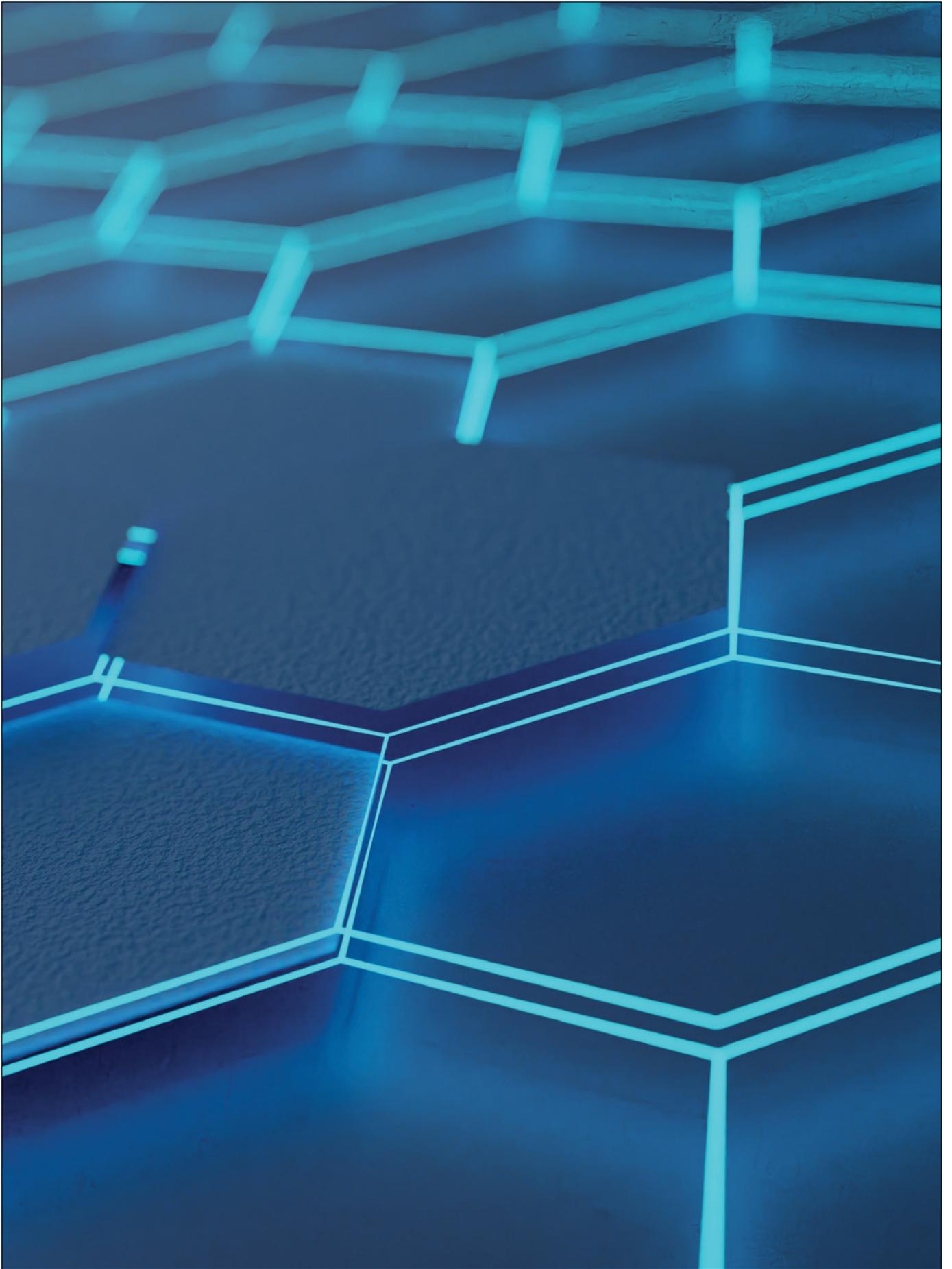STANFORD UNIVERSITY

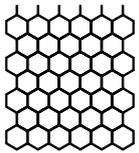# THE STANFORD EMERGING TECHNOLOGY REVIEW 2026

