

Materials innovation from quantum to global

Twentieth-century utopian visions of a space-age future have been eclipsed by dystopian fears of climate change and environmental degradation. Avoiding such grim forecasts depends on materials innovation and our ability to predict and plan not only their behaviour but also their sustainable manufacture, use and recyclability.

Philip Ball

In the long run, what we make will survive and define us. Our modern material culture already marks a dislocation from the past so profound that it will leave a distinct and abrupt imprint of the Anthropocene in geological strata¹. Here, all the wondrous new materials reported daily in the literature will be lost to posterity, and what remains will be the crudest, most widespread and most telling physical components of modernity: plastics, metal alloys, glass and the modified geological materials of construction, along with human-made radionuclides and the signals of our massive and ongoing perturbations of natural biogeochemical cycles. Sometimes only such a long view can wake us up to our present state.

But those advanced materials invisible to deep time might nonetheless indirectly define this stratigraphic signature. How significantly human activities will transform the global environment — and the geological signal it bequeaths — may depend on our ability, within the next blink of geological time, to innovate away from ecological catastrophe.

This is a strikingly different perspective on the materials future than that offered in the early twentieth century, when materials innovations such as synthetic plastics would be routinely presented at celebratory world fairs as harbingers of a utopian future. The Century 21 exposition in Seattle 60 years ago offered a perfect illustration of this optimistic vision, with its Space Needle pointing up towards the stars. General Motors unveiled its Firebird III automobile at the event, styled like a spacecraft with cockpits and a lightweight fibreglass body. Of course, Cold War anxieties lurked behind such a display of technological pre-eminence, but it should be noted how much more explicit and discomfiting the tensions are today in the widely reported images of an actual car (the Tesla Roadster) launched into space in 2018 on Elon Musk's SpaceX Falcon Heavy rocket: a perfect illustration of how efforts to assuage the climate crisis via electric vehicles collide with profligate, wasteful consumerism.

That very contradiction makes this latter image — a bright red state-of-the-art prestige vehicle framed against the backdrop of planet Earth — so iconic, albeit not in the way its creators intended. “People want everything,” writes US novelist Richard Powers in *Gain* (1998). “That’s their problem.” You can relate the trajectory of materials science over the past several decades in ways that tell very different stories. For instance, one might focus on the trend towards greener, less polluting and more sustainable technologies. Or you can tell it as a march towards stronger, tougher and more versatile materials that enable herculean feats, such as the launch of the Tesla Roadster into space and far bolder plans to reach and colonize other worlds. You can view it through the lens of information technologies, sustained by innovations in microelectronic and optical materials, that have radically transformed lives and societies (not always for the better). Biomedical materials, including the ability to shape and engineer living tissue, offer new possibilities in healthcare but also push against the boundaries of the human. Adaptive and self-repairing materials promise to reinvent what cities can be, in an age when urban living has become the dominant mode for humankind. All of these cutting-edge technologies have complex and uncertain implications for society, culture and governance. All coexist with continued global poverty, disease and inequality. All raise questions about the covenant between research and development and the societies that sustain them.

Materials innovation, arguably even more than biomedicine, confronts the research community with questions about how to set goals, how to regulate science, how innovation interacts with commercialism, and how far ethics can and should shape the questions we ask. But increasingly, materials science also shows how inextricably and dynamically applied science interacts with fundamental questions. To take one example, studies of quantum materials have revealed how new experimental possibilities stimulate new questions, such as whether we can engineer

(quasi)particles that the laws of nature permit and yet nature itself does not seem to realize — bringing materials science in unexpected proximity to theoretical questions previously adduced in particle physics. Meanwhile, the development of biomedical materials, increasingly reliant on tissue engineering, confronts deep questions about how life works at scales from molecules to cells to organs. No one can accuse the field of having narrow horizons fixated on practical use.

This brief and somewhat anecdotal survey of the materials landscape is, then, best seen within this wider context in which innovation becomes as much a source of as a solution to profound questions about both the physical world and society. The task of materials science is no longer to deliver a utopian future, but to reach an accommodation with the present by harnessing curiosity and ingenuity to create a palette of sustainable possibilities.

