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February 2026

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HOLD THE FLUOROWAX!

HOW TO MAKE FASHION SUSTAINABLE

CAN MUSHROOMS SAVE THE PLANET?

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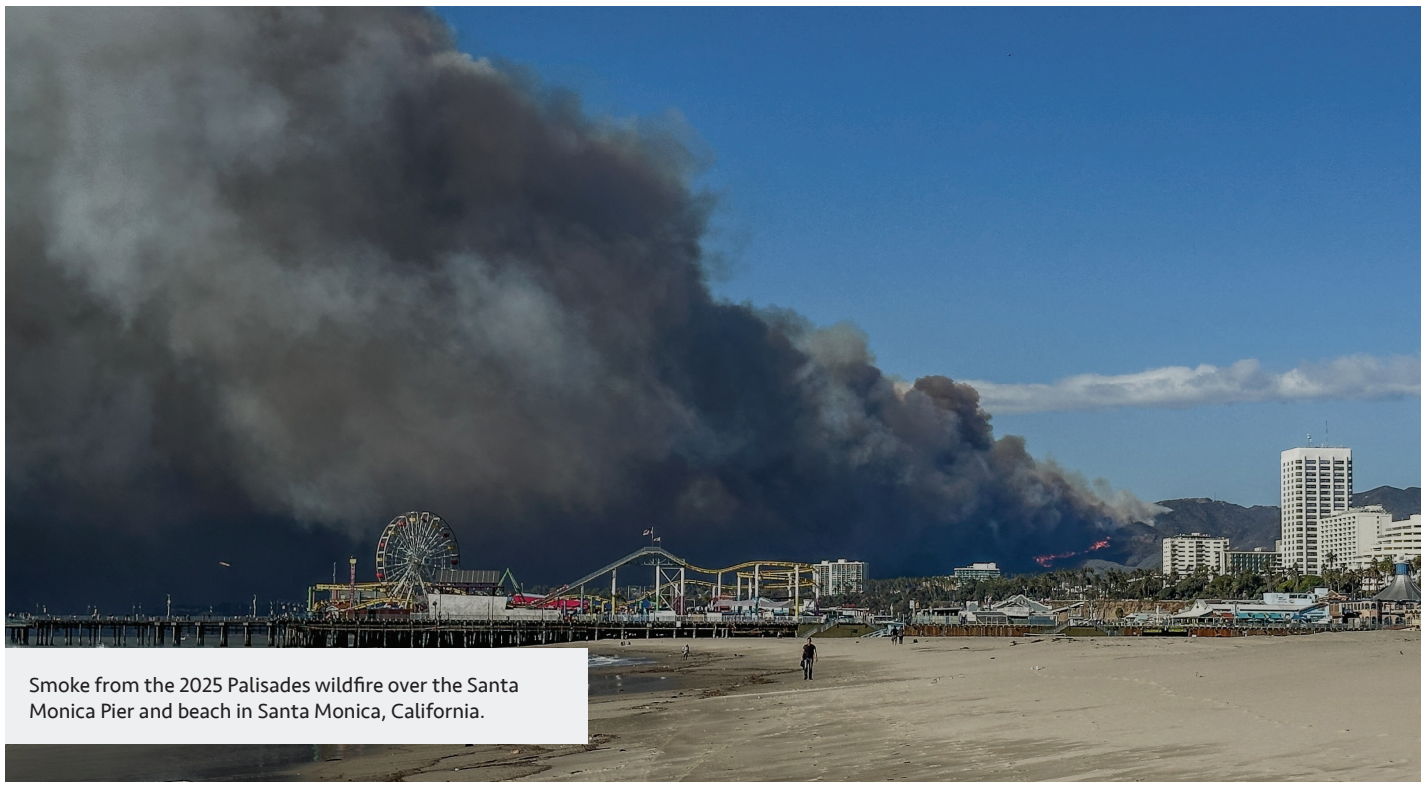


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GREEN CHEMISTRY & WILDFIRE SMOKE

By Max G. Levy

Few natural disasters feel more dangerous than wildfires. Their intense heat, upwards of 1,000 degrees Celsius, can melt building materials and vaporize their contents, and billows of black smoke can suffocate the local area and displace inhabitants. The Palisades and Eaton fires of January 2025 in Los Angeles, California, destroyed more than 15,000 homes and businesses, killed at least 31 people and may shorten the lives of many more. And while every fire—rural or urban—shares a potential for destruction the matter that they burn differs, and that difference results in unique chemical threats.



Smoke from the 2025 Palisades wildfire over the Santa Monica Pier and beach in Santa Monica, California.

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A DIFFERENT TYPE OF FIRE

When wildfires engulf urban areas, the smoke they create is more toxic. Forest fires typically eject large amounts of particulate matter smaller than 2.5 micrometers in diameter (PM2.5). These particles generally consist of carbon-rich organics. However, burning buildings release fumes from paint, roofing, plastics and furniture, and when a car burns, it releases toxic chemicals normally confined to its battery, tires and interior. In the immediate aftermath of the 2025 fires, experts reported higher than usual levels of heavy metals, such as lead and mercury, in the air, as well as toxic byproducts of plastics like dioxins and furan.

It's not just the air that is a problem. Hazardous compounds from smoke and fumes eventually settle back to the ground and waterways. Contaminated debris has invisibly littered areas of Los Angeles' soil. Health officials in the area continue to sample air, water and soil for persistent pollutants. Their concern is that children who play in contaminated soil could ingest heavy metals, which—even in small amounts—can hinder children's brain development.

The recent urban fires serve as an unfortunate reminder of the full life cycle of the materials we use in our daily lives. About 43% of home soil samples exceeded California's 80 milligrams per liter threshold for lead safety, according to the *Los Angeles Times*.

A 2025 paper from environmental health experts at Harvard University claimed that these state standards aren't strict enough. The authors of that study suggested revising soil limits to 55 milligrams per liter. In June 2025, Los Angeles public health officials offered free blood tests to fire victims to screen for lead; luckily, the vast majority of those tested did not show elevated lead levels.

Perhaps the most troubling aspect is that there are few methods of remediating soil contaminated by lead. Charred household items, pesticides and industrial contaminants also contribute to the disaster's chemical legacy. Yet even without fires, the chemicals pose a threat to human and environmental health.

TOWARD GREENER AIR

Many homes built before 1980 have walls painted with lead paint, joints sealed with polychlorinated biphenyl (PCB)-infused caulk, and walls and attics insulated with asbestos, all of which can cause serious health effects. These hazardous materials are released or transformed into other chemicals when these older homes are destroyed by fire.

While lead paint, PCBs and asbestos have been phased out, many residential buildings continue to be furnished with synthetic materials, such as nylon carpets, polyurethane foams and composite wood. These materials release volatile organic compounds (VOC)—off-gassing—even at room temperature, and this release only goes up when they are heated.

From the 1970s to the early 2000s, homebuilders treated wood with a pesticide containing chromium copper and arsenic (CCA) to protect it from insects and decay. Chromium and arsenic leach into the soil from the wood, and can enter the air during fires. CCA was phased out in 2004, but some CCA treated wood still remains in older buildings, and builders still need to protect the wood for outdoor use.

This is where green chemists play a key role. When materials are phased out, they seek and manufacture alternative materials that pose less risk to our environment and bodies.

Another popular construction material, polyvinyl chloride (PVC), is a controversial plastic that produces carcinogens, such as vinyl chloride, when burned. Some advocate for replacing PVC with ductile iron pipes, which won't melt in structure fires and don't release the organic chemicals that PVC does.

However, while impervious to fire, iron has disadvantages, too. It is heavy and expensive to make and transport. It is also susceptible to corrosion: iron rusts. Green chemists seek alternatives to PVC that do not have iron's drawbacks nor PVC's hazards.

When fires occur, the choice of building materials can influence health in both the long term and the short term. So, how do we balance the choice of building materials for highly efficient, well-insulated homes with the health risks they may cause during fires?

The matter is open for discussion.



HOLD THE FLUOROWAX!

By XiaoZhi Lim

THE HIGHEST-PERFORMING SKI AND SNOWBOARD WAXES ARE MADE WITH PER- AND POLYFLUOROALKYL SUBSTANCES (PFAS), ALSO CALLED "FOREVER CHEMICALS."

In February 2022, analytical chemist Christian Vogel went cross-country skiing with his boss, Franz-Georg Simon, in the Ore Mountains near the German-Czech border. This was not a typical ski trip, though. Carrying empty sample vessels in their backpacks, the two researchers traveled 20 kilometers along the popular Kammloipe cross-country track, stopping from time to time to collect samples of the snow on the ground.

Back at their laboratory at the Federal Institute for Materials Research and Testing (BAM) in Berlin, Germany, the researchers tested the snow samples for a specific type of chemical pollutant: per- and polyfluoroalkyl substances (PFAS), which are known as "forever chemicals" because they don't break down easily in the environment and may last hundreds or even thousands of years. Vogel and Simon found PFAS in every snow sample except for the one that was taken 50 meters before the start of the ski trail.

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PHOTOS COURTESY OF FRANZGEORGE-SIMON (LEFT) AND LISA SKEDUNG(RIGH)

(*Above*) Skedung at the Vasaloppet a 90 kilometer ski race between Sälen and Mora, Sweden. Although Skedung had been racing without fluorowaxes for many years, Vasaloppet began testing for fluorowaxes in 2024.

(*Left*) Vogel collects snow samples from Kammloipe, a 35-kilometer cross-country ski trail in Germany.

Because PFAS pollutants last so long, they end up spreading until they are ubiquitous in the environment. Common natural processes (such as sunlight and microbes) that break down most other substances are not known to degrade PFAS. In addition, some members of the PFAS family have been found to be highly toxic. For example, the film "Dark Waters" dramatizes the true story of how many communities in West Virginia and Ohio were sickened by perfluorooctanoic acid (PFOA) that infiltrated their drinking water from improperly disposed-of industrial waste.

While the PFAS plaguing some communities originated from industrial wastes or from fire-fighting foams that military bases or airports used, the PFAS polluting ski trails is different: it comes directly from consumers. On the slopes, the high-performing waxes that help skis and snowboards glide are the source of the PFAS pollution.

WAXES CONTAIN FOREVER CHEMICALS

Fluorowaxes are named after the key chemical element that they (and every other PFAS) contain: fluorine.

