) indicate the presence of pili on their surface. Nanobacteria can even be seen together with the corresponding bacteria (41:12). “The Rife story” includes more images of exploding bacteria (15:48, 16:02, 16:15, 1.56:03 and 1.56:14).

4. Explanation of Microbe Destruction by Resonance

4.1. Formulation of the Basic Problem

The first method that is customarily used when we are faced with unexplained phenomena is to make them plausible by referring to *analogies*. In a video of outstanding pedagogical quality, the music professor Anthony Holland used this method, since it is possible to shatter a wine glass by sound waves of adequate frequency [53]. The resonance frequency can be determined by tapping the wine glass or by rubbing its rim with a moist finger. The resulting stick-slip friction yields a continuous sound as for the bow and a vibrating string of violins. Though there are several modes of vibration for wine-glasses and bells, the dominant one corresponds to deformations of the rim along two orthogonal axes, as indicated in Figure 9(a). When the intensity of the exciting sound wave is strong enough, the glass is shattered, since it is quite brittle.

The relevant concept can be visualized in a more transparent way by means of a loop of steel wire, attached to a vertical vibrator that is activated by a frequency generator. There appear then “standing waves” with 4 knots for the lowest resonance frequency. More knots than in Figure 9(a) are also possible at higher frequencies. Figure 9(b) represents a “singing bowl”. This is a very old musical instrument, still used in China, Tibet and other Asian countries. It was made of bronze and vibrates like a wineglass, but does not break. When it is partly filled with water, bouncing droplets appear for strong enough excitation [54]. Nevertheless, these systems provide merely examples of *normal* resonance phenomena. Small scale surface waves of water result from surface tension and it is well-known that cohesion can then lead to the formation of drops.

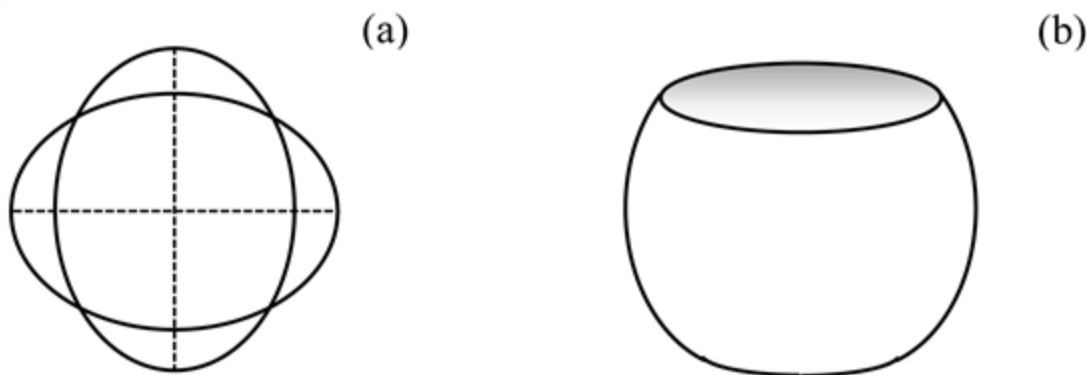


Figure 9. (a) Deformations of a vibrating wine glass. (b) A singing bowl or standing bell.

The spectacular collapse of the Tacoma Bridge is often cited as an example of resonance phenomena, but this resonance concerned a twisting vibration of the bridge that caused turbulent wind. This turbulence amplified the vibration and vice-versa, as visually explained in a video [55]. Positive feed-back can thus lead to *auto-amplification* and stronger resonances than normal ones. We will show that targeted destruction of viruses and other microbes results from such a mechanism and does also end with fatal disruption.

Anthony Holland did perform himself experiments concerning the effects of EM waves. He showed the results for a harmless unicellular organism, called "blepharisma". Its usual size is 75 - 300 μm and can thus easily be observed with a standard optical microscope. These entities are elongated and their surface is uniformly covered with short hair-like organelles (see Wikipedia). Holland's video [53] shows (at minute 10:43) that the membrane displays a blister before breaking up (11:13). It is interesting that another blister was forming at the other side (11:03) and that a small apparently exploring entity was unaffected at the imposed frequency. Holland showed then also exploding leukemia cells (13:00-13:24), by using the phanotron of a "Bare/Rife device". James Bare is an MD, wanting to help patients. It is respectable that he tried to understand what happens, but it is instructive to examine his attempted explanations to become aware of possible pitfalls. The term "resonant light technology" is not adequate, since the resonance is due to an EM wave and not by the luminous electron beam. Dr. Bare knew that, but he thought that it constitutes a "small antenna". He mentions even "solitons" [56], but an antenna is only a conducting wire, where electrons are set in longitudinal oscillation to produce a standing wave with maximal amplitude at both ends. This is the usual way to create EM waves, but we explained already that Rife produced EM waves by deceleration of electrons in the anode.

Since the microscope revealed that the membrane of nearly spherical cells was locally broken up, Dr. Bare and collaborators thought that the resonance is due to the hole. A spherical vessel with a short neck constitutes a "Helmholtz resonator", since the air in any closed vessel acts like a spring on the oscillating air in the neck. The resonance does spontaneously appear when an airstream is blowing fast enough over the opening, since stationary waves are then excited by turbulence, as inside some flutes. However, there is only one resonance frequency for a given size of the vessel and its neck, since there is a single oscillator. For flutes, there are several possible standing waves of different frequencies. Actually, the hole in the membrane of an exploding cell is a consequence of Rife's resonances and not its cause.

To explain the destruction of viruses and microbes by resonance, it is necessary to start with adopting an adequate model. Holland's analogy with shattering a wine glass could suggest that Rife excited deformations of the cell body. This would yield an ensemble of resonance frequencies [57], while Table 1 attributes only one resonance frequency to any particular type of microbes. Another possible hypothesis would be an electric polarization of the cell body. This mechanism leads to a resonance for particles that are very small compared to the wavelength λ of EM waves. They are bathing in a homogeneous electric field that induces surface charges, creating a secondary electric field inside the particle. It leads to a resonance for dipole oscillations. This accounts for the blue sky, since the electric field of sunlight does polarize very small particles in atmospheric air. This resonance frequency is situated in the domain of UV light and energy is only *absorbed* at this resonance frequency, but scattered at neighboring frequencies. This so-called "Rayleigh scattering" of sunlight results from the induced polarization. It is more intense for blue than for red light. This theory applies also to collective oscillations of electrons in very small metal particles and allowed us to explain

the “anomalous optical absorption” of thin granular metal films [58]. The same theory explains the resonance that radio-waves produce in red blood cells [59]. However, the mechanism of Rife’s resonance phenomenon is different and has not yet been explained.

4.2. Structure and Function of Virus Spikes

The Covid-19 pandemic and images of the relevant viruses suggested to the author that their spikes might be set in oscillation and could perhaps lead to a devastating resonance. We will test this hypothesis by establishing the relevant equation and solving it, but first of all, we had to know more about the structure and function of virus spikes. They are not merely flower-like decorations, but very efficient weapons for attacking cells, in order to use their machinery to reproduce themselves in great numbers.

The so-called “Spanish flue” of 1918 was due to a virus. It infected some 500 million people and killed at least 20 million persons [60]. This virus became more lethal during the pandemic, since its mutation led to a second wave, where lungs were filled with blood. The Corona-19 virus appeared in China and was partially controlled by containment, but not stopped. Social proximity, increased population densities, worldwide mobility and interwoven economies are major factors of its spreading. We see also that the search and testing of vaccines take time. Even a vaccine cannot protect us against unpredictable new mutations and the possible appearance of more virulent forms. It would thus be irresponsible to neglect already existing evidence that an *efficient, safe and rapidly adaptable biophysical method* is possible.

Rife’s method could have been tested at least by means of experimental procedures, but it was rejected since it seemed to be unbelievable. Nevertheless, it is also necessary to explain why the reported facts are true. We are thus confronted with a basic scientific problem. There are numerous examples, indeed, where something unexpected was discovered. It concerned still *hidden realities*. How can we get access to anything that is not directly observable? We have to imagine what might happen, draw logical consequences from this hypothesis and verify then if they are true or not. The first problem is thus to select a plausible hypothesis, deserving rigorous analysis ... It became possible at about 1980 to combine cryogenic electron microscopy with gene sequencing to understand the role of spikes. The resulting knowledge is summarized in Figure 10, but for clarity, we represent only one pair of macromolecules, while the flower-like hemagglutinin (HA) spikes contain 3 identical pairs. We are now accustomed to artistic representations, but they do not reveal what is essential. Figure 10(a) represents the normal state of the associated HA1 and HA2 proteins. The HA1 molecule contains negative charges (COO⁻) that belong to small sialic acid molecules that can move inside the molecule. Because of their mutual repulsion, they create surface charges. Electrostatics tells us that its density depends on the configuration of the surface and has to be greater near the pointed tip of the HA1 molecule. These charges polarize the electrically neutral HA2 molecule, which is a slender, helicoidally wound molecule. It tends to be straight, but is bent and kept in this state, because of the increased surface charges at the lower end of the HA1 molecule. The middle part of the coil spring is more irregular than indicated here, but it is only important that we get a *loaded spring trap*. It is anchored in the membrane of the virus. Its extremity, represented in green in Figure 10(a), is situated on the other side of the membrane of the virus. It is electrically charged and thus hydrophilic. This is usually sufficient to secure the implantation, but not for very strong traction.

Figure 10(b) shows what happens in the vicinity of a cell. Its pores allow ion transport that maintains a potential difference between the inner and outer surface of its membrane. This leads to an increased density of H^+ ions near the external surface. When a virus comes close to the membrane, these protons reduce the surface charge density of the HA1 molecule, since $COO^- + H^+ \rightarrow COOH$. The remaining surface charge is then too small to keep the HA2 spring in its bent state. It is suddenly released and its tip carries a fusion protein, indicated in red. It penetrates the membrane and this occurs simultaneously for the three HA

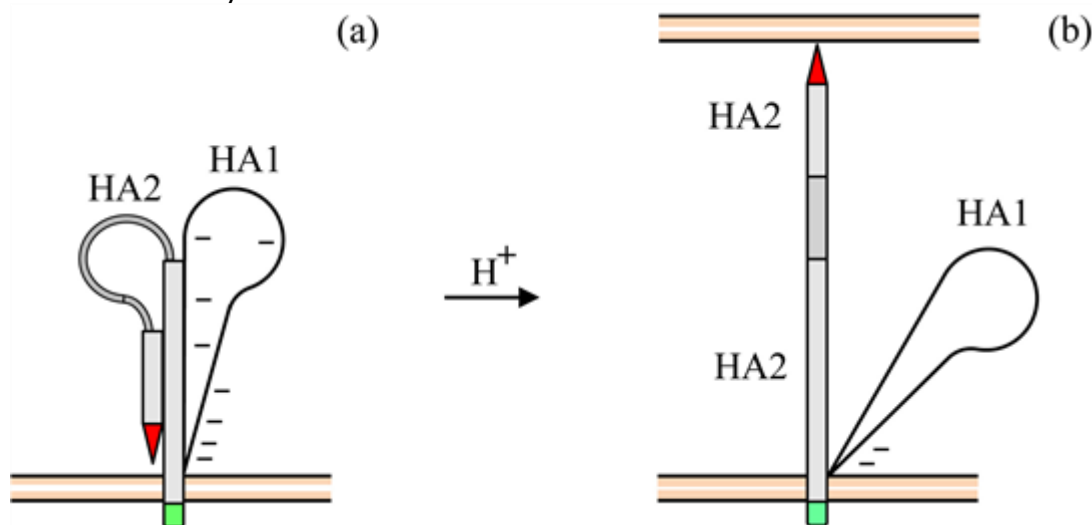


Figure 10. Schematic representation of one pair of HA1 and AH2 molecules, constituting spikes of viruses. (a) In the normal state, the helically wound molecule HA2 is bent and kept in place like a loaded spring. (b) It is released by neutralization of the HA1 molecule.

The redundancy strengthens the grabbing, as well as the rooting. Moreover, the structure of the HA1 part is modifiable by mutations to prevent the immune system from recognizing the potential invader. Viruses are terrorists, carrying jackknives under a coat. They are ready for stabbing cells that are in reach and their camouflage can be modified to escape detection. The HA2 part is on the contrary strictly conserved. This ingenious system was elaborated by natural selection, governed by survival of the fittest.

The existence of this war machine was recognized in 1993 [61]. To highlight the rapidly expanding research on this subject, we mention the review of the virologist Suzuki and a molecular biochemist [62]. Professor Stephen Harrison of Harvard medical school presented this theory in an excellent video [63] and explained how the spikes help the virus to penetrate into the cell [64]. We insist more on explaining the mechanism of automatic triggering. It is known that spikes of the SARS-2 virus have a conical form [65]. It differs from usual representations, although it is also attached to the membrane by a thin stalk.

4.3. Other Spikes of Viruses and the Pili of Bacteria

So far, we described only virus spikes that are made of hemagglutinin (HA), but viruses do also have another type of spikes. They are constituted of 4 neuraminidase (NA) proteins, which are also electrically charged [66]. 18 variants of HA and 11 subtypes of

NA are known [67]. The phylogenetic tree of the Corona virus [68] indicates thus quite great variability. Viruses were modified to become more efficient. The influenza virion carries 300 to 400 HA spikes and 40 to 50 NA spikes. Their relative numbers have to be balanced [69], since they cooperate to help the virus to get inside the pirated cell. The diameter of the spherical core of usual viruses is about 120 nm. The length of HA spikes can be about 12.5 nm long, while the length of NA spikes is slightly smaller or greater. *Rotaviruses* are different. They contain double-stranded RNA, instead of single-stranded one and are said to be non-enveloped. Actually, the lipid bilayer is replaced by a tightly fitting protein coat, but there are always spikes that undergo conformational changes and perforate the lipid bilayer of the target cell [70]. *Bacteria* are endowed with long corkscrew-like flagella. They allow for efficient propulsion, since they are activated by small individual motors, embedded in the cell membrane, but the whole surface of bacteria is covered with *pili*. The growth and molecular constitution of these hair-like structures are now well-known. The major part is a helical fiber with a sticky tip. This allows for adhesion and some stretching that causes retracting forces. The rod is hollow and can even allow for DNA transfer, but is also an electron conductor. The main function of pili or cilia of bacteria is to sense their environment and to facilitate sexual reproduction by fusion with the same type of bacteria. Antibacterial molecules interfere with this process, but do not prevent survivors from producing protective mutations. For us, it is essential that pili do also carry positive and negative parts [71], since that offers the possibility to act on them by means of an oscillating electric field.

4.4. The Normal Resonance and Parametric Amplifiers

To facilitate a rational understanding of Rife's resonance, we begin with analyzing the properties of a simple and familiar system. A pendulum is merely composed of a mass M , suspended at a fixed point by means of a string of constant length L . Figure 11(a) shows that an angular displacement θ with respect to the vertical implies a horizontal displacement $x = L \sin \theta \approx L \theta$. The mass M is subjected to the gravitational force $F = Mg$. Its tangential component $F \sin \theta = Mg \sin \theta \approx Mg \theta = Mg x / L$ is proportional to x , but opposite. This restoring force tends to reestablish equilibrium, but once the pendulum has started to oscillate, it has the tendency to remain in this state of motion. To show why and to make scientific reasoning accessible to non-specialist, also for later generalizations, we recall Newton's law. It states that the product of the mass M and its instantaneous acceleration $\ddot{x}$ is always equal to the sum of all applied forces. When air friction is negligible, we get thus for small angular displacements

$M\ddot{x} = -Mgx/L$ or $\ddot{x} + \omega_0^2 x = 0$ where $\omega_0^2 = g/L$ $M\ddot{x} = -Mgx/L$ or $\ddot{x} + \omega_0^2 x = 0$ where $\omega_0^2 = g/L$ (5)
Every dot indicates a derivation with respect to the time variable t . The solution of this equation is $x(t) = C \sin(\omega_0 t + \varphi)$ and accounts for free oscillations. The (angular) frequency ω_0 is determined by the value of the local gravitational acceleration g and the length L of the pendulum. The values of the amplitude C and the phase φ depend on the initial conditions. Indeed, a child that is sitting on a swing can initiate free oscillations by pushing with its feet on the ground. This means that $x(0) = 0$ and therefore $\varphi = 0$, but the initial velocity $\dot{x}(0) = \omega_0 C$. The amplitude C depends then on the impulse for starting the oscillation.

If air friction were really negligible, the amplitude C would remain constant. Actually, the oscillation is progressively damped, since the mass M is subjected to air friction. This braking force is proportional to the instantaneous velocity $\dot{x}$ and depends on the cross-sectional area. However, the oscillations can be sustained by means of a push at the adequate rhythm. The mathematical treatment is simplified for a constantly applied

driving force that oscillates at some frequency ω with constant strength S . The equation of motion is then

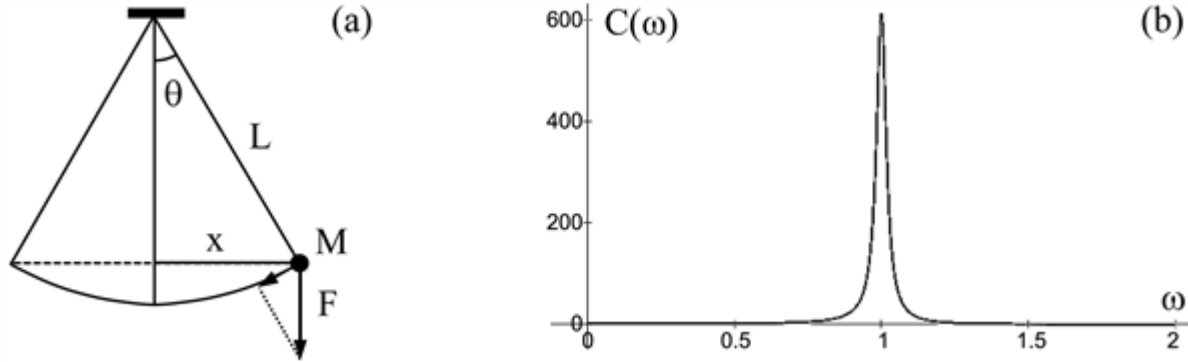


Figure 11. (a) Parameters needed to describe the motion of a simple pendulum. (b) The peak for possible amplitudes of forced oscillation is very high and narrow for low friction.

$$x'' + \omega_0^2 x + 2\nu x' = S \sin(\omega t) \quad x'' + \omega_0^2 x + 2\nu x' = S \sin(\omega t) \quad (6)$$

Thus,

$$x(t) = A \sin \omega t + B \cos \omega t = C \sin(\omega t + \varphi) \quad x(t) = A \sin \omega t + B \cos \omega t = C \sin(\omega t + \varphi) \quad (7)$$

The solution (7) describes *forced oscillations* that subsist when the initial conditions are not relevant anymore, because of damping. The mass M is oscillating at the imposed frequency ω , but the constants A and B are determined by substituting Equation (7) in Equation (6). We get then

$$(\omega_0^2 - \omega^2)A - 2\nu\omega B = S \quad (\omega_0^2 - \omega^2)A - 2\nu\omega B = S \quad \text{and} \quad (\omega_0^2 - \omega^2)B + 2\nu\omega A = 0 \quad (\omega_0^2 - \omega^2)B + 2\nu\omega A = 0$$

Thus,

$$A = \frac{(\omega_0^2 - \omega^2)S}{(\omega_0^2 - \omega^2)^2 + (2\nu\omega)^2} \quad A = \frac{(\omega_0^2 - \omega^2)S}{(\omega_0^2 - \omega^2)^2 + (2\nu\omega)^2} \quad \text{and} \quad B = \frac{-2\nu\omega S}{(\omega_0^2 - \omega^2)^2 + (2\nu\omega)^2} \quad B = \frac{-2\nu\omega S}{(\omega_0^2 - \omega^2)^2 + (2\nu\omega)^2}$$

Because of (7), $C^2 = A^2 + B^2$. The amplitude of the forced oscillation is therefore

$$C = \frac{S}{\sqrt{(\omega_0^2 - \omega^2)^2 + (2\nu\omega)^2}} \quad \text{while} \quad \tan \varphi = \frac{2\nu\omega}{\omega_0^2 - \omega^2} \quad C = \frac{S}{\sqrt{(\omega_0^2 - \omega^2)^2 + (2\nu\omega)^2}} \quad \text{while} \quad \tan \varphi = \frac{2\nu\omega}{\omega_0^2 - \omega^2} \quad (8)$$

These expressions describe the *normal* resonance phenomenon. Rife's resonance is more powerful, but the first relation (8) is already very useful to understand the physical meaning of resonances. The amplitude C of forced oscillations is maximal when the denominator is minimal, this happens when its derivative with respect to ω is zero and thus when $\omega = \omega_v$, where $\omega_0^2 - 2\nu^2 = \omega_v^2$. When friction is sufficiently small ($\nu \ll \omega_0$), the graph of $C(\omega)$ displays a symmetric peak that is centered on ω_0 . The resonance frequency has thus the same value ω_0 as for free oscillations. Figure 11(b) provides the graph of $C(\omega)$ when $S = 1$, $\omega_0 = 1$ and $\nu = 0.02$. In general, the height of the peak is $S/4\nu^2$ and its width at half height is equal to ν . The resonance becomes thus sharper for decreasing friction. The amplitude C would even become infinite in the absence of friction. The second relation (8) predicts the phase difference φ for different values of ω . This function is represented in Figure 12(a) for $\omega_0 = 1$ and $\nu = 0.02$. The change of sign means that the oscillator is able to follow the rhythm of the applied force when the imposed frequency is lower than ω_0 , but it stays behind when it is too fast.

We are now ready to answer a simple question: is a child, sitting on a swing, able to sustain itself the oscillations without any external help? Probably, you found the answer yourself by trial and error. It is fun to make discoveries and to master a situation oneself. It is even much more interesting and surprising to understand why this is possible. The child has to straighten up when it is approaching the highest points and to incline backwards when it is moving towards the other side. The effective length L of the pendulum is thus modified as shown in Figure 12(b).

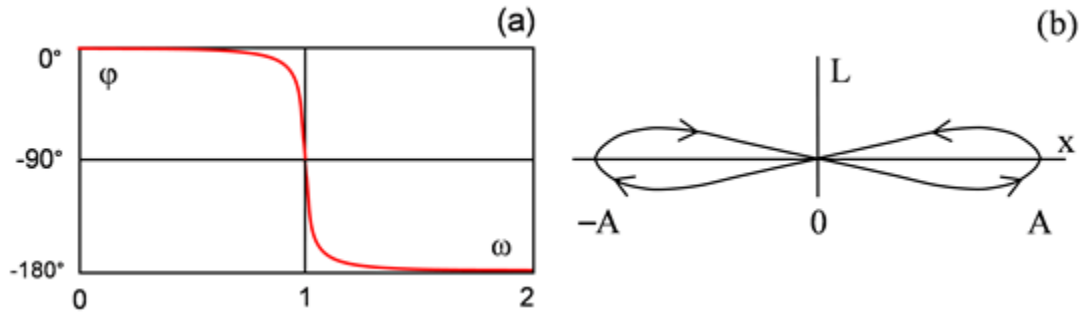


Figure 12. (a) The phase difference between the forced oscillation and the applied force. (b) This type of periodic variations of the effective length L of the pendulum yields a parametric amplifier.

The variation of L can be approximated by the function

$$L(t) = L_0(1 + 2\gamma \sin 2\omega t) \text{ when } x(t) = A \sin \omega t$$

$$L(t) = L_0(1 - 2\gamma \sin 2\omega t) \text{ when } x(t) = -A \sin \omega t$$

The variation of the parameter L is adapted to the actual frequency of oscillation, but the equation of motion (6) is then modified. It yields

$$x'' + \omega_0^2(1 - 2\gamma \sin 2\omega t)x + 2\nu x' = 0 \text{ when } S = 0$$

$$x'' + \omega_0^2(1 + 2\gamma \sin 2\omega t)x + 2\nu x' = 0 \text{ when } S = 0 \quad (9)$$

To solve this equation, we note that

$$2\sin 2\omega t \sin \omega t = \cos \omega t - \cos 3\omega t \quad (10)$$

This relation was proven in trigonometry, without mentioning its physical importance.

The fact that the product of two oscillating functions is equivalent to a sum of two oscillating functions implies that Equation (9) is equivalent to

$$x'' + \omega_0^2 x + 2\nu \omega A \cos \omega t = \gamma \omega_0^2 (\cos \omega t - \cos 3\omega t) x'' + \omega_0^2 x + 2\nu \omega A \cos \omega t = \gamma \omega_0^2 (\cos \omega t - \cos 3\omega t) \quad (11)$$

The periodic variation of the length L produces thus two oscillating *driving* forces. The first one does exactly compensate friction when $\omega = \omega_0$ and $\gamma = 2\nu/\omega_0$. The other force has negligible effects, since the frequency 3ω is too far away from the resonance frequency. The child can thus sustain the oscillations by its own muscular forces. Greater values of γ will not only compensate energy losses, but increase the amplitude. The system becomes then a *parametric amplifier* until equilibrium is reached. This can easily be verified by attaching a small mass on a string that is partially wrapped around a pencil. It is sufficient to rotate the pencil towards the left and the right at the adequate rhythm. Trapeze artists apply this method at a human scale.

We transposed this theory to explain the mysterious phenomenon of *ball lighting* [72]. Since skeptics did simply attribute it to illusions, in spite of numerous testimonies of serious witnesses, it is useful to show how the explanation was found. The example is also adequate to illustrate the method of imagining what is hidden and verifying if the logical consequences do agree with all observed facts. We assumed that ball lightning is similar to a soap bubble, but that the membrane is luminous, since it contains ionized

air. However, light emission results from recombination processes. The luminosity should decrease very rapidly, as for ordinary lightning. The difference is that the membrane allows for collective motions of the free electrons with respect to the heavier ions inside the membrane. The frequency ω_e of this “plasma oscillation” is determined by the density of free electrons, but they are radially oscillating inside the membrane. This makes the external surface alternatively positive and negative. Ball lightning does thus alternatively attract electrons and positive ions that are present in the ambient air near its surface. This replenishes not only the stock of charged particles, but modulates also the oscillation frequency as in Equation (9). This leads to *auto-oscillations*. They are sustained without requiring constant excitation by an oscillating electric field of external origin.

How can we test the validity of this explanation? The answer is that it accounts for apparently mysterious observations. Indeed, ball lightning is usually moving around in an apparently erratic way. We can now “mentally see” that it is constantly attracted towards the greatest density of charged particles in the ambient medium. It behaves thus like a living being that survives by feeding itself. Moreover, ball lightning can suddenly disappear in midair, as if the light had been extinguished. This is due to entering a region where the ambient air was not sufficiently ionized. It can also happen that ball lightning explodes, even very violently. The invisible cause is a locally greater ionization of the ambient air, which led to fatal parametric amplification. Although this was a digression, it is useful to understand an essential feature of science and to be prepared for another intellectual adventure. It concerns the destruction of viruses and other microbes by means of resonances, but they are quite special.

4.5. The Peculiar Resonance of Virus Spikes

The analogy with shattering a wine glass [49] is useful as a first approximation. It begins also with determining the resonance frequency and an experienced singer is able to produce a sound wave of precisely the same frequency. With laboratory instrumentation, we can prove that there are several possible ones and select one of these frequencies to produce a resonance [73]. Spikes can also be set in forced oscillations, but the resulting resonance is more powerful than normal resonances. Figure 13(a) shows the outline of the spikes of the Corona virus, according to data obtained by means of cryo-electromicrography [74]. The spike is normally straight and we know that its upper part is negatively charged. Figure 13(b) reduces the spike to its essential elements. It is then similar to a *cantilever* that is implanted in a larger body, but can be bent, when its effective tip

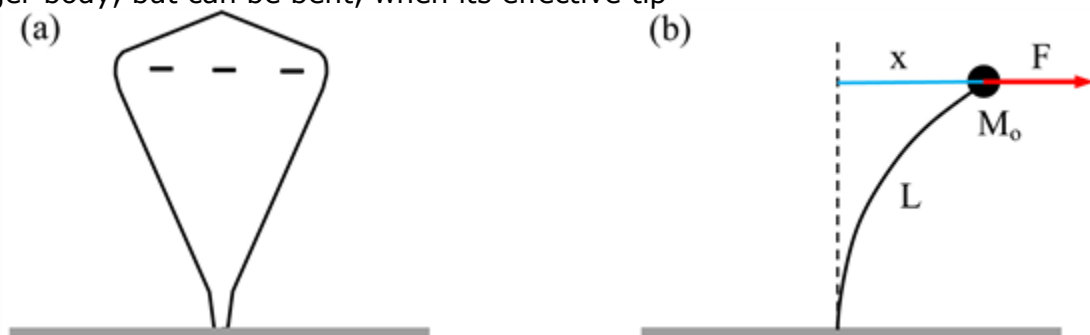


Figure 13. (a) The global shape of a Corona virus spike in its normal state. (b) The applied force produces a lateral displacement and allows for a powerful resonance.

mass M_o is subjected to a lateral force F . It produces then a displacement x with respect to the symmetry axis. How does it vary for an oscillating force?

Fortunately, Friswell's team established already in 2012 the equation of motion for *energy harvesters* [75]. They consist of a homogenous elastic beam that carries a tip mass and is implanted on a chariot. It is set in motion by random oscillations of a bridge and the resulting kinetic energy is transformed by detectors into electric energy. We adapt their equation to describe possible vibrations of virus spikes. The difference is only that their base remains fixed, while the oscillating force F is directly applied to the tip mass M_o . Although the stem of the spike is not homogeneous, we can keep the model of a uniform beam by defining average values. However, the spike is surrounded by a fluid instead of air and thus subjected to viscous friction. The equation of motion is then

$$M_o \ddot{x} = F(t) - \sigma \dot{x} - [k + a(\ddot{x} + \dot{x}^2)x + b x^2]x \quad M_o \ddot{x} = F(t) - \sigma \dot{x} - [k + a(\ddot{x} + \dot{x}^2)x + b x^2]x \quad (11)$$

where

$$M_o = M + 0.227L\mu + 2.467L^2I \quad M_o = M + 0.227L\mu + 2.467L^2I \quad \text{and} \quad k = 3.044L^3EI - 1.234LgM - 0.367g\mu$$

$$= 3.044L^3EI - 1.234LgM - 0.367g\mu$$

$$a = 1.523L^2M + 0.276L\mu + 6.091L^4I \quad a = 1.523L^2M + 0.276L\mu + 6.091L^4I \quad \text{and} \quad b = 3.756L^5EI \quad b = 3.756L^5EI$$

The effective mass M_o is thus defined by the real tip mass M , the length L of the beam and its averaged mass density μ . It is also necessary to account for the moment of inertia I of the spike with respect to the fixed point. The stiffness of the beam is mainly determined by the coefficient k , which depends on Young's modulus E of the constituting material, the length L of the cantilever and its moment of inertia I . For energy harvesters with a very flexible beam, the weights of the tip mass M of the beam will reduce the restoring force. This allows for two lateral equilibrium positions along a given direction. The nonlinear terms of Equation (11) lead then to *chaotic* behavior, where the tip mass can execute small oscillations around one of the possible equilibrium positions, but also pass from one side to the other. Indeed, very small changes of the instantaneous position and velocity at critical moments will produce qualitatively different motions. For spikes, surrounded by a fluid, we can neglect the weights because of buoyancy, but the nonlinear effects remain important. Actually, the equation of motion (11) is reduced to

$$\ddot{x} + \omega_0^2 x + 2v\dot{x} + 4\gamma[\ddot{x} + \dot{x}^2 + \beta x^2]x = S \sin \omega t \quad \ddot{x} + \omega_0^2 x + 2v\dot{x} + 4\gamma[\ddot{x} + \dot{x}^2 + \beta x^2]x = S \sin \omega t \quad (12)$$

$$\omega_0^2 = kM_o = 3.044EIL^3M_o \quad \omega_0^2 = kM_o = 3.044EIL^3M_o, \quad \gamma = a4M_o = 0.3813.467L^2 \quad \gamma = a4M_o = 0.3813.467L^2$$

$$\text{and} \quad \beta = baM_o = 2.4661.523EIL^3M_o = 1.6193.044 \quad \beta = baM_o = 2.4661.523EIL^3M_o = 1.6193.044 \omega_0^2$$

The spike does not simply behave like an inverted pendulum, since Equation (6) is generalized. The nonlinear terms depend on the instantaneous values of the displacement x , the velocity $\dot{x}$ and the acceleration $\ddot{x}$. When the tip mass is dominant, $I \approx ML^2$ and $M_o \approx 3.467M$. Measuring the displacement x in units $L = 1$, we get then $\gamma = 0.110$ and $\beta = 0.532$. Since forced oscillations occur at the imposed frequency ω

$$x = C \sin(\omega t + \varphi) \quad x = C \sin(\omega t + \varphi), \quad \dot{x} = \omega C \cos(\omega t + \varphi) \quad \dot{x} = \omega C \cos(\omega t + \varphi) \quad \text{and} \quad \ddot{x} = -\omega^2 C \sin(\omega t + \varphi) \quad \ddot{x} = -\omega^2 C \sin(\omega t + \varphi)$$

The value of φ depends on v , but when $\alpha = \omega t + \varphi$, we get always

$$4x^3 = C^3(3 \sin \alpha - \sin 3\alpha) \quad 4x^3 = C^3(3 \sin \alpha - \sin 3\alpha) \quad \text{and} \quad 4\dot{x}^2 x = \omega^2 C^3(\sin 3\alpha + \sin \alpha) \quad 4\dot{x}^2 x = \omega^2 C^3(\sin 3\alpha + \sin \alpha)$$

The nonlinear terms in Equation (12) are again equivalent to adding two forces. They oscillate at the frequencies ω and 3ω . The first one modifies the applied force and the second force can be neglected, since the frequency 3ω is too far off-resonance. To concentrate on essential features for the resonance, we assume that friction is negligible ($\nu = 0$ and $\varphi = 0$). The amplitude C of forced oscillations is then determined by Equation (12), which yields

$$(\omega_{20}-\omega_2)C\sin\alpha+2\gamma(\omega_{21}-\omega_2)C_3\sin\alpha=S\sin\omega t(\omega_{20}-\omega_2)C\sin\alpha+2\gamma(\omega_{12}-\omega_2)C_3\sin\alpha=S\sin\omega t$$

Indeed, $4(\ddot{x}x''+x'^2+\beta x^2)=(3\beta-2\omega_2)C_3\sin\alpha$ $4(\ddot{x}x''+x'^2+\beta x^2)=(3\beta-2\omega_2)C_3\sin\alpha$ and $\omega_{21}=3\beta/2=0.798\omega_{20}$ $\omega_{12}=3\beta/2=0.798\omega_{20}$. The amplitude C of forced oscillation is thus determined by the cubic equation

$$(\omega_{20}-\omega_2)C+2\gamma(\omega_{21}-\omega_2)C_3=S(\omega_{20}-\omega_2)C+2\gamma(\omega_{12}-\omega_2)C_3=S(13)$$

Thus

$$C=C_0(\omega)=S\omega_{20}-\omega_2C=C_0(\omega)=S\omega_{20}-\omega_2 \text{ when } \gamma=0\gamma=0$$

without nonlinear effects, we get the *normal* resonance. It corresponds to (8), but is simpler, since $\nu = 0$. It is represented by the black graph in Figure 14(a) and represents the actual amplitude of forced oscillations with a change of sign below and above the resonance frequency. It differs from Figure 11(b), which accounted only for the magnitude of $C(\omega)$ when $\nu = 0.02$, while the sign was determined by Figure 12(a). Nonlinear effects do modify the response of spikes, since Equation (13) allows for 3 possible solutions and in particular for

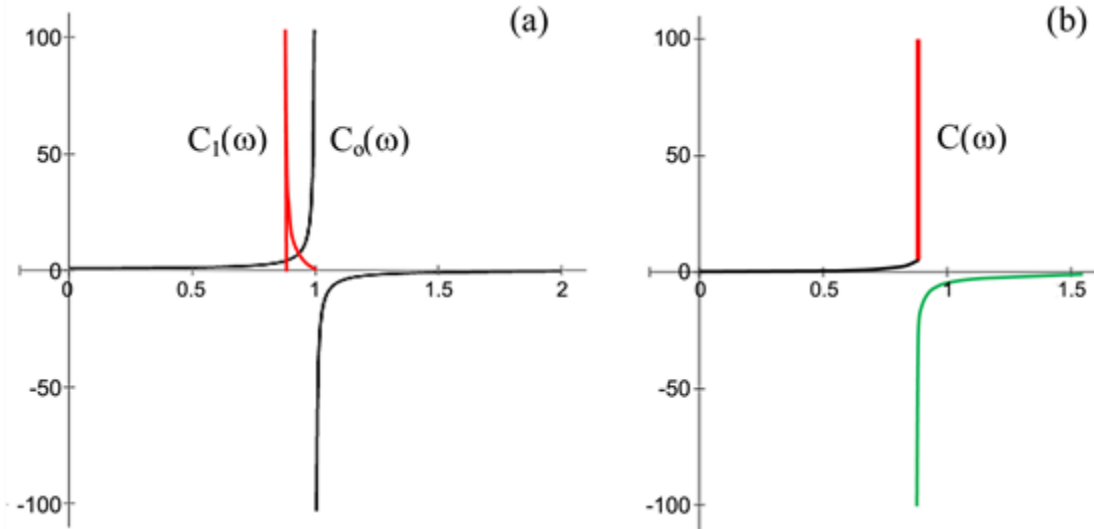


Figure 14. (a) The amplitude of forced oscillations of spikes would be $C_0(\omega)$ without nonlinear effects. The resonance frequency is then $\omega_0 = 1$. Nonlinear effects allow for auto-oscillations, characterized by $C_1(\omega)$. (b). This leads to a *synergy* when it is combined with constant excitation and yields then $C(\omega)$.