Quantum promise

The materials universe has been found over the past several decades to be much vaster and more subtly structured than our everyday experience might suggest. The classical phases — solids, liquids, gases and perhaps liquid crystals, plasmas and gels — are outnumbered by the menagerie of phases that appear when low temperatures make quantum effects more salient. Until the 1980s, the quantum phenomena of superconductivity and superfluidity were regarded as exotic anomalies. Effects such as the quantum Hall effect and materials such as ‘heavy electron’ systems, in which strong quantum correlations increase the effective electron mass, added to the appreciation that these interactions can elicit quasiparticle behaviours with unfamiliar electronic and magnetic properties. But the diversity of quantum quasiparticles and their associated phases — spin glasses and spin liquids, topological insulators, Weyl and Dirac semimetals, strange metals, and more — shows no sign of yet being exhausted. Attention is now turning from the question of what phases the laws of quantum physics permit to the challenge

of turning discovery into engineering: creating quasiparticles to order with properties that might prove useful². This union of fundamental physics and practical materials science has produced one of the most fertile arenas in the contemporary physical sciences. Not only is it a playground for finding and exploring new physics, but also there could be practical benefits in the form of novel electronic devices and fresh opportunities for exploiting quantum effects in information technologies.

Superconductivity established the paradigm for quantum materials by demonstrating how correlations between electrons give rise to quasiparticles — in that case the Cooper pairs that appear in the Bardeen–Cooper–Schrieffer theory (1957) of conventional superconductivity — which show different quantum statistics from electrons themselves. Meanwhile, the quantum Hall effect arises from quantized electron states that occupy localized looping orbits, instigated by the topological properties of the electronic band structure. Both here and in the high-temperature cuprate superconductors discovered in the mid-1980s, the electronic behaviour depends crucially on the two-dimensional (2D) nature of the material, highlighting dimensionality as a key feature of these quantum systems. In the fractional quantum Hall effect, a 2D electron gas condenses into quasiparticle states with just a fraction of the electron charge.

Reduced dimensionality, the interaction of electronic and magnetic properties, the importance of electron correlations and quasiparticle descriptions, and the topology of the band structure are the characteristic determinants of much of the behaviour of quantum materials. As Tokura points out in this issue, many of these exotic properties ultimately stem from broken symmetries in time and space³.

New particles from materials

One of the most intensively studied quantum materials of recent years is graphene: 2D sheets of graphitic carbon produced, for example, by exfoliation of graphite itself⁴. While the mechanical and structural properties of graphene connect it both to the long tradition of research in graphitic carbon composites and to research in the 1980s and 1990s on low-dimensional carbon allotropes such as fullerenes and carbon nanotubes, with potential application as a high-strength, conducting and ultralight material, graphene also serves as a model system for exploring fundamental physics.

It was long predicted to be a gapless semiconductor, having a full valence band and empty conduction band separated

by a bandgap that falls to zero at certain values of electron momentum where the conical peaks of the valence band and depressions of the conduction band touch. This electronic structure ushers the mobile electrons into quasiparticles with zero effective mass, allowing them to achieve high speeds and mobility, suitable for use in high-frequency electronics. Such ‘relativistic’ quasiparticles are known as Dirac fermions, and in graphene they constitute a 2D Fermi semimetal. Such behaviour can also be displayed in three dimensions, as has been predicted in materials such as Na₃Bi and Cd₃As₂. Here the Dirac fermions are ‘topologically protected’ by the shape of the band structure.

Dirac fermions can be considered to be composed of two chiral quasiparticles of opposite chirality, called Weyl fermions, which have been observed experimentally in Weyl semimetals⁵. Particles with these properties were first predicted in the 1960s to explain aspects of pion decay — just one of many examples of how quantum materials create a bridge between condensed-matter and high-energy physics. Another such bridge is created by the topological particles called skyrmions, again predicted decades ago in particle physics and now realized as vortex-like excitations in magnetic materials⁶. Anyons, predicted to display properties intermediate between fermions (with half-integer spin) and bosons (with integer spin), are now sought in the magnetic materials called quantum spin liquids: for example, α -RuCl₃, which has a layered quasi-2D hexagonal structure, and geometrically frustrated triangular-lattice materials including ZnCu₃(OH)₆Cl₂, Ca₁₀Cr₇O₂₈ and YbMgGaO₄. Additionally, Majorana particles (purported to be their own antiparticle) are being realized in quasiparticle form in zero-dimensional systems, such as the ends of semiconducting (InSb, InAs) nanowires coupled to superconductors in the presence of a magnetic field. They might be used to create quantum bits for quantum computing that are topologically protected against errors and thereby permit error-free quantum computing. Obtaining definitive proof of such quasiparticles has proved challenging⁷, however, in part because the space of possibilities in such quantum materials is so richly structured that it is hard to adduce a set of signature criteria that does not overlap with those of other quasiparticles.