Fluorine is the most electronegative element known and may be the most reactive element on Earth. Its high electronegativity results in large differences in polarity when it is bonded to carbon. As a result, the bonds between carbon and fluorine are some of the strongest bonds known in organic chemistry. In turn, these strong carbon-fluorine bonds make Teflon and other PFAS very stable.

Vogel and Simon had already studied PFAS in fluorowaxes before they set off for the Ore Mountains. As part of a request from the German Environmental Protection Agency to gather more information about PFAS in fluorowaxes, Vogel and his colleagues tested different ski waxes for PFAS. They bought 17 new ski waxes from German shops in 2021, and Simon—a long-time skier—had 18 waxes in his personal collection dating back to the 1980s.

From their analysis of different waxes, Vogel and his colleagues found that waxes labeled for high performance contained the highest amounts of PFAS. The new waxes also contained more PFAS than the ones from the 1980s, which Vogel describes as an indicator of the wax industry's quest for higher performance over time. During competitions, a good fluorowax can shave minutes off an elite skier's time.

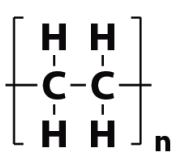
The high performance of fluorowaxes—and many other consumer products that contain PFAS—is a result of carbon-fluorine chemistry. "Carbon-fluorine chemistry is extremely unique," said Lisa Skedung, an environmental scientist at RISE Research Institutes of Sweden.

PFAS pollution has become widespread not only because forever chemicals do not break down in the environment, but also because they are found in many commercial products.

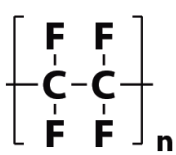
Teflon, for example, is a useful fluoropolymer—a substance with large molecules resembling those in plastics but that contains carbon-fluorine bonds instead of carbon-hydrgen bonds—that helps eggs slide off pans and medical catheters glide through blood vessels. On firefighters' protective gear or medical workers' garments, highly repellent PFAS coatings enable liquids, including water, fuels and blood, to splash off without soaking in, keeping those essential workers safe.

For ski waxes, repelling water and dirt is key. Regular hydrocarbon waxes can already repel

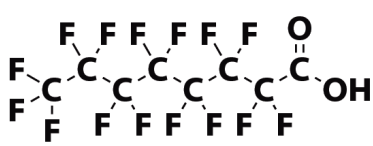
POLYETHYLENE PLASTIC



POLYTETRAFLUOROETHYLENE TEFLON



PERFLUOROOCTANOIC ACID



PFAS, also known as "forever chemicals," have similar structures to their hydrocarbon counterparts, but instead of C-H bonds, they have C-F bonds.

KELLEY J. DONAGHY

water, but fluorowaxes are even more hydrophobic than hydrocarbon waxes, explained Skedung. And because snow is often dirty, fluorowaxes can also help repel dirt, keeping skis and snowboards clean and lowering friction. Together, these make for a better glide, Skedung said.

BETTER GLIDE HAS A PRICE

Some PFAS are known to have severe health effects. PFOA, for example, has been linked to six diseases—testicular cancer, kidney cancer, thyroid disease, ulcerative colitis, high cholesterol and hypertension in pregnant women—through a large-scale study that involved more than 69,000 PFOA-exposed residents of West Virginia and Ohio, which was documented in "Dark Waters." A 2025 long-term study of pregnant women and their children found that increased exposure to a variety of PFAS molecules was found to reduce the ability of 18-month-old children to develop antibodies in response to vaccines.

The most common PFAS exposure occurs when people drink contaminated water or eat contaminated food. People can be exposed to PFAS from ski waxes by inhaling them. Ski waxes are applied to skis by melting them with a hot iron. This process produces PFAS-containing vapors, which the wax technician can inhale.

"We knew that we were supposed to be kind of careful around them from a health perspective, and if you used a lot of them, you could feel eye and throat irritation," said Kathryn Crawford, an environmental health scientist at Middlebury College in Vermont who grew up skiing. "But we didn't think a lot about it, and they made our skis a lot faster, so we really liked them from that perspective."

Studies have found that wax technicians, who work full-time during the winter sports seasons waxing skis and snowboards, suffer from extremely high PFAS exposure. A study that measured PFAS levels in wax technicians' blood found levels that were comparable to—or even higher than—those of workers at facilities that produce PFAS. "That was quite an eye opener for people in the industry who had known that there were some kind of acute discomfort symptoms, but did not really understand the larger implications," Crawford said.

Exposure could be significant for people who ski regularly, too, Crawford and her colleagues found. In 2022, Crawford and her



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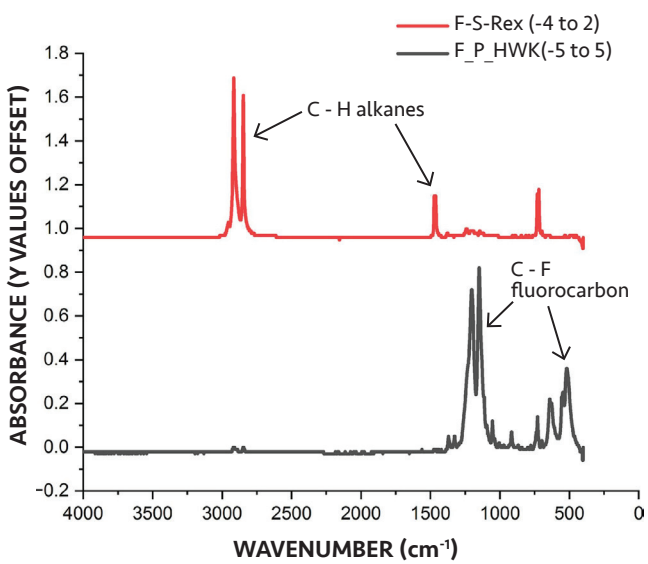
ENFORCING A FLUOROWAX BAN

Detecting the use of banned substances at competitions, like doping in the Olympics, is a quintessential problem for analytical chemists. After deciding in 2019 to ban fluorowaxes, the International Ski and Snowboard Federation (FIS) had to postpone the implementation of the ban for a few years because there wasn't a good way to enforce it and prevent cheating.

Scientists at Bruker, a manufacturer of analytical instruments, have developed a handheld version of a classic instrument, the infrared spectrometer. This instrument exposes materials in question to infrared light, which interacts with molecules in the materials. Different molecules absorb wavelengths of infrared light differently, a detector senses these changes and a computer algorithm produces a spectrum that helps identify the chemical bonds present—in this case, the carbon-fluorine bonds.

Before a race starts, officials press one end of the spectrometer against a ski and obtain an infrared spectrum for it. This measurement takes about 20 seconds, Vogel said. Because fluorowaxes need to be applied in significant amounts to be effective, this technique is sensitive enough to detect quantities that would be relevant for cheating, but not for picking up traces of PFAS that might have unintentionally gotten there. Athletes still need to be careful: If they have previously used fluorowaxes on their gear but have not cleaned it off properly, the cross-contamination could be significant enough to disqualify them from races.

Perhaps the simplest thing to do would be to issue a standard wax for competition. "If everyone has the same ski waxes, we can see who the best athlete is, not who has the best material," Vogel explained.



Powdered ski waxes are composed almost entirely of PFAS compounds, and their FTIR bands are easy to distinguish from hydrocarbon waxes.

colleagues surveyed 569 U.S. skiers and snowboarders, and 67% reported personally having applied fluorowaxes.

In a follow-up study, Crawford and her colleagues recruited 30 adult skiers from New England who ski regularly every year to check the PFAS levels in their blood. They found PFAS in all of the blood samples taken, with higher levels in ski coaches, winter athletes who have been active for more than 10 years and skiers who waxed their skis more than 100 times per year. The researchers also identified an association between the higher PFAS levels and high cholesterol levels in the participants. However, Crawford emphasized that at this stage, researchers still cannot directly connect fluorowax use to any specific health problems.

PFAS from fluorowaxes are turning up inside humans, but they are also ending up in the environment, and there is not a clear understanding of where they could go or what effects they could produce. In December 2022, Vogel and Simon returned to the Kammloipe ski track and collected soil before the first snow of the season fell. Unsurprisingly, they found that high levels of PFAS had been retained in the soil.

It is still unclear what happens to the PFAS at Kammloipe. But at other ski resorts—such as those in Park City, Utah—PFAS pollutants from fluorowaxes migrated into the aquifer that supplies the city with drinking water, affecting the broader public.



SKIING WITHOUT FLUOROWAXES

When Vogel and Simon went to Kammloipe, they did not use fluorowaxes. Crawford and Skedung, both avid skiers, have not used fluorowaxes for years. Skedung has even completed the Vasaloppet, a 90 kilometer cross-country race in Sweden, without them. "You can still ski competitively without fluorinated ski waxes," she said.

Skedung does acknowledge that fluorowaxes offer the best glide, particularly in warm and wet conditions. "There is no alternative that matches the fluorinated ski waxes," she said. But more importantly, Skedung adds, "you can also question: Do you really need that level of performance?"

Elite skiers have decided that they don't. Beginning with the 2023-2024 winter season, the FIS banned fluorowaxes from competitions, including the World Cup and the Winter Olympics. While fluorowaxes are still legal for personal recreational use, Skedung hopes that the competition ban will help convince the broader public to shun fluorowaxes as well. "We realized that if we are to change something here, we need to work with competition skiing," Skedung said.

"I think it's really good that we are not allowed to use fluorinated ski waxes anymore, because it reduces the health effects for people who wax skis," said Vogel. In addition, fluorowaxes are almost always more expensive than regular hydrocarbon waxes, so banning them at competitions helps to level the playing field between richer and poorer teams as well, he added.

DISPOSAL OF FOREVER CHEMICALS

But what should you do if you already have fluorowax in your garage? Researchers, including Vogel, are studying how to completely destroy PFAS in the fluorowaxes. "This is a major problem now," he said.

This problem extends to other consumer products, such as weatherproof outdoor jackets and boots that are often coated in PFAS. Disposal isn't easy. For example, incinerators for regular waste may not be hot enough to fully break down PFAS molecules, Vogel explains. This incomplete combustion causes researchers to worry that there may be PFAS gases being spewed into the atmosphere with the exhaust from the incinerators.

With more companies beginning to focus on the sustainability of their products, some have begun proactively eliminating PFAS from their products. "This is a topic on many companies' agenda at the moment," said Skedung, who is working with several companies across various industries to find out if their products contain PFAS and to identify suitable alternatives.