A Report on Ten Key Technologies and Their Policy Implications

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DIRECTOR AND EDITOR IN CHIEF Herbert S. Lin | **MANAGING EDITOR** Martin Giles

05

MATERIALS SCIENCE

KEY TAKEAWAYS

- Materials science is a foundational technology that underlies advances in many other fields, including robotics, space, energy, and synthetic biology.

- The field will exploit artificial intelligence as another promising tool to predict new materials with new properties and to identify novel uses for known materials.

- Future progress in materials science requires new funding mechanisms and access to additional computational power to more effectively transition from innovation to implementation.

Overview

From semiconductors in computer chips to plastics in everyday objects, materials are everywhere. Knowing how to synthesize and process them, as well as understanding their structure and properties, has helped to shape the world around us. Materials science contributes to the development of stronger, lighter, and more flexible materials that improve everything from battery electrodes to medical implants and from automobiles to spacecraft.

It is a wide field. At Stanford University, for example, faculty working on materials science research programs are found in many departments, including materials science and engineering, chemical engineering, electrical engineering, bioengineering, chemistry, and physics.

Broadly speaking, materials science research focuses on four major areas:

- **Synthesis of materials** Understanding how materials can be created and assembled from the atomic to macroscopic scale

- **Characterization of materials** Determining their structure and properties, such as conductivity, chemical reactivity, and elasticity

- **Modeling and computational analysis** Studying how materials are formed and how they adapt in specific situations

- **Manufacturing and scaling** Assessing how materials can be produced and scaled for industrial applications

Basics of Materials Science

All materials are composed of atoms. The periodic table of the elements (figure 5.1) lists all the known types of atoms. Certain ones can be combined with others into molecules that have vastly different properties than the individual atoms involved. For example, table salt consists of sodium and chlorine, which are elements. Sodium burns on contact with water, and chlorine is a poisonous gas, yet the table salt we consume every day is a completely different substance.

The periodic table contains ninety-two naturally occurring elements alongside twenty-six laboratory-synthesized ones (with the latter having an atomic number larger than 92). Elements positioned within the same column exhibit roughly similar properties,

FIGURE 5.1 The periodic table of the elements

Source: Adapted from Wikimedia Commons, CC BY-SA 4.0

enabling researchers to extrapolate findings from one element to others within its group.

Atoms can be arranged spatially in various ways. A crystal, for example, is the result of arranging atoms in a periodically repeating lattice. The silicon wafer at the heart of the semiconductor industry is one such crystal; more precisely, it's a slice of a single silicon crystal.

Many elements can be combined with one another, generating an extensive array of potential compounds from which materials scientists must identify those with practical applications. This effort is increasingly supported by machine learning (ML) techniques that predict material properties with enough accuracy to expedite identification of promising candidate materials.

Molecules, which are composed of atoms, can, in turn, be linked together into structures called macromolecules (see figure 5.2). These can occur naturally, as is the case for proteins, DNAs, and cellulose, or they can be synthesized artificially and used to create things such as polymers. The polymer chains in plastics dictate the material's properties. If the polymer chains can deform and slip past each other, then the material will be flexible and malleable. The harder it is for the polymer chains to move, the more rigid that material will be. Research on new polymer structures can be used to develop plastics that are easier to recycle or have advantageous mechanical properties while weighing less than metals.

FIGURE 5.2 Objects of study in materials science
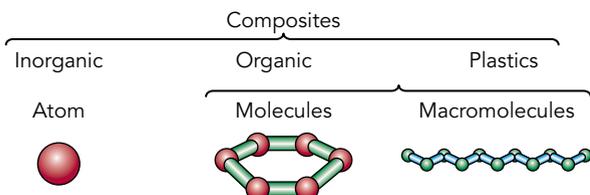
Key Developments

Some interesting present-day applications of materials science are discussed below.

