

MOLECULAR MANUFACTURING

INCLUDING 3D PRINTING

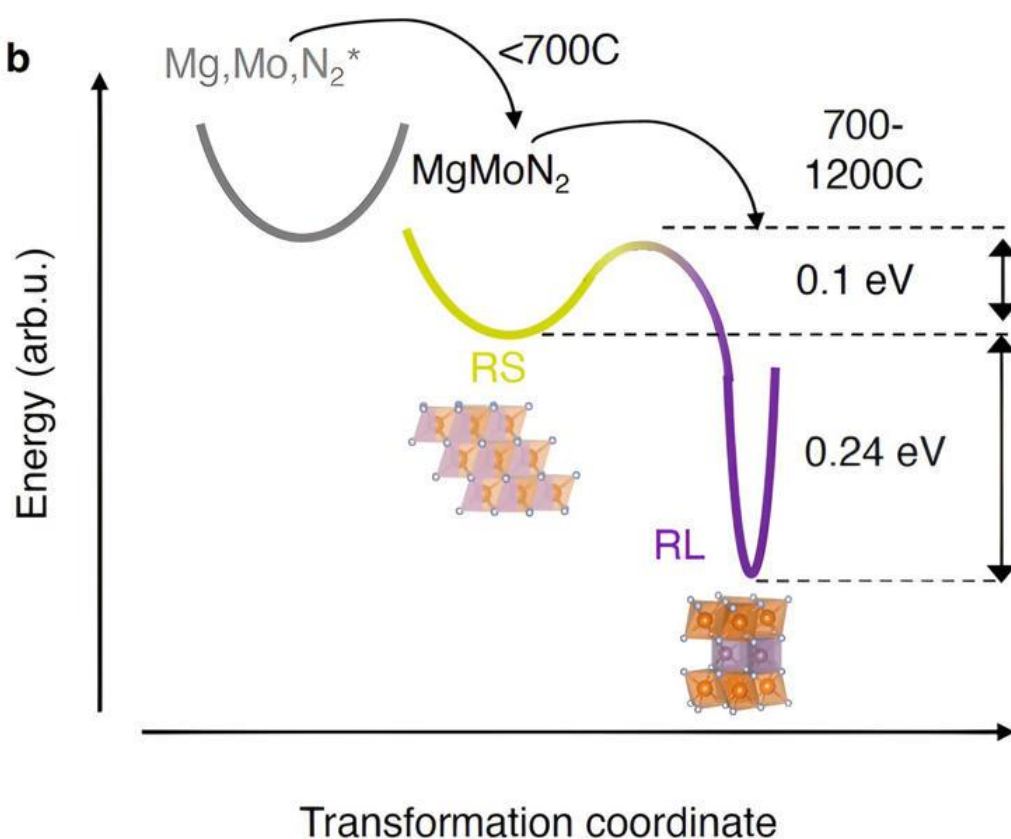


NREL researcher Andriy Zakutayev (left) and Mines professor Vladan Stevanovic are part of a team that uses supercomputers, algorithms, and experiments to find and create materials with the ideal properties for useful applications. Credit: Dennis Schroeder, NREL

A research team discovered a method to transform materials with three-dimensional atomic structures into nearly two-dimensional structures—a promising advancement in controlling their properties for chemical, quantum, and semiconducting applications.

The field of materials chemistry seeks to understand, at an atomic level, not only the substances that comprise the world but also how to intentionally design and manufacture them.

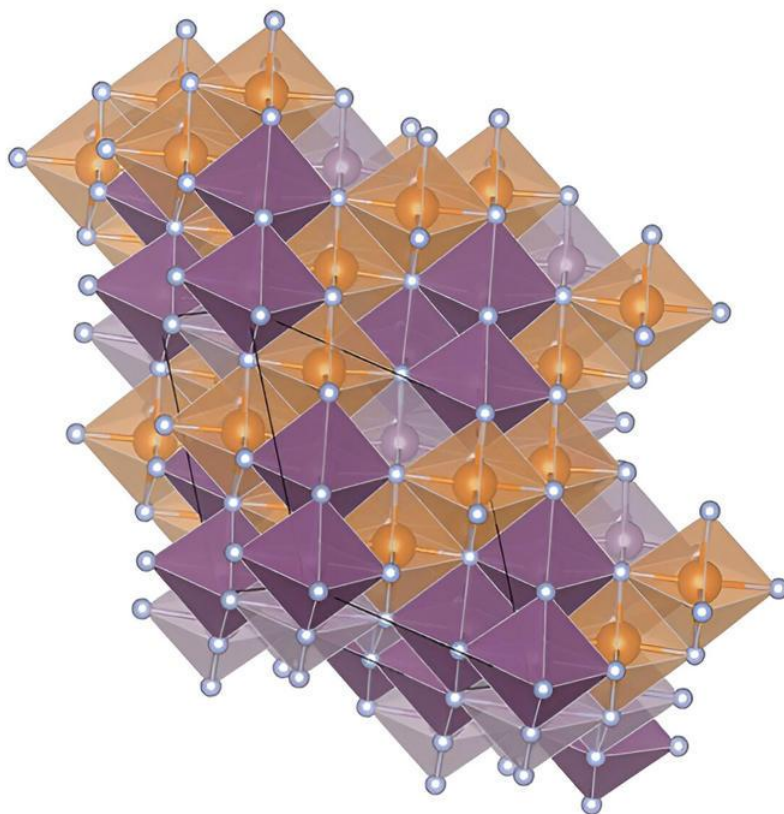
A pervasive challenge in this field is the ability to precisely control chemical reaction conditions to alter the crystal structure of materials—how their atoms are arranged in space with respect to each other. Controlling this structure is critical to attaining specific atomic arrangements that yield unique behaviors. This process results in novel materials with desirable characteristics for practical applications.



A three-dimensional to two-dimensional synthesis pathway for the compound MgMoN₂ extends to other materials chemistries: a low-energy barrier between the broad metastable three-dimensional energy valley and the narrow stable two-dimensional energy well. Credit: Nature Synthesis (2024). DOI: 10.1038/s44160-024-00643-0

A team of researchers led by the National Renewable Energy Laboratory (NREL), with contributions from the Colorado School of Mines (Mines), National Institute of Standards and Technology, and Argonne National Laboratory, discovered a method to convert materials from their higher-energy (or metastable) state to their lower-energy, stable state while instilling an ordered and nearly two-

dimensional arrangement of atoms—a feat that has the potential to unleash promising material properties.



The metastable phase of MgMoN₂ has the most disorder, and it becomes the most stable structure at temperatures above 2000°K. Credit: Nature Synthesis (2024). DOI: 10.1038/s44160-024-00643-0

The researchers published their findings in a paper titled "[Synthesis Pathways to Thin Films of Stable Layered Nitrides](#)," in *Nature Synthesis*.

"A compelling reason to find ways to produce stable thin films with layered, nearly two-dimensional structures is that many of them have unusual chemical, semiconducting, or quantum properties. This is because electrons in such two-dimensional materials interact only with other electrons sideways—not above or below," said NREL's Andriy Zakutayev, senior physics researcher who synthesized the materials and led this study.

"These two-dimensional properties could be promising for practical applications, such as electrocatalysts for hydrogen production, energy-efficient electronic devices, or superconducting qubits for quantum computing."

Understanding the formation of disordered metastable phases

Nitrides are nitrogen-containing chemical compounds that can form robust materials. They are known for their chemical resistance and thermal stability, and these properties make them indispensable in high-performance industrial applications, especially in thin films that are often only a few atoms thick. Common applications for these films include use as semiconductor insulation layers and as protective coatings for optical lenses and machining tools.

However, the process of creating a thin nitride film tends to produce molecular structures that are three-dimensional and not fully stable. To achieve nitrides with the stable two-dimensional layered structures that are useful for chemical or quantum applications, NREL researchers examined why these intermediate phases form at all.

When a compound's constituent atoms reach low-energy areas—called local minima—the compound tends to settle into that structure. The regions from which an atom will move toward these local minima are called basins of attraction. Compounds with stable structures that have smaller basins of attraction are more likely to be stuck in a metastable state—between stability and instability.

"From a theoretical perspective, the larger the basin of attraction, the more likely it is that a compound will settle into that arrangement, which is why three-dimensional metastable nitrides form—like rainwater flowing into a large puddle formed in a big pothole on the road," said Mines' Vladan Stevanovic, associate metallurgical and materials engineering professor who performed the study's theoretical calculations with his team of students.

"Here, we discovered how certain metastable three-dimensional structures might change into stable, nearly two-dimensional layered structures. This is exciting—it's like finding a space wormhole in science fiction."

Discovering a pathway to achieve thin films of stable layered nitrides

The team synthesized thin nitride films with magnesium and molybdenum by radio frequency sputtering—a procedure in which the precursor metals are blasted with energetic ions, removing atoms that will form thin films—in an atmosphere of argon and nitrogen. The new compounds were then subjected to a rapid heat treatment process under an atmospheric nitrogen environment.

"The experimental observations indicate that the compounds, as deposited, crystallize into a three-dimensional, metastable cubic structure with elemental disorder," Zakutayev said.

"But when we applied heat above 700°C (1,292°F), the compounds transformed into nearly two-dimensional thin films with hexagonal structure with elemental order. We were quite surprised by the emergence of the order from disorder—it was like throwing together mixed pasta, cheese, and veggies all together into a pan and then taking it out of an oven and finding a delicious, layered lasagna there."

The key to solving this mystery was an elemental order hidden on the very short atomic length scale in the otherwise disordered metastable materials. The team validated this discovery with three other nitride materials and two independent experimental measurements in addition to theoretical calculations.

Implications of a thin-film transformation pathway

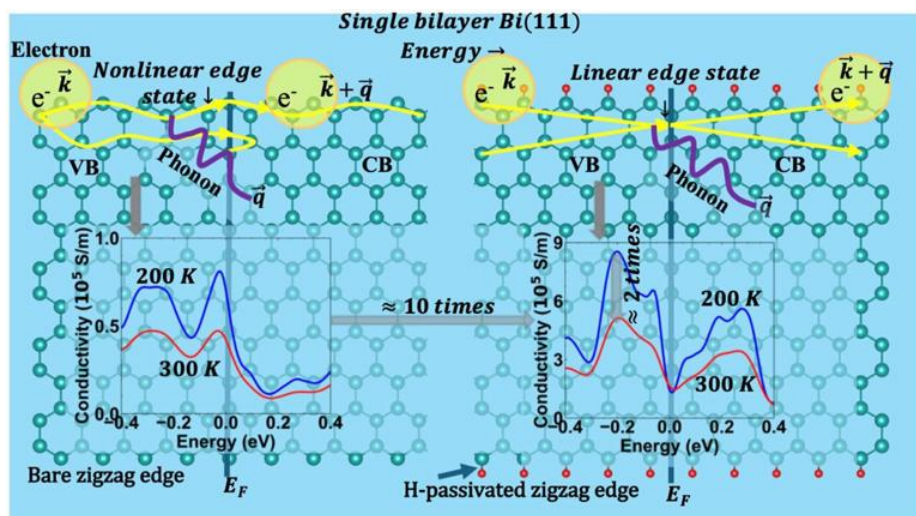
Beyond the specific compounds in the team's experiments, the team's discovery is also applicable to other nitride thin films that are only known to form three-dimensional cubic structures. Control over a material's final atomic structure is essential to changing that material's properties.

This is especially true for materials with quantum properties that respond rapidly to slight changes in atomic structure and for materials with semiconductor properties that are adjustable with atom rearrangement.

"Our team was able to synthesize three other nitride compounds in a layered, nearly two-dimensional structure using this same method, demonstrating the universality of our approach," said NREL's Rebecca Smaha, materials science researcher who performed synchrotron measurements.

"We also developed a theoretical explanation for how these materials can be synthesized, making this synthesis method suitable for other chemistries beyond nitrides. I'm excited to see how this synthesis pathway can be leveraged to discover completely new materials in inorganic solid-state materials chemistry."

More information: Andriy Zakutayev et al, Synthesis pathways to thin films of stable layered nitrides, *Nature Synthesis* (2024). DOI: [10.1038/s44160-024-00643-0](https://doi.org/10.1038/s44160-024-00643-0)



Electron-phonon interactions at linear and nonlinear electronic edge states, demonstrating impact on energy transport in these edge states. Credit: *Nanoscale* (2024). DOI: [10.1039/D4NR02172J](https://doi.org/10.1039/D4NR02172J)

Topological insulators raise the exciting hope of realizing lossless energy transport, which is true at ultralow temperatures. However, topological insulators fail to maintain this lossless 'magic' at room temperature.

Researchers from Monash University, part of the FLEET Center, have uncovered new insights into the efficiency of topological insulators, illuminating the significant disparity between their magic lossless energy transport at ultralow temperatures and the detrimental issues that arise at room temperature.

The [study](#), which was published in *Nanoscale*, investigates why topological insulators face serious challenges in maintaining their feature in a practical working environment, particularly by the role of electron-phonon interactions.

Topological insulators, particularly two-dimensional (2D) topological insulators, are well-known for their unique feature of conducting electricity through the boundary/edge while the bulk surface remains electrically insulating.

This unique feature allows one-way carrier transport without backscattering, with the resulting negligible scattering-induced electrical resistance giving rise to expectations of dissipationless carrier transport.

Indeed, at ultralow temperatures, these topological insulators often exhibit dissipationless carrier transport, lining up with the expectation. However, sustaining this feature faces a serious challenge when the temperatures rise towards room temperature, where phonons (quanta of lattice vibrations) come into play with carriers.

The role of electron-phonon interactions

This study delivers a thorough analysis of interplay between carrier and phonon, and energy transport in the 2D topological insulator under different temperatures.

The interplay between electron and phonon (i.e., electron-phonon interactions) plays a crucial role in the significant increase in electrical resistance observed.

Theoretical modeling revealed electron-phonon scattering to be a significant source of backscattering at the topological edge states, with the strength of interactions strongly correlated to dispersion of the electronic edge states.

The interactions increase significantly with temperature, and are much stronger at the nonlinearly dispersed edge states of native edges compared to the linearly dispersed edge states of passivated edges, causing a significant energy dissipation in the temperature range of 200–400 K.

This study therefore illuminates the divergence between the performance at ultralow temperature and at practical, operating room temperature.

"As we considered both linear and nonlinear edge dispersions in this study, our results can be applicable to a diverse range of topological insulators," said Enamul Haque, lead author of the study.

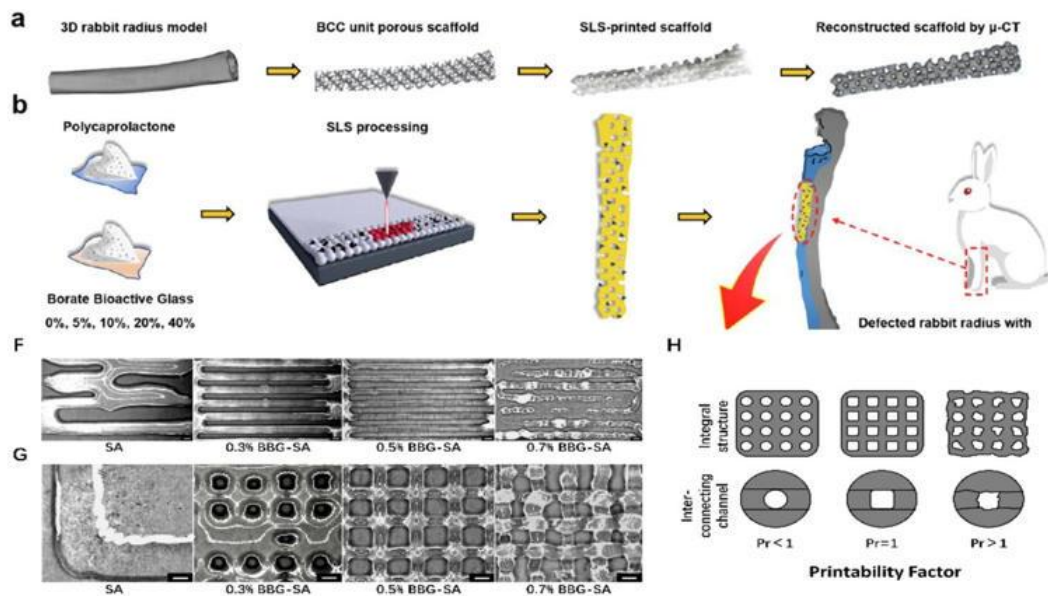
Improved fundamental understanding of the role of electron-phonon scattering at the edges of 2D topological insulators is considered vital to progressing the technology of 2D topological insulator-based future electronics. However, previous work has focused largely on surface states of 3D topological insulators and insulating surfaces of 2D topological insulators.

"Our findings could play a crucial role for advancing the applications of topological insulators in practical electronic devices," says Haque.

The understanding from this study can guide the search for new quantum materials or how to overcome the existing limitations. By overcoming these issues at room temperature, scientists can advance in realizing the full-potential applications of topological insulators in practical technologies, for example, quantum transistors and quantum devices.

"A clear understanding of electron-phonon interactions in the topological edge states can help develop strong quantum decoherence in qubits, which would potentially enhance the stability and scalability of quantum computers," said Professor Nikhil Medhekar, lead researcher and FLEET Chief investigator.

More information: Enamul Haque et al, Electron–phonon interactions at the topological edge states in single bilayer Bi(111), *Nanoscale* (2024). DOI: [10.1039/D4NR02172J](https://doi.org/10.1039/D4NR02172J)



Novel BGG-based composite 3D bioprinting materials for tissue engineering. Credit: Ma Kun

3D bioprinting is an advanced tissue engineering technique that builds complex tissues using bioactive substances like living cells and scaffolds. It provides personalized tissue repair solutions, reducing immune rejection by using patient-specific cells. Common-used 3D bioprinting materials include polycaprolactone (PCL) and poly lactic-co-glycolic acid (PLGA) for hard tissue and hydrogels for soft tissue.

Bioactive boron-based glass (BBG) can be used in combination with PCL or sodium alginate (SA), a carrier medium for 3D bioprinting of cells and a diverse array of bioactive substances, to form materials with high mechanical strength and good processability.

BBG is effective in bone regeneration by promoting hydroxyapatite formation and has an adjustable degradation rate to suit different repair needs. Therefore, its application in 3D bioprinting materials shows great potential.

By introducing BBG into the SA matrix, a research team led by Prof. Wang Junfeng at the Hefei Institutes of Physical Science of the Chinese Academy of Sciences developed novel 3D bioprinting composite materials dedicated to both bone and soft tissue repair.

The findings are [published](#) in the *International Journal of Biological Macromolecules*.

"By leveraging the bioactivity of BBG and the customizable properties of these materials, we are offering better solutions for tissue repair," said Prof. Wang.

The research team developed BBG/PCL composites with varying BBG contents using selective laser sintering (SLS) technology for bone defect repair.

Evaluation on pore geometry, porosity, mechanical strength, degradation behavior, and cell compatibility of the materials, showed that the 20% BBG composite was the optimal choice. It exhibited a porosity of 68.5%, a pore size of 650 microns, and a compressive strength of 0.860 MPa, making it highly effective in supporting bone healing and regeneration.

For soft tissue repair, the researchers turned to BBG-SA bioinks. Using extrusion-based 3D printing technology, they incorporated BBG particles into sodium alginate to create bioinks with high precision and improved gelation properties.

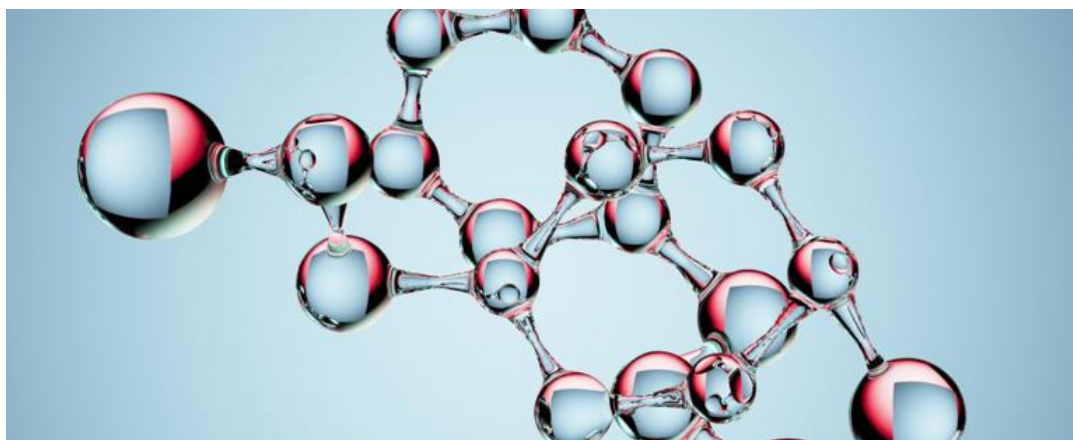
Traditional hydrogels often suffer from problems such as low printing accuracy and significant shrinkage during gelation. The BBG-SA bioinks provided an effective solution.

The optimal 0.5% BBG-SA hydrogel demonstrated excellent printability, improved structure, and enhanced biocompatibility, encouraging cell adhesion and promoting the expression of genes and proteins associated with soft tissue repair.

"Our work will significantly enhance the potential of bioactive glass in 3D bioprinting materials and provide a crucial research foundation for developing novel bio-based 3D printing materials," said Prof. Ma Kun, one of the corresponding authors of this study.

More information: Zeyong Guo et al, Borate bioactive glass enhances 3D bioprinting precision and biocompatibility on a sodium alginate platform via Ca^{2+} controlled self-solidification, *International Journal of Biological Macromolecules* (2024). DOI: [10.1016/j.ijbiomac.2024.134338](https://doi.org/10.1016/j.ijbiomac.2024.134338)

Provided by Chinese Academy of Sciences



Glass molecular structure© Provided by ScienceAlert

An analysis of a vast database of compounds has revealed a curious repeating pattern in the way matter composes itself.

Of more than 80,000 electronic structures of experimental and predicted materials studied, a whopping 60 percent have a basic structural unit based on a multiple of four.

What's so strange about this is that the research team that discovered this pattern couldn't figure out why it happens. All we know at the moment is that it's real and observable. It just evades explanation.

"Through an extensive investigation, in this work we highlight and analyze the anomalous abundance of inorganic compounds whose primitive unit cell contains a number of atoms that is a multiple of four, a property that we name rule of four," [write a team](#) led by physicist Elena Gazzarrini, formerly of the Swiss Federal Institute of Technology Lausanne in Switzerland, now at CERN.

"The study provides a starting point for future investigations on the rule's emergence, given that a fully satisfactory explanation of such anomalous distribution is as yet lacking."

One of the most basic questions about the Universe around us is why some properties are more abundant than others. Why is there [more matter than antimatter](#)? Why are the [building blocks of life left-handed](#)? And why do materials behave the way they do?

This last one is of keen interest in materials science, which seeks to understand the properties and behavior of different combinations of atoms to help develop and refine them. But it's a question that's difficult to approach, since there's just such a vast variety in the way particles can come together.

This is why Gazzarrini and her colleagues became intrigued when they noticed a pattern seeming to emerge in two databases of materials, the Materials Project (MP) database and the Materials Cloud 3-dimensional crystal structures 'source' database (MC3Dsource). The majority of inorganic compounds in both databases have unit cells – that is, the smallest possible unit that repeats within a crystal structure – based on multiples of four.

This was concerning, because theoretically all structure types should be equally represented in these databases. Having such a dominant pattern emerge could mean that there is a flaw in the data somewhere, an error that hasn't been noticed.

"A first intuitive reason could come from the fact that when a conventional unit cell (a larger cell than the primitive one, representing the full symmetry of the crystal) is transformed into a primitive cell, the number of atoms is typically reduced by four times," Gazzarini explains. "The first question we asked was whether the software used to 'primitivize' the unit cell had done it correctly, and the answer was yes."

Once they ruled out obvious errors, they had to dig deeper, and look for other patterns that might explain the rule of four.

One possible explanation was silicon, which can bind four other atoms to its central atom. If all the rule of four compounds contained silicon, that would solve the mystery... but not all the materials had silicon in them. Similarly, there was no rhyme or reason to the formation energies of the rule of four compounds.

So, the next step was to build a more powerful algorithm. This was accomplished with the aid of engineer Rose Cernosky of the University of Wisconsin. The algorithm grouped the compounds together according to similarities in their atomic properties. Once again, there was no discernible pattern.

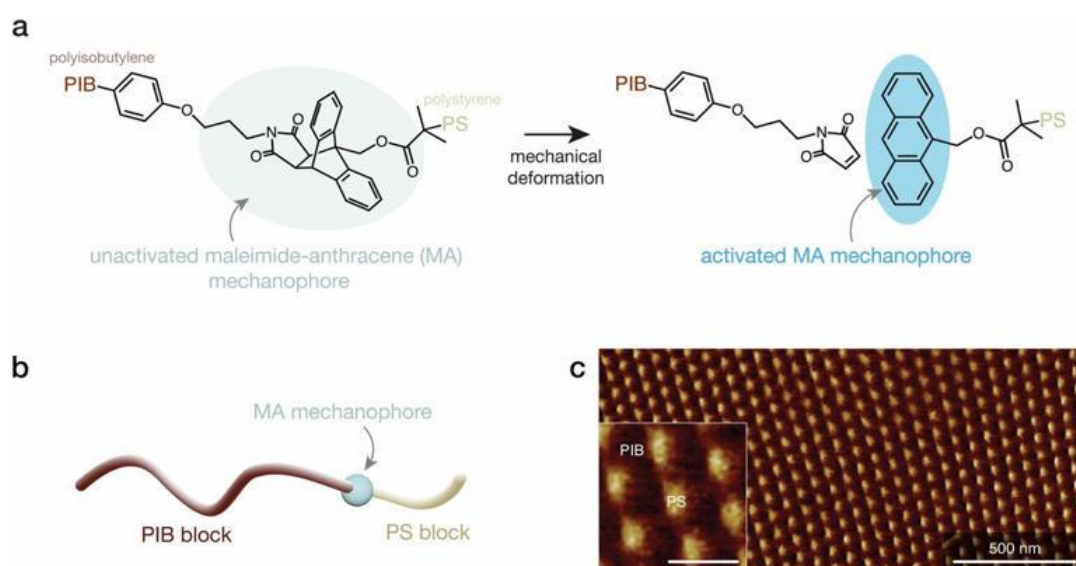
No matter what the team tried, nothing stuck. The pattern is real, and doesn't appear to be an error, but there was no other property that could accurately

predict whether or not a compound will follow the rule of four – at least when a person was the one doing the predicting.

When the team ran the data through a [machine learning algorithm](#) that can achieve high-accuracy predictions from datasets, the output results predicted whether or not a compound would obey the rule of four with up to 87 percent accuracy. This suggests that there may be something that we're missing about the rule of four compounds that could help explain what produces the pattern.

It may be currently difficult to study patterns in materials; but the findings suggest that, with ever more powerful computational techniques, we might be able to start making some fascinating headway.

The team's research has been published in [npj Computational Materials](#).



The chemistry and structure of the maleimide-anthracene-functionalized block copolymer (MA-BCP) material. Credit: Nature Communications (2024). DOI: 10.1038/s41467-024-52663-1

Sustainability is a complex problem with many different players and influenced by policies, society, and technical perspectives. Scientists within ASU's School of Molecular Sciences (SMS) and the Biodesign Institute's Center for Sustainable Macromolecular Materials and Manufacturing (SM3) are pursuing a multi-pronged approach towards a more circular economy, with projects focused on biosourcing, recycling, water purification, or carbon capture to name a few.

One obvious strategy to limit the vast amount of materials wasted is to reduce the need to produce plastics worldwide. "That is easier said than done," says associate professor Yoan Simon of ASU's SMS and SM3. "However, the antidote could simply be to prolong the lifespan of parts."

From tethers in backpacks to container lids, we are surrounded by parts that must withstand thousands of opening and closing cycles. Likewise, bike and football helmets must withstand repeated impacts and maintain a given level of protection without failing.

As the saying goes, "If it ain't broke, don't fix it! But how exactly does it break?" asks Simon. "What happens when you throw a projectile at a material supposed to absorb shocks repeatedly?"

A collaborative team co-led by the Simon research group at ASU in collaboration with the National Institute of Standards and Technology (NIST), the University of Southern Mississippi, Rensselaer Polytechnic Institute, and the Army Corps of Engineers have developed a new material that provides new information about how materials respond to impact at high velocity.

The study, [published](#) in *Nature Communications*, demonstrates how a polymer containing mechanophores -molecules that illuminate under large mechanical force- can visually record the response of the material to high-speed projectile impacts. Notably, the mechanophores captured subsurface distortions in the material, information that was previously impossible to access.

By integrating molecular-level interactions with advanced imaging techniques, the scientists can now visualize the formation of Mach cones-acoustic waves that travel faster than the speed of sound in the material.

Simply speaking, they have introduced molecular reporters that light up like a Christmas tree (or in this case a Mach cone) when the speed of the projectile exceeds the speed of sound in the material, similar to the boom that occurs when a jet fighter goes supersonic.

Simon, whose group has spent decades working on introducing luminescent or color-changing probes in materials to understand how materials respond to mechanical events, is buoyant about this collaborative piece of work.

"For years, many groups have shown activation in materials whose deformation was visible to the naked eye, limiting the applicability of these molecular probes," explains Simon.

"What's really novel about this study is that it provides us with a unique tool to look at what happens deep inside the material. We get to see how waves propagate in the material upon impact."

This work combined some heavy computational efforts with advanced analytical methods developed at NIST to evaluate the aftermath of the impact.

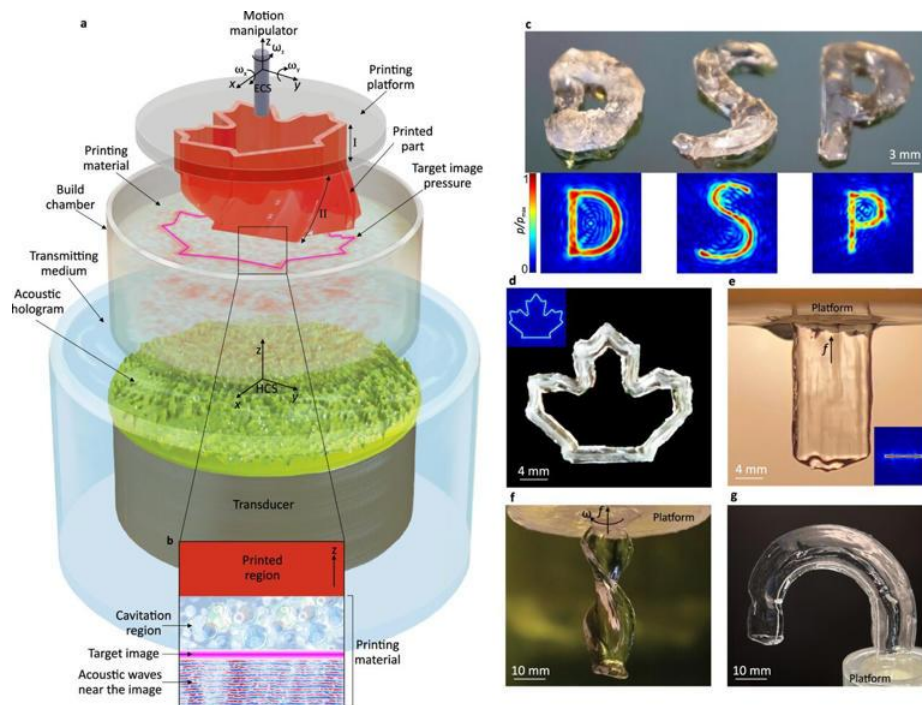
"In simple terms, we used a microscopic gun to shoot microprojectiles at materials and use ultrafast cameras and advanced microscopy to get some critical information about the energy absorbed and how it is transmitted through the material," says Simon.