A large effort is underway to identify which uses of fluorinated chemicals society cannot do without. One of the largest ways to reduce the spread of PFAS chemicals is to phase out non-essential uses and limit them to only essential uses—that is, the ones critical to health and safety or the functioning of society, such as medical devices, vaccine vials, high-temperature fluorinated rubber seals for jet engines and the materials used to manufacture lithium-ion batteries—if they can be used and disposed of responsibly.

"Compared to saving lives and keeping the environment free of hazardous chemicals, going a few seconds faster on the slopes is an example of a non-essential use of PFAS," Skedung said.

XiaoZhi Lim is a freelance science writer from Singapore.

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HOW TO MAKE FASHION Sustainable

By Max G. Levy

Take a minute to think about what you're wearing right now. Not the colors or cuts of fabric you grabbed out of your closet this morning—but the textiles your clothes are made of.

Before your clothes became clothes, they were raw resources that were collected, processed, woven into textiles, then cut and sewn into the garments on your back. And their life cycle doesn't end there. Nearly 90% of clothing takes a final trip from closet to landfill. The problem is that although this process provides short-term convenience for customers and the fashion industry, in the long run, it's not sustainable. Making and transporting clothes consumes raw materials and, at every step in the process, emits greenhouse gases.

Does it have to be that way? Or can we reduce the fashion industry's environmental footprint by recycling used clothes, like we do with plastic bottles? Plastic bottles consist of polymers such as polyethylene, $(C_2H_4)_n$, a derivative of fossil fuels.

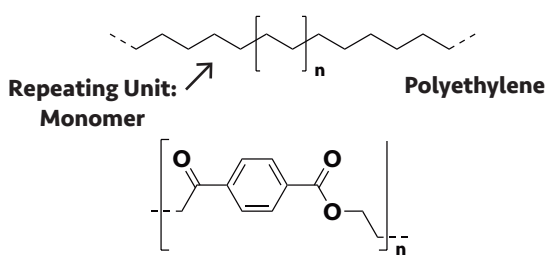
Your clothes are not much different. Many synthetic materials, such as polyester, are also made of polymers derived from fossil fuels, which are a nonrenewable resource.

While it's common for plastic to be collected for recycling, clothing recycling is rare. However, researchers and some in the fashion industry have recognized that textile manufacturing and waste is a growing problem, so they are working hard to fix the issue.

"In order to keep materials in use for everybody, we've got to be able to reuse them and remake them," said Kate Goldsworthy, co-director of the Centre for Circular Design at University of the Arts London.

The question is: What will it take to meet this goal?

COMMON TEXTILE POLYMERS



Polyethylene is a common plastic; poly(ethylene terephthalate) is the polymer most people know as polyester.

KELLEY J. DONAGHY



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Clothing Chemistry

For Finnish chemical engineer Simone Haslinger, pursuing textile-recycling research was an opportunity to help tackle serious environmental problems.

"I really saw that [clothing recycling] can be useful, and that this is something that can help everyone," Haslinger said. "It's so important because we've had all of these climate change issues."

The textile industry churns out the equivalent of 1.2 billion metric tons of planet-warming carbon dioxide (CO_2) every year, according to a 2017 analysis from the Ellen MacArthur Foundation. That's 30% more than all the world's commercial flights. The industry also guzzles about 93 billion metric tons of clean water annually—roughly half the amount that the U.S. population drinks. Additionally, the world is on track to triple clothing production by 2050. Because 97% of source materials in clothing production are new, not recycled, the growing demand places enormous pressure on land, energy resources and water.

Heaping our unwanted clothing in landfills also creates an environmental burden. As natural fibers degrade, they release methane

(CH_4), a potent greenhouse gas. Disposing and washing fabrics also releases microfibers, dyes and specialized coating chemicals into the environment.

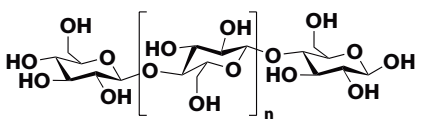
To help curb the environmental burden of fashion, Haslinger worked as a Ph.D. student at Aalto University in Espoo, Finland on developing techniques to recycle old clothes. She now designs sustainable kids' wear as a scientist for the Reima label.

Haslinger said that many technologies exist to break down and rebuild specific polymers, but the biggest lingering challenge is clear: "It's the multitude of different materials."

While the fibers in clothes are all polymers—long chains of chemically linked repeating molecules, called monomers—there are many different types. Polyester fibers, for example, are in durable fibers found in 55% percent of textiles. Polyester is inexpensive, but producing it requires a lot of energy.

Cotton fabrics, including denim, make up 27% of all textiles and consist of biological polymers called cellulose. In nature, cellulose strengthens plants' structures and is the most abundant polymer on Earth.

Most of the cellulose we use in clothing is manufactured from cotton plants, which require a lot of processing. Approximately 20,000 liters of water are used to make a single pair of jeans.



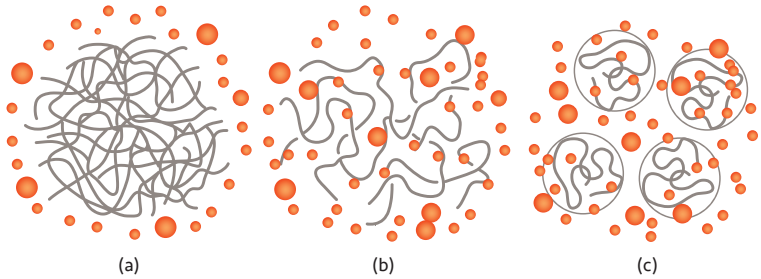
CELLULOSE

KELLY J. DONAGHY

Another 5% of textiles contain human-made cellulosic fibers. Lyocell is a popular example of this type of material. It can be produced from wood scraps or eucalyptus trees, which require far less water and pesticides than cotton plants. Producing lyocell, however, isn't completely harmless, as it is very energy intensive.

The bottom line is that resources are limited, and using them has a cost to the environment, while demand is increasing for these finite resources.

POLYMERS IN SOLUTION



(a) Polymer molecules (gray) are long chains that coil and tangle. (b) To dissolve them, a solvent (orange) must overcome the intermolecular forces holding strands together. (c) In the solvent, polymer molecules will eventually separate and disperse into solution.

RS GRAPHX, INC.

"The stuff on Earth is all we've got," Goldsworthy said. "The population is growing, and of course, even that will peak at some point. It's just not possible to imagine that [making new clothes] can go on and on and on forever the way we're doing it."

After pumping so much energy and resources into textiles around the world, only 13% of those textiles get recycled. The majority cascade down the quality chain to live a second life as insulation or stuffing. Less than 1% of clothing loops back to be made into clothing again.

Part of the reason why clothes-to-clothes recycling is so rare is because companies can't just take used clothes, shred them and spin the shredded bits into strong new yarn. Polymer length equates to fiber strength, and the length shortens with use.

"When you spin it, [the length] reduces; when the consumer wears it and washes it, it reduces," said Haslinger. By the time clothes get tossed out, their polymers are too short to turn back into a quality fabric.

New Technologies

Enter solvent-based recycling. Although polymer fibers from old clothes are too short and weak from use to spin into new yarn through a mechanical process, there's a way to reclaim the fibers for reuse. The underlying idea is simple: Collect used textiles, dissolve the polymers using solvents and then spin the fibers into yarn.

However, unlike simple solutes such as sugar or table salt, polymers are chains of molecules that easily tangle, and they require special solvents to isolate them from each other. Imagine trying to dissolve a piece of denim in water—a fabric that dissolves in the washing machine isn't going to be very useful! Even if you shred your pair of jeans into tiny pieces, intermolecular forces between polymer strands keep them together.

Finding the right solvent means making sure the polymer-solvent intermolecular attraction outweighs the polymer-polymer forces—the solvent needs to tug on the polymer molecules enough to detach strands from each other. In these processes, the groups of polymers untangle into individual strands, but not necessarily individual monomers. The result is usually a clear tinted liquid with a viscosity dependent on the size and concentration of the polymer molecules.

Haslinger's doctoral work involved a technology called Ioncell, which dissolves cellulose from cut-up pieces of

5 WAYS TO REDUCE YOUR FASHION FOOTPRINT

What can we all do to make fashion more sustainable? Haslinger recommends being more conscious about the clothes you buy and avoiding those that you know will end up in the trash soon. "Try to keep your various [clothes] longer, maybe repair it, or buy from secondhand," she says. "And if you buy something, try to buy something that is not blended that much."

1. Reduce demand by buying only what you need.
2. Buy used clothes from consignment stores, thrift stores or resale websites.
3. Buy clothes that are built to last, and actually wear them—a lot!
4. Avoid blended materials that current recycling technologies cannot handle (for example, spandex blends).
5. Buy clothes from sustainable manufacturers that use recycled textiles and renewable energy.

cotton clothes, wood, cardboard or paper with 1,5-diazabicyclo[4.3.0]non-5-ene acetate—an ionic liquid.

To understand ionic liquids, first imagine if table salt, NaCl, which normally melts at 801 °C, could be liquid at room temperature. Its electrically charged cations and anions would exist as a fluid. Ionic liquids are similar, in that they are conductive salts with melting points below 100 °C, but they are composed of an organic cation and either an organic or inorganic anion.

The cations and anions in ionic liquids like Ioncell's readily engage in hydrogen bond interactions between cellulose strands. When hydrogen bonds break between cellulose strands (threads), the individual threads become more soluble.