Flexible Electronics

Flexible or stretchable electronics involves the creation of electrical devices that can bend, stretch, and deform without compromising their performance. Such electronics can be used as wearable, skinlike devices. For example, "electronic skin," or e-skin, can conform to real skin and sense things such as temperature and pressure, as well as encode these into electrical signals.[1] A "smart bandage" with integrated sensors to monitor wound conditions and with electrical stimulation can accelerate the time needed to heal chronic wounds by 25 percent.[2]

Additive Manufacturing

One of the most promising advances in materials processing over the past fifteen years is additive manufacturing, colloquially known as 3-D printing. The technology comes in different forms. For instance, a method known as continuous liquid interface production (CLIP) uses directed ultraviolet (UV) light to form structures from a polymer resin.[3] (See figure 5.3.) A key aspect of CLIP is its use of an oxygen-permeable window placed above a UV light projector that prevents the resin from curing in unwanted places.

Especially at high speeds, 3-D printing struggles with producing small features. The 3-D printing process requires several components to perform in concert, including the material resin, the light source, and the build platform where an object is printed. That is technically challenging, but by printing on a tensioned film made from polyethylene terephthalate that's fed through a CLIP printer, it's possible to 3-D print very small particles at a pace of one million a day from a single machine.[4]

FIGURE 5.3   A CLIP-based 3-D printer created a miniature print of the Eiffel Tower
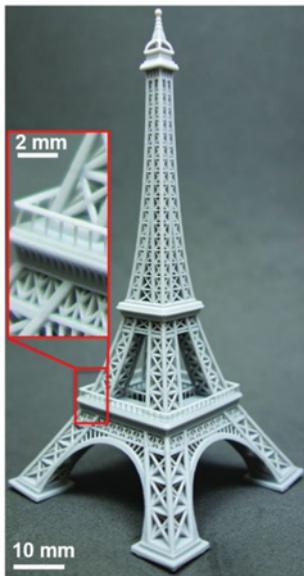
Source: Carbon Inc. / John Tumbleston

Nanotechnology

Nanotechnology is a large subfield of materials science. Size has a profound impact on the properties of a material. Figure 5.4 compares the length of a water molecule (below a nanometer [nm]), a human hair (roughly 10^5 nm), and a human eyeball (at 10^7 nm). A structure is typically referred to as nanoscale if at least one of its dimensions is in the 1 to 100 nm range.

In the past thirty-five years, nanoscience and nanotechnology have attracted enormous interest because the properties of nanoscale materials—including their electronic, optical, magnetic, thermal, and mechanical properties—are often very different from the same material in bulk form.[5] Nanomaterials are classified based on how many of their dimensions are nanoscale:

- **Nanoparticles** have zero dimensions larger than 100 nm.
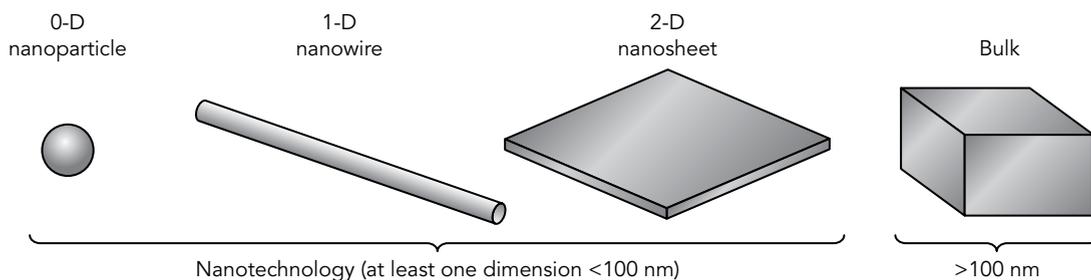
- **Nanowires** (or nanorods) have one dimension larger than 100 nm (i.e., two dimensions are below 100 nm).