A further indication of the fecundity of materials systems dominated by quantum effects is the diversity of new behaviours elicited by the simple expedient of bringing one sheet of graphene into proximity with another so that they may interact

electronically. Their properties may then depend on the relative orientation of the two: that is, on the twist angle between the two sheets of hexagonal carbon. Features in the electronic structure known as Van Hove singularities, where the density of electronic states diverges, may generate spectroscopic peaks that vanish at a small relative twist angle of around 1.16° (ref. ⁸). At this ‘magic angle’, the velocity of electrons at the Fermi level goes to zero and it is as easy for the electrons to move through one graphene layer as it is for them to tunnel to the other layer. The dependence of electronic behaviour on the angle-dependent commensuration of lattices earns these structures the label moiré phases, after the familiar moiré optical effect in superposed grids.

The electronic properties of such ‘magic-angle twisted bilayer graphene’ are exquisitely tunable, with the experimentally controllable twist angle acting as a ‘knob’ for dialling in new physics. These systems have narrow electronic bands (meaning the electrons have little kinetic energy) and hence the repulsive interaction energy between electrons plays a dominant role — creating many possible many-body ground states that can exhibit, for example, superconductivity, correlated insulator behaviour and magnetic phases⁹. They are a model system for exploring physics related to, for example, the fractional quantum Hall effect and high-temperature superconductivity. The possibilities have now been expanded by producing similar moiré effects in other 2D systems, such as layered transition-metal dichalcogenides, as well as exploring hetero-bilayers and trilayer graphene. Applications are not irrelevant (for example, in spintronics), but would be a bonus beyond this rich fundamental physics.

Energy and light

Among the applications mooted for graphene and layered dichalcogenides are energy technologies such as photovoltaics and battery electrode materials, since both materials may act as versatile intercalator of ions. This is a long-recognized property of layered materials in general: the propensity of clays to absorb water and intercalate ions was explored in the nineteenth century. The term ‘intercalation compounds’ was introduced in the 1950s, and the possibility of using intercalation to produce exotic electronic behaviour was illustrated by the discovery in 1970 that intercalation could boost the superconducting transition of TaS₂ (ref. ¹⁰). That heralded two decades of intense research on layered compounds, including the discovery of alkali-metal ion intercalation in dichalcogenides in 1974¹¹. The oil crisis of the 1970s prompted

interest in whether such discoveries might be used for energy storage, and during that decade Whittingham and others developed the concept of the rechargeable lithium-ion battery based on layered metal oxides and dichalcogenides¹². Such devices took another two decades to acquire sufficient power densities and stabilities to be commercially viable, based now on intercalation of lithium in graphitic carbon at the cathode and Li_xCoO_2 (sometimes with partial substitution of Co by Ni or Mn) at the anode¹³. Here, then, is an example of a materials technology motivated by one crisis that has flourished because of its potential to address another.

Other key energy technologies reliant on materials innovation include the development of supercapacitive storage devices¹⁴, photovoltaics, thermo-electrics and organic materials with lower power consumption¹⁵. After many years of reliance on silicon-based solar cells (with some competition from more efficient but more expensive semiconductors such as cadmium telluride), organic materials now offer competitive power conversion efficiencies of almost 20% (ref. ¹⁵). One of the most promising new materials systems for photovoltaics are inorganic perovskite materials (with the generic formula ABX_3), which are robust and relatively cheap. These too are 'old' materials now recognized to have new uses, and in the laboratory their light-harvesting efficiency can rival that of the best (single-crystal) silicon devices¹⁶. As ever, the challenge is to scale-up the technology without significantly compromising performance. Prototype large modular photovoltaic panels using perovskites have attained respectable efficiencies of around 10%, but some manufacturers are aiming for commercial devices with three times that figure — which would substantially outperform silicon panels. Other challenges include the long-term stability of the compounds and the toxicity of lead, which most of these photovoltaic perovskites currently include.