Beyond this work, these probes could provide deeper insights into various impulsive events, including mild traumatic brain injuries, cold spray additive manufacturing, or hypervelocity impacts in space.

"Edwin Chan and his team (NIST) have been instrumental in getting this project together," explains Simon. "He and I were classmates in grad school at the University of Massachusetts, Amherst, many moons ago and that friendship has enabled this project to see the light of day."

More information: Polette J. Centellas et al, Mechanochemically responsive polymer enables shockwave visualization, *Nature Communications* (2024). DOI: [10.1038/s41467-024-52663-1](https://doi.org/10.1038/s41467-024-52663-1)

Provided by Arizona State University



HDSP concept and printed objects. Credit: Nature Communications (2024). DOI: 10.1038/s41467-024-50923-8

Researchers at Concordia have developed a novel method of 3D printing that uses acoustic holograms. And they say it's quicker than existing methods and capable of making more complex objects.

The process, called holographic direct sound printing (HDSP), is described in a recent article in the journal *Nature Communications*. It builds on a [method introduced in 2022](#) that described how sonochemical reactions in microscopic cavitations regions—tiny bubbles—create extremely high temperatures and pressure for trillionths of a second to harden resin into complex patterns.

Now, by embedding the technique in acoustic holograms that contain cross-sectional images of a particular design, polymerization occurs much more quickly. It can create objects simultaneously rather than voxel-by-voxel.

In order to retain the fidelity of the desired image, the hologram remains stationary within the printing material. The printing platform is attached to a robotic arm, which moves it based on a pre-programmed algorithm-designed pattern that will form the completed object.

Muthukumaran Packirisamy, a professor in the Department of Mechanical, Industrial and Aerospace Engineering, led the project. He believes this can improve printing speed by up to 20 times while at the same time using less energy.

"We can also change the image while the operation is under way," he says. "We can change shapes, combine multiple motions and alter materials being printed. We can make a complicated structure by controlling the feed rate if we optimize the parameters to get the required structures."

Related video: Proto Hologram: Revolutionizing Communication and Entertainment Tech (Dailymotion)

A technological leap

According to the researchers, the precise control of acoustic holograms allows it to store information of multiple images in a single hologram. This means multiple objects can be printed at the same time at different locations within the same printing space.

As a result, acoustic holography will be a launching pad for innovation across any number of fields: it can be used to create complex tissue structures, localized drug and cell delivery systems and advanced tissue engineering. Real-world applications include the creation of new forms of skin grafts that can enhance healing and improved drug delivery for therapies that require specific therapeutic agents at specific sites.

He adds that, as soundwaves can penetrate opaque surfaces, HSDP can be used to print inside a body or behind solid material. This can be helpful in repairing damaged organs or delicate parts located deep within an airplane.

The researchers believe that HDSP has the potential to be a paradigm-shifting technology. He compares it to the advancement light-based 3D printing technology saw with the evolution from stereolithography, in which a laser is used to harden a single point of resin into a solid object, to digital light processing, which cures entire layers of resin simultaneously.

"You can imagine the possibilities," he says. "We can print behind opaque objects, behind a wall, inside a tube or inside the body. The technique that we already use and the devices that we use have already been approved for medical applications."

More information: Mahdi Derayatifar et al, Holographic direct sound printing, *Nature Communications* (2024). DOI: [10.1038/s41467-024-50923-8](https://doi.org/10.1038/s41467-024-50923-8)

Provided by Concordia University

Combining unique methods, researchers discover new protein functions, explore physical space of proteins

Electron density of wild-type and D110C T4 bacteriophage crystal structures. Credit: Nature Structural & Molecular Biology (2024). DOI: [10.1038/s41594-023-01177-3](https://doi.org/10.1038/s41594-023-01177-3) © Provided by Phys.org

Researchers in the lab of John Kuriyan, professor of biochemistry and dean of the School of Medicine Basic Sciences, have revealed a key element of how a molecular machine responsible for high-speed DNA replication works. The results of their study build on growing theories of molecular evolution.

The article, "[Autoinhibition of a clamp-loader ATPase revealed by deep mutagenesis and cryo-EM](#)," was published in the journal *Nature Structural & Molecular Biology*.

Clamp loaders—proteins that help load DNA replication machinery onto the DNA—have a variety of biological functions that change as their structure evolves. These proteins are found in all of life—from single-celled organisms to humans. Over the last decade, the structure and function of the clamp loader were thought to be well understood based on a handful of snapshots of its three-dimensional structure. This research, led by co-first authors postdoctoral fellow

Kendra Marcus and research assistant professor Yongjian Huang, revealed the bigger picture.

"By combining deep mutagenesis and cryogenic electron microscopy , we found a key structural intermediate that was not seen in these [snapshots] and illustrated the conformational changes needed for the clamp loader to do its job," Marcus said. "Not only this, but we see regions of the protein that we thought were 'unimportant' participate in highly coordinated processes."

The unique pairing of deep mutagenesis and cryo-EM is what led to this discovery. Deep mutagenesis maps important regions of a protein by revealing its mutational sensitivity, or how a protein responds to a mutation, and cryo-EM produces three-dimensional visualizations that aren't usually seen in crystal structures. Studying the mutational sensitivity of proteins sheds light on how the protein architecture influences its function and how evolution can tune these variables to give proteins new tasks.

The researchers first inferred a new state of the clamp loader based on the deep mutagenesis data and then visualized it using cryo-EM, which revealed a previously unseen conformational state, or arrangement of atoms that gives the clamp loader its shape.

"One of the unique strengths of cryo-EM lies in its power to capture the ensemble of conformational states adopted by these macromolecular machines, such as the clamp-loader," Huang said. "In this study, cryo-EM allows us to visualize the molecular details of a newly discovered conformational state and the critical conformational changes required for the function of clamp loader."

These findings have implications in evolutionary theory and how proteins use 'insignificant' places in these molecular machines to become conditionally important in the adaptation of new functions, Marcus said.

Following this discovery, the Kuriyan lab will leverage machine learning techniques to design and test new clamp loader proteins based on their current findings. These types of experiments offer tremendous utility toward understanding how proteins change function because of disease-related mutations or in response to drugs.

"We hope that these results inspire biochemists and molecular biophysicists to apply creative methods to explore the physical space of proteins," Marcus said. "This work illustrates how evolutionary theory can elevate our structurally oriented understanding of protein functions."

More information: Kendra Marcus et al, Autoinhibition of a clamp-loader ATPase revealed by deep mutagenesis and cryo-EM, *Nature Structural & Molecular Biology* (2024). DOI: [10.1038/s41594-023-01177-3](https://doi.org/10.1038/s41594-023-01177-3)

Provided by Vanderbilt University

Living plastics: A new solution for plastic degradation through synthetic biology

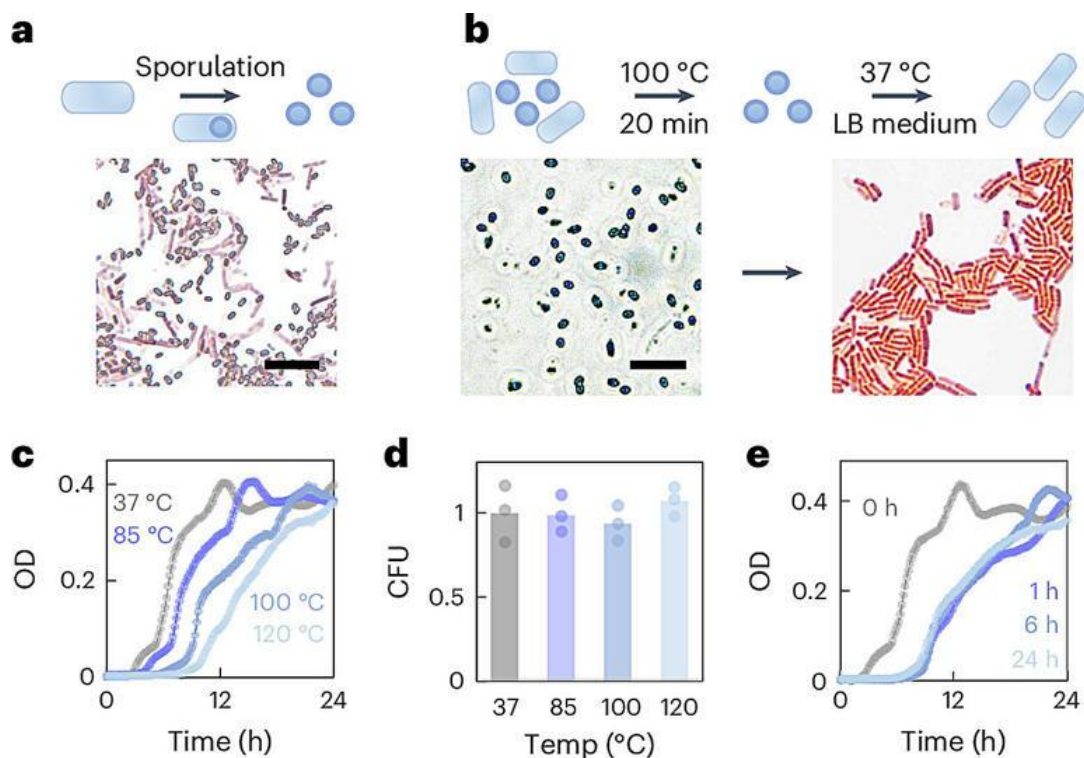
Plastics are widely used but difficult to degrade, posing an ecological challenge. A team from SIAT developed degradable "living plastics" using synthetic biology and polymer engineering. They engineered *Bacillus subtilis* spores to produce *Burkholderia cepacia* lipase (BC-lipase), an enzyme that breaks down plastic. These spores were mixed with poly(caprolactone) (PCL) to create the plastics, maintaining the material's physical properties. When the plastic surface is eroded, the spores release the enzyme, leading to nearly complete breakdown of the plastic. Credit: Dai Zhuojun

A study [published](#) in *Nature Chemical Biology* leverages the natural resilience of spores, which can endure extreme environmental conditions, by programming them to secrete plastic-degrading enzymes under specific circumstances. These spores are embedded into plastic matrices through standard plastic processing methods, such as high temperature, high pressure, or the use of organic solvents.

In normal conditions, the spores remain dormant, ensuring the plastic's stable performance. However, when exposed to specific triggers like surface erosion or composting, the spores activate and initiate the degradation process, leading to the plastic's complete breakdown.

The invention of plastics has improved our daily lives, but the massive production and improper disposal of plastic waste have made plastic pollution a major environmental issue. In 2016, Yoshida and team discovered a bacterium, *Ideonella sakaiensis*, in poly (ethylene terephthalate) (PET)-contaminated soil near

a recycling facility in Japan. This bacterium can grow using PET as its main carbon source by producing two key enzymes: PETase and MHETase.



The spores were resilient to environmental perturbations. Credit: Nature Chemical Biology (2024). DOI: 10.1038/s41589-024-01713-2, <https://www.nature.com/articles/s41589-024-01713-2>

Since then, numerous synthetic biology research has been focusing on discovering, designing and evolving the relevant plastic-degrading enzymes. There has been little exploration of innovative methods for creating degradable plastics.

Dormant spores and living plastics

Microorganisms have developed intrinsic mechanisms to defend harsh conditions over billions of years. One classical example is the formation of spores that are resilient to dryness, high temperatures and high pressure (similar conditions in plastics processing).

Using synthetic biology, the research team engineered *Bacillus subtilis* with a genetic circuit to control the secretion of a plastic-degrading enzyme (lipase BC

from *Burkholderia cepacia*). Under stress from heavy metal ions, *Bacillus subtilis* forms spores.

The team mixed these engineered spores with poly (caprolactone) (PCL) plastic granules and produced spore-containing plastics through high-temperature extrusion or solvent dissolution. Tests showed that these "living plastics" had similar physical properties to regular PCL plastics. During daily use, the spores remain dormant, ensuring the plastic's stable performance.

Spore release and degradation initiation

The first key step in plastic degradation is to release the spores embedded in the living plastic for cell reviving. Researchers have first demonstrated two methods of spore release. One method uses an enzyme (lipase CA) to erode the plastic surface.

These released spores then germinated and expressed the lipase BC, which bound to the ends of PCL polymer chains and near-completely degraded the PCL molecules (final molecular weight <500 g/mol). The results showed that living plastic could degrade efficiently within 6–7 days, while ordinary PCL plastic subjected only to surface damage (lipase CA) still had a large amount of plastic debris after 21 days.

Another method for releasing spores is composting. In the absence of any additional exogenous agents, living plastics in soil could completely degrade within 25–30 days, while traditional PCL plastic took about 55 days to degrade to a level that was invisible to the naked eye.

Beyond PCL plastics

As mentioned earlier, PCL's processing conditions are relatively "mild" among plastics. To verify the system's general applicability, the team continued to test other commercial plastic systems. They mixed spores carrying GFP expression plasmids with PBS (polybutylene succinate), PBAT (polybutylene adipate-co-

terephthalate), PLA (polylactic acid), PHA (polyhydroxyalkanoates), and even PET (poly [ethylene terephthalate]) and processed the mixture at temperatures as high as 300°C.

By releasing the spores through physical grinding, they surprisingly found that the spores could still revive and express the GFP. These results have laid a solid foundation for extending the method with other types of plastics.

To validate the potential for scaling up the system, the research team also conducted a small-scale industrial test on a PCL system using a single-screw extruder. The generated living PCL still exhibited rapid and efficient degradation property (degrading within 7 days). In the absence of external factors, the living PCL maintained a stable shape, demonstrating its robustness during the service (stable in Sprite for two months).

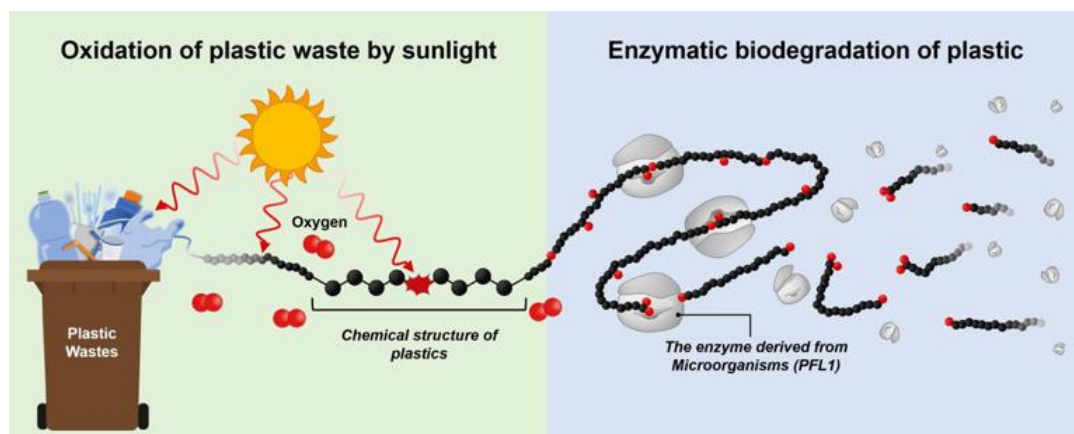
This study provides a novel method for fabricating green plastics that can function steadily when the spores are latent and decay when the spores are aroused and sheds light on the development of materials for sustainability.

The research, titled "Degradable Living Plastics Programmed by Engineered Spores," was performed by Dr. Dai Zhuojun's research group at the Shenzhen Institute of Advanced Technology (SIAT), Chinese Academy of Sciences (CAS).

More information: Tang, C. et al. Degradable living plastics programmed by engineered spores, *Nature Chemical Biology* (2024). DOI: [10.1038/s41589-024-01713-2](https://doi.org/10.1038/s41589-024-01713-2). www.nature.com/articles/s41589-024-01713-2

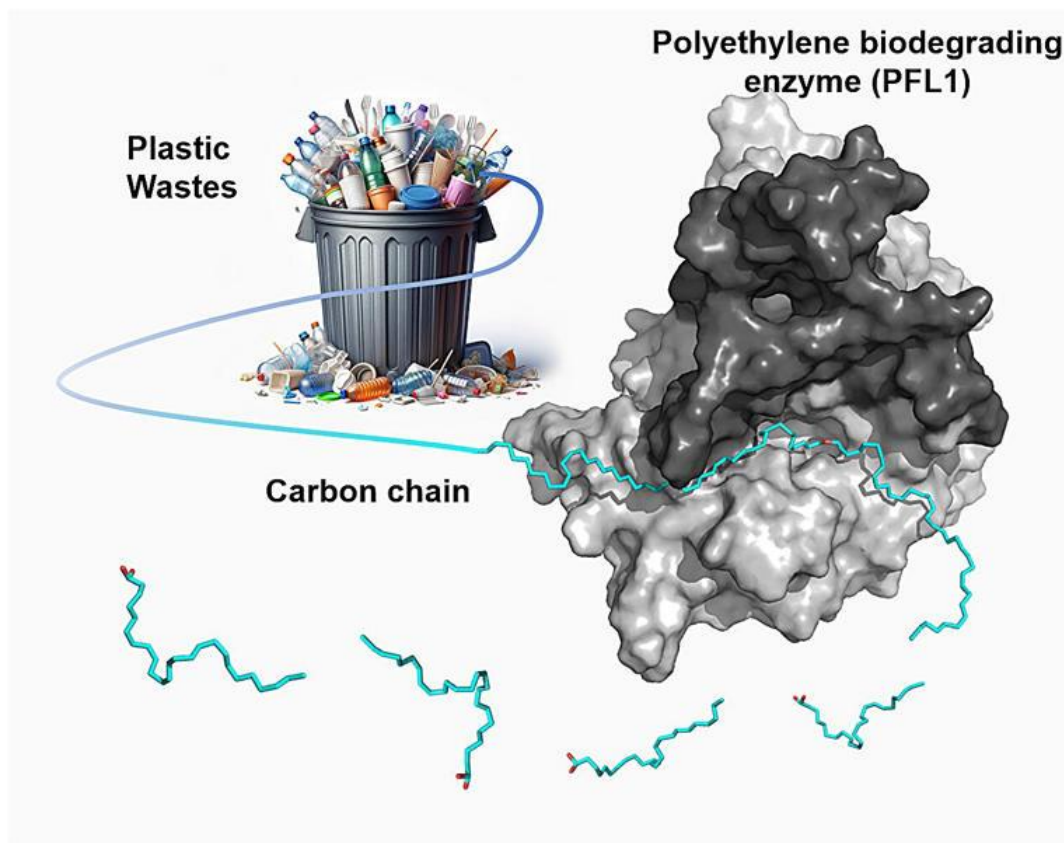
Provided by Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences

Bacteria-derived enzyme shows potential for polyethylene biodegradation



A diagram illustrating the process in which plastic waste is oxidized by sunlight and then degraded by enzymes.
Credit: Korea Institute of Science and Technology

Every year, 400 million tons of plastic products are produced worldwide, half of which are single-use items discarded within a year. In particular, non-biodegradable plastic waste, which takes over 500 years to decompose naturally, is mostly treated through landfills. During this process, microplastics are formed, disrupting ecosystems or accumulating in organisms, increasing their harmful effects. With landfill sites worldwide reaching capacity, addressing this issue has become increasingly urgent.



Surface images of polyethylene before and after enzyme treatment, captured using scanning electron microscopy.
Credit: Korea Institute of Science and Technology

Dr. Ahn, Jung Ho's research team at the Clean Energy Research Center of the Korea Institute of Science and Technology (KIST) has developed a technology that uses enzymes derived from microorganisms to biodegrade polyethylene.

Polyethylene accounts for 35% of the plastic produced annually and is widely used for various purposes, including packaging materials and plastic bags. Like other non-biodegradable plastics, polyethylene is often disposed in the ocean or soil, where it undergoes continuous oxidation due to air and sunlight.

A research team has successfully identified an enzyme capable of breaking down this oxidized polyethylene for the first time. The findings are [published](#) in the journal *Bioresource Technology*.

The research team focused on lipase, an enzyme that breaks down the natural polymer lipid, which has a chemically similar structure to polyethylene. They then developed a purification and production process for lipase based on synthetic biology and successfully discovered *Pelosinus fermentans* lipase 1 (PFL1).

When this lipase, derived from the anaerobic bacterium *Pelosinus fermentans*, was applied to polyethylene, the weight-average molecular weight decreased by 44.6% and the number-average molecular weight by 11.3%, both indicating the degree of biodegradation. Additionally, through electron microscopy, they observed tears and cracks on the surface of the degraded polyethylene, confirming the biodegradation process caused by the enzyme.

The research team also used computer simulations to analyze the interaction between PFL1 and polyethylene, elucidating the biodegradation mechanism for the first time. They observed that the PFL1 enzyme binds strongly to the surface of polyethylene and then breaks it down into small segments.

These findings are expected to aid in enhancing the properties of the PFL1 enzyme and in the search for new plastic biodegrading enzymes.

Current methods for plastic waste disposal, such as incineration and chemical degradation, generate toxic substances during decomposition and require expensive catalysts.

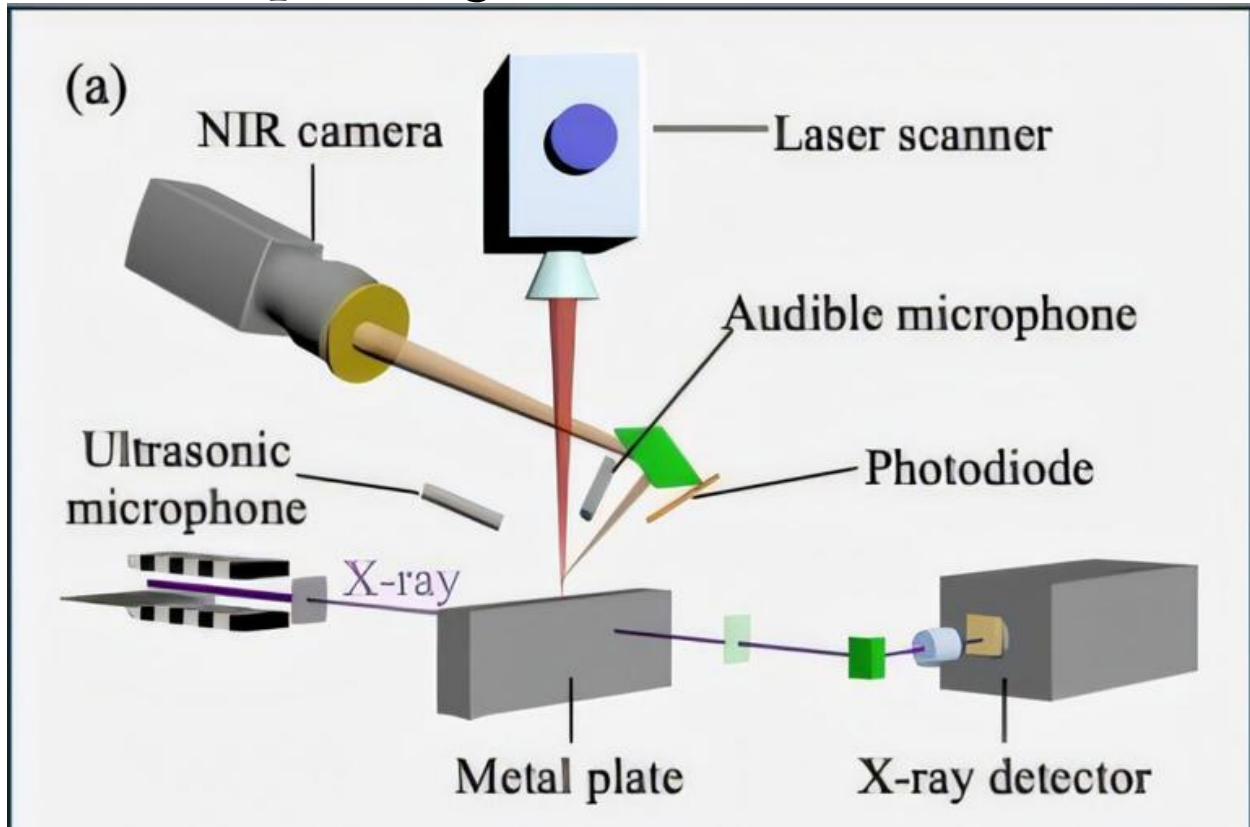
However, the PFL1 enzyme can be mass-produced using renewable resources, and the process does not generate toxic substances, making it an environmentally friendly technology. Furthermore, the alcohols and carboxylic acids produced during the biodegradation process can be used for plastic re-synthesis or the production of chemical materials.

Dr. Ahn stated, "The newly discovered enzyme has shown the possibility of biodegrading non-degradable plastic waste, which was previously difficult to handle. We aim to commercialize the technology to solve the landfill saturation issue and achieve a sustainable circular economy for plastics."

More information: Do-Wook Kim et al, Biodegradation of oxidized low density polyethylene by *Pelosinus fermentans* lipase, *Bioresource Technology* (2024). DOI: [10.1016/j.biortech.2024.130871](https://doi.org/10.1016/j.biortech.2024.130871)

Provided by National Research Council of Science and Technology

Machine learning enhances defect detection in metal 3D printing



Approach for detecting keyhole pore generation in laser powder bed fusion. Credit: Zhongshu Ren, Jiayun Shao, Tao Sun at Northwestern University

Researchers from Northwestern University, University of Virginia, Carnegie Mellon University, and Argonne National Laboratory have made a significant advancement in defect detection and process monitoring for laser powder bed fusion (LPBF) additive manufacturing.

By using accessible sensors (such as microphones and photodiodes), along with machine learning, they achieved over 90% accuracy with a temporal resolution of 0.1 milliseconds in detecting keyhole pore formation. This breakthrough paves the way for intelligent, closed-loop control systems for LPBF and a faster qualification and certification process for metal additive manufacturing parts.

The work has recently been [published](#) in the online edition of *Materials Futures*.

As 3D printing continues to transform manufacturing, particularly in high-stakes fields like aerospace, defense, and energy, ensuring the quality of printed parts is crucial. One major challenge in metal 3D printing, specifically in LPBF, is the formation of microscopic defects known as "keyhole" pores. These pores can significantly weaken parts and reduce their service life, making them unsuitable for demanding applications. Detecting these defects in real-time during the printing process has been challenging due to the speed and complexity of LPBF technology.

To address this challenge, the researchers developed an innovative, machine learning-based approach that uses simple light and sound sensors to monitor the printing process and accurately detect when and where keyhole pores form. The core of this approach lies in measuring the oscillations of the keyhole—a vapor depression formed in the melt pool during printing.

High-speed synchrotron X-ray imaging was used to establish a precise "ground truth," which helped train the machine learning model to recognize conditions that lead to pore formation. Remarkably, the model achieved over 90% accuracy in detecting defects with a temporal resolution as short as 0.1 milliseconds.

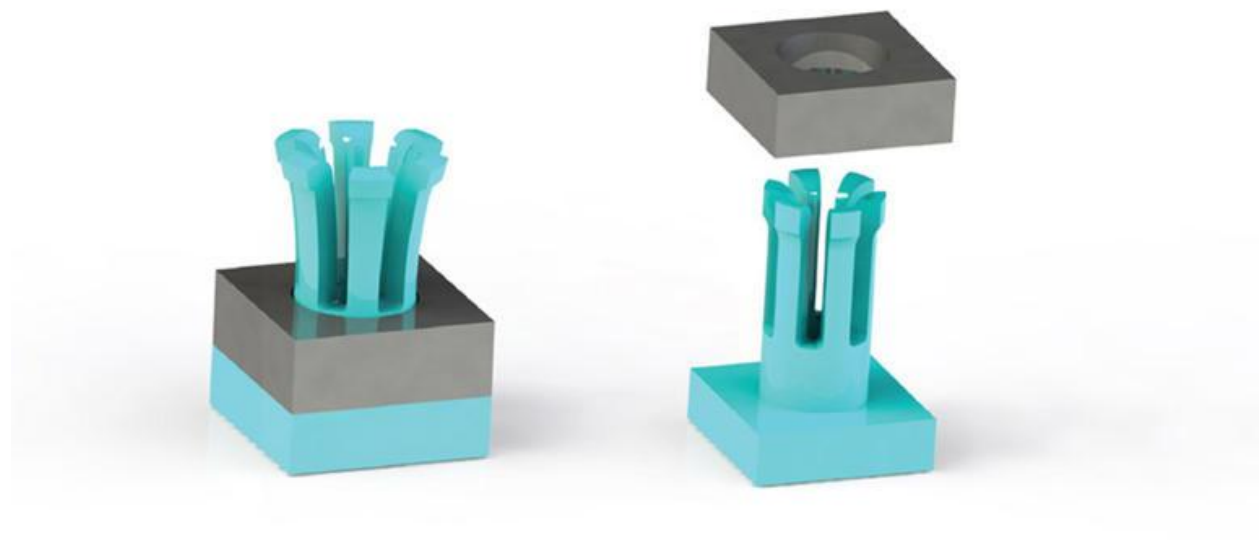
The potential impact of this technology is substantial. With this approach, manufacturers could detect defects during the printing process, allowing for adjustments or pauses to prevent the production of flawed parts. This capability not only reduces the time and cost associated with post-production inspections and repairs but also helps maintain the high quality required in applications where safety is paramount.

Looking forward, the researchers are focused on making this technology more accessible and scalable for widespread use. Future work will aim to further improve the accuracy of the method by integrating additional sensors. While this study achieved high accuracy in single-track laser melting experiments, future efforts will extend this approach to 3D part builds, including analyzing pore movements within the melt pool and assessing pore removal during repeated melting cycles.

More information: Zhongshu Ren et al, Sub-millisecond keyhole pore detection in laser powder bed fusion using sound and light sensors and machine learning, *Materials Futures* (2024). DOI: [10.1088/2752-5724/ad89e2](https://doi.org/10.1088/2752-5724/ad89e2)

Provided by Songshan Lake Materials Laboratory

Goodbye to nuts, bolts: 3D-printed nickel-titanium alloys promise stronger structures



Goodbye to nuts, bolts: 3D-printed nickel-titanium alloys promise stronger structures

Researchers from Texas A&M University and Sandia National Laboratories have significantly improved a new joining technology called interlocking metasurfaces (ILMs).

This technology aims to enhance the strength and stability of structures compared to traditional methods like bolts and adhesives.

The researchers achieved this by using shape memory alloys (SMAs).

ILMs offer the potential to transform the mechanical joint design in manufacturing for aerospace, robotics, and biomedical devices.

Shape memory alloys

"ILMs are poised to redefine joining technologies across a range of applications, much like Velcro did decades ago," said Dr. Ibrahim Karaman, professor and head of the Department of Materials Science and Engineering Department at Texas A&M.

"In collaboration with Sandia National Laboratories, the original developers of ILMs, we have engineered and fabricated ILMs from shape memory alloys. Our research demonstrates that these ILMs can be selectively disengaged and re-engaged on demand while maintaining consistent joint strength and structural integrity."

Similar to Legos or Velcro, ILMs enable the [joining](#) of two bodies by transmitting force and constraining movement. Until now, this joining method has been passive, requiring force for engagement.

Using 3D printing, the teams designed and fabricated active ILMs by integrating SMAs, specifically [nickel-titanium](#), which can recover their original shape after deformation by changing temperatures.

Control of joining technology through temperature changes opens new possibilities for smart, adaptive structures without loss in strength or stability and with increased options for flexibility and functionality.

"Active ILMs have the potential to revolutionize mechanical joint design in industries requiring precise, repeatable assembly and disassembly," said Abdelrahman Elsayed, graduate research assistant in the materials science and engineering department at Texas A&M.

Stronger structures

Practical applications include designing reconfigurable aerospace engineering components where parts must be assembled and disassembled multiple times.

Active ILMs could also provide flexible and adaptable joints for robotics-enhancing functionality.