- **Nanosheets** have two dimensions larger than 100 nm (i.e., one dimension is less than 100 nm).

- **Bulk** materials have all three dimensions larger than 100 nm (i.e., no dimensions are less than 100 nm).

FIGURE 5.4   The size of nanoscale objects
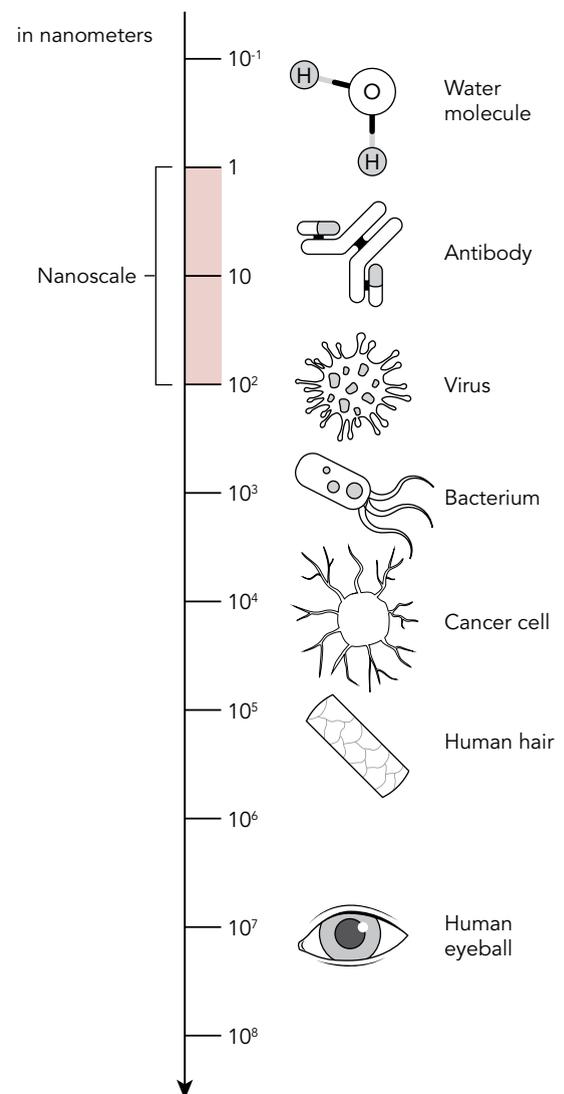
FIGURE 5.5 Dimensionality of nanomaterials

See figure 5.5 for an illustration.

The unique properties of nanomaterials have enabled breakthrough applications across numerous fields, from medicine to electronics. These applications demonstrate how manipulating matter at the nanoscale can solve complex technological challenges and create entirely new possibilities. Some current uses of the technology include the following:

- **Quantum dots** These are metallic, carbonaceous, or semiconductor spherical nanocrystals less than 10 nm in size that emit bright monochromatic light in response to excitation by a light source with a higher energy.[6] Their many applications include being used in medical imaging, as fluorescent markers for biological structures, and in the energy sector, where they enable solar cells to capture more of the solar spectrum.

- **Vaccine stabilization** Vaccines can be encapsulated in lipid nanoparticles (very tiny spheres), making it easier to transport them inside the body and preventing immediate degradation of their contents.[7] This is especially useful for mRNA vaccines, such as the ones developed for COVID-19.