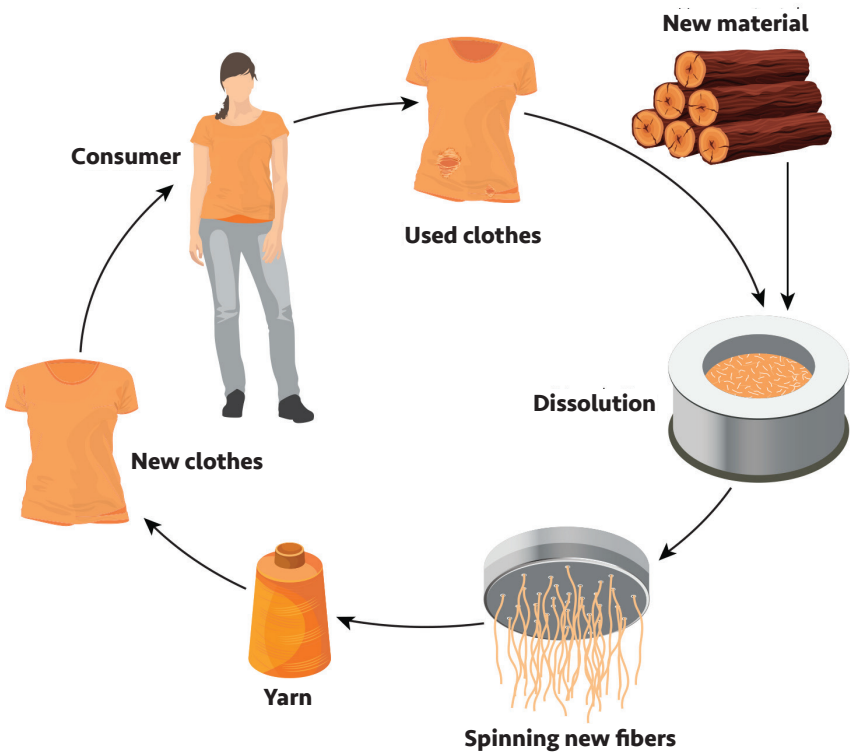
Liquid from the Ioncell process gets squeezed through tiny holes at high pressure, dripping threads of cellulose into a water bath. Because the ionic liquid is soluble in water, when the polymer drips into the water, the solvent (the ionic liquid) washes away and the solutes (cellulose threads) hydrogen bond to each other again and form solid fibers. The final steps involve stretching the fibers even thinner to make them suitable for clothes.

While Ioncell proves that recycling cotton is possible, the problem solving doesn't end there. An additional challenge is that chemical recycling that works for cotton won't necessarily work for rayon, nor is it guaranteed to break down cotton clothing at different stages.

Recycling processes are also sensitive to impurities. Additives such as spandex, water-repellent coatings and dyes add to the chemical complexity. Processing technologies often have to be optimized for a combination of factors, including impurity content, fabric quality and the type of polymer.

Another approach to clothing recycling involves restoring a polymer to its original quality. This requires depolymerization. As its name suggests, depolymerization is a process that breaks down a polymer into its monomers.

CLOTHES-TO-CLOTHES RECYCLING



Cellulose from used cotton clothes and other cellulose-rich materials, such as wood and paper, can be dissolved and spun into new fibers for textile manufacturing. Such processes can help reduce the need for virgin cotton.

RS GRAPHX, INC.



Clothing makers have started to use textiles made from used apparel and other cellulose-rich waste.

INFINITED FIBER

The Challenge Ahead

Another challenge to recycling used clothing is that many of our clothes contain blends of different fibers.

"The more components you have—especially elastane—the harder recycling gets," said Haslinger. Elastane, more commonly known as spandex, impairs recycling processes.

"That's why I think all those that are now trying to commercialize [recycling are] saying: 'We only focus on bedsheets,' for example, or 'We only focus on denim.' Because they know [a broader approach is] very difficult," Haslinger said. "None of them can say, 'We'll just take all of it,' and recycle everything."

And slowly but surely, through steady determination and innovation, scientists and clothing manufacturers are introducing recycled clothing fibers to the market. Adidas and Levi Strauss, for example, have released limited-edition garments containing NuCycl, a novel fiber made from 100% post-consumer cotton by U.S.-based company Evrnu. And a Finnish company, Infinited Fiber, teamed up with H&M Group to release a line of jeans in Europe that combines its regenerated textile fiber with organic cotton.

The vision of those developing all of these technologies is ultimately to build a circular economy, using waste as a resource rather than depleting raw resources to make new clothes and more waste. Understanding the chemistry of fabrics plays a huge role in closing that loop!

Max G. Levy is a freelance science writer based in Los Angeles, California.

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CROCHET CHEMISTRY

Chemistry Shapes Every Stitch

By Victoria Russell

"My overarching goal in the lab is to understand organic reactions by studying their electron transfer mechanisms," said Kristine Legaspi, a chemistry graduate student at the San Diego State University in California. "At the root of everything, I'm an analytical chemist, and I use electrochemistry to understand things."

But this Saturday morning, Legaspi is far from the lab. At a bustling farmers market in Inglewood, California, she sets out an unusual display—crocheted plushies shaped like laboratory tools: a soft blue beaker, a pastel pink Erlenmeyer flask and even a cuddly purple benzene ring (a hexagon of six –CH groups bonded by alternating single and double bonds: C_6H_6). These objects are instantly recognizable to chemists, but at the farmers market, they are transformed into something playful and huggable.

In 2023, Legaspi joined a science communication program that encourages participants to share science through their hobbies. Her choice, crochet, quickly became a hit. At events like maker fairs and farmers markets, her handmade plushies of beakers and molecules draw in kids, parents and teachers alike, sparking conversations about chemistry in a surprising, approachable way.



COURTESY OF KRISTINE LEGASPI

Kristine Legaspi shows off her plush chemistry-inspiried crochet creations such as beakers, flasks, testbuves, the mole and a even plush benzene model.

"I think the thing that I love about chemistry the most is that it feels like making something out of nothing," she said. "That's also true of art, especially crochet—you start with a tiny circle or a knot and watch it grow into something completely original. That's what I love about the lab, too. When I mix reagents into a solvent and let it stir, it might not look like much at first, but later it's bright pink or green, and suddenly I've made something entirely new. The basic building blocks might seem like nothing on their own, but together they become something you never expected. That's why crochet helps me connect with my science—I love seeing the growth in both."

Crochet might seem like just a yarn and a hook, but underneath every stitch lies chemistry. The softness of the yarn, the vibrancy of the colors and even whether your finished project holds its shape all depend on molecules and how they interact.

YARN CHEMISTRY: POLYMERS MAKE THE FABRIC

Crochet creates fabric by interlocking loops of yarn with a hooked needle. The word crochet comes from the French word croche, which means "small hook." Each stitch is built by pulling a loop of yarn through another loop. With enough stitches, you can make everything from flat blankets to three-dimensional plushies.

The real star of crochet, though, is the yarn. Yarn is made by spinning fibers into long, continuous strands. Those fibers can come from many sources. The chemistry of those fibers determines how the yarn behaves, whether it feels scratchy, stretches or shrinks, lasts for years or wears out quickly.

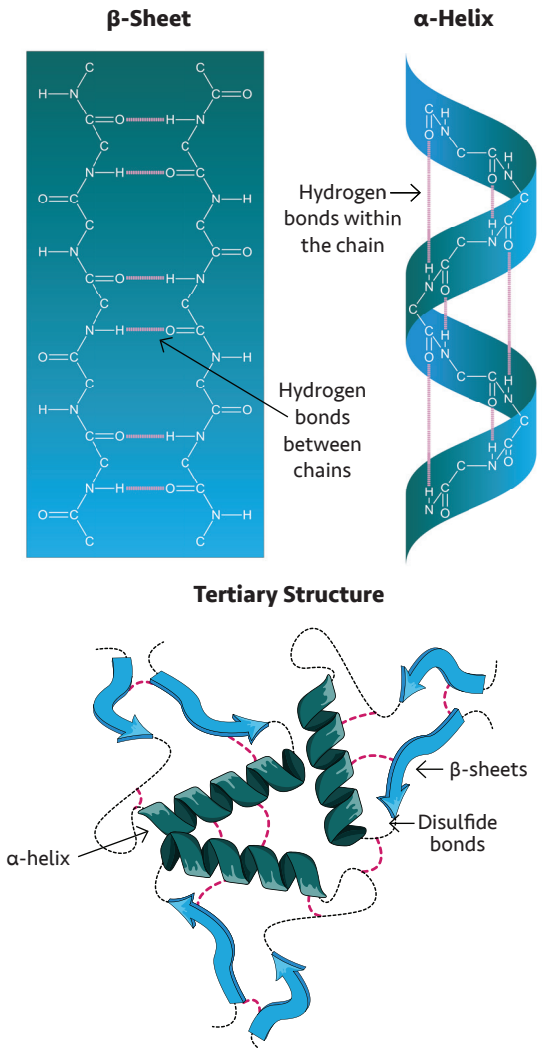
Fibers fall into three broad categories: natural, synthetic or semi-synthetic. Natural fibers come from plants or animals. Synthetic fibers are entirely man-made, usually from petroleum-based chemicals. Regenerated or semi-synthetic fibers are made by chemically modifying natural fibers. Three of the most common natural fibers are cotton, wool and silk.

Cotton yarn is almost pure cellulose, a carbohydrate polymer found in plant cell walls. Polymers are huge molecules made up of repeating monomer units (small molecules). Each cellulose molecule is a polymer made of repeating glucose units linked together. These chains line up side by side, and hydrogen bonds between the chains via each chain's hydroxyl (–OH) groups give cotton its strength and durability. The large number of –OH groups on the monomers that make up cellulose also means it can hydrogen bond easily with water, so cotton is excellent at absorbing moisture. This property makes it perfect for towels. Those same hydroxyl groups also provide binding sites for dyes, helping cotton fabrics hold bright, long-lasting colors.

Wool yarn comes from sheep fleece and is made of keratin, a protein found in human hair and fingernails. Proteins are polymers of amino acids, and in wool, keratin chains form α-helices. An α-helix is a rod-like, coiled shape stabilized by hydrogen bonds within the chain. These coiled keratin molecules act like springs, giving wool its elasticity. That's why a wool hat can stretch over your head but spring back to shape. Wool also naturally insulates because the fibers trap air pockets.

Silk, spun by silkworms, consists mainly of fibroin—a protein rich in glycine, alanine and serine. The hydrogen bonding between fibroin polymers causes the amino acids to pack tightly into β-sheets—flat sheet-like pleated shapes—creating a crystalline structure that gives silk its strength while also making it smooth and lustrous, but much less stretchy than α-helices.

Not all yarn comes from plants or animals; some are designed by chemists. Acrylic yarn is spun from polyacrylonitrile, a polymer made of acrylonitrile monomers. Acrylic yarn is inexpensive, lightweight and moth-resistant, making it a popular alternative to wool. Other synthetic fibers include polyester—built from repeating ester linkages—and nylon—a polyamide formed by linking monomers with amide bonds (–CONH). Polyester resists wrinkles and stretching, while nylon is tough and resilient. Synthetic fibers are often blended with natural fibers to balance comfort with durability.



TWISTING CHEMISTRY: FROM FIBERS TO YARN

Spinning fibers aligns them side by side and increases the friction that keeps them from slipping apart. In wool, tiny scales on the surface of each fiber catch and lock together, adding strength. In cotton, hydrogen bonds between cellulose chains help the fibers stick to one another and hold the twist in place.

