Animate materials

PERSPECTIVE

THE ROYAL SOCIETY

Emerging technologies
As science expands our understanding of the world it can lead to the emergence of new technologies. These can bring huge benefits, but also challenges, as they change society's relationship with the world. Scientists, developers and relevant decision-makers must ensure that society maximises the benefits from new technologies while minimising these challenges. The Royal Society has established an Emerging Technologies Working Party to examine such developments. This is the second in a series of perspectives initiated by the working party, the first having focused on the emerging field of neural interfaces.

Animate materials
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Animate materials

This report identifies a new and potentially transformative class of materials: materials that are created through human agency but emulate the properties of living systems. We call these 'animate materials' and they can be defined as those that are sensitive to their environment and able to adapt to it in a number of ways to better fulfil their function. These materials may be understood in relation to three principles of animacy. They are 'active', in that they can change their properties or perform actions, often by taking energy, material or nutrients from the environment; 'adaptive' in sensing changes in their environment and responding; and 'autonomous' in being able to initiate such a response without being controlled.

Artificial materials that are fully animate in all these dimensions do not exist at present, but there are many examples of materials with some features that correspond with our definition of animacy, as well as research that indicates potential ways to improve and extend their capabilities. The development of such materials has been identified by the Royal Society as an area of research with potential to deliver major change, most noticeably in the built environment, from roads and buildings to transport and industry, as well as in sectors such as medicine and clothing. Development and implementation of proto-animate materials are currently being pursued in many disciplines, but without any formal co-ordination. The Royal Society is seeking to support interdisciplinary efforts in the field of animate materials, as well as to improve understanding of their potential, while identifying steps needed to accelerate their development in a socially responsible manner.

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Image:
Self-healing concrete
© Dr Tanvir Qureshi.

An introduction to animate materials

MESSAGE FROM THE CO-CHAIRS

Across the scientific world, researchers are developing tools and ideas to create materials that have life-like properties.

Look out of your window or around your room. You will see a wide range of materials – metals, wood, plastics, glass. You might also see living organisms – people, plants, animals. These might seem to be very different entities: one lifeless, the other alive.

But across the scientific world, researchers are developing tools and ideas, many of them inspired by the mechanisms of nature, to create materials that have life-like properties; in other words, materials that can sense, move, change shape and adapt to their environment to fulfil particular goals such as growing or obtaining nutrients.

An example of animate properties in the natural world is displayed by a tree. It is an organism that obtains energy and nutrients from the environment to sustain, grow and repair itself. It adapts its shape and internal structure to the constraints and opportunities supplied by the environment. And it exists within and as a component of a wider ecosystem.

The tree achieves these goals through processes that operate on many scales, from individual molecules to cells to different types of tissues that form its organs, such as leaves and roots.

Different cells, tissues and structures have different functions. Some are structural: they are a part of the growing fabric. Others transport water, minerals and sugars from leaves to roots or vice versa.

Imagine buildings, roads, bridges, walls and perhaps entire cities that have qualities like these, composed of building blocks that can mimic some of the characteristics of cells and that operate autonomously together to promote growth, adaptation and healing. These are 'animate materials'.

Self-healing materials are at the forefront of the field, with self-repairing paints already commercially available and multiple projects exploring possibilities for self-healing asphalt, concrete and fibre-reinforced polymers, such as those used in aircraft. However, as this *Perspective* shows, these only represent early branches of animate materials, along with current applications in medicine, robotics and elsewhere. Other very different branches may develop out of a diverse range of research now taking place into life-replicating qualities of materials at the molecular level. As understanding of animate materials evolves, multiple applications may emerge across many sectors.

To develop such animate materials from scratch, researchers need to draw on knowledge from a wide range of separate disciplines. Techniques for making, analysing and testing them will be grounded in the fields of materials science and engineering. However, animate materials will also draw from the expertise of other fields, such as organic and inorganic chemistry, synthetic biology, cell biology and physics.

Animate materials could eventually have a transformative effect on all spheres of life. Buildings could become an active part of local ecosystems, harvesting carbon dioxide from the environment to heal themselves. The walls of buildings could act as bioreactors, using inputs such as light, water, heat, algae, bacteria, nutrients and gases to generate a range of products such as purified water, power, oxygen, recoverable biomass and heat.

Medical implants may be able to interact with our bodies to enhance healing or deliver medicines in appropriate doses in targeted parts of the body.

Material goods that reach the end of their useful life could be programmed to separate into their basic components for reuse and recycling.

Clothing may become responsive, being more like assistive technology which adapts to changes in people's requirements. New materials are being created that could make clothing or bandages[1] respond to changes in a person's body temperature and detect possible illness[2].

Robotic-like devices may be developed that are not controlled entirely by some centralised information-processing unit, but instead have a degree of intelligence built into their fabric, resembling the swarming behaviour of some insects and birds. This could involve the use of soft, responsive materials rather than the hard substances of traditional robotic engineering. These devices might harvest their power from ambient sources rather than needing periodic charging. They could be sent to places to perform tasks that are highly hazardous for humans, such as dealing with radioactive contamination.

Animate materials could eventually have a transformative effect on all spheres of life.

The Recovery of Youth, or at least some of ye Marks of it, as new Teeth, new Hair colour'd as in youth.

The Art of Flying.

The Art of Continuing long under water, and exercising functions freely there.

The Cure of Wounds at a Distance.

The Cure of Diseases at a distance or at least by Transplantation.

The Attaining Gigantick Dimensions.

The Emulating of Fish without Engines by Custome & Education only.

The Acceleration of ye Production of things out of Seed.

The Transmutation of Metalls.

The makeing of Glass Malleable.

The Transmutation of Species in Mineralls, Animals, & Vegetables

The Liquid Alkaest and Other dissolving Menstruums.

The making of Parabolicall and Hyperbolicall Glasses.

The making Armour light and extremely hard.

The practicable & certain way of finding Longitudes.

The use of Pendulums at Sea and in Journeys, and the Application of it to watches

Potent Druggs to alter or Exalt Imagination, Waking, Memory, and other functions, and appease pain,

Boyle's list and future thinking in science

The idea of being surrounded by active, animate materials may seem like science fiction, but part of the scientist's job is to pursue far-off visions with ambition. Over 300 years ago, the natural philosopher, chemist and founding Fellow of the Royal Society, Robert Boyle, set out a list of things he hoped could be achieved through science. Many, such as the prolongation of life or the art of flying, would have seemed outlandish to his contemporaries. Yet since Boyle's time, life expectancy in the UK has more than doubled, and over 7,000 aircraft now take off or touch down in the UK on a typical day[3]. Perhaps a modern-day Boyle would include in such a list the ambition of creating materials that sustain and repair themselves as well as their environment, just as a tree does.

Image:
17th century predictions for the future of science written in the 1660s by Robert Boyle FRS.

In the future, if and when such complex materials and devices have been developed, they would be inherently less predictable, at least to some degree. They could require careful regulation and ethical consideration to avoid any unintended consequences of their behaviour. This might include rigorous processes for approval and monitoring, new design codes and standards, measures to manage the risk of failure and, ultimately, mechanisms by which autonomous properties could be deactivated. It will also be important to communicate the risks clearly, given the potential for misunderstanding in relation to materials with life-like properties created in the laboratory. The overarching aim must be to develop materials with life-like properties for the benefit of society.

In order to create a future of animate materials, two general priorities are clear. One is to find ways of bringing together diverse areas of research: to develop shared language and goals and to reveal connections that already exist. The other is to consider how animate materials might change the ways humans interact with their environment, as well as approaches to manufacturing goods and resource management, so that such innovations can be most efficiently and safely directed towards social good and the urgent need to create sustainable societies. ■

What are animate materials?

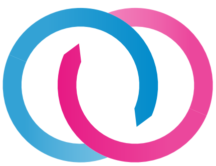
Animate materials can be defined as those that are sensitive to their environment and able to adapt to it in a number of ways to better fulfil their function.

Like life itself, animacy is hard to define precisely but generally clear enough when it is seen. In the natural world, humans and animals are clearly animate. In a different sense, so are plants and oceans. Although lacking animal sentience, they move and change, often in response to the environment. Rocks can be seen at the other end of a scale of animacy, but even they can take animate form, such as when molten rock or magma reaches the surface in an erupting volcano.

Some natural substances and structures display some degree of animacy because of the action of physical forces such as heat. Others exhibit greater intrinsic and self-actuating animate qualities because of the way they interact with their environment.

Wood is animate when it constitutes the fabric of a tree – there it dictates both the structure and the function of the object it produces. It grows, mutates and heals, using energy from its surroundings. But wood has far less animacy once the tree is felled, separated from its sources of energy and used as timber.

Animate materials – those created by human agency – can be defined as those that are sensitive to their environment and able to adapt to it in a number of ways to better fulfil their function. This behaviour can be broken down into three characteristics, or principles, of animacy, each of which can be demonstrated at different levels, namely being active, adaptive and autonomous.



ACTIVE
'Active' means that the materials can change their properties or perform actions, often by taking energy, material or nutrients from the environment.

ADAPTIVE
'Adaptive' means that they can sense changes in their environment and respond in a way that maintains or promotes their function, typically with a single predetermined outcome.

AUTONOMOUS
'Autonomous' means that they can automatically 'decide', perhaps through some internal computation, or computation-like process, on an appropriate response to signals or changes in the environment from a repertoire of possible outcomes, without being monitored or controlled.

A goal for this emerging field of animate materials could be defined as making these three qualities intrinsic aspects of the materials system.

True animate materials, like living systems, would rate highly in terms of all three principles. However, the field is at a very early stage of evolution. Some materials that are being tested or deployed in practical contexts, such as self-repairing paints, concrete and roads, are clearly active and adaptive. Other examples display all three features clearly but remain the focus of curiosity-driven laboratory research at a molecular level.

In the following section we review many materials that are now the subject of research or development. All are active, to a degree, in that they move or mutate, and many are adaptive, in reacting to environmental stimuli, often with a predetermined response. The third principle, autonomy, is not synonymous with total spontaneity, acting without external stimulus, but rather means adapting or reacting in a way that is not predetermined but selected by the material itself from a number of potential responses. Inasmuch as a hierarchy exists among such materials, being active is the most fundamental quality, with adaptation representing a further step in sophistication and autonomy characterising the most advanced materials.