- **Two-dimensional (2-D) semiconductors, graphene, carbon nanotubes, and nanoscale materials** 2-D semiconductors are semiconductors with atomic-scale thickness. These are at the forefront of the next generation of high-tech electronic devices. Active research efforts are designing new methods to integrate 2-D or carbon nanotube semiconductors into electronics that are currently silicon based to improve their energy efficiency and heat management.[8]

Electrochemistry

Electrochemistry studies how electrical energy and chemical reactions interact through electron transfer, typically at electrode-electrolyte interfaces. Electrochemical devices can generate electrical energy through a spontaneous chemical reaction—batteries are a typical example of this—or they can use electrical energy to drive a chemical reaction. Electrocatalytic platforms used to produce hydrogen are a good example of the latter category of device. Materials scientists play a key role in electrochemistry by, for example, developing degradation-resistant battery electrodes and discovering efficient nanocatalysts that drive chemical reactions with electricity.

Batteries

Battery technology has become critical for global energy storage and was recognized by the 2019 Nobel Prize in Chemistry. Current research in

materials science addresses three key challenges related to the field: developing better materials for longer-lasting batteries, creating safer alternatives to flammable components, and finding cost-effective substitutes for expensive raw materials. The main obstacles to progress remain achieving higher energy storage levels and faster charging speeds and reducing manufacturing costs—all while ensuring safety and reliability.

Key developments include the following:

- **Nanotechnology in batteries** Using silicon nanowires as battery anodes allows Li-ion batteries to achieve ten times greater energy capacity and maintain stable performance over time. This is because these nanowires can handle large volume changes during charging without breaking apart, overcoming the main limitation of silicon in traditional battery designs.[9]

- **Improved battery cycling** An ML analysis of 186 batteries revealed that faster charging during battery manufacture actually increases battery lifespan by 50 to 70 percent, contradicting traditional slow-charging methods.[10]

- **Solid-state batteries** These replace flammable liquids with ceramics for better safety. However, metal deposits can still penetrate the ceramics, so success depends on preventing manufacturing defects in them.[11]

- **Polymer coatings for safety** Using such coatings with lithium-metal batteries improves their safety. It also helps them achieve over 99.5 percent efficiency and enables them to carry significantly more electrical energy per kilogram than current lithium-ion technology.[12]

- **Battery electrolyte design** ML helped researchers discover that lower oxygen content in electrolyte solvents leads to better cycling (the repeated process of discharging followed by charging) in lithium-metal batteries.[13]

- **Sodium-ion batteries** Unlike lithium-based batteries, which rely on volatile lithium supplies, sodium-ion batteries use abundant materials and could reach cost parity with lithium ones by 2030. Although they may not outperform lithium-based batteries, sodium-ion batteries will enhance supply chain security if they become more widely available.[14]

Electrocatalysis

Electrocatalysis involves using catalysts to accelerate electrochemical reactions. It is essential in processes like water splitting (definition below), fuel cells, and carbon dioxide (CO_2) recycling. Nanomaterials are particularly well suited as electrocatalysts.[15] This is because of their high surface-to-volume ratio, which means many more active catalytic surface areas can participate in a reaction than would be the case for the same material in bulk.

Water splitting uses electricity to convert water into its constituent parts of hydrogen and oxygen. Platinum and other metal nanoparticles are currently used as electrocatalysts to reduce water to hydrogen gas,[16] although scientists are exploring less expensive replacements for them.[17] This process enables renewable energy storage in the form of hydrogen, which can then be consumed in fuel cells to provide on-demand electricity by combusting the hydrogen when needed.

CO_2 electrocatalysis (also known as CO_2 reduction) is a process that uses electricity to convert CO_2 into valuable products such as synthetic fuels, chemicals like methanol and ethylene, and precursors for plastics. It achieves this through the use of specialized catalysts in an electrochemical cell.[18] By transforming CO_2 into essential commodities, this technology provides a route for reducing it in the atmosphere and for storing electricity in chemical form.

> One of the foremost challenges of materials science as a discipline is the vast number of possible materials and material combinations that can be used and the associated time and cost involved in synthesis and characterization.