The way yarn is spun also changes its behavior. A single-ply yarn is just one twisted strand, while multi-ply yarns combine several strands twisted in opposite directions. The counter-twist balances out the tension, reducing curling and making the yarn easier to crochet. Chemically, the polymers inside each fiber don't change during spinning, but the process mechanically transforms them, turning weak, flimsy fibers into a strong material ready for crocheting.



Stitching Abbreviations & Notes

lp loop **st** stitch **yo** yarn over **rnd** round

ch chain stitch; yo, pull through lp on hook

sc single crochet stitch; insert hook into next st, yo, pull through st on hook, yo, and pull through both lp on hook

dc double crochet; yo, insert hook in next st, yo, pull through st, [yo, pull through 2 lps] x2

inc increase stitch; stitch 2 sc into a single st

dec decrease stitch; insert hook into flo next 2 st, yo, pull through both st, yo, pull through both lp on hook

sl st slip stitch; insert hook into next st, yo, pull through both lp on hook

blo stitch in back loop only

flo stitch in front lp only

hdc half double crochet; yo, insert hook in next st, yo, pull through st, yo, pull through 3 lps

- *Yarn and hook gauges are not critical in these projects.*
- *Tension is not critical, but tighter is recommended to prevent filling from showing*



Test Tube

If you're feeling a little "testy," this easy pattern is sure to improve your day. Whip up a whole rack of these fun test tubes in a variety of colors to brighten up your lab, study nook, or anywhere!

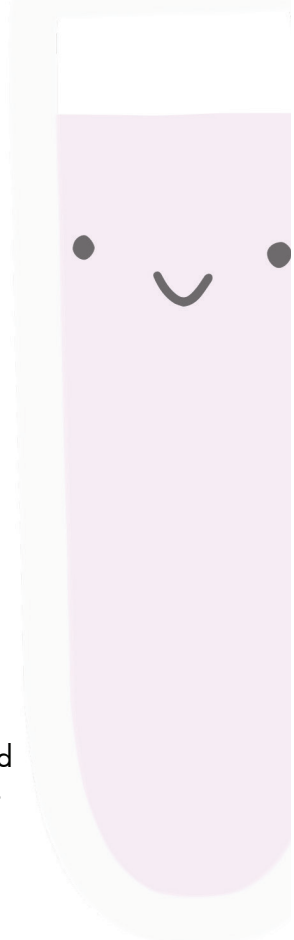
Materials

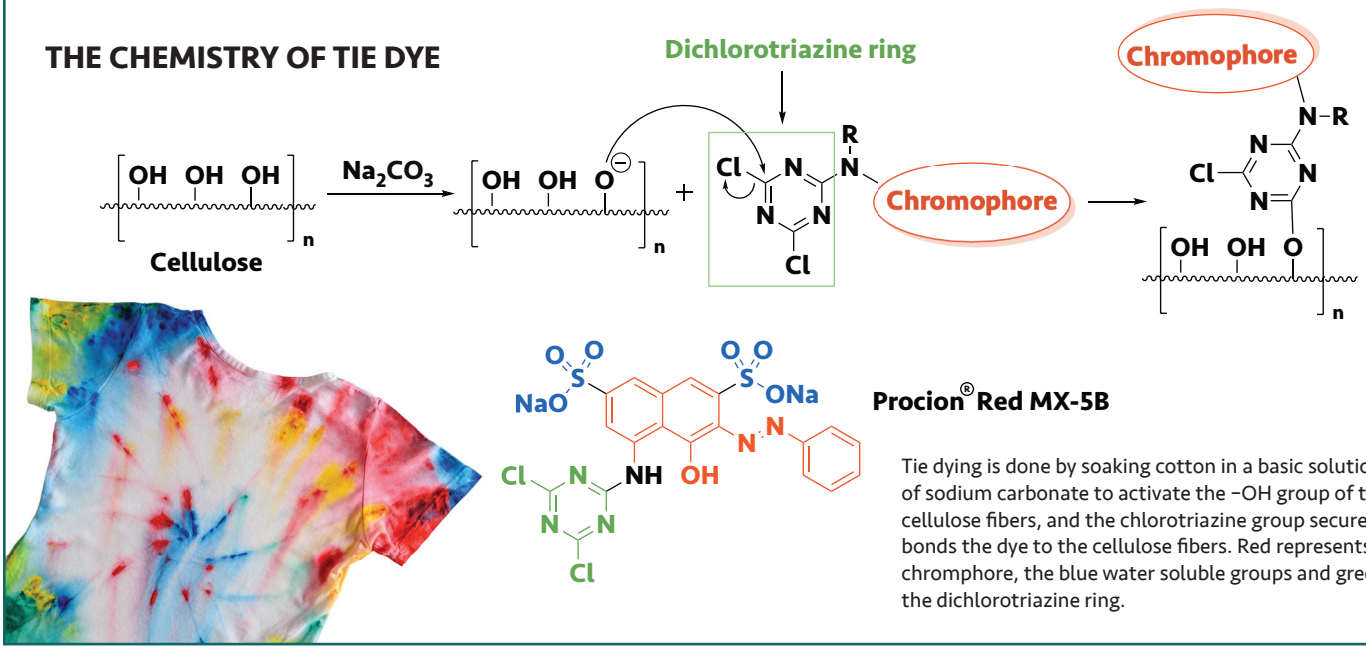
- *Color A yarn (liquid color)*
- *Color B yarn (test tube color)*
- *2 x 10 mm black safety eyes*
- *Crochet hook*
- *Stitch marker*
- *Yarn needle*
- *Polyfill*

Pattern Notes

1. *(Optional) replace rnds 1 & 2 with 8st in a magic ring*
2. *Add or remove rnds to achieve desired beaker and liquid height*
3. *(Optional) Instead of sl st, use needle to whip stitch each st; pull to close plushie*

Rnd 1:[1] starting with yarn B, ch 2 (2)
Rnd 2: 8 sc in the 2nd ch from hook (8)
Rnd 3: inc in each st (16)
Rnd 4: inc in each st (32)
Rnd 5: blo sc around (32)
Rnd 6: [1 sc in each of 2 st, 1 dec] x8 (24)
Rnd 7: flo sc around (24)
Rnds 8-11[2]: sc around (24)
Rnds 12-23[2]: switch to yarn A, sc around (24)
Insert safety eyes at desired position.
Rnd 24: [1 sc in 1st st, 1 dec] x8 (16)
Stuff with Polyfill.
Rnd 25: dec around (8)
Rnd 26:[3] sl st in every other stitch until plushie is closed and tie off
Finish: optional, use black yarn to stitch a mouth and stitch rim of test tube using yarn B to make edge flat





Tie dying is done by soaking cotton in a basic solution of sodium carbonate to activate the –OH group of the cellulose fibers, and the chlorotriazine group securely bonds the dye to the cellulose fibers. Red represents the chromphore, the blue water soluble groups and green the dichlorotriazine ring.

SHUTTERSTOCK/KELLEY J. DONAGHY

COLOR IN EVERY STITCH

What's a ball of yarn without color? Dyeing yarn is one of humanity's oldest chemistries, dating back thousands of years to natural dyes from plants, insects and minerals. But dyeing isn't simply dipping a thread into a colored liquid. Dyeing involves a physical or chemical process that makes the color stay put through wear and washing.

At its core, a dye is a molecule that absorbs certain wavelengths of visible light and reflects others. Unlike pigments, which remain as tiny, suspended particles, dyes attach directly to the fibers, either chemically or physically. This attachment depends on the chemistry of the fiber itself.

Reactive dyes contain special chemical "hooks," such as dichlorotriazine rings, that can form covalent bonds with cellulose through base-activation of the –OH groups on the cellulose chains. Once locked in, the color is permanent, like superglue at the molecular level. A simpler method, called direct dyeing, skips covalent bonds. Instead, large, flat dye molecules wedge between the polymer chains and hold on with weaker hydrogen bonds and van der Waals forces. The result is dye bonded more like a sticky note than superglue: easier to apply, but more likely to fade.

Animal fibers, like wool and silk, need a different approach because they're made of proteins such as keratin and fibroin. These proteins are made up of amino acids, and each amino acid has a unique side chain that determines its chemical properties. Amine side chains ($-NH_2$) become positively charged ($-NH_3^+$) in acidic solutions, turning the fiber into a surface covered in tiny magnets for negatively charged molecules. Acid dyes, which carry negatively charged sulfonate groups ($-SO_3^-$), snap onto those magnets through ionic attraction. Because the acid dyeing process is relatively gentle, it's especially suited for delicate fibers like silk.

Synthetic fibers pose their own challenges. Acrylic yarn, made mostly of polyacrylonitrile, doesn't naturally provide sites for dye molecules to grab onto. To fix this, manufacturers add negatively charged sulfonated sites directly into the polymer. Positively charged basic dyes then attach to these sites through electrostatic interactions—positive charges attract negative charges.

Polyester is perhaps the trickiest fiber to dye. Its long, nonpolar chains act like plastic wrap—slick, smooth and unwilling to interact with water-based dyes. The solution is disperse dyes, small, non-polar molecules that can slip between polyester chains. Heat is essential; it softens the polymer so the dye can diffuse into spaces between the chains. When the polyester cools and the polymer chains contract, the dye is trapped.

Vat dyes–dyeing in a bucket or vat–use a variation on this approach. The dye is suspended in hot water and the fabrics are left to soak up the dye, then like polyester, when the fabric cools, the dye is trapped by the polymer strands. Indigo, one of the most ubiquitous dyes used to dye jeans blue, is a vat dye. However, indigo isn't water soluble so an extra step is required. Dyers use a reducing bath to convert indigo into a soluble, yellowish form called leucoindigo. The yellow leucoindigo solution soaks into the fabric. Then when the fabric is exposed to oxygen in the air, the leucoindigo re-oxidizes to insoluble blue indigo. Because no covalent bond is formed between the indigo molecule and the fabric, fabric dyed with indigo fades over time as the dye molecules wash out.

WHY COLORS APPEAR

To understand why dyes appear colorful, we need to zoom in to the molecular level. Dyes absorb certain wavelengths of light because of conjugated

CROCHET VS. KNITTING: WHAT'S THE DIFFERENCE?

At first glance, crochet and kitting might look similar. They both use yarn to make fabric, but the techniques are quite different.