$C=0C=0$ or $C_2=(\omega_{20}-\omega_2)2\gamma(\omega_2-\omega_{21})C_2=(\omega_{20}-\omega_2)2\gamma(\omega_2-\omega_{12})$ when $S=0S=0$
We expected, of course, that without excitation there is no response, but because of nonlinear effects, spikes are able to produce a driving force that yields *auto-oscillations*. This is similar to what happened for a pendulum, when its effective length was periodically modified, but the reason is different. Now, it does not compensate friction,

since we considered even the case where $\nu = 0$. The stiffness of spikes allows them to oscillate by themselves, but only in a limited frequency domain, since C^2 has to be positive to yield a real value for the amplitude C . It is necessary that $\omega_1 \leq \omega \leq \omega_0$, $\omega_1 \leq \omega \leq \omega_0$. The resulting function $C_1(\omega)$ is represented by the red curve in Figure 14(a). It defines the amplitude of the auto-oscillation and diverges when $\omega = \omega_1 \approx 0.9\omega_0$, $\omega = \omega_1 \approx 0.9\omega_0$. There is a resonance, but at a lower frequency than for the normal resonance. Equation (13) tells us what happens when the spike is constantly subjected to an excitation of strength S , oscillating at some given frequency ω . The normal resonance is then modified, since $C_0(\omega)$ has to be replaced by a function $C(\omega)$ that is represented in Figure 14(b). It can only be defined by *real* solutions of (13). This yields 3 curves represented in different colors. They are simultaneously possible in a very small frequency domain (from 0.8933 to 0.89621 when $\omega_0 = 1$).

The rigorous treatment of this problem was necessary, because of past contestations. It is also instructing from a theoretical point of view, since it illustrates the usually hidden mechanism of nonlinear systems. Moreover it is and should be of great practical importance. We can now harvest the fruits. We measured displacements in units $L = 1$, but when the mass M is dominant, the moment of inertia I is proportional to L^2 . The value of ω_1 is thus proportional to $1/L$. The resonance frequency is greater for short spikes, since they are stiffer. However, $\gamma \approx 0.11/L^2$. The amplitude of forced oscillations is thus proportional to $L^2 S$ and greater for long spikes than for short ones. Moreover, there is only *one* resonance frequency for every particular type of microbes, in agreement with Rife's measurements. Since its value ω_1 does not depend on the strength S of the applied force, it is sufficient to determine ω_1 for *one* particular strength S , although greater values of S do increase the amplitude of forced oscillations. Empirical discoveries can make sense, of course, without understanding the underlying mechanism. It is then only necessary to verify that the observed facts are trustable. When it turns out that they are real, they have to be explained, but that requires other methods and may be delayed.

4.6. The Mechanism of Targeted Microbe Destruction

Constructing a theory consists in choosing a plausible hypothesis and deducing logical consequences. Even a correct theory is only valid when its predictions agree with all known facts and further experimental verifications. Figure 15(a) represents a cantilever that is set in forced oscillation at a frequency ω that is close to the resonance frequency. When $\omega = \omega_1$, the amplitude C of the oscillation

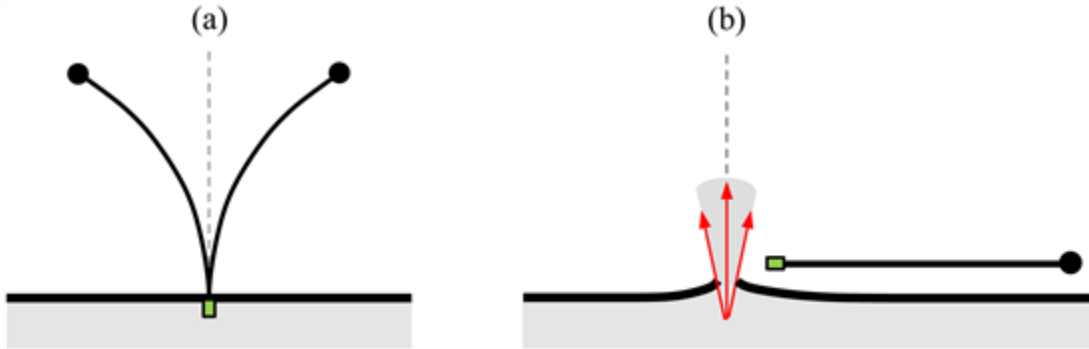


Figure 15. (a) Forced oscillations of a spike or pili. (b) At resonance, it is extracted and creates a hole in the membrane that destroys the microbe by extrusion of its content.

becomes quasi infinite, even when friction is not totally negligible. Resonance would thus imply enormous stretching of spikes or pili, if they were solidly implanted in the membrane or any equivalent structure. Normally, this would cause plastic deformations and eventually fracture, but that is replaced by extraction from the membrane and creation of a hole.

This causes expulsion of the content of the virus, as represented in [Figure 15\(b\)](#). The virus is definitively destroyed. We recall that spikes are only fastened by the hydrophilic tail of their backbone, represented in green. This fixation is usually sufficient, but not secured, as can be achieved by means of bolts and screws. This system was invented in Antiquity at about 400 BC and it was recognized that the screw has to be well-tightened. The explanation is that dry friction between nonmoving surfaces is greater than kinetic friction and increased by pressure. This insight came much later and required even repeated discoveries [by da Vinci, Amontons and Coulomb, respectively at about 1500, 1700 and in 1785]. The fastening of spikes is improved by triple implanting, but not enough to resist at the resonance frequency. Even trees can be deracinated by strong wind, in spite of their distributed roots.

This theory applies also to *pili*, covering the surface of bacteria and nanobacteria. Since they carry electrical charges, they can also be set in forced vibrations by an oscillating electric field. They behave like cantilevers that can be elastically bent, but because of nonlinear effects, they allow for auto-oscillation and extremely great amplitudes of oscillation at their resonance frequency ω_1 . The creation of a hole and destruction of microbes could be observed. Holland's video [\[53\]](#) shows even local *bulging* of the membrane of bacteria before the explosive eruption. This means that a bunch of pili was involved at a place, where the electric field was perpendicular to these structures. Bulging began also at the opposite side, where the electric field is also effective. Moreover, microbes are immobilized before breaking up, since the propelling function of pili is already disturbed. It does not only depend on motorized flagella.

The sophisticated spikes of viruses are highly efficient weapons, but they have an inherent weakness that can be exploited when we are aware of this possibility. Although pili of bacteria and nanobacteria have other functions, they lead also to total destruction, without survivors that could initiate securing mutations. It is only necessary to impose a frequency that is precisely equal to the resonance frequency. It was a huge error to claim that the observed facts had to be bogus, even without verifying, since it deprived humanity from making use of a simple and secure method to fight sicknesses, plagues and even cancer.

Rife found not only that BX and BY bacteria are involved in cancer, but also that they are proliferating after radiotherapy. This merits special attention. It has been rediscovered that oscillating electric fields can be used for cancer therapy. A possible mechanism has been proposed [\[76\]](#) [\[77\]](#), but it is still a hypothetical one and should be reexamined in a larger context. Since pleomorphic transformations are reversible, it is plausible that the total number of pili is conserved in size reduction. Their surface density would then be increased for nanobacteria and explain why they become more virulent. Nevertheless, they remain vulnerable for Rife's resonances.

It should be noted that a cantilever, constituted of a steel wire, does also allow for another mode of oscillation, where a knot is created near the free end. However, the resonance frequency is significantly higher and this type of deformations can be excluded for virus spikes. We mention also that it is possible to use UV light for disinfecting surfaces. Low pressure mercury lamps produce UVC light at 254 nm. It is absorbed by RNA and produces there local defects [\[78\]](#), but this method is only applicable to viruses that are directly exposed to this radiation on a surface, in aerosol

droplets or very thin liquid films. The FDA issued a warning, since UVC light damages the human skin and is dangerous for our eyes [79]. Rife's method is not dangerous at all and efficient for destroying virulent microbes anywhere inside our body.

5. Summary and Conclusions

Rife did prove that *optical* microscopes allow for much greater magnification and higher resolution than had been assumed. Since he constructed himself several supermicroscopes with purely classical means, his scientific creativity and accomplished craftsmanship deserve recognition and respect. With his instruments, he could clearly observe that when bacteria are exposed to stress, they reduce their size. They keep only what is essential to survive, but are more aggressive. Naessens did also prove the reality of pleomorphism, but some authorities did not like that. They declared that these pioneers are quacks, but refused to verify if the reported facts were real or not. This attitude is more than strange.

Moreover, Rife discovered already about 100 years ago that bacteria and nanobacteria can be destroyed by resonance. His phanotron was an ingenious instrument that produced the required electric field by means of braking radiation. Instead of emitting EM waves in all directions by means of an antenna, like Hertz did and is usual for broadcasting, his system generated a local beam of EM waves. The destruction of bacteria by resonance was already observable with standard optical microscopes, but Rife was also able to see exploding nanobacteria. Actually, he had to persevere during more than a decade to make these tiny microbes visible. He did then prove that some of them are present in cancer tissue and that after being cultured, they do also cause cancer. He determined the resonance frequency for targeted destruction of various microbes. These values were confirmed by two collaborators, using different equipment. The efficiency of his method for healing cancer was clinically tested, but even these results were declared to be bogus, since they required modifying cherished postulates. For those who had the power to crush Rife, it did not matter that the reported results might be true. Rife was prosecuted. His documents were stolen. Instruments were wrecked and all traces of his achievements were eradicated from official medical records. That was *profoundly unjust, truly antiscientific and detrimental* for the worldwide health system.

We solved the basic scientific puzzle with mathematical rigor by considering that spikes of viruses, as well as pili of bacteria and nanobacteria can be set in forced oscillation. Nonlinear effects make the resonance stronger and sharper than usual ones. There is only one resonance frequency for every particular type of microbes. It depends on the length of the oscillating structures and is thus specific. This theory is experimentally confirmed and leaves no rational reason to negate the possibility of targeted destruction of microbes. The author of this study has no financial interest whatsoever in a general implementation of this method. His concern is merely truth, justice, but also reduction of unnecessary suffering and death. Other persons and institutions have now to go on in the direction that was pointed out by Rife.

The Coronavirus pandemic and its social implications should make everyone attentive to the existence of a biophysical method that differs from the usual biochemical one, but is *effective, secure and rapidly adaptable*. It is only necessary to determine the adequate resonance frequency very carefully, but this can be done with inexpensive equipment and by means of direct microscopic observation. Even the constant threat of unpredictable mutations can rapidly be countered. The treatment of patients requires only a few minutes, at intervals of three days. Because of the sharp resonance, this

method is selective and can eliminate side effects when it is objectively controlled like cars and traffic, for instance.

There is also rising evidence that our precious arsenal of antibiotics is endangered. *Multiple antibacterial resistances* are increasing [80]. The US Centers for Disease Control and Prevention concluded already in 2015 that “coordinated efforts to implement new politics, renew research efforts, and pursue steps to manage the crisis are greatly needed.” This was thought to “require considerable investment of human and financial resources”, but that is not true for Rife’s method. Basically, it only required to change some habits of thought.

We have to insist that dogmatism and concentration of power endanger scientific progress by blocking freedom of thought. When it is guided by observing reality and rational analysis, it is more efficient than *ideology*, but dictatorship and reckless use of power are always a temptation. In this context, we have to mention the research of the Russian chemist Tamara Lebedeva [81]. She made intensive research on *trichomonade* parasites and proved that they can cause cancer. Their reproduction rate was found to be increased by radiotherapy, but Lebedeva’s work was not recognized by medical authorities. Alfons Weber studied the impact on cancer of protozoa causing malaria [82]. He published his results in 1967 and promptly lost his approbation as medical doctor. It is now appearing that there are connections between malaria and cancer [83]. The plasmodium parasite is involved in both fields and cross-fertilization in medicine should be encouraged. The common feature of the research of Lebedeva and Dr. Weber was to consider that cancer is an infectious disease. We have to add that these types of parasites are not the only possible cause of cancer, but their effects should also be investigated.

To provide a concrete and still actual example of tenacious preconceptions related to medicine, we mention that Dr. Jacques Benveniste did experimentally prove the existence of “water memory” in the 1980th. Nevertheless, it was declared (even by a world-famous scientific journal) that this is impossible. This claim was based on the apparently obvious idea that when biologically active molecules are repeatedly dissolved in water, they cannot be active any more when all of them have been eliminated. Since Benveniste found that the final solution did produce the same effect as if these molecules were still present, this fact required an explanation. From a scientific and human point of view, it is shocking that it was accepted to pretend that Dr. Benveniste and his team were merely victims of an illusion. The real problem required to verify if the active molecules could be replaced by substitutes, resulting from structuring water. Is it really impossible that thermal agitation of water molecules in the liquid state could cause structuring of water molecules according to the initial template?

Since this concerns condensed matter physics, we tried to solve this problem and published in 2018 a rational explanation [84]. Since water molecules are dipolar, they can constitute very dense crystallites, where all these dipoles have the same orientation. We proved that they are spherical and so small that they could not be observed with standard optical microscopes. These nano-pearls are formed by the electric field of charged parts of biologically active molecules. Being also dipolar, these “water pearls” constitute chains, where they are set in rotation at the frequency of the vibrating charged part of active molecules. The resulting standing wave limits the length of these chains by preventing further growth. Since the length of these chains depends on the frequency of oscillation of the charged part of active molecules, they become relevant information carriers. Their existence is real.

They are even multiplied by successive dilutions, always accompanied by vigorous shaking, since some chains are then broken, but are reconstituted by the oscillating electric field of the majority of intact chains. This process yields numerous efficient substitutes of the active molecules. It explains also about a dozen other experimental observations, made in the meantime. It accounts even for *homeopathy*, which is at present under harsh attack by those who claim that these products can merely act as placebos. Without understanding the real mechanism, it is more difficult to abandon preconceptions, but it is surprising that even a high-level "Scientific Advisory Council" did participate in lobbying to eliminate homeopathy by legal procedures [85]. Ideology and financial interests can even overrule normal scientific procedures.

This fact has to be combined with objective evidence that pharmaceutical industries are radically and recklessly oriented towards big profits in a capitalistic way. This dreadful situation was recently documented by Luc Hartmann [86] and shows that Big Pharma is out of control. This is not always true, of course, but according to trustable authorities [86], they can indirectly pay institutions that should evaluate the efficiency, as well as already reported side effects. Political and legislating authorities should urgently react to avoid more scandals and flagrant injustices.

Rife made a great discovery. We did only explain why apparently unbelievable, but observed facts are true. Now it is up to other persons and institutions to carry on. The fast development of vaccines merits praise, but there is now much more at stake than protection of already gigantic industrial empires. We appeal therefore to the World Health Organization, all Ministers of Health and Governments, as well as the United Nations to initiate and organize also another way to cope with unnecessary suffering and death. That is possible and urgently needed.

The Science Behind Rife Machines

With the dramatic increase in cancer cases, exploring innovative and holistic treatment options is crucial. The Rife machine, developed by Dr. Royal Raymond Rife in the 1930s, is based on the principle that every organism, including tumor cells, has a unique electromagnetic frequency. By targeting these specific frequencies, the Rife machine aims to disrupt the cellular structures of pathogens and tumor cells without harming healthy tissue

Global surge in cancers among the under 50s over past three decades

*New cases have risen 79%, overall, with fastest rise in windpipe and prostate cancers
Heaviest death toll for cancers of breast, windpipe, lung, bowel, and stomach*

There's been a striking 79% increase in new cases of cancer among the under 50s around the world over the past three decades (1990-2019), finds research published today in the open access journal BMJ Oncology. [Source](#)

The Science Behind Rife Machines

Rife machines, developed by [Dr. Royal Raymond Rife in the 1930s](#), are based on the principle that every organism has a unique electromagnetic frequency. By [targeting these frequencies](#), Rife believed that it was possible to [destroy harmful pathogens](#) without affecting healthy cells. Here's an in-depth look at why Rife machines and frequencies are considered beneficial for healing: [Rife original Frequencies](#)

How It Works

Electromagnetic Frequencies The machine generates frequencies that match the resonant frequencies of disease-causing organisms, potentially destroying them through resonance.

Royal Rife focused on refining his method of destroying viruses. He used the same principle to kill them, which made them visible - resonance. By increasing the intensity of a frequency with his Rife machine which resonated naturally with these microbes, Royal Rife increased their natural oscillations until they distorted and disintegrated from structural stresses. Rife called this frequency

the mortal oscillatory rate, or MOR. Importantly noted is the fact that mortal oscillator did not harm the surrounding tissues.

To better understand this principle, think about how a wine glass can be shattered by an intense musical note, while other breakables near the glass are not affected. Every material has a natural frequency at which it vibrates, called a resonant frequency. If you put energy into the substance at its resonant frequency, you will force it to vibrate or resonate. Some singers can sing a note equal to the natural resonant frequency of the wine glass and cause it to shatter. Since everything else has a different resonant frequency, nothing but the glass is destroyed. (Resonance has even caused bridges to collapse. Marching troops of soldiers will often break cadence when crossing a bridge to prevent a resonance collapse.)

History of the Development of a Successful Treatments by Royal Rife

Resurgence of Interest In recent years, there has been renewed interest in alternative and complementary cancer treatments, including the use of Rife machines.

Early Successes Initial reports claimed **success in treating cancer patients**, leading to interest in Rife's work.

And NOW :Amplitude-modulated electromagnetic fields for the treatment of cancer: Discovery of tumor-specific frequencies and assessment of a novel therapeutic approach .

Targeted Frequency Therapy

Specific Frequencies: Each microorganism, including viruses, bacteria, **and cancer cells**, has a specific resonant frequency. Rife's research suggested that **applying the right frequency** could disrupt

these pathogens' structure, effectively neutralizing them. [Read More Here](#)

Medical applications of electromagnetic fields

This concept has been tested in vitro on malaria parasites and found to be effective. This may provide a low cost effective treatment for malaria infection in humans. The rationale for cancer treatment using low-intensity EMF is based on two concepts that have been well established in the literature: (1) low-intensity non-thermal EMF enhances cytotoxic free radicals via the iron-mediated Fenton reaction; and (2) cancer cells have higher amounts of free iron, thus are more susceptible to the cytotoxic effects of EMF. Since normal cells contain minimal amount of free iron, the effect would be selectively targeting cancer cells. Thus, no adverse side effect would be expected as in traditional chemotherapy and radiation therapy. This concept has also been tested on human cancer cell and normal cells in vitro and proved to be feasible.

Medical applications of electromagnetic fields

Authors: Lai, Henry C.; Singh, Narendra P.

Selective Destruction: Unlike conventional treatments that can harm healthy cells, Rife frequencies aim to selectively target only the [harmful cells](#), reducing collateral damage and side effects.

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Examination of patients with cancer led to the identification of frequencies that were either specific for a given tumor type or common to two or more tumor types. We observed that most frequencies were tumor-specific. Indeed, when the analysis of frequencies is restricted to tumor types analyzed following a minimum of 60 frequency detection sessions (breast

*cancer, hepatocellular carcinoma, ovarian cancer and prostate cancer), at least 75% of frequencies appear to be tumor-specific. Some frequencies such as 1873.477 Hz, 2221.323 Hz, 6350.333 Hz and 10456.383 Hz are common to the majority of patients with a diagnosis of breast cancer, hepatocellular carcinoma, prostate cancer and pancreatic cancer. [The optimum rife system](#)
[Source](#)*

Is there a Rife Frequency for my issues

Non-Invasive and Painless

Gentle Treatment: Rife machines offer a non-invasive and painless alternative to traditional treatments like chemotherapy and radiation, making it an appealing option/addition for patients seeking gentler therapies.

Minimal Side Effects: Users report fewer side effects compared to conventional treatments, as the frequencies are designed to target pathogens without affecting the body's normal functions.

Holistic Healing

Comprehensive Approach: Rife machines can be used to address a wide range of conditions, from infections to chronic diseases, providing a holistic approach to health and wellness.

Integrative Approach Some practitioners use Rife machines as part of an integrative approach to cancer therapy, combining conventional treatments with alternative methods.

Low-intensity electric current-induced effects on human lymphocytes and leukemia cells

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Seattle, WA
USA

The purpose of this study is to investigate whether low-intensity current affects cells in culture. Two types of human cells: white blood cells (lymphocytes) and leukemia cells (molt-4 cells), were studied. A low-intensity time-varying electric current (0.14 milliamp) generated by the Clark Zapper was applied to cell cultures via two platinum electrodes for 2 hrs at 37o C. Cell counts were made at different times after electric current application. Results show that the current had no significant effect on human white blood cells up to 24 hrs after exposure, whereas it significantly inhibited the growth of leukemia cells. At 24 hrs after exposure, concentration of leukemia cells exposed to the electric current was only 58% of that of non-exposed leukemia cells. These data suggest that the electric current can selectively inhibit the growth of leukemia cells and does not significantly affect normal cells. A manuscript describing these results is in preparation for publication.

Further research should investigate whether this selective electric current-induced growth inhibition also occurs in other types of cancer cells. The critical current parameters and mechanism of this effect should also be investigated. [Source](#)

Immune System Support: By eliminating harmful microorganisms, Rife machines can help reduce the burden on the immune system, allowing it to function more effectively.

Modern Resurgence and Integration

Renewed Interest: With growing interest in alternative and complementary medicine, Rife machines are seeing a resurgence as part of integrative health practices.

Technological Advancements: Modern Rife machines are equipped with advanced technology, allowing for more precise frequency delivery and better user experience. [Read more click here](#)

An excerpt from a massive study conducted by the Department of Biomedical Engineering, NovoCure Ltd., Haifa, Israel; B. Rappaport Faculty of Medicine, Technion—Israel Institute of Technology, Haifa, Israel; Department of Molecular Cell Biology, Weizmann Institute of Science, Rehovot, Israel; and Elisha Medical Centre, Haifa, Israel.

Disruption of Cancer Cell Replication by Alternating Electric Fields

In the present study we show for the first time, to our knowledge, that very low-intensity (<2 V/cm), intermediate-frequency (100–300 kHz), alternating electric fields induced by insulated electrodes have specific inhibitory effects on dividing cells in culture. We demonstrate that applying these fields to cancerous cells leads to proliferation arrest and cell destruction. When applied to syngeneic mice tumor models, these tumor treating fields (TTFields) cause a significant reduction in tumor growth rate without any significant side effects.

In conclusion, we have demonstrated that TTFields inhibit both the proliferation of malignant cells in culture and the growth of tumors in mice while showing no general side effects or local histopathological damage. The mechanism of action of the fields is, at least in part, dependent on disruption of the microtubules of the mitotic spindle and the electric forces resulting from focusing of the field in the dividing cells. The highly specific effects of these fields on dividing cells, together with the relative ease of applying them, focusing them, and screening from them, make them an attractive candidate to serve as a novel treatment modality for cancer.

Research and Anecdotal Evidence

Ongoing Studies: While anecdotal evidence and early studies suggest positive outcomes, ongoing research is crucial to validate the efficacy and safety of Rife machines in various treatments.

User Testimonials: Many users report significant improvements in their health conditions, attributing their recovery to the consistent use of Rife machines.

"I am writing my next book, How Cancer Saved My Life. My 4.9 x 4.9 cm tumor shrunk in half in ONE month, simply by using the Rife machine. I was cancer free in less than 6 months....I did do the holistic infusions in Mexico also but the Rife machine is KEY to my healing and I am 100% certain"*
Rhonda Spellman
USA

[Source](#) Machine used Option 2h See below

*From: R..... R.....
We used your Ride frequency machine to cure my brother of cancer 21 years ago. Most recently I used it to cure my mother of her "incurable" bone disease. I have been in natural healing ever since we cured my brother 21 years ago. I would like to be an affiliate for your products. Kind Regards, R...y
R.....
USA
[Source](#)*

In 2009, sixteen years after Hulda Clark first published that parasites can cause cancer, the Queensland Institute of Medical Research publishes:

Parasite turns cells cancerous

Scientists have found that the human liver fluke (Opisthorchis viverrini) contributes to the development of liver cancer by secreting granulin, a growth hormone that is known to cause uncontrolled cell growth.

“It has been known that certain proteins secreted by O. viverrini cause cell growth, however the identity of the protein was unknown. We also knew that the parasite secreted granulin but we did not know that it could affect the human cells around it,” said Dr Loukas.

“This discovery leads the way to a better understanding of how this parasite causes such a devastating form of cancer,” said Dr. Loukas.

It is now thought that the granulin secreted by the parasite is a major contributing factor to developing bile duct cancer.

[*The Rife machine closes to the original Design*](#)

Hello Barry,

RIFE:

It has been a while so I thought I would give you an update. My son L.....e is doing very well. He has not needed a transfusion since April 2022 and has been back to work since July 2022. His doctor has no idea why he is doing so well. At first we Rifed him for Lyme and Babesia which fixed his Hemolytic Anemia after one time. We have run this once a week since then and are considering stopping that based on his most recent lab numbers which are really good. He also has suffered from chronic low platelets (ITP). We started using a Rife for low platelets and again after the first use he responded with better platelet numbers. We are running this

on him weekly and based on his recent labs we may taper back. Pretty amazing.

I have been using the Rife on myself for cataracts that were just starting to show up in my last eye checkup about a year ago. I noticed them too when driving at night when I encountered on coming head lamps. After Rifing once a week for 6 weeks I am starting to notice an improvement and will let you know what my eye doctor says after my next checkup.

*Best Regards,
R.. S.....e-
USA
[Source](#)*

Rife 3h see below

Conclusion

The historical use of Rife machines in cancer treatment is a fascinating journey of innovation, controversy, and ongoing exploration. Rife machines and their frequency-based treatments offer a promising alternative for those seeking non-invasive and holistic healing methods. While [more scientific information](#) is needed by some, the reported potential benefits make them an exciting area of exploration in the field of alternative medicine.

"The most intelligent action is to think for yourself."

Stoicism Rules for Life

“When the standards have been set,” Epictetus said, “the work of philosophy is just this, to examine and uphold the standards, but the work of a truly good person is in using those standards when they know them.”

Define your rules. Live by them:

1. Focus on what you can control.
2. You control how you respond to things.
3. Ask yourself, "Is this essential?"
4. Meditate on your mortality every day.
5. Value time more than money and possessions.
6. You are the product of your habits.
7. Remember you have the power to have no opinion.
8. Own the morning.
9. Put yourself up for review. Interrogate yourself.
10. Don't suffer imagined troubles.
11. Try to see the good in people.
12. Never be overheard complaining—even to yourself.
13. Two ears, one mouth for a reason.
14. There is always something you can do.
15. Don't compare yourself to others.
16. Live as if you've died and come back (every minute is bonus time).
17. "The best revenge is not to be like that." —Marcus Aurelius
18. Be strict with yourself and tolerant with others.
19. Put every impression, emotion, to the test before acting on it.
20. Learn something from everyone.
21. Focus on process, not outcomes.
22. Define what success means to you.
23. Find a way to love everything that happens.
24. Seek out challenges.
25. Don't follow the mob.
26. Grab the "smooth handle."
27. Every person is an opportunity for kindness.
28. Say no (a lot).
29. Don't be afraid to ask for help.
30. Find one thing that makes you wiser every day.
31. What's bad for the hive is bad for the bee.
32. Don't judge other people.
33. Study the lives of the greats.
34. Forgive, forgive, forgive.
35. Make a little progress each day.
36. Journal.
37. Prepare for life's inevitable setbacks.
38. Look for the poetry in ordinary things.
39. To do wrong to one, is to do wrong to yourself.
40. Always choose "alive time."
41. Associate only with people that make you better.
42. If someone offends you, realize you are complicit in taking offense.
43. Fate behaves as she pleases...do not forget this.
44. Possessions are yours only in trust.
45. Don't make your problems worse by bemoaning them.
46. Accept success without arrogance, handle failure with indifference.

- 47. Courage. Temperance. Justice. Wisdom. (Always).
- 48. The obstacle is the way.
- 49. Ego is the enemy.
- 50. Stillness is the key.

I'll leave you with the one rule that captures all the rules. It comes from Epictetus: "Don't explain your philosophy. Embody it."

Marcus Aurelius reminded himself and now us, "Waste no more time talking about what a good man is like. Be one."

APRIL 11, 2025

A fluid battery that can take any shape



Researchers at Linköping University have developed a battery that can take any shape.

Credit: Thor Balkhed

Using electrodes in a fluid form, researchers at Linköping University have developed a battery that can take any shape. This soft and conformable battery can be integrated into future technology in a completely new way. Their study has been [published](#) in the journal *Science Advances*.

"The texture is a bit like toothpaste. The material can, for instance, be used in a 3D printer to shape the battery as you please. This opens up for a new type of technology," says Aiman Rahmanudin, assistant professor at Linköping University.

It is estimated that more than a trillion gadgets will be connected to the Internet in 10 years' time. In addition to traditional technology such as mobile phones, smartwatches and computers, this could involve wearable medical devices such as [insulin pumps](#), pacemakers, hearing aids and various health monitoring sensors, and in the long term also [soft robotics](#), e-textiles and connected nerve implants.

If all these gadgets are to work in a way that does not hinder the user, new types of batteries need to be developed.

"Batteries are the largest component of all electronics. Today they are solid and quite bulky. But with a soft and conformable battery, there are no design limitations. It can be integrated into electronics in a completely different way and adapted to the user," says Aiman Rahmanudin.

Together with his colleagues at the Laboratory of Organic Electronics, LOE, he has developed a battery that is soft and malleable. The key has been a new approach—converting the electrodes from a solid to a liquid form.



The research group at the Laboratory of Organic Electronics, LOE, at Linköping University. Credit: Thor Balkhed

Previous attempts to manufacture soft and stretchable batteries have been based on different types of mechanical functions, such as rubbery composite materials that can be stretched out or connections that slide on each other. But this does not deal with the core of the problem—a large battery has higher capacity, but having more active materials means thicker electrodes and thus higher rigidity.

"Here, we've solved that problem, and we're the first to show that capacity is independent of rigidity," says Rahmanudin.

Fluid electrodes have been tested in the past but without any great success. At that time, liquid metals such as gallium were used. But then the material can only function as an anode and has the risk of being solidified during charging and discharging—losing its fluid nature. In addition, many of the stretchable batteries previously made have used rare materials that have a major environmental impact when mined and processed.

The researchers at LiU Campus Norrköping have instead based their soft battery on conductive plastics (conjugated polymers) and lignin, a byproduct from paper production. The battery can be recharged and discharged over 500 times and still maintain its performance. It can also be stretched to double the length and still work just as well.

"Since the materials in the battery are conjugated polymers and lignin, the [raw materials](#) are abundant. By repurposing a byproduct like lignin into a high-value commodity such as a battery material, we contribute to a more circular model. So, it's a sustainable alternative," says Mohsen Mohammadi, postdoctoral fellow at LOE and one of the lead authors behind the article.

The next step is to try to increase the electrical voltage in the battery. According to Rahmanudin, there are currently some limitations that they need to overcome.

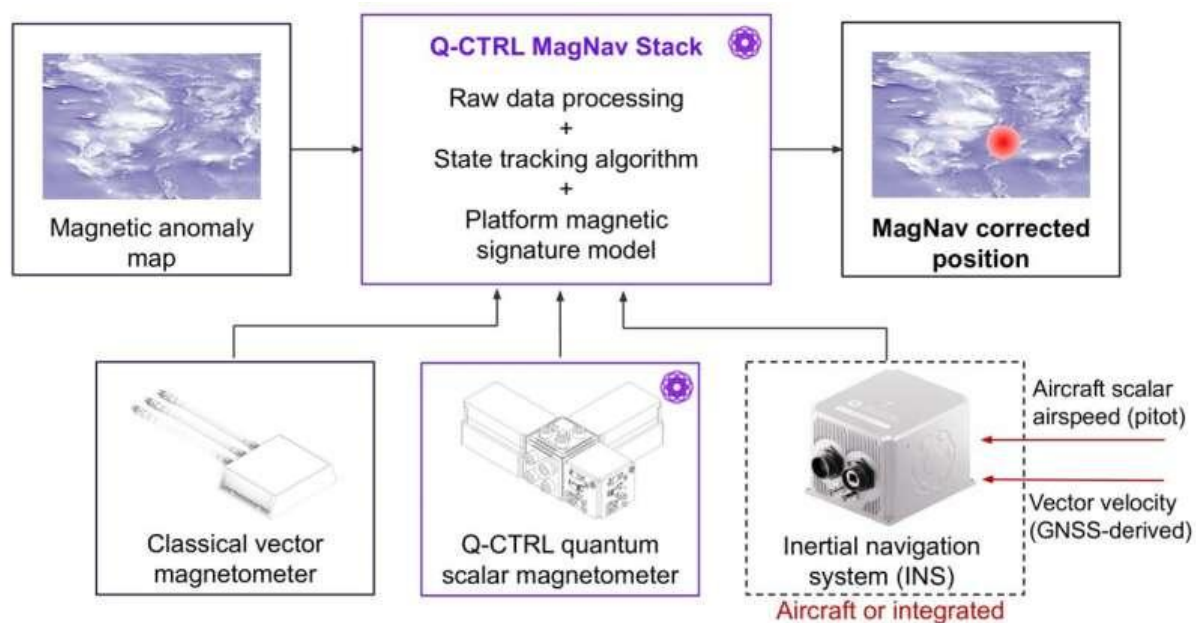
"The battery isn't perfect. We have shown that the concept works but the performance needs to be improved. The voltage is currently 0.9 volts. So now we'll look at using other chemical compounds to increase the voltage. One option that we are exploring is the use of zinc or manganese, two metals that are common in Earth's crust," says Rahmanudin.

More information: Mohsen Mohammadi et al, Make it flow from solid to liquid: redox-active electrofluids for intrinsically stretchable batteries, *Science Advances* (2025). DOI: [10.1126/sciadv.adr9010](https://doi.org/10.1126/sciadv.adr9010). www.science.org/doi/10.1126/sciadv.adr9010

Journal information: [Science Advances](#)

New quantum-based navigation system 50 times more accurate than traditional GPS

by Bob Yirka , Tech Xplore



System architecture of the MagNav system used in the trials. Boxes with purple borders indicate Q-CTRL produced components. Black boundary boxes indicate third-party inclusions (e.g. the "classical" vector fluxgate magnetometer). We include an INS in our test system, but this may be optionally replaced with a feed direct from the vehicle's flight-management system. In the flight tests presented below we leverage different airspeed-sensor inputs as a part of system validation; ultimate GNSS-denied performance would only incorporate signals from onboard airspeed sensors. The INS used in the ground trials had no source of velocity aiding. Credit: *arXiv* (2025). DOI: 10.48550/arxiv.2504.08167

A team of researchers at Q-CTRL, a quantum infrastructure software-maker based in Sydney, Australia, has announced the successful demonstration of its newly developed quantum navigation system called "Ironstone Opal."

The group has written a paper describing how their system works and how well it tested against currently available backup GPS systems and has [posted](#) it on the *arXiv* preprint server.