The ability to adjust implants and prosthetics to body movements and temperatures in biomedical devices could offer patients a better option.

The current findings utilized the shape memory effect of SMAs to recover the ILMs' shape by adding heat.

The researchers hope to build on these findings by using the superelasticity effect of SMAs to create ILMs that can withstand large deformation and instantaneously recover under very high-stress levels.

"We anticipate that incorporating SMAs into ILMs will unlock numerous future applications, though several challenges remain," said Karaman.

"Achieving superelasticity in complex 3D-printed ILMs will enable localized control of structural stiffness and facilitate reattachment with high locking forces. Additionally, we expect this technology to address longstanding challenges associated with joining techniques in extreme environments. We are highly enthusiastic about the transformative potential of ILM technology."

Other contributors include Dr. Alaa Elwany, associate professor in the Wm Michael Barnes '64 Department of Industrial and Systems Engineering, and doctoral student Taresh Guleria in the industrial systems and engineering department.

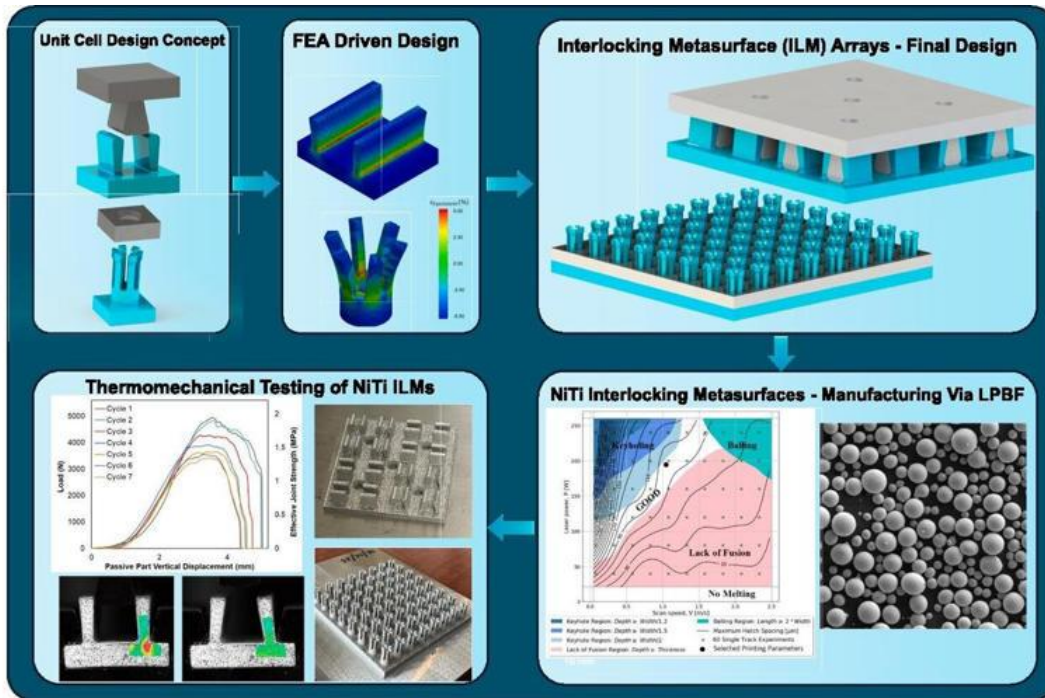
The Texas A&M Engineering Experiment Station (TEES), the official research agency of Texas A&M Engineering, administers funding for this research.

Move over, bolts: Meet the future of stronger structural connections with interlocking metasurfaces



An individual cell of the two proposed versions of ILMs in their different engagement states. Credit: Dr. Ibrahim Karaman

In a collaborative effort between Texas A&M University and Sandia National Laboratories, researchers have significantly improved a new joining technology, interlocking metasurfaces (ILMs), designed to increase the strength and stability of a structure in comparison to traditional techniques like bolts and adhesives, using shape memory alloys (SMAs).



Credit: Materials & Design (2024). DOI: 10.1016/j.matdes.2024.113137

ILMs offer the potential to transform mechanical joint design in manufacturing for aerospace, robotics and biomedical devices.

"ILMs are poised to redefine joining technologies across a range of applications, much like Velcro did decades ago," said Dr. Ibrahim Karaman, professor and head of the Department of Materials Science and Engineering Department at Texas A&M.

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The findings can be found in [Materials & Design](#).

Similar to Legos or Velcro, ILMs enable the joining of two bodies by transmitting force and constraining movement. Until now, this joining method has been passive, requiring force for engagement.

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Practical applications include designing reconfigurable aerospace engineering components where parts must be assembled and disassembled multiple times. Active ILMs could also provide flexible and adaptable joints for robotics-enhancing functionality. In biomedical devices, the ability to adjust implants and prosthetics to body movements and temperatures could offer a better option for patients.

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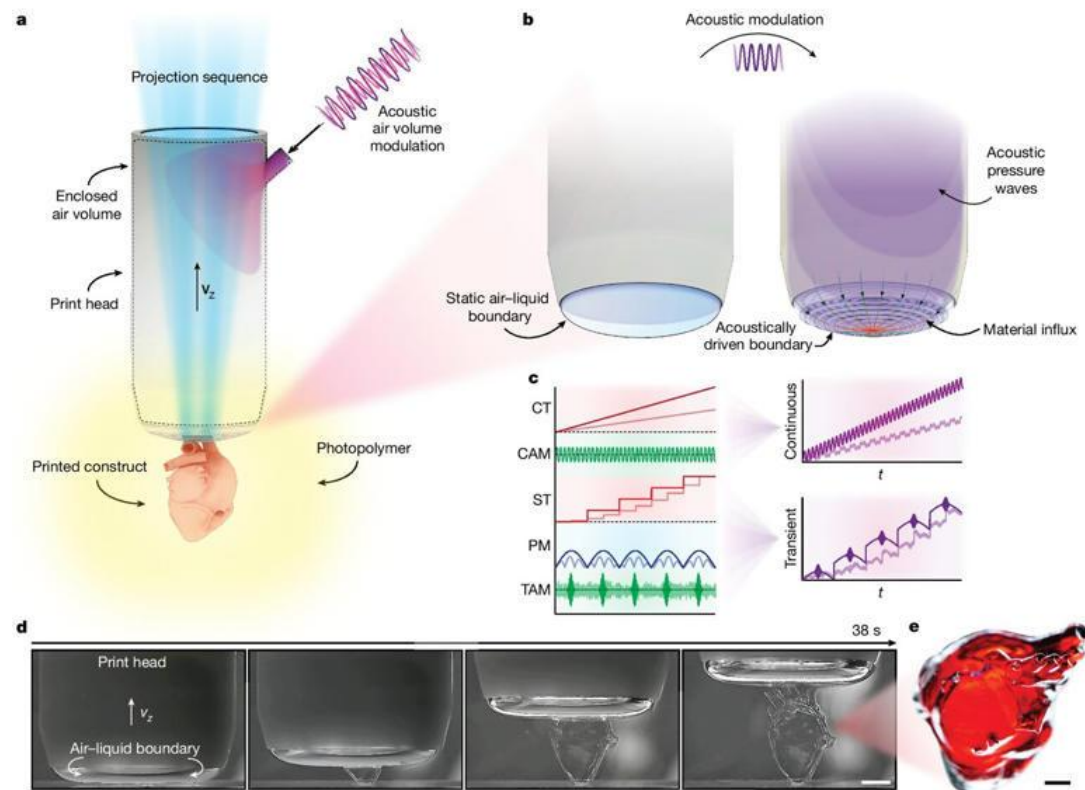
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More information: Abdelrahman Elsayed et al, Active interlocking metasurfaces enabled by shape memory alloys, *Materials & Design* (2024). DOI: [10.1016/j.matdes.2024.113137](https://doi.org/10.1016/j.matdes.2024.113137)

Provided by Texas A&M University College of Engineering

New digital light manufacturing approach resolves common problems associated with 3D printing



Schematic illustration of DIP. Credit: Nature (2024). DOI: [10.1038/s41586-024-08077-6](https://doi.org/10.1038/s41586-024-08077-6)

A team of materials scientists, medical researchers and engineers affiliated with a large number of institutions across Australia has developed a new way to conduct digital light manufacturing that overcomes problems with current methods. In their [paper](#) published in the journal *Nature*, the group describes their new technique, how it works and ways it might be used.

Traditional 3D printing involves precisely spraying a liquid material from a nozzle onto an object where it hardens as it cools, causing it to grow as layers are added. Digital light manufacturing is a type of 3D printing that involves the use of a laser to produce 3D objects instead of a nozzle—the laser light causes a liquid material to harden.

Two approaches have been developed. The first is window-based, in which a laser is fired up through a transparent window in a tank of precursor liquid and onto a platform, resulting in the precursor hardening and growing the desired object downward. The second approach is called top-down, and as its name suggests, it involves firing a laser down into a precursor solution, resulting in an object growing upward.

Both approaches suffer from problems ensuring a steady flow of the precursor and in dissipating heat. In this new effort, the research team has developed a modified form of the top-down approach that overcomes both problems—they call it dynamic interface printing.

The method involves changing the point of printing to the meniscus, which is the curve of the surface of the (precursor) liquid. It is done by employing a tank to hold the precursor fluid and then using a tubular pressurized printhead situated above the tank. It has a valve that allows for adding acoustic vibrations that serve to oscillate the air pressure.

To print, light patterns are projected down through the tube onto the meniscus as the printhead moves. The desired object grows upward from the bottom of the tank, immersed in the precursor fluid. The pressure inside of the tube is used to control the shape taken by the meniscus. Recoating of the liquid onto the object being printed is controlled by surface tension and is accelerated by the vibrations, resulting in an even flow of the precursor.

Testing showed that the method is capable of printing at speeds up to 0.7 millimeters per second, with few errors and minimal problems with heat dispersal due to continuous movement of the precursor fluid.

More information: Callum Vidler et al, Dynamic interface printing, *Nature* (2024). DOI: [10.1038/s41586-024-08077-6](https://doi.org/10.1038/s41586-024-08077-6)

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Novel etching technique enhances absorptivity of powders for metal 3D-printing

A team from Lawrence Livermore National Laboratory, Stanford University and the University of Pennsylvania introduced a novel wet chemical etching process that modifies the surface of conventional metal powders used in 3D printing. By creating nanoscale grooves and textures, the researchers reportedly increased the absorptivity of these powders by up to 70%, allowing for more effective energy transfer during the laser melting 3D printing process. Credit: Brendan Thompson/LLNL

In a significant advancement for metal additive manufacturing, researchers at Lawrence Livermore National Laboratory (LLNL) and their academic partners have developed a technique that enhances the optical absorptivity of metal powders used in 3D printing.

The approach, which involves creating nanoscale surface features on metal powders, promises to improve the efficiency and quality of printed metal parts, particularly for challenging materials like copper and tungsten, according to researchers.

Additive manufacturing (AM)—more commonly known as 3D printing—has transformed the way products are designed and produced, allowing for the creation of complex geometries and customized components that traditional manufacturing methods struggle to achieve.

However, one of the persistent challenges in laser powder-bed fusion (LPBF) metal 3D printing is the high reflectivity of certain metals, which can lead to inefficient energy absorption during the printing process and can even damage some printing machines. This inefficiency often results in inadequate print quality and increased energy consumption, according to researchers.

Tackling this issue head-on in a study [published](#) as the September cover of the journal *Science Advances*, the team led by scientists from LLNL, Stanford University and the University of Pennsylvania has introduced a novel wet chemical etching process that modifies the surface of conventional metal powders. By creating nanoscale grooves and textures, the researchers reported they have increased the absorptivity of these powders by up to 70%, allowing for more effective energy transfer during the laser-melting process.

"Currently, with standard commercial laser-based machines, high-quality pure copper metal AM is generally considered infeasible," said co-lead author and LLNL materials scientist Philip DePond. "Our method combines the effects of traditional surface treatments [that increase absorptivity] but doesn't compromise the purity or material properties of copper that make it desirable—namely its high thermal and electrical conductivity.

"More fundamentally, we showed that laser-powder interactions extend to regions beyond the melt pool. This has been shown in simulations, especially those of high-fidelity done at LLNL, but not really detailed experimentally. We demonstrated that those interactions exist and can be beneficial to the process."

The wet-etching technique is relatively simple, but highly effective, researchers said. The team immersed metal powders such as copper and tungsten in specially formulated solutions that selectively remove material from the surface.

This process results in the formation of intricate nanoscale features that enhance the powder's ability to absorb laser light. To characterize the surface features of the etched powders, the researchers employed advanced imaging techniques including synchrotron X-ray nanotomography, which provided detailed 3D representations of the powder particles, allowing the team to analyze and accurately model the electromagnetic influence of the nanoscale modifications.

The team conducted extensive experiments, to demonstrate and attribute the mechanism of increased absorptivity to the modified powders. Process optimization studies and eventually bulk and complex sample printing were performed using custom-built LPBF systems housed at LLNL's Advanced Manufacturing Laboratory and MIRILIS laser-material interaction laboratory.

Researchers said the enhanced absorptivity of metal powders is a promising step forward for reducing energy consumption in manufacturing, particularly as the demand for more sustainable and efficient manufacturing processes continues to grow.

One of the team's key findings was that they could print high-purity copper and tungsten structures using lower energy input, less than 100 J/mm^3 for copper, which is around the range for high density titanium and stainless-steel alloys, and $\sim 700 \text{ J/mm}^3$ for tungsten, around 1/3 less energy than is typically employed.

"In a broad sense, we are enabling the printing of copper without the risk of damaging the AM system itself," DePond explained. "The process parameter window becomes wider as well, which allows a wider variety of scanning conditions to be explored, which often are needed when printing complex geometries. Finally, a handful of machine manufacturers have even gone the great lengths of creating entirely new machines to process copper and other highly reflective materials. These turn out to be nearly double the cost of a traditional machine, so the barrier of entry to printing these materials is prohibitively high."

The potential applications of the findings could have an immediate impact on production. Researchers said the ability to print with less energy not only reduces operational costs but also minimizes the environmental impact of the manufacturing process and opens copper 3D printing up to a whole new contingent of producers.

"This method enables even commercial machines of fairly low laser power output to print copper, thus democratizing the process and providing access to a wider community," Energy Security Program leader Dan Flowers said, adding that he hopes the work will allow industry to better utilize copper in advanced manufacturing.

"From heat exchange to catalysis, more efficient printing of copper supports the development of many clean energy and decarbonization technologies," Flowers said. "The LLNL community and our low-carbon energy mission stand to benefit from this capability."

The enhanced absorptivity and improved powder dynamics also could enable the production of high-quality printed parts with greater relative densities. In their experiments, the researchers achieved relative densities of up to 92% with half the energy input compared to other printed copper components, and over 99% with higher energies, indicating the potential for producing stronger and more durable metal parts.

The team is next looking to examine the effects of nanotexturing on elemental mixing of powders, such as materials that typically need drastically different energies to melt.

More information: Ottman A. Tertuliano et al, High absorptivity nanotextured powders for additive manufacturing, *Science Advances* (2024). DOI: [10.1126/sciadv.adp0003](https://doi.org/10.1126/sciadv.adp0003)

Provided by Lawrence Livermore National Laboratory

Accelerating 3D nanofabrication using a sensitive cationic photoresist

© Provided by Phys.org

Two-photon laser direct writing lithography or TPL is a cutting-edge technique used for creating nanoscale structures. It works by leveraging specific materials known as photoresists, which change their chemical properties when exposed to light. These materials absorb laser light in a unique way, enabling precise control during exposure to laser beams.

Unlike conventional ultraviolet (UV) photolithography, which uses light to create images, TPL can directly build complex three-dimensional (3D) shapes that include features like overhangs and suspended elements at a resolution smaller than the width of a human hair. However, the production speed of TPL cannot match that of UV lithography. To speed up the TPL process, highly sensitive photoresists are essential.

To date, the classic SU-8 epoxy photoresist series remains a popular choice because of its numerous benefits, such as a high depth-to-width ratio, minimal shrinkage, and no issues with oxygen interference during processing. However, cationic photoresists like SU-8 generally take longer to fabricate and result in less detailed structures compared to free-radical-based photoresists, which can limit their applications in creating intricate microdevices.

Recently, a research team headed by Professor Cuifang Kuang from the Zhejiang Lab at Zhejiang University made a significant breakthrough by developing a new type of cationic epoxy photoresist. This innovative material exhibited around 600

times greater sensitivity to two-photon laser exposure than the traditional SU-8 photoresist, thanks to a unique bimolecular sensitization system.

The findings are [published](#) in the journal *Advanced Functional Materials*.

Professor Kuang explains, "We demonstrated the 3D fabricated structures with fine features of less than 200 nanometers (nm) and a fast writing speed of 100 millimeters/second (mm/s) using nanolattices to show potential application for high-throughput nanofabrication of microscopic 3D devices."

The bimolecular photosensitized initiation system developed in this research effectively separates the processes of light absorption and energy transfer, enhancing the material's ability to absorb light. The researchers introduced 5-nitroacenaphthene, a photosensitizer that broadens the absorption spectrum, allowing it to capture light wavelengths down to 430 nm.

By combining this photosensitizer with pyrazoline-based sulfonium salt as a photoacid generator (PAG) and polyfunctional epoxy as a building block, the team created a new cationic photoresist called TP-EO. This innovative material can achieve an impressive lithography speed of 100 mm/s and can produce fine features with a minimum width of about 170 nm. The performance of TP-EO in terms of speed and resolution is better than other existing cationic photoresists.

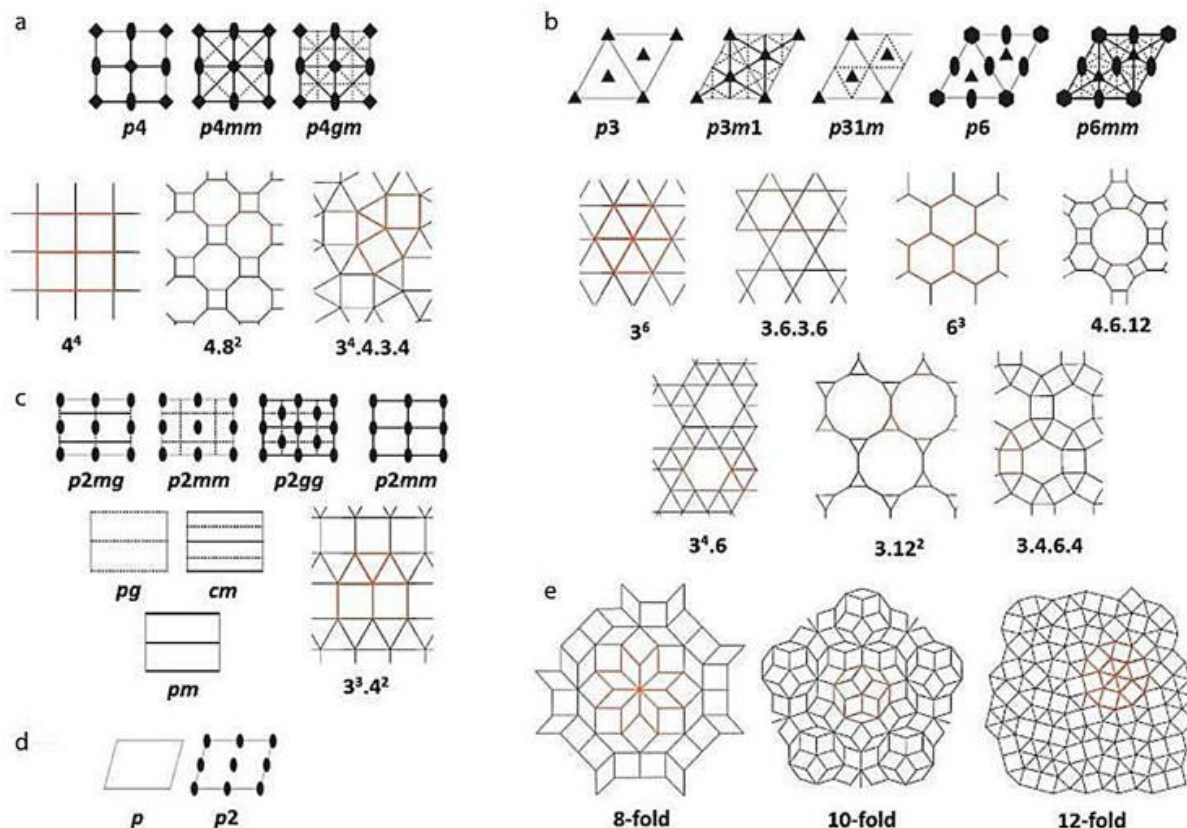
To demonstrate the potential applications of the TP-EO resin, the researchers successfully fabricated a topological liquid diode with nanoscale features.

Professor Kuang says, "Such a high-performance TP-EO photoresist is suitable for the scalable fabrication of complex architectures for various applications, such as optical gratings, diffraction elements, micro-electromechanical systems, microfluidic devices, and tissue engineering scaffolds."

More information: Zhiyuan Ma et al, Highly Sensitive Cationic Photoresist for High-Throughput Two-Photon Nanofabrication, *Advanced Functional Materials* (2024). [DOI: 10.1002/adfm.202409859](https://doi.org/10.1002/adfm.202409859)

Provided by Cactus Communications

The art of molecular self-assembly: Crafting 2D nanostructures for advanced materials



Summary of two-dimension structures. Credit: Chinese Journal of Polymer Science (2023). DOI: 10.1007/s10118-023-3038-8© Provided by Phys.org

Creating periodic nanostructures is vital for progress in material science and nanotechnology. Traditional methods often struggle with complexity and scalability. Integrating bottom-up self-assembly of block molecules with top-down lithography offers a solution, enabling the formation of sophisticated nanostructures. These challenges necessitate innovative approaches to fabricate advanced nanostructures.

A new review addresses these issues by leveraging the unique properties of block molecules, which can self-assemble into complex two-dimensional (2D) patterns,

promising significant advancements in nanofabrication and potential applications across various technological fields.

A team from the Beijing National Laboratory for Molecular Sciences, led by Wen-Bin Zhang and Yu Shao, published their [review](#) on unconventional 2D periodic nanopatterns in the *Chinese Journal of Polymer Science* on August 24, 2023.

Their work focuses on the self-assembly of block molecules to create intricate nanostructures, combining both bottom-up and top-down techniques to push the boundaries of nanofabrication.

The review investigates the self-assembly of block molecules, leading to the formation of diverse 2D periodic nanopatterns, such as tetragonal, hexagonal, rectangular, and oblique structures. The researchers detail the evolution from simple columnar phases to complex 2D tiling morphologies in materials like block copolymers, liquid crystals, and giant molecules.

By combining directed self-assembly with top-down lithography, sophisticated nanostructures with specific functions can be achieved.

The study highlights advanced nanofabrication techniques that enable the creation of intricate and functional nanostructures. Emphasizing the need for increased complexity in block molecules and refined lithography methods, the researchers provide a pathway to low-dimensional ordered morphologies.

This innovative approach has the potential to revolutionize nanotechnology by creating more complex and functional structures than traditional methods allow.

Dr. Wen-Bin Zhang from the Beijing National Laboratory for Molecular Sciences stated, "Our findings demonstrate the immense potential of block molecules in creating complex nanostructures. By integrating self-assembly with advanced nanofabrication techniques, we can pave the way for new applications in nanotechnology, overcoming the limitations of traditional methods."

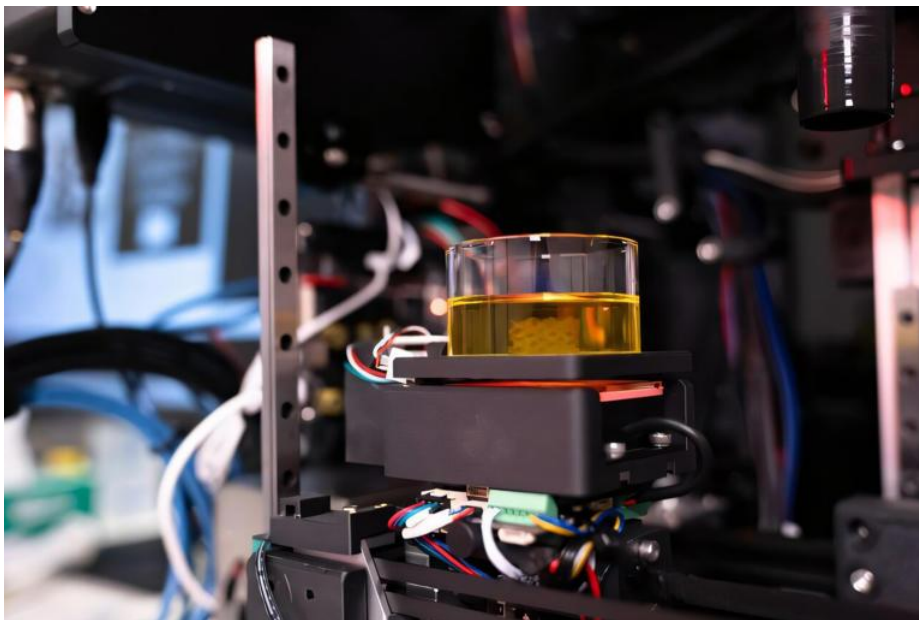
The development of unconventional 2D periodic nanopatterns has significant implications for nanotechnology. These sophisticated structures can be utilized in various applications, including electronics, photonics, and materials science.

The integration of bottom-up and top-down approaches offers a pathway to creating more intricate and functional nanostructures, potentially revolutionizing

manufacturing processes and enabling the development of next-generation technologies.

More information: Bo Hou et al, Unconventional 2D Periodic Nanopatterns Based on Block Molecules, *Chinese Journal of Polymer Science* (2023). DOI: [10.1007/s10118-023-3038-8](https://doi.org/10.1007/s10118-023-3038-8)

High-speed 3D bioprinter can fabricate structures that closely mimic diverse tissues in human body



The 3D bioprinter at the Collins BioMicrosystems Laboratory at the University of Melbourne. Credit: University of Melbourne

Biomedical engineers from the University of Melbourne have invented a 3D printing system, or bioprinter, capable of fabricating structures that closely mimic the diverse tissues in the human body, from soft brain tissue to harder materials like cartilage and bone.

This cutting-edge technology offers cancer researchers an advanced tool for replicating specific organs and tissues, significantly improving the potential to predict and develop new pharmaceutical therapies. This would pave the way for more advanced and ethical drug discovery by reducing the need for animal testing.

The research is [published](#) in the journal *Nature*.

Head of the Collins BioMicrosystems Laboratory at the University of Melbourne, Associate Professor David Collins said, "In addition to drastically improving print speed, our approach enables a degree of cell positioning within printed tissues. Incorrect cell positioning is a big reason most 3D bioprinters fail to produce structures that accurately represent human tissue.

"Just as a car requires its mechanical components to be arranged precisely for proper function, so too must the cells in our tissues be organized correctly. Current 3D bioprinters depend on cells aligning naturally without guidance, which presents significant limitations.

"Our system, on the other hand, uses acoustic waves generated by a vibrating bubble to position cells within 3D printed structures. This method provides the necessary head start for cells to develop into the complex tissues found in the human body."

Most commercially available 3D bioprinters rely on a slow, layer-by-layer fabrication approach, which presents several challenges. This method can take hours to finish, jeopardizing the viability of living cells during the printing process. Additionally, once printed, the cell structures must be carefully transferred into standard laboratory plates for analysis and imaging—a delicate step that risks compromising the integrity of these fragile structures.

The University of Melbourne research team has flipped the current process on its head by developing a sophisticated optical-based system, replacing the need for a layer-by-layer approach.

The innovative technique uses vibrating bubbles to 3D print cellular structures in just a matter of seconds, which is around 350 times faster than traditional methods and enables researchers to accurately replicate human tissues with cellular resolution.

By dramatically reducing the 3D printing time and printing directly into standard lab plates, the team has been able to significantly increase the cell survival rate, while eliminating the need for physical handling. Ensuring the printed structures remain intact and sterile throughout the process.

Ph.D. student Callum Vidler, the lead author on this work, said the groundbreaking technology was already generating excitement in the medical research sector.

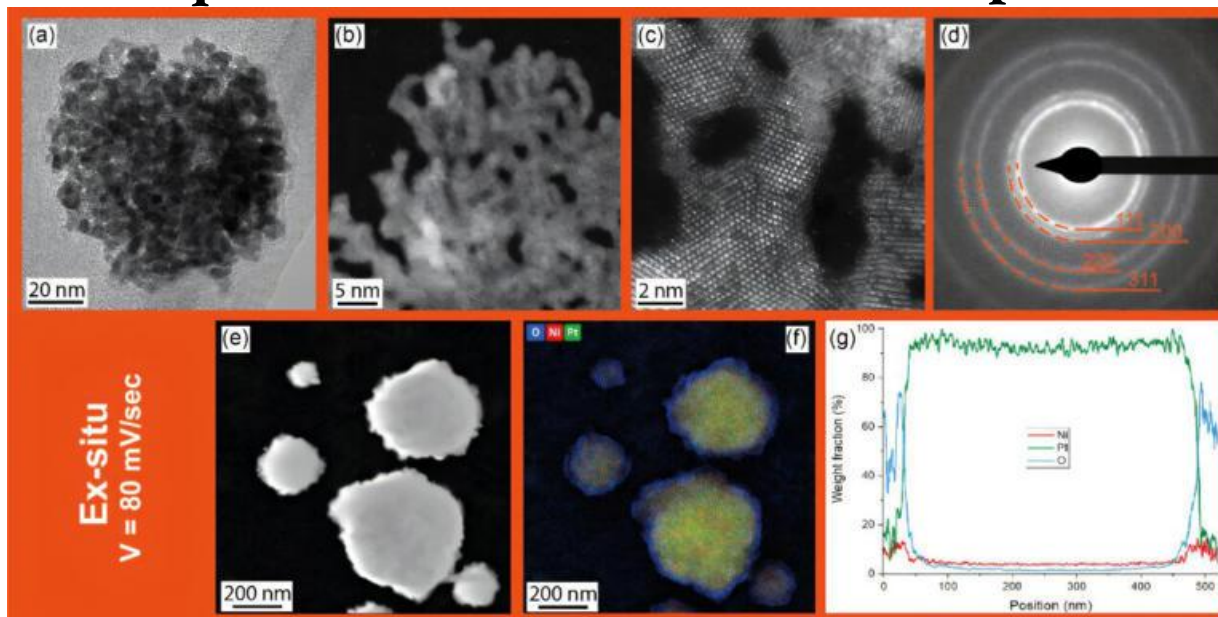
"Biologists recognize the immense potential of bioprinting, but until now, it has been limited to applications with a very low output," he said. "We've developed our technology to address this gap, offering significant advancements in speed, precision, and consistency. This creates a crucial bridge between lab research and clinical applications.

"So far, we've engaged with around 60 researchers from institutions including the Peter MacCallum Cancer Centre, Harvard Medical School, and the Sloan Kettering Cancer Centre, and the feedback has been overwhelmingly positive."

More information: Callum Vidler et al, Dynamic interface printing, *Nature* (2024). DOI: [10.1038/s41586-024-08077-6](https://doi.org/10.1038/s41586-024-08077-6)

Provided by University of Melbourne

How are nanostructures created? Imaging techniques unveil secrets of electrodeposition



(S)TEM and EDS analysis of the PtNi film grown ex situ on a molybdenum TEM grid with lacey carbon foil with the corresponding selected area diffraction pattern. (a) BF TEM overview image of a single nanoparticle. (b) Higher-magnification HAADF STEM image of the branched structure of the NPs. (c) HR-HAADF STEM image of the atomic structure of the branches. (d) SAED corresponding to the particle shown in panel a. (e) HAADF STEM image with (f) corresponding EDS map of the distribution of Pt, Ni and O. (g) Line scan across the bottom right particle. Credit: Nano Letters (2024). DOI: 10.1021/acs.nanolett.4c02228

Metallic nanoparticles, consisting of a few to several thousand atoms or simple molecules, are attracting significant interest. Electrodes coated with layers of nanoparticles (nanolayers) are particularly useful in areas such as energy production, serving as catalysts.