Knitting uses two needles to build a series of interconnected loops. Many stitches stay "open" on the needles at the same time, and the technique generally leads to stretchy, flexible fabric. This makes it ideal for lightweight shawls or scarves that flow easily or socks, hats or sweaters that need flexibility.

Crochet uses a single hook to pull one loop through another. Each stitch is finished before moving on to the next. This usually creates a denser, sturdier fabric than knitting. Crocheting may be the preferred method for blankets that need warmth and structure, or bags, baskets and toys (like amigurumi) that need to hold their shape.

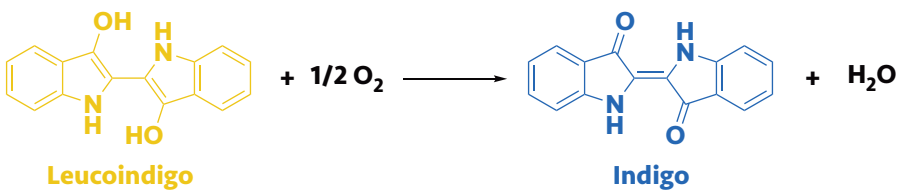




SHUTTERSTOCK/KELLEY J. DONAGHY

(*Left*) Vat dyes, such as indigo, are heated baths that fabric is dipped into. When the fabric cools, the dye is locked into the fibers of the material. As air interacts with the leuco form of the dye, it is oxidized, changing the structure and converting it to the deep-blue indigo form.

(*Below*) The conjugation—repetition of single and double bonds—of organic dyes determines the wavelength of light absorbed and transmitted. Leucoindigo has fewer double bonds than indigo and is a different color.



Leucoindigo Indigo

systems, alternating single and double bonds that create delocalized electrons. These electrons are freer to move than electrons in molecules with only single bonds, and that mobility changes how the molecule interacts with energy. When light hits the dye, the electrons can absorb a specific amount of energy, which corresponds to a particular wavelength of visible light. We don't see the absorbed light; we see the complementary color that is reflected back to our eyes.

The blue dye indigo, for example, has a conjugated system that absorbs orange light, leaving blue as the color we see. The natural dye madder red (alizarin) absorbs green wavelengths, so it looks red. Azo dyes, which contain nitrogen-nitrogen double bonds, have long conjugated systems. By tweaking the side groups on azo dyes, chemists can fine-tune which wavelengths are absorbed, creating colors that range from sunny yellows to deep reds and even blues.

The relationship between molecular structure and visible color is so strong that chemists can often predict a dye's appearance just by analyzing its electronic transitions. In other words, the rainbow of colors in yarn is written directly into the arrangement of bonds and electrons.

BLOCKING AND SETTING THE SHAPE

A finished crochet project is blocked, a final step where makers wet their fabric, stretch or pin it into the desired shape and let it dry. The result is a smoother, more even piece that remembers its new shape.

Chemistry is behind the fibers' ability to remember their shape. In wool, for example, water molecules slip between the keratin chains and temporarily break the hydrogen bonds that hold the fibers' structure in place as new hydrogen bonds are formed between the keratin chains. While the wet piece is pinned into shape, the fibers can shift and realign. As the fabric dries, new hydrogen bonds form between the keratin chains in this new arrangement, locking the project into its new shape. Cotton behaves in a similar way, though its lack of natural elasticity means the effect is less dramatic.

Synthetic fibers, however, are trickier. Because they are hydrophobic, water doesn't easily disrupt their structures. To reshape them, heat must be applied. High temperatures soften the polymer chains, allowing them to be stretched and pinned. Once cooled, the polymers harden, fixing the fabric into position. Blocking is more than a finishing touch; it's a controlled molecular makeover that helps each stitch settle into place.

BLENDING CROCHET, SCIENCE AND ART

For Legaspi, art has always been more than a pastime—it's been a lifeline. Before returning to school, she balanced two jobs while taking part-time classes at a community college and supporting her family. In the midst of all that responsibility, creative hobbies like painting—and later crochet—gave her space to be herself, separate from the pressures of work and school. In college, her walls became crowded with canvases as she painted through midterm stress while her roommates looked on with amused disbelief at the growing collection.

There was no single lightning bolt moment when Legaspi realized she also loved chemistry. Following her family's hopes, she began college on a pre-med track with plans to go to medical school. She had always liked science, but it didn't yet feel like a passion. But as she moved deeper into her coursework, she found herself drawn less to medicine and more to chemistry itself. She switched her major and began exploring electives in atmospheric chemistry, polymers and materials. Each new class revealed another layer of possibility, and over time, she fell in love with chemistry—not because it was expected of her, but because she discovered it for herself. After graduation, she chose to continue that journey in graduate school, working toward a doctorate in chemistry.

Her artistic background continues to shape her approach as a chemist. "I think that me coming from a creative background translated well into becoming a scientist," she said. "My creative side allows me to design experiments, think outside the box and carry a project from the idea stage all the way to completion."

CHEMISTRY IS WOVEN IN

When you wrap yourself in a crocheted scarf or cuddle a plush molecule, you're holding the results of centuries of chemistry. The hydrogen bonds of cellulose, the disulfide crosslinks of keratin and the covalent linkages of synthetic polymers all combine to make yarn strong, stretchy, colorful and versatile.

Chemistry makes crochet possible. Every stitch is built on molecular interactions, woven together by human creativity.

So, the next time you pick up a hook and yarn, remember: You're crocheting with chemistry.

Victoria Russell is a chemist and science writer based in Salt Lake City, Utah.

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HOW DO INSULATED WATER BOTTLES WORK?

By Brian Rohrig



When I was in school, nobody carried a water bottle. If you were thirsty, you stood in line for a sip of lukewarm water at the drinking fountain.

In 2026, water bottles, tumblers and their numerous variations are an essential school supply. A classy one can set you back $50. Why are they so expensive? And how do they keep their contents cold (or hot) all day long?

A simple observation can provide some insight. When you take an aluminum can of soda from the fridge, the can feels cold. Metal is a good thermal conductor—heat freely travels through it. If your goal is to keep your soup warm, don't serve it in a metal bowl; it rapidly loses heat and might burn your hand when you pick it up.

But a high-tech water bottle—like its cousin, the thermos—never feels hot or cold to the touch. The secret to these water bottles' success lies with, believe it or not…nothing.

In this case, "nothing" actually refers to a vacuum: a volume empty of matter, which sits between two layers of stainless steel. Your expensive water bottle is actually a bottle within a bottle.

While air is a good insulator—think Styrofoam cups and down jackets that have air-filled spaces—a vacuum is a far better insulator than air. An insulator keeps things apart or restricts energy from moving. Heat is energy in motion, and it travels in three different ways: conduction, convection and radiation. A vacuum flask defends against all three.

Conduction is the transfer of energy through direct contact. Metals are good conductors of heat because they hold their valence (outermost) electrons loosely. These delocalized electrons are not bound to a specific nucleus; instead, they exist in a kind of electron soup that sloshes around between the atoms of the metal. When a metal is heated, these electrons readily collide with adjacent electrons, quickly transferring energy.

In a double-walled vacuum flask, heat cannot travel between the two layers via conduction because there are no molecules to carry the energy. If you have a string of upright dominoes arranged in a line, one falling domino would cause an adjacent domino to fall, but a gap in the line of dominoes would stop the fall. A vacuum provides this gap.

Heat can also be transmitted via convection, which occurs when a fluid rises or sinks due to density differences. A hot cup of coffee left open to the air loses considerable heat due to the convection that occurs. Hot fluids are less dense than cold fluids.

Consider a hot cup of cocoa: As the cocoa on the surface cools, it becomes denser and sinks, forcing warmer cocoa to the top, where it loses energy to its surroundings and sinks. The air that surrounds the cup of cocoa also plays a role. As the air warms, it becomes less dense and rises, carrying away the heat. Cooler air replaces it, continuing the cycle. These processes continue as the cocoa cools to room temperature. In a vacuum flask, the thick, insulated lid prevents heat from escaping via air movement, and this—along with the vacuum space—stops convection dead in its tracks.

However, there is one way for heat to travel through a vacuum. Thermal energy is the kinetic energy generated by the tiny random motions of particles in an object. Thermal radiation is the conversion of thermal energy into electromagnetic radiation. Every substance above absolute zero (0 kelvin) emits waves of electromagnetic radiation. Electromagnetic waves travel best in a vacuum where there are no molecules of matter to get in the way and slow them down.

Watch » How vacuum flasks are made.

The radiation we experience as heat usually falls in the infrared portion of the electromagnetic spectrum. Infrared waves cannot penetrate metal, so for them to travel through the vacuum, heat first needs to be conducted into the metal. Within the metal, this heat is converted into infrared radiation, which can then traverse the vacuum.

Vacuum flasks are designed to minimize the conduction of infrared waves—heat—into its metal walls. Stainless steel contains chromium, which reacts with oxygen to create a layer of protective chromium(III) oxide on its surface, making it shiny. Shiny objects reflect radiant heat and reduce heat absorption. Old-fashioned thermos bottles were made of silvered glass, reflecting back energy that tried to escape.

Still, no matter how exquisitely designed, even the best vacuum flask will experience some heat transfer. Given enough time, the contents will achieve thermal equilibrium with their surroundings, because no flask is perfectly sealed. But if you're staying properly hydrated, you will drain the contents of your vacuum flask long before thermal equilibrium is achieved.

Brian Rohrig is a high school teacher based in Columbus, Ohio.

Curated by Wynne Parry

A Shirt That Tracks Your Workout

Clothing is getting smarter. Yoga pants can help you improve your poses, a denim jacket can connect to your phone and socks can scan your feet as you run. And more body-monitoring garments are coming. Researchers at Cornell University have developed a T-shirt they call SeamFit that can track exercise.



SeamFit shirts are regular cotton T-shirts that contain electrically conductive wires sewn into their seams. Movement, like that from a lunge or a sit-up, changes the wires' shape and alters the capacitance, or charge they can hold. A removable circuit board at the neck transmits this signal to a laptop, where algorithms determine if the wearer is exercising, which exercise they are doing and the number of repetitions.

In addition to helping people improve their workouts, the data the shirt collects could be used to train robots to move more like humans, researchers say.