With the advent and subsequent reliance on GPS by private and [military vehicles](#) and aircraft for navigation, governments have come to understand how vulnerable such systems can be. Outages can lead to drivers being stranded, pilots scrambling to use outdated systems and difficulties deploying military assets. Because of that, scientists around the

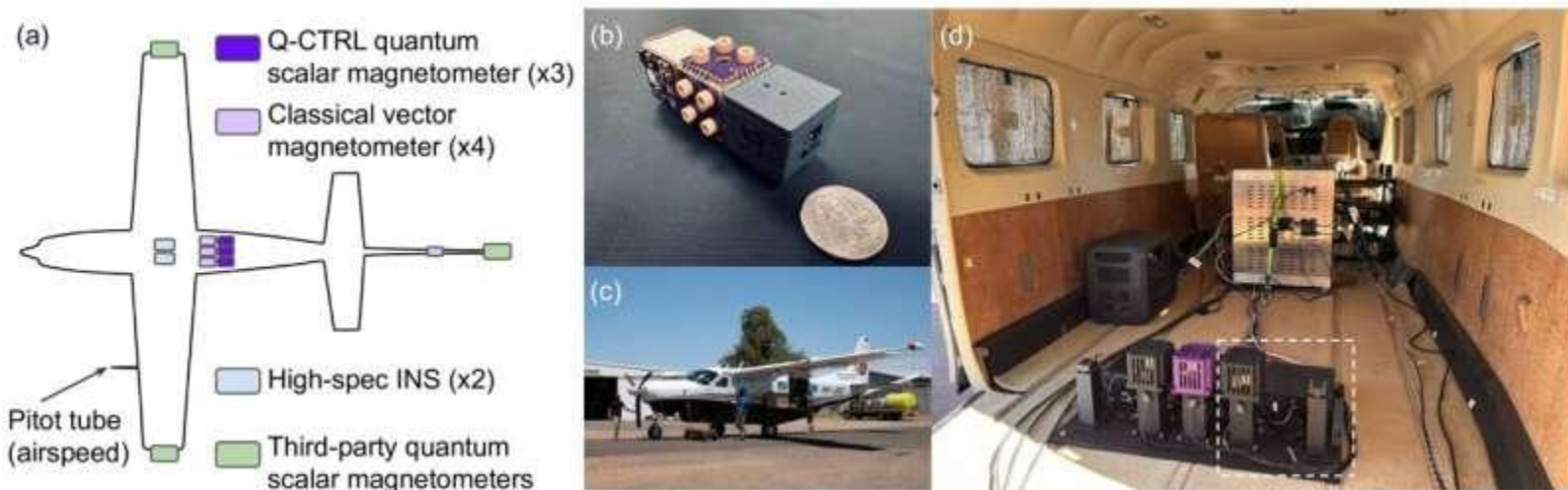
world have been looking for reasonable backup systems, or even possible alternatives to GPS.

In this new effort, the team at Q-CTRL has developed such a backup system and is claiming that it is 50 times more accurate than any other backup GPS currently available under some scenarios.

The new system, Ironstone Opal, uses [quantum sensors](#) that are so sensitive they can be used to precisely self-locate an object using the Earth's [magnetic field](#). The team at Q-CTRL noted that the magnetic field varies depending on location relative to the Earth. To take advantage of that, they built sensors that can precisely read the field and then use AI-based software to give X and Y geographic coordinates in the same fashion as GPS.

The researchers note that their system is passive, which means it does not emit signals that could be "heard" by other devices and cannot be jammed. They also note that their software system can filter out noise generated by vehicles or planes carrying the sensors. They point out that the system is small enough to be installed in any car, truck, or other land vehicle, as well as in drones and other aircraft.

Testing of the system on the ground, the researchers claim, showed it to be 50 times as accurate as any other GPS backup system. In the air, it was found to be 11 times more accurate than other backup systems.



(a) Schematic showing the instrumentation layout on the flight trial aircraft. The Q-CTRL quantum magnetometers were mounted internally in a high noise location. Additional magnetometers were placed externally in order to obtain ground truth and for comparison purposes. The pitot tube provided a scalar velocity input for INS aiding. (b) Photograph of a single colinear Q-CTRL scalar quantum magnetometer, shown alongside a US quarter-dollar coin for a sense of scale. (c) Cessna 208B Grand Caravan used for the trials. (d) Positioning of the Q-CTRL sensor package, power supply, control electronics and logging equipment inside the aircraft. This is a triple-redundant configuration employed for testing and validation; a single scalar/vector magnetometer pair comprises a complete MagNav hardware system. The dashed box shows a potential minimal configuration consisting of

one Q-CTRL scalar magnetometer, one fluxgate vector magnetometer, and the ancillary control electronics, with a total volume of 4.2 L. The same onboard system operated in strapdown configuration is employed in ground-based trials. Credit: *arXiv* (2025). DOI: 10.48550/arxiv.2504.08167

More information: Murat Muradoglu et al, Quantum-assured magnetic navigation achieves positioning accuracy better than a strategic-grade INS in airborne and ground-based field trials, *arXiv* (2025). DOI: [10.48550/arxiv.2504.08167](https://doi.org/10.48550/arxiv.2504.08167)

Journal information: [arXiv](#)

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APRIL 16, 2025

Pitfalls of post-human, AI governance in real-world 'city brain' project explored in study

by [Trinity College Dublin](#)



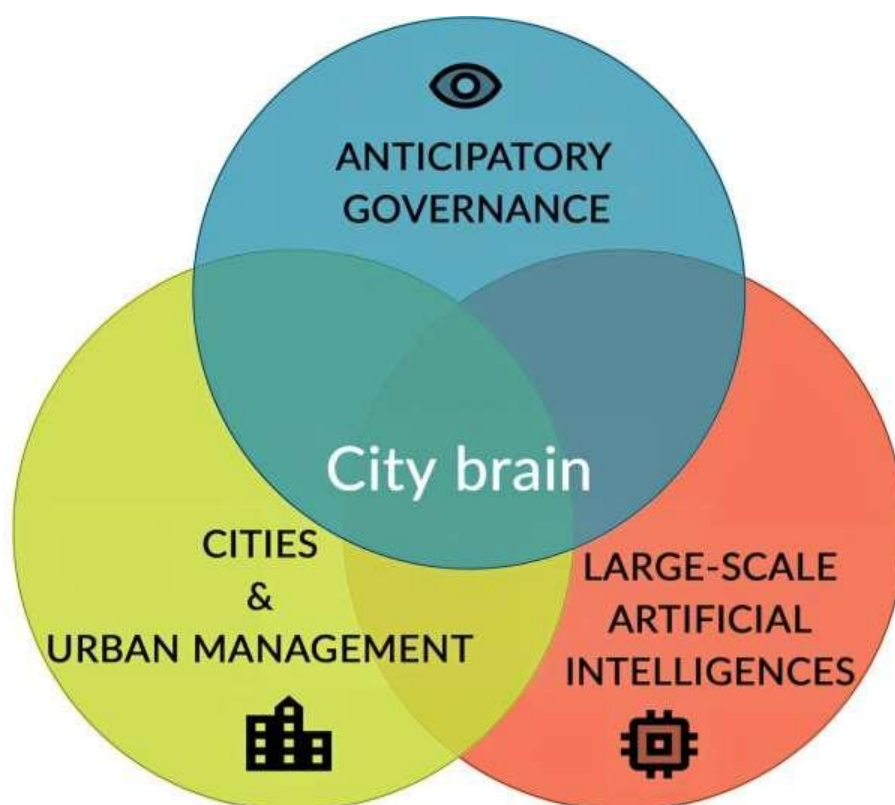
The dashboard of an existing City Brain system in China. Credit: Dr Ying Xu.

Generative Artificial Intelligence (AI) is boosting anticipatory forms of governance around the world, helping state actors to predict the future and focus their efforts in the present where the AI predicts they can have the greatest positive impact.

This phenomenon is particularly evident in China, but similar forms of governance mediated by generative AI are also becoming increasingly popular in Europe and the seeds of this trend are already visible in Ireland.

In this context, "city brains" represent an emerging type of generative AI currently employed in urban governance and [public policy](#) in a growing number of cities. City brains are large-scale AIs residing in vast digital urban platforms, which use Large Language Models (LLMs) to generate visions of urban futures: visions that are in turn used by policymakers to generate new urban policies. In China alone, there are over 500 cities developing city brains.

However, one of the main foreseeable dangers is the formation of a policy process that, under the influence of unintelligible LLMs, risks losing transparency and thus accountability, with another being the marginalization of human stakeholders (citizens, in particular) as the role of AI in the management of cities keeps growing and governance begins to turn posthuman.



A

Venn diagram conceptualizing the city brain. Credit: *Policy and Society* (2024). DOI: 10.1093/polsoc/puae025

And by focusing on a real-world city brain project operating in the Haidian district of Beijing (China), which has a population of around 3,000,000 people and gathers data from over

14,000 CCTV cameras and over 20,000 environmental sensors, the researchers have been able to show these dangers are not just theoretical.

Dr. Federico Cugurullo, Associate Professor in Trinity's School of Natural Sciences, is a leading expert in AI urbanism and the first author of the research, which has been [published](#) in the journal *Policy and Society*.

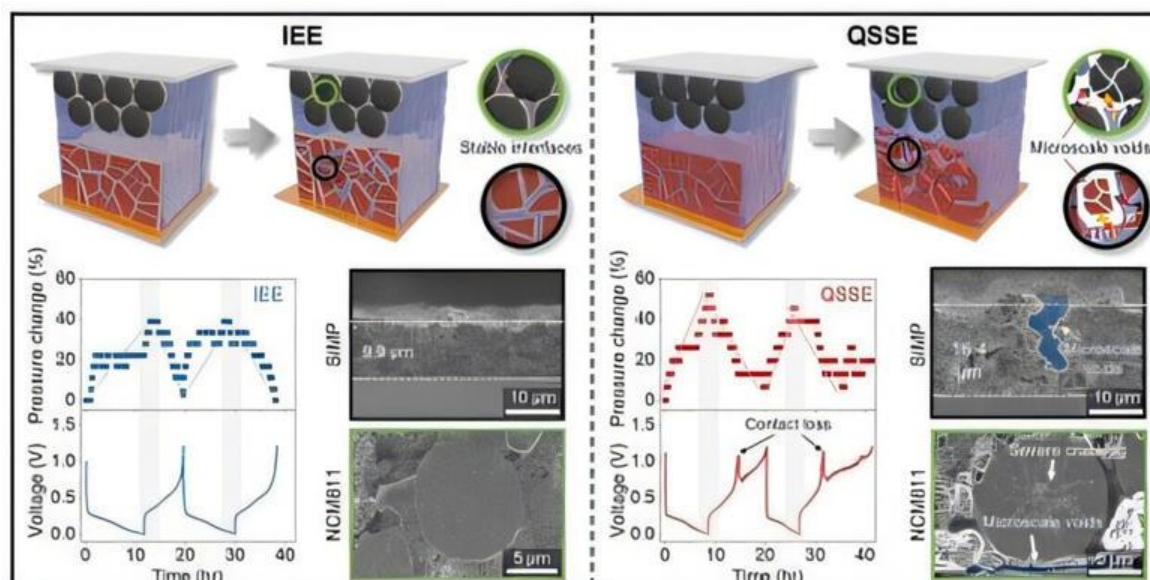
He said, "We can think of the Haidian city brain project as a gigantic panopticon that constantly observes what is happening in the city. It is operated by AI and focuses on three main areas of [governance](#) that are shaped by its predictions: environmental risk management, traffic management and public security."

"For example, in the case of an impending natural disaster, policies are rapidly implemented to build new infrastructure meant to reinforce riverbanks and increase the efficiency of the city's drainage systems. Outcomes also include direct interventions when, for example, [police officers](#) are dispatched to prevent illegal activities in an area where, according to the city brain, crimes are likely to take place in the near future."

"However, the predictions of the Haidian city brain are far from being infallible. Our research reveals that the accuracy rate of what the city [brain](#) predicts varies from 60% to 90%, which leaves a significant margin of error around such important decisions, for which there is no understanding as to why they have been implemented. This is particularly dangerous when it comes to predictive policing, since any error made by AI means that an innocent person will be targeted by the police for hypothetical crimes that never took place."

More information: Federico Cugurullo et al, When AIs become oracles: generative artificial intelligence, anticipatory urban governance, and the future of cities, *Policy and Society* (2024). DOI: [10.1093/polsoc/puae025](https://doi.org/10.1093/polsoc/puae025)
Provided by [Trinity College Dublin](#)

Interlocked electrodes push silicon battery lifespan beyond limits



Comparison of electrode-electrolyte interfacial stability between the IEE and conventional QSSE system. Credit: POSTECH

As demand surges for batteries that store more energy and last longer—powering electric vehicles, drones, and energy storage systems—a team of South Korean researchers has introduced an approach to overcome a major limitation of conventional lithium-ion batteries (LIBs): unstable interfaces between electrodes and electrolytes.

Most of today's consumer electronics—such as smartphones and laptops—rely on graphite-based batteries. While graphite offers long-term stability, it falls short in energy capacity.

Silicon, by contrast, can store nearly 10 times more lithium ions, making it a promising next-generation anode material. However, silicon's main drawback is its dramatic volume expansion and contraction during charge and discharge, swelling up to three times its original size.

This repeated expansion and contraction causes mechanical gaps between the electrode and the electrolyte, quickly degrading battery performance.

To address this, researchers have explored replacing liquid electrolytes with solid or quasi-solid-state electrolytes (QSSEs), which offer better safety and stability. Yet, QSSEs still struggle to maintain full contact with the expanding and contracting silicon, leading to separation and performance loss over time.

Now, a collaborative research team from POSTECH (Pohang University of Science and Technology) and Sogang University has developed an in-situ Interlocking Electrode–Electrolyte (IEE) system that forms covalent chemical bonds between the electrode and electrolyte.

The work is [published](#) in *Advanced Science*.

Unlike conventional batteries where components merely touch, the IEE system bonds the two into a chemically entangled structure, like bricks held together by hardened mortar, so they remain tightly connected even under intense mechanical stress.

Electrochemical performance tests showed a dramatic difference: while traditional batteries lost capacity after just a few charge-discharge cycles, those using the IEE design maintained long-term stability.

Most notably, the IEE-based pouch cell demonstrated an energy density of 403.7 Wh/kg and 1,300 Wh/L, representing over 60% greater gravimetric energy density and nearly twice the volumetric energy density compared to typical commercial LIBs. In practical terms, this means electric vehicles can travel farther and smartphones can operate longer using the same-sized battery.

"This study offers a new direction for next-generation energy storage systems that simultaneously demand high energy density and long-term durability," said Professor Soojin Park of POSTECH, who co-led the study.

Professor Jaegeon Ryu of Sogang University added, "The IEE strategy is a key technology that could accelerate the commercialization of silicon-based batteries by significantly enhancing interfacial stability."

More information: Dong-Yeob Han et al, Covalently Interlocked Electrode–Electrolyte Interface for High-Energy-Density Quasi-Solid-State Lithium-Ion Batteries, *Advanced Science* (2025). DOI: [10.1002/advs.202417143](https://doi.org/10.1002/advs.202417143)

Covalently Interlocked Electrode–Electrolyte Interface for High-Energy-Density Quasi-Solid-State Lithium-Ion Batteries

Dong-Yeob Han, Im Kyung Han, Jin Yong Kwon, Seoha Nam, Saehyun Kim, Youngjin Song, Yeongseok Kim, Youn Soo Kim, Soojin Park, Jaegeon Ryu

First published: 16 April 2025

<https://doi.org/10.1002/adv.202417143>

Abstract

Quasi-solid-state batteries (QSSBs) are attracting considerable interest as a promising approach to enhance battery safety and electrochemical performance. However, QSSBs utilizing high-capacity active materials with substantial volume fluctuations, such as Si microparticle (SiMP) anodes and Ni-rich cathodes (NCM811), suffer from unstable interfaces due to contact loss during cycling. Herein, an in situ interlocking electrode–electrolyte (IEE) system is introduced, leveraging covalent crosslinking between acrylate-functionalized interlocking binders on active materials and crosslinkers within the quasi-solid-state electrolyte (QSSE) to establish a robust, interconnected network that maintains stable electrode–electrolyte contact. This IEE system addresses the limitations of liquid electrolyte and QSSE configurations, evidenced by low voltage hysteresis in (de)lithiation peaks over 200 cycles, stable interfacial resistance throughout cycling, and the absence of void formation. A pressure-detecting cell kit further confirms that the IEE system exhibits lower pressure changes during cycling without any voltage fluctuations from contact loss. Moreover, the SiMP || NCM811 full cell with the IEE system demonstrates superior electrochemical performance, and a bi-layer pouch cell configuration achieves an impressive energy density of 403.7 Wh kg⁻¹/1300 Wh L⁻¹, withstanding mechanical abuse tests such as folding and cutting, providing new insights into high-energy-density QSSBs.

1 Introduction

The global shift toward electrification has catalyzed significant growth in markets such as electric vehicles, unmanned aerial vehicles, high-performance electronics, and distributed energy storage systems.^[1] As a result, there is an increasing demand for advanced electrochemical energy storage systems that exceed the performance limits of conventional

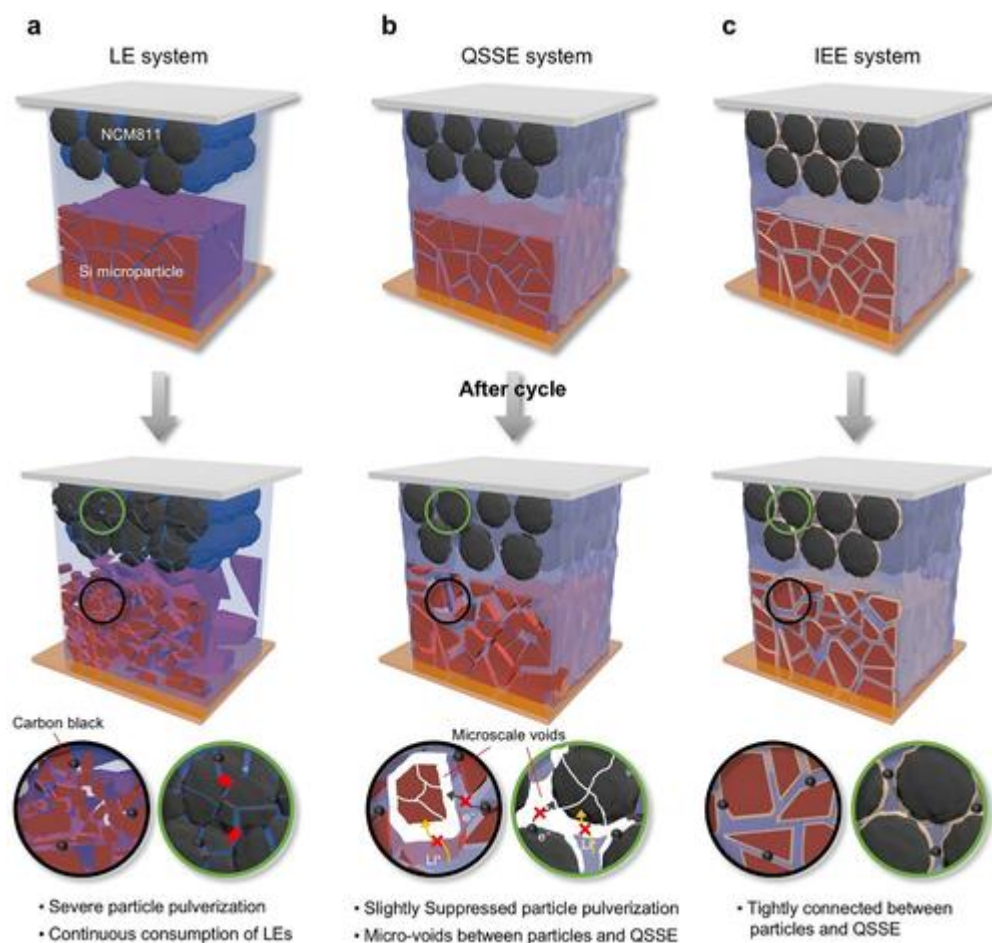
lithium-ion batteries (LIBs). The energy density of traditional LIB configurations, featuring LiCoO_2 or LiFePO_4 cathodes paired with graphite anodes, has reached its theoretical limit.^[2] Integrating high-capacity silicon (Si) anodes (3579 mAh g^{-1} with a low operating potential of $\approx 0.2 \text{ V vs Li/Li}^+$) and Ni-rich layered cathodes, such as $\text{LiNi}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.1}\text{O}_2$ (NCM811) (200 mAh g^{-1} at 4.3 V vs Li/Li^+), has emerged as a promising approach to significantly enhancing energy density in LIBs.^[3]

However, the reliance on liquid electrolytes (LEs) in conventional LIBs poses safety risks and limits long-term stability, particularly in high-energy-density configurations. Solid-state electrolytes (SSEs) have, therefore, gained attention as a next-generation solution, offering improved safety and higher energy density by replacing flammable LEs.^[4] Despite their promise, critical challenges remain, including poor electrode–electrolyte interface stability, sluggish kinetics, and high operating pressure.^[5] For Ni-rich cathodes such as NCM811, mechanical and chemical degradation at the interface, exacerbated by volume changes during cycling, significantly limits performance.^[6] In particular, intragranular cracking of those cathodes triggers the formation of interfacial gaps between the active materials and the SSEs, resulting in increased interfacial resistance, degraded Li-ion kinetics, and poor cycle performance, along with a low initial Coulombic efficiency (ICE).^[7] On the anode side, SSEs provide enhanced mechanical support toward the large-volume-change anodes, thereby promoting the use of Si microparticles (SiMPs) in solid-state batteries (SSBs) rather than Si nanoparticles (SiNPs).^[5, 8] Given the increased rigidity of SSEs, carbon-free SiMP anodes for SSBs were reported, which achieved long-cycle performance at a high current density.^[9] However, the configuration of SiMP || NCM811 full cells exhibits only about half of their theoretical capacity due to interface instability and sluggish electrode kinetics. In particular, lithium extraction from the fully charged SiMP anodes results in contact loss and the formation of large voids between the SiMP anode and the SSE, which leads to increased interfacial resistance and failure of subsequent cycles.^[5, 10] Securing contact in SSBs typically requires high stack pressures, up to even several tens to hundreds of megapascals (MPa) during cell assembly and operation, which is unrealistic for practical application.^[11] Moreover, the operation of typical SSBs necessitates high-temperature conditions due to the intrinsically low ionic conductivity of SSEs.^[12]

Quasi-solid-state electrolytes (QSSEs), which encapsulate LEs within a polymer matrix, have been proposed and extensively studied owing to their structural flexibility and high compatibility with the differently shaped battery electrodes, thereby partly addressing the electrode–electrolyte contact issue.^[13] QSSEs also exhibit comparable ionic conductivity to LEs, enabling operation at room temperature while offering enhanced safety compared to conventional LEs. A supremely elastic QSSE has been developed to serve as an intraelectrode cushion to reduce the expansion of SiNPs during lithiation and to facilitate electrode recovery during delithiation.^[14] Additionally, fluorinated carbon-incorporated SiMPs with elastic QSSE have demonstrated the ability to partially dissipate the stress associated with the volume expansion of SiMPs.^[15] However, even molecularly engineered elastic QSSEs are incapable of fully accommodating the substantial volume contraction of high-capacity active materials, especially SiMPs, during delithiation as frequently complemented by auxiliary methods such as the restriction of particle size to submicron scales or partial utilization of Si capacity (e.g., state-

of-charge (SOC) control) which ultimately reduce the overall energy density of the battery. To this end, the interlocking of active materials with the QSSE is essential for sustaining an intimate and stable electrode–electrolyte interface throughout battery cycling, thereby preventing the void formation and capacity loss.

Herein, an in situ interlocking electrode–electrolyte (IEE) system for monolithic full cells is proposed, enabling the stable operation of SiMP anodes and Ni-rich layered cathodes in quasi-solid-state batteries (QSSBs). The IEE is realized through covalent crosslinking between acrylate groups on a designed interlocking binder (IB) on the active materials and those on a crosslinker during QSSE formation. This interconnected network ensures stable and intimate contact between the electrode and electrolyte throughout cycling, preventing capacity decay and reducing charge transfer resistance. In comparison, the LE system suffered from severe SiMP pulverization due to drastic volume fluctuations and continuous side reactions with NCM811, resulting in significant capacity decay within five cycles (**Scheme 1a**). Although the QSSE system mitigated volume expansion during lithiation, it could not fully recover during delithiation, forming substantial amounts of microscale voids between the active materials and the QSSE formed at the electrode–electrolyte interface (**Scheme 1b**). Consequently, interfacial resistance sharply increased, and further utilization of isolated active materials was prohibited. By tightly interlocking the active materials and QSSE, the IEE system maintained an intimate electrode–electrolyte interface and mitigated mechanical degradation, delivering superior electrochemical performance with low interfacial resistance (**Scheme 1c**). Specifically, the SiMP half cell with the IEE system demonstrated 81.3% capacity retention after 200 cycles, with full utilization of the Si capacity (SOC $\approx$ 100%). Furthermore, the SiMP || NCM811 monolithic full cell exhibited stable cycling behavior, with quick Coulombic efficiency (CE) stabilization at 99.5% within three cycles. Additionally, a bi-layer pouch-type monolithic full cell with the IEE system achieved a high-energy density of 403.7 Wh kg⁻¹/1300 Wh L⁻¹, surpassing previously reported Si-based full cells. The IEE pouch cell also demonstrated enhanced safety, showing stable operation under mechanical abuse, such as folding and cutting, confirming its feasibility for high-energy-density applications.



Scheme 1

[Open in figure viewerPowerPoint](#)

Schematic illustration of three different systems. Graphical depictions before and after the cycle along with challenges from a) LE system, b) QSSE system, and c) IEE system.

2 Results and Discussion

The IB was designed and synthesized to perform both binding and interlocking functions via a simple grafting reaction of polyacrylic acid (PAA) with methacrylic anhydride (MA) in phosphate-buffered saline (PBS, pH = 7.4) at 50 °C (Figure S1a, Supporting Information).^[16] Methacrylate groups (interlocking sites) were introduced on the carboxyl (–COOH) groups of PAA, providing interlocking sites capable of crosslinking under thermal treatment. The ¹H nuclear magnetic resonance (NMR) spectroscopy confirmed successful substitution, revealing that ≈33% of the hydroxyl groups were substituted with methacrylate groups (Figure S1, Supporting Information). Importantly, the remaining carboxyl groups enabled hydrogen bonding with the high-capacity active materials (Si and NCM particles) and current collectors (Cu and Al foils), thereby improving interfacial adhesion and stability (Figure 1a). This hydrogen bonding arises from the surface oxide layers present on Si and NCM811, which contain oxygen-rich functional groups capable of interacting with carboxyl groups in IB.^[3, 17] Similarly, Cu and Al current

collectors develop native oxide layers upon air exposure, facilitating additional hydrogen bonding with IB.^[18] This dual-functionality allowed the IB to act as an “interlocker” on the electrode side through acrylate groups, while trimethylolpropane propoxylate triacrylate (TMPTA) served as a crosslinker for the electrolyte side. This resulted in a robust IEE system through the in situ polymerization of TMPTA, tightly bonding the IB to the electrolyte during thermal curing (Figure 1b).

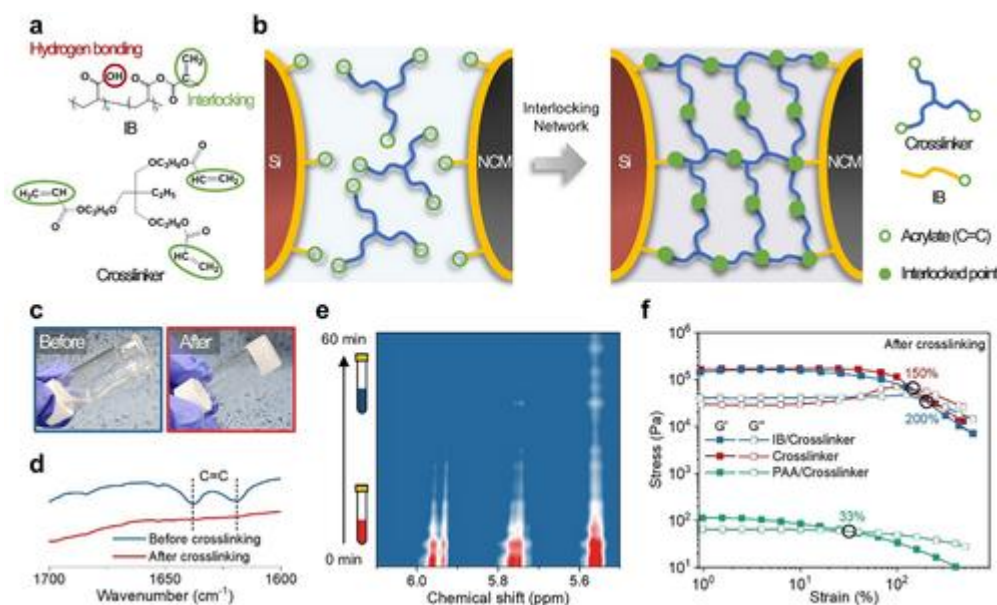


Figure 1

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Characterization of the IEE system. a) Molecular structures of IB and crosslinker used in the IEE system. b) Schematic illustration of the interlocking process between electrodes and electrolytes. c) Digital photos and d) FT-IR spectra of a quasi-solid gel with IB and crosslinker before and after crosslinking. e) In real-time monitoring of forming a quasi-solid gel with IB and crosslinker at 60 °C using in situ ¹H NMR. f) Strain amplitude sweep of different quasi-solid gels at a frequency of 1 rad s⁻¹.

To validate the interlocking network, a model system was developed with IB (or PAA for comparison), TMPTA, benzoyl peroxide (initiator), and a cosolvent. The component weight ratio was 1:6:0.2:93, with the solvent comprising distilled water and an organic solvent in a 2:8 ratio. A cosolvent was necessary due to the differential solubility of IB and TMPTA; IB dissolves only in water, while TMPTA dissolves in organic solvents. Heating the precursor solution at 60 °C for 1 h resulted in a quasi-solid gel (QSG) via in situ polymerization of the crosslinker (Figure 1c). Fourier-transform infrared (FT-IR) spectroscopy showed the disappearance of C=C characteristic stretching vibrations at 1618 and 1637 cm⁻¹, confirming the crosslinking reaction of acrylate groups in IB and TMPTA (Figure 1d).^[19] In situ ¹H NMR monitored real-time crosslinking dynamics with a similar model system prepared using deuterated water (D₂O). The initial ¹H NMR spectra showed distinct vinyl proton peaks at 5.95, 5.76, and 5.56 ppm (Figure 1e).^[20] As the system was heated at 60 °C, these peaks gradually diminished with near complete disappearance after 1 h, signifying the completion of crosslinking. Combined FT-IR

and in situ ^1H NMR analysis confirmed successful interlocking between IB and TMPTA, forming a robust network at 60 °C within 1 h.

Differential scanning calorimetry analysis of QSGs before crosslinking showed a T_g of 119.7 °C. Upon crosslinking, the formation of a crosslinked network restricts chain mobility, resulting in an increased T_g ($T_{g1} = 177.7$ °C, $T_{g2} = 194.6$ °C), shifting it to a higher temperature region. (Figure S2, Supporting Information). Additionally, the mechanical properties of QSGs with different configurations were assessed via rheological tests. A strain amplitude sweep from 1% to 500% at a constant frequency of 1 rad s⁻¹ provided modulus measurements (Figure 1f). The gels displayed higher storage modulus (G') than loss modulus (G'') at lower strains, typical solid-like behavior, with G' and G'' intersecting at higher strain values, marking the transition from gel to sol behavior.^[21] Notably, the IB/crosslinker gel showed the highest cross-over strain of 200%, highlighting its superior mechanical integrity. Compared to the gel with only a crosslinker ($\approx 150\%$ cross-over strain), the enhanced properties of IB/crosslinker are attributed to effective crosslinking between the long polymer chains of IB and the poly(TMPTA) network, which dissipates mechanical stress efficiently.^[22] This interlocked network yields a cohesive structure with greater resilience and deformation tolerance.^[23] In contrast, the gel formed with PAA and the crosslinker (PAA/Crosslinker in Figure 1f) exhibited a much lower cross-over strain ($\approx 33\%$) and ≈ 200 times lower stress values. This is attributed to the lack of acrylate functional groups in PAA, preventing covalent crosslinking with TMPTA. Instead, physical entanglements between PAA chains interfere with effective crosslinking, resulting in a weaker network with inferior mechanical integrity. These findings demonstrate that interlocking between IB and TMPTA significantly enhances the structural integrity and robustness of QSG under mechanical stress.

To further evaluate the impact of covalent interlocking on interface adhesion, 180° peel-off and shear stress tests were conducted on electrodes prepared with QSSE and IEE (Figure S3, Supporting Information). The IEE system exhibited significantly stronger adhesion than QSSE in both tests, with the shear adhesion force exceeding 2.2 kgf cm⁻¹, more than twice that of QSSE. This improvement is attributed to the covalent bonding between IB and QSSE, which reinforces the electrode-electrolyte interface and prevents delamination. In contrast, QSSE displayed weaker adhesion, likely due to insufficient bonding at the interface. Strong interfacial adhesion in the IEE system is crucial for maintaining stable contact, reducing interfacial resistance, and mitigating mechanical degradation during prolonged cycling.

To assess the fundamental electrochemical performances of LE and QSSE, room-temperature ionic conductivity, lithium transference number, and oxidative stability were measured. LE exhibited a slightly higher ionic conductivity of 9.13×10^{-4} S cm⁻¹ compared to 7.63×10^{-4} S cm⁻¹ for QSSE, likely due to the unrestricted ion mobility in LE, whereas the polymer matrix in QSSE introduces mild segmental restrictions (Figure S4a,b, Supporting Information). However, QSSE demonstrated a significantly higher lithium transference number ($t_{\text{Li}^+} = 0.61$), indicating selective Li-ion transport due to reduced anion mobility in the polymeric network (Figure S5, Supporting Information). Moreover, QSSE exhibited superior anti-oxidative ability, maintaining a stable current response up to 6 V, while LE showed a slight current increase from 5 V, suggesting solvent decomposition at high voltage. This result confirms that QSSE possesses a

wider electrochemically stable window, which is advantageous for high-voltage battery applications (Figure S6, Supporting Information). To further examine whether the covalently crosslinked network in the IEE system affects ionic conductivity, we measured the ionic conductivity of PAA+QSSE (QSSE system) and IB+QSSE (IEE system) under identical conditions. Both systems exhibited nearly identical ionic conductivities ($4.10 \times 10^{-5} \text{ S cm}^{-1}$ for the QSSE system and $4.09 \times 10^{-5} \text{ S cm}^{-1}$ for the IEE system), confirming that the IEE system does not compromise ionic conductivity (Figure S4c,d, Supporting Information). These results confirm that while QSSE has slightly lower ionic conductivity than LE, its improved transference number and oxidative stability enhance its suitability for high-energy-density applications.

The electrochemical performance of the IEE system was evaluated using coin-type half cells, with SiMP as the working electrode and Li metal serving as both counter and (pseudo-)reference electrodes, respectively. The SiMPs used, with an average size of $3.0 \mu\text{m}$, are relevant for industrial applications (Figure S7, Supporting Information). Four different systems were evaluated for their electrochemical behavior: IEE, QSSE, IB/LE, and PAA/LE. Both the IEE and QSSE systems employed the same electrolyte (6 wt.% TMPTA and 94 wt.% LE with 0.15 wt.% benzoyl peroxide) but different binders (IB for IEE and PAA for QSSE). IB/LE and PAA/LE systems lacked polymeric matrices, relying solely on LE and their respective binders. During the formation cycle at 0.05C ($1\text{C} = 3.2 \text{ A g}^{-1}$), the IEE system exhibited the highest ICE (>92%) and delivered near-theoretical capacities (3606 mAh g^{-1}), outperforming other systems (Figure 2a; Table S1, Supporting Information). The superior performance of the IEE system is attributed to the tightly interlocked interface between SiMP electrodes and QSSE, enabling efficient Li-ion transport and maintaining intimate electrode-electrolyte contact. While the QSSE system offered flexibility and buffering effects that enhanced initial ICE over PAA/LE, the absence of interlocking resulted in insufficient accommodation of SiMP volume changes, limiting performance. The IB/LE system showed the lowest ICE and capacity because, without crosslinking with the electrolyte, the acrylate groups in IB could not act as effective interlockers, and its lower hydroxyl group concentration limited its ability to accommodate initial SiMP expansion.