'Smart materials', a relatively well-established concept in materials engineering, can be classified as active and often adaptive, but are not yet autonomous. Smart materials change their properties in response to stimuli such as moisture, temperature change or electricity. One example is shape-memory polymers that alter their shape in response to changes in temperature or stress.

A goal for this emerging field of animate materials could be defined as making these three qualities intrinsic aspects of the materials system, rather than capabilities supplied by some external computational network. Thus, an animate material is itself the mechanism.

The three qualities also serve to delineate the limits of animate materials, showing not only what they are but what they are not. They comprise a set of life-like properties but do not include all the properties of living beings; for example, they are not sentient, nor do they have the ability to reproduce as animals or plants do.

The '3A' framework, which outlines active, adaptive and autonomous principles of animacy, is not intended to be definitive but simply to act as a working model to guide what is still an emerging field and provide a standardised language that can aid development across disciplines. ■

The science behind animate materials

Research groups from around the world have been driving progress towards the development of animate materials. Some of this research takes direct inspiration and guidance from nature; some seeks to develop animate properties from scratch, by rational design. Some is directed very much at specific applications and problems; some is purely exploratory and curiosity driven. The research is happening in, and drawing on, diverse disciplines, from civil engineering and materials science to molecular biology.

The following sections discuss some of this research that falls within the three dimensions of the tripartite working definition of animacy.

ACTIVE MATERIALS

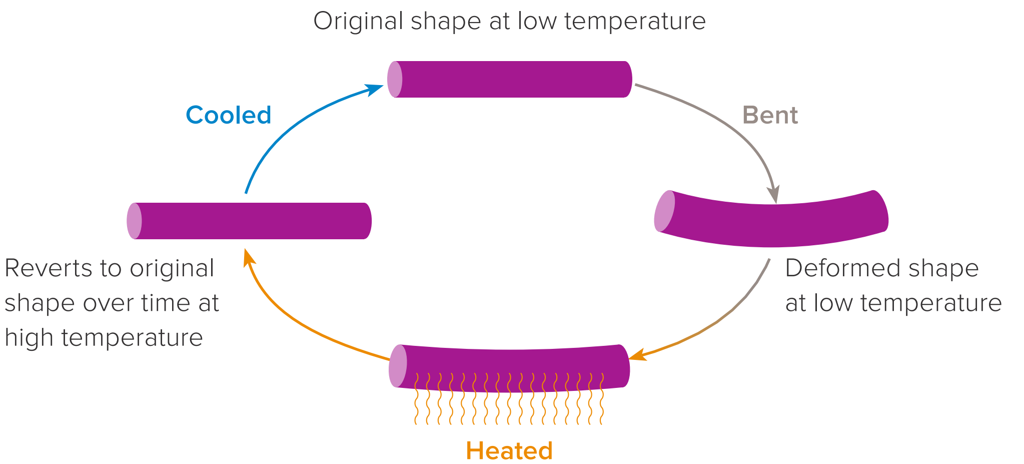
Active materials can change their properties or perform actions, taking energy, material or nutrients from the environment. This section provides an overview of the emerging science and technology that could underpin active materials of the future. Few active materials are close to being ready for use in everyday consumer products, but work is underway to create novel applications that could transform fields such as engineering and medicine.

Materials with active properties have been known and used for a long time. One of the first examples of such properties to be discovered was piezoelectricity – the electric charge that accumulates in materials such as quartz. When squeezed, it produces an electrical voltage – and conversely its shape can be changed by electric fields. Materials with these properties have been used widely in everyday devices such as headphones and electric toothbrushes, as well as specialist equipment such as vibration sensors, sonar systems and electrically controlled positioning devices.

Another attribute of active materials is the ability to 'remember' a shape, so that the material can return to that shape after being deformed, when given the right stimulus. Shape-memory alloys such as nitinol (a mixture of nickel and titanium) can be 'programmed' with a shape while warm. The alloy can then be cooled and bent, but, when it is reheated, it returns to its original shape (Figure 1). Such materials have been used as strong 'artificial muscles' in robotics and as components of thermostats.

FIGURE 1

The phase transformation process for shape-memory alloys.



Molecular machines

Much of the current research on active materials is happening at a micro- or nanoscale, in part because a lot of this work has been inspired by living matter, which is driven by processes taking place at these scales. Living cells rely on a variety of protein molecules that can change their shape in response to external stimuli, producing movement. These proteins have also been called ‘molecular machines’ because of their ability to perform machine-like actions, such as transporting objects from one part of a cell to another or changing the shape of cells and tissues; for example, the proteins that drive muscle contractions (Figure 2).

Several types of synthetic molecular machines have been created by researchers, some of them leading to Nobel Prizes in Chemistry. These include: molecular motors that rotate in response to an energy input such as light; molecular switches that can flip between two stable forms in response to stimuli such as pH or temperature; and molecular tweezers – molecules that can hold onto and transport an object[4]. By seeking to emulate some of the basic actions that cells and their components perform, these synthetic molecular machines could eventually be building blocks for more complex active materials.

FIGURE 2

Illustration of a molecular machine created by Jean-Pierre Sauvage. In this example two molecular loops have been threaded together, creating a structure that can stretch and contract.

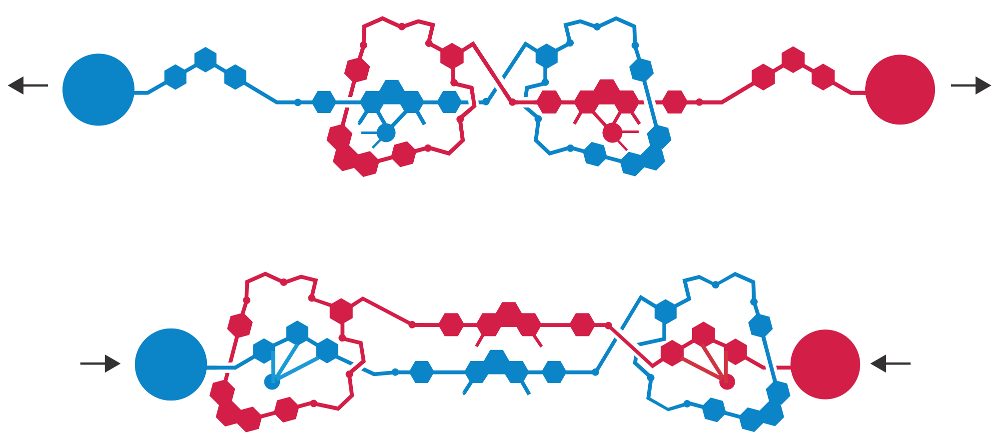


Image:
A murmuration of starlings at Gretna.

Experimental and theoretical tools

Molecular machines represent one of many types of what scientists know as 'active matter'. Active matter consists of systems that are made up of units that can extract energy from their environment and transform it into movement or mechanical work.

The theory of active matter draws on ideas from the field of statistical physics and considers what kinds of collective, emergent motion might arise in these systems. Examples of natural systems that exhibit emergent motion include flocks of birds and bacteria cultures in a Petri dish. Only with this sort of understanding is it likely to be possible to engineer specific types of activity in active matter and in animate materials. There is therefore a need to develop new experimental and theoretical tools to understand what active matter can achieve and how it behaves under different circumstances.

Active materials in medicine

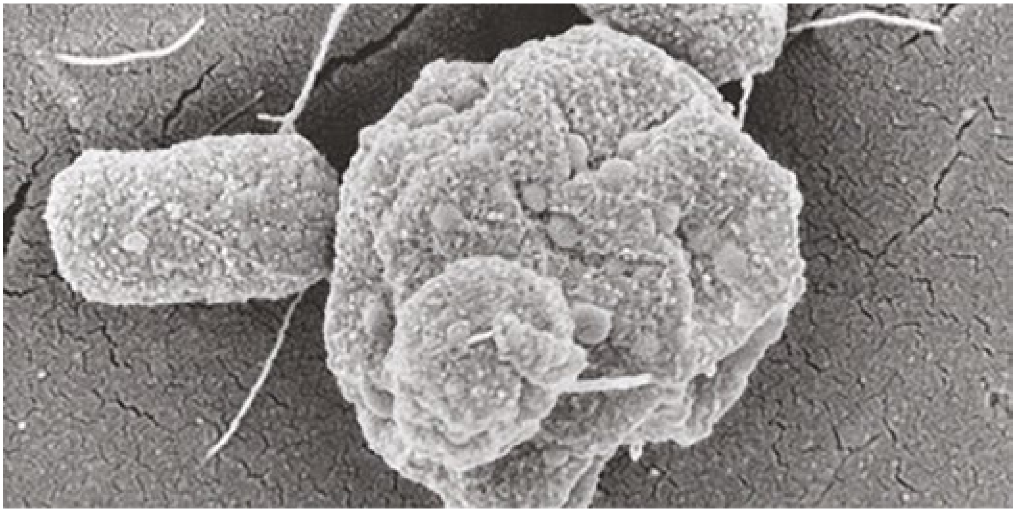
One area set to benefit from the creation of materials capable of movement and action is medicine. To carry out surgery or take biopsies, invasive procedures are often required in order to reach the target tissues. However, molecular or microscopic machines small enough to be injected into the bloodstream might be able to make small incisions, repair damage, or sense and collect data[5].

One challenging issue for medicine is that treatments often act in areas beyond the target area. Chemotherapy, for example, not only attacks cancer cells but also kills many others. One way that some researchers have sought to address this issue in cervical cancer treatment is to modify sperm cells so that they can transport chemotherapy drugs directly to the tumour. Sperm cells loaded with the chemotherapy agent doxorubicin and released in a dish containing miniature cervical cancer tumours swam to the tumours, killing 87% of the cells in three days[6]. Bacteria too are being adapted for use as 'micro-swimmers' or 'bacteria-bots' to deliver drugs[7].

Another active material with potential for use in drug delivery and elsewhere is the self-propelled chemical micromotor, which can take a variety of forms. One example is the so-called 'Janus-faced' micromotor, a tiny sphere whose two halves are made of different substances, such as platinum and silica. The microsphere is placed in a liquid, such as a solution of hydrogen peroxide, a chemical that decomposes on the platinum side only and acts to propel the object. Bubbles can also be generated that accelerate the propulsion[8 – 10].

