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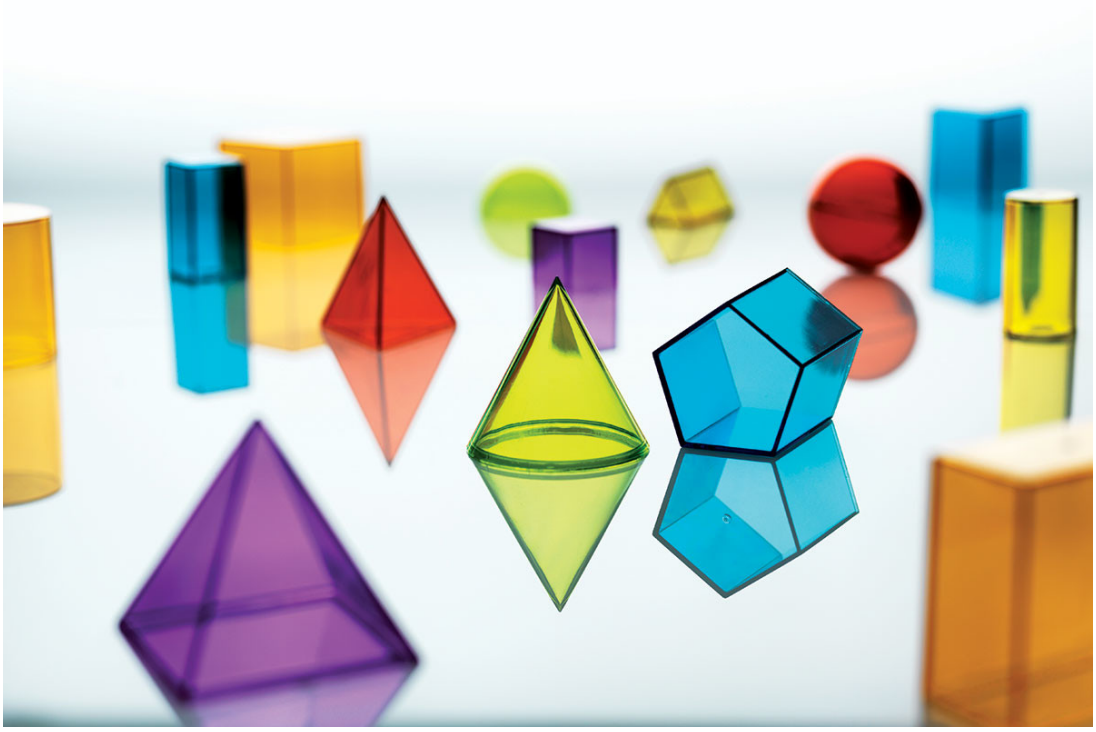
Plastic fantastic: The quest to create the smartest materials

Plastics transformed life in the 20th century, but we're still amateurs at making them. Can we create another polymer revolution by mimicking nature?



Making plastic fantastic
Andrew Brookes/Getty

IT IS so ubiquitous that we hardly notice it, even when it is right in front of our eyes. We use it to wrap food, make toys, build cars – and yes, these days even the contact lenses and "glasses" that enhance our vision are made from it. We are talking about plastics, of course – materials that, through their seemingly limitless morphing of forms and function, have shaped the past century.

But here's a secret. Despite the panopoly of plastics we produce, we are still rank amateurs compared with the machinery that churns out very similar stuff right under our noses – throughout our bodies, to be precise. Learn to replicate nature's material-weaving tricks, as we are just beginning to do, and we would usher in a whole different gamut of materials that will shape the next century.

What we call a plastic a chemist will probably know as a polymer. The basic idea is simple. Take a molecule with two reactive ends – a monomer in chemists' parlance – and mix lots of them together. They react to form a long string, like carriages coupling in a train.

Before the first synthetic polymers appeared, most everyday objects were made directly from natural materials such as wood, stone and metal. The first proper plastic was a self-styled wonder material called Bakelite, patented in 1909. Based on monomers of formaldehyde, it could be moulded into shape while hot, then resolutely hold the shape. Over time, we duly made Bakelite TVs, jewellery, telephones and even caravans.

Vary the chemical identity of the monomer and the length of the chains, and you can create a raft of other polymers with widely varying properties. Polymers using a range of monomers largely isolated from crude oil went on to colonise the world. Think nylon shirts, polythene plastic bags, Gore-Tex waterproof coats, plastic electronics and Kevlar bulletproof vests.

But that is truly nothing compared with the polymer frenzy biology whips up. Nature's monomers are amino acids,

which it uses to make proteins. These are polymers right enough, but with a crucial difference. Nature creates an incomparable diversity of proteins not by switching monomers for each and every application, but by controlling the precise order in which a set of different monomers link up. The result is everything from fingernails to tendons to digestive enzymes – all made from a palette of just 21 amino acids, stitched together in different orders and running to different lengths.