Central to the development of improved photovoltaic and light-emitting materials is better understanding and control of the interactions of light and matter. Those considerations are vital too for photonic information technologies, for which the use of optics in chip-based devices could enhance speed and provide easy access to quantum-based processing¹⁷. The ability to confine, direct and modulate light at the nanoscale is opening up new applications of photonics ranging from sensing to tomographic and subwavelength imaging and optical probing of neuronal networks¹⁸.

Help from artificial intelligence

As battery technologies exemplify, optimizing a material formulation for applications is a complicated balance, involving considerations of performance, stability, cost, manufacturability, availability, toxicity and sustainability. The choices are too vast, and the costs and benefits too nuanced and multifactorial, for theories or even heuristics to provide a reliable guide. Battery materials are just one field that has become increasingly reliant on artificial intelligence (AI), especially machine learning (ML), to explore the possibilities. Sometimes it is the sheer complexity of the materials themselves that confounds the application of intuition and heuristics — a case in point being the high-entropy alloys typically composed of five or more elements and stabilized by configurational entropy¹⁹.

There are, in general, two approaches to using ML to guide materials discovery. In supervised learning, one assumes that certain parameters matter most for the property of interest: the valence states or atomic radii of the constituent atoms, say. Then the algorithm searches the database of known materials for some functional relationship between these inputs and the target behaviour. Once this relationship has been refined to the required degree of fidelity, it can be used to make predictions. The approach draws on both the exhaustive number-crunching power of the algorithm and expert human intuition about what to look for and which parameters matter most in determining it. In contrast, unsupervised learning leaves the machine free, so to speak, to make its own choices: to seek for composition–property correlations in the dataset without prejudice. This may sometimes be the best choice when considering complex materials formulations for which chemical intuition is a poor guide.

A search for new materials based solely on empirical correlations between composition and useful properties is sometimes regarded as a blind brute-force alternative to discovery informed by fundamental theory — for example, first-principles quantum calculations of electronic structure using density-functional theory. But that distinction is becoming ever less clear. Conducting quantum calculations that are sufficiently simple to be tractable yet sufficiently realistic to yield meaningful predictions has been notoriously challenging. But the computational crystal ball may be clarified by using ML — for example, to predict the results of density-functional calculations — without having to run the full calculations²⁰. It is reasonable also to expect quantum computations of materials properties to

be usefully assisted within the next decade by the advent of large-scale quantum computing: the objective that motivated Feynman's original proposal for this type of computing in 1981. The quantum circuits predicted by some road maps for the early 2030s contain several thousand qubits: adequate for realistic quantum simulation of many-atom systems.

What is more, ML methods can supply reliable predictions of crystal structures²¹, which are again difficult to predict from first principles but may be central to properties. And while there is a gulf between identifying a promising material candidate and finding a way to synthesize it, algorithms can now help with that too, mining the literature for potential synthetic methods and even being used to formulate hypotheses and test them by designing and iteratively refining experimental procedures²². One important issue to which ML has not yet been much applied is multiscale materials modelling: the need to develop joined-up methods for predicting behaviour over a wide range of scales in space and time. Designing materials from first principles is, after all, not just about crystal structures but also, say, grain boundaries and dislocation networks, or (particularly in soft matter) non-equilibrium dynamics.

AI can, then, assist in principle with all the steps in materials discovery. This raises the prospect of completely automating that process, perhaps in conjunction with robotics platforms for conducting experiments. But there is a widespread view that human intuition may still be needed to keep the process on track, preventing it from spinning off into the eccentric or nonsensical outcomes to which ML is still vulnerable. AI initiatives in materials discovery are likely to remain human–machine collaborations: the materials scientist will not become obsolete any time soon.

Moreover, the quality of the outcomes is vitally dependent on the quality and extent of the training dataset: ML is typically good at interpolating within that set (provided that properties change continuously), but not at extrapolating beyond it. The estimated 200,000–500,000 known inorganic materials still sample a mere fraction of materials space, and often the data in the literature are not in a form that can be easily collated and mined in standardized databases. Moreover, it may be skewed by the tendency to only publish positive rather than negative results — we have a reasonable picture of what works, but not what doesn't. The ultimate goal is to speed up materials discovery: the Materials Genome Initiative launched in 2011 and supported by the US Departments of Energy, Defense, Commerce and others,