Developments in active materials could also lead to more sensitive biosensors that could allow earlier diagnosis or new treatments. These sensors could be supplied by nanoplasmonics, a field that explores the interactions between light and metallic nanoparticles such as tiny spheres of gold or silver. Nanoparticles can be coated with surface molecules that bind to a target to be detected – a certain cell type or a virus or pollutant. Such binding may change the wavelength of the light that the nanoparticle emits or absorbs, thereby signalling that the target molecule has been detected. In terms of treatments, these nanoparticles can be designed to target and destroy cancer cells using electromagnetic radiation such as infrared laser light[11 – 13].

Image:
A scanning electron microscopy image of a 'bacteria-bot', which are being studied for targeted drug delivery.



The rapid changes in colour that nanoplasmonic materials can exhibit in response to environmental changes could also be used to produce chameleon-like transformations in response to temperature or voltage signals[14,15]. Recent work has combined such colour changes with the selective release of antibiotics to produce an active bandage that could help combat antimicrobial resistance[16]. This bandage changes from green to yellow when it detects a bacterial infection and releases antibiotics. When drug-resistant bacteria are present, the bandage turns red. Doctors can then shine a light on the bandage, causing it to produce oxidants that weaken or kill the bacteria (Figure 3).

Ambient electromagnetic fields

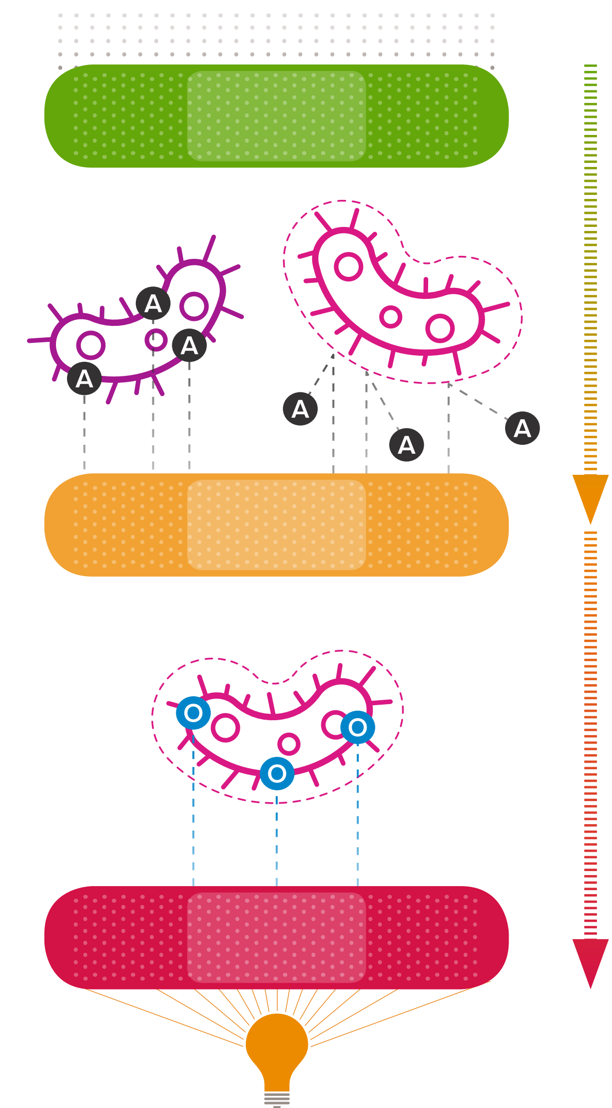
The possibilities for active materials are broadening with the development of materials systems that can harvest power from ambient electromagnetic fields, in particular from Wi-Fi signals. Scientists have created a rectifying antenna, or 'rectenna', a few atoms thick which captures such electromagnetic waves and converts them to electrical current. Devices like these could be used to provide battery-less power for smartphones, laptops, medical devices and wearable technology[17]. Using the same principle, animate materials of the future could harvest their energy from ambient sources such as Wi-Fi signals, temperature gradients and mechanical vibrations. ■

FIGURE 3

Illustration showing how an active, colour-changing bandage could help combat antimicrobial resistance.

KEY

Drug-sensitive bacteria | Drug-resistant bacteria | A Antibiotics | O Oxidants



Smart bandage is able to detect bacterial infection

Bacterial infection detected
The green smart bandage turns yellow when it detects a bacterial infection and releases antibiotics.

Drug-resistant bacteria still present
When drug-resistant bacteria are present, the bandage turns red. Doctors can then shine a light on the bandage, causing it to produce oxidants that weaken or kill the bacteria.

Light shone onto bandage

ADAPTIVE MATERIALS

Adaptive materials are those that sense changes in their environment and respond through action to maintain or promote their function – for example, by self-healing, including those that overcome typical problems of degradation such as cracks in roads or walls, or scratches on the paint of a car.

Image:
Lime mortar has long-established self-healing properties and has been used widely in buildings for thousands of years, including in the Egyptian pyramids. © L-BBE. CC BY 3.0.

Such adaptive self-healing has existed to a degree for millennia. For example, lime mortar, which has been used in buildings since the Egyptian pyramids, heals itself by growing new crystals in cracks when water enters, enabling it to react with carbon dioxide in the air[18,19].

The asphalt mixture used in roads also displays some self-healing properties as it contains both gravel or rock and bitumen, a viscous black liquid that can flow into small cracks in the material. However, the process is very slow because of the high viscosity of bitumen and is frequently insufficient to prevent such cracks growing to become potholes.

Researchers are now seeking to build on these long-established processes with the ultimate goal of creating materials that do not require maintenance because they are able to self-diagnose continuously and repair any damage they suffer.

There are already several commercial examples of self-healing paints and coatings being marketed for use in buildings and vehicles[20,21].

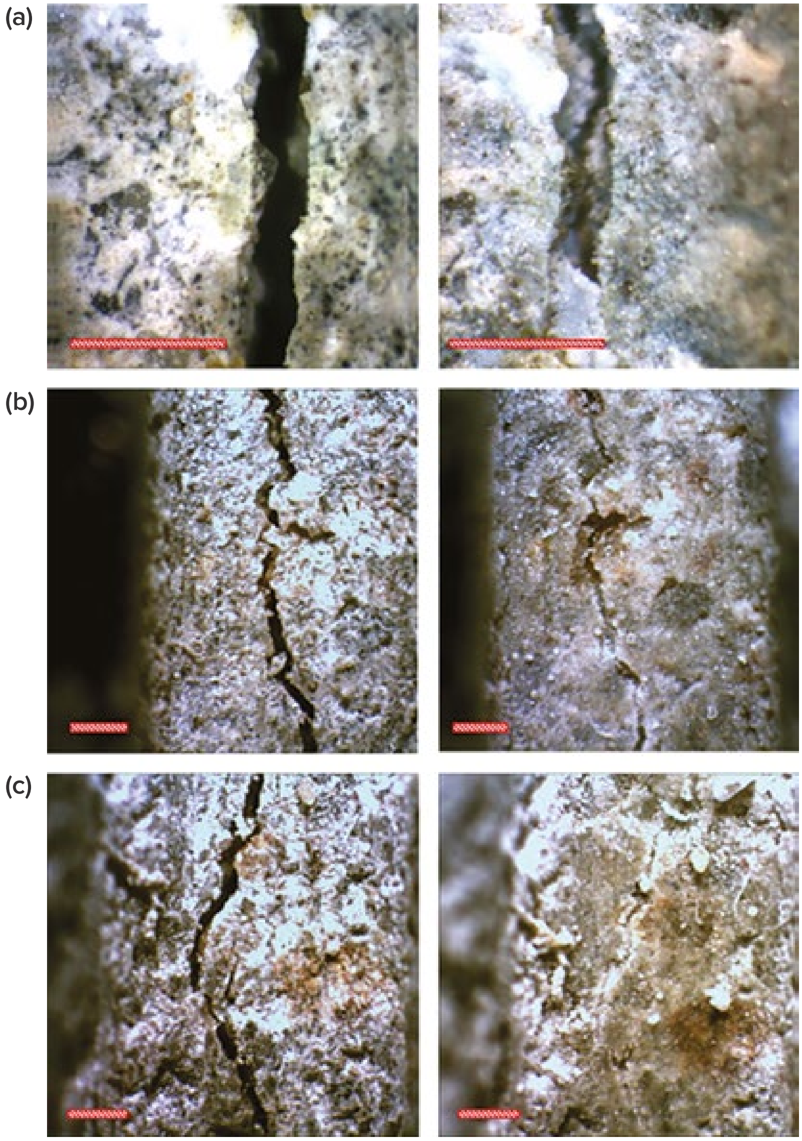
As and when self-healing materials become commonplace and used in multiple structures, the risks of failure will need to be managed by building in layers of resilience so that any failure to activate does not create hazards for human safety or structural integrity.

Extrinsic self-healing

Road repair is a major area of research focus as the annual highway maintenance budget for England and Wales is around £3.5 billion[22] and British drivers are reported to spend nearly £1 billion a year on repairs to vehicle damage caused by potholes[23]. Technologies to prevent the formation of potholes currently being explored include the 3D printing of asphalt patches[24] to cover cracks identified by autonomous driverless cars and drones, and heating roads using infrared[25], microwave[26] or magnetic energy sources[27]. While these are essentially means of complementing or accelerating the natural healing process of asphalt, other researchers are working on new technologies to promote self-repair.

FIGURE 4

Images showing cracks in cement-based materials taken on the day of cracking (left) and after 28 days of healing (right) for: (a) a control sample without microcapsules; (b) a sample with a medium concentration of microcapsules and (c) a sample with a high concentration of microcapsules. For both samples with microcapsules, the cracks are almost completely healed after 28 days.



Note: solid bars correspond to 500 µm.

One approach that has been used for asphalt, concrete and polymers is the addition of capsules that crack when they are damaged and release healing agents (Figure 4). In asphalt, these capsules are typically filled with oil-based bitumen solvents that fill the cracks faster than bitumen solvents that aid crack repair[28]. In concrete, the capsules are often made of soft polymers such as gelatin or gum arabic filled with epoxy adhesive or sodium silicate, which mineralises on exposure to air and water[29].