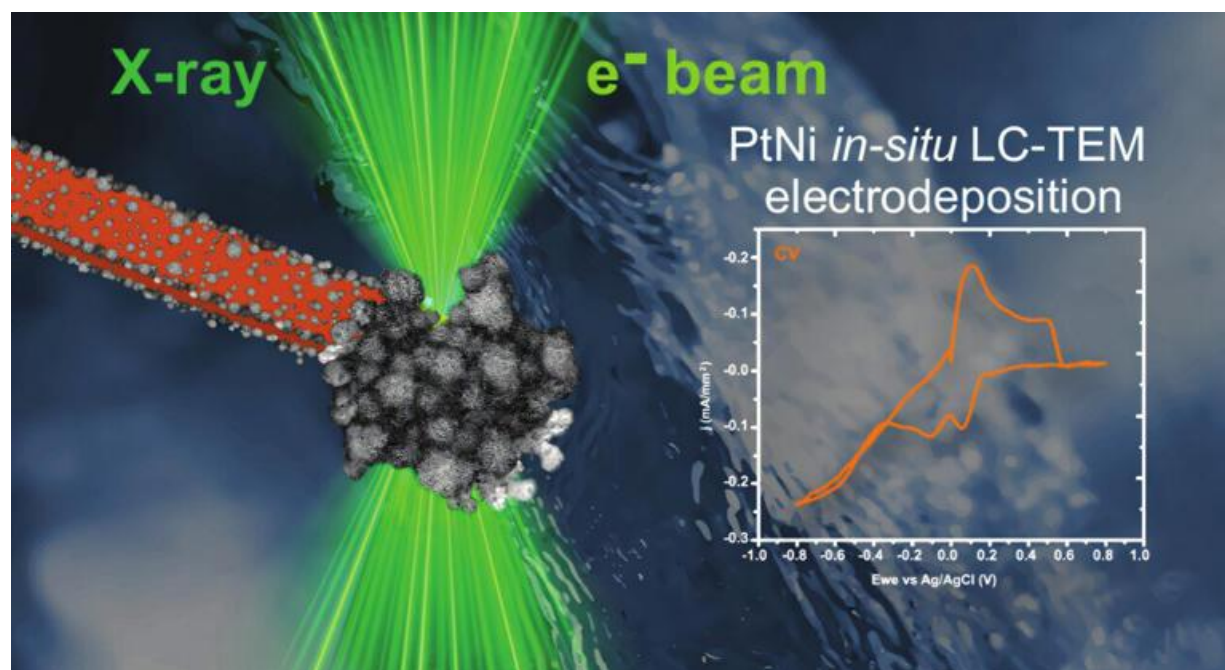
A convenient method for producing such layers on electrodes is electrodeposition, the subtle complexities of which have just been revealed by an international team of researchers led by scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences in Krakow. Their paper is [published](#) in the journal *Nano Letters*.

Research on nanoparticles is yielding promising results for technologies related to energy, medicine, and electronics. One of the key challenges is effectively controlling the synthesis and growth of nanostructures.

The team of scientists conducted an advanced experiment demonstrating the electrodeposition process of a platinum-nickel (PtNi) nanolayer on an electrode. Utilizing state-of-the-art imaging techniques, the researchers had a unique opportunity to observe in real-time how structures form at the atomic level, which is a significant step towards better designing materials with precisely controlled properties.

Electrodeposition is a rapid and convenient method for producing nanostructures. It involves immersing an electrode in a metal salt solution, from which the layer is to be grown, followed by applying an appropriate voltage that causes ions near the electrode surface to reduce, initiating layer growth.

To closely examine the process of electrodeposition, transmission electron microscopy (TEM) techniques are essential. TEM allows for imaging materials with sub-angstrom resolution (i.e., less than one ten-millionth of a millimeter) since it uses an electron beam with a much shorter wavelength than visible light. Ideally, it would be possible to observe, in real-time, how nucleation (the initial growth stage where nanoparticle seeds form) and layer growth occur on the electrode.



In-situ liquid-cell transmission electron microscopy electrodeposition of PtNi nanoparticle films on a carbon electrode during cyclic voltammetry. The electron beam (here in green color) illuminated the electrode (here in orange color) submerged in the platinum and nickel salt solution, enhancing the growth of the PtNi nanoparticle film (grey color) on the electrode. The film thickness increases with each cycle and by the fourth cycle reaction-rate limited growth of branched and porous structures were observed. Credit: Nano Letters (2024). DOI: 10.1021/acs.nanolett.4c02228

However, TEM imaging comes with certain limitations: the samples need to be as thin as possible and entirely dry. To overcome these challenges and enable the imaging of chemical reactions, the researchers thus utilized a special imaging technique in a liquid cell flow chamber.

"The flow cell consists of two silicon chips equipped with a 50-nanometer-thick SiN_x membrane. This membrane is electron-transparent, and an additional electrode is placed on its surface. By applying a voltage, the microscope user can observe how the layer grows on the electrode. Experiments using such a cell require a special holder for flow experiments in the TEM," explains Prof. Magdalena Parlińska-Wojtan, Ph.D.

Experiments conducted at the Silesian University of Technology using a TEM microscope confirmed that the PtNi layer indeed grows directly on the electrode, providing crucial insights into the fundamentals of the entire process. An alternative mechanism would involve nanoparticles first forming in the electrolyte and then drifting toward the electrode to attach. This effect was also observed, but only in areas illuminated by the beam, due to the fact that the electron beam interacts with water, behaving like a reducing agent.

Subsequent "dry" observations revealed that the layer is actually composed of spherical nanoparticles with diameters of several tens of nanometers. Further magnification of TEM images showed that the surface of these nanoparticles consists of densely branched, fine dendritic structures (multiple branching).

"As part of our collaboration with the Fritz Haber Institute of the Max Planck Society in Berlin, we conducted an additional experiment by extending the reaction time and reducing the rate of voltage changes. This allowed us to observe additional effects: the nucleation of individual nanoparticles, which rapidly grow and merge to form a continuous layer.

"During voltage changes in subsequent electrodeposition cycles, the nanoparticles undergo alternating growth and dissolution. However, growth is a faster process than dissolution, which ultimately results in a stable layer," explains Prof. Parlińska-Wojtan.

As part of the research, another experiment was conducted in liquid environment using a different, but also unique, apparatus: a scanning transmission X-ray microscope (STXM), available at the National Synchrotron Radiation Center SOLARIS in Kraków. During STXM imaging, X-ray radiation is used. The resulting images do not have as high a resolution as the ones from electron microscopy, but they reveal other properties of the materials under study, such as the oxidation states of atoms in nanoparticles.

The result of electrodeposition is not always pure metal; sometimes it is a metal oxide. Depending on whether it is a metal or an oxide (and the oxidation state of the oxide), materials absorb X-ray radiation at different energies. An STXM image taken with the appropriate energy beam allows for a detailed investigation of the produced nanoparticles.

The STXM microscope at the SOLARIS center in Kraków also enabled an experiment in a liquid environment using a flow cell nearly identical to the one used in the TEM. The authors thus performed PtNi electrodeposition inside the STXM and, in real time, investigated the range of X-ray absorption by the nanoparticles. In this way, they determined that the layer actually consists of nickel(II) oxide and metallic platinum.

"Conducting an experiment using microscopic techniques in a liquid environment is quite a challenge. Nevertheless, our team succeeded in producing the expected PtNi layer using two different techniques, and the obtained results were complementary," says Prof. Parlińska-Wojtan.

"Such research is important for several reasons. The technical reason is that we are still exploring the capabilities and limitations of relatively new, high-end measurement tools. There was also a more important scientific reason: understanding the fundamental factors that govern the synthesis, growth, and properties of nanostructures. This knowledge may help in the future in the fabrication of nanostructured materials tailored better for applications such as fuel cells or medicine."

More information: Magdalena Parlinska-Wojtan et al, Understanding the Growth of Electrodeposited PtNi Nanoparticle Films Using Correlated In Situ Liquid Cell Transmission Electron Microscopy and Synchrotron Radiation, *Nano Letters* (2024). DOI: [10.1021/acs.nanolett.4c02228](https://doi.org/10.1021/acs.nanolett.4c02228)

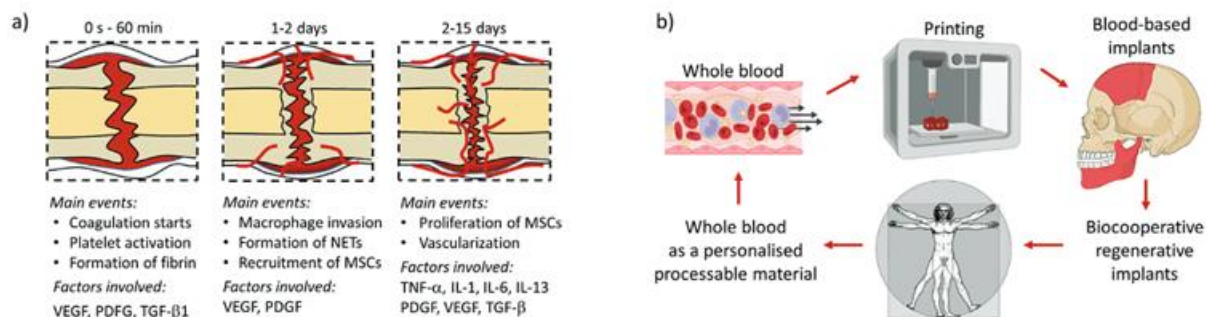
Scientists turn blood into a 3D-printed bone repair material. For now, just in rats

When you get a cut or fracture, your body springs into action, turning liquid blood into a solid clot that stops bleeding and kickstarts the healing process. This clot, called a regenerative hematoma (RH), is packed with cells and proteins that orchestrate the repair of tissues. The initial formation of the RH is critical — it provides a scaffold where cells can gather, promoting the formation of new tissue and blood vessels.

Soraya Padilla-Lopategui and her team at Queen Mary University of London and the University of Nottingham wanted to use this mechanism. Basically, they developed a way to use a patient's own blood to repair their broken bones.

Using the body's defenses

Our bodies are naturally equipped to repair minor injuries through a sophisticated process involving the regenerative hematoma. And it's not just us. Many mammals have similar mechanisms too, the key is to be able to replicate it in a controlled fashion.

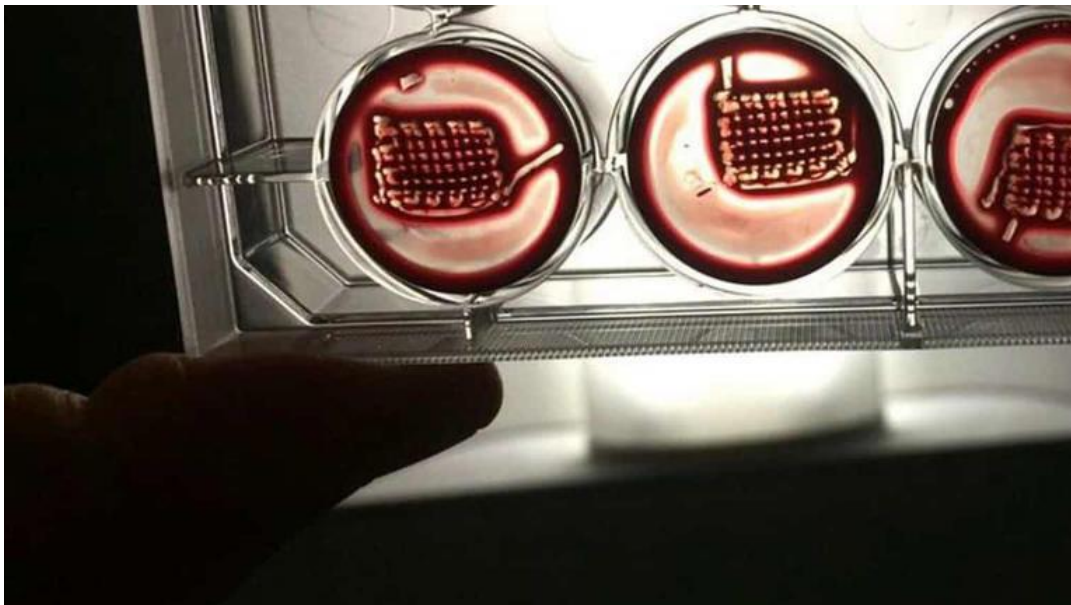


Main biological events and factors involved in the formation of a regenerative/hematoma clot (a) and a vision of the workflow from whole blood to personalized, 3D printed biocooperative implants.© ZME Science

The crux of this breakthrough lies in the use of peptide amphiphiles (PAs) — molecules that can self-assemble into nanofibers and interact with blood proteins to create biocompatible gels. By blending these PAs with blood, the researchers were able to engineer a material that not only mimics the natural RH but also enhances its properties.

Essentially these PAs self-assemble when mixed with blood. They form a 3D network that incorporates essential proteins, platelets, and growth factors from the blood. Thus, it creates a scaffold that closely resembles natural RH. This structure provides a constant source of growth factors like vascular endothelial growth factor and platelet-derived growth factor, which are vital for cellular growth and healing.

“For years, scientists have been looking at synthetic approaches to recreate the natural regenerative environment, which has proven difficult given its inherent complexity. Here, we have taken an approach to try to work with biology instead of recreating it. This “biocooperative” approach opens opportunities to develop regenerative materials by harnessing and enhancing mechanisms of the natural healing process. In other words, our approach aims to use regenerative mechanisms that we have evolved with as fabrication steps to engineer regenerative materials,” says Alvaro Mata, Professor in Biomedical Engineering and Biomaterials in Nottingham University.



Researchers holding 3D printed PA-blood constructs. Image credits: Nottingham University.© ZME Science

To make the technology even more exciting, you can tweak and personalize parts of it based on your own body.

Because the material uses the patient's own blood, it reduces the risk of immune rejection and simplifies the process of creating individualized implants. By using whole blood, the team bypasses the need for complex processing steps often required with synthetic materials, making this approach more viable for clinical use.

"The possibility to easily and safely turn people's blood into highly regenerative implants is really exciting. Blood is practically free and can be easily obtained from patients in relatively high volumes. Our aim is to establish a toolkit that could be easily accessed and used within a clinical setting to rapidly and safely transform patients' blood into rich, accessible, and tuneable regenerative implants," added co-author Cosimo Ligorio, from the Faculty of Engineering at Nottingham University.

The researchers started in lab studies, converting blood samples into biocooperative gels that could be customized in terms of shape and structure through 3D printing. They controlled the speed and pressure of this 3D printing, crafting specific shapes with robust mechanical properties. The experiment with two formulations of the gel demonstrated 62% and 56% new bone formation, respectively, compared to 50% for the commercially available solutions and 30% for untreated defects, indicating the material's potential in clinical applications.

Although the study was only carried out on rat cells, the researchers are confident a similar approach can be used on humans as well.

The ability to tune the material's properties opens doors to applications in areas where precise mechanical and biological properties are essential. The team envisions future studies to optimize the PA-blood gel for specific types of injuries, with a focus on integrating other types of cells or molecules that promote healing.

Furthermore, while this study focused primarily on bone healing, the PA-blood technology holds potential for a broad range of applications. For instance, the gel could be used as a hemostatic agent, rapidly forming clots in response to bleeding, which would be especially useful for patients with clotting disorders.

Moreover, the method could be adapted for other tissues such as skin or nerves, which have their own unique regenerative requirements.

A few challenges remain

Despite its promise, several challenges remain before the PA-blood gel can be widely adopted in clinical settings. For instance, the variability in blood composition between individuals may affect the material's performance. Also, it's not fully clear how well the findings would translate to human cells

Another challenge lies in scaling up production of these personalized materials. While the 3D printing approach shows promise for creating customized shapes, the feasibility of integrating this technology into standard clinical workflows will need further exploration. The development of user-friendly devices that allow clinicians to create these implants directly from patient blood samples could streamline the process, making it more accessible to a wider range of healthcare facilities.

The study provides promising insights. It remains preclinical, and further research is needed to explore its applicability in human medicine. However, the researchers found that their approach can achieve reproducible results across different blood samples.

The potential applications of this technology are vast, ranging from surgical implants to trauma care. As research continues, this PA-blood technology could serve as a foundation for other regenerative solutions, providing new hope for patients who need accessible, effective, and personalized therapies.

Journal Reference: Soraya Padilla-Lopategui et al, Biocooperative Regenerative Materials by Harnessing Blood-Clotting and Peptide Self-Assembly, *Advanced Materials* (2024). DOI: [10.1002/adma.202407156](https://doi.org/10.1002/adma.202407156)

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Mit breakthrough: Fast liquid metal printing revolutionizes industry



Scrap has a chance to get a second life in 3D printing.© Pixabay, Antranas

The technology of 3D printing is rapidly conquering various sectors of industry, although existing methods have not been free of flaws. However, scientists from the Massachusetts Institute of Technology (MIT) have introduced an innovative printing technique using liquid metal, which opens up new possibilities in the technology industry.

Although there are already 3D printers that use liquid metal, previous technologies were limited by their slowness. Specialists from MIT have developed a new method that overcomes these limitations, offering a fast and efficient process.

Scrap metal gets a second life

The innovative method, called LMP (liquid metal printing), involves spreading liquid metal on a surface covered with fine glass beads. This allows for the creation of large elements in seconds, and the metal hardens within a few minutes.

The device designed as a part of this technology features a furnace for melting aluminum, which is an ideal material due to its wide use in construction and low recycling cost. Aluminum remains in a liquid state in a heated chamber, and a special nozzle precisely distributes the metal onto a surface with beads that are approximately 0.004 inches in diameter, allowing quick hardening due to heat absorption by the microscopic beads.

According to the MIT team, LMP technology is **significantly faster than previous liquid metal printing methods**. This process is also more energy-efficient and allows for the use of aluminum scrap, making it environmentally friendly. Although the precision of models may be lower, the material is solid enough for later processing, such as milling.

Does the new technology have a chance to simplify everyday life?

Skylar Tibbits, an associate professor in the Department of Architecture at MIT and co-director of the Self-Assembly Lab, emphasizes that this **innovative technique introduces a new perspective to metal production**. Although the method is not without flaws, its speed, scalability, repeatability, and energy efficiency are advantages that could revolutionize modern industry.

Although this technology still requires improvements, **scientists are working to enhance the even heating of the nozzle to prevent metal sticking**. They are also developing ways to increase the uniformity of prints using larger nozzles.

While the LMP printer is primarily an industrial tool, it has demonstrated the printing of structural elements such as chairs and tables, showcasing its potential. Scientists suggest this technology could find wide applications, for example, in the aerospace and automotive industries, especially for prototype creation.

Researchers achieve historic breakthrough with new metal made from 3D printing technology — and it could revolutionize air travel

Researchers achieve historic breakthrough with new metal made from 3D printing technology — and it could revolutionize air travel

Scientists just achieved something amazing that could make air travel both lighter and cleaner. They have created a new metal that can handle extreme heat while weighing less than traditional materials — and they made it using 3D printing [technology](#).

Researchers at Oak Ridge National Laboratory and the National Energy Technology Laboratory have developed the world's lightest heat-resistant alloy that won't crack under pressure. This new material can withstand temperatures above 2,400 degrees Fahrenheit without melting, which is perfect for use in airplane engines, according to a press release from [Oak Ridge National Laboratory](#).

Think of it like upgrading from a cast iron skillet to a modern non-stick pan, except this upgrade happens inside jet engines. The new alloy combines seven different elements centered around a metal called niobium, making it 48% more heat-resistant than previous materials used in airplane turbines. This breakthrough could [transform air travel](#). When airplane engines run at higher temperatures without needing heavier materials to stay intact, they become more efficient. That means planes can fly using less fuel, which benefits both airlines and our environment.

"No one has been able to develop and print alloys with such a high melting temperature and low density without cracks before," said Saket Thapliyal from Oak Ridge National Laboratory. "This is significant. We're making something lighter that can hold its structural integrity at ultra-high temperatures."

While traditional heat-resistant metals like tungsten could handle the heat, they would weigh down the aircraft too much to be practical. By using 3D printing technology to create this innovative alloy, researchers have opened the door to a future where [air travel](#) could leave a much smaller environmental footprint.

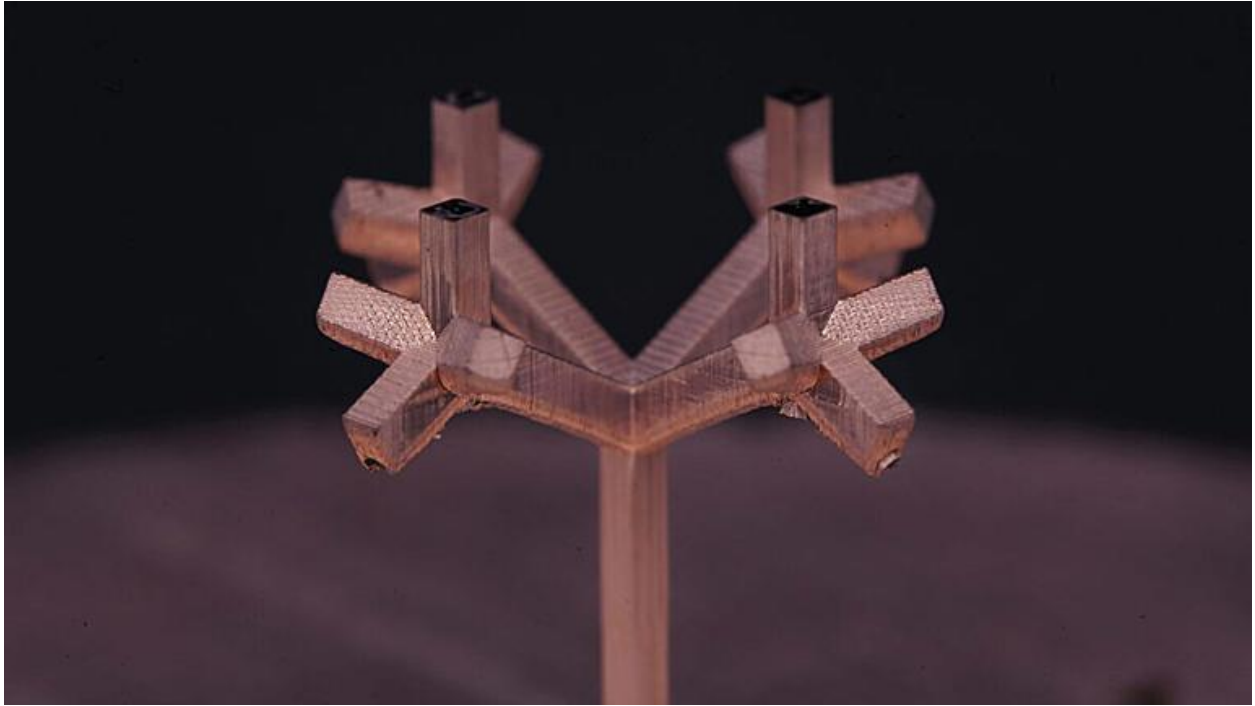
It's exciting to see how cutting-edge technology like this could help make [everyday air travel](#) more sustainable. By making engines [more efficient](#), this innovation could reduce the aviation industry's [carbon impact](#) while keeping ticket prices in check.

Engineers 3D print tiny, intricate antennas



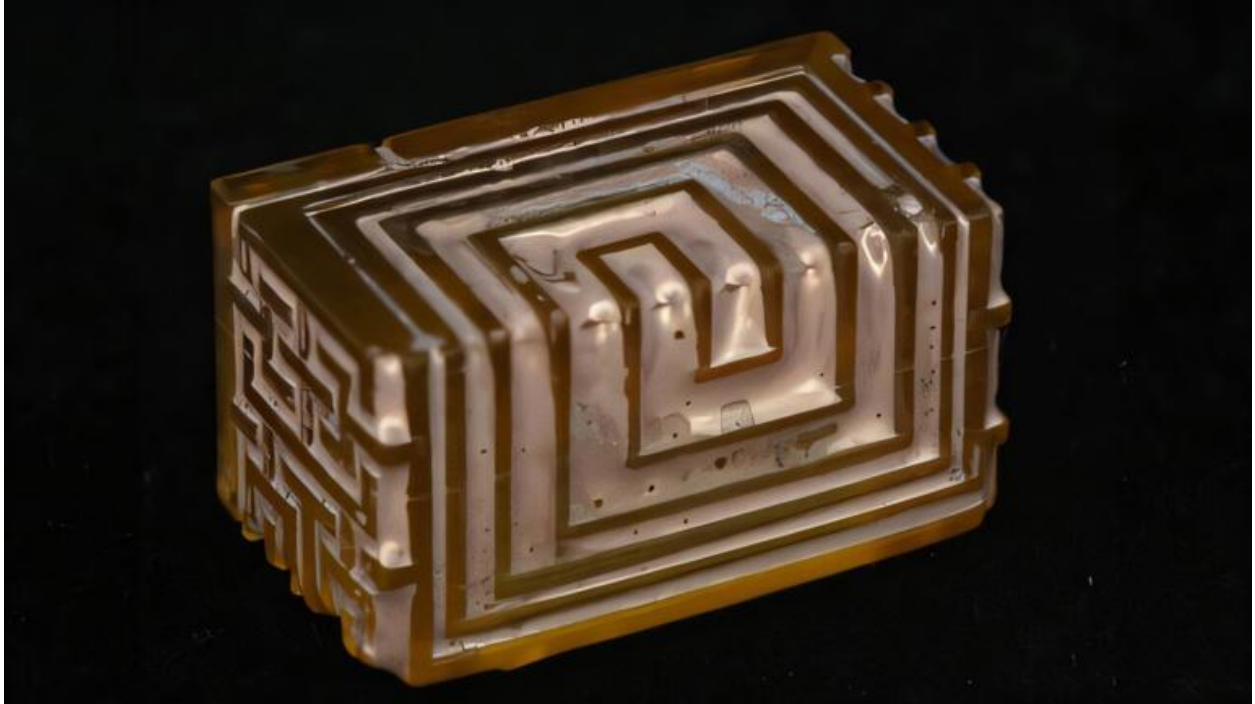
A CPD-fabricated gradient phase transmitarray for generating highly directive radiation. The antenna features three layers of gradually tilted architected S-ring unit cells. Credit: University of California - Berkeley

Today, nearly all personal electronic devices rely on antennas to send and receive data. In fact, demand is also rising for lightweight antennas for new applications, including the latest in 5G/6G networks, advanced wearable devices and aerospace applications like CubeSats. However, standard manufacturing techniques have limited the structural complexity and use of multiple materials that would unlock still more features and capabilities from antennas.



A 3D fractal tree antenna fabricated using charge programmed multi-material 3D printing (CPD). With high printing precision, simple process protocol and vast design freedom, CPD offers a universal platform for fabricating all types of lightweight antennas. Credit: University of California - Berkeley

Now, a team led by Xiaoyu (Rayne) Zheng—associate professor in UC Berkeley's Department of Materials Science and Engineering and faculty co-director of Berkeley Sensors and Actuator Center (BSAC) and the Jacobs Institute for Design Innovation—has developed a new 3D printing/additive manufacturing platform that offers "unparalleled flexibility in antenna design and the capability for rapid printing of intricate antenna structures."



A 3D folded implantable electrically small antenna featuring interpenetrating Archimedean spirals and Hilbert curves.
Credit: University of California - Berkeley

As [reported](#) in the latest issue of *Nature Communications*, the new platform—dubbed "charge programmed multi-material 3D printing" (CPD)—is a universal system for rapid production of nearly all 3D antenna systems. It can pattern highly conductive metals with a wide range of dielectric materials into a 3D layout.

Zheng emphasized that the platform is not an expensive 3D printer for metals that would involve pricey metal powders and high-energy lasers. "This technology can be applied to desktop-friendly light-based printers," he said.

The CPD method combines a desktop digital light 3D printer and a catalyst-based technology that can pattern different polymers at different locations where they will attract metal plating. Its auto-catalytic or selective plating technology enables the polymers to selectively absorb metal ions into prescribed locations that are defined by the desired antenna design outcome.

CPD can broadly integrate with a variety of multi-material 3D printing methods, Zheng said. "It allows essentially any complex 3D structure, including complex lattices, and has demonstrated deposition of copper with near pristine

conductivity, as well as magnetic materials, semiconductors, nanomaterials and combinations of these."

Zheng has been working on the CPD platform since 2019 when his group first came up with the concept. In 2020, his team published their [first paper](#) in *Nature Electronics* on this technology, followed by a [2022 paper](#) in *Science* that described the use of it to make microrobots.

This latest paper is specific to the antenna application. CPD, Zheng said, is "very uniquely suited for antennas, because nearly all antennas need two components: One is the metal phase, the conductor, and the other is the dielectric phase, which is not conductive—and [until now] there has been no technology capable of directly patterning or synthesizing the conductor and dielectric materials together."

Zheng explained that the first application they considered was in antennas. After discussing the technology with colleagues who specialize in this area, they realized that this technique could revolutionize how antennas are printed and open many new design possibilities.

Printing both the conductor (metal) and dielectric materials is especially important for antennas to be used in extreme environments. For example, Zheng says, "you cannot use a regular polymer in space. You need a high temperature polymer like Kapton, which is a good material in aerospace [stable at both very high and very low temperatures]. Now you can have Kapton and a pattern of metal traces interwoven in 3D at the same time."

The team has also shown that through proper 3D designs, these antennas, without having to sit on a bulky substrate, achieve substantial weight savings compared to current antennas.

Co-author Yahya Rahmat-Samii, professor of electrical and computer engineering at UCLA, believes the CPD platform could significantly expand the possibilities for new antenna technologies and enable data-drive designs—allowing out-of-the box antenna designs for diverse applications. "There are probably numerous different antenna structures, depending on the application you have in mind," he said.

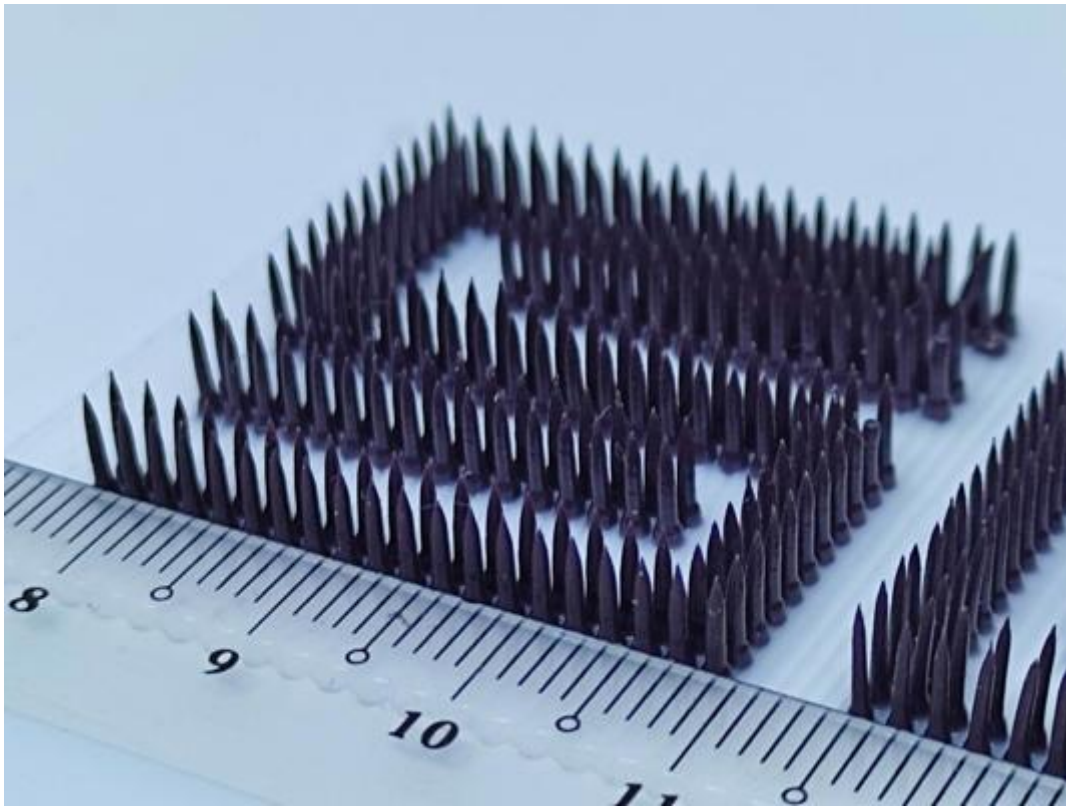
Zheng and Rahmat-Samii next want to explore the full complexity of antenna design achievable with their new 3D printed antenna technology. Control of an antenna's complexity gives them control over the ability to shape electromagnetic waves, much as a painter controls the application of paint with a brush. Aiming to advance applications for this technology, the team at UC Berkeley has formed a startup company focused on flexible medical sensors that would conform, say, to the shape of a hand.