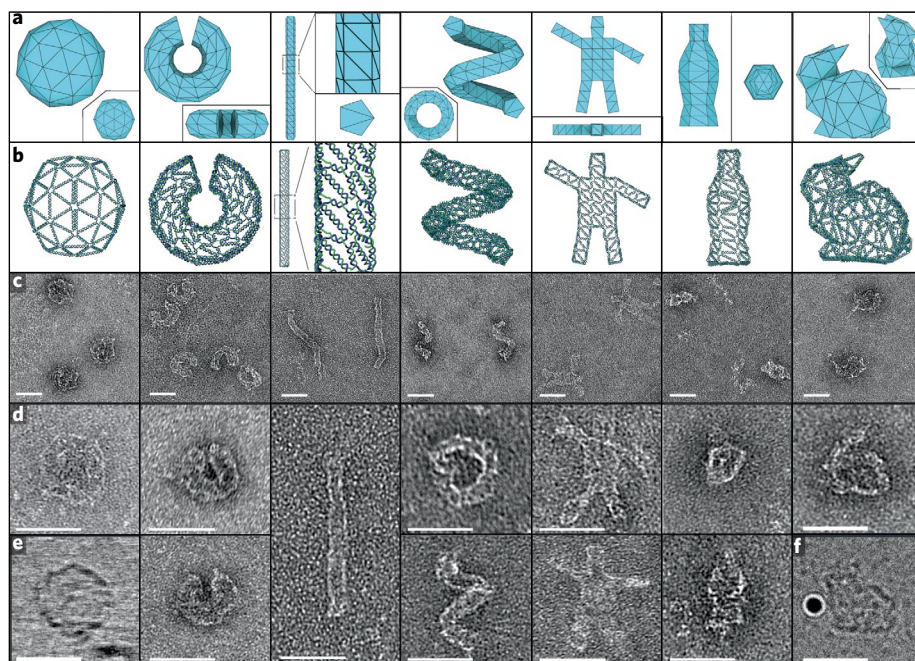


Fig. 1 | Three-dimensional meshes rendered in DNA. **a**, Computational designs. **b**, The corresponding DNA designs, with scaffolds in green and the ‘staples’ holding them together in blue. **c–e**, Electron micrographs of the structures at different magnification. Scale bars, 50 nm. Figure reproduced with permission from ref. ³⁰, Springer Nature Ltd.

aims to “discover, manufacture, and deploy advanced materials twice as fast, at a fraction of the cost”.

Designed self-assembly

ML might be considered to have added a third vertex to the traditional polarity of rational design versus trial-and-error experimentation: to have created a way to design materials that does not demand explicit, first-principles knowledge of how the components will assemble. That goal of rational design was barely much more than an aspiration in the mid-1990s when, for example, simple heuristics about molecular size could guide the formation of mesoporous solids templated by the self-assembly of surfactant micelles²³. At that time, the idea that molecular components might be assembled in a similar way to Lego blocks, for example, by metal–organic coordination chemistry, was just beginning to germinate²⁴. Today, such designed metal–organic frameworks have become mainstream, and are robust enough to function as selective catalysts, filters and gas storage media²⁵. Control of these porous frameworks is now possible over a hierarchy of length scales, leading to the production of complex superstructures, modular multifunctional arrays, and nested ‘crystals within crystals’²⁶.

The goal of using supramolecular chemistry to create what Lehn foresaw in 1995 as informed matter²⁷ that self-assembles to a design is brought still closer by DNA nanotechnology, where DNA strands are programmed for hybridization via their complementary sequences. The synthesis of 3D DNA structures to order was pioneered by Seeman’s use of strand-crossover Holliday junctions as the vertices of frameworks²⁸ to make sheets and 3D solids. Rothemund, meanwhile, used hairpin turns to produce complex ‘origami’ folding patterns that can be programmed to fold into arbitrary tiles²⁹ — an approach now also extended to making arbitrary 3D mesh-like folds and shapes³⁰ (Fig. 1). Here, again, the complexity of the design space is too great to be navigated with chemical intuition alone — computational assistance is needed. Such structures may incorporate mechanical actuators such as molecular motors that allow for controllable and predictable shape changes, and can be programmed to enact computational processes. They are intrinsically biocompatible and may be functionalized with proteins for making materials capable of enzymatic catalysis, binding of specific target molecules, or other biological functions³¹.