Biosensing

Electrochemistry enables the detection of biological molecules—such as metabolites, hormones, and therapeutic agents—through the use of electrical signals. In electrochemical biosensors, a special biological component like an enzyme, antibody, single strand of DNA, or other material is placed on an electrode and reacts specifically with the substance the sensor is trying to detect. This interaction generates or alters an electrochemical signal (e.g., an electrical current) that is measured by the electrode. The high sensitivity, low cost, and portability of electrochemical biosensors, such as wearable glucose sensors for managing diabetes, make them ideal for medical diagnostics, environmental monitoring, and pathogen detection.

The Application of Artificial Intelligence in Materials Science

One of the foremost challenges of materials science as a discipline is the vast number of possible materials and material combinations that can be used and the associated time and cost involved in synthesis and characterization. ML offers a solution by recognizing patterns in existing data that can help models make predictions about new materials and their properties.[19] While this approach has been successful with relatively simple materials, complex ones remain difficult to predict.

To truly understand and forecast the properties of materials, more accurate, comprehensive, and tailored databases are needed. Their many applications could include helping accelerate the development of materials that enable researchers to overcome bottlenecks in chip assembly as semiconductors continue to be miniaturized. Databases such as the Materials Project, led by Lawrence Berkeley National Laboratory, represent the significant effort being made to improve data gathering.[20] However, these efforts are still limited with respect to the range of materials' properties that are covered. Major companies are already using artificial intelligence (AI) to discover new materials. Google DeepMind's Graph Networks project uses neural networks to predict material properties, while IBM, Citrine Informatics, and MaterialsZone combine materials expertise with data science to speed up development and improve product design.

To tackle the problem of limited experimental data, researchers are developing autonomous laboratories that can quickly synthesize and test materials at scale. The A-Lab at University of California–Berkeley (figure 5.6) exemplifies this approach, using robotic arms and AI-guided synthesis alongside automated characterization equipment to discover new materials.[21] However, the scientific community has questioned the accuracy of A-Lab's characterization work and structural analysis, with researchers noting areas for improvement.[22] This emphasizes that computational and integrated approaches still need careful validation and human oversight but hold great promise. Future automated labs may be capable of accurately predicting and creating new

Source: © 2023 The Regents of the University of California, Lawrence Berkeley National Laboratory

materials, reducing the human effort needed to design them.

By combining advanced algorithms with expanded databases and automated experimentation, researchers are working on exciting efforts to explore the vast landscape of possible materials more efficiently than ever before.

Over the Horizon

Enhancing the Human Body Through Materials Science

Advancements in materials science are revolutionizing how we repair, restore, and augment the human body. From supporting regenerative medicine to brain–machine interfaces, engineered materials are enabling technologies once thought to be science fiction. Prosthetics and bionics have made major leaps thanks to high-performance materials. Lightweight composites like carbon fiber and shape memory alloys allow artificial limbs to move naturally and respond dynamically. Electrically conductive and biocompatible polymers help to form soft bioelectronic interfaces that are powering neuroprosthetics.[23] These prosthetics aim to restore and enhance motor and sensory function by connecting directly with the nervous system.

A particularly exciting frontier is brain–machine interfaces, which depend on materials that are both biocompatible and capable of recording or stimulating neural activity. (These interfaces are discussed further in chapter 6, on neuroscience.) Pliant, ultra-thin electrodes made from composite materials, such as flexible polymers embedded with 2-D conductors like graphene, carbon nanotubes, and metal nanowires, are designed to conform to the brain's surface without damaging tissue.[24] These materials interface seamlessly with neurons and can detect and decode brain signals with high resolution. This,

in turn, enables the execution of computer tasks and the control of robotic limbs, providing a means of communication for paralyzed patients.

While scientists improve brain–machine interfaces for neural activity decoding, the next goal is active neuromodulation, or the ability to control neural activity with an implanted device. Currently, deep-brain neuromodulatory devices are being used to successfully mitigate symptoms of Parkinson's disease. Researchers are also working with them to affect mood and memory.[25] Such advances suggest that our ability to engineer materials is enabling the construction of devices that are fundamentally expanding what the human body and mind can do.