"We can achieve a tunable antenna," Zheng says. "And so the question now is, where can that technology help us best?"

More information: Zhen Wang et al, Ultra-light antennas via charge programmed deposition additive manufacturing, *Nature Communications* (2025). DOI: [10.1038/s41467-024-53513-w](https://doi.org/10.1038/s41467-024-53513-w)

Provided by University of California - Berkeley

Bioinspired 3D printing: Architected design creates efficient structures



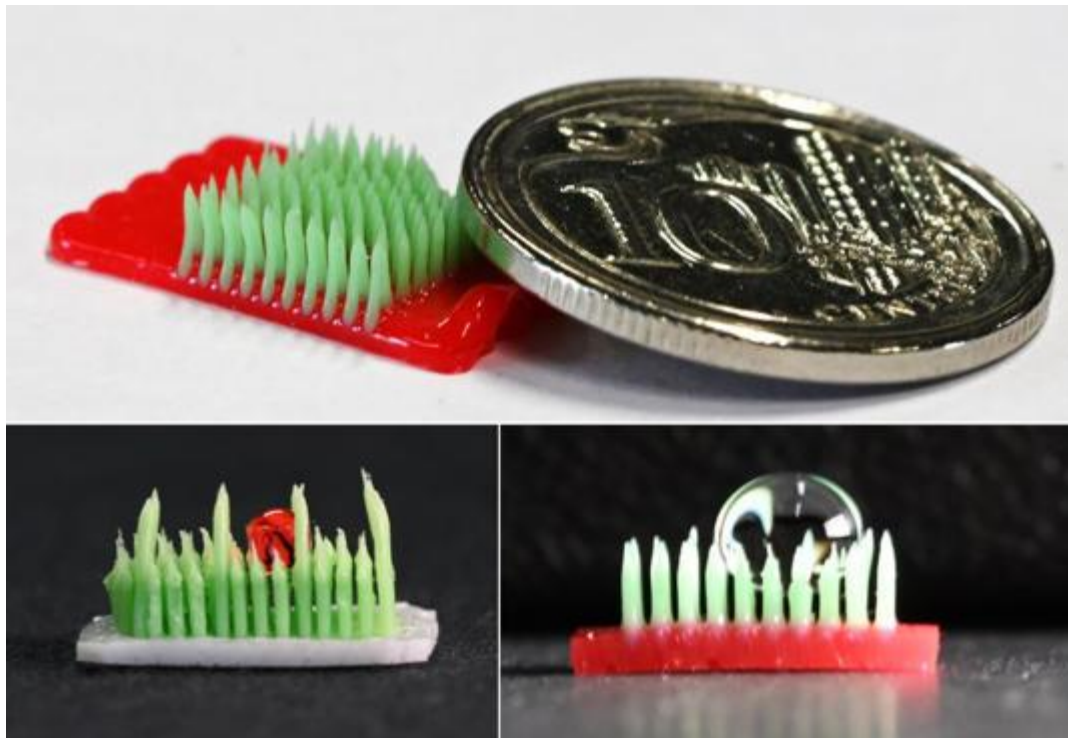
3D printed cilia formations depicting the letter "S" Credit: SUTD

When 3D printing was first introduced in 1985, it marked a major turning point for the manufacturing industry. In addition to being cheaper than traditional manufacturing technologies, it also promised the ability to customize designs and make prototypes on demand. While its technology is still considered relatively new, there has been an accelerating demand for 3D printing methods across sectors in the past decade, ranging from aerospace and defense to medicine.

Yet, Associate Professor Pablo Valdivia y Alvarado from the Singapore University of Technology and Design (SUTD) believes that there are still ways to go before 3D printing can achieve its full potential. In traditional 3D printing, a nozzle is used to print the material layer by layer, and the path that the nozzle takes is known as the toolpath.

However, layer-by-layer printing is incompatible for use with materials like silicone, epoxies, and urethanes that are slow-curing and take more time to harden. These types of materials are often used to create soft mechanical metamaterials which, in turn, are used for lightweight, nature-inspired structures, such as lattices and web structures. Deposition-based processes in 3D printing,

such as direct ink writing, would be able to work with these materials to create such structures, but these suffer from non-optimized tool paths.

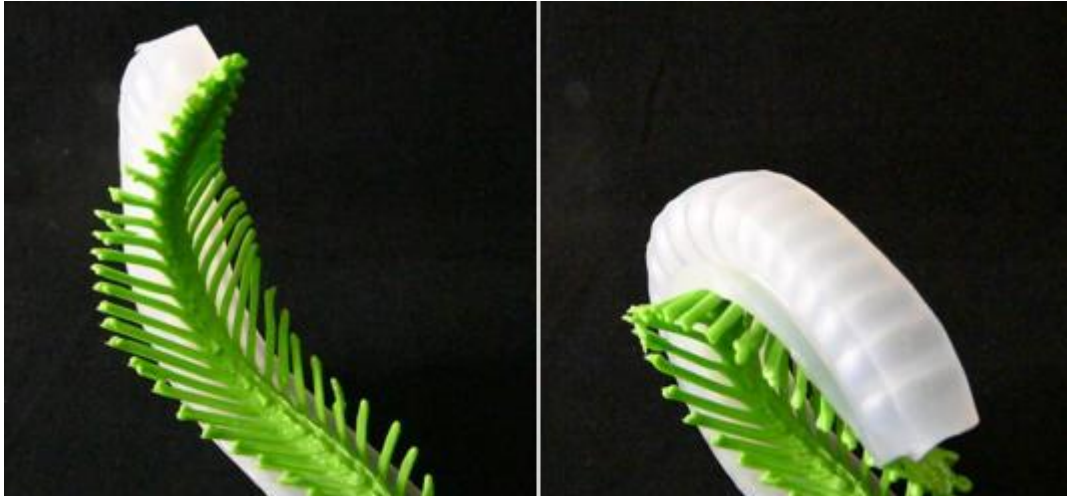


Water droplet on a hierarchical and structured 3D printed cilia array. Credit: SUTD

"These issues lead to extended print times and are further exacerbated by the dynamic material behaviors in their uncured state," explained Assoc Prof Valdivia y Alvarado. It therefore remains challenging to 3D-print complex bioinspired structures.

To tackle this challenge, Assoc Prof Valdivia y Alvarado and his team at SUTD proposed an architected design approach, which they have published in the paper "[Architected design and fabrication of soft mechanical metamaterials](#)" published in *Advanced Intelligent Systems*.

Looking specifically at how direct ink writing can be used to fabricate lightweight structures, the team first designed a method to optimize the toolpaths. By breaking down the object's 3D design into points and simple shapes, the team could then make use of both segmented and continuous toolpath designs to improve the overall toolpath. Through this, the team was able to generate toolpaths that contained fewer unnecessary starts and stops.



3D printed fern leaf-like Pneunet actuator. Credit: SUTD

To test the approach, the team printed several types of bioinspired structures using this method for generating optimized toolpaths. The team first sought to tune the properties of the printing materials to further enhance their suitability for direct ink writing. By selecting three commercially available silicone materials, and then adding a modifier known as Thivex, the team created and characterized nine distinct material combinations that were more suitable for direct ink writing.

The researchers then proceeded to 3D-print cilia, webs, leaf-like structures, and lattices using their proposed approach, and tested the functionalities of the structures in different settings. For the 3D-printed cilia, the team found that adding it to suction cups improved the suction cups' pull-off force; meanwhile, the 3D-printed lattice proved to be an effective energy-absorbing structure, demonstrating a reduction of maximum impact peak forces by up to 85 percent.

With these findings, the team is optimistic about the future development of deposition-based 3D printing methods for printing bioinspired structures.

Said Assoc Prof Valdivia y Alvarado, "Although the approach is still in the research phase, its potential for customized, high-performance designs makes it highly relevant for industries focused on robotics, wearable technologies, and advanced metamaterials."

He also explained that deposition-based additive manufacturing processes could find a niche in advanced applications, complementing traditional methods that would remain essential for producing high-volume and standardized structures.

For now, the team is focused on improving the scaling efficiency of their method, reducing its costs, and expanding the versatility of the materials to industrial settings. To do this, the team plans to explore multi-material printing which would allow different materials to be printed, in turn creating what the team has coined as "engineered metamaterials." In addition, the team will also be investigating how machine learning techniques can enable 3D printing users to specify performance metrics for the metamaterial designs that they wish to generate.

"These advancements will further unlock the potential of 3D-printed metamaterials for a wide range of applications, including soft robotics and wearable protective gear," mused Assoc Prof Valdivia y Alvarado.

More information: Thileepan Stalin et al, Architected Design and Fabrication of Soft Mechanical Metamaterials, *Advanced Intelligent Systems* (2024). DOI: [10.1002/aisy.202400514](https://doi.org/10.1002/aisy.202400514)

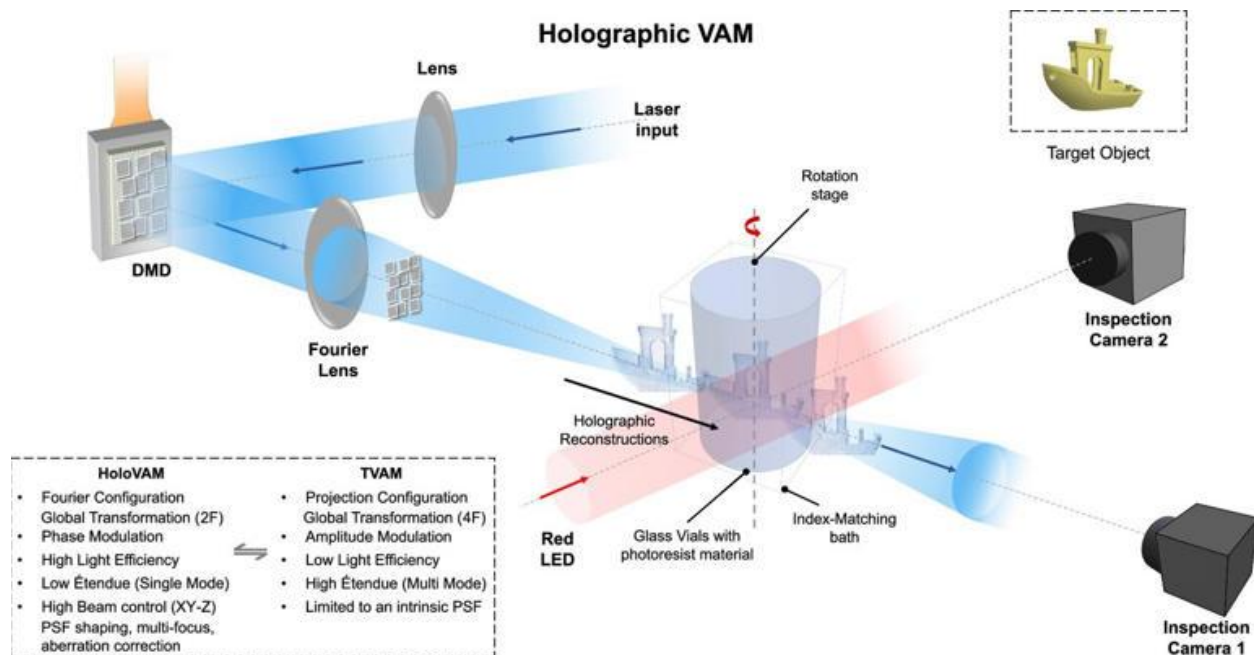
Provided by Singapore University of Technology and Design

Holograms boost 3D printing efficiency and resolution



The method allows the fabrication of millimeter-scale objects within seconds. Credit: LAPD EPFL

While traditional 3D printers work by depositing layers of material, tomographic volumetric additive manufacturing (TVAM) involves shining laser light at a rotating vial of resin until it hardens where accumulated energy exceeds a certain threshold. An advantage of TVAM is that it can produce objects in [a matter of seconds](#), compared to around 10 minutes for layer-based 3D printing. But a disadvantage is that it is very inefficient, because only around 1% of the encoded light reaches the resin to produce the desired shape.



Optical configuration for holographic volumetric additive manufacturing. Credit: Nature Communications (2025). DOI: 10.1038/s41467-025-56852-4

Researchers from EPFL's Laboratory of Applied Photonic Devices, led by Professor Christophe Moser, and from the SDU Centre for Photonics Engineering, led by Professor Jesper Glückstad, have [reported](#) a TVAM method in *Nature Communications* that significantly reduces the amount of energy required to fabricate objects, while simultaneously boosting resolution.

The technique involves projecting a three-dimensional hologram of a shape onto the spinning vial of resin. Unlike traditional TVAM, which encodes information in the amplitude (height) of projected light waves, the holographic method takes advantage of their phase, or position.

This small change has a big impact. "All pixel inputs are contributing to the holographic image in all planes, which gives us more light efficiency as well as better spatial resolution in the final 3D object, as the projected patterns can be controlled in the projection depth," Moser summarizes.

In the recently published work, the team printed complex 3D objects such as miniature boats, spheres, cylinders, and art pieces in under 60 seconds with exceptional accuracy, using 25 times less optical power than previous studies.

Mimicking complex biological structures

The holograms are generated using a technique called HoloTile, which was invented by Professor Glückstad. HoloTile involves superimposing multiple holograms of a desired projection pattern, and eliminates random light interference called speckle noise that would otherwise create grainy images. Although holographic volumetric additive manufacturing has been reported previously, the joint EPFL-SDU team's approach is the first to yield such high-fidelity 3D-printed objects, largely thanks to the use of HoloTile.

EPFL student and lead author Maria Isabel Alvarez-Castaño explains that another unique aspect of the holographic approach is that the hologram beams can be made "self-healing," meaning they can spread through a resin without being thrown off course by small particles. This self-healing property is essential for 3D printing with bio-resins and hydrogels that are loaded with cells, making the method ideally suited for biomedical applications.

"We are interested in using our approach to build 3D complex shapes of biological structures, allowing us to bio-print, for example, life-scale models of tissues or organs," says Alvarez-Castaño.

Going forward, the team aims to improve the efficiency of their method another twofold.

Moser says that with some computational enhancements, the ultimate goal is to use holographic volumetric additive manufacturing to fabricate objects by simply projecting a hologram onto a resin, without needing to rotate it. This could further simplify volumetric additive manufacturing and increase the potential for high-volume, energy-efficient fabrication processes.

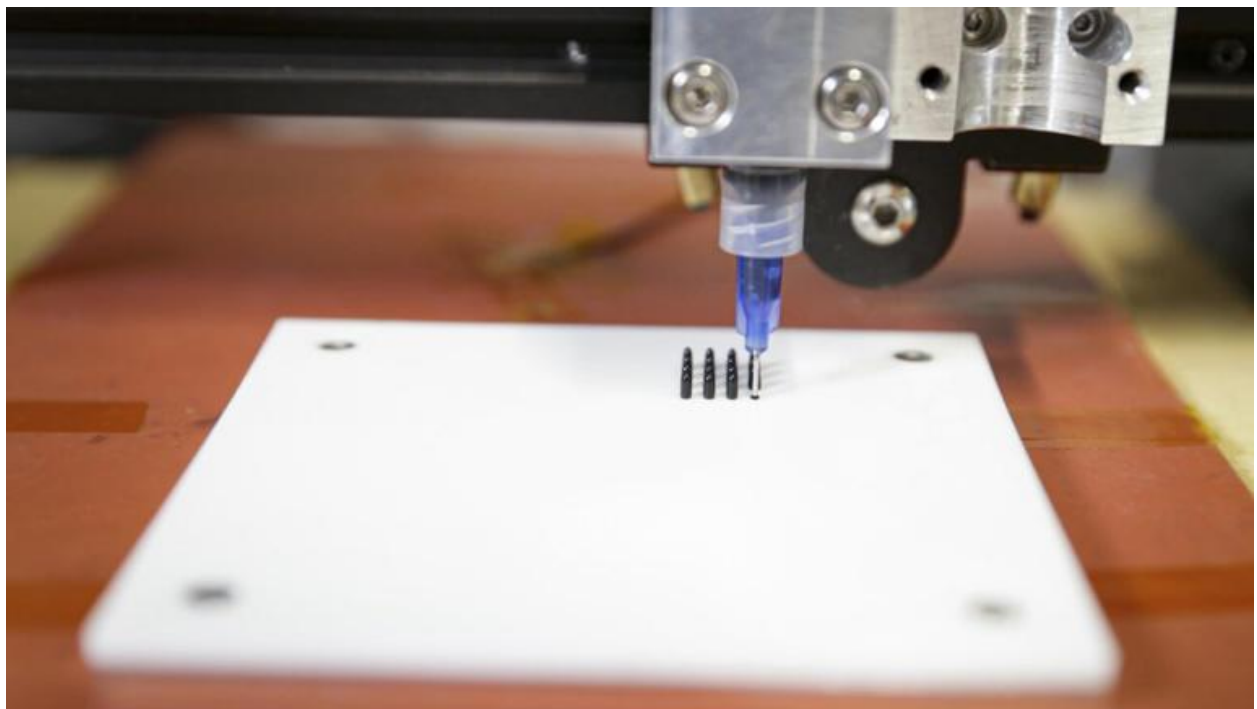
He adds that the fact that the holograms can be coded using standard commercial equipment adds to the practicality of the approach.

"The holographic addition to TVAM technology sets the stage for the next generation of efficient, precise, and rapid volumetric additive manufacturing systems," he summarizes.

More information: Maria Isabel Álvarez-Castaño et al, Holographic tomographic volumetric additive manufacturing, *Nature Communications* (2025). DOI: [10.1038/s41467-025-56852-4](https://doi.org/10.1038/s41467-025-56852-4)

Provided by Ecole Polytechnique Federale de Lausanne

Researchers 3D print high-performance, sustainable thermoelectric materials

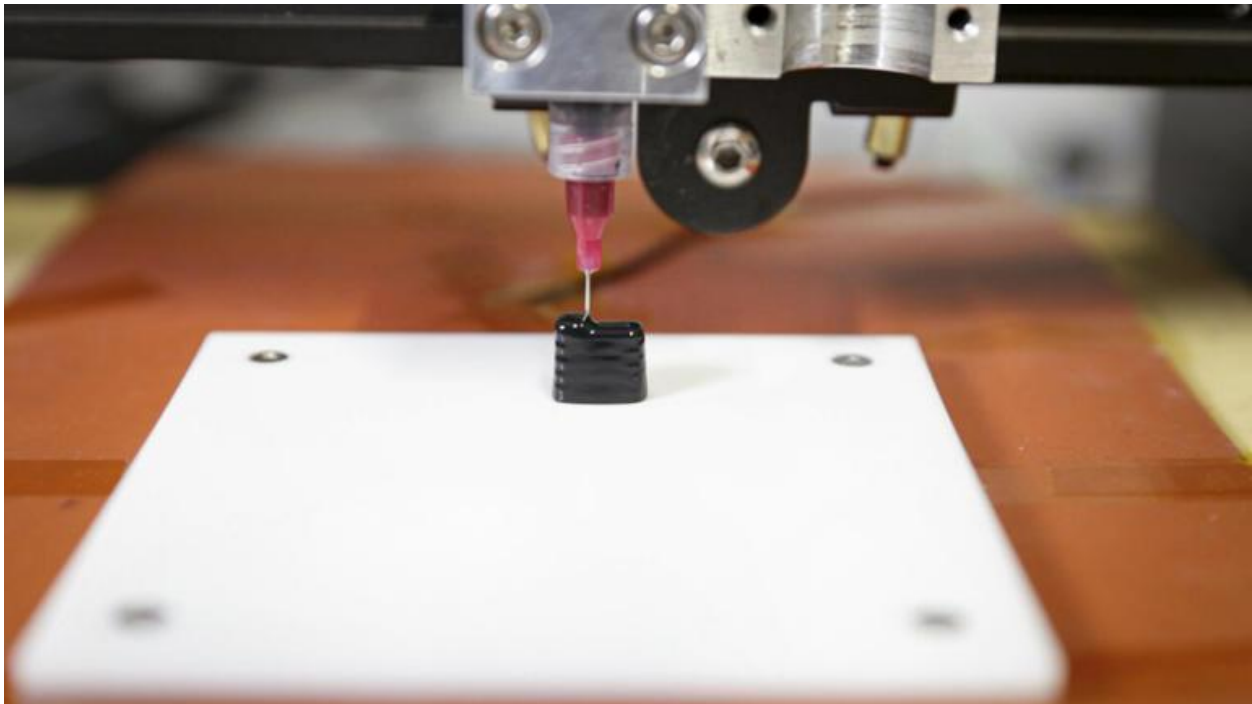


Printing of pillars for the thermoelectric cooler. (Video still, Video available on request). Credit: Shengduo Xu | ISTA

Rapid, localized heat management is essential for electronic devices and could have applications ranging from wearable materials to burn treatment. While so-called thermoelectric materials convert temperature differences to electrical voltage and vice versa, their efficiency is often limited, and their production is costly and wasteful.

In a paper [published](#) in *Science*, researchers from the Institute of Science and Technology Austria (ISTA) used a 3D printing technique to fabricate high-performance thermoelectric materials, reducing production costs significantly.

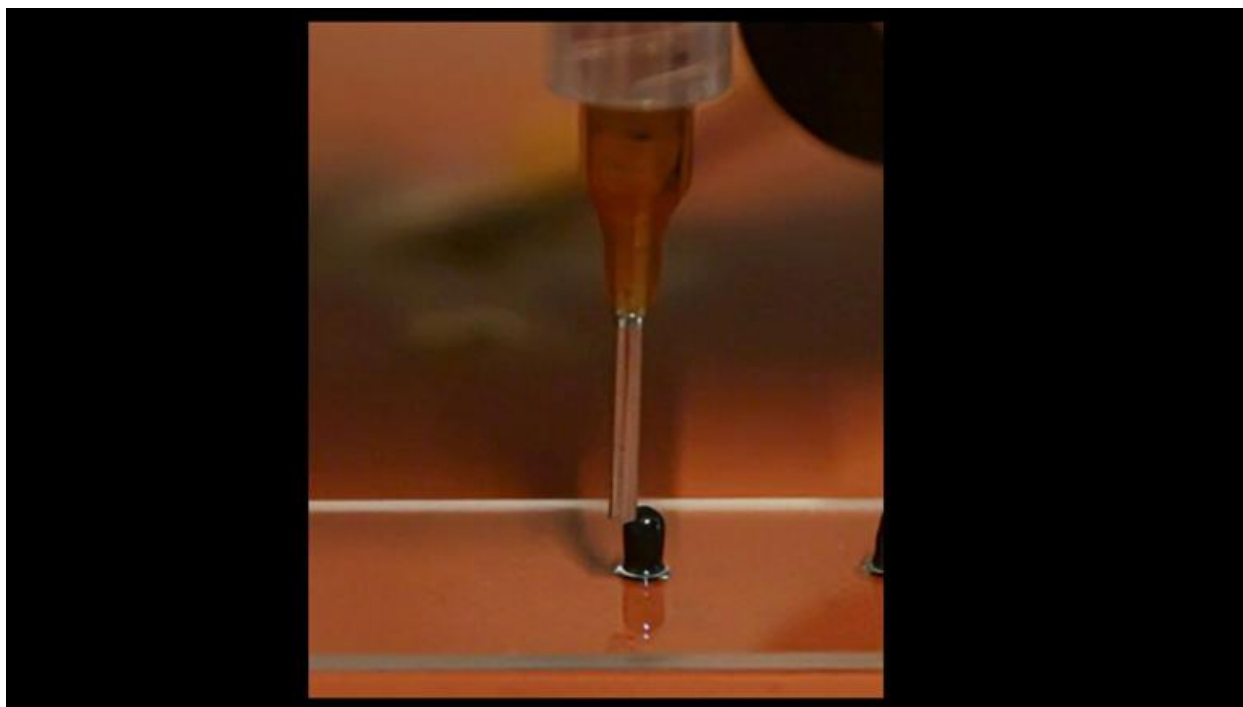
Thermoelectric coolers, also called solid-state refrigerators, can induce localized cooling by using an electric current to transfer heat from one side of the device to another. Their long lifetimes, invulnerability to leaks, size and shape tunability, and the lack of moving parts (such as circulating liquids) make these devices ideal for diverse cooling applications, such as electronics.



Printing of pellets used for the measurement of thermoelectric properties. Credit: Shengduo Xu | ISTA

However, manufacturing them out of ingots is associated with high costs and generates lots of material waste. In addition, the devices' performance remains limited.

Now, a team at the Institute of Science and Technology Austria (ISTA), led by Verbund Professor of Energy Sciences and Head of the Werner Siemens Thermoelectric Laboratory, Maria Ibáñez, with first author and ISTA postdoc Shengduo Xu, developed high-performance thermoelectric materials out of the 3D printer and used them to build a thermoelectric cooler.



Scratching method to remove the cone tip from a printed pillar. Credit: Shengduo Xu | ISTA

"Our innovative integration of 3D printing into thermoelectric cooler fabrication greatly improves manufacturing efficiency and reduces costs," says Xu.

Also, in contrast to previous attempts at 3D printing thermoelectric materials, the present method yields materials with considerably higher performance.

Pushing the boundaries of thermoelectric technologies

While all materials demonstrate some thermoelectric effect, it is often too negligible to be useful. Materials exhibiting a high enough thermoelectric effect are usually so-called "degenerate semiconductors," i.e., "doped" semiconductors, to which impurities are introduced intentionally so they behave like conductors.

Current state-of-the-art thermoelectric coolers are produced using ingot-based manufacturing techniques—expensive and power-hungry procedures requiring extensive machining processes after production, where a lot of material is wasted.

"With our present work, we can 3D print exactly the needed shape of thermoelectric materials. In addition, the resulting devices exhibit a net cooling

effect of 50 degrees in the air. This means that our 3D-printed materials perform similarly to ones that are significantly more expensive to manufacture," says Xu.

Thus, the team of ISTA material scientists proposes a scalable and cost-effective production method for thermoelectric materials, circumventing energy-intensive and time-consuming steps.

Printed materials with optimized particle bonding

Beyond applying 3D printing techniques to produce thermoelectric materials, the team designed the inks so that, as the carrier solvent evaporates, effective and robust atomic bonds are formed between grains, creating an atomically connected material network.

As a result, the interfacial chemical bonds improve the charge transfer between grains. This explains how the team managed to enhance the thermoelectric performance of their 3D-printed materials while also shedding new light on the transport properties of porous materials.

"We employed an extrusion-based 3D printing technique and designed the ink formulation to ensure the integrity of the printed structure and boost particle bonding. This allowed us to produce the first thermoelectric coolers from printed materials with comparable performance to ingot-based devices while saving material and energy," says Ibáñez.

Medical applications, energy harvesting, and sustainability

Beyond rapid heat management in electronics and wearable devices, thermoelectric coolers could have medical applications, including burn treatment and muscle strain relief. In addition, the ink formulation method developed by the team of ISTA scientists can be adapted for other materials to be used in high-temperature thermoelectric generators—devices that can generate electrical voltage from a temperature difference.

According to the team, such an approach could broaden the applicability of thermoelectric generators across various waste energy harvesting systems.

"We successfully executed a full-cycle approach, from optimizing the raw materials' thermoelectric performance to fabricating a stable, high-performance end-product," says Ibáñez.

Xu adds, "Our work offers a transformative solution for thermoelectric device production and heralds a new era of efficient and sustainable thermoelectric technologies."

More information: Shengduo Xu et al, Interfacial bonding enhances thermoelectric cooling in 3D-printed materials, *Science* (2025). DOI: [10.1126/science.ads0426](https://doi.org/10.1126/science.ads0426). www.science.org/doi/10.1126/science.ads0426

Provided by Institute of Science and Technology Austria

FEBRUARY 20, 2025

Optical tweezers reveal forward and backward motion is symmetric in molecular shuttling

by [IMDEA Nanociencia](#)

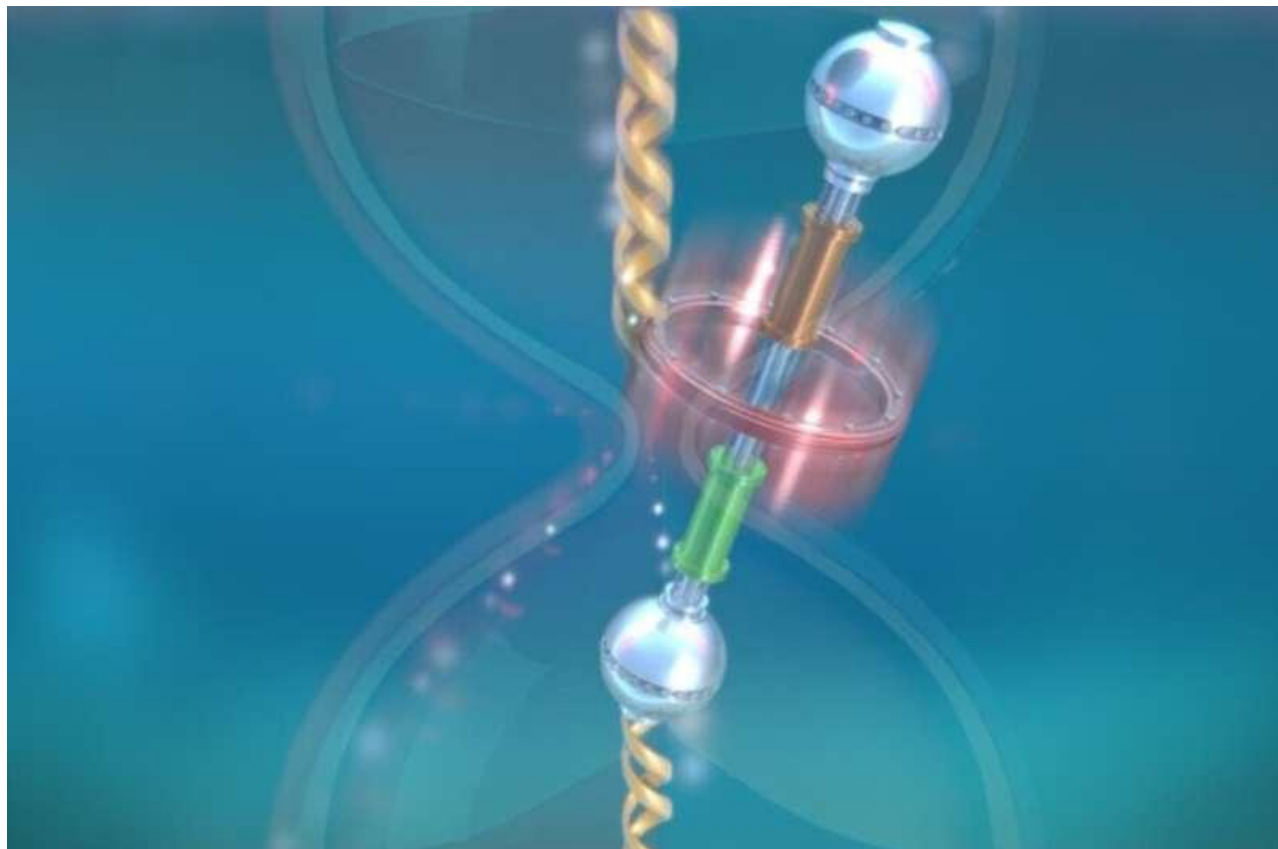
Transition path times of individual molecular shuttles show symmetry. Credit: *Chem* (2025). DOI: [10.1016/j.chempr.2024.102410](https://doi.org/10.1016/j.chempr.2024.102410)

In molecular shuttles, a ring molecule is threaded onto a linear molecular strand and can move between two portions of the strand, called stations, in response to external stimuli. Chemical stimuli, light or mechanical forces determine the time the shuttle spends at each station while it hops back and forth by random thermal motion. Measuring individual trajectories during the operation of such synthetic devices is crucial for a thorough understanding of their operation and in the optimization of molecular machines.