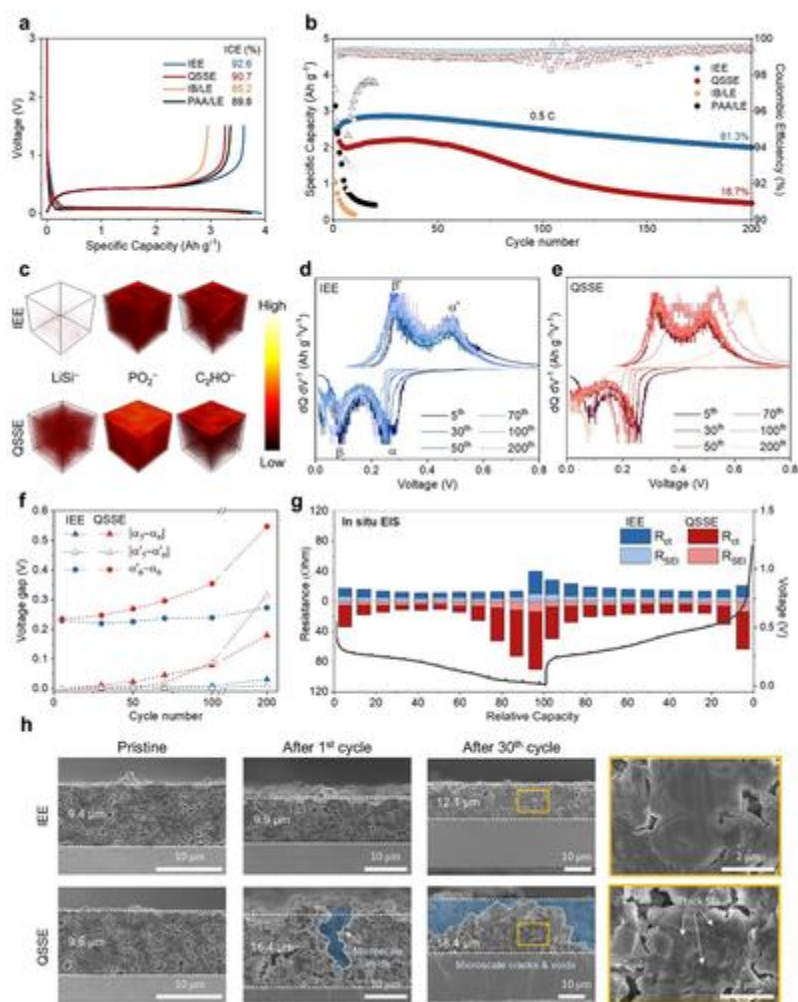


Figure 2

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Electrochemical performance and stability of IEE system in SiMP half cells. a) Galvanostatic charge-discharge profiles of SiMP half cells with different systems. b) Long-term cycling performance and corresponding CEs of Si electrode half cells in different systems at 0.5C (1C = 3.2 A g⁻¹). c) TOF-SIMS 3D reconstruction images for LiSi⁺, PO₃⁻, and C₂HO⁻. Differential capacity curves (dQ/dV versus V) of SiMP half cells in d) IEE and e) QSSE systems. f) Voltage gaps between the lithiation and delithiation peaks in differential capacity curves across the cycles. g) In situ galvanostatic EIS measurements of Si electrodes with different systems (in situ characterization). h) Cross-sectional SEM images of Si electrodes in the pristine state, after the 1st cycle, and after the 30th cycle with different systems.

The long-term cycling stability of SiMP half cells was evaluated at 0.5C up to 200 cycles (Figure 2b). The IB/LE and PAA/LE systems suffered from rapid capacity decay and low CEs, suggesting that polymeric binders alone cannot alleviate SiMP volume fluctuations. The QSSE system showed improved stability initially but exhibited gradual capacity and CE decay, retaining only 18.7% of its initial capacity after 200 cycles. This was attributed to the inability of QSSE to fully recover from SiMP contraction during delithiation, leading to microscale voids at

the electrode–electrolyte interface that compromised Li-ion transport. In contrast, the IEE system retained 81.3% of its initial capacity after 200 cycles. The tight interlocking in IEE prevented void formation, allowing consistent Li-ion transport and minimizing mechanical degradation, with CE stabilizing above 99.5% within a few cycles. The IEE system also showed superior capacity retention at high current densities compared to the QSSE system, attributed to the stable interconnected network (Figure S8, Supporting Information). The versatility of the IEE system was further demonstrated by testing variations with different crosslinking monomers, including dipentaerythritol hexaacrylate (DPH) and pentaerythritol tetraacrylate (PTTA) (Figure S9, Supporting Information). The SiMP half cells with IEE using DPH and PTTA crosslinkers exhibited outstanding cycling performance, retaining 80.1% and 70.2% of their initial capacities after 200 cycles. This demonstrates that the interlocking mechanism ensures strong mechanical integrity and efficient Li-ion transport, independent of the specific monomer used.

Insights into the interfacial stability of the IEE system were gained through SEI layer analysis, focusing on interfacial structures. Time-of-flight secondary ion mass spectrometry (TOF-SIMS) revealed significant differences in SEI composition between QSSE and IEE systems (Figure 2c). QSSE showed higher PO_2^- and C_2HO^- intensities on SiMP surfaces, indicating SEI formed due to inhomogeneous parasitic reactions from contact loss. In contrast, the IEE system formed a thinner, more uniform SEI layer, as evidenced by lower PO_2^- and C_2HO^- intensities, reducing electrolyte decomposition and maintaining interfacial stability through its robust covalent network. Moreover, the QSSE system also showed higher LiSi^- signal intensity, indicating irreversible Li trapping, while the IEE system exhibited negligible residual Li, reflecting homogeneous and reversible lithiation/delithiation cycles, correlating with stable cycling performance and higher CE of the IEE system.^[24]

The reversibility of electrochemical reactions was further assessed via differential capacity (dQ/dV) curves for SiMP half cells (Figure 2d,e). Both systems displayed broad lithiation (α and β) and delithiation (α' and β') peaks, corresponding to different Li_xSi alloy phases.^[25] In the IEE system, lithiation peaks exhibited only slight shifts (less than 0.03 V) over 200 cycles, while delithiation peaks remained unchanged, reflecting stable and reversible electrochemical processes. The stable peaks indicate consistent electrode–electrolyte contact in the IEE system, allowing repeatable lithiation/delithiation of SiMPs with minimal capacity loss. In contrast, the QSSE system showed substantial peak shifts, where β and β' became distorted and eventually disappeared, indicating interfacial degradation and increased resistance over time. The reversibility of the lithiation/delithiation processes was further quantified by calculating the voltage hysteresis between α and α' peaks throughout cycling. For the IEE system, hysteresis remained relatively constant from the 5th to 100th cycle (<4% increase) and showed only a slight rise by the 200th cycle. The QSSE system, however, displayed a gradual increase in hysteresis starting from the 30th cycle, reaching 0.354 and 0.547 V by the 100th and 200th cycles, respectively. This corresponds to a 50.6% and 132.8% increase from the 5th cycle, reflecting increasing irreversibility in electrochemical reactions. The peak shifts in α_n and α'_n (where “n” is the cycle number) from the 5th cycle (α_5 and α'_5) were also monitored to assess lithiation/delithiation stability (Figure 2f). The IEE system showed negligible shifts even after 200

cycles, confirming high reversibility, while QSSE displayed continuous shifts, especially in delithiation peaks, indicating difficulty in lithium extraction from SiMPs due to rising interfacial resistance and contact loss.

Electrochemical impedance spectroscopy (EIS) further revealed the evolution of interfacial resistance, focusing on SEI layer resistance (R_{SEI}) and charge transfer resistance (R_{ct}). After the initial cycle, the IEE system exhibited significantly lower R_{ct} (24.2 Ω) compared to the QSSE system (51.4 Ω), reflecting a more stable, low-resistance interface due to robust interlocking (Figure S10, Supporting Information). After 100 cycles, both systems showed increases in R_{SEI} and R_{ct} due to cumulative SEI formation and interface changes. However, the QSSE system exhibited a marked increase in both resistances (R_{SEI} : 52.8 Ω , R_{ct} : 86.5 Ω), indicating the formation of a thick, nonuniform SEI layer and unstable interface, which increased impedance and degraded Li-ion kinetics over time. In situ galvanostatic EIS provided real-time resistance changes during lithiation and delithiation, correlating interface stability with relative capacity. Both systems exhibited a characteristic “w” pattern in EIS profiles, indicative of the Si lithiation process (Figure 2g; Figure S11, Supporting Information).^[26] In QSSE, R_{ct} was initially high during the early stage of lithiation due to the unstable interface, hindering efficient Li-ion transport. As lithiation progressed, R_{ct} decreased significantly, which may be attributed to the disruption of the vulnerable SEI layer due to SiMP expansion and the formation of lithiated Si (Li_xSi) which improved Li-ion kinetics.^[27] During deep lithiation to $Li_{15}Si_4$, both R_{SEI} and R_{ct} increased, obstructing further Li-ion diffusion. In delithiation, the QSSE system initially showed a decrease in resistance until reaching $\approx 30\%$ relative capacity, after which resistance abruptly increased. This increase signified contact loss, further destabilizing the interface, as the non-uniform SEI layer continually decomposed and reformed in response to SiMP volume changes, exacerbating Li-ion transport hindrances and electrical isolation of active materials. In contrast, the IEE system displayed consistently lower R_{SEI} and R_{ct} values, with minimal changes throughout lithiation and delithiation, reflecting the stable and low-resistance interface provided by the interlocking network, which maintained homogeneous ion/electron transport and suppressed SEI decomposition–reformation cycles seen in the QSSE system.

The morphological evolution of SiMP electrodes was examined via scanning electron microscopy (SEM) in pristine state, after the 1st and 30th cycle (Figure 2h; Figure S12, Supporting Information). The IB/LE system showed drastic volume expansion (81.9%) and severe particle pulverization after the first cycle, attributed to the absence of a flexible buffer layer (Figure S13, Supporting Information). Analogously, the QSSE system exhibited significant swelling after the first cycle, with an increase in thickness of $\approx 72.6\%$, while it slightly suppressed the particle pulverization. In contrast, the IEE system showed minimal swelling, with only a 5.3% increase in thickness, indicating effective volume accommodation through the interlocking network. Notably, both the QSSE and IEE systems experienced severe volume expansion during the 1st lithiation, with increases of 295% and 241%, respectively. However, only the IEE system almost fully recovered to its original thickness after delithiation, demonstrating the advantage of its interconnected network. The QSSE system, on the other hand, exhibited microscale voids after the 1st delithiation, confirming its inability to recover and sustain a seamless interface during contraction. This contact loss disrupted uniform ion/electron transport to active Si sites

and reduced mechanical support, accelerating mechanical and electrochemical degradation, resulting in capacity fading and low CE. After 30 cycles, the QSSE system showed further structural degradation, with a thickness increase to 18.4 μm (93.7% expansion) and enlarged visible microvoids and cracks, indicating severe aging and interface instability from repeated contact breaking. In contrast, the SiMP electrode in the IEE system displayed a comparatively modest thickness increase of 28.7%, reflecting superior structural retention provided by the interlocking network. The enlarged cross-sectional SEM image further underscored these differences: the IEE preserved SiMP integrity and maintained a smooth, well-defined interface, while the QSSE system showed a thick SEI layer, microcracks, and pulverized SiMP particles. These observations highlight the limited ability of the QSSE system to manage the large volume changes inherent to SiMPs, which promoted SEI reformation, particle fragmentation, and interface degradation.

To gain deeper insights into the interfacial stability of the IEE system, a pressure-detecting cell kit was utilized to monitor pressure changes through a load cell positioned beneath the kit (**Figure 3a**). Unlike coin-type cells, this cell kit captures pressure changes due to volume fluctuations of SiMPs without reverting to its original volume after delithiation, as it lacks a spring component. This setup enables precise tracking of pressure variations directly linked to SiMP volume changes during cycling, providing insights into the interfacial behavior of the system.^[28] SiMP half cells were cycled under an initial stack pressure of 0.5 Mpa, equivalent to that applied in the 2032 coin-type cells used in this study.^[11] During two cycles, the IEE system demonstrated a stable galvanostatic discharge–charge voltage profile with moderate pressure fluctuations, peaking at a 38% increase during lithiation (**Figure 3b**). This relatively moderate pressure change indicates that the interlocking network effectively buffers SiMP volume expansion, preserving electrode integrity. In contrast, the QSSE system displayed larger pressure changes, reaching up to 52% (**Figure 3c**). These changes were accompanied by sudden voltage drops and large fluctuations during delithiation, suggesting significant contact loss between the electrode and the QSSE. These voltage fluctuations and pressure changes indicate that the QSSE system struggles to maintain a stable interface as the SiMPs expand and contract, leading to mechanical disconnection and poor electrochemical performance. Additionally, while the IEE system returned back to its initial pressure after delithiation, indicating a reversible response to volume changes, the QSSE system exhibited persistently elevated pressures, confirming its inability to recover to the original configuration. These findings highlight that while the flexibility of QSSEs as a buffering layer is essential, it is insufficient alone; robust interlocking between the electrodes and the QSSE is critical to accommodate volume changes, ensuring stable and repeatable cycling without contact loss.

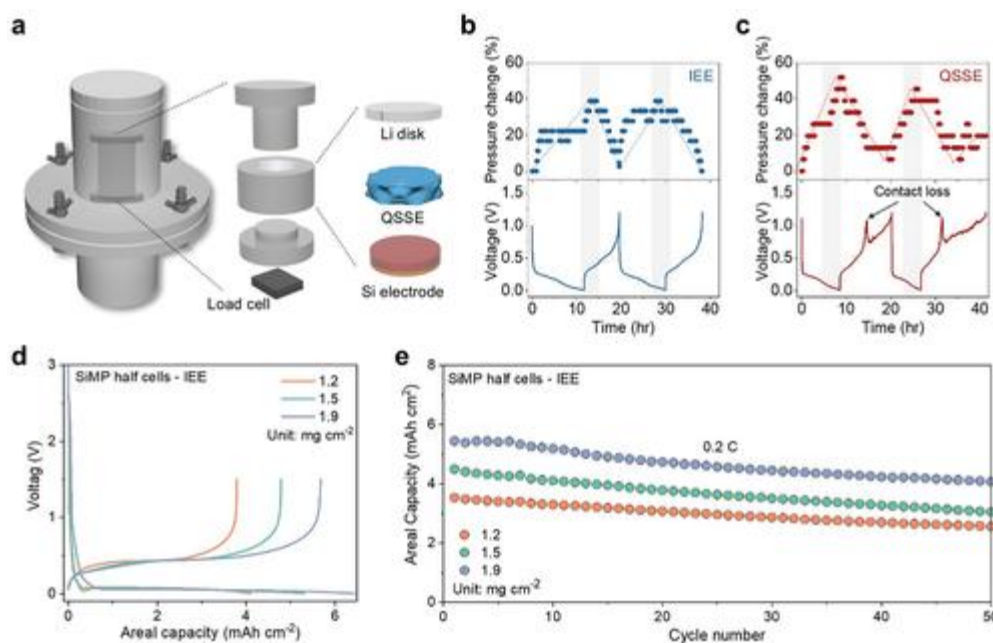


Figure 3

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Characterization of Si electrodes half cells with different systems. a) Schematic illustration of a cell integrated with a force sensor and the components in the cell. Pressure changes and voltage profiles for b) IEE system and c) QSSE system. d) Galvanostatic charge-discharge voltage profiles and e) areal capacity retention of SiMP electrode half cells in IEE system with various areal mass loadings.

Building on the excellent electrochemical performance and interface stability observed in the IEE system, its practical viability was further evaluated by testing high areal mass loadings of SiMPs, which are essential for achieving high areal capacity and volumetric energy density in practical battery applications. The IEE system enabled the stable operation of electrodes with an areal mass loading of up to 1.9 mg cm⁻², corresponding to an areal capacity of ≈ 5.7 mAh cm⁻² (Figure 3d). Even at these high mass loadings, SiMP half cells using the IEE system maintained stable cycling over 50 cycles with minimal capacity degradation, without the need for SOC controls (Figure 3e). The robust interlocking network and QSSE flexibility effectively accommodate SiMP volume changes, preventing void formation and contact loss, thereby enabling consistent performance over commercially relevant loadings.

The performance and practical applicability of the IEE system were validated by assembling SiMP || NCM811 full cells with Ni-rich layered cathodes (16 mg cm⁻²) at an n/p ratio (capacity ratio of the anode to cathode) of 1.05. The NCM811 cathodes were also fabricated with the IB to form a cohesive and stable interface with the QSSE, creating a monolithic interlocking system from the SiMP anode through the QSSE to the NCM811 cathode, providing comprehensive interfacial stability. During the formation cycle, the IEE system demonstrated a higher ICE (85.7%) and specific capacity (168.5 mAh g⁻¹) compared to the LE and QSSE systems, which exhibited ICEs of 78.1% and 80.2%, respectively, coupled with lower specific capacities of 142.7 and 149.1 mAh g⁻¹ (Figure 4a). The specific capacity of the full cells was normalized with the

mass of cathode active materials. Long-term cycling further highlighted the durability of the IEE system, with SiMP || NCM811 full cells retaining 73.1% capacity over 200 cycles without implementing additional measures such as pre-lithiation steps or SOC control by increasing the n/p ratio (Figure 4b). In stark contrast, the LE and QSSE systems suffered from substantial capacity decay, retaining only 16.5% and 29.3% after 40 and 100 cycles, respectively. The IEE system also achieved rapid CE stabilization (99.5% within three cycles), whereas the QSSE system required 42 cycles to reach 99.0%. The high ICE, rapid CE stabilization, and superior long-term stability of the full cell using the IEE system underscore the importance of not only having a flexible buffer layer to accommodate volume expansion during lithiation but also ensuring a stable electrode–electrolyte interface that prevents contact loss during the delithiation process. This interlocking mechanism is crucial for achieving high reversibility and consistent cycling performance in SiMP || NCM811 full cells.

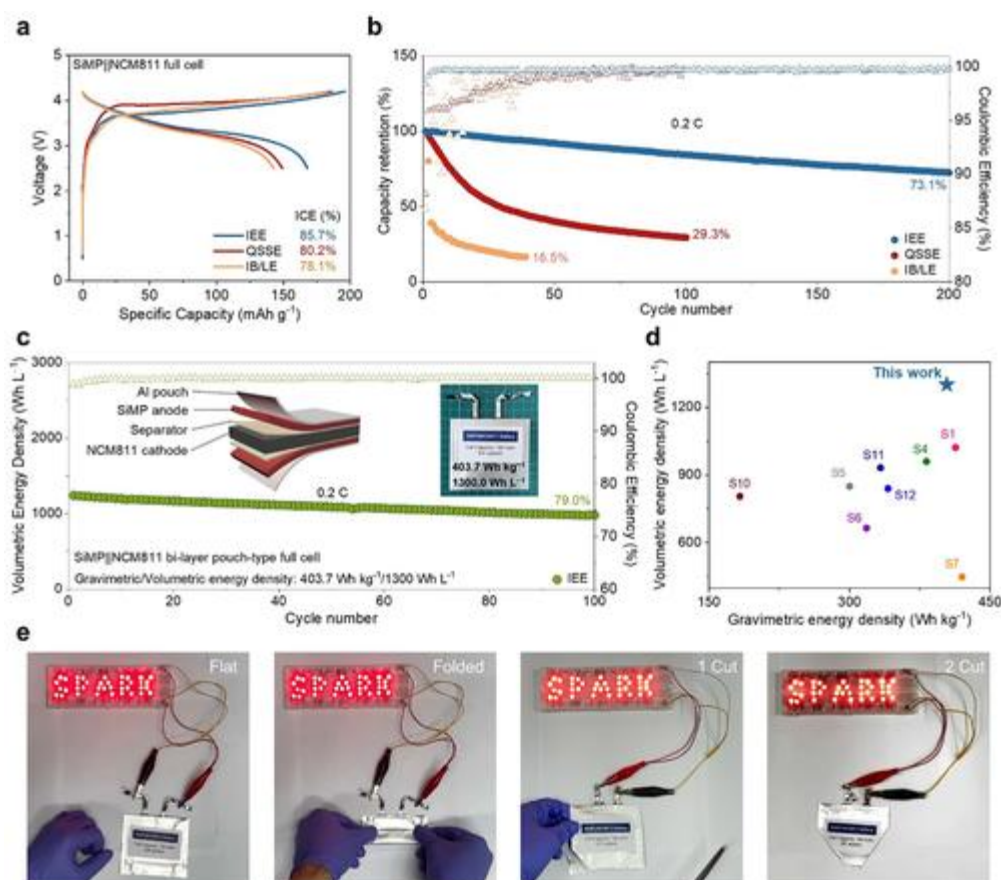


Figure 4

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Electrochemical performance of SiMP || NCM811 full cell with IEE system. a) Galvanostatic charge–discharge profiles of the SiMP || NCM811 full cells with different systems. b) Capacity retention and corresponding CEs of the SiMP || NCM811 full cells with different systems at 0.2C (1C = 0.2 A g⁻¹). c) Cycle performance of bi-layer pouch-type SiMP || NCM811 full cell with IEE system (Inset: Digital photo and cell configuration of a bi-layer pouch-type full cell). d) Comparison of the gravimetric and volumetric energy densities of the pouch-type full cell in this

work and previously reported using Si-based anode full cells. e) Optical images for the LEDs powered by a bi-layer pouch-type full cell under various conditions, including flat, folded, cut once, and cut twice.

The scalability of the IEE system was demonstrated in a bi-layer SiMP || NCM811 pouch-type full cell assembled using the IEE system with the same n/p ratio (capacity ratio of the anode to cathode) as coin-type cells, delivering a reversible capacity of 178.9 mAh and achieving an impressive energy density of 403.7 Wh kg⁻¹/1300.0 Wh L⁻¹ (Figure 4d; Figure S14, and Tables S2–S4, Supporting Information). The pouch cell exhibited robust cycling stability with an energy density retention of 79.0% after 100 cycles, attributed to limited polarization and stable voltage (Figure 4c; S15, Supporting Information). These results represent a significant step toward realizing commercial high-energy-density, stable battery technologies. To validate the practical application and safety of the pouch cell, a series of demonstrations and safety evaluations were performed under real-world conditions. The pouch cell consistently powered customized light-emitting diodes (LEDs) in a flat state and maintained operation under mechanical abuses such as folding and partial cutting, with no electrolyte leakage or safety issues (Figure 4e). The ability of QSSE to remain intact under mechanical stress further confirms the practical viability of the IEE system for real-world applications. Additional tests with a drone as the load assessed the performance of the IEE system under varied mechanical conditions. The drone was charged in both flat and folded states, demonstrating stable functionality regardless of mechanical deformation (Figure S16, Supporting Information). In parallel, flammability tests highlighted the enhanced flame-retardant properties of the QSSE (Figure S17, Supporting Information). When a separator soaked in highly flammable LE was exposed to an external flame, it ignited immediately and continued burning for over 10 s, resulting in the consequential burning of the supporting Al pouch. On the contrary, QSSE effectively mitigated flammability and leakage risks by immobilizing LE within its crosslinked polymer matrix, self-extinguished within just 3 s, and preserving the Al pouch. These tests validate the potential of the IEE system for integration into various electronic devices and applications prioritizing flexibility, stability, and safety.

A noticeable performance difference was observed between QSSE and IEE systems in full cell configurations, compared to the SiMP half cells. In half cells, the Li metal serves as a relatively soft counter electrode, forming a stable interface with QSSE. However, full cells introduce additional complexities, as both SiMP anodes and NCM811 cathodes face compounded interfacial challenges. Although NCM811 cathodes undergo less volumetric change than SiMP anodes, they still suffer from structural and interfacial instability during cycling. During charging (delithiation), NCM811 particles shrink, leading to the formation of interfacial gaps between the cathode and QSSE, adversely impacting Li-ion transport and forming a thick and nonuniform CEI layer indicative of degraded kinetics. To validate the effectiveness of the IEE system in maintaining cathode stability, a post-mortem analysis of NCM811 cathodes was conducted following the full cell test. TOF-SIMS 3D reconstruction images revealed significant differences in CEI layer formation (Figure 5a,b). In the QSSE system, Ni²⁺ fragments were scarcely detected on the NCM811 surface, while high intensities of organic/inorganic CEI components such as C₂H₃O⁻, C₂HO⁻, LiF₂⁻, PO₂⁻, and C₂P⁻ were observed (Figure 5b).^[29] This accumulation of CEI species suggests the formation of a thick, uneven CEI layer from electrolyte decomposition,

which hinders Li-ion kinetics and contributes to structural degradation. In contrast, the IEE system exhibited a well-distributed Ni^- fragment signal with significantly lower intensities of the aforementioned CEI components, indicating a thin, uniform CEI layer that maintains efficient ion/electron transport (Figure 5a).

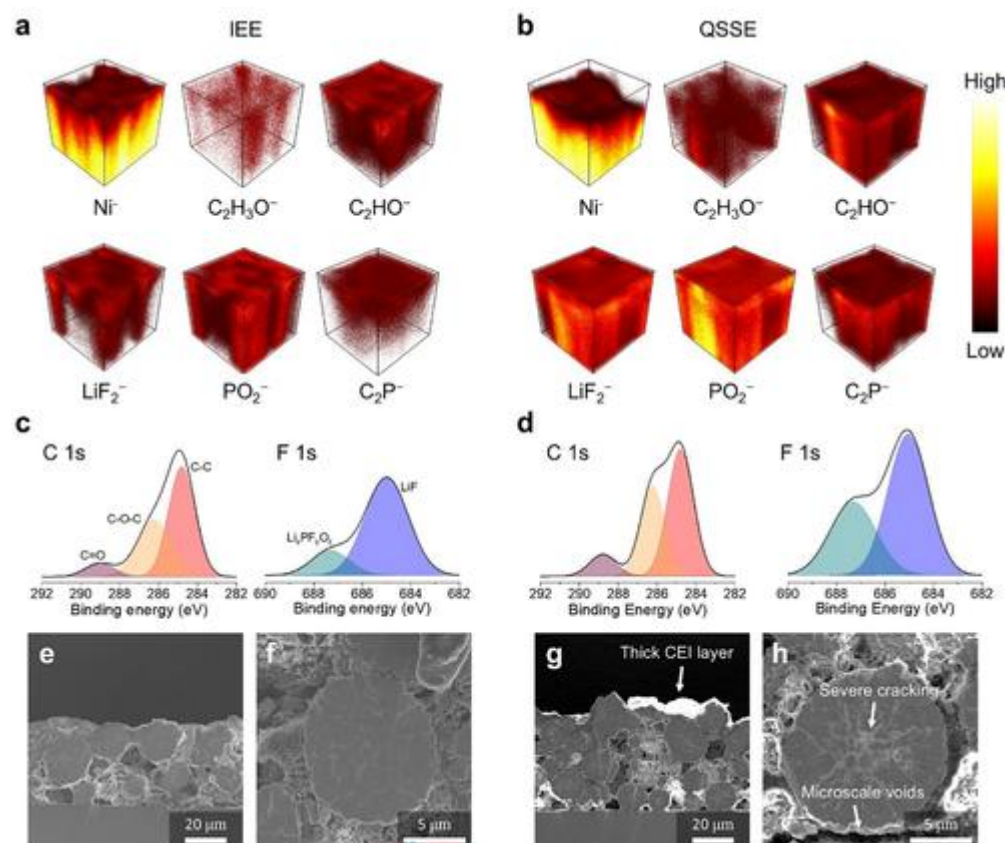


Figure 5

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Post-mortem analysis of NCM811 cathodes with IEE system. TOF-SIMS 3D reconstruction images of certain species from NCM811 cathodes after 100 cycles of full cells with a) IEE and b) QSSE systems. XPS spectra of C 1s and F 1s of NCM811 cathodes from full cells with c) IEE and d) QSSE systems. Cross-sectional SEM images of cathodes from full cells with e,f) IEE and g,h) QSSE systems.

X-ray photoelectron spectroscopy (XPS) further confirmed these findings by comparing the chemical composition of the CEI on the NCM811 cathodes. The C 1s spectra from the IEE system displayed reduced peaks for C–O–C and C = O species, associated with solvent decomposition, compared to the QSSE system, which displayed significantly higher intensities for these peaks (Figure 5c,d).^[29, 30] Similarly, the F 1s spectra of the IEE system showed lower intensities for LiF and $\text{Li}_x\text{PF}_y\text{O}_z$ peaks, linked to salt and additive decomposition. The TOF-SIMS and XPS analyses confirm that the IEE system promotes a thin, stable CEI layer on the NCM811 particles, facilitating an interconnected ion/electron transport network, essential for maintaining the electrochemical and structural stability of the cathode during cycling. To

investigate the structural integrity of NCM811 particles, cross-sectional SEM images were obtained using ion-milling to cut through the electrodes. SEM images revealed that cathodes in the IEE system exhibited a uniform, smooth surface with no visible cracks (Figure 5e,f). In contrast, NCM811 electrodes from the QSSE system displayed nonuniform thickness and a thick, irregular CEI layer on the surface, which caused severe cracking in NCM811 particles (Figure 5g,h). These cracks result from the unstable interface and thick CEI layer, which cause nonuniform lithiation/delithiation.^[30] To further analyze the CEI layer thickness, high-resolution transmission electron microscopy (HR-TEM) was performed on NCM811 cathodes from both the IEE and QSSE systems (Figure S18, Supporting Information). The HR-TEM images confirm that the IEE system enables the formation of a thin and uniform CEI layer (≈ 10 nm), which effectively maintains ion transport pathways. In contrast, the QSSE system exhibits a highly nonuniform and thick CEI layer, varying between 10 and 50 nm, which exacerbates interfacial instability. Such findings highlight the challenges of the QSSE system, where unstable and nonuniform CEI formation compromises electrode performance and longevity.

3 Conclusion

In summary, an in situ interlocking electrode–electrolyte system is proposed to enhance the stability and performance of QSSBs with SiMP anodes and NCM811 cathodes. Achieved through covalent crosslinking between acrylate groups on a designed IB and a crosslinker within the QSSE, the IEE system creates a robust, interconnected network that effectively mitigates mechanical degradation and maintains stable interfacial contact throughout cycling. Compared to traditional LE and QSSE configurations, which suffer from severe capacity decay due to SiMP pulverization, high interfacial resistance, and unstable SEI formation, the IEE system effectively mitigates these challenges, enabling high capacity retention and stable cycling performance. Notably, the SiMP half cell with the IEE system retained 81.3% of its capacity over 200 cycles, and the SiMP || NCM811 full cell achieved rapid CE stabilization at 99.5% within three cycles. The bi-layer pouch cell configuration further demonstrated the scalability of the IEE system, delivering a high energy density of $403.7 \text{ Wh kg}^{-1}/1300 \text{ Wh L}^{-1}$ and enhanced safety under mechanical abuses, underscoring its potential for high-energy-density and durable energy storage applications.

What if walls could become batteries?

Story by Adrien BERNARD

Turning building walls into actual rechargeable batteries: this is the ambition of a Franco-Spanish research team. Their goal is to propose a new electrochemical storage technology based on geopolymers, paving the way for direct integration of energy storage functions into construction materials.

With the rise of renewable energy, often intermittent, the need for stationary storage solutions is becoming crucial. While the idea of storing energy in concrete is not new, it has long remained marginal due to unsatisfactory performance, mostly limited to thermal storage.



What if walls could become batteries? 🏠

Inspired by geopolymers already used as an alternative to traditional cement in low-environmental-impact concrete, scientists propose a new, much more efficient electrochemical system thanks to the direct conversion of chemical energy into electricity. This device could, for example, store electricity generated by solar panels or wind turbines directly in building walls for later use.

Researchers from the Institute of Condensed Matter Chemistry of Bordeaux (CNRS/University of Bordeaux/Bordeaux INP), in collaboration with Spain's Centro de Física de Materiales, have made a major breakthrough by designing a solid-state battery with an electrolyte made of a metakaolin-based geopolymer—an aluminosilicate inorganic polymer obtained by calcining clays. Known for its excellent mechanical properties, this geopolymer is an eco-friendly alternative to ordinary Portland cement as a concrete binder, as its production emits far less

CO₂. The rechargeable battery developed by the team is a Zn-ion battery that uses this geopolymer matrix as an electrolyte separating conventional electrodes: zinc for the negative electrode and manganese dioxide for the positive electrode. Activated by a zinc sulfate solution, the porous matrix contains a residual liquid phase that ensures the transport of Zn²⁺ ions from one electrode to the other.

The result? An energy density of 3.3 Wh/L, four times higher than that (0.8 Wh/L) measured in traditional Portland cement-based devices. Admittedly, this density is much lower than that of conventional Li-ion batteries (~570 Wh/L). But here, storage is integrated into the very volume of the structure, which largely compensates for the lower density. Still at an early fundamental stage, several technical challenges remain, such as improving the stability of zinc electrodes and enhancing the mechanical properties of the solid electrolyte. But these hurdles seem surmountable given the rapid advances in aqueous Zn-ion batteries and the growing applications of geopolymers in the construction sector.

In the long run, this new concept, published in *Materials Horizons*, could support the development of energy-positive buildings, where walls themselves store the electricity produced on-site. Could the energy of the future be hidden in tomorrow's bricks?

SUPERWOODWORK

MAY 18, 6:00 AM EDT BY [JOE WILKINS](#)

Startup Claims Its "Superwood" Is Stronger Than Steel

"Eventually we want to get to the bones of the building."

[/ Earth & Energy/ Construction/ Startup/ Wood](#)



Image by InventWood

A new startup claims it can mass-produce "Superwood," a material that's stronger and lighter than steel, with 90 percent lower carbon emissions compared to the widely used alloy.

InventWood, the company behind the material, says its new product "has the capacity to substitute up to 80 percent of steel used globally," and "reduce greenhouse gas emissions by over 2 gigatons."

According to the firm, its Superwood has [up to 50 percent](#) more tensile strength compared to steel, has "minimal expansion and contraction," and a Class A fire rating — all crucial details for architects who might someday use Superwood in their buildings.

As [TechCrunch reports](#), the startup has already secured \$15 million in a Series A funding round, which its founder, materials scientist Liangbing Hu, says will go toward the company's first factory.

The whole thing came about in 2018, when Hu published a [landmark research paper](#) detailing how to "transform bulk natural wood directly into a high-performance structural material."

It's a relatively simple process that involves boiling wood in a mixture of [lye](#) and [sodium sulfite](#) — widely available compounds often used as additives in industrial food operations.

Lu's paper says the strategy has been found to be "universally effective" for all species of lumber.

The research has been used to launch startups like [Cambium](#), a "global tech platform for recycled wood," as Lu worked to refine the process and launch his own commercial venture.

But whether Superwood lives up to its founders claims is another story.

The materials science industry moves at a snail's pace, thanks to the many factors involved in approving new products for use in buildings. The caution only increases with [lumber](#), which could suffer unforeseen changes due to time, moisture, heat, stress, and transportation, [according to the Construction Specifier](#), a trade publication.

Cross-laminated timber (CLT), for example, while used in Europe for decades, has had a tough time [catching on](#) in the US, as untested American manufacturers rush their products to market and architects struggle to find construction firms with CLT experience.

That's led to incidents like the [Peavy Hall collapse](#) at Oregon State University, where a 1,000-pound section of a newly constructed CLT building caved in on a lower floor.

Prior to the collapse, manufacturers charmed regulators and project managers with [similar promises](#) of their product's strength and environmental impact.

At the moment, it seems like InventWood is taking it slow and building out its enterprise selling Superwood as a decorative material, rather than structural beams.

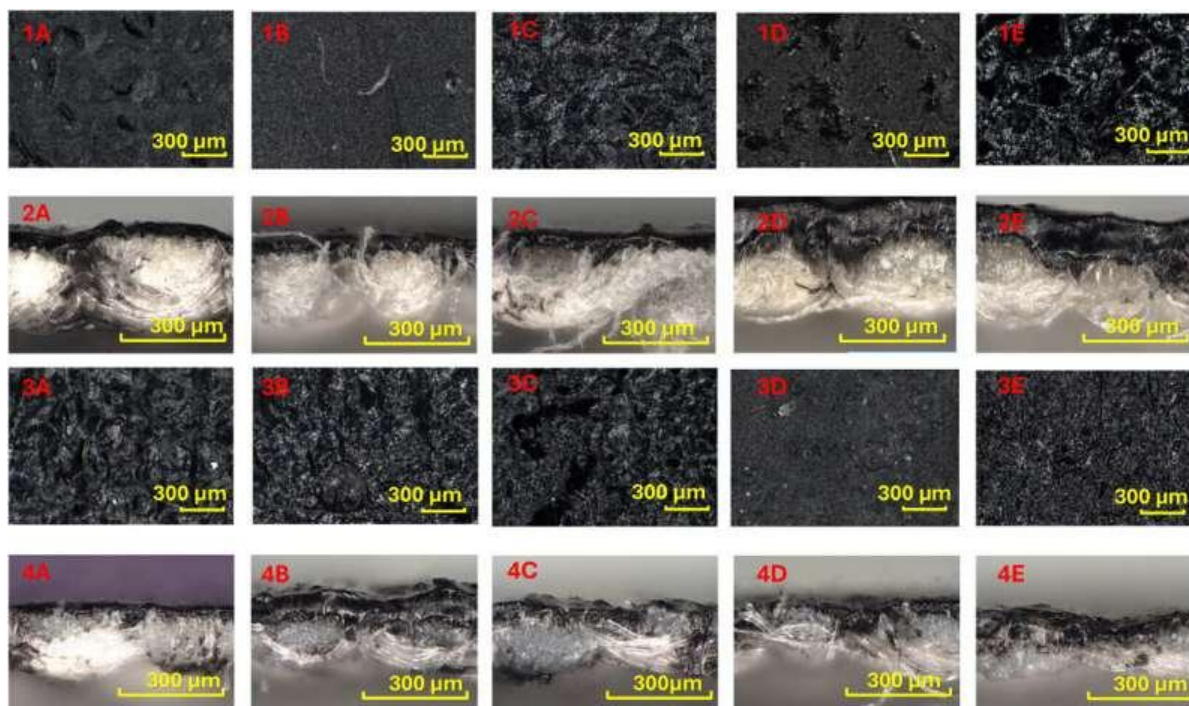
"Right now, coming out of this first-of-a-kind commercial plant — so it's a smaller plant — we're focused on skin applications," the company's CEO Alex Lau told *TechCrunch*, referencing building skins. "Eventually we want to get to the bones of the building."