Another approach to self-healing concrete, known as microbially induced calcite precipitation[30], uses lightweight capsules containing spores of bacteria. When the concrete cracks and the conditions become favourable, the spores germinate and the bacteria break down the nutrients and precipitate calcite into the concrete cracks[31–34].

Self-repair capsules are embedded in the material from the beginning. Once they have been used they cannot be replaced, making healing a single-shot process. In order to achieve repeated healing, researchers have introduced vascular-like networks into materials, through which healing agents can be pumped whenever necessary, with potential for different agents to be used under different circumstances[35].

Intrinsic self-healing

Extrinsic self-healing is limited either by the number of times the healing can occur, in the case of capsule-based systems, or by the need for monitoring and intervention, in the case of vascular systems.

It would be preferable to make self-healing an intrinsic property of the material itself, a possibility that has been explored in polymers, particularly plastics and paints. Polymers are large, chain-like molecules made of repeating sequences of smaller molecules joined together by chemical bonds. When polymers are damaged, these chemical bonds may be able to achieve some degree of recovery, usually by exploiting a particular chemical bond or reversible mechanism in the molecular arrangement. This is typically thermally activated, although other stimuli such as light can be utilised. Such ‘remendable’ polymers do not usually exhibit impressive inherent mechanical characteristics, often being elastomeric in nature[36]. Broken chain fragments are particularly able to heal if the molecular components are linked by relatively weak and reversible physical bonds, which act rather like molecular hook-and-loop patches that can be pulled apart and reunited[37].

Another option for self-healing makes use of the way polymer chains become entangled: if the chains can be made loose and floppy by heating, they can re-tangle to seal a scratch or crack.

Images:
Soft robotic hands are able to manipulate fragile objects with dexterity and repair themselves when damaged. © Brubotics (VUB).

Image:
An arch made from living building materials, or 'living bricks'.
© Dr Srubar / University of Colorado Boulder College of Engineering and Applied Science.

A ground-breaking example is a highly extensible rubber that can be stretched to many times its original length and that, when cut, can be repaired simply by bringing together the surfaces to self-heal at room temperature[38].

Self-healing polymers are also receiving increased attention in the development of soft robotics, which are robots made from flexible materials such as those found in organisms. Among the challenges with soft robots are that rubbery polymers can be prone to damage and repairs are often costly. The Horizon 2020 *Future and Emerging Technologies Programme* project on Self-Healing Soft Robotics (SHERO) aims to create robots that can use sensors to identify damage and autonomously self-heal[39].

From repair to growth

Adaptivity in materials has the potential to move beyond self-repair and to replicate the way living systems grow and adapt to their surroundings.

One example is that of living building materials[40], or 'living bricks'. These are made by mixing *Synechococcus* bacteria with off-the-shelf additives such as gelatin, calcite and sand. These materials can be regenerated in response to temperature and humidity changes in ways that potentially go beyond self-repair to growth.

Hydrogels are materials that swell or shrink in response to changes in temperature, light or acidity[41]. They have been used for controlled drug delivery[42,43] in fields such as cardiology, oncology, immunology, wound healing and pain management. Some are used in the form of injectable particles that self-assemble in the body. Typically, they release drugs, either as they are biodegraded or as they swell, so that the drug molecules previously trapped among the polymer chains can escape[44].

Other adaptive materials interact with living systems to grow and develop – for example, to meld with tissues in the body. One well-established example is bioactive glass such as Bioglass™, which has been implanted in over 1.5 million people for orthopaedic and dental surgery over more than two decades[45,46].

Traditionally, implants were deliberately designed to be inert to avoid provoking inflammation and immune rejection. Bioactive glasses are, by contrast, designed to bond with bone without triggering the formation of scar tissue.

Bioactive glasses can also deliver other active ions that have a therapeutic effect, such as strontium to treat osteoporosis[47] or medication for chronic wounds in patients with diabetes who have not responded to other treatments[48]. A new form of 3D-printed and self-healing ‘bouncy’ bioactive glass is now being explored as a way of stimulating cartilage growth following sports injuries[49]. Structural regenerative materials may respond to changes in mechanical load or biochemical stimuli to trigger therapeutic or healing mechanisms. ■

Image:
Hydrogels swell and shrink in response to environmental signals. CC BY-SA 4.0.

AUTONOMOUS MATERIALS

Autonomous materials are those that select an appropriate response to stimuli without any kind of external control or guidance. Unlike adaptive smart materials that have a single response to a specific prompt, such as glasses that darken in response to ultraviolet light, autonomous materials show versatility in combining various inputs to generate a suitable behaviour from a diverse repertoire.

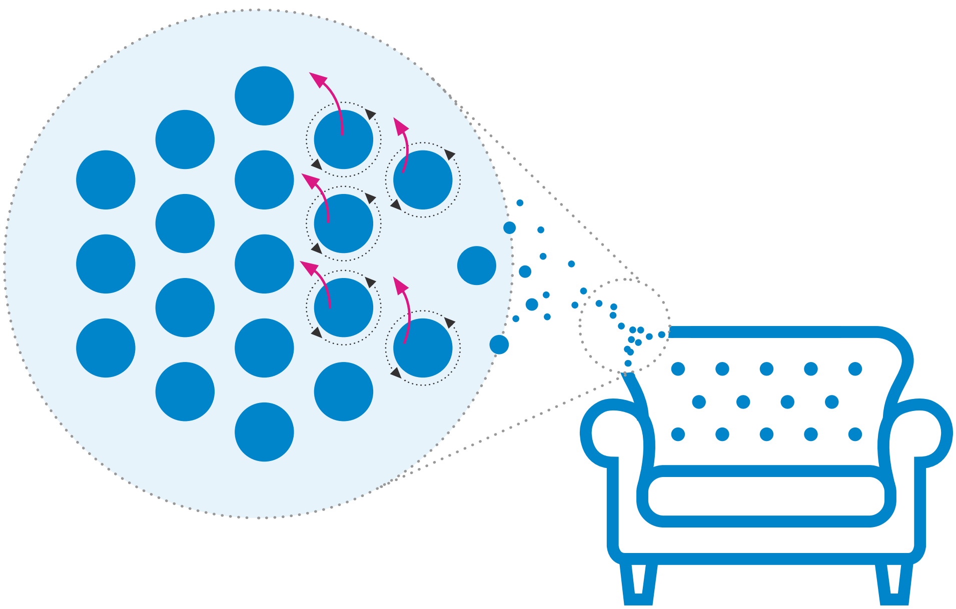
Early research has built on advances in materials science, manufacturing, distributed computing and miniaturisation to create multifunctional materials that sense, compute, communicate and move. Examples include robotic-like materials, such as an amorphous facade that recognises and changes colour in response to a user's gestures and an intelligent skin that senses touch and texture using sensor nodes to detect vibrations[50]. With further advances across scales, specialists believe autonomy could enable responsive infrastructure and prosthetics, as well as everyday items such as table tops that warm or cool food[51].

The key in creating such bio-inspired applications is to replicate the logical deductions that living beings make as they fulfil basic needs, such as recognising that food and warmth are required for self-preservation. These behaviours can be viewed as a type of computation. Environmental and self-generated signals provide the inputs for networks that operate like algorithms among cells, organs or even whole ecosystems to create outputs that enable the organism to survive or adapt. Like an organic network, this sort of 'computation' does not need a brain or a central command system, although it does involve a complex distributed network of interacting molecular elements[52].

These are the kinds of capabilities that would qualify an animate material as being truly autonomous. But creating materials that are capable of even the most basic computations is challenging, and there is no single path to get there. Three possible approaches are: materials made up of smaller components that can be programmed and exhibit complex collective behaviour; materials that can store and process information; and material systems that can help us understand living systems themselves and their origins.

FIGURE 5

Researchers are working to create tiny robotic modules, sometimes called claytronic atoms or 'catoms', that in the future may be able to assemble and disassemble into arbitrarily shaped objects such as a chair.

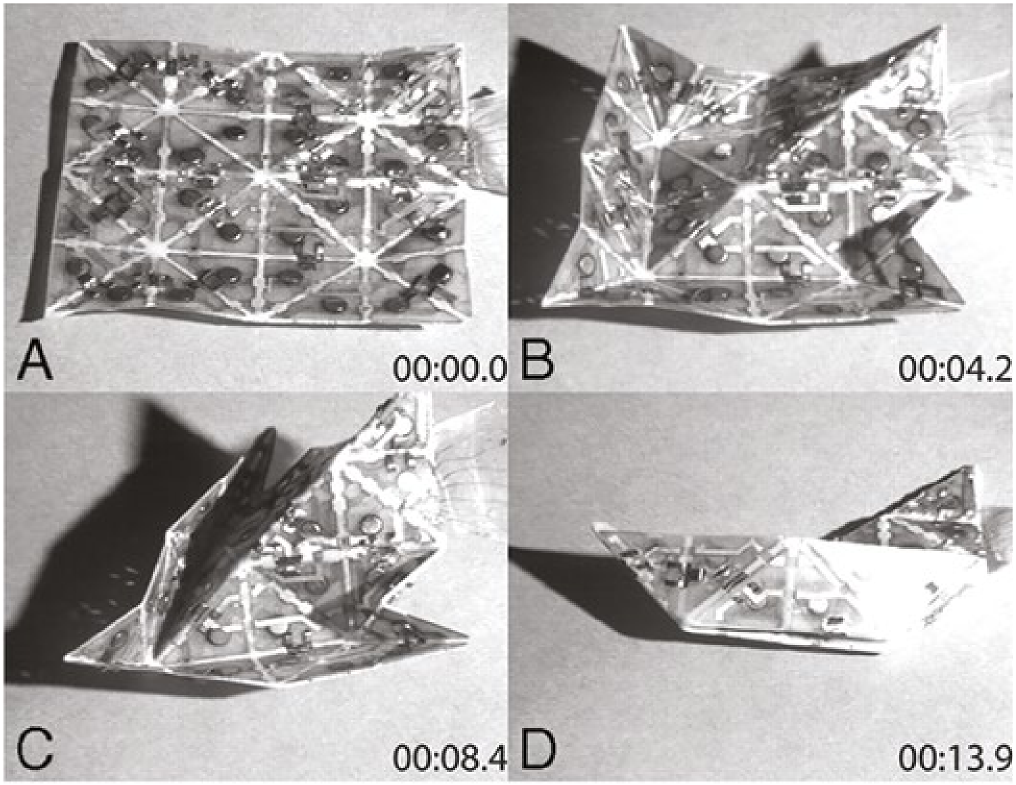


Programmable matter

At the molecular level, the signalling processes of living systems use chemical principles. Unlike rocks and minerals, which have rigid structures held together by strong covalent or ionic bonds, molecules in living systems – proteins and nucleic acids for example – generally have weak or loose interactions such as hydrogen bonding, which enable molecular entities to associate, assemble and disassemble.