Technologies of living substance

Biomedical materials science two decades ago focused on the development of synthetic materials and devices that were compatible with the body while being typically either corrosion-resistant or biodegradable. Although such objectives remain for applications such as drug delivery and prosthesis, today the distinction between biomaterials, tissue engineering and developmental biology is barely visible. We can reasonably claim that the vision of physiologist Jacques Loeb in 1912 of a ‘technology of living substance’ has come to pass: engineering principles of design are being applied to living cells and tissues. The feasibility of such a field owes most to advances in biology itself: to elucidation of the rules by which cells assemble, collaborate and differentiate into structures with specific morphologies and physiological functions. Organoid technologies, in which stem cells are guided towards differentiating and organizing into organ-like structures in vitro, have revealed that cells are at the same time imbued with collective morphological potential and able to adapt plastically and responsively to non-natural circumstances³². The ability to reprogram both stem and somatic cells into new states with specific self-organizing capabilities has not only expanded the possibilities for making novel living structures, but also created the potential to grow them from a patient’s own cells, eliminating problems of immune rejection for transplants.

All the same, there is still a highly incomplete understanding of the rules that govern the spontaneous emergence of a multicellular form in biology: a complex process that involves two-way interactions between shape and cell state, mediated but not necessarily specified by gene activity. The substantial achievements in synthetic biology, which themselves have great potential for materials engineering (for example, by providing bacterial sources of non-natural feedstocks for chemical processing), have been largely limited to single-celled organisms. To harness the abilities of cells to grow into complex structures — composed of the same living fabrics as the body but not necessarily mirroring them — we need to know more about the morphological rules of development and tissue growth. The goal now is to use those principles to make so-called multicellular engineered living systems³³, a field sometimes called synthetic morphology (Fig. 2). Some of these efforts will involve a collaboration of the biological and the synthetic, for example by using 3D printing methods³⁴ or biological scaffolds made from extracellular matrix to guide,

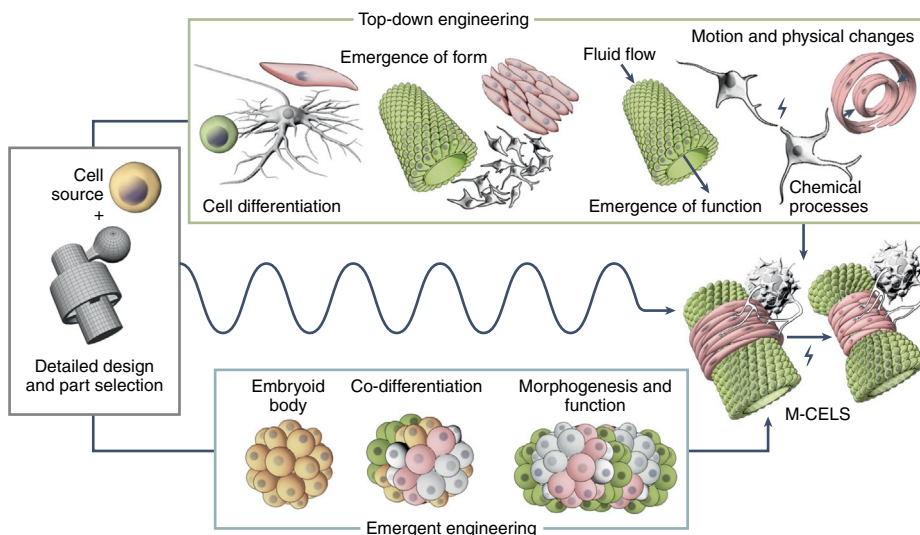


Fig. 2 | Alternative strategies for making multicellular engineered living systems (M-CELS). Here, as an example, is shown a tube-and-sleeve valve. These structures might be scaffolded into predetermined shapes and then assembled (top). Alternatively, the principles governing the morphogenesis of tissues might be harnessed and programmed to enable cells to organize spontaneously into the target shapes (bottom). Figure reproduced from ref. ³³, under a Creative Commons licence CC BY 4.0 (<https://creativecommons.org/licenses/by/4.0/>).

but not rigidly to control, cell and tissue growth. Here, advances in understanding soft matter are supplying new and improved ways of engineering active interfaces between the synthetic and the biological³⁵, and many bioactive and biomimetic materials systems are now hybrids of the two³⁶.