Whether they do will depend on it gaining the confidence of architects and engineers, a process which will require years of patience. As with all startups, it's one thing to build it out on paper — now they have to do it for real.

MAY 13, 2025

3-D printed smart fabrics maintain flexibility and sensing ability after repeated washes

by Washington State University



Surface (1s and 3s) and cross-sectional (2s and 4s) images of printed cotton (1s and 2s) and polyester/cotton (3s and 4s) fabrics with the five solutions (A: 15-1; B: 15-2; C: 18-1; D: 18-2; E: 20-1). Credit: *ACS Omega* (2025). DOI: 10.1021/acsomega.4c11367

Imagine a T-shirt that could monitor your heart rate or blood pressure. Or a pair of socks that could provide feedback on your running stride. It may be closer than you think, with new research from Washington State University demonstrating a particular 3D ink printing method for so-called smart fabrics that continue to perform well after repeated washings and abrasion tests. The research, [published](#) in the journal *ACS Omega*, represents a breakthrough in smart fabric comfort and durability, as well as using a process that is more environmentally friendly.

Hang Liu, a textile researcher at WSU and the corresponding author of the paper, said that the bulk of research in the field so far has focused on building technological functions into fabrics, without attention to the way fabrics might feel, fit, and endure through regular use and maintenance, such as washing.

"The materials used, or the technology used, generally produce very rigid or stiff fabrics," said Liu, an associate professor in the Department of Apparel, Merchandising, Design and Textiles. "If you are wearing a T-shirt with 3D printed material, for example, for sensing purposes, you want this shirt to fit snugly on your body, and be flexible and soft. If it is stiff, it will not be comfortable and the sensing performance will be compromised."

Initial methods of developing smart wearables involved gluing, weaving or sewing functional components such as conductive threads or sensors into fabrics. Newer approaches involving printing have shown promise, but have still faced problems with comfort and maintenance.

Liu's team used direct ink writing 3D [printing technology](#) to print solutions of polybutylene succinate—a biodegradable polyester that is compatible with [natural fibers](#)—containing carbon nanotubes onto two types of fabric. The printed fabrics showed excellent electrical conductivity, [mechanical strength](#), gauge factor and stability under repeated strains, and the solution's ability to penetrate and bond with fibers gave the fabrics an enhanced washability and resistance to abrasion.

They tested printed fabrics for [tensile strength](#), electrical conductivity, their ability to function as motion sensors, and other qualities. They found the fabrics continued to perform well after 20 cycles of washing and drying, and the surfaces did not scratch or crack after 200 cycles of abrasion testing or 500 cycles of tensile cyclic testing.

The team also used a biodegradable, nontoxic solvent, Cyrene, for processing, which is more environmentally friendly than commonly used toxic solvents.

Smart fabrics are an emerging trend, offering the promise of clothing items that can perform some of the same tasks as smart watches and other such devices. The technology has the potential for applications in health care, for first responders, in the military and for athletes.

The study was a part of the doctoral dissertation of one of Liu's students, Zihui Zhao, who was the lead author. Liu has been working on various elements of smart fabrics for several years; she [developed a fiber](#) with the flexibility of cotton and the [electrical conductivity](#) of a polymer that could have use in wearable tech, as detailed in a paper published in 2023.

The most recent work on 3D printing focused on the ability of fabrics to sense and monitor information; developing functional smart wearables will also require [power source](#) and data transmission technologies.

"This is only one part of the whole smart system," Liu said.

More information: Zihui Zhao et al, Flexible and Durable Direct Ink Writing 3D-Printed Conductive Fabrics for Smart Wearables, *ACS Omega* (2025). DOI: [10.1021/acsomega.4c11367](https://doi.org/10.1021/acsomega.4c11367)

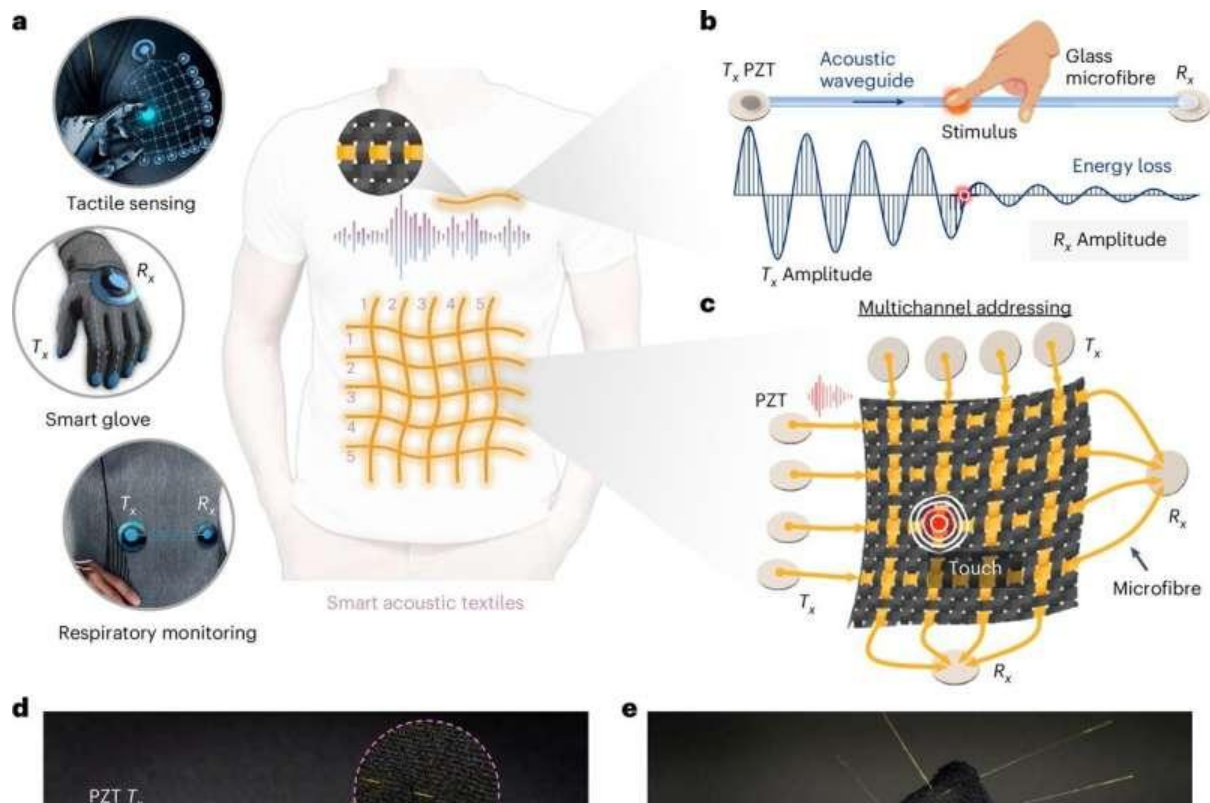
Journal information: [ACS Omega](#)

MAY 19, 2025

Using sound waves to create a smart T-shirt

by Deborah Kyburz , [ETH Zurich](#)

edited by [Lisa Lock](#), reviewed by [Robert Egan](#)



Smart textiles using glass-fiber acoustic waveguides. Credit: *Nature Electronics* (2025).

DOI: 10.1038/s41928-025-01386-2

Imagine wearing a T-shirt that measures your breathing or gloves that translate your hand movements into commands for your computer. Researchers at ETH Zurich, led by Daniel Ahmed, Professor of Acoustic Robotics for Life Sciences and Healthcare, have laid the foundations for just such smart textiles.

Unlike many previous developments in this area, which usually use electronics, the ETH researchers rely on acoustic waves passed through glass fibers. This makes the measurements more precise and the textiles lighter, more breathable and easier to wash. "They are also inexpensive because we use readily available materials, and the [power consumption](#) is very low," says Ahmed.

Acoustic sensors embedded in fabric

The researchers call their development SonoTextiles. They have transformed normal fabrics into smart sensors that react to touch, pressure and movement. "While research has already been conducted into smart textiles based on acoustics, we are the first to explore the use of glass fiber in combination with signals that use different frequencies," explains Yingqiang Wang, the first author of the study that has been [published](#) in *Nature Electronics*.

Credit: ETH Zurich

The researchers have woven glass fibers into the fabric at regular intervals. At one end of each glass fiber is a small transmitter that emits [sound waves](#). The other end of each of the glass fibers is connected to a receiver that measures whether the waves have changed.

Each transmitter works at a different frequency. This means it requires little computing power to determine which fiber the sound waves have changed on. Previous smart textiles often struggled with data overload and signal processing issues, since each sensor location had to be evaluated individually. "In the future, the data could be sent directly to a computer or smartphone in real time," says Ahmed.

When a glass fiber moves, the length of the acoustic waves passing through it changes, as they lose energy. In the case of a T-shirt, this can be caused by body movement or even breathing. "We used frequencies in the ultrasonic range, around 100 kilohertz—well beyond the range of human hearing, which is between 20 hertz and 20 kilohertz," Wang emphasizes.



Example of a smart textile woven with glass fibers. Credit: Yingqiang Wang / ETH Zurich

Highly versatile

The researchers have shown that their concept works in the lab. In the future, SonoTextiles could be used in a variety of ways: as a shirt or T-shirt, they could monitor the breathing of asthma patients and trigger an alarm in an emergency.

In sports training and performance monitoring, athletes could receive real-time analysis of their movements, to optimize their performance and prevent injuries. The textiles also have the potential for [sign language](#): gloves with this technology could simultaneously translate hand movements into text or speech. They could also be used in virtual or augmented reality environments.

"SonoTextiles could even measure a person's posture and improve their quality of life as an [assistive technology](#)," adds Chaochao Sun, who shares first authorship of the study. People who want to improve their posture could receive targeted feedback to correct poor posture. The textiles could also indicate when a wheelchair user needs to change position to prevent pressure ulcers.

Although the everyday usability of SonoTextiles is potentially very high, Ahmed adds that there is still room for improvement in terms of practical application. Glass microfibers worked well as sound conductors in the lab, but they could potentially break in everyday use.

"The beauty is that we can easily replace the glass fibers with metal. Sound also propagates effectively through metal," explains Ahmed. "We would like to expand our research in this direction and also into other applications." The researchers now want to make the system more robust and examine how the electronics can be better integrated into the textiles.

More information: Yingqiang Wang et al, A smart acoustic textile for health monitoring, *Nature Electronics* (2025). DOI: [10.1038/s41928-025-01386-2](https://doi.org/10.1038/s41928-025-01386-2)
Journal information: [Nature Electronics](#)
Provided by [ETH Zurich](#)

MAY 16, 2025

Study maps three decades of white LED progress and key innovation drivers

by [Ingrid Fadelli](#), Tech Xplore

Don't be fooled – this is not one of the light bulbs that your grandfather used. Instead of a heated Tungsten filament, these bulbs use microscopic LED chips, covered in a yellow phosphor substance to mimic a retro aesthetic while achieving high energy efficiency in lighting. Credit: Rambling Geek (<https://500px.com/p/ramblinggeek>). Wikimedia Commons. White light-emitting diodes (LEDs), the semiconductor devices underpinning the functioning of countless lighting technologies on the market today, were first released to the public in 1996. Following their commercial debut, these devices have fueled significant advancements within the electronics and lighting industry, due to their remarkable energy efficiencies and extended lifespans.

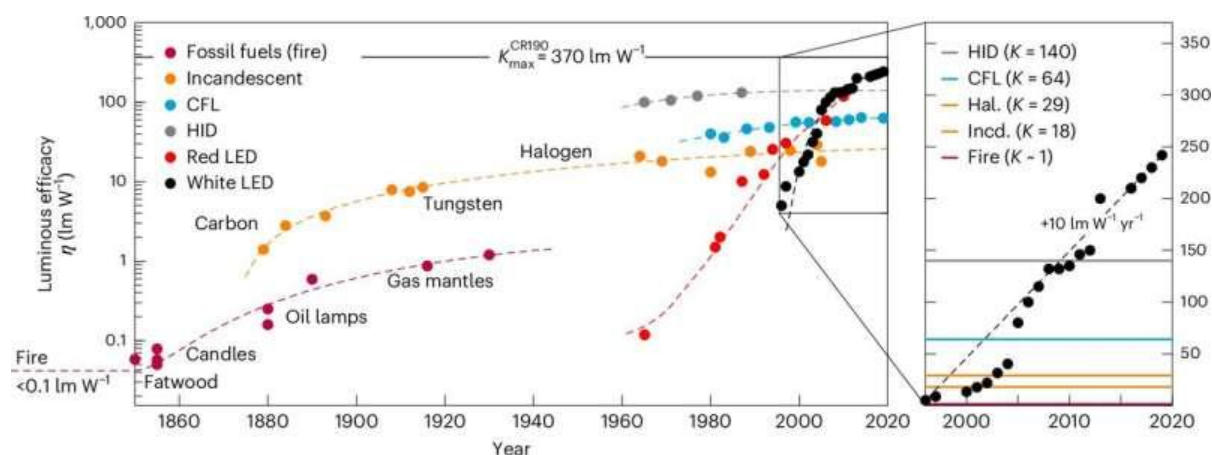
Researchers at the University of Cambridge and ETH Zurich recently carried out a study aimed at re-tracing the development of white LEDs over the past three decades, as well as trends in their costs and innovations in other engineering fields that fueled their advancement. Their paper, [published](#) in *Nature Energy*, was part of a larger research project that investigated the factors driving innovation in the clean energy sector.

"As part of our research, we looked at three key technologies at the forefront of the ongoing energy transition: solar photovoltaics for [energy generation](#), lithium-ion batteries for [energy storage](#), and white LEDs for efficient energy use in lighting," Michael P. Weinold, first author of the paper, told Tech Xplore.

"Each of the three technologies has experienced rapid cost declines and impressive performance improvements in the past decades. Understanding these drivers of progress can help us accelerate innovation in other low-carbon technologies."

The researchers' study dealt with the complex challenge of tracing advancements in the development of LEDs. They achieved this by browsing through hundreds of patents, [scientific publications](#), technical reports, and market data released up to 2020.

"We also conducted interviews with prominent experts in solid-state lighting technology, semiconductor manufacturing, and phosphor development," explained Weinold. "This allowed us to identify key technological and manufacturing innovations that contributed to historical progress in LED cost and performance. We then used this information as an input to the manufacturing cost and performance models we developed to quantify the contribution of individual innovations to overall progress."



Historical progress in luminous efficacy of a light source η of the most widely used lighting technologies in human history. Credit: *Nature Energy* (2025). DOI: 10.1038/s41560-025-01757-1

The analyses carried out by Weinold and his colleagues showed that most improvements in the energy efficiency of LEDs were driven by research and development (R&D) efforts. Surprisingly, however, the researchers found that R&D contributed relatively little to reductions in the cost of the devices, which were instead linked to economies of scale and continuous manufacturing process improvements over time.

"We also identified a particularly intriguing role of 'technology spillovers'—technical knowledge from other technologies and scientific fields finding new applications in white LEDs—in driving improvements in the quality of LED light that were instrumental in increasing the adoption of this technology by consumers," said Weinold.

"These findings suggest that innovation in LEDs and other consumer-facing demand-side energy technologies may require different approaches to R&D management and policy support than in supply-side energy technologies such as solar and wind energy."

The findings of this recent study offer new valuable insight into the factors that have contributed to the advancement and widespread adoption of LEDs over the past decades,

which could guide future efforts aimed at further improving these devices. Based on their analyses, the researchers suggest that LED manufacturers should focus more on the needs of users, while also deliberately searching for external knowledge and research advancements that could drive innovation in the field.

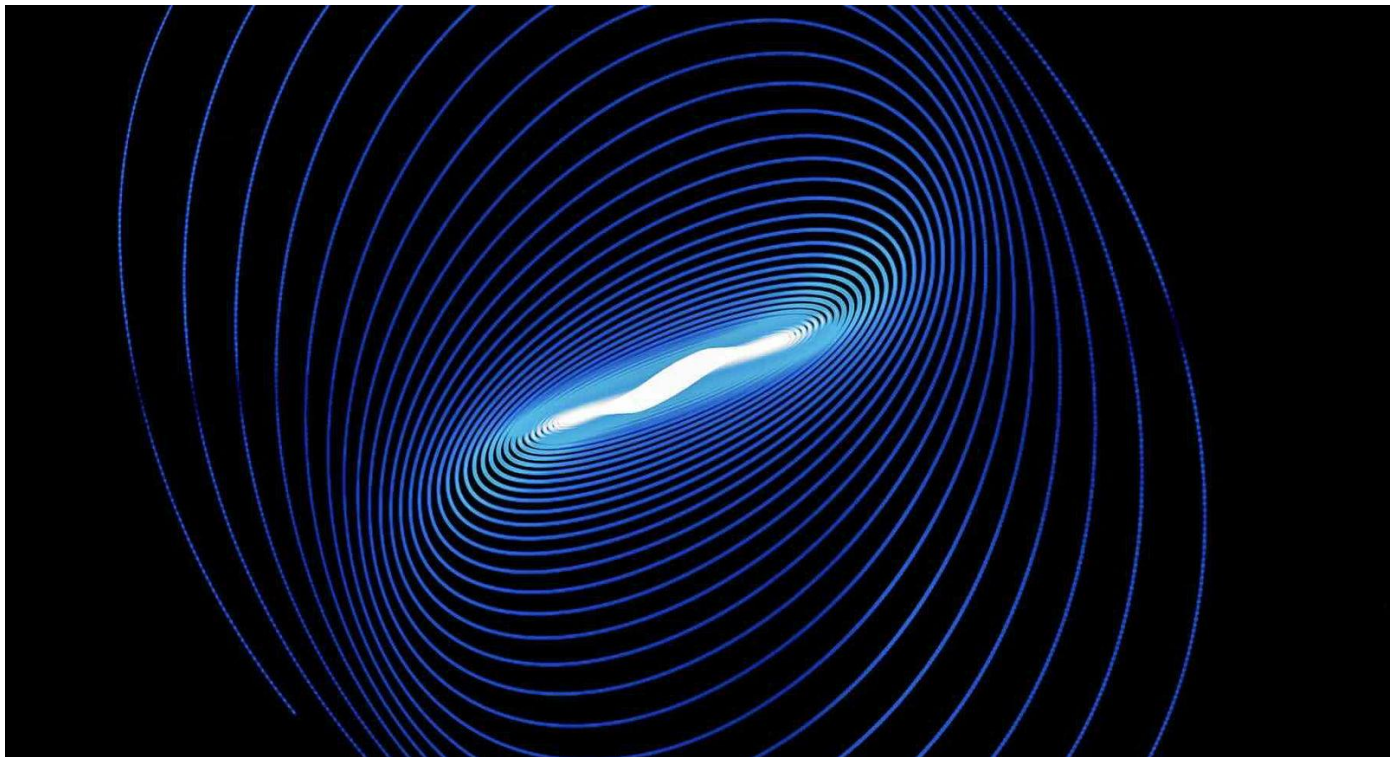
"We are now working on synthesizing the findings of the project across the three technologies—white LEDs, solar photovoltaics and [lithium-ion batteries](#)—to make recommendations for policymakers and R&D managers on how to accelerate low-carbon innovation," added Sergey Kolesnikov, another author of the paper.

"In parallel, using data on past cost and performance trends that we collected for LEDs and other energy technologies, we work on developing new probabilistic technology cost forecasting methods that will allow us to predict future costs of critical technologies while simultaneously accounting for the inherent uncertainty of the [innovation](#) process."

More information: Michael P. Weinold et al, Rapid technological progress in white light-emitting diodes and its source in innovation and technology spillovers, *Nature Energy* (2025). DOI: [10.1038/s41560-025-01757-1](https://doi.org/10.1038/s41560-025-01757-1)

Journal information: [Nature Energy](#)

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BREAKTHROUGH METAMATERIAL LEVERAGES SOUND WAVES FOR TOUCH-FREE CONTROL OF SUBMERGED OBJECTS

• MAY 21, 2025

A new [metamaterial](#) enables [sound waves](#) to manipulate [underwater](#) objects with no physical contact, enabling easier and more accessible operation in [aquatic](#) environments.

University of Wisconsin–Madison researcher Dajun Zhang presented the new [metamaterial](#) to peers on May 20 at the joint 188th Meeting of the Acoustical Society of America and the 25th International Congress on [Acoustics](#). The work builds on other [acoustic](#) applications, like mapping the [ocean floor](#) or shattering kidney stones, to harness sound for human endeavors.

A NOVEL ACOUSTIC METAMATERIAL

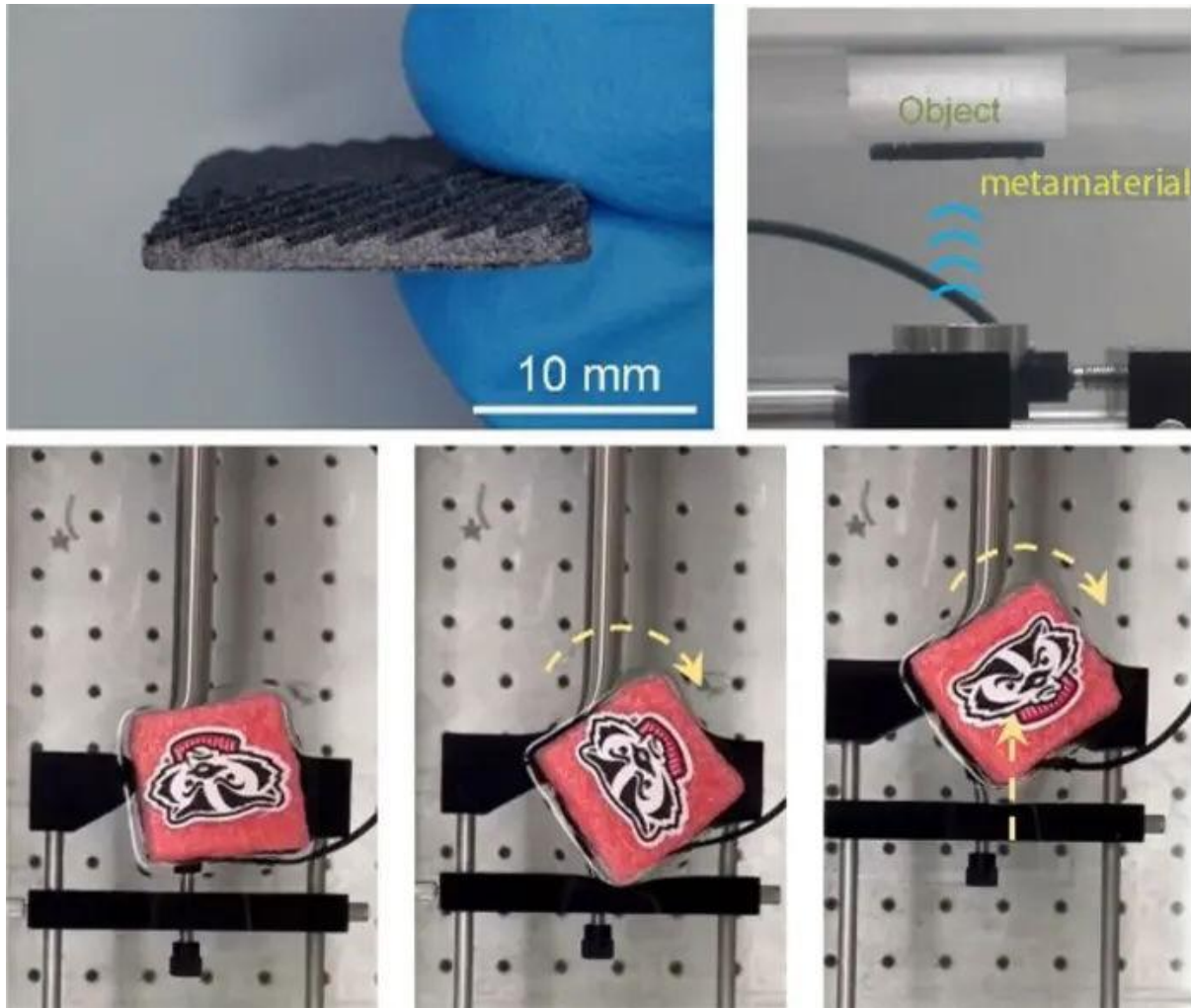
Metamaterials are novel composites containing structures that produce unique effects. In Zhang’s case, he structured his metamaterial with a sawtooth–patterned surface. The novel surface allows sound waves to exert different forces on the material due to how they divergently reflect off the unique shape of the material’s “teeth.” By targeting these waves, Zhang can precisely push and rotate a floating or submerged object attached to the material.

The resulting advancement in acoustic manipulation opens a path to greatly increasing the ease of underwater operations. Additionally, since the human body is primarily composed of water, surgery and drug delivery could be optimized with the metamaterial. That secondary application remains further in the future.

TESTING THE WATERS WITH SOUND

“Our metamaterial offers a method to apply different acoustic radiation forces on objects in liquid media, such as underwater robots and vehicles, parts for assembly, or medical devices and drugs,” [said Zhang](#).

When testing the metamaterial, Zhang did not construct an object solely of the composite, but attached it to existing items. These included wood, wax, and plastic foam floating above the water, as well as other objects that he completely submerged. Acoustic waves successfully pushed, pulled, and rotated the objects in Zhang’s tests, with submerged objects demonstrating the material’s effectiveness for 3D manipulation.



(Credit: Dajun Zhang)

SCALING AND IMPROVING THE METAMATERIAL

At this point, the greatest challenge to scaling Zhang's work for commercial use is the limited capabilities of conventional manufacturing. Fortunately, Zhang has already advanced a solution that not only eases production concerns for his composite but also for underwater metamaterials in general.

“Current fabrication methods for underwater metamaterials do not provide the resolution or material properties required and are usually very expensive,” said Zhang. “To solve this issue, I developed a new fabrication method. This method is not only low cost and easy to

implement but also achieves high fabrication resolution and large acoustic impedance contrast with water, which are keys to underwater metamaterials.”

EXPANDING ACOUSTIC TECHNOLOGIES

Since sound travels through water at four times the speed it moves through air, acoustic technologies are highly useful under the waves. At the same meeting as Zhang, University of Texas at Austin scientist Connor Hodges [revealed a new method](#) to explore the depths for unexploded munitions using sound, potentially removing human bodies from the dangerous but necessary pursuit.

Also at the conference, Trinity Consultants presented new noise control techniques aimed at silencing large data centers. With expanding needs for large scale computing power, neighbors are becoming fed up with the noise of these installations, often built in residential areas.

As far as Zhang is concerned, the next step will be to push toward achieving smaller, more flexible paths toward the production of the material, with a specific focus on development of novel underwater robotics and medical applications.

“Our research opens new opportunities for both underwater acoustic metamaterials and remote manipulation,” said Zhang.

“Acoustic metamaterials and metasurfaces can now be used to generate forces remotely for underwater or in-body levitation, actuation, and manipulation applications.”

INCREDIBLE NEW NANOTECH MATERIAL CAN PRODUCE CLEAN ENERGY INSIDE YOUR BODY

Electricity has a surprisingly long history of use in medical science. Going all the way back to ancient Rome, physicians were known to use electric rays and other creatures capable of producing electricity with the organs in their bodies in the treatment of gout and other ailments. By the middle of the 17th century, the human cardiovascular system was recognized as being bio-electric, although it would be more than a century before the concept of cardiac stimulation by electrical means would appear in the *Registers of the Royal Human Society of London* in 1774.

The following year, Nickolev Abildgaard began conducting some of the earliest recognized experiments regarding the effects of electricity applied to the body. Today, use of electrical devices in stimulating and regulating organ function and other parts of the body are quite common, and devices like pacemakers which use lithium batteries to provide the small amounts of electricity required to regulate the human heartbeat are implanted within close to one million individuals around the world every year.

However, new nanotech research being undertaken by an international team of researchers at Tel Aviv University are exploring whether electric currents can be produced within the human body without the use of electrical devices, and instead through the activation of the body's own organs. With the help of a new biological material similar to collagen, the researchers say that the body may be able to produce its own clean energy that can be used to power devices implanted within the body, which may no longer require batteries in the future.

The research appeared in *Nature Communications*, and was led by Professor Ehud Gazit, Founding Director of the Blavatnik Center for Drug Discovery and a staff member at the Wise Faculty of Life Sciences Shmunis School of Biomedicine and Cancer Research, who

worked with an international team based out of Australia, China, and Ireland.

According to Gazit, collagen, the most abundant protein in the our bodies, is a biological material with a variety of physical properties that include both flexibility and mechanical strength, which make it uniquely suited for a variety of medical applications. The problem is that, in terms of its molecular structure, collagen is complex and therefore somewhat difficult to use. Scientists who study collagen's unique properties like those among the team at TelAviv University have long considered how a simpler molecule that can perform similar functions might be used in its place.

"About a year and a half ago, in the journal *Nature Materials*, our group published a study in which we used nanotechnological means to engineer a new biological material that meets these requirements," Gazit.

Professor Ehud Gazit.

The new molecule is a *tripeptide*, which represents a very short molecule containing just three amino acids. Compared to the 1050 amino acids that appear in collagen, the new molecule possesses remarkably similar properties: it is capable of self-assembly into helical structures like its molecularly complex cousin, but also boasts the flexibility of collagen. It also possesses strength comparable to titanium, although what researchers working with Gazit in the recent study hoped to determine is whether it possessed another unique trait collagen is known to display: *piezoelectricity*, or the ability to produce electrical currents when mechanical force is applied to it.

A number of substances that occur in nature possess piezoelectricity, from the tendons and bones in our bodies, to quartz crystals. When researchers applied mechanical pressure to the new collagen-like material, it not only succeeded in producing electrical current, but also appears to possess what may be the highest piezoelectric potential ever observed, capable of outperforming common materials used in medical applications today.

“Most of the piezoelectric materials that we know of today are toxic lead-based materials,” Gazit says. This, or they are polymers, “meaning they are not environmentally and human body-friendly.”

“Our new material, however, is completely biological, and therefore suitable for uses within the body,” Gazit adds.

The discovery is significant and could propel future studies in nanotech in a variety of innovative ways, which includes its use in creating motors or power systems within tiny nanotech devices in the coming years.

Gazit and his team recognize the potentials as far as using this newly discovered material in a variety of nanotech applications that include powering pacemakers and similar devices. Any kind of regular movement that occurs within the body, from the movement of joints to the regular beating of a heart, could be harnessed to charge such devices.

The significance of the discovery of this material has been described as “immense,” and its range of scientific and technological applications are almost limitless, extending [well beyond just medical applications](#) for use within our bodies. An added bonus is that the material is also more environmentally friendly than many other piezoelectrical materials in use today, which are lead-based and are therefore toxic and potentially dangerous for use in nanotech and other applications.

Gazit and his team’s study, titled “Molecular engineering of piezoelectricity in collagen-mimicking peptide assemblies,”

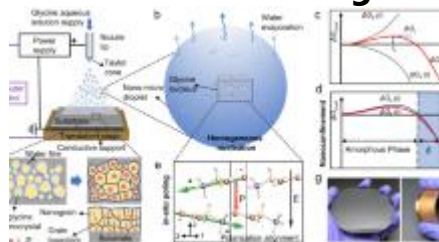
Molecular engineering of piezoelectricity in collagen-mimicking peptide assemblies

[Nature Communications](#) **volume 12**, Article number: 2634 (2021)

Abstract

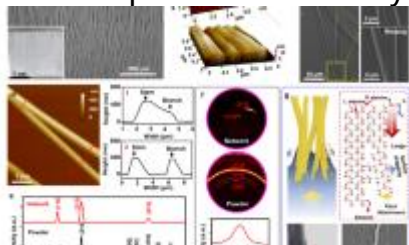
Realization of a self-assembled, nontoxic and eco-friendly piezoelectric device with high-performance, sensitivity and reliability is highly desirable to complement conventional inorganic and polymer based materials. Hierarchically organized natural materials such as collagen have long been posited to exhibit electromechanical properties that could potentially be amplified via molecular engineering to produce technologically relevant piezoelectricity. Here, by using a simple, minimalistic, building block of collagen, we fabricate a peptide-based piezoelectric generator utilising a radically different helical arrangement of Phe-Phe-derived peptide, Pro-Phe-Phe and Hyp-Phe-Phe, based only on proteinogenic amino acids. The simple addition of a hydroxyl group increases the expected piezoelectric response by an order of magnitude ($d_{35} = 27 \text{ pm V}^{-1}$). The value is highest predicted to date in short natural peptides. We demonstrate tripeptide-based power generator that produces stable max current $>50 \text{ nA}$ and potential $>1.2 \text{ V}$. Our results provide a promising device demonstration of computationally-guided molecular engineering of piezoelectricity in peptide nanotechnology.

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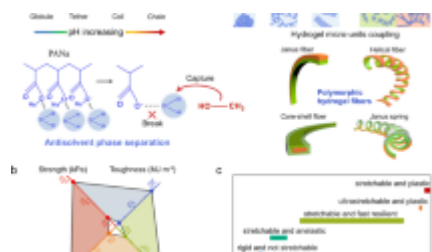
Active self-assembly of piezoelectric biomolecular films via synergistic nanoconfinement and in-situ poling

Article Open access 11 July 2023



Stretchable piezoelectric biocrystal thin films

Article Open access 17 October 2023



Macromolecule conformational shaping for extreme mechanical programming of polymorphic hydrogel fibers

Article Open access 11 June 2022

Introduction

Piezoelectric materials generate electrical energy in response to mechanical deformation. Piezoelectric devices are commonly made from a variety of inorganic materials and organic polymers^{1,2,3,4,5}, which limits their deployment in health monitoring and regenerative medicine due to reliance on toxic starting metals, complicated synthesis procedures, weak oxidation stability and poor sustainability⁶. Green piezoelectric materials that satisfy the requirements of ultra-high mechanosensitivity, flexibility and durability would provide a promising route to biocompatible multifunctional smart energy harvesters. Piezoelectricity has been widely observed in several natural materials including bone, collagen, viruses, cellulose and chitosan^{7,8,9,10}. However, the piezoelectric response exhibited by these biomaterials is typically in the range of 0.1–10 pm V⁻¹, which is low for many potential applications¹¹. Among these various piezoelectric biopolymers, collagen exhibits useful chemical and physical properties of extensibility, high tensile strength and swelling^{12,13}. Moreover, the piezoelectricity of collagen may play a pivotal role in controlling bone growth¹⁴, with fibrillar rat tail collagen exhibiting the highest measured shear d_{14} value for a biomaterial of 12 pm V⁻¹ (pC N⁻¹)¹⁵.

Biomimetics provides potentially disruptive advances in design and fabrication of novel functional materials. Using a minimalistic approach, self-assembled short peptides have emerged as versatile building blocks due to their inherent biocompatibility and highly engineerable properties that provide tailored functionality^{16,17,18,19}. Although nanostructures formed by ultra-short peptide sequences predominantly exhibit β -sheet organization^{20,21,22}, the collagen

structure is helical²³. The large number of directionally aligned hydrogen bonds in the helical structure creates a macroscopic dipole that can couple with external electric fields and shear force to produce the piezoelectric response of collagen²⁴. Examination of all collagen residues has demonstrated the post-translationally modified amino acid hydroxyproline (Hyp) to show the highest piezoelectric response²⁵. Yet, by itself, Hyp does not exhibit the fibrillar assembly and helical structural pattern of collagen, and it has only very recently proved possible to design ultra-short peptides that can mimic the collagen supramolecular architecture²⁶. On the other side, earlier findings suggested that the dynamic interactions of aromatic amino acid side chains in peptide-based structures can increase electrical conductivity^{27,28}. The aromatic Phe-Phe-based β -sheet-rich biomaterials have been investigated and utilized for fabrication of green energy harvester^{29,30}. However, tailor-made design of ultra-short peptide to achieve high piezoelectric response similar to collagen through mimicking its supramolecular architecture has remained elusive.

Molecular modelling, in particular density functional theory (DFT), has emerged as an effective tool for predicting and rationalizing the piezoelectric response of materials, from classic inorganic crystals^{31,32} to polymers³³ and novel two-dimensional structures^{34,35}. Our previous work has utilized DFT to accurately predict the elastic and piezoelectric tensors of amino acid^{10,11}, peptide²⁵ and biomineral crystals³⁶. DFT can be used to complement techniques such as piezoresponse force microscopy (PFM)^{37,38} or used in standalone predictive modelling studies of nanoscale electromechanical phenomena³⁹. Classical molecular dynamics (MD) simulations are also widely used to study the kinetics of piezoelectric systems⁴⁰ and are particularly effective at studying systems in a liquid environment⁴¹ and over a range of temperatures⁴².