It is this peerless "sequence control" that we would dearly love to master, to power a second polymer revolution. That would allow us to place particular groups of atoms anywhere we fancy within a polymer string. Unfortunately, we can't use amino acids outside the wet and warm environment of cells. But we might create robust, chemically complementary monomers that are attracted to one another. They would force the polymers to fold into different origami forms with different characteristics: super-light and strong materials for aircraft wings, say, or materials perfectly shaped to grab hold of and quench the toxins from bacteria. With sequence control perfected, the possibilities would be nigh unlimited.

> **"DNA is touted as a wonder information storage material, but we could do better if we start from scratch"**

If only it were that easy. "You can't just mix all the different monomers in a bag and say 'go'. You just end up with a bunch of random sequences," says Ronald Zuckermann, a materials chemist at the Lawrence Berkeley National Laboratory in California.

Over the years, chemists have learned to hitch one molecule to another in almost any way they like, but every connection – and a polymer might have thousands – requires careful, pure reactions that take many hours. Perhaps the closest we have come so far to nature's mastery is the block copolymer. These are a bit like a train made from six blue carriages followed by six red ones. That's how the elastic polymer Lycra looks (see "Perfect polymers").

Now, however, Zuckermann and others are beginning to close the divide between biological and artificial polymers. "We are certainly hiking off the trail," says Zuckermann. "But there's another valley on the other side where there are fruits that nobody has picked." Will Gutekunst and Craig Hawker at the University of California, Santa Barbara, are two other intrepid hikers. Last year they developed a way of building circular "super monomers" that already have a sequence of chemical units built into them before polymerisation. Gutekunst can change the sequence of the units they contain far more easily than has been possible before. Instead of relying on the ring's inherent properties he uses an external chemical trigger to start the polymerisation. Gutekunst reckons the preprogrammed monomers should enable him to make a huge assortment of new sequence-controlled polymers, including biodegradable varieties which he hopes to use as envelopes to carry drugs to specific places in the body.

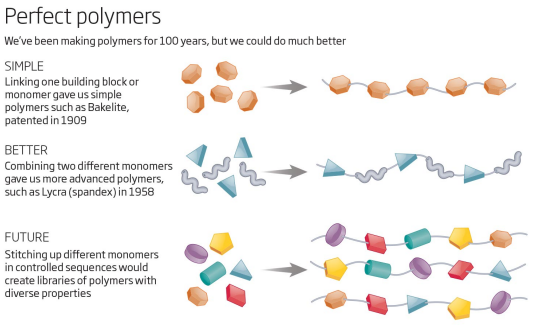
The method is not perfect though. "Although those polymers have defined sequences, they don't have defined lengths," says chemist Jeremiah Johnson of the Massachusetts Institute of Technology. When nature churns out a protein, it's always the same length, which produces the same sequence and ensures the protein folds up into the same shape and so functions properly. With artificial polymers, many chains grow simultaneously in the flask, some ending up longer than others. That limits the amount of control over the material and its function.

Johnson has an alternative strategy known as iterative exponential growth that works by running several reactions in parallel. For instance, in one flask you put monomers A and B together, while in another you link up monomers C and D. Then, half of each flask would be poured into the other to make ABCD in both, then halved and switched again to make ABCDABCD. This allows a polymer chain to precisely double in length with every reaction cycle.

The sequences are still limited to repetitions. But Johnson has constructed a flow reactor that continuously runs these sequential additions and rapidly produces tens of grams of material, mountains in his line of work. That's handy: it allows him to test how simple sequence changes alter the polymer's real-world properties.

Order, order!

"We don't even know how the mechanical properties of a polymer change if we go from one sequence to another: would it be stretchy, would it be soft or hard?" says Johnson. No one else has ever made enough of a sequence-controlled polymer this way to answer such questions. So far, Johnson has found that even tiny tweaks, switching from say an ABAB pattern to AABB, can change the temperature at which the material goes from stiff to rubbery by 10 °C. "That is a huge change for such a subtle structural difference," he says.



But is all this a case of reinventing the wheel? Our cells contain deft machines called ribosomes that stitch amino acids together in the correct order within seconds. Another strategy, then, might be to copy nature and build an artificial ribosome to create polymers. That's the approach favoured by David Leigh, who develops molecular machines at the University of Manchester, UK. "It's the ultimate in miniaturisation," he says.

In 2013, Leigh's team unveiled a first stab at a synthetic ribosome, a nanosized molecular ring programmed to move down a track picking up building blocks and stringing them together. It was limited to a three-monomer chain and worked desperately slowly. But Leigh is refining the design. In December he reported a molecular robotic arm that can swivel to pick up and put down building blocks, although not yet in specific locations. His aim is to combine several different machines into a sort of molecular assembly line.