Researchers at IMDEA Nanociencia, led by Emilio Pérez and Borja Ibarra, have used [optical tweezers](#) to measure the individual transition paths of molecular shuttles between two stations under mechanical equilibrium. Their results showed that the transition-path times present wide distributions while maintaining a [time-reversal symmetry](#).

In collaboration with Prof. Raymond Astumian (University of Maine, U.S.), the researchers confirmed experimentally that the transition paths times show symmetry. That is, the shuttle does take the same time going up through the energy profile as it does going down.

The data analysis showed that the mean values of transitions are identical, showing similar shapes for the forward and reverse reactions. The shuttle spends the same time in each step between the two stations, independently of the direction of the shift. This symmetry of the transition-path time distributions was confirmed in accordance to the principle of microscopic reversibility.



The molecular shuttle is attached to two polystyrene beads through two DNA molecules. The hourglass symbolizes the symmetric trajectories of the shuttle. Credit: Scixel for IMDEA Nanociencia

Microscopic reversibility states that, at the [molecular level](#), every process and its reverse occur with the same probability in equilibrium. It is a very well-established principle in [statistical mechanics](#), but it is hard to measure experimentally, as it involves tracking the trajectories of individual molecules.

Molecular shuttling involves passage through a high-energy transition state, forming an energy barrier between stable states. The properties of the transition paths through these states contain all the fundamental mechanistic information about the shuttling process.

Up to date, transition paths have been studied theoretically, but their short lifetimes in the order of milliseconds, as well as their intrinsic stochastic nature have prevented their direct

observation experimentally until now. The results reported here provide a first experimental look at the principle of microscopic reversibility in molecular shuttles.

The study paves the way for a detailed and quantitative understanding of the dynamics of synthetic molecular machines. This is possible due to the extreme resolution and sensibility of the experimental setup.

Optical tweezers have the capability of measuring and controlling precisely molecular devices in the range of forces of picoNewton. Back in 2018, researchers Pérez and Ibarra followed, for five full minutes, the position of a molecular shuttle. Then, they focused on how much time the shuttle spent on each station.

Now, they focus on the journey, giving a thorough analysis of the transition paths, the full trajectory—position vs. time—of the molecule, extracting the energy profile along the thread.

The field of molecular shuttles is of relevance to nanotechnology in its quest for nanoscale [electronic components](#) and also to biology, where many biological functions are based on molecular shuttles. This study has been performed in water, an advantage that pushes forward the possibility of using this device for biotechnological applications.

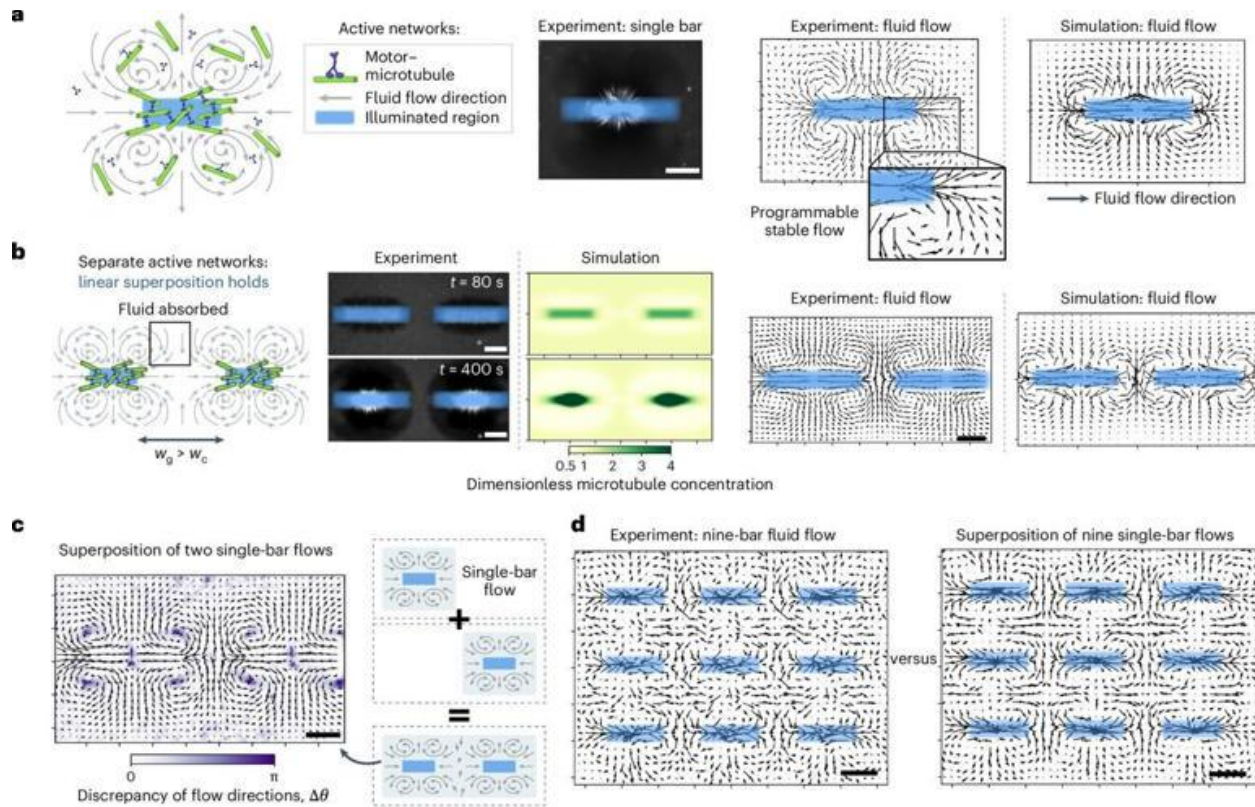
The examples of molecular machines are many: programmable molecular switches and sensors, nanovalves for drug-delivery systems, adaptive biomaterials, molecular muscles, etc. The Nobel Prize in Chemistry to Feringa, Sauvage and Stoddart already recognized in 2016 that there is an enormous potential in the development of molecular machines.

The research, recently [published](#) in the journal *Chem* paves the way to explore the temporal sequence of events during shuttling and investigate the possibility of taking multiple paths through the energy landscape. The information uncovered by this study will guide the rational design of efficient molecular switches and motors with a tailored response for applications in nanotechnology and biomedicine.

More information: Tomás Nicolás-García et al, Transition-path times of individual molecular shuttles under mechanical equilibrium show symmetry, *Chem* (2025). DOI: [10.1016/j.chempr.2024.102410](https://doi.org/10.1016/j.chempr.2024.102410)

Journal information: [Chem](#)
Provided by [IMDEA Nanociencia](#)

First 'programming language' for active material enables precise control at cellular level



Linear superposition quantitatively predicts fluid flow fields induced by optically controlled active matter. Credit: Nature Materials (2025). DOI: 10.1038/s41563-024-02090-w

In 2019, Caltech researchers demonstrated a new method to use light to control active matter—a kind of material made up of individual energy-consuming pieces that act as a whole to create mechanical motion. The process works similarly to how many individual birds form a swarm that seems to move as a whole. In the research, the team focused on active matter in the form of millimeter-sized protein filaments that normally make up a cell's skeleton, or "cytoskeleton."

Now, powered by insights from computational theory, the team has developed the first "programming language" for active matter, enabling researchers to conduct precise operations in tiny volumes of fluid on the cellular level. The method has major applications in nanotechnology and for studying cell interactions.

The research was a collaboration between the laboratories of Matt Thomson, professor of computational biology and a Heritage Medical Research Institute Investigator, and Rob Phillips, the Fred and Nancy Morris Professor of Biophysics, Biology, and Physics. The work is described in a paper [appearing](#) in the journal *Nature Materials*. Postdoctoral scholar Fan Yang and graduate student Shichen Liu are the study's co-first authors.

Cellular skeletons, or cytoskeletons, are shapeshifting networks of tiny protein filaments that enable cells to propel themselves, carry cargo, and divide. The "bones" of the cytoskeleton are thin, tube-like filaments called microtubules that can form together into three-dimensional scaffolds.

Creating Synthetic Life

Each microtubule is 1,000 times thinner than a human hair and only about 10 micrometers long (about 1,000 times smaller than a common black ant). Along with motor proteins that power movement, these incredibly small structures combine to propel the relatively large cell—analogous to ants steering and powering a car.

"Active matter has been a potential new material or resource for bioengineering but has, until this point, been impossible to control," Thomson says. "Using theoretical and computational modeling, Fan utilized principles of linear superposition—which only hold in specific size regimes—to develop the first programming language for active matter. Fan's theoretical insight enabled the development of the programming framework."

Cells naturally use gradients of chemicals to induce changes in the structure of their microtubule skeletons. In 2019, the team [engineered protein microtubules to respond instead to gradients of light](#), which allowed the researchers to shine specific patterns of light on a clump of microtubules and induce them to organize into a specific shape or pattern. But the system was not programmable because the team had not yet discovered how to design light patterns to generate fluid flow fields to accomplish tasks like moving cells or mixing fluids.

In the new work, Yang developed a programming language to design active matter fluid flows that can move, sort, and assemble cells; mix chemicals; and apply mechanical stresses to small objects like lipid vesicles in cells. Liu, an

experimentalist, then conducted the lab work to verify that the microtubules did in fact assemble as predicted.

The work has major applications for how researchers manipulate cells for study. Usually, scientists need to use needle-like micropipettes to stretch and separate individual cells, risking damage to those cells. With active matter, researchers can add light-activated microtubules to a clump of cells and gently nudge them to desired positions using only light.

"We were inspired by Erik Winfree's work on DNA computing and programming strand displacement reactions," Thomson says. "Now, we are starting to work with people like Magdalena Zernicka-Goetz to apply light-controlled, active matter to control cells during the construction of synthetic embryos. We are also using the system to manipulate immune cells, and to apply mechanical forces to tissues in the lab to simulate mechanical stresses."

Winfree is a Caltech professor of computer science, computation and neural systems, and bioengineering; Zernicka-Goetz is Caltech's Bren Professor of Biology and Biological Engineering.

In addition to Yang, Liu, Phillips, and Thomson, Caltech staff scientist Heun Jin Lee is a co-author.

More information: Fan Yang et al, Dynamic flow control through active matter programming language, *Nature Materials* (2025). DOI: [10.1038/s41563-024-02090-w](https://doi.org/10.1038/s41563-024-02090-w)

Provided by California Institute of Technology

FEBRUARY 24, 2025

Novel system optimizes the electrical, thermal and mechanical behavior of 3D printed materials

by [Carlos III University of Madrid](#)



Optimization of 3D printed materials. Credit: UC3M

Universidad Carlos III de Madrid (UC3M), in collaboration with the University of Oxford, Imperial College London and the BC Materials research center in the Basque Country, has developed an innovative computational model that makes it possible to predict and improve the behavior of multifunctional structures manufactured using 3D printers. This breakthrough, recently [published](#) in the journal *Nature Communications*, opens the door to new applications in sectors such as biomedicine, soft robotics and other branches of engineering.

"Currently, conductive thermoplastics are very promising because of their ability to transmit [electrical signals](#) while providing structural support," explains one of the study's authors, Daniel García-González, from the UC3M Department of Mechanics of Continuous Media and Theory of Structures. "But the main challenge in the manufacture of these materials is the control of their internal structure, since the bonding between filaments and the presence of small cavities affect both their mechanical resistance and their capacity to transmit electrical signals," explains the scientist.

Until now, these factors were considered unavoidable shortcomings of the 3D printing process. However, the researchers have managed to control these characteristics by integrating advanced computational tools and experimental trials, which has allowed them to manufacture structures that are sensitive and capable of transforming mechanical signals into electrical signals.

"A key point about this discovery is that it can be extrapolated to other types of 3D [printing technology](#) in which softer materials could be used," adds Javier Crespo, also from UC3M's Department of Mechanics of Continuous Media and Theory of Structures. The researcher is optimistic that it will be possible to design materials that lay the foundations for future advances in additive manufacturing, thanks to the combination of these new computational tools.

Credit: Carlos III University of Madrid

This new research, backed up by extensive experimental validation, provides a reliable approach to minimizing the differences between the different behaviors of conductive components and represents a major step forward in the design of multifunctional materials, according to its authors.

"For example, in the field of engineering, these structures could be used both for the manufacture of soft robots and for obtaining virtual data that can serve machine learning technologies," notes Javier Crespo.

Emilio Martínez-Pañeda, professor at the University of Oxford and co-author of the study, pointed out that "the research opens up endless opportunities, enabling the development of intelligent materials and sensors that could be of great use in the aerospace industry or in infrastructure monitoring."

"And not only that," adds Daniel García-González, "with these new materials we could also create patches or dressings that warn us how many times we are flexing our knees, so that in the event that we have an injury, we are alerted if we are passing certain critical points where we are going to cause damage to our muscles."

More information: Javier Crespo-Miguel et al, In-silico platform for the multifunctional design of 3D printed conductive components, *Nature Communications* (2025). DOI: [10.1038/s41467-025-56707-y](https://doi.org/10.1038/s41467-025-56707-y)

Journal information: [Nature Communications](#)

Provided by [Carlos III University of Madrid](#)

“There is Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics”

This is the transcript of the classic talk that Richard Feynman gave on December 29th, 1959 at the annual meeting of the American Physical Society at Caltech and was first published in the February 1960 issue of Caltech's Engineering and Science.

I imagine experimental physicists must often look with envy at men like Kamerlingh Onnes, who discovered a field like low temperature, which seems to be bottomless and in which one can go down and down. Such a man is then a leader and has some temporary monopoly in a scientific adventure. Percy Bridgman, in designing a way to obtain higher pressures, opened up another new field and was able to move into it and to lead us all along. The development of an ever higher vacuum was a continuing development of the same kind.

I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. This field is not quite the same as the others in that it will not tell us much of fundamental physics (in the sense of, “What are the strange particles?”) but it is more like solid-state physics in the sense that it might tell us much of great interest about the strange phenomena that occur in complex situations. Furthermore, a point that is most important is that it would have an enormous number of technical applications.

What I want to talk about is the problem of manipulating and controlling things on a small scale.

As soon as I mention this, people tell me about miniaturization, and how far it has progressed today. They tell me about electric motors that are the size of the nail on your small finger. And there is a device on the market, they tell me, by which you can write the Lord's Prayer on the head of a pin. But that's nothing; that's the most primitive, halting step in the direction I intend to discuss. It is a staggeringly small world that is below. In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.

Why cannot we write the entire 24 volumes of the Encyclopedia Britannica on the head of a pin?

Let's see what would be involved. The head of a pin is a sixteenth of an inch across. If you magnify it by 25,000 diameters, the area of the head of the pin is then equal to the area of all the pages of the Encyclopaedia Britannica. Therefore, all it is necessary to do is to reduce in size all the writing in the Encyclopaedia by 25,000 times. Is that possible? The resolving power of the eye is about 1/120 of an inch — that is roughly the diameter of one of the little dots on the fine half-tone reproductions in the Encyclopaedia. This, when you demagnify it by 25,000 times, is still 80 angstroms in diameter — 32 atoms across, in an ordinary metal. In other words, one of those dots still would contain in its area 1,000 atoms. So, each dot can easily be adjusted in size as

required by the photoengraving, and there is no question that there is enough room on the head of a pin to put all of the Encyclopaedia Britannica.

Furthermore, it can be read if it is so written. Let's imagine that it is written in raised letters of metal; that is, where the black is in the Encyclopedia, we have raised letters of metal that are actually 1/25,000 of their ordinary size. How would we read it?

If we had something written in such a way, we could read it using techniques in common use today. (They will undoubtedly find a better way when we do actually have it written, but to make my point conservatively I shall just take techniques we know today.) We would press the metal into a plastic material and make a mold of it, then peel the plastic off very carefully, evaporate silica into the plastic to get a very thin film, then shadow it by evaporating gold at an angle against the silica so that all the little letters will appear clearly, dissolve the plastic away from the silica film, and then look through it with an electron microscope!

There is no question that if the thing were reduced by 25,000 times in the form of raised letters on the pin, it would be easy for us to read it today. Furthermore; there is no question that we would find it easy to make copies of the master; we would just need to press the same metal plate again into plastic and we would have another copy.

How do we write small?

The next question is: How do we write it? We have no standard technique to do this now. But let me argue that it is not as difficult as it first appears to be. We can reverse the lenses of the electron microscope in order to demagnify as well as magnify. A source of ions, sent through the microscope lenses in reverse, could be focused to a very small spot. We could write with that spot like we write in a TV cathode ray oscilloscope, by going across in lines, and having an adjustment which determines the amount of material which is going to be deposited as we scan in lines.

This method might be very slow because of space charge limitations. There will be more rapid methods. We could first make, perhaps by some photo process, a screen which has holes in it in the form of the letters. Then we would strike an arc behind the holes and draw metallic ions through the holes; then we could again use our system of lenses and make a small image in the form of ions, which would deposit the metal on the pin.

A simpler way might be this (though I am not sure it would work): We take light and, through an optical microscope running backwards, we focus it onto a very small photoelectric screen. Then electrons come away from the screen where the light is shining. These electrons are focused down in size by the electron microscope lenses to impinge directly upon the surface of the metal. Will such a beam etch away the metal if it is run long enough? I don't know. If it doesn't work for a metal surface, it must be possible to find some surface with which to coat the original pin so that, where the electrons bombard, a change is made which we could recognize later.

There is no intensity problem in these devices — not what you are used to in magnification, where you have to take a few electrons and spread them over a bigger and bigger screen; it is just the opposite. The light which we get from a page is

concentrated onto a very small area so it is very intense. The few electrons which come from the photoelectric screen are demagnified down to a very tiny area so that, again, they are very intense. I don't know why this hasn't been done yet!

That's the Encyclopaedia Britannica on the head of a pin, but let's consider all the books in the world. The Library of Congress has approximately 9 million volumes; the British Museum Library has 5 million volumes; there are also 5 million volumes in the National Library in France. Undoubtedly there are duplications, so let us say that there are some 24 million volumes of interest in the world.

What would happen if I print all this down at the scale we have been discussing? How much space would it take? It would take, of course, the area of about a million pinheads because, instead of there being just the 24 volumes of the Encyclopaedia, there are 24 million volumes. The million pinheads can be put in a square of a thousand pins on a side, or an area of about 3 square yards. That is to say, the silica replica with the paper-thin backing of plastic, with which we have made the copies, with all this information, is on an area of approximately the size of 35 pages of the Encyclopaedia. That is about half as many pages as there are in this magazine. All of the information which all of mankind has ever recorded in books can be carried around in a pamphlet in your hand — and not written in code, but a simple reproduction of the original pictures, engravings, and everything else on a small scale without loss of resolution.

What would our librarian at Caltech say, as she runs all over from one building to another, if I tell her that, ten years from now, all of the information that she is struggling to keep track of — 120,000 volumes, stacked from the floor to the ceiling, drawers full of cards, storage rooms full of the older books — can be kept on just one library card! When the University of Brazil, for example, finds that their library is burned, we can send them a copy of every book in our library by striking off a copy from the master plate in a few hours and mailing it in an envelope no bigger or heavier than any other ordinary air mail letter.

Now, the name of this talk is "There is Plenty of Room at the Bottom" — not just "There is Room at the Bottom." What I have demonstrated is that there is room — that you can decrease the size of things in a practical way. I now want to show that there is plenty of room. I will not now discuss how we are going to do it, but only what is possible in principle — in other words, what is possible according to the laws of physics. I am not inventing anti-gravity, which is possible someday only if the laws are not what we think. I am telling you what could be done if the laws are what we think; we are not doing it simply because we haven't yet gotten around to it.

Information on a small scale

Suppose that, instead of trying to reproduce the pictures and all the information directly in its present form, we write only the information content in a code of dots and dashes, or something like that, to represent the various letters. Each letter represents six or seven "bits" of information; that is, you need only about six or seven dots or dashes for each letter. Now, instead of writing everything, as I did before, on the surface of the head of a pin, I am going to use the interior of the material as well.

Let us represent a dot by a small spot of one metal, the next dash, by an adjacent spot of another metal, and so on. Suppose, to be conservative, that a bit of information is going to require a little cube of atoms 5 times 5 times 5 — that is 125 atoms. Perhaps we need a hundred and some odd atoms to make sure that the information is not lost through diffusion, or through some other process.

I have estimated how many letters there are in the Encyclopaedia, and I have assumed that each of my 24 million books is as big as an Encyclopaedia volume, and have calculated, then, how many bits of information there are (10^{15}). For each bit I allow 100 atoms. And it turns out that all of the information that man has carefully accumulated in all the books in the world can be written in this form in a cube of material one two-hundredth of an inch wide — which is the barest piece of dust that can be made out by the human eye. So there is plenty of room at the bottom! Don't tell me about microfilm!

This fact — that enormous amounts of information can be carried in an exceedingly small space — is, of course, well known to the biologists, and resolves the mystery which existed before we understood all this clearly, of how it could be that, in the tiniest cell, all of the information for the organization of a complex creature such as ourselves can be stored. All this information — whether we have brown eyes, or whether we think at all, or that in the embryo the jawbone should first develop with a little hole in the side so that later a nerve can grow through it — all this information is contained in a very tiny fraction of the cell in the form of long-chain DNA molecules in which approximately 50 atoms are used for one bit of information about the cell.

Better electron microscopes

If I have written in a code, with 5 times 5 times 5 atoms to a bit, the question is: How could I read it today? The electron microscope is not quite good enough, with the greatest care and effort, it can only resolve about 10 angstroms. I would like to try and impress upon you while I am talking about all of these things on a small scale, the importance of improving the electron microscope by a hundred times. It is not impossible; it is not against the laws of diffraction of the electron. The wave length of the electron in such a microscope is only 1/20 of an angstrom. So it should be possible to see the individual atoms. What good would it be to see individual atoms distinctly?

We have friends in other fields — in biology, for instance. We physicists often look at them and say, "You know the reason you fellows are making so little progress?" (Actually I don't know any field where they are making more rapid progress than they are in biology today.) "You should use more mathematics, like we do." They could answer us — but they're polite, so I'll answer for them: "What you should do in order for us to make more rapid progress is to make the electron microscope 100 times better."

What are the most central and fundamental problems of biology today? They are questions like: What is the sequence of bases in the DNA? What happens when you have a mutation? How is the base order in the DNA connected to the order of amino acids in the protein? What is the structure of the RNA; is it single-chain or double-chain, and how is it related in its order of bases to the DNA? What is the organization of the microsomes? How are proteins synthesized? Where does the RNA go? How does it sit?

Where do the proteins sit? Where do the amino acids go in? In photosynthesis, where is the chlorophyll; how is it arranged; where are the carotenoids involved in this thing? What is the system of the conversion of light into chemical energy?

It is very easy to answer many of these fundamental biological questions; you just look at the thing! You will see the order of bases in the chain; you will see the structure of the microsome. Unfortunately, the present microscope sees at a scale which is just a bit too crude. Make the microscope one hundred times more powerful, and many problems of biology would be made very much easier. I exaggerate, of course, but the biologists would surely be very thankful to you — and they would prefer that to the criticism that they should use more mathematics.

The theory of chemical processes today is based on theoretical physics. In this sense, physics supplies the foundation of chemistry. But chemistry also has analysis. If you have a strange substance and you want to know what it is, you go through a long and complicated process of chemical analysis. You can analyze almost anything today, so I am a little late with my idea. But if the physicists wanted to, they could also dig under the chemists in the problem of chemical analysis. It would be very easy to make an analysis of any complicated chemical substance; all one would have to do would be to look at it and see where the atoms are. The only trouble is that the electron microscope is one hundred times too poor. (Later, I would like to ask the question: Can the physicists do something about the third problem of chemistry — namely, synthesis? Is there a physical way to synthesize any chemical substance?)

The reason the electron microscope is so poor is that the f -value of the lenses is only 1 part to 1,000; you don't have a big enough numerical aperture. And I know that there are theorems which prove that it is impossible, with axially symmetrical stationary field lenses, to produce an f -value any bigger than so and so; and therefore the resolving power at the present time is at its theoretical maximum. But in every theorem there are assumptions. Why must the field be symmetrical? I put this out as a challenge: Is there no way to make the electron microscope more powerful?

The marvelous biological system

The biological example of writing information on a small scale has inspired me to think of something that should be possible. Biology is not simply writing information; it is doing something about it. A biological system can be exceedingly small. Many of the cells are very tiny, but they are very active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvelous things — all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small which does what we want — that we can manufacture an object that maneuvers at that level!

There may even be an economic point to this business of making things very small. Let me remind you of some of the problems of computing machines. In computers we have to store an enormous amount of information. The kind of writing that I was mentioning before, in which I had everything down as a distribution of metal, is permanent. Much more interesting to a computer is a way of writing, erasing, and writing something else. (This is usually because we don't want to waste the material on which we have just

written. Yet if we could write it in a very small space, it wouldn't make any difference; it could just be thrown away after it was read. It doesn't cost very much for the material).

Miniaturizing the computer

I don't know how to do this on a small scale in a practical way, but I do know that computing machines are very large; they fill rooms. Why can't we make them very small, make them of little wires, little elements — and by little, I mean little. For instance, the wires should be 10 or 100 atoms in diameter, and the circuits should be a few thousand angstroms across. Everybody who has analyzed the logical theory of computers has come to the conclusion that the possibilities of computers are very interesting — if they could be made to be more complicated by several orders of magnitude. If they had millions of times as many elements, they could make judgments. They would have time to calculate what is the best way to make the calculation that they are about to make. They could select the method of analysis which, from their experience, is better than the one that we would give to them. And in many other ways, they would have new qualitative features.

If I look at your face I immediately recognize that I have seen it before. (Actually, my friends will say I have chosen an unfortunate example here for the subject of this illustration. At least I recognize that it is a man and not an apple.) Yet there is no machine which, with that speed, can take a picture of a face and say even that it is a man; and much less that it is the same man that you showed it before — unless it is exactly the same picture. If the face is changed; if I am closer to the face; if I am further from the face; if the light changes — I recognize it anyway. Now, this little computer I carry in my head is easily able to do that. The computers that we build are not able to do that. The number of elements in this bone box of mine are enormously greater than the number of elements in our "wonderful" computers. But our mechanical computers are too big; the elements in this box are microscopic. I want to make some that are submicroscopic.

If we wanted to make a computer that had all these marvelous extra qualitative abilities, we would have to make it, perhaps, the size of the Pentagon. This has several disadvantages. First, it requires too much material; there may not be enough germanium in the world for all the transistors which would have to be put into this enormous thing. There is also the problem of heat generation and power consumption; TVA would be needed to run the computer. But an even more practical difficulty is that the computer would be limited to a certain speed. Because of its large size, there is finite time required to get the information from one place to another. The information cannot go any faster than the speed of light — so, ultimately, when our computers get faster and faster and more and more elaborate, we will have to make them smaller and smaller.

But there is plenty of room to make them smaller. There is nothing that I can see in the physical laws that says the computer elements cannot be made enormously smaller than they are now. In fact, there may be certain advantages.

Miniaturization by evaporation

How can we make such a device? What kind of manufacturing processes would we use? One possibility we might consider, since we have talked about writing by putting atoms down in a certain arrangement, would be to evaporate the material, then evaporate the insulator next to it. Then, for the next layer, evaporate another position of a wire, another insulator, and so on. So, you simply evaporate until you have a block of stuff which has the elements — coils and condensers, transistors and so on — of exceedingly fine dimensions.

But I would like to discuss, just for amusement, that there are other possibilities. Why can't we manufacture these small computers somewhat like we manufacture the big ones? Why can't we drill holes, cut things, solder things, stamp things out, mold different shapes all at an infinitesimal level? What are the limitations as to how small a thing has to be before you can no longer mold it? How many times when you are working on something frustratingly tiny like your wife's wrist watch, have you said to yourself, "If I could only train an ant to do this!" What I would like to suggest is the possibility of training an ant to train a mite to do this. What are the possibilities of small but movable machines? They may or may not be useful, but they surely would be fun to make.

Consider any machine — for example, an automobile — and ask about the problems of making an infinitesimal machine like it. Suppose, in the particular design of the automobile, we need a certain precision of the parts; we need an accuracy, let's suppose, of $4/10,000$ of an inch. If things are more inaccurate than that in the shape of the cylinder and so on, it isn't going to work very well. If I make the thing too small, I have to worry about the size of the atoms; I can't make a circle of "balls" so to speak, if the circle is too small. So, if I make the error, corresponding to $4/10,000$ of an inch, correspond to an error of 10 atoms, it turns out that I can reduce the dimensions of an automobile 4,000 times, approximately — so that it is 1 mm. across. Obviously, if you redesign the car so that it would work with a much larger tolerance, which is not at all impossible, then you could make a much smaller device.

It is interesting to consider what the problems are in such small machines. Firstly, with parts stressed to the same degree, the forces go as the area you are reducing, so that things like weight and inertia are of relatively no importance. The strength of material, in other words, is very much greater in proportion. The stresses and expansion of the flywheel from centrifugal force, for example, would be the same proportion only if the rotational speed is increased in the same proportion as we decrease the size. On the other hand, the metals that we use have a grain structure, and this would be very annoying at small scale because the material is not homogeneous. Plastics and glass and things of this amorphous nature are very much more homogeneous, and so we would have to make our machines out of such materials.

There are problems associated with the electrical part of the system — with the copper wires and the magnetic parts. The magnetic properties on a very small scale are not the same as on a large scale; there is the "domain" problem involved. A big magnet made of millions of domains can only be made on a small scale with one domain. The electrical equipment won't simply be scaled down; it has to be redesigned. But I can see no reason why it can't be redesigned to work again.

Problems of lubrication

Lubrication involves some interesting points. The effective viscosity of oil would be higher and higher in proportion as we went down (and if we increase the speed as much as we can). If we don't increase the speed so much, and change from oil to kerosene or some other fluid, the problem is not so bad. But actually we may not have to lubricate at all! We have a lot of extra force. Let the bearings run dry; they won't run hot because the heat escapes away from such a small device very, very rapidly.

This rapid heat loss would prevent the gasoline from exploding, so an internal combustion engine is impossible. Other chemical reactions, liberating energy when cold, can be used. Probably an external supply of electrical power would be most convenient for such small machines.

What would be the utility of such machines? Who knows? Of course, a small automobile would only be useful for the mites to drive around in, and I suppose our Christian interests don't go that far. However, we did note the possibility of the manufacture of small elements for computers in completely automatic factories, containing lathes and other machine tools at the very small level. The small lathe would not have to be exactly like our big lathe. I leave to your imagination the improvement of the design to take full advantage of the properties of things on a small scale, and in such a way that the fully automatic aspect would be easiest to manage.