Metamaterials: Programming Physical Properties

Metamaterials are artificially engineered materials with optical or acoustic properties not found in nature. These properties arise from arranging engineered microscopic structural components in particular patterns, with feature sizes smaller than the wavelength of light or sound that is of interest. The internal structure of metamaterials enables extraordinary manipulation of electromagnetic or acoustic waves, including bending them in previously impossible ways, opening new possibilities for controlling light or sound.

In recent years, the field has shifted from proof-of-concept demonstrations to various applications.[26] These include:

○— **Invisibility cloaks**   Bending light around objects to render them nearly invisible to the naked eye

○— **Superlenses**   Imaging with resolution beyond the diffraction limit in microscopes and medical imaging

○— **Advanced radio antennas**   Creating compact, efficient antennas with improved signal strength for communications

○— **Seismic protection**   Shielding buildings from earthquakes by redirecting seismic waves

○— **Acoustic control**   Improved materials for sound insulation, muffling vibrations, or sound filtering in medical and industrial settings

Advances in manufacturing and fabrication have been the main reason for the implementation of metamaterials in the physical world. Advances in laser processing and multi-material processing, among other things, have made complex metamaterial designs commercially viable at scale.

In the future, new applications in telecommunications, biomedicine, and energy are expected.[27] Reconfigurable intelligent antenna surfaces for 6G communications show promise for future growth. Biomedical applications include metamaterial-enhanced wireless power for implants and multi-disease diagnosis with high-frequency biosensors. Metamaterials are also well positioned as a foundational technology for next-generation systems spanning from quantum computing to autonomous sensing.

Policy Issues

Research Infrastructure

Today's materials science research infrastructure does not adequately support the transition from research to real-world applications at scale. Such transitions generally require construction of a small-scale pilot project to demonstrate the feasibility of potential large-scale manufacturing. At this point, the technology is too mature to qualify for most research funding—because basic science does not address issues related to scaling up—but not mature enough to be commercialized by actual companies.

Neither government funders nor venture capital investors are particularly enthusiastic about financing

Historically, the United States has led the world in nanotechnology, but the gap between it and China has narrowed.

pilot projects given the significant up-front invest- ment needed. Therefore, different forms of funding are required to bridge the gap between bench-scale research and company-level investment. Although the US government does occasionally support pilot projects, additional support in this area could also establish national rapid prototyping centers where academic researchers can find the help and tools necessary to build prototypes and pilot plants for their technology.

Today's research processes are also ill-suited to rapid transitions to real-world applications. Such processes emphasize sequential steps. The standard process has been to characterize a material and then proceed to a simple demonstration of how it might be used. Today, addressing big societal challenges calls for a more scalable, system-level approach that involves extensive rapid prototyping and fast, reli- able demonstrations to provide feedback on the potential value of specific materials and to fill in knowledge gaps.

Current research arrangements make this difficult. For example, in collaborations with a medical school, it is often necessary to bring almost-finished prod- ucts to clinical tests to validate the true impact of a new medical device that is using innovative mate- rials. There is typically a window of thirty minutes or less in which to place a device on a patient and gather data. This means that any malfunction, such as a sudden equipment failure or a loose wire, can jeopardize an entire experiment and potentially halt future patient interactions. Lab-assembled devices

may not meet this standard of reliability, even if they do demonstrate the value of the underlying science.