Such molecular assembly processes can be used to translate information stored at the molecular level into some sort of animate function as a consequence of the assembly process. This opens up the prospect of materials that could be constructed to assemble and disassemble in various ways – so-called 'programmable matter'.

Image:
A self-folding 'boat' made from programmable matter (time shown in lower right—mm:ss.s). Images show: (a) flat sheet prior to folding; (b) all actuators receiving current; (c) immediately before magnetic closures engage and (d) finished boat on side (D). © The Harvard Microrobotics Lab.



Large-scale robots and other devices can already swarm and interact, from drones to autonomous vehicles. Very small units have self-assembled in two-dimensional systems and some researchers are now focused on possibilities for self-assembly in three dimensions at smaller and smaller scales, typically building prototypes at the macroscopic scale as an initial step. In one approach[53], researchers are seeking to create tiny robotic modules, sometimes called claytronic atoms or 'catoms', that can assemble and disassemble into arbitrarily shaped three-dimensional objects[54] – a coffee cup, say, or an injectable medical instrument (Figure 5). Although a long way off, the goal would be to program the catoms with assembly instructions so that a featureless mass of them turns spontaneously into the desired object. Other researchers have produced sugar-cube-sized 'smart pebbles', which are essentially mini-robots that move and form into well-defined shapes. The pebbles use simple processors, flywheels and magnets for movement and assembly, and are able to self-organise with no central commands[55].

The long-term ambition is to shrink these components to micrometre or nanometre scales to create what some have called 'smart dust'[56]. Such tiny elements could be used to make nanodevices capable of sensing, actuating and analytical tasks. However, miniaturisation is challenging. As well as inherent difficulties in making components smaller, as the size scales are reduced, the physical forces that govern the interactions change drastically. For example, the different physics of the nanoscale world requires the use of entirely new design principles, consistent with those of cell biology, that make use of the different features of this environment, such as self-assembly and responsiveness by molecular shape change[57].

Paradoxically, if self-assembly is achieved at the nanoscale one of the opportunities created would be to build structures that morph at a large scale by assembling, disassembling and reassembling at the molecular level. Some researchers have envisaged applications such as matter that could be shaped into tools such as hammers or wrenches, or clothing that could change its insulating properties according to the weather[58,59]. Among the scientific challenges involved in developing such materials are creating the algorithms needed to program the units to assemble in one out of a huge number of possible patterns[60].

Computational materials

Autonomous materials of the future could share some characteristics with today's digital computing systems if organic, microscopic, non-digital equivalents can be found. Just as self-driving cars have been programmed to be able to make decisions about speed and direction, responding to information from their environment, autonomous materials could be programmed to respond to internal or external stimuli.

One approach to encoding information in materials is based on using DNA, which is a highly compact, natural medium for storing and transferring vast volumes of information in living cells. Researchers are now investigating ways to store data using technologies that synthesise long strands of artificial DNA to write data such as video into individual molecules[61]. As well as its storage potential, DNA can also be designed to assemble and could be used to connect units of nanomaterials into complex structures[62].

Chemical information processing can also be done with molecular systems that are much simpler than DNA[63] and that have light photons as an output signal. These systems can perform computer-like operations involving two input signals such as 'AND' – where two signals are required to trigger a reaction – or 'XOR' – where the presence of one but not another signal is required. Conversely, the photons might be inputs that the molecules absorb. Or they could be chemical: the presence or absence of some molecule or ion that binds to the molecular logic gate.

Chemical equivalents of computations can also be carried out in an analogue fashion by exploiting chemical reactions that occur continuously over time. This approach typically makes use of reactions such as the Belousov–Zhabotinsky reaction, a process in which the reaction of two ingredients creates constant pulses that spread outwards from their source like ripples, through changes in the composition of the mixture via chemical waves. The interactions between the waves in these chemical systems have been shown to be capable of carrying out tasks such as image processing, if the reaction is tweaked to make it light sensitive[64]; programmable pattern recognition[65]; or logic computations[66].

A different kind of life

While some research on autonomous systems is directed towards specific applications, other curiosity-driven studies are targeted towards the overlapping goals of creating new life-like materials and probing the origins and nature of life as it exists. Some of these seek to replicate the natural building blocks of life as closely as possible, while others are trying to create new cell-like entities that could lead to different evolutionary pathways.

Experiments on 'proto-cells' made from non-biological components might point to a bottom-up route to animate capabilities. For example, researchers have explored the synthesis of liquid–droplet protocells called coacervates, by bringing together two kinds of particles with opposite electrical charges (such as DNA strands and clay particles). These droplets, unlike biological cells, have no membrane – but this can be an advantage as it enables them to engulf one another, dividing and reforming[67]. Researchers have also made polymeric thermo-responsive 'protocell' particles capable of self-assembling into artificial tissues that swell and shrink in response to changes in heat[68].

Researchers are also working to develop chemical systems with properties that have historically been seen as uniquely biological. These life-like characteristics might include the potential to evolve by 'inheritable' transmission of information.

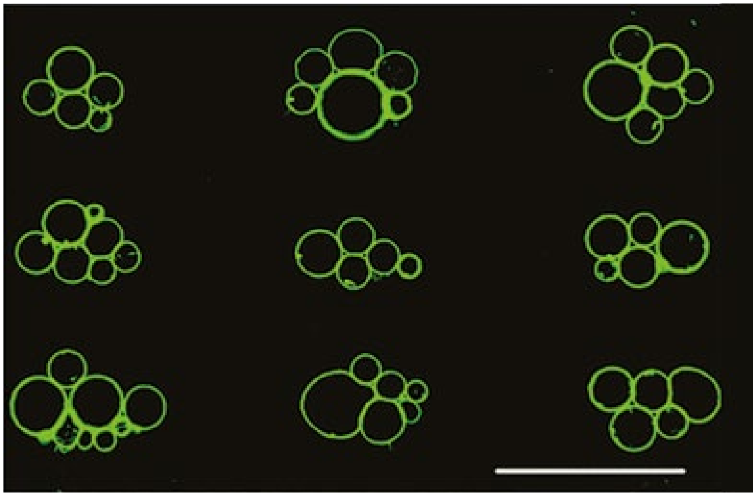


Image:
Representative fluorescence microscopy image of micro-arrays of giant unilamellar lipid vesicles (GUVs). GUVs are being explored as platforms to implement chemical signaling in protocells. © 2019 Mann *et al* / CC-BY-NC.

For example, they have enabled cell-like compartments to self-assemble from inorganic molecules[69]. The possibility that structures might divide and pass on properties to successors raises the possibility that their behaviour could be tuned and honed by evolving over time in response to the environment. The researchers might also impose conditions that favour the selective emergence of structures with particular desired properties. Such work raises possibilities for new types of evolutionary systems that might cause public concerns. These would need to be subject to controls and regulation to avoid unintended consequences as outlined later in this *Perspective*. ■

Direction of travel: The animacy continuum

The diagram below organises materials by their overall animacy. It shows a rough direction of travel from familiar materials to materials that are in their infancy but may underpin the creation of future animate materials.

Flint has no animate properties. It is inert and its properties are fixed.

Quartz changes shape in response to electricity and produces an electric charge when deformed. It was one of the first materials with active properties to be discovered.

Lime mortar has long-established self-healing properties and has been used widely in buildings for thousands of years.

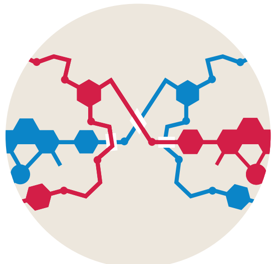
Textiles | **Woods** | **Composites**

PAST Inanimate materials

Glues | **Ceramics** | **Metals** | **Polymers**

Concrete has no intrinsic animate properties. However, work is underway to make concrete more adaptive by enabling it to self-heal.

Asphalt or **bitumen** used in asphalt mixture road surfaces is a viscous substance that naturally drains slowly into cracks and thereby exhibits some self-healing properties. New research is trying to increase its ability to self-heal and be more resilient to damage.



Molecular machines can carry out a variety of tasks such as transporting other molecules and moving in specific ways and may be the building blocks of new materials in the future. The 2016 Nobel Prize in Chemistry was awarded for 'the design and synthesis' of molecular machines[70].

Biomaterials

Sensors

Nanotechnology

Energy-harvesting materials

Proto-living technologies

Living technologies

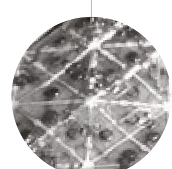
Animate materials **FUTURE**

Smart materials

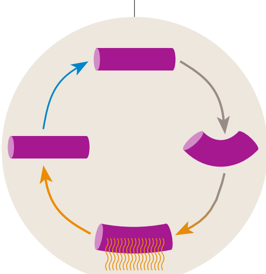
Self-healing materials

Synthetic biology

Hydrogels swell and shrink in response to environmental signals.



Programmable matter can be implanted with instructions like a computer-driven device, such as cell-like units which are programmed to replicate and grow which are programmed to replicate and grow.
4D printing is a type of programmable matter. It creates 3D objects that transform over time in reaction to changes in their environment. Image © The Harvard Microrobotics Lab.



Shape-memory alloys return to their original shape when heated, having been deformed when cold.

Many of the benefits and risks of animate materials are only likely to emerge with their democratisation through multiple applications used by millions of people.

BOX 1

Animate materials and the perception of risk

As animate materials develop, risks will need to be carefully assessed and managed, both to prevent harm resulting from the actual properties of such materials and also to avoid distorted or unfounded perceptions of risk becoming commonplace and hampering progress.

What kinds of risk might animate materials create?