Efforts to engineer tissue growth have stimulated interest in the materials properties of natural tissues: the folding and flexing of sheets of cells, say, which give rise to the emergent meso- and macroscale shapes of organs and organisms. An understanding of such processes is rendered challenging by the two-way feedback whereby macroscale shape may (perhaps via mechanosensory cell signalling) alter the epigenetic state of the cells that constitute the building blocks. This hierarchical sensitivity to circumstances is just one of the aspects that might be usefully incorporated into wholly synthetic systems with some of the characteristics of living matter, which some have dubbed animate materials³⁷. Among the objectives for such systems are self-repair, adaptive growth, harnessing of environmental energy sources and self-recycling. Some current self-repairing materials seal damage via a vascular-like system of channels connected to reservoirs of adhesive; others employ polymerization of molecular self-assembly based on weak bonds that can ‘heal’ after disruption. Such capabilities are currently rudimentary and limited in their cyclability;

an ultimate goal would be to produce buildings, roads and perhaps even electronic devices that will autonomously repair themselves in a sustainable manner. At the same time, materials may blur the interface between the natural and the artificial. Flexible, biodegradable electronics³⁸ can be printed directly onto fabrics or skin, offering functionality (such as biomedical monitoring) that is cheap, conformable and unobtrusive.

Problems of sources and resources

Some of the motivation for these developments in bio-inspired and bio-friendly materials engineering is environmental: the reduction of waste and efficient use of resources, the elimination of toxic degradation products and the use of green feedstocks that minimize greenhouse gas emissions. It has become ever more clear that ‘retrofitting’ materials processing with sustainable innovations such as green solvents or carbon-capture technologies is cumbersome, expensive and inefficient; materials use and design needs to be wholly integrated into such environmentally considerate processing from the outset.


Such accounting needs to dig deep, including the carbon costs of materials extraction and transportation. Some of these costs may be hidden by the way advanced economies tend to outsource production: around two-fifths of raw materials globally

are extracted just to enable the export of goods and services around the world. A more accurate measure of materials consumption is arguably the material footprint³⁹, which takes into account all the embodied materials use in a given product. Developed countries may look greener when scrutinized solely on the basis of national materials use but, in general, economic growth does not truly reduce the carbon footprint via improvements in manufacturing or recycling efficiency. Overall, materials consumption per capita grows as wealth does: a 10% increase in gross domestic product entails, on average, a 6% growth in materials footprint.

We cannot take our materials resources for granted. A study in 2013⁴⁰ found that, for 12 of 62 different metals and metalloids currently in use, substitutes are either inadequate or non-existent. Although scarcity of important materials is nothing new, today the market is more global and thus more susceptible to the vagaries of international geopolitics — just as the Russian invasion of Ukraine has demonstrated for energy resources. Additionally, the complexity of materials usage has increased, lengthening the roster of critical elements. A 2006 audit by the US National Research Council identified several metals, including rhodium, manganese, platinum and niobium, to be ‘at risk’ of scarcity.

Sustainability too can benefit from ML to handle big data, a notion pursued by the Computational Sustainability Network (CSN) (www.compsust.net), an initiative sponsored by the US National Science Foundation and involving 13 US academic institutions, as well as international partners. One major strand of the CSN is the discovery of new materials for energy generation and storage (fuel cells, batteries, solar and so on) from high-throughput X-ray diffraction experiments⁴¹, seeking to correlate observed structures with functional properties. Initiatives such as this aim to ensure that potentially useful innovations emerge already embedded in the wider picture, so that they generate not merely a citable piece of research but a technology that will make a difference to the world.

Making a difference matters more than ever. The COVID-19 pandemic has acted as a microcosm for demonstrating the interconnectedness of our technologies, our material culture and our societies. Materials scientists showed how existing know-how — for example, to make testing kits, masks and other protective clothing, and monitoring equipment — can be rapidly repurposed to meet new emerging threats. But, in a way, this experience served to highlight how much more might be done already to

address the greater threat of climate change. Dramatic change is possible when the need is acknowledged, and the pandemic revealed the best of science, even in the face of some of the worst of politics and societal responses. We already know more than enough to create the material basis for a better world; the future depends on how wisely we use that knowledge. 

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Published online: 24 August 2022

<https://doi.org/10.1038/s41563-022-01350-x>

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Competing interests

The author declares no competing interests.