» **LEARN MORE:** Smart Shirt Tracks Workouts—and Goes Straight to the Wash, *IEEE Spectrum*. May 5, 2025: https://spectrum.ieee.org/smart-clothing-cornell (Last viewed December 2025)



Colored Fabric, Made by Microbes

Cotton, linen and other fibers derived from plants contain the polymer cellulose. Microbes, too, can make cellulose fiber for fabric, which is typically white. Korean researchers have doubled down on this approach—using bacteria not only to make cellulose, but also to color it.

To accomplish this, they used cellulose-producing *Komagataeibacter xylinus* bacteria and strains of pigment-producing *Escherichia coli*. Getting the two types of bacteria to work together was tricky. The researchers had to develop different strategies for coloring the cellulose with cool-toned pigments called violaceins versus the warmer carotenoids. In the end, they produced cellulose in seven colors, including red, yellow and purple.

Conventional fabric production often relies on petroleum and non-ecofriendly dying reagents. This microbe-based approach could offer a more sustainable, less harmful alternative, according to researchers.

» **LEARN MORE:** Scientists invent way to use E. coli to create and dye rainbow-colored fabric in the lab, LiveScience. Nov. 15, 2025: https://www.livescience.com/chemistry/scientists-invent-way-to-use-e-coli-to-create-and-dye-rainbow-colored-fabric-in-the-lab (Last viewed December 2025)



Redesigning The Pimple Patch

Pimples: If you have skin, you've probably had them. Researchers at a South Korean university and biotech company are looking to improve one method for treating them: the sticker-like pimple patch, which absorbs oil, dirt and water and sometimes delivers medication.

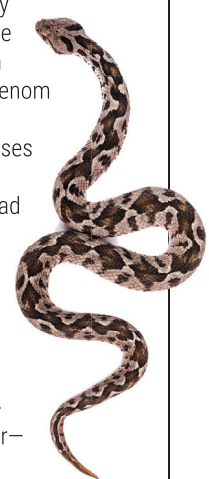
Like existing medicated patches, the researchers' design adheres to the skin with a microarray of tiny spikes. The researchers designed their spikes to have an arrowhead shape intended to keep them locked in place. But they don't need to stay there long. Within 90 minutes, the skin absorbs the array, which is made of hyaluronic acid, an ingredient in many skin care products.

In a study, 20 people used patches containing antibacterial compounds mixed with hyaluronic acid. Then, they switched to another version containing anti-inflammatory ingredients. After seven days, all the pimples the participants treated were gone. Ninety-five percent of them said they were satisfied with the results.

» **LEARN MORE:** Researchers develop a pimple patch that actually seems to work, *Popular Science*: Sept. 24, 2025: https://www.popsci.com/health/researchers-develop-a-pimple-patch-that-actually-seems-to-work/ (Last viewed December 2025)

Treating Snake Bites With 'Nanobodies'

As many as 138,000 people die from snake bites every year and even more become disabled, according to the World Health Organization. To help reduce this toll, an international research team is developing a new antivenom made of immune proteins called nanobodies.



Antivenoms are typically produced by exposing horses or sheep to venom and collecting the antibodies their immune systems make. The researchers turned instead to llamas and alpacas, which make small antibodies called nanobodies. The team injected a llama and an alpaca with venom from 18 African snakes. Then, they genetically engineered bacteria to mass produce the animals' nanobodies, and they identified the most promising eight.

In experiments with mice, the researchers administered the eight nanobodies along with—or shortly after—doses of venom. In most cases, the nanobodies did a better job of protecting the rodents than the currently available antivenom. One of the researchers speculates this is because the nanobodies' small size allows them to better reach the wound.

» **LEARN MORE:** "Innovative antivenom is a 'potential game changer' for snakebites, *Science News*. Oct. 29, 2025: https://www.science.org/content/article/innovative-antivenom-potential-game-changer-snakebites (Last viewed December 2025)

SHUTTERSTOCK



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A rotting tree log covered in mycelium threads.

Can Mushrooms Save the Planet?

Mushrooms are finding their way into myriad green products from faux-leather shoes and handbags to biodegradable coffins.

By Cynthia Washam

Throughout most of her career in aerospace engineering, Professor Valeria La Saponara at the University of California, Davis (UC Davis), never considered making anything out of mushrooms beyond an occasional dinner. Whenever she worked on a new design at work, her go-to materials were plastic-based composites

"After spending close to 30 years experimenting in this field," she said, "I started developing sensitivity to a lot of these chemicals." Around the same time, she began hearing about mushrooms being used to create fungi-based substitutes for petroleum-based materials. Curiosity drove her to buy a mushroom-growing kit. Her first batch thrived—along with lots of mold. Still, she was hooked.

Since 2020, La Saponara and her colleagues at UC Davis have worked to incorporate mushroom-based fibers into composite materials to replace polystyrene, polyurethane and other petroleum-based building blocks. They have used mushroom-based foam in children's bike helmets and as the interior filler for giant wind turbines. And rather than breaking down into harmful materials at the end of a product's life, mushroom-based products are bio-contributing—they add useful nutrients to the soil.

BURIED TREASURE

To understand how squishy mushroom blobs can be made into solid consumer goods, consider their structure. The part visible above ground, the cap, is what most people call the mushroom. However, similar to an apple on a tree, the cap is just the fruiting body, which is only a small part of the overall organism. The rest of the mushroom is the mycelium, the part of the mushroom that anchors it to whatever it is growing on. Mycelium is a white, fibrous material that is lightweight, heat-resistant and moldable as it grows. Heating it stops the growth, and the material becomes a hard, dense foam that is similar to styrofoam.

Unheated mycelium resembles cotton: Both are fibrous and can be spun into threads and used in textiles. A distinct advantage of mycelium over cotton is that mushrooms can grow in the dark, so no forest needs to be cleared. Instead of using sunlight as an energy source, mushrooms thrive in dark, damp places and consume sawdust, straw, coffee grounds—just about anything that contains carbon. Mushrooms are heterotrophs and, as such, cannot produce their own food. Instead, they decompose organic matter.



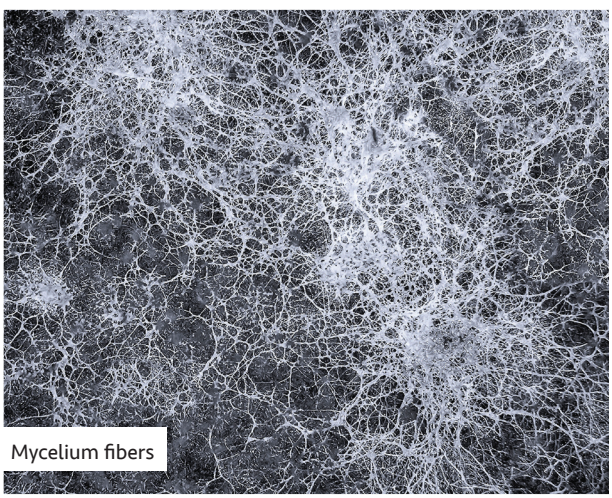
COURTESY OF LOOP BIOTECH

A biodegradable coffin made from mushrooms. »



COURTESY OF VALERIA LA SAPONARA

The white block in the foreground was made from mycelium that was grown in a mold shaped like a block. The wind turbine in the back contains mycelium blocks surrounded by bamboo slats to form the turbine blade.



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Mycelium fibers



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Cotton fibers

La Saponara incorporates textile waste into mycelium-based blocks. "Textile waste is a big problem," La Saponara said. "Fast fashions are cheap, and you cannot get rid of them." Many textile items are made from petroleum-based synthetic fibers that take a long time to biodegrade. These fads are problematic environmentally; they use a lot of water and produce more than 10% of the global carbon emissions.

After the mycelium growth is halted with salty water, the interiors of the blocks resemble tempeh or nougat candy, and the exterior has a rough, mostly white surface. To convert mycelium into textiles, La Saponara combines it with shredded textiles, bamboo, ground almond shells and fava-bean roots. The mixture is then incubated in a mold with water and nutrients under ambient conditions for six to 14 days.

"We're just at the beginning of this technology," La Saponara said. "Because [the mycelium-based blocks are] made primarily from plants and fungi, eventually it's going to degrade if you don't do anything to it." She expects to experiment with coatings to protect the blocks from moisture soon.

CARBON CHOWHOUNDS

You might have seen mushrooms growing on the ground, on the side of tree trunks or on animal dung, but not growing on plastics unless you are on Dr. Ali Abbas's chemical engineering research team at the University of Sydney in Australia.

"We wanted to tackle a problem that was challenging," said Abbas. That problem was polypropylene, a plastic widely used in food packaging, textiles and construction materials. Polypropylene makes up a third of all plastic waste and takes hundreds of years to degrade. Unfortunately, removing food residue, which is necessary for recycling, is so costly that only 1% of discarded polypropylene is recycled, according to Abbas.

Many common plastics, such as polypropylene, are petroleum-based, meaning they are made from fossil fuels. First, the fuels are refined to create hydrocarbon monomers, then these small hydrogen and carbon molecules are linked to form larger polymers—the basis of plastic. Plastics degrade slowly because of the strong covalent bonds that hold the atoms and monomers together. In a landfill, even carbon-gobbling mushrooms can't degrade them. But, Abbas surmises, maybe they could with some help.

Mushrooms start degrading organic matter by producing enzymes that break complex compounds into simpler carbon molecules. "Fungi incorporate that carbon into their biomass and release carbon dioxide and water," Abbas explained. His team chose two mushroom species, *Aspergillus terreus* (*A. terreus*) and *Engyodontium album* (*E. album*), for their polypropylene study because of their abundant enzyme supplies and ability to withstand harsh conditions, including low moisture and nutrients.

To spur degradation to weaken and break the polymer bonds, the researchers experimented with three types of pretreatments. Polypropylene



Propylene **Polypropylene**



SHUTTERSTOCK

samples were treated with either heat, ultraviolet (UV) light or Fenton's reagent, a solution of hydrogen peroxide (H_2O_2) and a catalytic amount of iron(II) sulfate ($FeSO_4$). Following pretreatment, Abbas's team incubated mushrooms with the polypropylene for 90 days.

They measured their results by weighing the polypropylene samples following incubation. Polypropylene samples pretreated with heat were consumed by *A. terreus* such that a weight loss of 27% was observed. Pretreatment of the plastic with UV was nearly as effective, with a weight reduction of 25% with *A. terreus*. Biodegradation was lower with *E. album* but still noticeable.

"Fungi, if they solve the [plastic waste] problem at an industrial scale, will be a very attractive solution," Abbas said. "We're one to two years away from the first pilot plants and another year or two before the first commercial plant."