Here, aiming to engineer a minimalistic collagen-mimicking short peptides, we develop radically different organization of Phe-Phe-derived short peptide based only on natural amino acid by including both Hyp and aromatic Phe moieties in the sequence. Both Pro-Phe-Phe and Hyp-Phe-Phe tripeptides assemble into a helical-like sheet that is stabilized by the dry hydrophobic zipper interface of Phe residues. The self-assembled fibrillar biomaterial

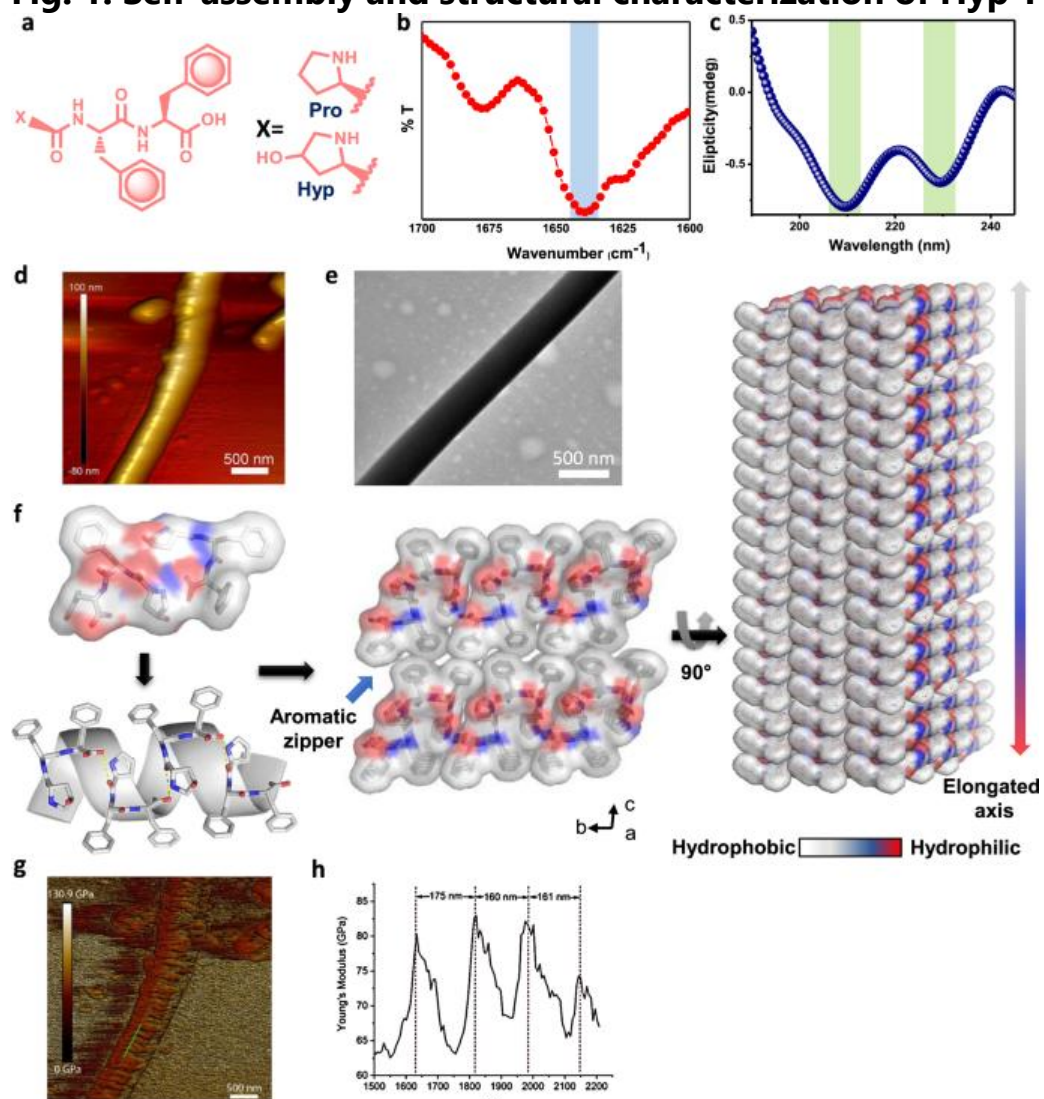
composed of helical-like molecular arrangement of the tripeptides exhibits excellent mechanical strength and high piezoelectric response (see benchmarks in Supplementary Table 1), which is maximized in the strong H-bonding Hyp variant. We designed the material to exhibit markedly higher piezoelectricity, which is achieved by modulating the electromechanical response of the tripeptide via side-chain engineering to optimize supramolecular polarization. When used as the active component in a power generator, the helical tripeptides show much larger short-circuit current and open-circuit voltage output as compared to β -sheet-rich peptide. Our findings demonstrate the rational modulation of peptide self-assembly to create tailored functionality and mark a significant step forward in molecular engineering of peptide piezoelectricity for nanotechnology applications by exemplifying the importance of targeting both primary and secondary structure.

Results and discussion

Characterization of Hyp-Phe-Phe assemblies

To engineer collagen-mimicking natural piezoelectric short peptides, we chose the self-assembling tripeptide, Pro-Phe-Phe (Fig. 1a), an ultra-short helical natural peptide with high mechanical stability similar to that of collagen^{26,43}. We substituted Pro for Hyp (Fig. 1a), as it exerts the highest piezoresponse among the collagen component amino acids²⁵. Building on the recently solved solution state morphology and secondary structure of Pro-Phe-Phe²⁶, we used Fourier transform infrared (FTIR) and circular dichroism (CD) spectroscopy techniques to characterize the solution secondary structure of Hyp-Phe-Phe. The FTIR spectra showed a sharp amide I peak at 1645 cm^{-1} with a shoulder at 1680 cm^{-1} , indicating the predominant helical structure (Fig. 1b) similar to Pro-Phe-Phe. The small peak shift towards lower wavenumber (compared with the standard helical structure, which usually falls near $1650\text{--}1655\text{ cm}^{-1}$) agrees with the predicted frequency shift for ultra-short helices⁴⁴. The CD spectrum strongly supported the FTIR data, as it exhibited double negative maxima, characteristic of helical conformations (Fig. 1c). The maxima at 210 and 230 nm were faintly red shifted compared to canonical double helix, as expected for shorter length peptides⁴⁵.

Fig. 1: Self-assembly and structural characterization of Hyp-Phe-Phe.



a Chemical structure of Pro-Phe-Phe and Hyp-Phe-Phe. **b** FTIR analysis of Hyp-Phe-Phe assemblies showing the characteristic peak of helical conformation. **c** CD spectrum of the tripeptide reveals the presence of helical assemblies in solution. **d** AFM image of the tripeptide demonstrating fibrillar morphology. **e** TEM image of the tripeptide fibres. **f** Single-crystal structure of Hyp-Phe-Phe showing the formation of an elongated structure by stacking of helices through intermolecular hydrogen bonding and aromatic zipper-like packing. CCDC ref. no. 1823367²⁶. **g, h** Mechanical strength of the Hyp-Phe-Phe fibres. **g** Nanoscale mapping of Young's modulus (Z-scale = 140 GPa). **h** Line section through one fibril as highlighted by the green

line in **g**, showing the periodic variation in stiffness along the fibril. Additional AFM and TEM data are given in Supplementary Figs. 1–3.

The supramolecular assembly of Hyp-Phe-Phe was explored using atomic force microscopy (AFM) and transmission electron microscopy (TEM) (Fig. 1d, e and Supplementary Figs. 1 and 2). The images revealed that the tripeptide self-assembled into uniform high aspect ratio fibres of 500 nm in diameter that extended for several micrometres (aspect ratio, $L/D > 500$). Single-crystal X-ray diffraction structures revealed the favourable molecular level interactions that direct the supramolecular organization (Fig. 1f). The asymmetric unit of the Hyp-Phe-Phe crystal comprised two peptide molecules sharing common structural features²⁶. The torsion angles of the Phe₂ moiety were found to be localized within the right-handed helical region of the Ramachandran plot, with φ_2 and ψ_2 values of -71.1° , -70.5° and -43.2° , -41.9° , respectively, comparable to that of the Pro-Phe-Phe crystal. In the crystallographic *b*-direction, the adjacent molecules were connected through head-to-tail intermolecular H-bonds, generating an extended helical-like molecular organization (Fig. 1f, left and right illustrations). Neighbouring helical-like structural modules connected in a parallel orientation with the interface of the dimer stabilized by the aromatic zipper structure built from π – π interactions between the Phe side chains (Fig. 1f, middle illustration). Such a dry steric zipper interface has long been assumed to provide mechanical rigidity to amyloid fibres⁴⁶ and may provide additional stability to the Hyp-Phe-Phe assemblies. To investigate the nanomechanical properties of Hyp-Phe-Phe fibres, we used quantitative nanomechanical mapping AFM (QNM-AFM) (Fig. 1g, h). The measured Young's modulus of the fibrils varied in the range of 60–90 GPa, producing the same order of magnitude mechanical stiffness as recorded by AFM nanoindentation in the corresponding single crystal²⁶. The preservation of the single-crystal level of mechanical rigidity in the peptide fibre was quite remarkable for a biomaterial and comparable with stiff biological materials such as the bone, collagen and enamel⁴⁷ from which we conclude that the presence of the “aromatic zipper” molecular motif led to the fabrication of the stiff macroscopic biomaterial. Definite corrugation was observed perpendicular to the long axis of the fibril (green line in Fig. 1g), with a peak to peak distance of ~ 165 nm and a periodicity of 84.9 nm, as

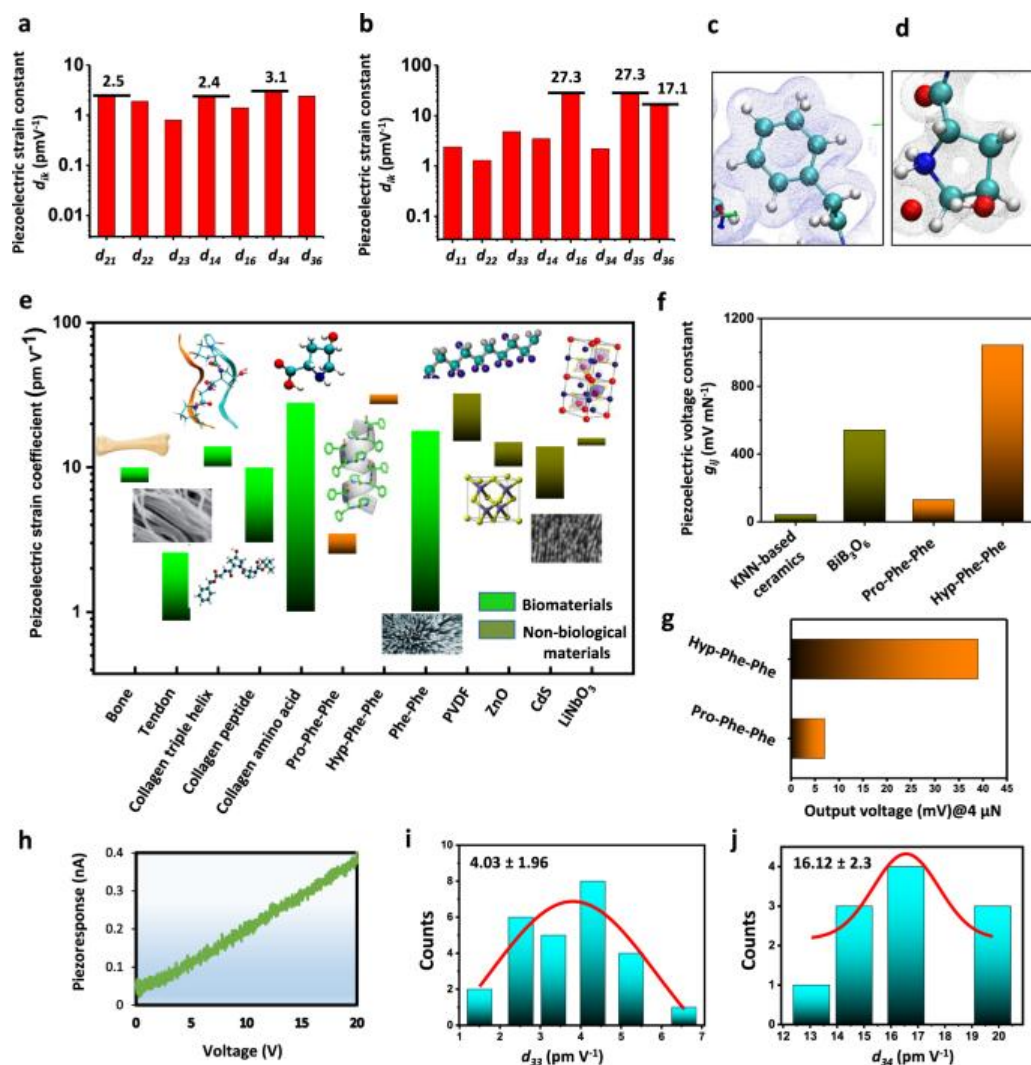
determined by direct Fourier transform analysis using the open source software FiberApp (Supplementary Fig. 3)⁴⁸. This “mechanical periodicity” cannot be observed in the topography channel but is clear in the Young’s modulus channel. Natural collagen exhibits similar lateral periodicity of 67 nm due to gaps in the hierarchical structure of the triple helix⁴⁹.

Piezoelectric response of Pro-Phe-Phe and Hyp-Phe-Phe assemblies

Having verified helical conformation, lateral periodicity and high mechanical robustness similar to collagen, we used DFT to predict the elastic, dielectric and piezoelectric constants of the tripeptides (Fig. 2 and Table 1). Calculations were carried out on the obtained solid-state XRD crystal structures, which contained no waters of crystallization. Full details of the computational methodology can be found in the ‘Methods’ section. The Pro-Phe-Phe and Hyp-Phe-Phe assemblies have very similar predicted dielectric constants ϵ_r , with only a slight increase in the hydroxylated peptide (3.3 vs. 3.1, see Supplementary Table 2). This stems from 25% increase in the ϵ_3 tensor component for Hyp-Phe-Phe, compared to Pro-Phe-Phe (4.0 vs. 3.2). This axis of highest permittivity also gives the highest predicted piezoelectric charge tensor values. The lower shear elastic stiffness values in Hyp-Phe-Phe (Supplementary Table 3) indicate higher shear piezoelectric strain constants and voltage constants for this crystal, as the lower stiffness produces larger ionic displacement under an applied force. Supplementary Tables 4 and 5 show the DFT-computed piezoelectric charge (e), strain (d) and voltage (g) tensors of Pro-Phe-Phe and Hyp-Phe-Phe, respectively. For Pro-Phe-Phe, we observe that low charge tensor components of up to 56 mC/m² results in moderate d_{ij} values of up to 3.1 pm V⁻¹ (Fig. 2a). However, as with most biomaterials¹¹, the low dielectric constants produce significant voltage constants of up to 108 mV m/N (g_{22}). In Hyp-Phe-Phe, hydroxylation lowers the symmetry of the unit cell (monoclinic to triclinic), which increases the number of non-zero piezoelectric constants in each tensor. Hydroxylation also gives a fivefold increase in the highest charge tensor value ($e_{33} = 0.1 \text{ C m}^{-2}$). Due to the increase in e_{ij} values and decrease in c_{ij} values, we notice a significant increase in the magnitude of the predicted piezoelectric strain constants, with $d_{\text{max}} = d_{35} = -27.3 \text{ pm V}^{-1}$ and $d_{33} = 4.8 \text{ pm V}^{-1}$ (Fig. 2b). Looking at the full piezoelectric tensor of the crystals enables more

meaningful comparisons to other piezoelectric materials and identifies possible applications for these crystals. The monoclinic Pro-Phe-Phe crystal has eight finite tensor components, whereas the low-symmetry Hyp-Phe-Phe crystal has 17 components. The most commonly exploited piezoelectric response in devices is the longitudinal d_{33} value (or crystallographic equivalent d_{11} and d_{22}). Both tripeptide crystals have modest longitudinal constants that would see them fit similar applications to aluminium nitride, quartz and zinc oxide (ZnO) as evidenced by the values cited in Supplementary Table 1. The Pro-Phe-Phe crystal shows a narrow range of tensor values, with coefficients in the range 0.8–2.5 pm V⁻¹. Hyp-Phe-Phe has a much wider range of values, varying from 0.1 pm V⁻¹ to the maximum 27.3 pm V⁻¹ (d_{16} and d_{35}). The high predicted shear value and doubling of the longitudinal response in the Hyp-Phe-Phe crystal highlights that simple chemical modifications can induce piezoelectric response in biomaterials that exceeds that of many inorganic crystals (Fig. 2e). The maximum calculated response for Hyp-Phe-Phe is as large as the d_{31} value of poled polyvinylidene difluoride, but is predicted to occur without the application of heat or a large external electric field. Given the similar ϵ_r values for Hyp-Phe-Phe and Pro-Phe-Phe, we predict high voltage constants, on the order of 1 V m/N (Hyp-Phe-Phe, $g_{\max} = g_{16} = 1043$ mV m/N). For comparison (Fig. 2f), (K_{0.5}Na_{0.5})NbO₃ (KNN)-based ceramics have exhibited voltage constants of $g_{33} = 40$ mV m/N³¹. Other studies have reported values of up to 540 mV m/N (g_{33}) for single crystals of BiB₃O₆³². Combining our predicted piezoelectric voltage constants with approximate crystal dimensions, we can estimate single-crystal voltage outputs (Fig. 2g). For example, applying a loading force of 4 μ N⁵⁰ along the two axis of a Pro-Phe-Phe single crystal will give a predicted voltage output of ~7 mV. For Hyp-Phe-Phe single crystal, the calculated voltage output is 39 mV, fivefold higher under similar conditions. The benefit of predicting the full piezoelectric tensor with DFT and screening for individually high-tensor components is that we can design devices and orientate biomolecular crystals and assemblies in a way that maximizes output.

Fig. 2: Piezoelectricity of Pro-Phe-Phe and Hyp-Phe-Phe assemblies.



a, b Calculated piezoelectric strain constants for Pro-Phe-Phe (**a**) and Hyp-Phe-Phe (**b**). Selected values are marked above relevant columns. **c, d** Zoom-in on the electronic structure of the Hyp-Phe-Phe crystal. The π -density of the diphenylalanine motif remains identical across both crystals (**c**) and **d** shows the hydroxylated pyrrolidine structure of the Hyp residue in the Hyp-Phe-Phe crystal. **e** Comparison of piezoelectric strain response of different biological and non-biological materials: collagen piezoelectric response at different length scales¹⁰⁻²⁵⁻⁵³ has been emphasized as compared to that of Pro-Phe-Phe and Hyp-Phe-Phe. **f** The predicted voltage coefficient of Pro-Phe-Phe and Hyp-Phe-Phe in comparison with some currently used inorganic materials. **g** Calculated output voltage upon applied force of 4 μ N. **h–j** Experimental measurement of coefficients using PFM. **h** Linear relationship between the vertical piezoresponse of Hyp-Phe-Phe as measured by the

photodiode system and applied voltage. Statistical distribution of the vertical d_{33} coefficients (i) and shear d_{34} coefficients (j). Additional PFM data are given in Supplementary Figs. 5–16.

Table 1 DFT calculated molecular dipoles and crystal dipoles for each tripeptide, and the corresponding experimentally measured piezoelectric response.

The supramolecular packing modes in the crystal confer the significant d_{33} response for Hyp-Phe-Phe, as applying a force along the 3-axis will align the hydroxylated pyrrolidines and couple to the net dipole in the unit cell. Our DFT and MD molecular models show that by strengthening the H-bonding network, we remodel the aromatic zipper motif and alter the net dipole in the unit cell (Table 1, Supplementary Table 6 and Supplementary Fig. 4) to create more opportunities for charge transfer under stress. We have previously observed that lowering the crystal symmetry lowers the shear elastic constants and allows for more ionic displacement around the unit cell axes, for angles $> 90^\circ$ (in Hyp-Phe-Phe, the angle is 97°)¹⁰. Finally, the binding energy along the 3-axis is slightly larger for Pro-Phe-Phe than for Hyp-Phe-Phe in the unstrained crystals (2.3 eV vs. 2.0 eV, Supplementary Table 7), which suggests that molecular arrangements that can facilitate an increase in intermolecular interactions under stress may create higher piezoelectric response.

To study the hierarchical influence of hydroxylation⁵¹, we compare the current findings on tripeptide crystals and fibres to previous results obtained on Hyp and proline single crystals²⁵. Only very small difference is observed in the predicted stiffness constants between proline and Hyp (24 GPa vs. 28 GPa), with this trend extending to the tripeptide crystals. The lower shear stiffness predicted for Hyp-Phe-Phe results in Young's modulus of 12 GPa, slightly below the value of 14 GPa for Pro-Phe-Phe. Both tripeptides and amino acids show large increase in charge tensor values after hydroxylation and decrease in stiffness constants, despite decrease in the predicted molecular dipole. The net crystal dipoles for both crystals are along the crystallographic b or piezoelectric 2 axis, with absolute values of 2.8 Debye for Pro-Phe-Phe and 1.9 Debye for Hyp-Phe-Phe. The projected dipole moments along each crystal axis

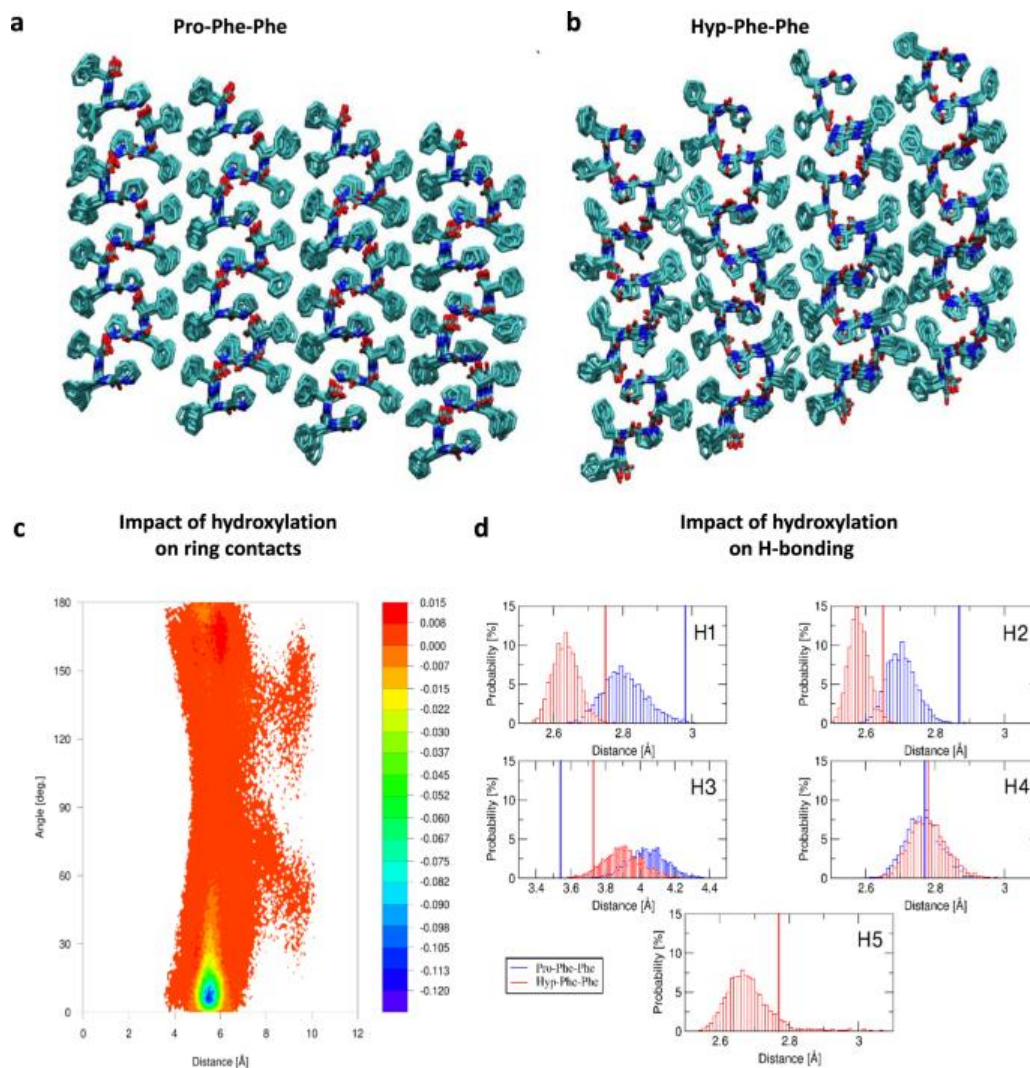
(Supplementary Table 6) show that Pro-Phe-Phe has a unidirectional dipole moment, as it only has a 22 longitudinal response. The lowering of symmetry in Hyp-Phe-Phe gives three longitudinal components, which disperses the dipole moment along all three axes (Supplementary Fig. 4). The trend for piezoelectric strain tensor values in Pro-Phe-Phe and Hyp-Phe-Phe tracks almost exactly as that for proline and Hyp amino acids with an increase in d_{max} from ~ 3 to $\sim 30 \text{ pm V}^{-1}$.

To experimentally validate our predictive modelling, we first employed piezoresponse force microscopy (PFM) to characterize the crystals (Fig. 2h–j and Supplementary Figs. 5–16). Due to the small size of the peptide single crystals, conventional PFM imaging of topography, amplitude, phase, etc., was not possible. The crystals moved during imaging attempts. In line with best practice techniques^{34,52}, we then carried out PFM point measurements where the probe was brought into contact with the single crystal and held stationary while the applied voltage was varied and the piezoresponse recorded. These were used to generate plots similar to Fig. 2h, which were then used to create statistical distributions of the response. The measurements were carried out with the probe stationary relative to the sample and at a low frequency (21 kHz), which minimized artefacts resulting from topographic crosstalk or resonance enhancement of the signal. Stiff probes with a spring constant of 5–6 N m^{-1} were used to mitigate electrostatic and flexoelectric contributions³⁴. All measurements were carried out at 20 °C and 40% relative humidity (RH) ambient laboratory conditions to ensure uniformity in the measurement conditions. Identical point measurements were carried out on both positive and negative controls, to verify the accuracy of the technique and to rule out any instrumental backgrounds or parasitic effects contributing to the signal, as described in detail in Supporting Information section 3. The linear relationship between the piezoresponse as measured by the photodiode system and applied voltage, and also the minimal frequency dependence of output piezoresponse are indicative of a genuine piezoelectric property (Fig. 2h and Supplementary Figs. 13–16). The results revealed the vertical coefficient $d_{33\text{eff}}$ of Pro-Phe-Phe assemblies to be $2.15 \pm 0.86 \text{ pm V}^{-1}$ (Supplementary Fig. 13), which rose to $4.03 \pm 1.96 \text{ pm V}^{-1}$ (Fig. 2i) for Hyp-Phe-Phe. Measuring the shear

piezoelectricity of Hyp-Phe-Phe yielded an effective shear piezoelectric coefficient d_{34}^{eff} of $16.12 \pm 2.3 \text{ pm V}^{-1}$ (Fig. 2j), which is higher than the experimentally measured magnitude of LiNbO_3 (13 pm V^{-1}), ZnO (12 pm V^{-1}), amino acid γ -glycine (10 pm V^{-1}) and protein/peptide biomaterials M13 bacteriophage ($6\text{--}8 \text{ pm V}^{-1}$) and collagen film (1 pm V^{-1})^{10,50,53}.

To further probe the assemblies, we performed MD simulations (Fig. 3, Supplementary Figs. 17–22 and Supplementary Table 8). These simulations are performed on a nanocrystal of each peptide immersed in a large water box to model bulk solvation, as described in the ‘Methods’ section. MD are calculated at constant room temperature and atmospheric pressure at physiological pH of 7.4. The most important finding is that the tightening of the H-bond network in the Hyp variant is associated with increased conformational freedom in the Phe-Phe rings, showing the balance between electrostatic and π – π interactions in the creation of the helical assemblies. Figure 3 shows the computed supramolecular packing in both assemblies with the computed difference map in Fig. 3c comparing the separation vs. contact angle distributions in the Phe-Phe ring contacts for Hyp-Phe-Phe and Pro-Phe-Phe. The angle–distance contour plot makes it possible to identify different conformations between neighbouring phenyl rings, which helps characterize the changes induced by the additional –OH group in the Hyp variant. The difference map is used to highlight these changes. The negative value in the 5–6 Å and small angle region on Fig. 3c show that Pro-Phe-Phe presents larger density of highly ordered π – π contacts. By contrast, the Phe-Phe ring distance is shifted towards larger values in Hyp-Phe-Phe with an overall broadening of the density peaks, illustrating the increased conformational freedom. The evidence for the stability of the zipper for both Pro-Phe-Phe and Hyp-Phe-Phe have been obtained from both MD simulations and crystal structures, which confirm the rigidity and durability of the zipper as a structure-building motif (Supplementary section 4 and Supplementary Fig. 20–23).

Fig. 3: Molecular dynamics (MD) simulations of Pro-Phe-Phe and Hyp-Phe-Phe assemblies.

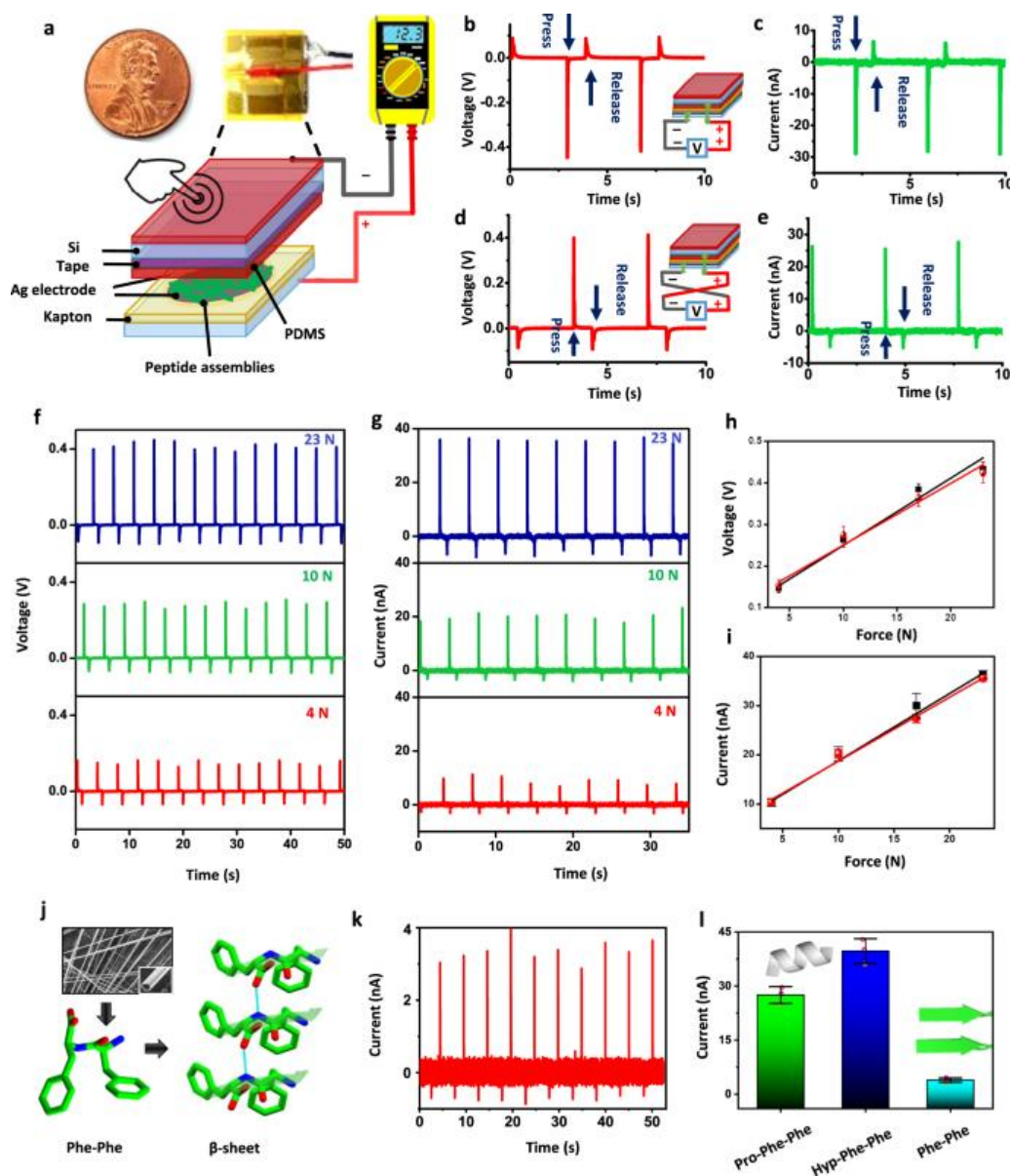


a, b The computed supramolecular packing structure in the assemblies after 0.1 μ s of room temperature dynamics of Pro-Phe-Phe (**a**) and Hyp-Phe-Phe (**b**). The balance between increased H-bonding and more flexible π - π contacts is quantified in the Pro-Phe-Phe vs. Hyp-Phe-Phe difference map in **c**. The distance corresponds to the distance between neighbouring phenyl rings and the angle to the angle between the same two rings, as described in the 'Methods' section. The density is the normalized histogram and is given as a percentage. The 2D histogram is built with a 200×200 matrix. H-bond distributions are plotted in **d**. Additional supporting MD data are provided in Supplementary Figs. 14–19 and Supplementary Table 8.

Characterisation of peptide-based power generator

Finally, to test the potential of the peptide assemblies for energy harvesting and piezoelectric sensing in integrated microdevices, a coin-size power generator was designed and fabricated by tightly sandwiching the tripeptide assembly film between only the two Ag electrodes that were connected to the measuring instrument via copper wires (Fig. 4a and Supplementary Fig. 24). The entire device was firmly laminated with kapton tape to protect against mechanical stress, dust and humidity. When the device was compressed and released, the peptide-based nanogenerator converted the mechanical energy into electricity. Mechanical loads were applied to the generators using a dynamic mechanical test system and the resulting electrical output signal was characterized by measuring the short-circuit current and open-circuit voltage. A periodic compressive force was applied on the power generator and the output performance is shown in Fig. 4b, c. The switching-polarity test showed that the current and voltage signals were reversed when the device connection was switched (Fig. 4d, e)⁵⁴. The switching-polarity test results excluded the errors from the variation of contact resistance or parasitic capacitance and confirmed that the detected electrical signal was truly from the piezoelectric peptide assemblies.

Fig. 4: Characterization of the helical peptide-based nanogenerator.



a Photograph and schematic configuration of coin-sized piezoelectric energy generation measurement set-up utilized as a direct power source with peptide assemblies as the active component. **b, c** Open-circuit voltage (**b**) and short-circuit current (**c**) of piezoelectric energy harvester in the forward connection. **d, e** The generated voltage output (**d**) and current output (**e**) in the reverse connection. **f, g** Variable external load was applied onto the device. The measured open-circuit voltage (**f**) and short-circuit current output (**g**) of Hyp-Phe-Phe under different applied force. **h, i** Linear dependence of the voltage (**h**) and current (**i**) output on the applied force. The black and red lines indicate forward and reverse connection, respectively. **j-l** Comparison of

piezoelectric response of the engineered helical tripeptides with β -sheet forming Phe-Phe peptide assemblies. **j** The self-assembled nanostructures and β -sheet molecular arrangement in the crystal structure of Phe-Phe (CCDC ref. no 16340⁸³). **k** Short circuit current obtained from the generator using Phe-Phe assemblies as the active component upon applied force = 23 N. **l** Comparison of output current of Phe-Phe with helical peptides, Pro-Phe-Phe and Hyp-Phe-Phe. Error bars = SD ($n = 3$).

For Pro-Phe-Phe, under an applied force $F = 55$ N, the output open-circuit voltage (V_{oc}) reached 1.4 V (Supplementary Figs. 25a, c), which is significantly higher than reported peptide and inorganic alternatives (Supplementary Table 9). The corresponding short-circuit current (I_{sc}) was 52 nA (Supplementary Figs. 25b, d), which is significantly higher than the output current obtained from nanogenerators based on M13 bacteriophage virus (6 nA) or fish skin collagen (1.5–20 nA) (Supplementary Table 9). Using the Hyp-Phe-Phe assemblies as the active layer (Fig. 4f, g), similar short-circuit current output (39.3 nA) was achieved when the applied force was only 23 N, half that applied for Pro-Phe-Phe. This validated our theoretical predication of increased piezoelectric response due to simple hydroxylation of the side chain. The corresponding output voltage was 0.45 V. The peak voltage and current increased linearly as a function of the applied force at rates of 15.08 mV N⁻¹ and 1.33 nA N⁻¹, respectively (Fig. 4h, i), demonstrating linear piezoelectric response of the peptide assemblies. Furthermore, the high mechanical rigidity suggests that power generation can be sustained under a cyclic force (17 N) (Supplementary Fig. 26) and the output voltage showed no degradation over 1000 press/release cycles for more than 60 min, indicating the high durability of the peptide-based devices. Finally, the voltage output characteristic was measured with different external load resistors connected to a nanogenerator, while it was repeatedly deformed, and the result is shown in Supplementary Fig. 27. The output voltage continually rises with the growth of load resistance, demonstrating the electrical characteristics of the power device and illustrating its potential for practical applications.