That is an incredible challenge. But it might be possible to build a drastically stripped-down version of the machine, perhaps even borrowing some components from nature. DNA is the instruction manual that ribosomes use for making proteins and it is this that Rachel O'Reilly of Warwick University, UK, is repurposing as a direct template for polymerisation. Her idea is to loosely attach several different monomers to a snippet of DNA a few base pairs long. That snippet acts like a shunting engine, pushing the monomer to a specific place on a second, longer strand of DNA that preordains the sequence. The monomers then link up and the template is removed.

With this method, O'Reilly recently concocted several polymers with different sequences simultaneously in one pot. This is a stepping stone to her goal of creating huge libraries of sequenced polymers, so you could select the right one for a particular job, such as grabbing hold of a particular molecule. "Imagine if you could make synthetic polymers that replicate or evolve," says O'Reilly. We can already artificially evolve sequences of amino acids to slot perfectly into enzymes to generate medicinal effects. With synthetic polymers, you could add unnatural chemical groups, raising the bar of what is possible. After all, a gradual process of evolution is how nature managed to perfect its polymers.

Of course O'Reilly's work is predicated on being able to make the DNA templates, and DNA is itself a sequence-controlled polymer. In the 1950s, biologists started working on machines that would automatically synthesise DNA; today it is routine. It involves adding what are called "protected" monomers, individual DNA monomers that are chemically capped so that when you add them to the growing chain no further monomers can be added. Those monomers are then "de-protected" so another protected monomer of your choice can be added. Lengths of DNA can be synthesised easily, if slowly, in this way.

Developing a similar stepwise method for making artificial polymers is the ultimate homage to nature. However, perfecting a way to protect and de-protect the monomer's sticky ends while not disturbing the rest of the polymer has been tough.

But it's not impossible. Back in 1992, Zuckermann began experimenting with a method for making a synthetic polymer called a "peptoid", a similar beast to a protein but with small chemical differences that make it more robust outside cells. He altered the monomers so that they could be added to the chain but only permit further growth with the right chemical go-ahead.

Memory strings

After decades of using this method to make different sequences, Zuckermann has peptoids that fold into sheets. He can pepper these with an array of different chemistries, making them useful sensors. He says he is now working with the US Department of Defense on an early warning system for chemical weapons. "We need systems that are dynamic and versatile like proteins, but that can survive rugged environments," he says. "We envisage a patch worn on military uniforms containing maybe a million different nano-sheets that could react with any given toxic threat, like a synthetic immune system."

Many chemists envisage this future for sequence-specific polymers: not as commodities like polythene, but as

tailored materials for specialised applications. But others have a totally different endgame in mind – one that's a shade closer to reality, even though it hasn't been fully realised.

Enter Jean-François Lutz, a chemist at the Charles Sadron Institute in Strasbourg, France. He sees sequence control as a way to mimic nature's ability to store information.

Researchers have been touting DNA as a wonder information storage material for decades. After all, it could theoretically store all the information held by the world's major tech companies in a blob the size of a USB stick. Unlike a memory stick though, DNA would preserve the data for hundreds of thousands of years, if kept in the correct conditions. But there is a catch. DNA is both fragile and tricky to read and write outside a cell.

Why not start from scratch and create a better coded polymer? That is just what Lutz is up to. He has applied a set of fast, no-fuss chemical reactions – called "click chemistry" because they work so well – to polymer synthesis. He uses just two types of monomer, which act as the 0 and 1 of binary code. The result is a process that works in a similar way to automatic DNA synthesis, except it takes just minutes to attach each monomer.

Last year, Lutz used the approach to make a perfectly sequence-defined chain 100 monomers long, in less than 12 hours. "This is a very, very short time on the lab scale," he says. He reckons linking one monomer per second is achievable. It is also possible to read out the information stored in the polymers using a mass spectrometer, a device that detects the different masses of the monomers. Lutz says he is also combining his chemistry with Leigh's machine. Already, he has produced longer chains than the synthetic ribosome can make on its own.

A rewritable chemical memory device is the ultimate goal, but Lutz has already been discussing a more immediate use for his coded matter. You could embed it into the fibres of expensive products to act as the ultimate incognito barcode, he says. Drugs, which are subject to major counterfeiting, as well as money and luxury clothing would be candidates. "You would use a tiny amount and disperse it in another polymer to be like a little label," he says. "It would be hard to find without knowing the specific sequence."

You might think we already have enough polymers to be going on with. But if Lutz and his colleagues are right, there will soon be many more. Prepare for the second polymer revolution.

Explore how polymers shaped life and fashions in the 20th century:

This article appeared in print under the headline "Chasing rainbows"