A friend of mine (Albert R. Hibbs) suggests a very interesting possibility for relatively small machines. He says that, although it is a very wild idea, it would be interesting in surgery if you could swallow the surgeon. You put the mechanical surgeon inside the blood vessel and it goes into the heart and "looks" around. (Of course the information has to be fed out.) It finds out which valve is the faulty one and takes a little knife and slices it out. Other small machines might be permanently incorporated in the body to assist some inadequately-functioning organ.

Now comes the interesting question: How do we make such a tiny mechanism? I leave that to you. However, let me suggest one weird possibility. You know, in the atomic energy plants they have materials and machines that they can't handle directly because they have become radioactive. To unscrew nuts and put on bolts and so on, they have a set of master and slave hands, so that by operating a set of levers here, you control the "hands" there, and can turn them this way and that so you can handle things quite nicely.

Most of these devices are actually made rather simply, in that there is a particular cable, like a marionette string, that goes directly from the controls to the "hands." But, of course, things also have been made using servo motors, so that the connection between the one thing and the other is electrical rather than mechanical. When you turn the levers, they turn a servo motor, and it changes the electrical currents in the wires, which repositions a motor at the other end.

Now, I want to build much the same device — a master-slave system which operates electrically. But I want the slaves to be made especially carefully by modern large-scale machinists so that they are one-fourth the scale of the "hands" that you ordinarily maneuver. So you have a scheme by which you can do things at one-quarter scale

anyway — the little servo motors with little hands play with little nuts and bolts; they drill little holes; they are four times smaller. Aha! So I manufacture a quarter-size lathe; I manufacture quarter-size tools; and I make, at the one-quarter scale, still another set of hands again relatively one-quarter size! This is one-sixteenth size, from my point of view. And after I finish doing this I wire directly from my large-scale system, through transformers perhaps, to the one-sixteenth-size servo motors. Thus I can now manipulate the one-sixteenth size hands.

Well, you get the principle from there on. It is rather a difficult program, but it is a possibility. You might say that one can go much farther in one step than from one to four. Of course, this has all to be designed very carefully and it is not necessary simply to make it like hands. If you thought of it very carefully, you could probably arrive at a much better system for doing such things.

If you work through a pantograph, even today, you can get much more than a factor of four in even one step. But you can't work directly through a pantograph which makes a smaller pantograph which then makes a smaller pantograph — because of the looseness of the holes and the irregularities of construction. The end of the pantograph wiggles with a relatively greater irregularity than the irregularity with which you move your hands. In going down this scale, I would find the end of the pantograph on the end of the pantograph shaking so badly that it wasn't doing anything sensible at all.

At each stage, it is necessary to improve the precision of the apparatus. If, for instance, having made a small lathe with a pantograph, we find its lead screw irregular — more irregular than the large-scale one — we could lap the lead screw against breakable nuts that you can reverse in the usual way back and forth until this lead screw is, at its scale, as accurate as our original lead screws, at our scale.

We can make flats by rubbing unflat surfaces in triplicates together — in three pairs — and the flats then become flatter than the thing you started with. Thus, it is not impossible to improve precision on a small scale by the correct operations. So, when we build this stuff, it is necessary at each step to improve the accuracy of the equipment by working for awhile down there, making accurate lead screws, Johansen blocks, and all the other materials which we use in accurate machine work at the higher level. We have to stop at each level and manufacture all the stuff to go to the next level — a very long and very difficult program. Perhaps you can figure a better way than that to get down to small scale more rapidly.

Yet, after all this, you have just got one little baby lathe four thousand times smaller than usual. But we were thinking of making an enormous computer, which we were going to build by drilling holes on this lathe to make little washers for the computer. How many washers can you manufacture on this one lathe?

A hundred tiny hands

When I make my first set of slave “hands” at one-fourth scale, I am going to make ten sets. I make ten sets of “hands,” and I wire them to my original levers so they each do exactly the same thing at the same time in parallel. Now, when I am making my new

devices one-quarter again as small, I let each one manufacture ten copies, so that I would have a hundred “hands” at the 1/16th size.

Where am I going to put the million lathes that I am going to have? Why, there is nothing to it; the volume is much less than that of even one full-scale lathe. For instance, if I made a billion little lathes, each 1/4000 of the scale of a regular lathe, there are plenty of materials and space available because in the billion little ones there is less than 2 percent of the materials in one big lathe.

It doesn't cost anything for materials, you see. So I want to build a billion tiny factories, models of each other, which are manufacturing simultaneously, drilling holes, stamping parts, and so on.

As we go down in size, there are a number of interesting problems that arise. All things do not simply scale down in proportion. There is the problem that materials stick together by the molecular (Van der Waals) attractions. It would be like this: After you have made a part and you unscrew the nut from a bolt, it isn't going to fall down because the gravity isn't appreciable; it would even be hard to get it off the bolt. It would be like those old movies of a man with his hands full of molasses, trying to get rid of a glass of water. There will be several problems of this nature that we will have to be ready to design for.

Rearranging the atoms

But I am not afraid to consider the final question as to whether, ultimately — in the great future — we can arrange the atoms the way we want; the very atoms, all the way down! What would happen if we could arrange the atoms one by one the way we want them (within reason, of course; you can't put them so that they are chemically unstable, for example).

Up to now, we have been content to dig in the ground to find minerals. We heat them and we do things on a large scale with them, and we hope to get a pure substance with just so much impurity, and so on. But we must always accept some atomic arrangement that nature gives us. We haven't got anything, say, with a “checkerboard” arrangement, with the impurity atoms exactly arranged 1,000 angstroms apart, or in some other particular pattern.

What could we do with layered structures with just the right layers? What would the properties of materials be if we could really arrange the atoms the way we want them? They would be very interesting to investigate theoretically. I can't see exactly what would happen, but I can hardly doubt that when we have some control of the arrangement of things on a small scale we will get an enormously greater range of possible properties that substances can have, and of different things that we can do.

Consider, for example, a piece of material in which we make little coils and condensers (or their solid state analogs) 1,000 or 10,000 angstroms in a circuit, one right next to the other, over a large area, with little antennas sticking out at the other end — a whole series of circuits. Is it possible, for example, to emit light from a whole set of antennas, like we emit radio waves from an organized set of antennas to beam the radio programs to Europe? The same thing would be to beam the light out in a definite direction with

very high intensity. (Perhaps such a beam is not very useful technically or economically.)

I have thought about some of the problems of building electric circuits on a small scale, and the problem of resistance is serious. If you build a corresponding circuit on a small scale, its natural frequency goes up, since the wave length goes down as the scale; but the skin depth only decreases with the square root of the scale ratio, and so resistive problems are of increasing difficulty. Possibly we can beat resistance through the use of superconductivity if the frequency is not too high, or by other tricks.

Atoms in a small world

When we get to the very, very small world — say circuits of seven atoms — we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things. We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc.

Another thing we will notice is that, if we go down far enough, all of our devices can be mass produced so that they are absolutely perfect copies of one another. We cannot build two large machines so that the dimensions are exactly the same. But if your machine is only 100 atoms high, you only have to get it correct to one-half of one percent to make sure the other machine is exactly the same size — namely, 100 atoms high!

At the atomic level, we have new kinds of forces and new kinds of possibilities, new kinds of effects. The problems of manufacture and reproduction of materials will be quite different. I am, as I said, inspired by the biological phenomena in which chemical forces are used in repetitious fashion to produce all kinds of weird effects (one of which is the author).

The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big.

Ultimately, we can do chemical synthesis. A chemist comes to us and says, "Look, I want a molecule that has the atoms arranged thus and so; make me that molecule." The chemist does a mysterious thing when he wants to make a molecule. He sees that it has got that ring, so he mixes this and that, and he shakes it, and he fiddles around. And, at the end of a difficult process, he usually does succeed in synthesizing what he wants. By the time I get my devices working, so that we can do it by physics, he will have figured out how to synthesize absolutely anything, so that this will really be useless.

But it is interesting that it would be, in principle, possible (I think) for a physicist to synthesize any chemical substance that the chemist writes down. Give the orders and the physicist synthesizes it. How? Put the atoms down where the chemist says, and so

you make the substance. The problems of chemistry and biology can be greatly helped if our ability to see what we are doing, and to do things on an atomic level, is ultimately developed — a development which I think cannot be avoided.

Now, you might say, “Who should do this and why should they do it?” Well, I pointed out a few of the economic applications, but I know that the reason that you would do it might be just for fun. But have some fun! Let’s have a competition between laboratories. Let one laboratory make a tiny motor which it sends to another lab which sends it back with a thing that fits inside the shaft of the first motor.

High school competition

Just for the fun of it, and in order to get kids interested in this field, I would propose that someone who has some contact with the high schools think of making some kind of high school competition. After all, we haven’t even started in this field, and even the kids can write smaller than has ever been written before. They could have competition in high schools. The Los Angeles high school could send a pin to the Venice high school on which it says, “How’s this?” They get the pin back, and in the dot of the “i” it says, “Not so hot.”

Perhaps this doesn’t excite you to do it, and only economics will do so. Then I want to do something; but I can’t do it at the present moment, because I haven’t prepared the ground. It is my intention to offer a prize of \$1,000 to the first guy who can take the information on the page of a book and put it on an area $1/25,000$ smaller in linear scale in such manner that it can be read by an electron microscope.

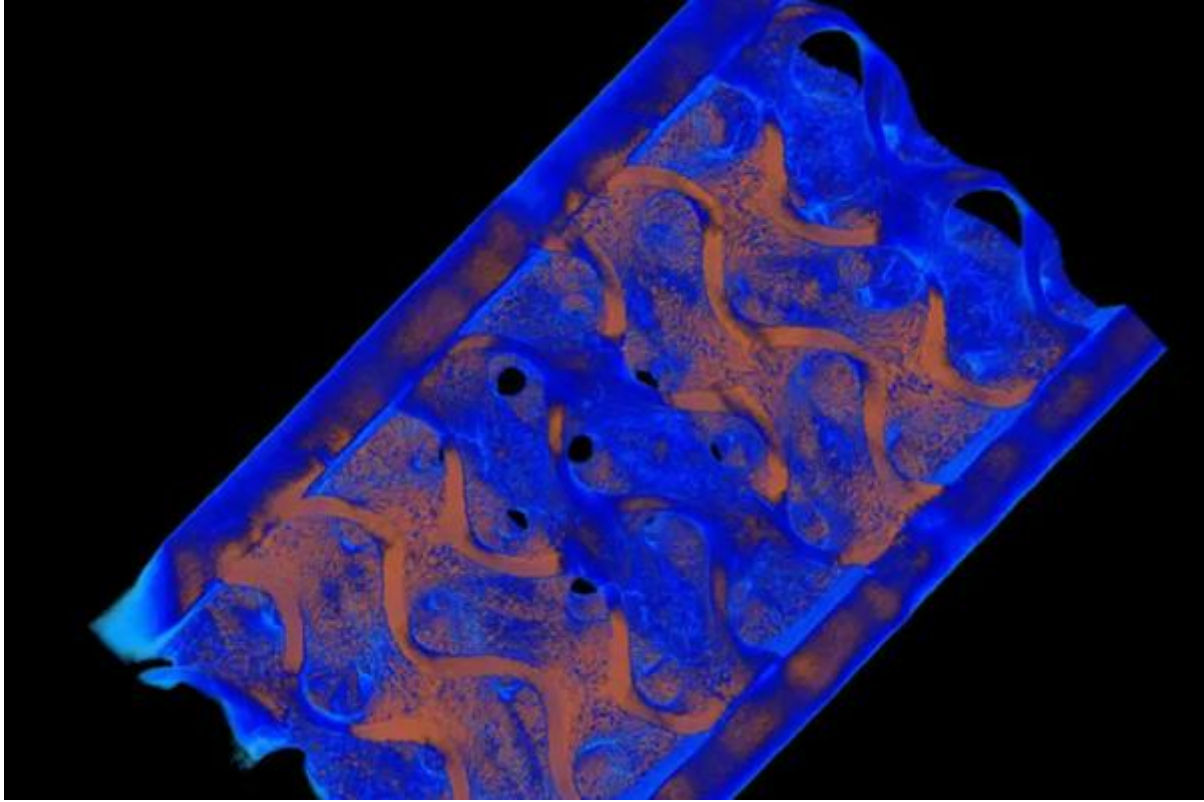
And I want to offer another prize — if I can figure out how to phrase it so that I don’t get into a mess of arguments about definitions — of another \$1,000 to the first guy who makes an operating electric motor — a rotating electric motor which can be controlled from the outside and, not counting the lead-in wires, is only $1/64$ inch cube.

I do not expect that such prizes will have to wait very long for claimants.

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Beyond welding: Researchers 3D-print a single complex structure containing two metals



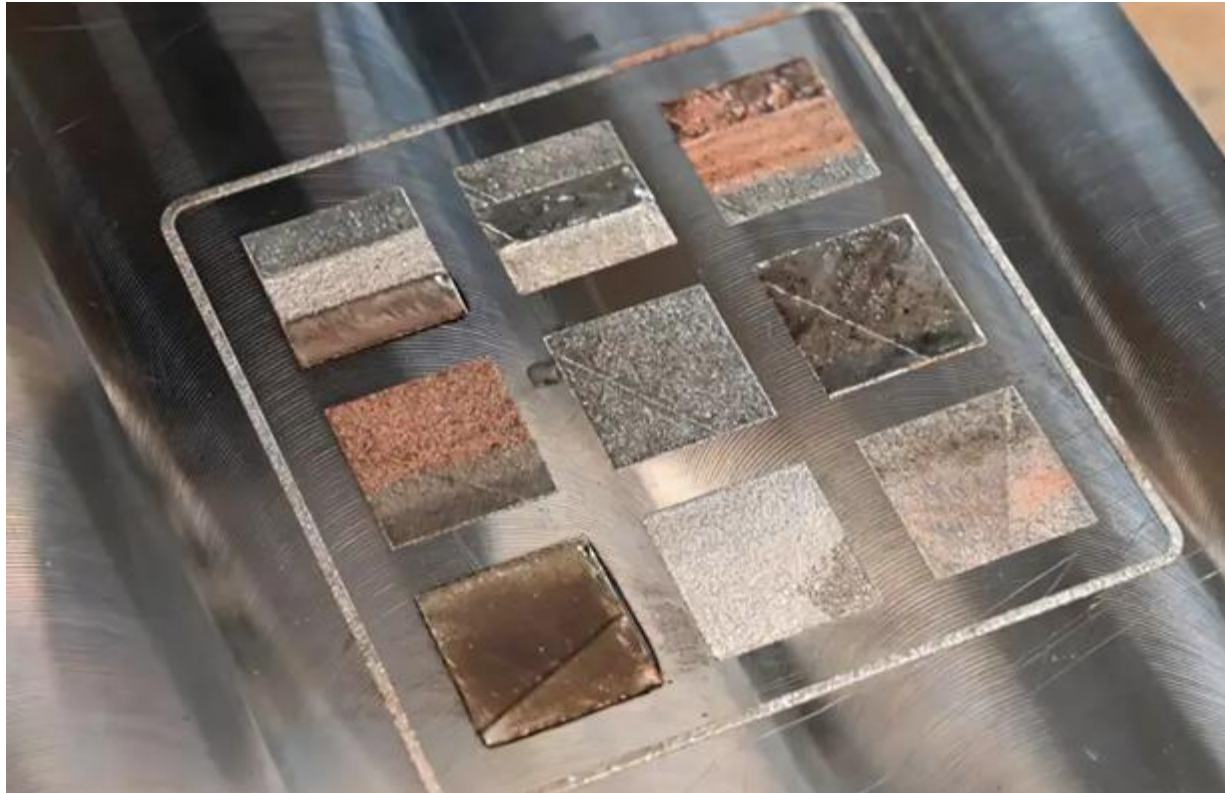
A micro-CT volume rendering of the multi-material gyroid beam, fabricated from low-carbon stainless steel, seen in blue, and bronze, seen in orange, using the Aerosint selective powder deposition system. Credit: Provided by the SHAPE Lab, CIMP-3D and the Penn State Center for Quantitative Imaging

A team of Penn State researchers has used a new 3D-printing method to produce a complex metal build that was once only possible with welding: fusing two metals together into a single structure.

Using an advanced additive manufacturing process known as multi-material laser powder bed fusion—enabled by a newly acquired system in Penn State's Center for Innovative Materials Processing Through Direct Digital Deposition (CIMP-3D)—the researchers printed a complex structure out of a blend of low-carbon stainless steel and bronze, which consists of 90% copper and 10% tin.

The researchers have [published](#) their approach in *npj Advanced Manufacturing*.

"In a process called selective powder deposition, we can now melt multiple powdered metals in a single layer during the additive manufacturing process—and we were the first university in the U.S. to do so," said Jacklyn Griffis, a doctoral candidate in mechanical engineering and first author of the paper. "The fine powders are tens of microns in diameter, almost like flour. We can selectively deposit the powder with micron-level resolution, then melt it together with a laser."



A close-up view of a build plate of test squares featuring the first sintered layer of three metals: stainless steel, Inconel and pure copper. The test squares demonstrated multi-material metal additive manufacturing using CIMP-3D's new selective powder deposition system. Credit: Provided by the SHAPE Lab, CIMP-3D and 3D Systems

Researchers used an Aerosint selective powder deposition system, which CIMP-3D acquired in August 2023, to print and test the metal part. The system was integrated into an existing 3D Systems ProX320 AM machine in the Systems for Hybrid-Additive Process Engineering (SHAPE) Lab at CIMP-3D. A one-centimeter-tall metal part includes thousands of layers of metal powder, Griffis said, and takes a few hours to print.

"We now have the processing technology to print these multi-material metal parts, as well as a way to monitor the melt pool and observe and address

potential issues in real time," said corresponding author Guha Manogharan, associate professor of mechanical engineering, head of the SHAPE Lab and co-director of CIMP-3D. "To do this, we produce a digital 3D rendering of the part through CT scans, which we use to look for pores, cracks at the interface or micron-scale defects."

In printing two metals in a single powder simultaneously, researchers had to work through complex questions on processing conditions and part quality. In this paper, they focused on analyzing the build orientation of the part to understand what would change if the part was printed upright, flat or on its side.

"In our analysis, we connected the part's build orientation to a number of observations about the structure, including defects like cracking and porosity, interfacial microstructures and the ways elements are diffused or blended across the interface," Griffis said. "We then connected those printed defects to the part's performance."

Their finished structure is a complex shape known as a gyroid, which is used in applications such as heat exchangers and biomedical implants. The researchers chose the gyroid shape to demonstrate the capabilities of the new manufacturing process—only multi-material laser powder bed fusion can create a multi-material gyroid shape.

"Penn State has always been a leader in metal additive manufacturing, but we now have the ability to manufacture complex multi-material parts, where we can not only make complex designs but control precisely where each material is placed," Manogharan said. "In order to get to full production, we need to understand the causes for defects based on materials and manufacturing conditions to address the question of why the parts failed at the interfaces."

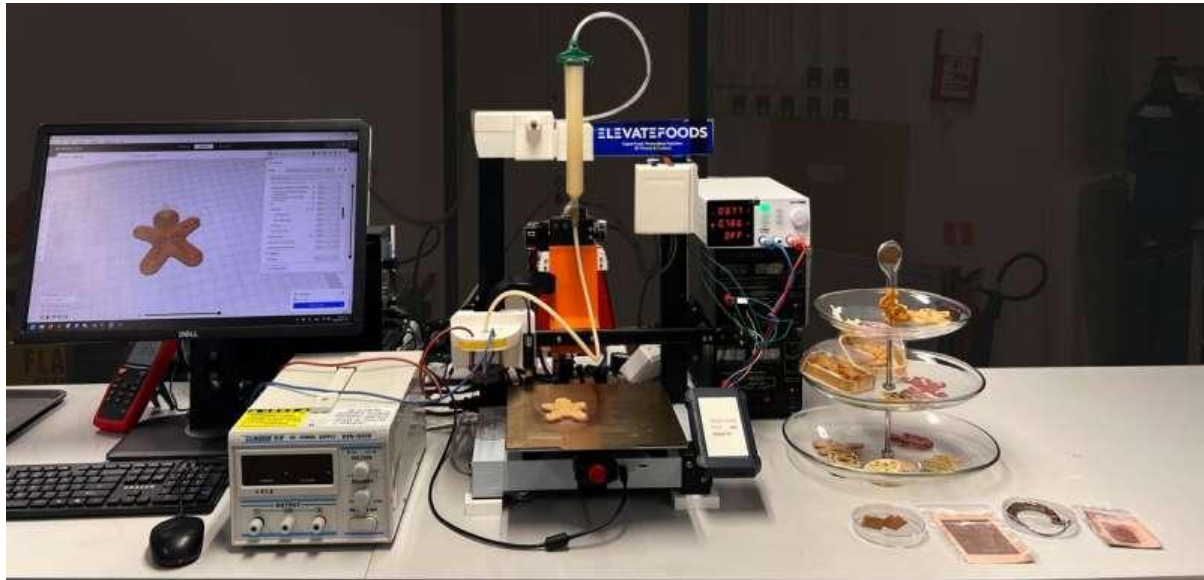
In future studies, the researchers will use an in-process monitoring system to transform the 3D-printing method into a more robust, production-ready method. They also plan to incorporate other metal alloys into multi-material laser powder bed fusion, such as Inconel and copper.

More information: J. C. Griffis et al, Multi-material laser powder bed fusion: effects of build orientation on defects, material structure and mechanical properties, *npj Advanced Manufacturing* (2025). DOI: [10.1038/s44334-025-00020-5](https://doi.org/10.1038/s44334-025-00020-5) Provided by Pennsylvania State University

MARCH 31, 2025

AI-enhanced 3D printing cooks food with infrared precision

by [Hong Kong University of Science and Technology](#)



The integrative 3D food printer and AI digital food design platform. Credit: HKUST
Researchers at the Hong Kong University of Science and Technology (HKUST) have developed a cutting-edge AI-assisted 3D food printing solution that combines printing with infrared cooking, paving the way for safer, more efficient, and visually appealing food production. The study, "Advanced 3D Food Printing with Simultaneous Cooking and Generative AI Design," was recently [published](#) in the journal *Advanced Materials*.

Traditional 3D food printing methods often require additional postprocessing steps, which can have unappealing food ingredients, imperfect shapes, and even potential microbial contamination.

To address these challenges, the team from the Division of Integrative Systems and Design (ISD) at HKUST has developed an AI-enhanced system that combines extrusion-based printing with simultaneous infrared heating for on-the-fly cooking of intricate starch-based foods. Using graphene heaters for cooking, they precisely controlled the [cooking process](#), ensuring that starch-based food items retain their intended shape and quality.

The system is supported by AI-assisted design, which employs generative algorithms and Python scripts to craft intricate food patterns. By leveraging AI, the [design process](#) became accessible to even computer novices.

The research tackles issues such as shape retention and contamination risks and opens up exciting prospects for tailored nutrition—benefiting individuals with special dietary needs,

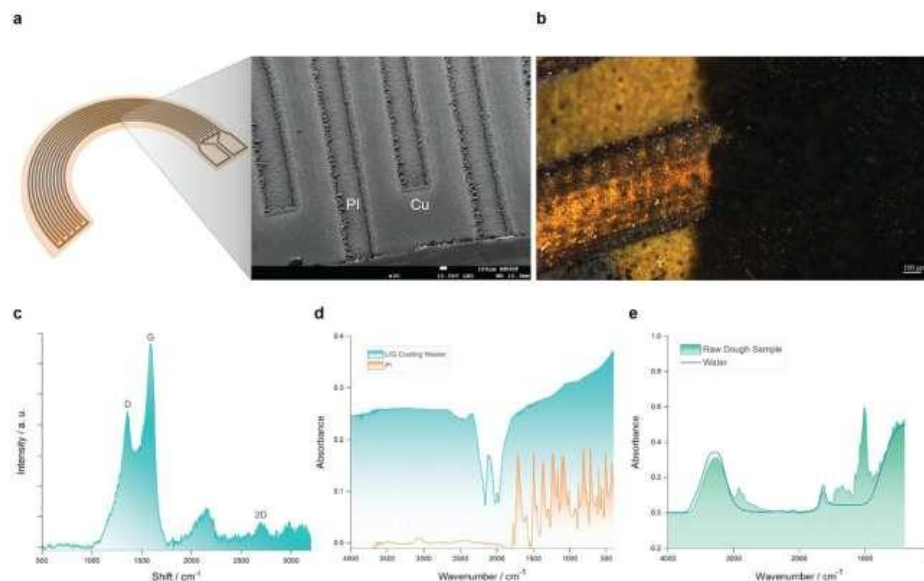
including patients with dysphagia. From enhancing meal customization in elderly care centers and central kitchens to meeting special dietary needs and enabling creative culinary experiences in restaurants, the [technology](#) offers a versatile solution for various sectors.

HKUST Researchers Develop an Advanced 3D Food Printing with Simultaneous Cooking and Generative AI Design. Credit: HKUST

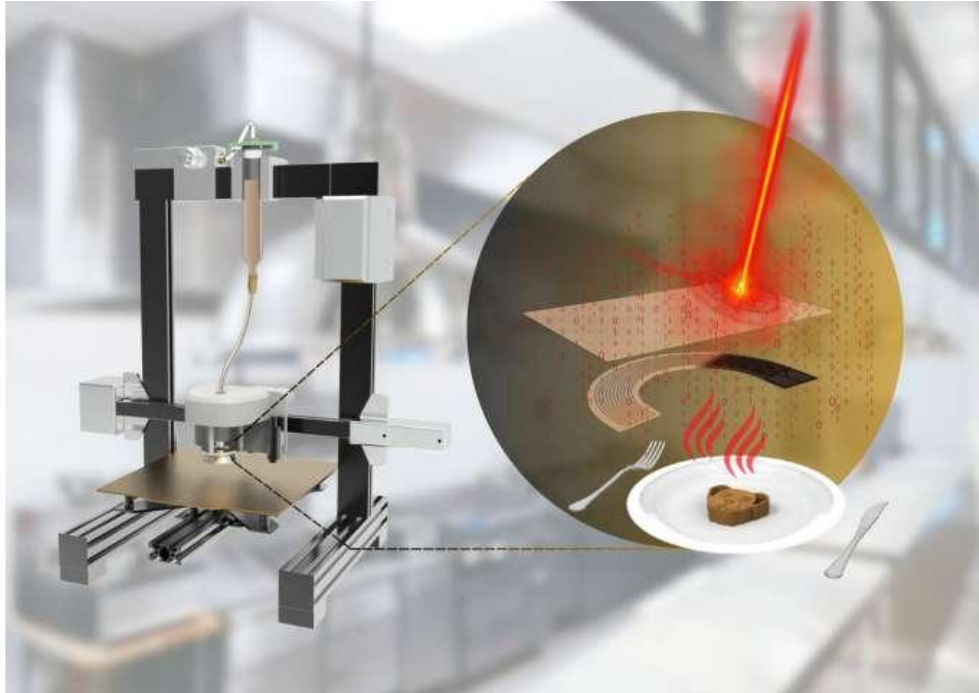
"With its potential to streamline food production processes, improve [food quality](#), and cater to individual preferences, this innovation can transform how food is prepared and served in diverse settings, paving the way for a future where personalized and visually appealing food creations are more accessible than ever before," said Prof. Mitch Li Guijun, Assistant Professor of ISD, who led the research team.

"We're excited about the potential of this technology to deliver customized, safe, and delicious food with a process that is both efficient and accessible. It represents a significant step forward in how we think about food creation," Prof. Li added.

Connie Lee Kong-Wai, the paper's first author and a Ph.D. student at HKUST, said, "We've reimagined what 3D food printing can achieve by merging technology and culinary creativity. Our cutting-edge integrative 3D food printing technology can potentially revolutionize personalized food creation."

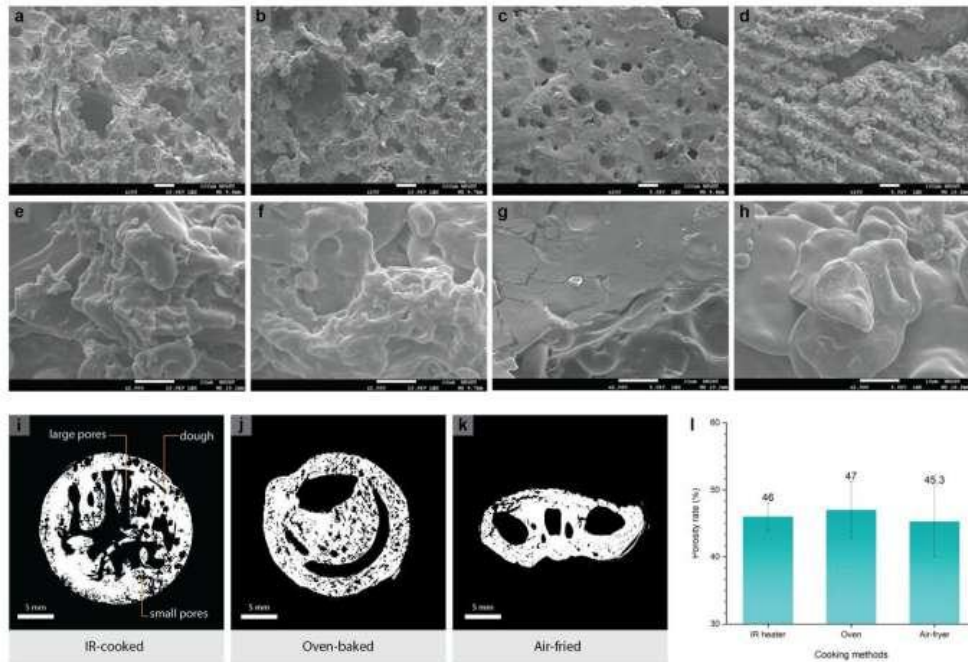


- a) Schematic diagram and scanning electron microscopy image of the LIG heating film. b) Optical microscope images of the LIG heating film. c) Raman spectra of the LIG heating film. d) Fourier transform infrared spectroscopy of the LIG heating film. e) Absorption spectrum of the printed dough sample. Credit: HKUST



3D food printer includes the real-time print and cook system. Credit: HKUST

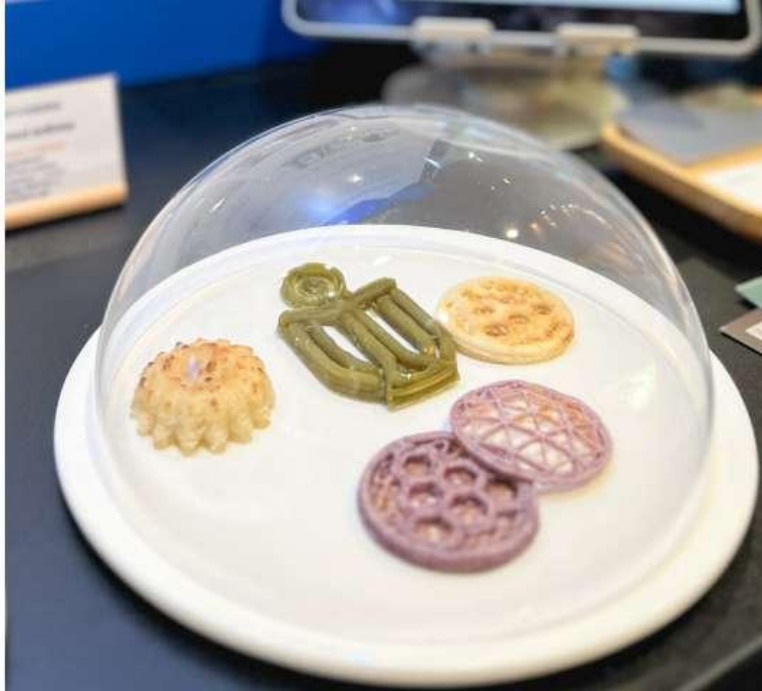
The



d) SEM images at $\times 100$ magnification of starch-based dough samples processed with air-frying, oven-baking, IR cooking, and laser cooking (from left to right). e–h) SEM images at $\times 2000$ magnification of starch-based dough samples processed with air-frying, oven-baking, IR cooking, and laser cooking (from left to right). i–k) Reconstructed micro-computed tomography 2D cross-section images of the printed dough with different cooking methods. l) Porosity rate (%) of the printed dough with different cooking methods. m) Printability test using a cylindric shape of $30 \times 30 \times 30$ mm as the testing model. n) Shape fidelity value (%) of untreated and IR-cooked samples in terms of

a–

length, width, and height. o) 3D printing process of the starch-based dough without heat treatment for 30 min. p) 3D printing process of the starch-based dough with LIG treatment for 30 min. Credit: HKUST



- Produced by the 3D food printer, the starch-based food items retain their intended shape and quality. Credit: HKUST

The research represents a [collaborative effort](#) spanning user-centric design, [mechanical engineering](#), food science, chemistry, and AI. This cross-disciplinary approach brought together diverse expertise to tackle the complex challenges associated with 3D food [printing](#).