We expect that the device performance can be further increased in the future by fabricating highly ordered aligned arrays⁴², which will allow to scale up our

peptide-based piezoelectric devices to generate a higher energy output. To further understand the relation between atomic level structural organization and macro-scale piezoelectricity, we fabricated a control device using the well-established β -sheet forming dipeptide, Phe-Phe (Fig. 4j and Supplementary Figs. 28 and 29). Under the same applied force, $F = 23$ N, the maximum output open-circuit voltage and short-circuit current was only 0.14 V (Supplementary Fig. 29a, b) and 3.9 nA (Fig. 4k), respectively. Although current and voltage output increased linearly with mechanical force (Supplementary Fig. 29c, d), the value was much lower compared to the helical peptides even at the highest applied force (Fig. 4l). The significantly decreased performance of the analogous aromatic dipeptide under a similar applied force highlights how differences in the structural organization at the atomic level can bear a dramatic effect on biomaterial piezoelectricity.

Structural component, molecular organization and piezoelectric response

Currently, the piezoelectricity of biomaterials is not fully understood at the molecular level. The hierarchical structural organization of biomaterials is not included in the classical piezoelectric models, leading to discrepancies between their predictions and experimental results⁵⁵. There is emerging evidence that the piezoelectric response of biomaterials profoundly depends on the atomic level structure and self-assembled hierarchical organization, as well as on the amplitude and sign of the dipoles of the constituent amino acid residues. Both collagen and its tripeptide minimalistic analogues Pro-Phe-Phe and Hyp-Phe-Phe exhibit helical structures. Moreover, the shortest repeating unit of collagen also displays a molecular arrangement and symmetry similar to that of the studied tripeptides⁵⁶. The Phe groups have been assumed to facilitate aromatic molecular orbital overlap in the underlying parent peptide, potentially leading to electron delocalization and generation of a significant band gap²⁸. Thus, previous molecular design incorporated aromatic Phe residues in helical peptide sequences in order to engineer electron transport properties in the resulting assembled structures. This is consistent with the lower piezoelectric response of the Hyp-Leu-Phe peptides, which retains the helical organization in the crystal but possesses reduced aromaticity (Supplementary section 6). At the same time, among the collagen amino acids, Hyp showed the highest piezoelectric response in a single-crystal form²⁵. Our

molecular models show that hydroxylation significantly increases the crystal polarizability under stress. Thus, Hyp-Phe-Phe satisfies all the specific requirement of high piezo sensitivity in terms of structure and interactions, thereby exhibiting the highest piezoelectric response among the studied natural short peptides.

Exploring the potential of renewable, sustainable and green energy sources to replace fossil fuels is one of the most significant and urgent challenges in energy research. The piezoelectric effect in proteins is an intriguing phenomenon that can potentially allow a better interface between the semiconductor and biological worlds. Molecular engineering of peptide piezoelectricity is critical not only to understand the molecular basis of piezoelectricity in biomaterials, but also to unravel the core recognition motif for modular design of short peptides with a predictable high piezoelectric response. Here we fabricated a simple biopiezoelectric device made from collagen-mimicking ultra-short peptide sequences that could achieve high current and voltage output, similar to that obtained using nanogenerators comprising inorganic materials or organic polymers. We found common helical molecular organization in the packing of collagen and our designed short peptides, which can explain their high piezoelectricity. A significantly enhanced energy output can be obtained by simple replacement of one constituent with another of higher polarizability (in our case, C-H $\rightarrow$ C-OH on a pyrrolidine ring). This engineered higher response to applied strain emphasizes the importance of incorporating polar building units in piezoelectric biomaterials. Moreover, sequence mutation by replacing Phe for Leu noticeably decreases the piezoelectric response, although having similar molecular organization emphasizing the significant role of aromatic groups. Our demonstration of collagen-level piezoelectricity in rationally designed ultra-short peptides reinforces the value of prediction-led molecular engineering of piezoelectricity to accelerate the deployment of peptides in nanotechnology applications.

Methods

Preparation of peptide assemblies

The peptides were purchased from DGpeptides Co., Ltd (Hangzhou City, Zhejiang Province, China) and purified to >95%, and their identity was confirmed by mass spectrometry. All peptides were stored at -20°C . For assembly, peptides were dissolved in phosphate buffer at pH 7.4 to a final concentration of 1.5 mg ml^{-1} by heating at 90°C and vigorous vortexing for 2 min. The peptide solutions were then incubated at 18°C for 2 weeks with frequent shaking before examination.

FTIR spectroscopy

A $30\text{ }\mu\text{l}$ aliquot of the peptide solution was deposited onto disposable KBr infrared sample cards (Sigma-Aldrich, Rehovot, Israel), which were then allowed to dry under open air and followed by vacuum. The samples were saturated twice with $30\text{ }\mu\text{l}$ of D_2O and vacuum dried. FTIR spectra were collected using a nitrogen-purged Nicolet Nexus 470 FTIR spectrometer (Nicolet, Offenbach, Germany) equipped with a deuterated triglycine sulfate detector. Measurements were performed at 4 cm^{-1} resolution and obtained values were averaged over 32 scans. The absorbance maxima values were determined using an OMNIC analysis programme (Thermo Scientific Nicolet). The background was subtracted using a control spectrum.

CD spectroscopy

CD spectra were collected using a Chirascan spectrometer (Applied Photophysics, Leatherhead, UK) fitted with a Peltier temperature controller set to 25°C , using quartz cuvettes with an optical path length of 0.1 mm (Hellma Analytics, Müllheim, Germany). Absorbance of the sample was kept within the linear range of the instrument during measurement. Data acquisition was performed in steps of 1 nm at a wavelength range of $190\text{--}240\text{ nm}$ with a spectral bandwidth of 1.0 nm and an averaging time of 3 s . The spectrum of each sample was collected three times and averaged. Baseline was similarly recorded for phosphate buffer and subtracted from the samples spectra. Data processing was performed using Pro-Data Viewer software (Applied Photophysics, Leatherhead, UK).

Transmission electron microscopy

A 5 μl aliquot of the peptide solution was placed on 400 mesh (theoretical square size of $\sim 64\text{ }\mu\text{m}$) copper grids. After 1 min, excess fluids were removed. For negative staining, the grid was stained with 2% uranyl acetate in water and after 2 min, excess fluids were removed from the grid. TEM micrographs were recorded using a JEM-1400 (JEOL, Tokyo, Japan) operating at 80 kV.

Quantitative nanomechanical AFM

Hyp-Phe-Phe fibres were formed by dissolving the peptide (1.5 mg ml^{-1}) in Milli-Q[®] water at $90\text{ }^{\circ}\text{C}$ for a minimum of 3 h to ensure the complete solvation of the monomeric peptide. During the course of the heating, the mixture was vortexed vigorously once every hour. After heating, the samples were cooled slowly and self-assembly was allowed to proceed over a period of 1 week at room temperature. All QNM-AFM experiments were performed in peakforce mode on a Multimode 8 AFM (Bruker) and a Nanoscope V controller (Bruker). All imaging was performed in air using RTESPA 525 cantilevers with a spring constant of $\sim 200\text{ N m}^{-1}$ and a resonant frequency of 525 kHz were used.

Density functional theory

Periodic DFT calculations⁵⁷ were performed on the single crystals using the VASP⁵⁸ code. Electronic structures are calculated using the Perdew–Burke–Ernzerh (PBE) functional⁵⁹, projector augmented wave (PAW) pseudopotentials⁶⁰ with a plane wave cut-off of 1000 eV, and k -point sampling of $4 \times 4 \times 4$. A finite differences method was used to calculate the stiffness tensor, with each atom displaced in each direction by $\pm 0.01\text{ }\text{\AA}$, using a plane wave cut-off of 1000 eV, and k -point sampling of $2 \times 2 \times 2$. Piezoelectric strain constants and dielectric tensors were calculated using density functional perturbation theory⁶¹ with a plane wave cut-off of 1000 eV, and k -point sampling of $2 \times 2 \times 2$. Binding energies were calculated between the two molecules in each unit cell using Grimme-D3 dispersion corrections⁶².

Single-molecule dipoles were calculated from gas-phase molecule electronic structures solved using the Gaussian16 software package⁶³, with the hybrid HF-DFT B3LYP functional^{64,65} and 6-311 + +g** basis set. Crystal dipole moments were calculated using periodic DFT⁵⁷ with the CP2K⁶⁶ code.

Electronic structures are calculated using the PBE functional⁵⁹ and PAW pseudopotentials⁶⁰ with a combination of plane wave and Gaussian basis sets⁶⁷⁻⁶⁸. The combination is performed on a multigrid with five levels of decreasing resolution. The cut-off of the finest grid was 1300 Ry (~17687 eV) and the cut-off controlling the grid at which a Gaussian is mapped was 70 Ry (~952 eV). The basis set was a double-zeta with polarization orbitals⁶⁹. The electronic cycle was performed with the orbital transformation⁷⁰ (OT) method, which uses the derivative of the wave function to reach the minimum of energy. The combination of a localized basis set with OT makes it possible to obtain the crystal dipole moment using the Berry phase approach. A supercell of $3 \times 2 \times 2$ unit cell units was used and both the lattice parameters and the ions were free to move during the geometry optimization. The space group symmetry is imposed through a homemade patch to CP2K.

Molecular dynamics

MD simulations were performed with the Gromacs 2018.4 package. All bonds involving a hydrogen atom were constrained using the LINCS⁷¹ algorithm, which allowed the use of an integration timestep of 2 fs in the leapfrog integrator⁷², and coordinates were saved every 10 ps. Long-range electrostatics were treated by the Particle Mesh Ewald method⁷³.

All systems were minimized for 100,000 steps and heated progressively from 0 to 300 K for a total 3 ns at constant volume, followed by 100 ns of equilibration at constant pressure and temperature. During equilibration, the reference temperature was set at 300 K with a time constant of 1 ps and the reference pressure was set at 1 bar with a time constant of 5 ps, using the Berendsen⁷⁴ thermostat and barostat, respectively. The subsequent production phase of dynamics was carried out in the constant pressure and temperature NPT (isothermal–isobaric) ensemble, with the reference pressure set at 1 bar with a time constant of 5 ps using the highly accurate Parrinello–Rahman barostat⁷⁵, and all molecules were coupled separately in groups to an external heat bath set at 300 K with a coupling time constant of 1 ps using the velocity-rescale thermostat⁷⁶. The pH is set by the protonation state of the amino acids at the physiological pH of 7.4 used in the crystallization experiments.

VMD 1.9.3 software was used to generate supercells from the crystal unit cell⁷⁷. Cells were replicated $14 \times 10 \times 6$ times in the x , y and z directions, respectively. Supercells of $\sim 7.1 \times 9.5 \times 12$ nm in dimension were then placed in large water boxes and subjected to room temperature constant-pressure MD using the GROMACS code with the CHARMM 36 m forcefield and TIP3P water⁷⁸. Hyp is not included in the CHARMM36m forcefield, so we used the Swissparam server to generate its parameters⁷⁹. Structures were heated to room temperature from 0 K over 5 ns of constant volume dynamics and then subjected to 100 ns of dynamics at constant pressure. In the core of the supercells, hydrogen bond statistics were measured across >10,000 structures during the final 50 ns of dynamics using VMD tools and in-house python scripts, together with contact distances between the stacked phenyl rings and between neighbouring helical structures for T-stacking rings. The distance between neighbouring rings is taken as the distance between their centres of mass as estimated by the midpoint between the γ -carbon and the two carbon atoms at meta positions on the phenyl ring. These three carbons are also used to define the plane of the ring, with the angle between two rings formed by the normal to each ring plane.

To validate the use of the CHARMM 36 m forcefield, designed for globular proteins in solution, and the set of parameters provided by SwissParam to model tripeptide crystals, the stability of the peptide crystal structures was tested using CP2K⁶⁵ with the supercell approximation. For both Pro-Phe-Phe and Hyp-Phe-Phe tripeptides, the supercell used was $7 \times 3 \times 2$ (the numbers indicate the number of replicas of the unit cell along the corresponding lattice vector). A cut-off of 1.2 nm, the same that was used for the MD simulations, was used for intermolecular interactions and the Ewald sum was used for long-range electrostatic interactions.

The unit cell space group and translation symmetries are conserved in the DFT calculations used to compute the electromechanical properties of the single crystals. They are not conserved in the MD simulations, as the crystal supercell or block is immersed in a large box of pre-equilibrated bulk water. These MD simulations were used to monitor the evolution of the supramolecular π - π and H-bond contacts in the tripeptide assemblies in the central region of

the block, to obtain time average values and error bars for the contacts identified in the starting X-ray structure.

Fabrication of peptide-based power generator

Two $0.7 \times 0.7 \text{ cm}^2$ Ag layers were deposited on two $1.2 \times 1.2 \text{ cm}^2$ silicon substrates that served as the top electrode and the bottom electrode. The smooth surface of a Kapton tape was first coated with a polydimethylsiloxane (PDMS) layer of thickness 0.40 mm. A strip of double-sided tape was then attached to the top surface of PDMS. A $0.7 \times 0.7 \text{ cm}^2$ hole was cut through the Kapton/PDMS/double-sided tape structure. The Kapton tape was attached to one silicon substrate with the Ag electrode exposed to the hole. The hole was then filled densely with the Phe-Phe, Pro-Phe-Phe and Hyp-Phe-Phe peptide assemblies, respectively. The other silicon substrate sputtered with silver film was then attached to the double-sided tape to complete the device fabrication without leaving any gap in the nanogenerator. To prevent cracking of the substrate due to the impact force from the linear motor, the top substrate was drop-coated with a PDMS damping layer. Two copper wires were connected to the silver electrodes using carbon ink (JELCON CH-8 MOD2) to complete the device fabrication. The stacking pattern of layers of the device is completely different from triboelectric-based nanogenerators⁸⁰⁻⁸¹.

Characterization of the power generator

The peptide-based power generator was vertically fixed onto a stainless-steel plate, which was mounted on a precision linear slide stage. A linear motor (E1100-RS-HC type with Force Control, LinMot) was used to periodically press the power generator. The outputs of the generator were recorded using a low-noise voltage preamplifier (Stanford SR560). The generator and measuring instruments were placed in a Faraday cage to avoid interference from the environment, and the linear motor was placed outside of the cage.

Crystal preparation and data collection

Crystals used for data collection were grown using the vapour diffusion method. The dry peptide was first dissolved in water, at a concentration of

5 mg/ml. Then, 50 μ l was deposited into a series of 8 $\times$ 40 mm vessels. Each tube was sealed with Parafilm®, in which a single small hole was pricked using a needle. The samples were placed inside a larger vessel filled with 2 ml of acetonitrile. The systems were ultimately capped and incubated at 18 °C for several days. Needle-like crystals grew within 10–12 days. For data collection, crystals were coated in paratone oil (Hampton Research), mounted on a MiTeGen cryo-loop and flash frozen in liquid nitrogen. Diffraction data were collected at 100 K on a Rigaku XtaLab^{Pro} with a Dectris Pilatus R 200K-A detector using Mo radiation λ = 0.71073 Å.

Processing and structural refinement of crystal data

The diffraction data were processed using CrysAlisPro 1.171.39.22a. Structure was solved by direct methods in SHELXT-2014/5⁸². The refinements were performed with SHELXL-2016/4 and weighted full-matrix least-squares against $|F|$ using all data. Atoms were refined independently and anisotropically, with the exception of hydrogen atoms, which were placed in calculated positions and refined in a riding mode. Crystal data collection and refinement parameters are shown in Supplementary Table 10, and the complete data can be found in the cif file as supplementary information. The crystallographic data have been deposited in the CCDC with no. 2008471 for Hyp-Leu-Phe.

MAY 21, 2025

OpenAI recruits legendary iPhone designer Jony Ive to work on AI hardware in \$6.5B deal

by MATT O'BRIEN and MICHAEL LIEDTKE edited by [Andrew Zinin](#)



Jony Ive attend The Metropolitan Museum of Art's Costume Institute benefit gala celebrating the opening of the "Superfine: Tailoring Black Style" exhibition on Monday, May 5, 2025, in New York. Credit: Photo by Evan Agostini/Invision/AP, File
OpenAI has recruited Jony Ive, the designer behind Apple's iPhone, to lead a new hardware project for the artificial intelligence company that makes ChatGPT.

OpenAI said it is acquiring io Products, a product and engineering company co-founded by Ive, in a deal valued at nearly \$6.5 billion.

Ive became renowned for a meticulous design aesthetic that shaped the cultural zeitgeist during a 27-year career at Apple, which he left in 2019. He did his most influential work after

Apple co-founder Steve Jobs returned to run the company in 1997, where the two forged a partnership that would hatch a succession of game-changing products like the iPhone.

The new OpenAI deal now thrusts Ive at the vanguard of AI—a technology driving the biggest industry shift since the iPhone's arrival.

The company hasn't said exactly what product they will be making but expect "physical AI embodiments" that bring generative AI chatbot technology out of computer screens into another form, such as through a car, humanoid robot or the AI-powered glasses being developed by competitors Google and Meta, said Gartner analyst Chirag Dekate, adding that it is too early to know for sure.

OpenAI said its CEO Sam Altman had been "quietly" collaborating since 2023 with Ive and his design firm, LoveFrom.

In a joint letter posted on OpenAI's website Wednesday, Ive and Altman said it "became clear that our ambitions to develop, engineer and manufacture a new family of products demanded an entirely new company."

That's when Ive co-founded io, which was incorporated in Delaware in September 2023 and registered in California in April 2024, according to state records. OpenAI said it already owns a 23% stake in io from a prior collaborative agreement signed late last year. It says it will now pay \$5 billion in equity for the acquisition.

OpenAI said Ive will not become an OpenAI employee and LoveFrom will remain independent but "will assume deep design and creative responsibilities across OpenAI and io." Both OpenAI and Ive's design firm are based in San Francisco.

Leading the new io division for OpenAI will be longtime executive Peter Welinder, who led robotics research in the startup's early years and more recently has been vice president of its "new product explorations" team that delves into hardware, robotics and other early stage research.

Altman, 40, can only hope his still-blossoming partnership with the 58-year-old designer, works out as well as the mind-meld between Jobs and Ive.

When he started his own firm, Ive derived the LoveFrom name from Jobs' observation that one way to hail humanity is by "making something with a great deal of care and love."

Ive also chose to base LoveForm in a historic part of San Francisco, located just near bars and cafes that were once frequented by such Beat Generation luminaries as "On The Road" author Jack Kerouac and "Howl" author Allen Ginsberg.

OpenAI is headquartered about two miles away. Founded nearly a decade ago as a nonprofit research laboratory dedicated to safely building better-than-human AI for humanity's benefit, it remains controlled by a nonprofit board of directors even as Altman, its co-founder, has increasingly pushed it toward commercializing ChatGPT and its other

inventions. It's not clear if Altman's collaboration with Ive began before or after Altman's short-lived ouster in November 2023, months after io's Delaware incorporation but before the new business was set up in San Francisco.

Altman earlier this month said OpenAI was abandoning plans to drop its nonprofit governance structure but is pursuing a plan to make changes that would make it easier to access capital and pursue mergers and acquisitions "and other normal things companies would do."

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MAY 22, 2025

The iconic designs of Jony Ive

edited by [Andrew Zinin](#)



Apple's digital music player, iPod, is displayed after its introduction by Apple Computer Inc. chief executive officer Steve Jobs during a news conference, Oct. 23, 2001, in Cupertino, Calif. Credit: AP Photo/Julie Jacobson, File

Jony Ive is renowned for crafting a meticulous product design aesthetic that shaped the tech cultural zeitgeist during a 27-year career at Apple.

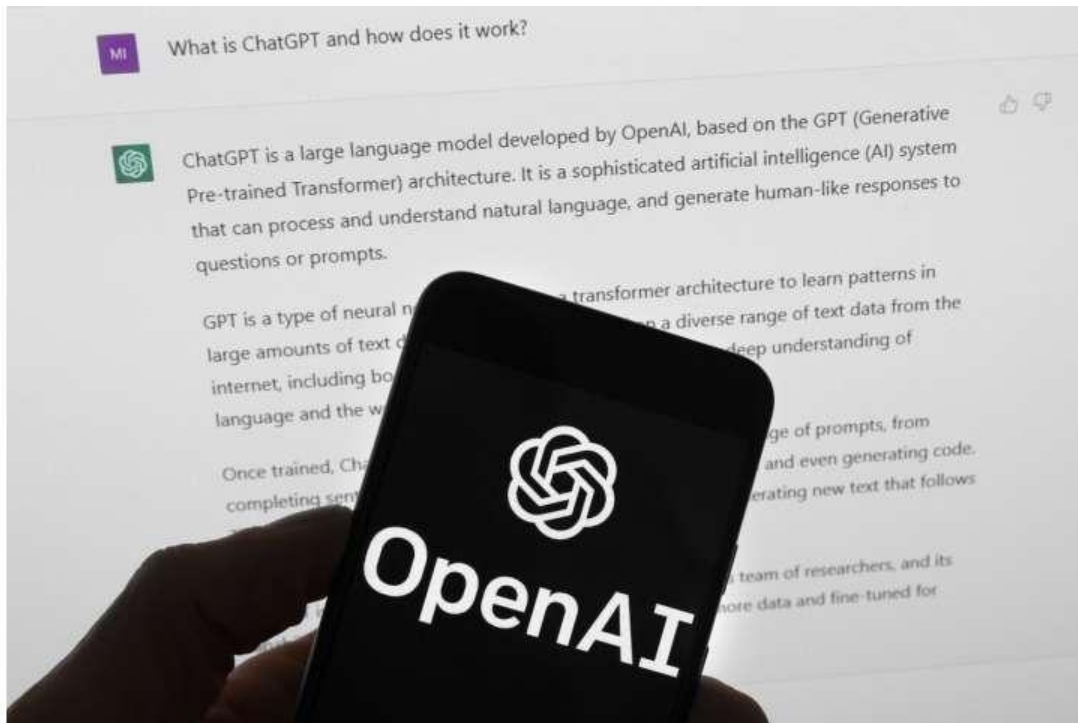
He did his most influential work after Apple co-founder Steve Jobs returned to run the company in 1997, where the two forged a partnership that would hatch a succession of game-changing products like the iPhone in 2007. Ive ultimately left the company in 2019.

Ive's name was thrust [back into the spotlight](#) on Wednesday when ChatGPT maker OpenAI recruited him and his [design](#) firm, LoveFrom, to lead a new hardware project.

But OpenAI CEO Sam Altman can only hope this still-blossoming [partnership](#) works out as well as the mind-meld between former Apple CEO Steve Jobs and Ive.

Ive became the paintbrush that Jobs used to bring his visions to life. The London-born Ive became the voice of Apple's effort to blend technological wizardry with sleek elegance. The company's TV commercials and product announcements were renowned for Ive discussing the intricacies of his designs [in British-accented voiceovers spoken in a hushed, almost reverential tone](#).

After Jobs died in 2011, Ive continued carry the torch for his late boss while still striving to create products that were as aesthetically mesmerizing as they were ground breaking. Ive led design work on the Mac, iPod, iPhone, iPad and Apple Watch.



• The OpenAI logo is seen on a mobile phone in front of a computer screen which displays output from ChatGPT, March 21, 2023, in Boston. Credit: AP Photo/Michael Dwyer, File



- Apple CEO Steve Jobs holds up an Apple iPhone at the MacWorld Conference in San Francisco, in this Jan. 9, 2007 file photo.. Credit: AP Photo/Paul Sakuma, File



- Jony Ive attend The Metropolitan Museum of Art's Costume Institute benefit gala celebrating the opening of the "Superfine: Tailoring Black Style" exhibition on Monday, May 5, 2025, in New York. Credit: Photo by Evan Agostini/Invision/AP, File



• This March 19, 1999 file photo shows Jonathan Ive, left, Apple Computer's vice president of design, and Jon Rubinstein, Apple's senior vice president of engineering, posing behind five iMac personal computers at Apple headquarters in Cupertino, Calif. Credit: AP Photo/Susan Ragan, file



• Steve Jobs, Founder and acting CEO of Apple Computer Inc., holds up one of the company's new consumer laptops called "iBook" after his keynote address at the

Macworld Expo in New York, Wednesday July 21, 1999. Credit: AP Photo/Bebeto Matthews, File



In this Monday, June 3, 2019 file photo, Apple CEO Tim Cook, left, and chief design officer Jonathan Ive look at the Mac Pro in the display room at the Apple Worldwide Developers Conference in San Jose, Calif. Credit: AP Photo/Jeff Chiu, File



The OpenAI logo is seen on a mobile phone in front of a computer screen which displays output from ChatGPT, March 21, 2023, in Boston. Credit: AP Photo/Michael Dwyer, File



- Apple CEO Steve Jobs holds up an Apple iPhone at the MacWorld Conference in San Francisco, in this Jan. 9, 2007 file photo.. Credit: AP Photo/Paul Sakuma, File

When he started LoveFrom, Ive derived the name from something Jobs once said about hailing humanity by "making something with a great deal of care and love." It's worked with brands like Airbnb, Ferrari and Moncler and created the coronation emblem for King Charles III.

He also chose to base LoveForm in San Francisco's historic Jackson Square, located near bars and cafes that were once frequented by Beat Generation luminaries such as "On The Road" author Jack Kerouac and "Howl" author Allen Ginsberg.

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MAY 22, 2025

A rule-breaking, colorful silicone that can conduct electricity

by [University of Michigan](#) edited by [Stephanie Baum](#), reviewed by [Robert Egan](#)



Test tubes containing the new silicone copolymers, separated by chain length, from long to short provide visual evidence of the varying band gap in the new semiconductor silicone. Shining a UV light creates a rainbow of beakers as the longer chain lengths shift towards the red end of the electromagnetic spectrum, requiring less energy to absorb and emit light at lower energies. Credit: Zijing (Jackie) Zhang

A newly discovered silicone variant is a semiconductor, University of Michigan researchers have discovered—upending assumptions that the material class is exclusively insulating.

"The material opens up the opportunity for new types of flat-panel displays, flexible photovoltaics, wearable sensors or even clothing that can display different patterns or images," said Richard Laine, U-M professor of materials science and engineering and macromolecular science and engineering and corresponding author of the study recently [published](#) in *Macromolecular Rapid Communications*.

Silicone oils and rubbers—polysiloxanes and silsesquioxanes—are traditionally insulating materials, meaning they resist the flow of electricity or heat. Their water-resistant properties make them useful in biomedical devices, sealants, electronic coatings and more.

Meanwhile, conventional semiconductors are typically rigid. Semiconducting [silicone](#) has the potential to enable the flexible electronics Laine described as well as silicone that comes in a variety of colors.

On a [molecular level](#), silicones are made up of a backbone of alternating silicon and [oxygen atoms](#) (Si–O–Si) with organic (carbon-based) groups attached to the silicon. Various 3D formations of polymer chains arise as they connect to one another, known as cross-linking, which alter the material's physical properties like strength or solubility.

While studying different cross-linking structures in silicone, the research team stumbled upon the potential for [electrical conductivity](#) in a copolymer, which is a [polymer chain](#) containing two different types of repeating units—cage-structured and then linear silicones, in this case.

The possibility for conductivity arises from the way electrons can move across Si–O–Si bonds with overlapping orbitals. Semiconductors have two main states: the ground state, which doesn't conduct electricity, and a conducting state, which does. The conducting state, also known as an excited state, occurs when some electrons jump up to the next electron orbital, which is connected across the material like a metal.

Typically, Si–O–Si bond angles don't allow for that connection. At 110°, they are a long way from a 180° straight line. But in the silicone copolymer the team discovered, these bonds started out at 140° in the [ground state](#)—and they stretched to 150° in the excited state. This was enough to create a highway for electrical charge to flow.

"This allows an unexpected interaction between electrons across multiple bonds, including Si–O–Si bonds in these copolymers," Laine said. "The longer the chain length, the easier it is for electrons to travel longer distances, reducing the energy needed to absorb light and then emit it at lower energies."

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The semiconducting properties of the silicone copolymers also enable its spectrum of colors. Electrons jump between the ground and excited states by absorbing and emitting photons, or particles of light. The [light emission](#) depends on the length of the copolymer chain, which Laine's team can control. Longer chain lengths mean smaller jumps and lower energy photons, giving the silicone a red tint. Shorter chains require bigger jumps from the electrons, so they emit higher energy light toward the blue end of the spectrum.

To demonstrate the connection between chain length and light absorption and emission, the researchers separated copolymers with different chain lengths and arranged them in test

tubes from long to short. Shining a UV light on the tubes creates a full rainbow as each absorbs and emits the light at different energies.

The colorful array based on copolymer chain length is particularly unique, because up to this point, silicones have only been known to be transparent or white because their insulating properties make them unable to absorb much light.

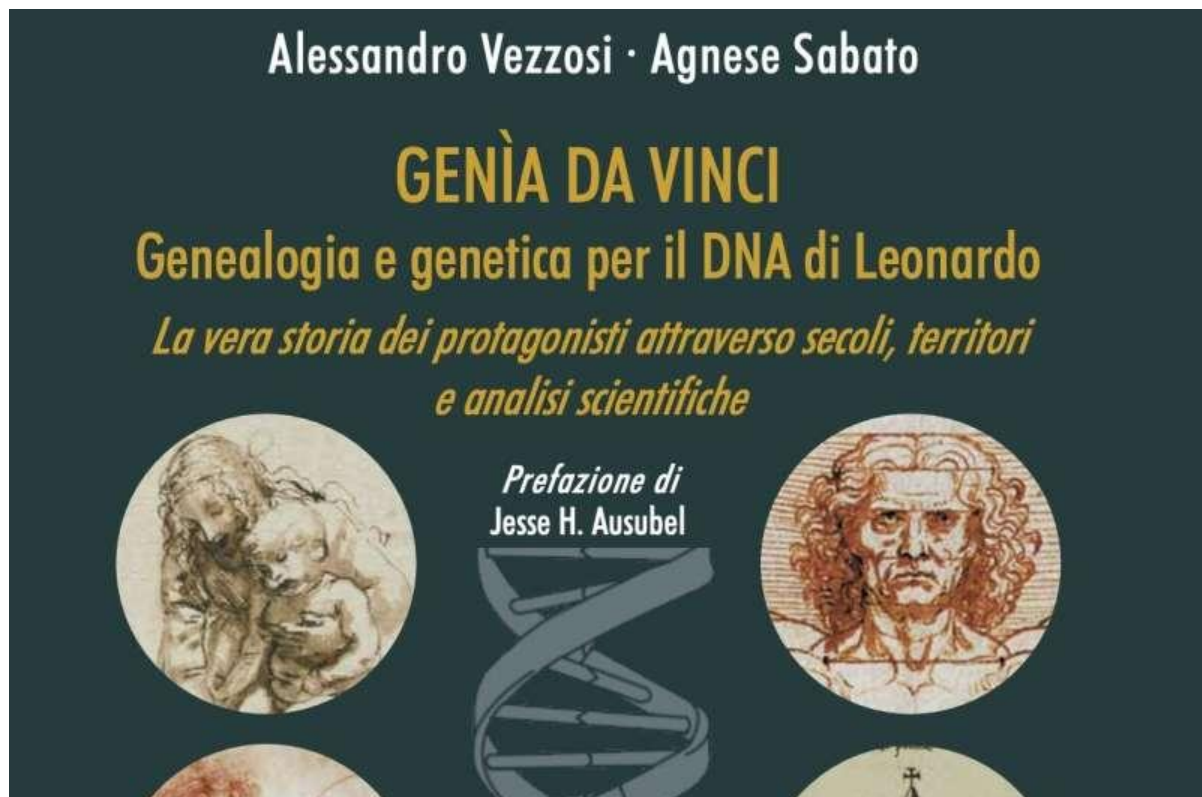
"We're taking a material everyone thought was electrically inert and giving it a new life—one that could power the next generation of soft, flexible electronics," said Zijing (Jackie) Zhang, U-M doctoral student of materials science and engineering and lead author of the study.

More information: Zijing Zhang et al, σ – σ^* conjugation Across Si–O–Si Bonds, *Macromolecular Rapid Communications* (2025). DOI: [10.1002/marc.202500081](https://doi.org/10.1002/marc.202500081)
Journal information: [Macromolecular Rapid Communications](#)
Provided by [University of Michigan](#)

MAY 22, 2025

Leonardo da Vinci's DNA: Researchers confirm Y chromosome shared by six living family descendants

by Leonardo da Vinci DNA Project dited by [Gaby Clark](#), reviewed by [Robert Egan](#)



"Genia Da Vinci," by Alessandro Vezzosi and Agnese Sabato. Credit: Angelo Pontecorboli Editors

For more than five centuries, Leonardo Da Vinci has been celebrated as a visionary artist, scientist, and inventor, known for his extraordinary talent and groundbreaking experiments. Today, an international collaboration known as the Leonardo DNA Project is closer than ever to uncovering the biological secrets of the greatest genius of the Renaissance.

In their new [book](#) "Genia Da Vinci. Genealogy and Genetics for Leonardo's DNA," published by Angelo Pontecorboli Editore, experts Alessandro Vezzosi and Agnese Sabato of the Leonardo Da Vinci Heritage Association, Vinci, present findings from 30 years of genealogical research that have culminated in groundbreaking insights.

The book documents an elaborate family tree tracing back to 1331, spanning 21 generations and involving more than 400 individuals. The work lays the groundwork for one of the most advanced historical-genetic investigations ever undertaken: the reconstruction of Leonardo's genetic profile.

Through meticulous analysis of sources and [archival documents](#)—now published in the book—Vezzosi and Sabato successfully reconstructed branches of the family to which Leonardo belonged, including the identification of 15 direct male-line descendants related genealogically to both Leonardo's father and to his half-brother, Domenico Benedetto.

This allowed David Caramelli, the Leonardo DNA Project's coordinator for anthropological and molecular aspects, and Director of the Department of Biology at the University of Florence, along with forensic anthropologist Elena Pilli, to subject six of these descendants to DNA testing. Their analysis revealed that segments of the Y chromosome—used for individual identification—matched across these men, confirming the genetic continuity of the Da Vinci male line, at least since the 15th generation.

The authors also confirmed the existence of a Da Vinci family tomb in the Church of Santa Croce in Vinci, currently under [archaeological excavation](#) in collaboration with the University of Florence. This may be the burial site of Leonardo's grandfather Antonio, uncle Francesco, and several half-brothers—Antonio, Pandolfo, and Giovanni.

The excavation leaders, University of Florence anthropologists Alessandro Riga and Luca Bachechi, recovered bone fragments, some of which have been radiocarbon dated. One specimen, consistent in age with Leonardo's presumed relatives, has undergone paleogenomic analysis. Preliminary results from Caramelli and molecular anthropologist Martina Lari indicate the individual was male.

"Further detailed analyses are necessary to determine whether the DNA extracted is sufficiently preserved," says Caramelli, who is also President of the University Museum System. "Based on the results, we can proceed with analysis of Y chromosome fragments for comparison with current descendants."

If the Y chromosome of the living descendants is also found in the older remains in the Vinci church tombs, it would support the accuracy of paternity records, the historical reconstruction of the lineage established through death registers, and would allow for a more in-depth examination of the biological material attributed to Leonardo, as well as traces left on his original manuscripts or other works, potentially leading to the reconstruction of his DNA.

Launched in 2016 and coordinated from The Rockefeller University, New York, the Leonardo da Vinci DNA Project involves the J. Craig Venter Institute of California, the University of Florence and other institutions, with support from the Achelis and Bodman Foundation (New York), the Richard Lounsbery Foundation (Washington, D.C.), and other public and private partners.

The team's scientific starting point was a hypothesis as simple as it is crucial: to trace the Y chromosome, which is passed unchanged from father to son.

"Our goal in reconstructing the Da Vinci family's lineage up to the present day, while also preserving and valuing the places connected to Leonardo, is to enable scientific research on his DNA," says Vezzosi. "Through the recovery of Leonardo's DNA, we hope to understand the biological roots of his extraordinary visual acuity, creativity, and possibly even aspects of his health and causes of death."