> ***As the world is changing, more people are looking at creating sustainable products and manufacturing methods.***
>
> DEBORA PORTER
> UNIVERSITY OF CALIFORNIA, MERCED

MYCOREMEDIATION

In California, meanwhile, scientists are taking a similar approach to removing pesticides, heavy metals and other pollutants from the ash that is left behind following urban wildfires. They fill porous tubes called wattles with straw and mushroom spores. The wattles are positioned to divert ashy runoff from waterways as the mushrooms absorb and break down contaminants. Mushrooms release enzymes that detoxify the soil. This process is called mycoremediation.

"Char from structures that burned can be difficult to degrade," said Dr. Mia Maltz, a University of Connecticut microbial ecologist who evaluated mycoremediation efforts in California. "Mushrooms could break these compounds down."

BIO-INSPIRATION

Bioinspired materials aim to use nature to create new materials and inventions. A classic example of bio-inspiration is Velcro, modeled by Swiss engineer George de Mestral after the tiny burrs he found in his dog's fur.

Mechanical engineer Debora Porter's group at the University of California, Merced, was likewise inspired by the interior structure of mushroom caps.

For her bioinspiration, Porter scrutinized the filtration capacity of mushrooms' porous surfaces. She wondered if these porous surfaces could help with an oil spill or be used to filter out heavy metals from contaminated soils.

The first step of the research was to understand mushroom microstructure. Then, she designed bio-templates, or copycats, that behave like mushrooms but can endure conditions mushrooms can't.

"If you need something that can withstand higher temperatures, you can't use mushrooms, as the organic matter can burn up," she explained. "Ditto if you need something that has greater mechanical resistance" or a different shape than a natural mushroom.



COURTESY OF DEBORA PORTER

After mushroom caps have been soaked in TEOS (left), silica particles are left behind in the shape of the mushroom (right) after the organic materials have been burned off.

To create the bio-template, Porter first soaks a mushroom in tetraethyl orthosilicate (TEOS), a colorless liquid with the formula $Si(OC_2H_5)_4$. As the TEOS is absorbed by the mushroom, she explained, the TEOS undergoes a chemical reaction to form a gel. Gels are colloidal solutions in which liquid particles are suspended in a solid medium, such as gel toothpastes. Following the soak, the mushroom is burned away in a furnace. When the mushroom is burned away, the TEOS is converted to silicon dioxide (SiO_2) particles that retain the mushroom's shape. SiO_2 is commonly called silica and is the main component of most sand.

Someone stumbling upon Porter's creations could easily mistake them for mushroom-shaped sugar donuts. "They're just light, delicate, silica mushrooms," Porter said. Though not a product of nature, these silica-based mushroom templates are gentler on the environment than the plastics they're likely to replace.

Watch » Making fabric from mycelium

MUSHROOM-CONTROLLED ROBOTS

One mushroom characteristic that scientists are just beginning to explore is their ability to produce electrical signals similar to nerve impulses in animals. Robotics engineer Dr. Anand Mishra of Cornell University in Ithaca, New York, knew from earlier studies that mushrooms produce signals in response to a variety of inputs including changes in their environment. This responsiveness inspired Mishra to consider using mushrooms to control robots.

"Fungi are good for bio-hybrid robots," he said. "They grow faster than plants and can live in extreme conditions."

His team built two small robots, one resembling a skateboard and the other a sea star. Each included a petri dish connected to electrodes. The researchers inoculated agar medium in the dish with mushroom spores and, five to 20 days later, had enough mycelium to test their robots.

Spontaneous signals from the mycelium were measured and used to control the robots to make them walk and roll. When the researchers exposed the mycelium to ultraviolet light, the robots' gait changed, indicating a response to an environmental change.

Mishra envisions the day robots take away the guesswork farmers face over treating their crops. Changes in soil conditions, he explained, could trigger electrical signals in mycelium-controlled robots. "We could use that information to add fertilizer or pesticides, anything that protects against disease," Mishra said. "This is a very possible application."

MUSHROOM LEATHER

Leather—tanned and chemically treated animal skin—is a popular material used in myriad consumer products such as clothing, furniture and luggage because of its durability and feel. After World War II, a scarcity of leather and an increase in consumer demand for animal-free products led manufacturers to seek synthetic alternatives. Polyurethane leather—a petroleum-based polymer (plastic)—emerged as a popular option and has been mass produced.

As consumers continue to seek plant-based alternatives, mycelium has developed as an alternative to petroleum-based or animal-based leathers. Two companies—Mylo and Mycoworks—have been developing mycelium leathers. Mycelium can grow in sheet pans where thickness and texture can be controlled.

Both companies start by growing mycelium and then pressing it into fabric-like sheets. The leathers produced by mycelium are rigorously tested for flexibility, durability and tensile strength—strength when pulled from both ends. Because mycelium can be grown on any carbon source, mushroom leather has a smaller environmental impact than both animal-based and polyurethane-based synthetic leathers.

CRADLE-TO-CRADLE

From wind turbines to leather clothing, mycelium is finding its way into the spotlight as a replacement for petroleum-based materials. Its strength, durability, small environmental impact and biodegradability make it a cradle-to-cradle product of the future.

"As the world is changing, more people are looking at creating sustainable products and manufacturing methods," said Porter, "and fungi [are being] pushed to the forefront."

Cynthia Washam is a science writer based in Florida.

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Simplifying Science onto a Screen

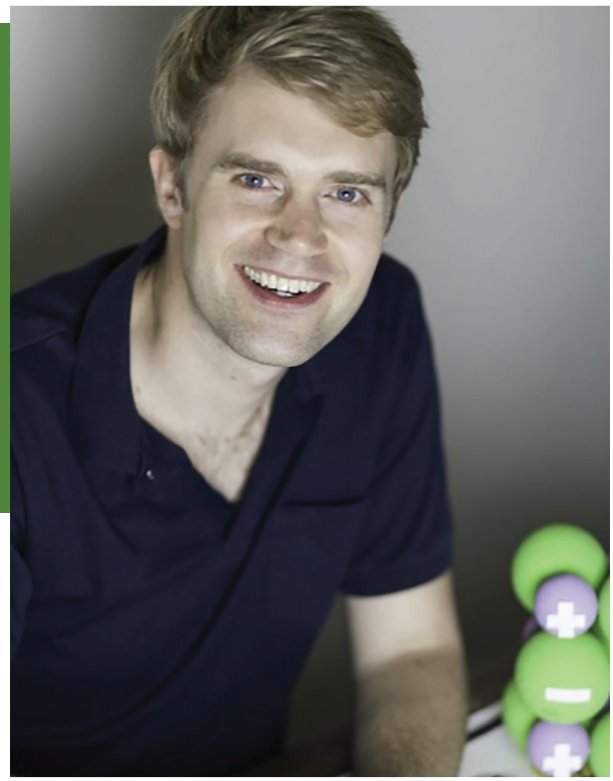
With more than 1.5 million subscribers and over 160 million channel views, it could be said that Tyler DeWitt's videos on YouTube have helped many people understand chemistry in a nontraditional way. He works at the intersection of technology, science and education. Over the years, he's gotten into virtual reality (VR), specifically using it to train people on how to do science in molecular biology labs. At the end of the day, his passion is using technology to help people learn more efficiently.
—Nejra Malanovic and Nandika Nair

This interview was edited for length and clarity.

TYLER DEWITT

EDUCATION
» **B.S.:** Biology, Brown University, Providence, Rhode Island
» **Ph.D.:** Microbiology, Massachusetts Institute of Technology (MIT), Boston, Massachusetts

WHAT HE DOES NOW
Education Creator on YouTube



COURTESY OF TYLER DEWITT

What sparked your interest in biology and chemistry?

My dad was a biochemistry and a professor at Williams College in Williamstown, Massachusetts, for many years. When I was a little kid, he taught me the basics of chemistry and biology. We'd walk through the forest, and he'd explain complicated, overarching concepts in a way that a 5-year-old could understand—how trees were doing photosynthesis, how they were making their own food from the air and using energy from the sun. That got me so interested that all I wanted to do was learn more.

What inspired you to start making educational videos?

Right after college, I got a job teaching at a high school. I would explain a concept, like pH or covalent bonding. During class, the students would learn the material and engage in lively discussions. However, they would come back the next day saying they struggled with these same concepts when they opened the textbook and tried to complete the homework. I decided to make videos of myself teaching and put them on YouTube so my students could go home and recreate that understanding they had in class. Eventually, I went to grad school, but I missed the high school classroom. I started making chemistry videos on all the stuff that I missed teaching. That's when my YouTube channel really took off.

How were you able to develop virtual reality experiences?

If I want to teach somebody how to do something in a lab in VR, I have to get artists to design a 3D lab. It's like designing a world from scratch. You need to plan how the program will respond to either correct decisions or mistakes, such as mixing the wrong chemicals together. You see this virtual world because you're wearing a headset. Then you can use your hands and grab a bottle off the virtual shelf, and the computer knows which bottle you're grabbing. The computer then processes this as either a correct choice or a mistake and provides appropriate feedback.

How has the use of interactive AI-driven virtual models impacted students' understanding of science?

I think it has worsened their understanding of science in every possible way. My concern is that AI is able to do all this technical work for students, which is unfortunate for two reasons. First, because obviously it's not their own work. Second, because I'm not a big believer that even if you could do a 50-step mole conversion by hand, it would be particularly impressive. We should focus more on having students understand the concepts and then successfully apply them.

How is AI and technology changing science education?

I don't think it's changing yet. At this stage, it's making it easier for students to fake doing their work. I haven't seen particularly good examples of science teaching changing too much in response to that yet. I'm going to be really interested to see what the actual responses are when every teacher out there, when every school system out there, realizes that any written work a student comes to class with may have been generated by AI.

What does the process look like for creating your videos?

I start by asking myself many questions as I prepare. What are the things that a first-time student is going to be confused about? How do I want to break this down in a way that introduces them to the topic? I consult textbooks, but then I do the exact opposite of what a textbook will do. I think about how to rearrange the information in a different way and how to present it in a different way. If I'm doing a digital video, I'll start putting them together in a graphic design program. A written script ensures that the information is as crystal clear as possible.

What advice would you give high school students?

When I was in high school, how you did academically was seen as so important. Over the years, I've learned that what matters more is having a strong work ethic and having something you're genuinely interested in that you stick with, and you get a little bit better at every day.

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