Animate materials are likely to present a variety of well-founded risks as they evolve. For example, use in buildings will raise questions about the consequences of failure. Medical applications will be examined for risks comparable to those of current therapies – such as sensors that might misdiagnose conditions, treatments that attack the wrong target or implants that have unforeseen side-effects.

As is often the case with new technologies, many of the benefits and risks of animate materials are only likely to emerge with their democratisation through multiple applications used by millions of people. At this early stage those benefits and risks are largely unknown.

However, one potential issue is the possible consequences of widespread access to programmable matter, described in more detail earlier in the report. There may be many positive uses of nanoscale particles that can assemble, disassemble and reform into multiple shapes, from tools to furniture or mechanical components, but fears may include the prospect of such materials falling into the hands of those who use them to create weapons.

How worried should society be about these risks?

We believe that short-term risks are relatively low as animate materials remain at the exploratory stage. In the medium term we anticipate risks to grow as materials are programmed but not yet fully autonomous. In the longer term, more autonomy can be expected and while the resulting materials promise many potential benefits they will be less predictable. Careful regulation and clear communication will be required to address such concerns. Society should prepare for this, but there is plenty of time to do so, and this should not hold back development in the short term. However, there is no room for complacency and the calls to action that conclude this *Perspective* include provisions for regulation, including a multidisciplinary committee to consider options for monitoring and regulation.

Risks of distortion and misrepresentation. What was the 'grey goo hypothesis'?

The risks of new and emerging technology can be distorted as a result of public misunderstanding or media coverage. In his 1986 book *Engines of Creation* Eric Drexler, one of the pioneers of nanotechnology, included a couple of paragraphs outlining an imaginary scenario in which tiny, out-of control, self-replicating molecular machines consume all the biomass on Earth, as they seek to build more of themselves. This speculative scenario was called the 'grey goo hypothesis', as the machines would turn the world into 'grey goo'.

Over time, the idea gained influence and exposure in relation to nanotechnology, appearing in a popular science fiction magazine *Omni* (1986), in a controversial article in *Wired* entitled *Why the future doesn't need us* (2000)[71] and in a novel, *Prey* (2002)[72], among many other publications.

In response to concerns over safety, regulatory and ethical challenges associated with nanotechnology, the Royal Society, in collaboration with the Royal Academy of Engineering, produced the report *Nanoscience and nanotechnologies: opportunities and uncertainties*. The report concluded that "…there is no evidence to suggest that mechanical self-replicating nanomachines will be developed in the foreseeable future"[73]. Drexler later commented that he wished he had "never mentioned the term 'grey goo'" as it had long hampered public rational debate about nanotechnology[74].

What can animate materials learn from the 'grey goo' experience?

In hindsight, the main problem with the 'grey goo hypothesis' is that it dominated public and media discussion around the risks of nanotechnology without being grounded in scientific plausibility. The unrealistic doomsday scenario overshadowed any open and constructive discussion around the emerging area of science.

For animate materials, open and constructive debate around the possible opportunities, risks and long-term impacts should be actively encouraged from the outset. This debate will be vital to ensure that the field has a positive impact on society. The learning point from the 'grey goo' experience is that information about the real benefits and the plausible risks of the technologies needs to reach the public early and thus create resistance to any distorted or exaggerated accounts of potential impacts. ■

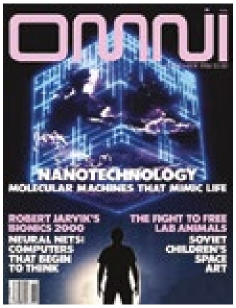
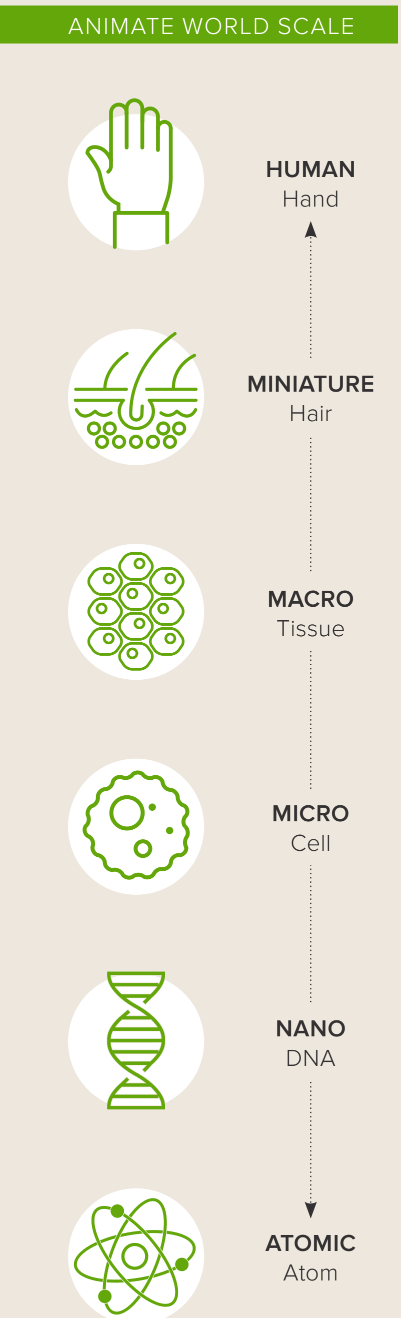


Image:
Omni magazine cover from November 1986. The edition contained a story that helped popularise the term 'nanotechnology'.
© Dale O'Dell 1986.

Animate materials **across the scales**



Examining how structures are built up over scales helps to highlight similarities and differences between animate and inanimate materials.

In some senses, living matter is no different from non-living matter. At the most basic level, all materials are made up of atoms, and all materials consist of structures at different levels, from the atomic to the nano to the macro. But while people experience materials as if they were uniform – a block of concrete looks monolithic; a spoon feels like a lump of indivisible steel – this uniform appearance is an illusion as materials have different kinds of organisation at different size scales.

Living materials in particular have a hierarchical architecture. This is what often gives them their distinctive and complex properties. It is also the hierarchical nature of materials that scientists, engineers and designers can learn from as they seek to build animate materials of the future.

The key distinction between living and non-living matter is that in living materials there is an extra degree of connectivity between the different scales. They actively organise their internal architecture by setting up communication between these scales. It is this communication that allows living materials to respond proactively to external stressors: to detect that a stress is occurring and adopt a course of action in response.

The key distinction between living and non-living matter is that in living materials there is an extra degree of connectivity between the different scales.

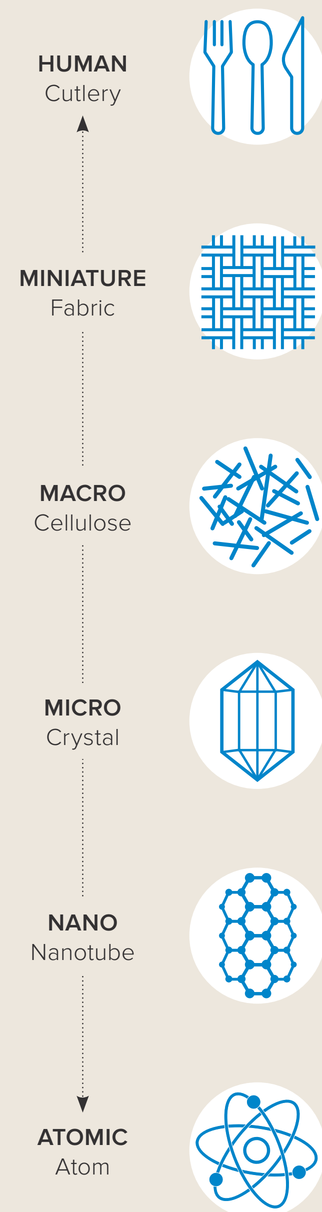
The communication may happen in a variety of ways. The most complex animal bodies have nervous systems that can send signals rapidly, in electrical form, from one part of the body to another, for example to transmit the detection of an environmental stimulus such as light. The vascular blood vessels of animals act as a fluid network for distributing chemical signals such as hormones and proteins, which can also supply the building blocks for tissue repair. Cells can detect and respond to changes in shape and mechanical stress is used as a form of communication in biological organisms.

Such diverse and intricate processes have been built up over billions of years. Scientists working in the field of animate materials recognise the scale of the challenge involved in seeking to use a sophisticated yet incomplete understanding of biology, physics and chemistry to replicate the complexity with which evolution has endowed living systems.

For makers of animate materials, the challenge will be to build in channels that perform functions like the nervous system of a human, or the internal xylem and phloem fluid networks of a tree, thereby linking up structures at all scales from the nano to the micro all the way up to the macroscopic. This would allow the development of truly animate materials in which the material is the mechanism – where changes in shape, for example, can happen automatically and without the need for some external controller that decides and imposes what it should be.

To create such materials will require a bottom-up process that involves collaboration between researchers working in an array of different disciplines and, crucially, at different scales. ■

INANIMATE WORLD SCALE



Machine learning and animate materials

How might machine learning and artificial intelligence (AI) accelerate the development of animate materials?

Animate materials may prove to be among the areas of science that become transformed by access to rapidly advancing computational tools such as machine learning and AI. Coupled with access to large datasets and extensive computing power, these advances provide scientists with opportunities to tackle problems that were previously seen as either too complex or only capable of being solved very slowly through laborious conventional computing and analysis.

What specific issues can AI help to address in the animate materials field?

One of the biggest challenges in designing a new material is the huge number of different ways in which atoms can be combined. Even a single type of atom might be arranged into a wide range of structures. Consider carbon, for example, which can be rearranged into such diverse materials as diamond, graphite, graphene, fullerenes and carbon nanotubes. Computational methods can help make the process of searching for useful combinations faster and more efficient.

AI can also be applied to comb existing stores of data and identify useful targets for study. Using machine learning algorithms and simulations trained on databases of existing materials, researchers can identify areas to explore and predict the properties of new materials before creating them in the laboratory.

One early initiative is an AI system designed to scan hundreds of thousands of research papers to deduce ‘recipes’ for producing particular materials[75]. The strategy is to determine what kinds of elements or structures tend to have particular properties, such as good heat conduction, and then use this knowledge to find other promising combinations.

Are there any examples of AI already being used in this area?