"Even a tiny fingerprint on a page could contain cells to sequence," says Jesse H. Ausubel of The Rockefeller University and director of the project. "21st-century biology is moving the boundary between the unknowable and the unknown. Soon we may gain information about Leonardo and other historical figures once believed lost forever."

Surprising revelations

The book's revelations extend beyond genetics. In 21 chapters, it takes readers on a rigorous and fascinating journey through genealogy, history, and geography to rediscover the environment that shaped Leonardo.

Through analysis of ancient land registries, the authors identified seven Da Vinci family homes in Vinci's village and castle, as well as two properties owned by Leonardo himself, inherited from his uncle Francesco and contested in a long dispute with his half-brothers.

The authors devote special focus to two key figures in Leonardo's life: His paternal grandfather Antonio—not merely a farmer but a merchant who traveled between Catalan Spain and Morocco—and Leonardo's mother, Caterina. Through careful examination of existing research, sources, and archives, a clearer, non-romanticized picture of Caterina emerges. Increasingly plausible is her identification as a slave in the service of wealthy banker Vanni di Niccolò di ser Vanni. A series of wills and donation records from 1449 onward document the relationship between Vanni and his executor, the young notary ser Piero, Leonardo's father.

A 'Unicorn Dragon' ... by Leonardo?

Among the most intriguing revelations: The authors publish for the first time a study hypothesizing that a mysterious charcoal drawing of rare expressive intensity may be attributed to Leonardo. It was discovered on the fireplace mantle of an old building in Vinci (formerly the Bracci house), now owned by the Municipality.

The fantastical creature features several striking iconographic elements, though worn by time: A spiral horn on the head, elongated snout and curved beak, hooked teeth, flaming tongue, clawed limbs, pointed ears, pronounced scales on the back and neck, and a fan-like membranous wing with fingered extensions—anticipating Leonardo's later studies of bird and bat flight—along with a serpentine tail.

Due to these features, Vezzosi and Sabato have named the work "Unicorn Dragon."
Particularly compelling is a comparison with a detail from [Windsor sheet RL 12370](#), dated to the 1470s.

The attribution hypothesis is currently supported by Roberta Barsanti, Director of the Leonardian Museum and Library, and by Vinci's Mayor, Daniele Vanni. The Municipality has planned [scientific analysis](#) and restoration of the large drawing (about 80x70 cm), under the supervision of the Superintendency of Archaeology, Fine Arts and Landscape for the Metropolitan City of Florence and the provinces of Pistoia and Prato.

Passive infrared contact lenses allow people to see in the dark, even with their eyes closed

University of Science and Technology of China develops non-invasive lenses using nanoparticles for enhanced infrared vision. From Cell Press 23/05/25 (first released 22/05/25)



Neuroscientists and materials scientists have created contact lenses that enable infrared vision in both humans and mice by converting infrared light into visible light.

Unlike infrared night vision goggles, the contact lenses, described in the Cell Press journal *Cell* on May 22, do not require a power source—and they enable the wearer to perceive multiple infrared wavelengths.

Because they're transparent, users can see both infrared and visible light simultaneously, though infrared vision was enhanced when participants had their eyes closed.

“Our research opens up the potential for non-invasive wearable devices to give people super-vision,” says senior author Tian Xue, a neuroscientist at the University of Science and Technology of China.

“There are many potential applications right away for this material.

For example, flickering infrared light could be used to transmit information in security, rescue, encryption or anti-counterfeiting settings.”

The contact lens technology uses nanoparticles that absorb infrared light and convert it into wavelengths that are visible to mammalian eyes (e.g., electromagnetic radiation in the 400-700 nm range).

The nanoparticles specifically enable detection of “near-infrared light,” which is infrared light in the 800-1600 nm range, just beyond what humans can already see. The team previously showed that these nanoparticles enable infrared vision in mice when injected into the retina, but they wanted to design a less invasive option.

To create the contact lenses, the team combined the nanoparticles with flexible, non-toxic polymers that are used in standard soft contact lenses.

After showing that the contact lenses were non-toxic, they tested their function in both humans and mice.

They found that contact lens-wearing mice displayed behaviors suggesting that they could see infrared wavelengths.

For example, when the mice were given the choice of a dark box and an infrared-illuminated box, contact-wearing mice chose the dark box whereas contact-less mice showed no preference.

The mice also showed physiological signals of infrared vision: the pupils of contact-wearing mice constricted in the presence of infrared light, and brain imaging revealed that infrared light caused their visual processing centers to light up.

In humans, the infrared contact lenses enabled participants to accurately detect flashing morse code-like signals and to perceive the direction of incoming infrared light.

“It’s totally clear cut: without the contact lenses, the subject cannot see anything, but when they put them on, they can clearly see the flickering of the infrared light,” said Xue.

“We also found that when the subject closes their eyes, they’re even better able to receive this flickering information, because near-infrared light penetrates the eyelid more effectively than visible light, so there is less interference from visible light.”

An additional tweak to the contact lenses allows users to differentiate between different spectra of infrared light by engineering the nanoparticles to color-code different infrared wavelengths.

For example, infrared wavelengths of 980 nm were converted to blue light, wavelengths of 808 nm were converted to green light, and wavelengths of 1,532 nm were converted to red light.

In addition to enabling wearers to perceive more detail within the infrared spectrum, these color-coding nanoparticles could be modified to help color blind people see wavelengths that they would otherwise be unable to detect.

“By converting red visible light into something like green visible light, this technology could make the invisible visible for color blind people,” says Xue.

Because the contact lenses have limited ability to capture fine details (due to their close proximity to the retina, which causes the converted light particles to scatter), the team also developed a wearable glass system using the same nanoparticle technology, which enabled participants to perceive higher-resolution infrared information.

Currently, the contact lenses are only able to detect infrared radiation projected from an LED light source, but the researchers are working to increase the nanoparticles' sensitivity so that they can detect lower levels of infrared light.

“In the future, by working together with materials scientists and optical experts, we hope to make a contact lens with more precise spatial resolution and higher sensitivity,” says Xue.

Study participant putting contacts in. Credit: Yuqian Ma, Yunuo Chen, Hang Zhao

Researcher places infrared contacts in participant's eyes. Credit: Yuqian Ma, Yunuo Chen, Hang Zhao
Preparation procedures for infrared contacts. Credit: Sheng Wang

ARTICLE May 22, 2025

Near-infrared spatiotemporal color vision in humans enabled by upconversion contact lenses

Yuqian Ma (马玉乾)^{1,2,6} — · Yunuo Chen (陈雨诺)^{1,2,6} · Sheng Wang^{3,6} — ·
... · Xinglong Gong³ — · Gang Han⁵ — · Tian Xue (薛天)^{1,2,7} — ... Show more
Affiliations & NotesArticle Info

Highlights

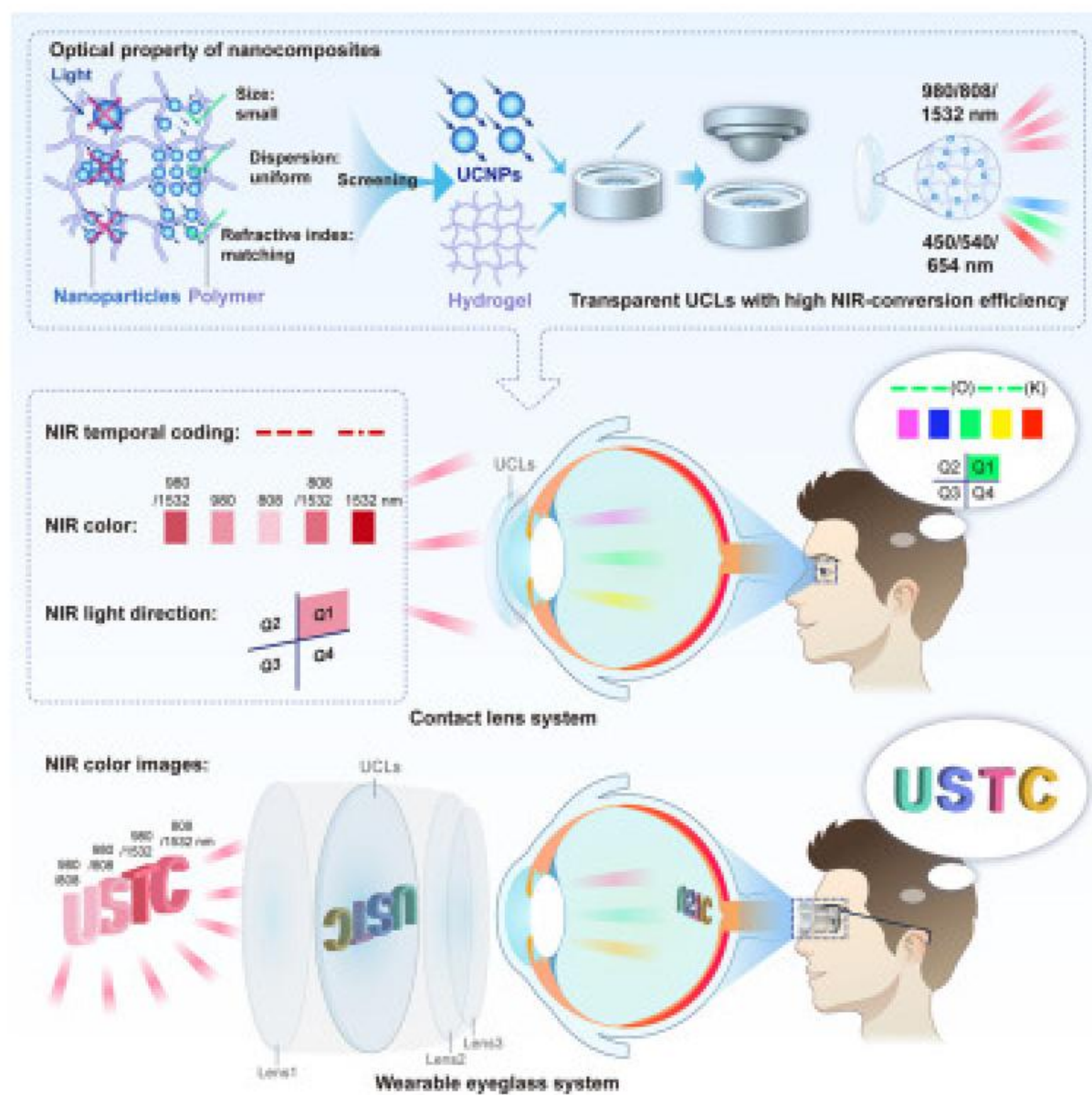
- Transparent UCLs with high NIR-conversion efficiency and biocompatibility were developed
- Humans and mice acquire wearable NIR spatiotemporal vision with UCLs
- Humans acquire NIR color vision via trichromatic UCLs converting multispectral NIR light
- Humans can identify the distinct NIR spectra of images by trichromatic UCLs

Summary

Humans cannot perceive infrared light due to the physical thermodynamic properties of photon-detecting opsins. However, the capability to detect invisible multispectral infrared light with the naked eye is highly desirable. Here, we report wearable near-infrared (NIR) upconversion contact lenses (UCLs) with suitable optical properties,

hydrophilicity, flexibility, and biocompatibility. Mice with UCLs could recognize NIR temporal and spatial information and make behavioral decisions. Furthermore, human participants wearing UCLs could discriminate NIR information, including temporal coding and spatial images. Notably, we have developed trichromatic UCLs (tUCLs), allowing humans to distinguish multiple spectra of NIR light, which can function as three primary colors, thereby achieving human NIR spatiotemporal color vision. Our research opens up the potential of wearable polymeric materials for non-invasive NIR vision, assisting humans in perceiving and transmitting temporal, spatial, and color dimensions of NIR light.

Graphical abstract



Keywords

1. [near-infrared light](#)
2. [color vision](#)
3. [upconversion nanoparticle](#)
4. [nanocomposites](#)
5. [contact lenses](#)
6. [spectrum](#)
7. [visual behavior](#)

Introduction

Light plays a particularly essential role in conveying a significant amount of external information for living organisms to comprehend the world.^{1,2} However, mammals can only perceive a small fraction of the electromagnetic spectrum as visible light, typically in the 400–700 nm range.^{3,4} This means that over half of the solar radiation energy, existing as infrared light (>700 nm),⁵ remains imperceptible to mammals. The perception limitation in the light spectrum is due to the physical thermodynamic properties of the photon-detecting opsins.^{6,7,8,9} As a consequence, this leads to a substantial loss of sensory information that could potentially be available. Although tools such as night vision goggles or infrared-visible converters have been used for infrared detection, they require additional energy support and typically cannot distinguish infrared information across multiple spectra. Additionally, each infrared-visible converter requires a multilayer structure, making them opaque and difficult to integrate with the human eye.^{10,11,12,13} We previously achieved near-infrared (NIR) vision ability in mice by subretinally injecting photoreceptor-binding upconversion nanoparticles (pbUCNPs) into the eyes.¹⁴ Nonetheless, the ocular injection of pbUCNPs may not be readily accepted by humans due to surgical invasiveness.^{15,16} Therefore, developing non-invasive NIR vision capabilities with naked eyes to detect multispectral NIR light remains critical and desirable for humans.

Herein, we designed the NIR vision system for humans by integrating upconversion nanoparticles (UCNPs) into soft, non-invasive, and wearable polymeric materials. We modified UCNPs and screened polymeric materials based on refractive index matching and obtained NIR-light upconversion contact lenses (UCLs) with suitable optical properties, hydrophilicity, flexibility, and biocompatibility. With these UCLs, mice could sense the visible light converted from NIR light and distinguish the temporal and spatial information of NIR light. Meanwhile, humans wearing UCLs could accurately recognize NIR temporal information like Morse code and discriminate NIR pattern images. Interestingly, both mice and humans with UCLs exhibited better discrimination of NIR light compared with visible light when their eyes were closed, owing to the penetration capability of NIR light.

In addition to the temporal and spatial information, visual perception can also convey abundant information in the color dimension. Color information in visible light is closely related to its specific wavelength.¹⁷ Infrared light spans a wider range of wavelengths

compared with visible light.¹⁸ To distinguish multiple spectra of NIR light, we replaced the conventional UCNP with trichromatic orthogonal UCNP that could convert NIR light in three different spectral bands into visible light in three primary colors.^{19,20} Through these trichromatic UCLs (tUCLs), we achieved NIR color vision in humans, which could encode more abundant NIR information, focusing specifically on the 800–1,600 nm range. NIR light in this range effectively penetrates biological tissues rich in water, such as eyelids and corneas,^{21,22} thereby enhancing NIR vision and biological imaging. Overall, this research enables humans to achieve non-invasive and multidimensional NIR image vision without the need for complex external devices. This technology has a wide range of practical applications, including infrared information encoding and transmission, enhanced vision in poor visibility conditions (e.g., foggy or dusty conditions), and integration into smart devices for rescue and emergencies.

Results

UCLs with suitable optical and mechanical properties

In order to achieve human NIR vision through non-invasive, wearable contact lenses, we need to develop polymeric nanocomposites suitable for human eyes. This means that the prepared contact lenses should have suitable optical transparency, hydrophilicity, mechanical properties, and biocompatibility. Currently, soft, transparent polymeric materials have become widely applied in this field.^{23,24} However, the fusion of nanoparticles within polymeric materials alters the optical properties of the polymer, making it challenging to obtain high-concentration, optically transparent nanocomposites.^{25,26,27} The optical properties of nanocomposites primarily depend on the light absorption and scattering of nanoparticles within the polymer, which are closely related to the size of the nanoparticles, their dispersion within the polymer, and the matching of their refractive indices (Figure S1A).

Figure S1 Screening strategy and some properties of UCLs, related to Figure 1

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To prepare NIR UCLs by incorporating UCNP into the polymeric materials (Figure 1A), we synthesized Au/NaGdF₄: Yb³⁺, Er³⁺ nanoparticles^{28,29} with a diameter of approximately 45 nm (Figure S1B) that exhibited relatively low light transmission loss (absorption and scattering) in the polymeric materials.³⁰ The majority of polymer materials employed in the contact lenses are hydrophilic, facilitating a comfortable fit between the lens and the cornea of the eye. However, hydrophobic oleic acid residues are often present on the surface of UCNP. To ensure their uniform dispersion within the polymeric materials, we eliminated the hydrophobic oleic acid residues from the surface of Au/NaGdF₄: Yb³⁺, Er³⁺ nanoparticles³¹ (Figure 1B). Even if UCNP possess an appropriate size and hydrophilicity, the refractive index difference between UCNP and the polymeric materials still affects the transparency of their composites.²⁵ We determined that the refractive index of oleate-free UCNP was 1.4388 (Figure 1C). To match the refractive index of the polymer with it, we conducted a screening of multiple polymers,^{32,33} including the hard contact lens material, polymethyl methacrylate (PMMA); soft contact lens

materials, polydimethylsiloxane (PDMS) and silicone hydrogel; the commonly used contact lens material, poly(2-hydroxyethyl methacrylate) (pHEMA); as well as other polymeric materials like polyvinyl alcohol (PVA) and polyacrylic acid (PAA). The nanocomposites with a significant refractive index difference between UCNPs and polymeric materials tended to exhibit lower transparency at a 3% mass concentration of UCNPs (Figures 1D, 1E, and S1C). While a hydrophilic pHEMA polymer (pHEMA-1) exhibited the most similar refractive index to oleate-free UCNPs, the transparency of the UCNPs-fused pHEMA-1 nanocomposite exceeded 90%. To achieve high conversion efficiency, we compared the transparency of UCNPs-fused pHEMA-1 UCLs with varying UCNPs mass fractions. We found that at a UCNP mass ratio of 7%, these lenses still displayed suitable optical properties, achieving over 85% transparency in visible light, with the majority of wavelengths exceeding 90% (Figures 1F and 1G). This suggests that we successfully balanced the concentration ratio of UCNPs in the UCLs and their optical properties. Through Ashby plot analysis, UCLs represent the highest level in terms of particle doping ratio and optical performance compared with various reported UCNP/polymer nanocomposites^{19,34,35,36,37,38,39,40} (Figure S1D).

Figure 1 Design and synthesis of soft, wearable, and non-invasive UCLs

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Meanwhile, in the scanning electron microscopy (SEM) images of UCLs, the zeta potential (-16 ± 1.2 mV) and the hydrodynamic size distribution of UCNPs in mixed solutions indicate that UCNPs fused well, were stable, and dispersed uniformly within the UCLs (Figures 1H, S1E, and S1F). This fusion process did not change the excitation and emission spectra of UCNPs in the UCLs, allowing them to emit a uniform green light upon NIR-light excitation (Figure 1I). The addition of UCNPs also had no impact on the hydrophilicity and water content of UCLs, comparable to commercial contact lenses (Figures S1G and S1H). The results of rheological tests on UCLs using shear modulus and shear cyclic loading revealed that they displayed similar flexibility and reliable fatigue resistance compared with commercial contact lenses (Figure S1I). The experiment on tensile modulus further confirmed the suitable mechanical stability of UCLs (Figure S1J). The intensities of 980 nm light absorbed and visible light emitted after passing through UCLs under different intensities of incident 980 nm light indicate the quantitative conversion of NIR light to visible light through UCLs (Figure S1K). Overall, the suitable mechanical properties and efficient upconversion capabilities of soft UCLs are appropriate for human wearing and human NIR vision.

Biocompatibility of UCLs

We then assessed the *in vivo* biocompatibility and potential side effects of the UCLs. After a single 6-h wearing in a short period, we found that the number of cell layers in the cornea and retinal outer nuclear layer did not differ between mice with or without UCLs through hematoxylin and eosin (H&E) staining (Figures 1J and S2A). Sparse signals of cell apoptosis were observed on the corneas in all groups, suggesting the wearing of UCLs did not increase the risk of corneal cell apoptosis (Figure 1K). The staining of microglia marker Iba1 showed that there was no microglia aggregation,

suggesting no inflammation response in retinæ of all groups ([Figure S2B](#)). For long-term toxicity tests, mice wore the UCLs for durations of 3, 7, or 14 consecutive days (6 h per day). We found that wearing contact lenses for 3, 7, and 14 days did not cause any changes in corneal thickness, retinal morphology, or retinal inflammation response. However, continuous wearing of either commercial contact lenses or UCLs led to a slight increase in corneal cell apoptosis after 7 and 14 days of wearing ([Figures S2C and S2D](#)). This could be attributed to the mechanical friction caused by wearing contact lenses. However, UCLs did not exacerbate this effect. Taken together, these results suggest that UCLs have good biocompatibility without detectable side effects on the corneas and retinæ of mice.

Figure S2 Long-term toxicological characteristics of UCLs on the corneas and retinæ, related to [Figure 1](#)

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NIR-mediated light sensation of mice with UCLs

After confirming the favorable biocompatibility of the UCLs, we proceeded to validate whether NIR light could effectively activate the visual system of mice through these UCLs. We performed the *in vitro* suction pipette recordings on the acutely dissected mouse retina, which was flat-mounted on a UCL disk ([Figure S3A](#)). Rod photocurrents were elicited by the 980-nm light pulse only with the UCL disk presented, and the amplitudes and dynamics were consistent with those activated by 535-nm visible light ([Figures S3B–S3D](#)). The *in vivo* electroretinography (ERG) recordings showed that wearing these UCLs had no effect on the ERG signals mediated by visible light, suggesting that UCLs did not interfere with normal vision with their high transparency ([Figures 2A and 2B](#)). Meanwhile, ERG signals evoked by NIR light in mice with UCLs exhibited a similar response pattern with those evoked by visible light. Whereas, in mice without UCLs, NIR light could not evoke any ERG signals.

Figure 2 NIR-mediated light sensation of mice with UCLs

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Figure S3 NIR-light-induced activation of photoreceptors and information discrimination in mice with UCLs and NIR-light sensitivity under brighter ambient light in humans with UCLs, related to [Figures 2, 3, and 4](#)

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Then, we investigated NIR-mediated light sensation in mice with UCLs at the behavioral level. The UCLs were secured onto the eyes of moving mice by an eyelid suture. To detect the pupil light reflex, we monitored the contralateral eye's pupil size while the eye with UCLs was illuminated by NIR light ([Figure 2C](#)). When mice wore UCLs, NIR light induced the pupillary constriction, while no response was observed in mice without UCLs ([Figures 2C and 2D](#)). In addition to sub-conscious pupillary light reflex behavior, we also investigated whether mice with UCLs could consciously sense NIR-converted visible light. Mice with UCLs displayed a preference for the dark box over NIR-light box

in the light-dark box assay and mice without UCLs could not (Figures 2E and 2F). In the light-induced fear-conditioning experiment, NIR light also could induce the freezing behavior in mice with UCLs but not in mice without UCLs (Figures 2G and 2H). These results indicate that mice with UCLs can acquire NIR-mediated light sensation ability.

In aforementioned NIR vision behavior tests, although the eyelids were sutured, NIR light could readily induce behavior responses in mice with UCLs, whereas visible light could not induce significant responses (Figures 2F and 2H). A potential explanation for this was that NIR light could penetrate the eyelids easily.^{42,43} We measured the transmittance of the mouse eyelids of 535- and 980-nm light (Figure 2I). The results showed that the transmittance of the mouse eyelids of 535-nm light was 0.388%, while that of 980-nm light was 23.292%. This demonstrates that NIR-light information can be transmitted stealthily even through closed eyes.

NIR-light information recognition of mice with UCLs

Other than innate behaviors induced by NIR-mediated light sensation, we further investigated whether mice with UCLs could recognize NIR light's spatial and temporal information. We recorded the visually evoked potential (VEP) at four different locations in the primary visual cortex of mice when the contralateral eyes were illuminated by visible light or NIR light (Figure 3A). As anticipated, wearing UCLs did not affect visible light-induced VEP signals. Meanwhile, we could record VEP signals in mice with UCLs under NIR-light illumination, but no signals were detected in mice without UCLs (Figures 3A and 3B). The amplitude and response time of VEP signals evoked by NIR light were consistent with those evoked by visible light.

Figure 3 NIR-light information discrimination of mice with UCLs

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Additionally, we performed intrinsic optical imaging of the primary visual cortex (V1).^{44,45} NIR and visible light grating stimulations at three different visual fields elicited well-separated intrinsic optical signals in the visual cortex of mice with UCLs (Figures 3C–3E and S3E). These well-separated V1 retinotopic responses indicated that spatial information of NIR light could be transmitted directly to the mouse visual cortex.⁴⁶ In the conditioned place-avoidance experiment,^{47,48} mice could distinguish NIR flickering light with two different frequencies (2 and 0.4 Hz) and made correct behavioral decisions to avoid being shocked (Figures 3F–3H, S3F, and S3G). These findings illustrate that NIR vision facilitated by UCLs enable mice to perceive NIR spatial and temporal information.

NIR vision of humans with UCLs

Having achieved non-invasive NIR vision in mice through the UCLs, we applied the UCLs to humans. Sensitivity tests for human perception of visible and NIR light were conducted in the dark or in ambient light conditions (Figures 4A and 4C). We observed no differences in the perception sensitivity to visible light in humans with or without

UCLs, indicating that highly transparent UCLs did not impact normal human vision (Figures 4B and 4D). Participants wearing UCLs were able to identify NIR light in the dark room (Figure 4B). When participants closed their eyes, their sensitivity to NIR light remained almost unchanged, but the sensitivity to visible light decreased over 200-fold. This was attributed to the better penetration ability of NIR light through the eyelid, as previously demonstrated in mice (Figures 2E–2I). Moreover, in ambient light condition (100, 200, and 300 lux), participants were still able to perceive NIR light (Figures 4C, 4D, S3H, and S3I), indicating that NIR vision via UCLs was ambient-daylight compatible and existed in parallel with native daylight vision. Interestingly, under an ambient light background, the sensitivity to NIR light increased by 3.7-fold when participants closed their eyes, while the sensitivity to visible light decreased by 4.5-fold (Figure 4D). This could be explained by the closed eyes reducing ambient visible light input while increasing the signal-to-noise ratio of NIR-light detection.

Figure 4 NIR vision of humans with UCLs

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We then measured the NIR vision flicker fusion frequency of humans with UCLs and found that it was similar to that of visible light vision (Figure 4E). On this basis, we used the NIR flickering light to implement temporal coding and found that participants with UCLs could accurately distinguish the letter sequences coded by NIR flashes (Figure 4F). In the spatial information recognition of NIR light, UCLs cannot achieve fine image perception from an optical principle standpoint. This is because the NIR light, which originally carried spatial information for imaging, is converted into scattered visible light before entering the human eye, altering the spatial information carried by the direction of light propagation. However, participants with UCLs exhibited the ability to recognize coarse NIR images, such as distinguishing the direction of NIR light coming from specific visual quadrants (Figure S3J). To achieve fine NIR image vision, we developed a wearable eyeglass system consisting of three convex lenses and a built-in flat UCL integrated into the optical path (Figure 4G). With this system, participants could distinguish the NIR moving gratings with a spatial resolution threshold of ~65 cycles per degree (c/d) (Figure 4H). Moreover, we demonstrated that participants with the UCLs were able to discriminate NIR pattern images (horizontal and vertical lines, S and O shapes, triangle and square) (Figure 4I). Taken together, these findings show the potential of UCLs for NIR-light information discrimination in both temporal and spatial dimensions in humans.

NIR color vision of humans with tUCLs

To perceive infrared light with the multi-spectra that widely exist in the natural environment, we used trichromatic UCNP with multi-wavelength conversion capabilities^{19,20} to replace the conventional UCNP. We synthesized trichromatic orthogonal UCNP with multiple NIR absorption-emission layers (Figures 5A and S4A–S4H). These UCNP exhibited efficient absorption of NIR light at peak wavelengths of 808, 980, and 1,532 nm, while emitting visible light at peak wavelengths of 540, 450, and 650 nm, respectively (Figure 5B). These emission peaks corresponded to the three

primary colors of green, blue, and red for humans. As expected, a single NIR excitation from this trichromatic orthogonal UCNPs could generate a relatively singular emission band (Figures 5A and 5B), thereby avoiding interference issues in the emission spectral bands compared with the direct mixture of three different conventional UCNPs. Indeed, in dual-spectral NIR-light excitation experiments, independently adjusting the intensities of NIR light at one spectrum could alter trichromatic UCNPs' visible light emission at the corresponding spectrum, suggesting their suitable trichromatic conversion capabilities and color separation (Figures 5C and S4I–S4Q).

Figure 5 NIR color vision of humans with tUCLs

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Figure S4 Size dispersion and luminescent upconversion spectra of trichromatic lanthanide nanoparticles, related to Figure 5

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Furthermore, we integrated the trichromatic orthogonal UCNPs (oleate-free) into pHEMA contact lenses and found that these contact lenses also had good transparency at a 7% mass fraction level (Figure 5D). To assess the effectiveness of the tUCLs in facilitating human NIR color visual perception, a color-matching experiment was conducted.^{50,51,52,53,54} During visible color matching, participants were tasked with adjusting the proportion of red/green/blue (R/G/B) light in visible composite light to match the color of various monochromatic lights at different peak spectra (403–700 nm) (Figures 5E, S5, S6A, and S6B). The R/G/B proportions in the visible composite light matching the color of each monochromatic light were presented as the spectral tristimulus values and the color space in the chromaticity diagram (Figures 5F and 5G). Similarly, through the tUCL conversion, participants adjusted the proportion of NIR light at three different spectra to match the color of various monochromatic lights (Figures 5E, S5, S6A, and S6B). We determined the tristimulus values of NIR light at three different spectra in the NIR composite light that matched the color of each monochromatic light and showed the NIR color space perceivable by humans (Figures 5H and 5I). The results showed that participants with tUCLs could effectively recognize NIR light with three wavelengths and perceive multiple NIR colors by adjusting the proportions of three NIR primary colors (Figures 5H and 5I). The spectral tristimulus values of the NIR light were similar to those of visible light (Figures 5F and 5H), except for minor discrepancies, which was possibly due to the UCNPs' emission leakage at non-primary wavelengths (Figure 5B). Likewise, the color space of the perceived NIR composite light on the color chart was highly similar to that of visible light and the National Television Standards Committee (NTSC) standard (Figures 5G and 5I). It indicates that human NIR color vision can be effectively achieved by tUCLs with non-interfering, orthogonal, and multispectral conversion properties.

Figure S5 Methodology for conducting a color-matching experiment along with the associated procedures for data analysis and calculation, related to Figure 5

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Figure S6 The spectra of monochromatic LEDs used in the color-matching experiment and the reflection of other different reflective mirrors, related to Figures 5 and 6

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With the NIR color recognition ability, participants with tUCLs could discriminate the letter sequences encoded by NIR color (Figures 5J and 5K). This indicates that by incorporating the NIR color dimension, more abundant information can be coded and transmitted. Additionally, through the combination of color and temporal information, participants with tUCLs could accurately interpret coded sentences with NIR light (Figure 5L). We also verified that participants with tUCLs could recognize various colorful NIR pattern images with the wearable eyeglass system (Figure 4G), including colored horizontal and vertical lines, S and O shapes, triangle and square (Figures 5M and 5N). These results demonstrate that our nanocomposite materials can enable humans to obtain multispectral NIR visual information.

Colorful reflective images under NIR light

Typically, most of the images we perceive are formed by visible light reflected from objects. The color of an object is determined by its reflection spectrum.^{55,56} In real scenes, different objects have various reflection spectra in the visible light band, creating colorful landscapes. Likewise, they also have different reflection properties in the NIR light band, which are undetectable to the human naked eye. However, these reflection properties can be detected by the tUCL system, allowing humans to recognize NIR “colors” of these objects under NIR light. To demonstrate the recognition of humans with tUCLs to a reflective image under NIR light, we employed a series of homogeneous reflective mirrors with different reflection spectra to simulate this process (Figure 6A). These reflective mirrors exhibited diverse colors under visible and NIR light, as confirmed by their coordinates on the chromaticity diagram (Figures 6B–6D and S6C–S6E). Interestingly, some reflective mirrors displayed a monotonous color under visible light but exhibited different colors under NIR light (Figures 6B, 6C, and S6C). Some other reflective mirrors displayed different colors under both visible and NIR light (Figures 6D and S6E). This indicates that our tUCL system enables humans to identify various reflection spectra of objects in the NIR-light band, thereby perceiving more abundant color information in the NIR region. Additionally, using the wearable eyeglass system, we could observe colorful letter patterns (Figures 6E and 6F). Some of these patterns appeared black or white under visible light but showed diverse colors under NIR light (Figure 6E), while other patterns displayed vibrant colors under both visible and NIR light (Figure 6F). These findings demonstrate that humans can acquire the ability to recognize colorful reflective images under NIR light through the tUCLs.

Figure 6 Colorful reflective image under NIR light

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Discussion

In this study, we developed soft, wearable, and non-invasive UCLs to extend human vision across multiple NIR spectra, allowing humans to distinguish NIR's temporal, spatial, and color information.

Soft and optically transparent contact lenses based on polymeric materials are widely used to correct the refractive errors of human eyes.^{23,33} This provides a wearable solution to achieve human NIR vision. However, integrating nanoparticles into polymeric materials alters their optical properties, posing a challenge in creating high-concentration, optically transparent nanocomposites.^{25,26,27} To address this, we modified UCNPs and screened polymeric materials based on refractive index matching. As a result, we developed NIR-light UCLs with over 90% transparency across most wavelengths at a UCNP mass ratio of 7%. This represents a significant increase compared with the 0.04%–2% mass ratio of UCNPs in some reported transparent nanocomposites.^{19,34,40,57} This indicates that we successfully balanced the fusion of UCNPs in the UCLs and their optical properties.

These wearable UCLs can transmit stealthy NIR information without energy support even with closed eyes. Because of the stronger penetration capability of NIR light, the UCLs can be applied not only for night vision but also in foggy or dusty conditions. Although participants wearing UCLs could recognize the temporal information of the flickering NIR light and the direction of NIR light from specific visual quadrants, UCLs cannot achieve fine image perception from an optical principle standpoint, because the upconverted scattered visible light alters the spatial information originally carried by the NIR light before entering the human eye. To overcome this, we designed the wearable eyeglass system to enable participants to distinguish the NIR moving gratings with a spatial resolution threshold of about 65 c/d. This is comparable to the typical spatial resolution threshold (~60 c/d) of human vision,^{58,59} suggesting that humans can achieve the NIR vision with normal visual spatial resolution through this method. In the future, to achieve fine NIR vision through UCLs, the UCNP emission process can be designed to ensure that the emitted visible light follows the same path as the incident NIR light, preserving the spatial information carried by the direction of light propagation. For instance, nanoparticles could be engineered to emit light only in the forward direction,⁶⁰ or microscale optical fiber channels could be embedded in the UCLs to guide the converted visible light exclusively toward the eye.

Additionally, we can convey multispectral NIR-light information through tUCLs and achieve human NIR color vision. Trichromatic orthogonal UCNPs in these tUCLs allow for the detection of NIR light across three different wavelength regions. Although some studies have reported on multispectral UCNPs, and even their integration with polymers, these works have not truly achieved human NIR color vision.^{20,38,61} The practical application of these technologies is limited by factors such as low concentrations of nanoparticle doping and the high-power NIR-light requirements. In contrast, we have overcome these challenges and provided an approach to achieving high-transparency and high-content characteristics through effective optimization of the refractive index of nanoparticles and hydrogels. As such, this work advances the development of trichromatic orthogonal particles for biological visual sensation and recognition. Furthermore, the excitation and emission spectra of these nanomaterials

can be adjusted by adding sensitizers and activators, altering core-shell nanostructures and host materials.^{62,63,64} This enables us to detect a wider range of NIR wavelengths through NIR color vision, thereby perceiving more comprehensive NIR information in the future.

Overall, this concept-proving study confirms that human super-vision ability can be achieved by wearable nano-biomaterials and paves the way to numerous applications of human NIR spatiotemporal color vision.

Limitations of the study

In this study, we demonstrated that humans could identify NIR-light information through UCLs at relatively low light intensities, specifically at the LED (Light Emitting Diode) level. However, detecting environmental NIR information in the natural conditions at night without NIR illumination still remains challenging, requiring further advancements in material science and optical design. Through a wearable eyeglass system that does not require battery power, humans can achieve fine NIR vision with normal visual spatial resolution. However, these contact lenses currently cannot achieve fine image perception due to the optical principle limitations. In the future, to achieve fine NIR vision through UCLs, UCNPs need to be designed to emit visible light in the same direction as the incident NIR light, or microscale optical fiber channels embedded in the UCLs are used to guide the emitted light directly to the eye. Additionally, multiplexing visible and infrared information could potentially affect the color constancy of certain objects. Nevertheless, users might adapt and gain integrative perceptions through short-term visual adaptation and learning. Furthermore, the sample size, as well as the sex, racial, and ethnic composition of the participants, may influence the results. Conducting validation studies with a more diverse population could enhance the generalizability of the findings. Although this work has its limitations, it opens the door to a richly informative, colorful NIR world that can be directly perceived by humans.

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Tian Xue (xuetian@ustc.edu.cn).