Looking ahead, the team plans to refine the technology by examining the preservation of heat-sensitive vitamins and optimizing starch digestibility. Future studies will also focus on consumer acceptance through sensory evaluations involving target users such as children or hospital caretakers, ensuring that the system is ready for real-world applications.

More information: Connie Kong Wai Lee et al, Advanced 3D Food Printing with Simultaneous Cooking and Generative AI Design, *Advanced Materials* (2025). DOI: [10.1002/adma.202408282](https://doi.org/10.1002/adma.202408282)

Journal information: [Advanced Materials](#)

Provided by [Hong Kong University of Science and Technology](#)

APRIL 2, 2025

3D-printing formula may transform future of foam

by Veronica Gonzalez, [University of Texas at Dallas](#)



Credit: University of Texas at Dallas

From seat cushions to mattresses to insulation, foam is everywhere—even if we don't always see it. Now, researchers at The University of Texas at Dallas have fused chemistry with technology to create a 3D-printed foam that is more durable and more recyclable than the polymer foam found in many everyday products.

The research, [published](#) in *RSC Applied Polymers*, focused on creating a sturdy but lightweight [foam](#) that could be 3D-printed, a method that is still largely unexplored in commercial manufacturing, said the study's co-lead author, UT Dallas doctoral student Rebecca Johnson BS'20.

"This is probably the longest project I've ever done," said Johnson, who plans to complete her Ph.D. in chemistry in May. "From start to finish, it was a little over two years. A lot of it was trying to get the polymer formulation correct to be compatible with the 3D printer."

Although making new materials that are compatible with 3D technology is challenging, Johnson said, the 3D-printing process allowed the researchers to create **complex shapes** that could be customized in manufacturing applications. To demonstrate the proof-of-concept, they produced foam in the shape of a balloon dog. They also described their work in a YouTube video.

"The goal of the project was to address some limitations in 3D printing in terms of making polymer foam," said Dr. Ron Smaldone, associate professor of chemistry and biochemistry in the School of Natural Sciences and Mathematics and the corresponding author of the study. "One of the main uses, or interests, of 3D-printable foams is insulation and shock absorption."

With more research and experimentation, Smaldone said, this type of foam and process could be used for high-impact absorption items such as motorcycle or football helmets, car bumpers or armor. He also noted that 3D printing enables the creation of more complex structures, such as fine lattices, which can increase the physical flexibility of the material and provide more versatility for applications.



Chemistry doctoral student Rebecca Johnson BS'20 holds a tiny dog-shaped piece of sturdy, lightweight 3D-printed foam she and her colleagues developed. Credit: University of Texas at Dallas

The researchers also examined how to make a material that could be 3D-printed into a consistent final product without a lot of defects. Most commercial foam is thermoset, meaning it undergoes a chemical reaction during molding that permanently locks its structure in place, preventing it from being reshaped, melted or dissolved. As a result, most polymer foam cannot be recycled and ultimately ends up in landfills, Smaldone said.

The UT Dallas researchers developed their durable foam using special reversible bonds, called dynamic covalent chemistry. Although the foam cannot be completely melted and reshaped like plastic, these bonds allow the material to repair itself when damaged, making it more versatile and longer lasting.

"We're certainly not the only ones trying to do this," Smaldone said. "The novelty is using dynamic chemistry to print really great foam material. The next question to address will be, how do we tune the properties and use this new kind of knowledge to fit a variety of different needs?"

Johnson and the study's other co-lead author, [chemistry](#) doctoral student Ariel Tolfree BS'23, developed their ideas after studying similar research in the field. Tolfree, who credits Johnson as her mentor, plans to expand on the research by examining how to make the foam more recyclable and exploring the foam's sustainability potential.

Tolfree said creating a foam balloon dog as one of the group's test objects was a natural choice.

"It's a simple shape but perfectly represents our foams," Tolfree said. "A balloon seems ordinary until it's twisted into something new, almost defying expectations. Our foams are the same—unassuming at first, but once expanded and transformed, they become something remarkable."

More information: Rebecca M. Johnson et al, 3D printable polymer foams with tunable expansion and mechanical properties enabled by catalyst-free dynamic covalent chemistry, *RSC Applied Polymers* (2025). DOI: [10.1039/D4LP00374H](https://doi.org/10.1039/D4LP00374H)
Provided by [University of Texas at Dallas](#)

MAY 29, 2025

3D printing metal molds poised to accelerate US auto manufacturing

by [Oak Ridge National Laboratory](#)

edited by [Sadie Harley](#), reviewed by [Andrew Zinin](#)



Using a toolpath strategy for weight reduction, two near-net shape dies were manufactured using a gas metal arc welding additive manufacturing process at the Lincoln Electric Additive Solutions facility. Credit: Lincoln Electric

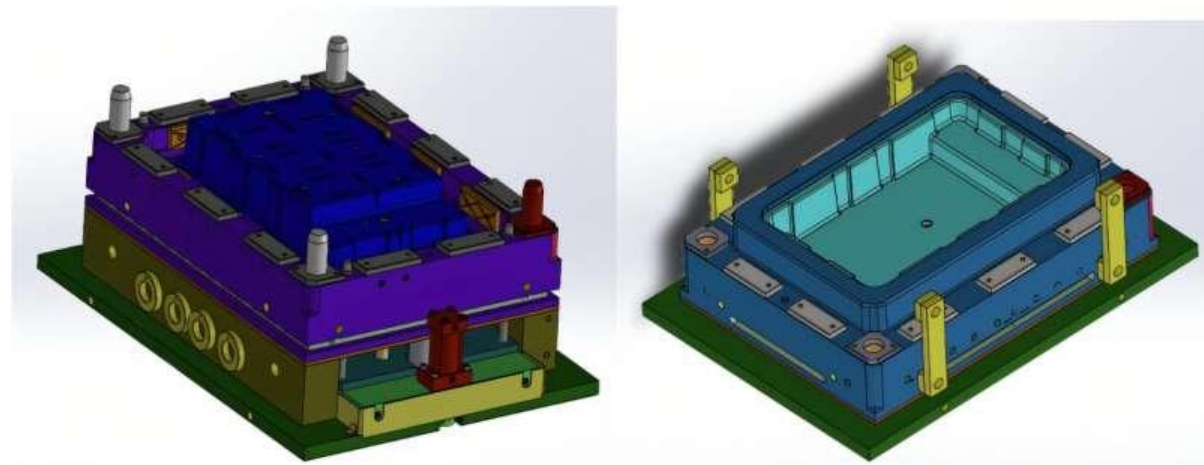
Recent advancements at the Department of Energy's Oak Ridge National Laboratory show that 3D-printed metal molds offer a faster, more cost-effective and flexible approach to producing large composite components for mass-produced vehicles than traditional tooling methods.

The research, conducted at the Manufacturing Demonstration Facility, or MDF, at ORNL, confirms that large-scale [additive manufacturing](#) is well-suited for creating complex [metal](#) molds, with efficiencies that could accelerate the adoption of lightweight composite materials in the automotive sector.

"This kind of technology can help reindustrialize the U.S. and boost its competitiveness by creating smarter, faster ways to build essential tools," said lead researcher Andrzej Nycz with ORNL's Manufacturing Robotics and Controls group. "It brings us closer to an automated, intelligent production process."

Traditionally, metal tools are made by subtracting material from large, forged steel blocks—a process that removes up to 98% of the original material, generates significant waste and often takes months due to supply chain delays. In contrast, additive manufacturing deposits metal layer by layer, using widely available welding wire as a feedstock and minimizing waste to about 10%.

Additive manufacturing also allows engineers to produce more complex mold geometries, such as internal heating channels, that would be difficult to achieve using conventional machining.



The lower mold, on the left, and the upper mold are shown fully assembled. Credit: Oak Ridge National Laboratory

"The more complex the shape, the more valuable additive manufacturing becomes," Nycz said.

The research team partnered with Collaborative Composites Solutions, or CCS, operator of IACMI—The Composites Institute, to put the concept to the test. They chose to 3D print a large battery enclosure mold, complete with intricate internal features.

Using a gas metal arc welding, or GMAW, additive manufacturing process at Lincoln Electric Additive Solutions, two near-net-shape dies were printed from stainless steel ER410 wire.

The GMAW process uses an electric arc to melt a consumable wire electrode to build up metal layers and create complex components while using a protective shielding gas to prevent contamination. The team applied a specialized toolpath strategy for [weight reduction](#) while maintaining strength.

Subsequent analysis confirmed the lightweighted mold met structural performance requirements, validating the feasibility of additive manufacturing for high-performance production tooling.

Provided by [Oak Ridge National Laboratory](#)

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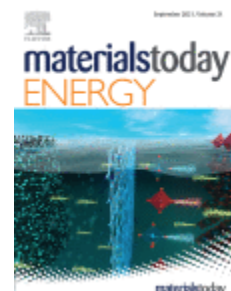
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[Volume 21](#), September 2021, 100714



Thermoelectric energy harvesting using cement-based composites: a review

Author links open overlay panelV.P. Singh, M. Kumar, R.S. Srivastava, [R. Vaish](#)

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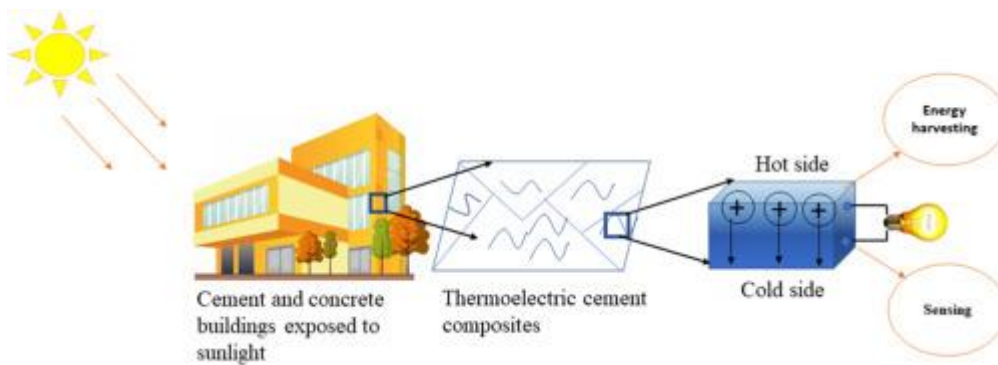
- •
The performance of cement-based [thermoelectric](#) composites has been characterized based on additives used.
- •
Carbon and steel fibers, metal oxides, graphene, and CNTs are found to alter the thermoelectric properties of cement.
- •
Most thermoelectric cement composites have ZT values below 10^{-3} .
- •
Challenges for more efficient and large-scale operation of thermoelectric-based cement composites are mentioned.

Abstract

In the modern era, cement and cement-based structures with additional functionalities are highly desirable. For example, the temperature difference induced between the outdoor and indoor surfaces of cement structures in buildings can be exploited for thermoelectric-based cement structures for [energy harvesting](#). This article reviews the application of thermoelectric-based [cement composites](#) for [energy harvesting](#) and thermal sensing. These properties could be exploited in structures such as buildings, roads, housing, dams, and bridges. The enormous exposure of solar energy over the area of civil infrastructures is stored thermally within the construction materials, which is harvested when thermoelectric-based cement materials are used. First, the review describes the basic properties of [thermoelectric](#) materials and their applicability in [cement composites](#). Furthermore, a broad classification of admixtures that are added in the cement composites for the enhancement of [thermoelectric](#) properties is made. The hole conduction improved significantly with the addition of carbon fibers in cement and [thermoelectric](#) power was recorded to be $-17 \mu\text{V}/^\circ\text{C}$, which is much higher as

compared to the pristine carbon fiber reinforced cement ($-0.8 \mu\text{V}/^\circ\text{C}$). Steel fiber [cement pastes](#) show higher volume electrical resistivity than carbon fiber [cement pastes](#) even when steel fiber content is raised to 1% by mass of cement. Hence, development in thermoelectric-based cement composites by the addition of different admixtures is summarized. Finally, the challenges for the more efficient and large-scale operation of thermoelectric-based cement composites are mentioned and discussed for further improvements.

Graphical abstract



Introduction

Cement, one of the major civil infrastructure constituents, covers the wide-ranging applicability of structure material. Owing to their remarkable mechanical properties, cement-based materials possess to be basic material as a binder in concrete for various construction, including building, roads, housing, dams, and bridges [[1], [2], [3], [4], [5]]. The cement-based structures in constructions are exposed to a large quantity of solar energy exposure. The amount of solar energy received over the exposed area is stored as thermal energy [6,7]. Thus, for harvesting this stored energy, either certain additional technologies or multifunctional materials are contemplated. In recent years, the use of multifunctional structural materials while preserving their structural properties has been apprehended [[8], [9], [10]], [11], [12], [13]]. By adding various additives to the cement, its properties can be altered for suitable applications. Therefore, the temperature difference induced between the outdoor and indoor surfaces of cement structures in buildings triggers thermoelectric-based cement structures for energy

harvesting. The thermoelectric-based cement materials dwell potentials to convert stored thermal energy from solar irradiation to electrical energy and reduce the surface temperature of the building [[14], [15], [16]]. Thus, decrease in building temperature servers for better indoor conditions and reduces the cooling load. Hence, eventually offers a reduction in electricity consumption for the air-conditioning cooling units in the building [17].

The use of multifunctional structural materials while preserving their structural properties has been seized in different ways [18]. Carbon-based structural composites hold budding capabilities for multifunctional applications, can act as an electrochemical energy storage device in parallel [19]. Likewise, structural capacitors developed by laminating glass-epoxy prepared with metalized film electrodes and based on laminates of activated structural carbon fiber (CF) fabric electrodes sandwiching a structural glass fiber separator filled with (structural) electrolyte [20,21]. However, it is still challenging to produce multifunctional-based composites for large-scale applications. The pavements and building roofs constituting the large surface are integrated with several technologies for directly serving in the reduction of temperature. There are quite a few techniques for pavement cooling, which are greatly affecting in reducing surface temperature, such as reflective cooling pavement, serpentine tubes under the road, and green roofs [22,23]. Conversely, these techniques store daytime solar energy and release it in the night time, which eventually results in a hotter night. Phase change materials encapsulated in building walls are also effective for reducing cooling loads and providing better indoor thermal comfort [24,25]. Although, the major portion of phase change material used is of non-use because of the low convective heat transfer coefficient.

Thermoelectric-based cement composites thus offer a reduction in surface temperature along with a better indoor thermal comfort level. In addition, the thermal energy stored is rather converted into electrical energy instead of just releasing it into the environment at night time. This proposes the strategy of the multifunctionality of the thermoelectric-based cement composites [26]. The thermoelectric modules are fabricated of conventional thermoelectric materials like Bi_2Te_3 positioned on walls and openings for cooling and heating indoor space [27]. However, proficient application dwelled when concrete walls themselves possessed thermoelectric characteristics. This offers a more

efficient and convenient way for energy harvesting applications using the thermoelectric effect.

The research areas of multifunctional structural materials, cementitious-based multifunctional structures, and free cooling systems for buildings are extensively explored. There are several review articles also on nanoengineered multifunctional composites, phase change material-based building cooling, and carbon nanotubes/nanofibers on cement admixture particles [28]. Han et al. reviewed the recent progress made by introducing nanoparticles in cementitious materials [29]. Several other articles on the free cooling system of the building using phase change materials have been reported [30]. However, the potential of thermoelectric technology for civil structures has also been explored and there has been notable work performed on cement-based thermoelectric composites. Although, it is to be noted that no such review article exists describing the performance and status of cement-based thermoelectric composites. Therefore, the present article presents a summary of the thermoelectric properties of cement composites. The classification was done based on various admixtures mixed in the cement to induce thermoelectricity. Potential applications, challenges, and future scope of these composites are also discussed.

Section snippets

Thermoelectric materials and applications

Thermoelectric materials, which can be applied for proficient cooling/heating including refrigeration, energy harvesting, and sensing, and thermopower systems, provide significant contributions for green and clean energy operations [[31], [32], [33], [34]]. The thermoelectric material-based devices cause no such carbon dioxide emission while its operation and have no moving parts, which make them very robust. The thermoelectric effect works based on the principle of Seebeck, Peltier, and

Cement-based thermoelectric composites

Generally, cement exhibits slight electron movements because of the presence of n-type conductivity. Therefore, with the addition of p-type conductive admixtures, hole

movements are present, which eventually develops electron–hole distribution in cement composites [36]. Thus, a voltage difference is attained and TEP is generated. The conductivity of the cement-based matrix can be enhanced even when admixtures are added below the percolation threshold (Fig. 2). However, there has been notable

CF composites

An introduction of CFs in the cement earlier was intended to enhance the optimal mechanical properties of cement and concrete. However, Sun et al. discovered the hole conduction aspect in CF admixed cement in 1998 [37]. Based on their experimental studies, it was proposed that hole conduction also exists in CF cement composites along with ionic and electronic conduction. In this report, the author reported the Seebeck coefficient concerning copper as used commonly for thermoelectric

Steel fiber composites

The addition of short steel fibers was initially found attractive for enhancing structural properties. However, in the early 21st century, it was discovered that short steel fibers are also beneficial for enhancing the p-type Seebeck effect. The absolute TEP for all the steel fiber cement composites is found to be more positive than the CF-cement composites. Steel fiber content increment leads to an increase in linearity and reversibility of Seebeck voltage as there exists a difference in

Carbon nanotube composites

Carbon nanotubes (CNTs) have a very wide range of applications in the fields of batteries, sensors, and transistors. They are formed from rolled graphite sheets having hollow tubular structure and registers superb electrical conductivity. Considering their microscopic length and nanoscopic diameter, the CNTs exhibit high strength nearly 100 times than steel because of their high strength to weight ratio. It is also expected that incorporating CNTs would increase the mechanical strength of

Graphite/graphene composites

Graphene is a two-dimensional form of carbon found abundantly in nature possesses excellent features such as high mechanical strength, electrical and thermal conductivity, lightweight, cheaper, and easily producible than CF and CNTs [55,56]. Graphene nanoplatelets (GNPs) can alter non-conductive material to be conductive material and improve the Seebeck coefficient, which makes it advantageous to enhance cement-based research. However, despite possessing excellent electrical and thermal

Metallic oxide composites

New thermoelectric materials such as Bi_2Te_3 , PbTe , SiGe , GaN , and their derivatives were discovered in the 19th century [61]. Transition metal oxides have attracted researchers in aid to their high Seebeck coefficients, temperature stability, minimal environmental effect, and advanced synthesis techniques. Manganese dioxide (MnO_2) determined for its structural flexibility and rich polymorphism is extensively used in electrodes, batteries, capacitors, and catalysis. MnO_2 shows excellent

Limitations and future scope

The cement-based thermoelectric materials seem quite promising for waste solar energy harvesting. Owing to major applicability in cement infrastructures, cement-based thermoelectric composites show effective potentials to recover waste heat present in abundance. The enhancement in the thermoelectric property of cement-based materials was attained by certain types of admixtures like carbon and steel fibers, carbon nanotubes, graphite, and metal oxides. Although there are more than 30 reports,

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Innovative method assembles charged molecular fragments for advanced thin-film applications

by [Leipzig University](#) edited by [Lisa Lock](#), reviewed by [Robert Egan](#)

An overview of the reactions of $[B_{12}X_{11}]^-$ and $[B_{12}I_8(S)(CN)]^-$ fragment ions on surfaces. Credit: Nature Reviews Chemistry (2025). DOI: 10.1038/s41570-025-00719-1

For the past five years, researchers at Leipzig University have been working on fundamentally new methods for selectively assembling gaseous, charged molecular fragments into new, complex molecules. The synthesized substances are deposited onto surfaces. This innovative process opens up new perspectives for applications in modern nanoelectronics and sensor technology. It also offers new avenues of research across various scientific disciplines—from catalyst research to medical applications.

The scientists at Leipzig University, together with their collaborators at Purdue University (U.S.), have [published](#) a summary of their findings from this period in Nature Reviews Chemistry.

"Until now, charged [molecular fragments](#) have mainly been studied in analytical chemistry to determine the structure of molecules. However, research in recent years has shown that these fragments are also highly relevant for synthetic applications.

"By selectively depositing them onto surfaces, it is possible to trigger [chemical reactions](#) that would not be feasible using conventional synthesis methods," explains Professor Jonas Warneke, head of the research group at the Wilhelm Ostwald Institute of Physical and Theoretical Chemistry at Leipzig University.

The [research instruments](#) used—specially optimized for so-called thin-film synthesis with charged molecular fragments—exist at only two locations worldwide. They were developed jointly by the research groups led by Professor Warneke and Professor Julia Laskin at Purdue University. Thin-film synthesis refers to the production of thin layers with thicknesses ranging from the nanometer to the micrometer scale.

The Leipzig authors of the review article—Professor Jonas Warneke (left), Dr. Markus Rohdenburg (center), and Dr. Harald Knorke (right)—pictured next to an instrument for synthesizing thin films using gaseous, charged molecular fragments. Credit: Ziyang Warneke
In the article, the Leipzig research team reports on its work involving the controlled formation of chemical bonds using "aggressive" molecular fragments. For example, the most chemically reactive negatively charged molecular fragment known to date—which has a long history of research in Leipzig—was specifically bonded to other molecules.

Even nitrogen from the air, which is generally considered to be unreactive, was bound in layers on surfaces. This opens up new possibilities for using such inert chemical feedstocks to synthesize new molecules and functional materials on surfaces, or to selectively modify the properties of material surfaces.

The publication also outlines the research conducted by the team at Purdue University on linking metal-containing, charged "nanoclusters"—small particles with a precisely defined number of atoms—which are of interest for quantum technologies due to their unique magnetic and electronic properties. The article also reports on the joint work of the two research groups on developing the instruments and studying the behavior of molecular, charged catalysts on surfaces.

"We aim to optimize our work in the coming years by developing even more powerful instruments for thin-film synthesis using molecular fragments," says Warneke. This could enable the synthesis of materials on the microscale and pave the way for applications of the remarkable new compounds assembled from molecular fragments in microsystems technology.

In addition, the Leipzig research team is developing new approaches for analyzing large biomolecules on surfaces by attaching charged molecular fragments—an advance that could contribute to a fundamental understanding of the biological functions of these molecules on cell surfaces.

More information: Jonas Warneke et al, Molecular synthesis with gaseous fragment ions on surfaces, *Nature Reviews Chemistry* (2025). DOI: [10.1038/s41570-025-00719-1](https://doi.org/10.1038/s41570-025-00719-1)
Provided by [Leipzig University](#)

JUNE 28, 2025

Team tackles support structure bottlenecks with dual-wavelength 3D printing

by [Lawrence Livermore National Laboratory](#)

edited by [Sadie Harley](#), reviewed by [Robert Egan](#)

Graphical abstract. Credit: *ACS Central Science* (2025). DOI: [10.1021/acscentsci.5c00337](https://doi.org/10.1021/acscentsci.5c00337)
Lawrence Livermore National Laboratory (LLNL) researchers have developed a novel 3D printing technique that uses light to build complex structures, then cleanly dissolves the support material, expanding possibilities in multi-material additive manufacturing (AM).

In 3D printing, traditional supports often add time, waste and risk to the process, especially when printing intricate parts. But in a new [study](#) published in *ACS Central Science*, an LLNL team—in collaboration with University of California, Santa Barbara (UCSB) researchers—outlines a "one-pot" printing approach that uses two light wavelengths to simultaneously create permanent structures and temporary supports from a single resin formulation.

The method addresses a longstanding challenge in AM: how to fabricate suspended or overhanging features without cumbersome scaffolding requiring manual removal, which is a key hurdle to the widespread adoption of digital light processing (DLP) 3D printing technologies.

"This work adds another option to the growing range of multi-material printing possibilities," said principal investigator and LLNL staff researcher Maxim Shusteff.

"Using multiple materials is critical to many manufacturing processes, and that's been hard to accomplish using 3D printing. And manually removing supports printed from the same material is one of the bottlenecks preventing the use of DLP in production activities and hurting part accuracy—dissolving a sacrificial material is much more automation-compatible and less cumbersome."

One of the study's key innovations lies in a custom-built, dual-wavelength negative imaging (DWNI) DLP printer, patented by co-author and LLNL engineer Bryan Moran. The system uses a single digital micromirror device to project both ultraviolet (UV) and visible light at the same time, each triggering a different chemical reaction. The UV light solidifies the final epoxy structure, while the [visible light](#) cures a degradable thermoset designed to dissolve post-printing.

After thermal postprocessing, the printed objects are placed in a basic water-based solution, where the supports gently dissolve, leaving the primary structure intact with no damage or residue. The team successfully demonstrated free-floating designs including interlocked rings and a ball-in-a-cage—shapes that are difficult or impossible to produce with conventional layer-by-layer methods.

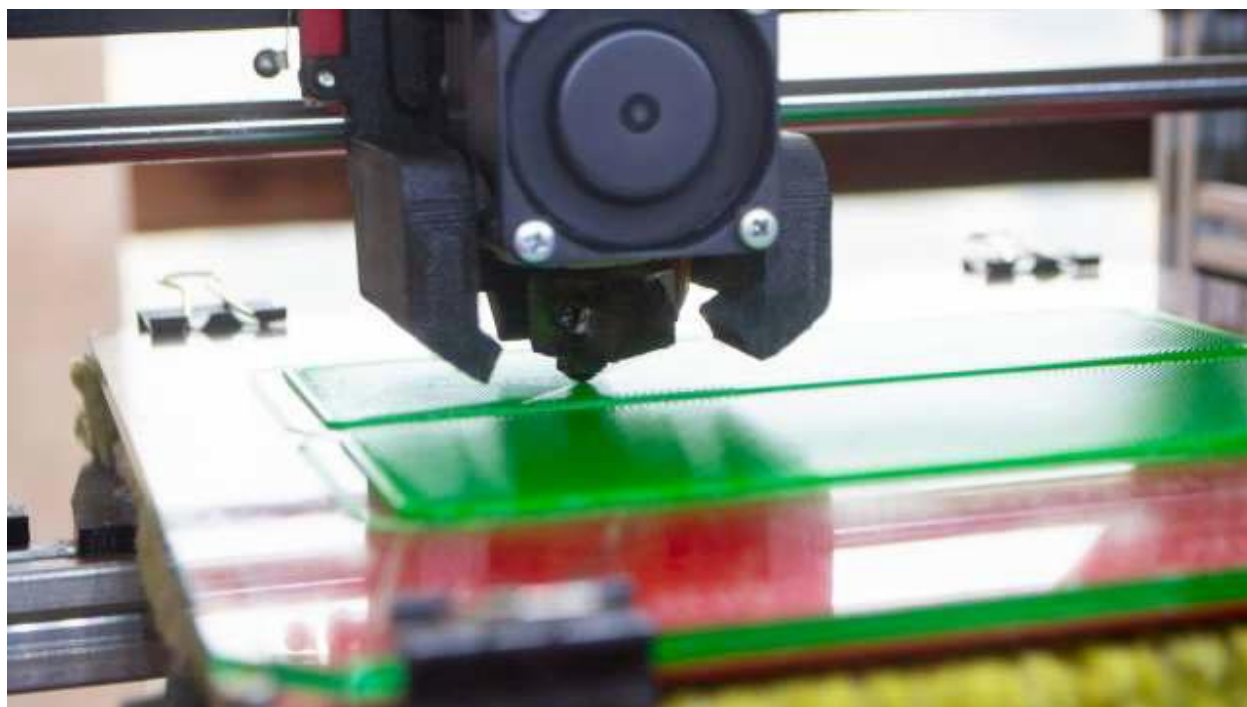
The approach offers practical advantages: reduced print time, minimal material waste and improved resolution. It also avoids the need to swap resins mid-print, a common obstacle in multi-material 3D printing, researchers said.

"Our one-pot embedded printing approach improves the fidelity of unsupported, free-floating structures, such as overhangs and cantilevers, by using degradable supports that act as temporary scaffolds to prevent collapse and misalignment during fabrication," said first author Isabel Arias Ponce, a UC National Laboratory Fees Graduate Scholar and soon-to-be LLNL materials engineer.

"Additionally, mobile components—such as hinges and interlocking systems—could be fabricated in place by simply patterning a degradable interface between multiple parts. This would eliminate the need for manual assembly and enhance production efficiency."

More information: Isabel Arias Ponce et al, Dual-Wavelength Simultaneous Patterning of Degradable Thermoset Supports for One-Pot Embedded 3D Printing, *ACS Central Science* (2025). DOI: [10.1021/acscentsci.5c00337](https://doi.org/10.1021/acscentsci.5c00337)
Journal information: [ACS Central Science](#)
Provided by [Lawrence Livermore National Laboratory](#)

Researchers make breakthrough in 3D printing: 'Building the next generation'



A team of researchers has made a breakthrough in the development of cutting-edge [3D-printed materials](#) that have the ability to sense damage, resist impact, and adapt to stress.

In a recent [study](#) published in the journal *Materials Horizons*, a team led by engineers out of the University of Glasgow explored the true capabilities of "self-monitoring lattices made from in-house-engineered polyetheretherketone," or PEEK. The state-of-the-art materials were also reinforced with carbon nanotubes for increased strength and electrical conductivity. Because of its adaptability and versatility, the materials could eventually be [utilized](#) across multiple industries.

Shanmugam Kumar, a professor at the University of Glasgow's James Watt School of Engineering and co-author of the study, [noted](#) the importance of the team's breakthrough.

"We've shown that it's possible to design PEEK lattices that are not only auxetic but also capable of sensing strain and damage without the need for embedded electronics," explained Kumar. "This could enable new applications in smart orthopaedic implants, aerospace skins, or even wearable technologies."

One of the most common materials used in 3D printing is [plastic](#). While the [technology](#) is still developing and more sustainable materials are being used, some prototype 3D prints may not enjoy long shelf lives. This can add to the growing amount of [plastic waste](#) found in our environment and landfills.

As seen with the research into PEEK lattices, computer models can now accurately predict how they may deform and fail through each use. By measuring electrical resistance in real time, the researchers could track how the material stretched, cracked, and eventually failed. This data could prove to be invaluable in the [advancement](#) of 3D printing.

Over time, this development could help reduce plastic waste and promote more sustainability within the 3D market. According to Kumar, the research has the ability to open a lot of doors in the future.

"We're essentially giving designers a toolkit for building the next generation of multi-functional materials, ones that are as intelligent as they are strong," Kumar [said](#). "We believe this could be transformative for several sectors, from personalized medicine to aerospace safety and structural health monitoring."