The potential of AI to imbue materials with complex, animate characteristics was shown in recent work that used computational methods to help design new 'living robot' life-forms, neither mechanical nor animal species, from frog cells.

The researchers used a 'genetic algorithm', which iteratively tried different configurations of the cells, found out which ones moved best and then slightly modified these designs in each successive round of tests. The shapes predicted to work by the computer were then approximated in clusters of cells and shaped by hand, which moved much as predicted[76].

Criteria for sustainability have also been included when AI is used to scan for potential materials. For example, the Computational Sustainability Network is a US-based initiative that seeks to harness AI for developing materials and other systems that will be integrated into a global vision of sustainability[77]. ■

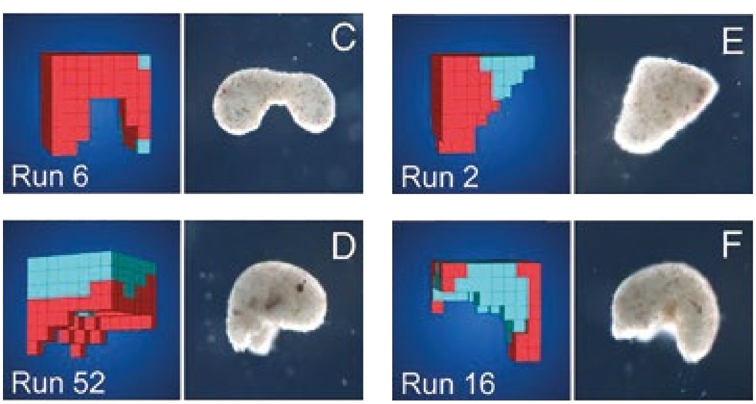


Image:
A machine learning genetic algorithm was used by researchers to design different simulated configurations of cells to achieve a goal, such as walking in one direction (left column). Researchers then designed by hand the shapes predicted to work by the algorithm into approximated clusters of cells (right column). These shapes, made from living cells, were shown to move much as predicted. © 2019 Kriegman *et al* / CC-BY 4.0.

Sustainability and circularity

What is needed to ensure animate materials are beneficial to the environment?

Will animate materials be sustainable and good for the environment?

Much of the work in progress on animate materials is being undertaken with an eye to environmental benefit. However, constant scrutiny is required to avoid unforeseen consequences and ensure that new materials are sustainable in all senses.

Any effort to develop new types of material must be informed by learning from the past. The histories of lead, asbestos and plastic all remind us how a material initially seen as a miracle invention can over time be exposed as a major risk to health, safety or the environment.

Aren't animate materials inherently sustainable if they are designed to regenerate themselves?

One of the promising aspects of animate materials is that their ability to self-regulate and self-heal could make them more durable and less in need of replacement. However, the ability to self-heal will not by default make animate materials better for the environment and society than existing materials. There are other factors to consider, such as whether the raw materials needed for their production face scarcity issues or involve unethical supply chains, as well as the environmental impact of the end-product.

Might animate materials see a new approach to planning for the end of the life cycle?

If at the end of its life cycle a material cannot be easily recycled, it will contribute to waste and pollution. Such considerations need to be taken into account as materials are developed, given that an estimated 80% of environmental impacts result from choices made at the research and design stages[78]. One approach might be to make materials that are inherently modular. By breaking down the behaviour of a complex system into modules that each have well-defined functions, it may be easier to disassemble materials into their constituent building blocks and reuse or recycle them. The ability of the material to disassemble itself at the end of its life could also be an attribute of the animacy of the material.

Will animate materials require new circular business models?

Consumer products made from animate materials that can maintain and heal themselves will be ill-suited to conventional business models that rely on customers buying a product and then replacing it once it wears out. ‘Circular’ business models that are based on repair, reuse and recycling may be better at incentivising the development and marketing of animate materials. For instance, the ‘product as a service’ circular business model involves a supplier retaining ownership of a product and when repairing or replacing it as needed, thereby delivering performance rather the product itself[79].

When such a model is applied to a self-healing tyre, for example, the service provider would be incentivised to invest in the research and development required for its improved longevity, as that would create value in the long term. At the same time, the user would benefit by receiving continually improving performance from the latest technology.

Will animate materials require monitoring and encouragement from beyond those who specialise in them?

Yes. Animate materials will have far-reaching impacts and therefore need to be understood by a wide range of stakeholders beyond those directly engaged in researching and developing them. Public understanding and input regarding such a new class of materials is critical and therefore mechanisms need to be developed to help guide the way they are created and applied, including scrutiny and advice from experts in related fields, from environmental science to ethics. Topics to cover would include managing risks and the possibility of creating standards to ensure minimum levels of performance, given that the materials might adapt in different ways.

A useful reference point for animate materials may be the 1975 Asilomar Conference on Recombinant DNA, which discussed the biohazards and regulation of biotechnology. The conference brought together participants from a range of disciplines to draw up voluntary guidelines for the emerging field, which later formed the basis of official US guidelines concerning the research[80]. Critical to the project’s success was its emphasis on bringing the public into the debate around the use of what was, at the time, a controversial area of research. ■

The future of animate materials

This report covers a wide range of materials that show some degree of active, adaptive or autonomous behaviour. In the short term, we expect further application of engineering solutions to make existing materials incrementally more animate. But the greatest potential for progress appears to lie where active, adaptive and autonomous properties converge to produce a fully animate outcome. Here we consider how the science may develop in the years to come and the benefits that might accrue.

£8 – 9 billion

Estimated annual amount spent by the construction industry on repair and maintenance of the building infrastructure of the UK in recent years.

Short term

Some of the biggest economic gains could be made by increasing the 'animacy' of materials in civil and structural engineering. Although self-healing concrete and asphalt are not highly animate, their development and commercialisation could result in longer lasting, safer buildings and roads that require significantly less spending on maintenance. The construction industry is estimated to have spent around £8 – 9 billion annually on repair and maintenance of the building infrastructure of the UK in recent years[81].

In industrial facilities such as factories, refineries and chemical plants, safety and efficiency could be improved by the use of equipment that repairs and renews itself. This might include self-repairing plastics or self-diagnostic coatings. Materials that hold their shape in the face of temperature fluctuations could reduce breakage and failure. Indeed, some zero-thermal-expansion materials already exist[82]. Other components could be designed to automatically self-degrade when they are no longer required. Self-repairing pipes, tanks and other industrial infrastructure components could help reduce the cost of corrosion, which has been estimated at $2.5 trillion a year worldwide[83].

In medicine, animate materials may enable treatments to be more precise and less invasive, as well as being adapted to each patient, improving quality of life and reducing the need for further procedures and cost of post-operative care. For example, nanoscale particles that can sense and report disease markers in the bloodstream, or accurately target and navigate their way to appropriate locations of treatment, could usher in new forms of smart medicine – and are already in development. Materials like bioactive glass adapt to the body and consequently reduce the formation of scar tissue. Traditionally, medicine has focused on having a minimal impact to the body, whereas future medical procedures may interact with the body in collaborative ways that improve treatment outcomes.

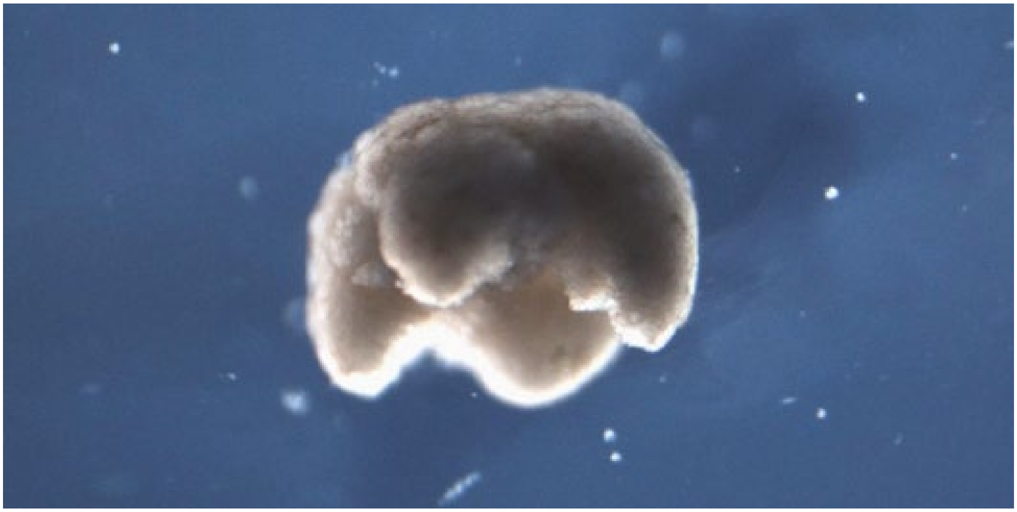


Image:
Researchers have created 'xenobots', biological machines built from living cells scraped from frog embryos.
© Douglas Blackiston/ Sam Kriegman.

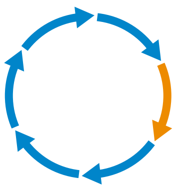
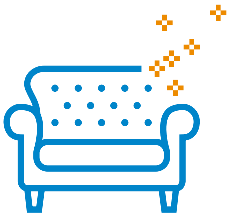
Long term

Fully animate materials have the potential to fundamentally alter the way humans design, build and create the structures that support their society. These long-term possibilities range from tiny molecular machines used in medicine to 'living robots' that perform high-hazard tasks, and from storage and processing of vast volumes of data in DNA to the creation of battery-less devices powered by captured electromagnetic waves.

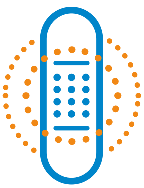
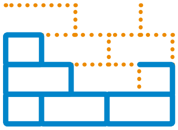
Ultimately, replicas of living cells could combine to drive a new evolutionary tree with different life-forms from those that have evolved on Earth thus far. Such a future would be intrinsically unpredictable. However, if we focus on some specific properties of animate materials now being researched and developed, we can envision how those characteristics might develop over the long term.

The present and future of animate materials

The greatest potential for progress appears to lie where active, adaptive and autonomous properties converge to produce a fully animate outcome.


	A material ecosystem	Animate materials that can be perceived	Materials with multiple actions
PRESENT	Materials' animacy that is self-contained; for example, self-healing concrete.	Active and adaptive materials that, to the naked eye, appear to be just like any other material; for example, self-healing paint, which is superficially indistinguishable from normal paint.	Materials able to perform a limited number of actions and able to respond to a limited number of environmental cues; for example, self-healing concrete, using capsules to release healing agents.
FUTURE	A new material, rather like a new species of plant, could not be simply inserted into an existing ecosystem without considering the knock-on effects.	Novel materials that humans can perceive as animate; for example, furniture that reassembles into new forms or windows that become more or less porous depending on the weather.	Materials able to respond to multiple external stimuli in a range of ways; for example, miniature robots capable of taking on different shapes in response to different stimuli.

	Energy-harvesting	New infrastructure	Materials in medicine	From repair to growth
PRESENT	Active materials that must be provided with a source of energy, such as heat.	Self-healing materials that conform to current standards of construction, architecture and design.	Materials and methods being developed for targeted and specific drug delivery or as biosensors that could be used to improve current diagnostic tests.	‘Living bricks’ containing bacteria that have the capacity to repair themselves.
FUTURE	Materials that can harvest and store energy for future use; for example, by performing a kind of artificial photosynthesis[84,85].	Animate materials that allow buildings to dynamically repair themselves. These will require new standards of construction, architecture and design and may also demand the development of new skill sets among workers.	Materials able to sense, treat and communicate information about medical conditions; for example, devices that can detect metastatic cells and kill them and structural materials that respond to changes in stress or chemical signals to heal tissue.	Living micro-organisms that can be expanded beyond the capacity of self-repair to create materials that grow.

Animate materials will require much more flexible design principles to guide the progress of a more dynamic product.

BOX 2

Adapting to animate materials

How might policies, design principles and standards need to adapt if materials become animate?
Ever since humans began constructing artefacts from materials – whether a stone bridge or a space rocket – design has been regarded as a fixed objective that provides a single outcome for a static product that maintains its form for its lifetime. Conventionally, the aim has been to use materials that resist change: that will not break, corrode or deform. But conversely, for animate materials, the model is that change is deliberately built into the material in such a way that interaction with the world can improve the original design. As a result, animate materials will require much more flexible design principles to guide the progress of a more dynamic product. Such new approaches should be mainly positive, providing product specialists, engineers and others involved with a wealth of new possibilities.

What does the advent of animate materials mean for regulation?
Animate materials will raise a range of issues for regulators, from safety concerns to ethical and practical questions, and new regulation will inevitably be required. As proposed in the calls to action that follow, an 'outcomes-based' approach is advocated whereby regulators define required standards for materials and their impact rather than focusing on manufacturing processes. This would be analogous, for example, to the shift in regulation of some utility companies from emphasis on inputs such as the amount of money spent on delivering a service to outcomes such as its safety and quality.

Might animate materials need to be assessed in different ways?
Materials that have increasing functionality and less predictability may require sophisticated testing regimes which are matched to their uncertain properties and behaviours. Ethical considerations may need to be evaluated much earlier in the design process. Such complications have already become apparent in the development of driverless cars: if more human control is relinquished to the autonomy of the system, it becomes less clear where conventional responsibilities begin and end.

Are animate materials being seriously considered in the architecture community?
Interest in adaptive and active architecture has been increasing recently, with several exhibitions showcasing different ways that active materials could be used. In particular, it is clear that the potential for animate materials is not only to make structures last longer and serve a practical function, but also to enable them to fulfil an aesthetic role and change the way in which people experience buildings[86]. ■

Interest in adaptive and active architecture has been increasing recently, with several exhibitions showcasing different ways that active materials could be used.

Image:
The project HygroSkin – Meteorosensitive Pavilion explores a novel form of climate responsive architecture, its intricate wooden designs autonomously opening and closing in response to changes in the weather. © ICD University of Stuttgart.

Calls to action

- Interdisciplinary science and long-term sustainability
- Risks, safety and regulation
- Communicating with the public

Interdisciplinary science and long-term sustainability

Clearly there is a great deal of diverse research that can be considered relevant to the development of animate materials. But at present there is very little synergy between different strands or disciplines.

CALL TO ACTION 1

More collaboration across disciplines and scales.

The development of animate materials requires collaboration and communication among materials scientists, architects, designers, chemists, biologists, engineers and others, working together to exchange data and share approaches and methods. A focus on the fundamental principles and science of how to develop the core active, adaptive and autonomous properties in different materials systems and at different scales is needed.

Such collaboration can grow from 'bottom-up' activity, whereby researchers start to work across fields, or from 'top-down' actions to fund or co-ordinate relevant programmes. With so much work in progress in different disciplines, a relatively small top-down incentive may be sufficient to prompt a significant increase in partnership working.

An avenue to creating this multidisciplinary community would be for animate materials to be incorporated as one of the UKRI's multidisciplinary programmes. This would facilitate the process of identifying and engaging with researchers and businesses working in both the applied and basic science areas of animate materials.

CALL TO ACTION 2

Build in sustainability and circularity from the outset.

Beyond creating an 'inner ring' of collaboration among researchers developing these technologies, there is scope for a supportive 'outer ring' of environmental scientists, sociologists, policy experts, ethicists, economists, lawyers and other businesses to collaborate with the scientists in applying and commercialising the technologies.

Ideally, animate materials might be manufactured from resources already in circulation. For instance, recovering cobalt from scrap requires just 7 – 14% of the energy needed to extract it from ore[87]. In practice, this will require an economically viable recycling chain of key resources, from the point of waste collection to the sale and dissemination of recycled materials.

As computational methods continue to be developed and applied to finding new materials, it is important that criteria for sustainability are incorporated in how these new compounds are selected or ruled out. The measures of sustainability that are used in research should be adapted over time, and should be developed collaboratively with researchers in other fields who study materials from a systems perspective.

Funding bodies and policy-makers can incentivise the inclusion of sustainability measures by building them into funding applications or evaluations. Furthermore, governments could levy an obsolescence tax on companies based on the average life of their products, tapering off for those that achieve the highest measures of longevity or ease of recycling and reuse.

Risks, safety and regulation

New materials with some degree of animate nature could carry new risks, such as the biosafety of structures that are made in new ways and the difficulty of accounting for autonomous materials that do things that cannot always be predicted. There are three key dimensions to ensuring the safety of such materials: managing their inherent risks; regulating to control their application; and communicating with the public to ensure that perceptions of risk are accurate and proportionate.

Managing inherent risks

The key difference between smart materials and animate materials is that animate materials may make decisions and act autonomously whereas smart materials adapt to the environment in a predetermined and limited manner. With increasing autonomy, however, may come greater complexity and less predictability. For example, active-matter research suggests that materials in which the building blocks are self-propelled may show complex collective behaviours and properties that are hard to predict. Strategies to manage the risk arising from such unpredictability may be needed to ensure that animate materials are safe for humans and the environment.

CALL TO ACTION 3

Make animate materials understandable.

In order to improve animate materials and make them safer, it will be crucial to develop clear ways to diagnose what caused the material to behave in an unexpected desirable or undesirable way. Mechanisms that allow us to understand why animate materials behave in a particular way are analogous to ongoing developments in explainable AI, which seeks to build understanding in how or why an AI-enabled system led to a specific output[88]. This is not just a safety measure; transparency of behaviour might be needed for users to develop trust in the material.

CALL TO ACTION 4

Make autonomy controllable.

In the medium to long term, if and when materials emerge with a high degree of autonomy, measures may be required to manage the risks inherent in such materials and to avoid unexpected consequences. These might include mechanisms to ensure that autonomy among materials is controllable and ultimately can be deactivated.

Regulating applications

In addition to making safe animate materials, there may be regulatory barriers to approving these materials for commercial applications. Animate materials will be fundamentally different from any existing material in that they are built to change and adapt throughout their lifetime. This departure from the expected and desired behaviour of materials will present a challenge when setting the standards that need to be met for a material to be used in particular contexts. As mentioned earlier, an 'outcomes-based' approach is advocated which sets standards for the materials produced as opposed to rules for their production.

For example, a simple definition of toxicity for biomaterials might need to be replaced with a framework that seeks to anticipate possible health hazards from a range of potential biomedical scenarios and responses. Regulations for building materials based on say, criteria for failure or degradation might need also to consider the safety margins of self-repair and self-renewal. There could be a blurring of the boundaries between medical diagnosis and treatment, or of the proper places for and limits of human intervention in those processes.

An even greater legal and regulatory challenge would arise if future animate materials contain biological components – as many of the examples covered in this report do. The UK has strict legislation controlling the deliberate release of genetically modified organisms into the environment, for example[89], which would apply should genetically modified bacteria be used instead of environmental bacteria for self-healing concrete. Large-scale deployment of such materials may only be possible after the long-term safety has been carefully assessed[90]. It is not obvious at this stage that animate materials would require any new biosafety regulations – but they may necessitate such regulations being applied in new contexts.

CALL TO ACTION 5

Create a multidisciplinary committee to discuss and set principles and standards for animate materials.

As animate materials are in the early stages of development, it is difficult to predict to what extent and in what ways regulations, design codes and standards will need to be changed for these materials to be used outside the research context. However, it is important to establish an ongoing discussion of how these materials will be assessed for safety for there to be a smoother transition from the laboratory into widespread commercial application. A multidisciplinary committee could be formed to keep track of advances in animate materials and to decide what regulatory constraints these materials could and should face.

Communicating with the public

A final important dimension to safety is the public's perception of how safe animate materials are.

Would people find durable materials that adapt to the environment exciting, or would they be scared at the prospect of materials that will continuously change in ways that they cannot control or even predict? If the field of animate materials is to develop in a successful and sustainable manner, actors in the field must consider how its applications are perceived, and take action to earn the public's trust over the long term. Clear and timely communications are needed to inform and reassure the public and minimise the risk of the role of animate materials being distorted or misunderstood.

CALL TO ACTION 6

Bring the public in early by fostering collective imagination.

This public engagement would be not just about building trust, but about harnessing ideas, creating a repository of ideas for future applications of animate materials and providing reassurance. In this way, the public could work with researchers to co-curate a 'library of future materials' and to identify characteristics that are desirable and have real social benefit and spot ones that could pose challenges in the future. ■

Acknowledgements

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