Regulation of Products Incorporating (Nano)Materials and Environmental Concerns

As with other areas of technology, materials science faces concerns about the appropriate regulatory balance between the need to ensure public safety and the imperative to innovate quickly and leapfrog possible competitors. In the biomedical space, the US Food and Drug Administration (FDA) created a Nanotechnology Regulatory Science Research Plan in 2013.[28] Today, FDA regulation and review of nano- technology is governed by Executive Order 13563.[29] Outside of biomedicine, regulation of and infrastruc- ture for nanomaterials research from the govern- ment side is based largely in the agencies involved in the National Nanotechnology Initiative. These include the US Department of Energy, the National Cancer Institute, the National Institutes of Health, the National Institute of Standards and Technology in the Department of Commerce, and the National Science Foundation.

Nanoparticles raise particular concerns because their small size may enable them to pass through various biological borders, such as cell membranes or the blood–brain barrier, potentially harming bio- logical systems. Nanoscale particles inhaled into the lungs, for example, may lodge there permanently, causing severe health outcomes, including pulmo- nary inflammation, lung cancer, and penetration into

the brain and skin.[30] Nanoparticles may result from air pollution and even doing laundry. However, the most common source of nanoparticles is through combustion linked to the mechanical abrasion of common objects such as cookware and car tires. By comparison, laboratory-engineered nanoparticles are an insignificant source of nanoparticle contamination today.

Finally, end-of-life considerations that take into account environmental sustainability and resource conservation are inherently a part of developing and distributing new materials. This is especially important for plastics and materials containing per- and polyfluoroalkyl substances (PFAS), which pose significant environmental and health risks. Material developers can incorporate recyclability into their design processes. For PFAS and other persistent chemicals, the US Environmental Protection Agency strategic road map of October 2021 provides guidance for their use and disposal, and calls for research into safe alternatives and effective degradation methods.[31]

The Mineral Supply Chain

Sourcing minerals involves a complex, global network that encompasses the mining, processing, and distribution of critical raw elements such as lithium, cobalt, nickel, copper, and rare-earth elements (e.g., neodymium and yttrium). These minerals are in high demand for technologies like batteries, renewable energy systems, and consumer and defense electronics.

The mining of these minerals is often concentrated in a few sites that are controlled by countries that may not be aligned with the United States. For example, the Democratic Republic of the Congo exports 74 percent of the world's cobalt from mines that exploit slave and child labor and are operated by Chinese companies.[32] Additionally, China accounts for over 90 percent of the refining capacity of rare-earth elements, which are critical for the manufacturing of magnets used in modern electronics

and other industries.[33] This means China can unilaterally squeeze the supply of key minerals and negatively impact electronics manufacturing in the United States and other countries.

It is imperative that America's supply chain for minerals becomes more secure. Solutions include diversifying sources, investing in recycling and the reuse of materials that would otherwise have to be mined, and developing alternative materials. Strengthening domestic processing capabilities and fostering international partnerships are also critical strategies to enhance security, transparency, and resilience in the mineral supply chain.

Foreign Collaboration and Competition

Historically, the United States has led the world in nanotechnology, but the gap between it and China has narrowed. For example, in 2024, China's output of publications in nanotechnology was about 5.3 times higher than that of the United States.[34]

As great power competition intensifies, many researchers are concerned that fundamental research in the United States could now be subject to export controls. Policy ambiguity can inadvertently hinder innovation by creating obstacles for foreign researchers wishing to contribute to work in America and by deterring international collaborations with allies and partners who are important for advancing the field.

It is essential that scholars can collaborate broadly on fundamental research at an international level so that the exchange of ideas and perspectives can foster new ways of thinking that increase the likelihood and speed of technological breakthroughs. In nanomaterials, for example, researchers in South Korea are making significant strides with biomedical applications and applications for consumer electronics. There is an urgent need for clarification of these policies, particularly those delineating fundamental research and export-controlled research.

Infrastructure for ML-Assisted Materials Science

The United States benefits from having some of the world's largest supercomputing resources, which are essential not only for ML but also for developing extensive databases. However, better access to computing power is necessary for researchers in materials science to generate and analyze databases effectively. Greater access to data, including to databases that might not always be openly available to academics, is also needed.

One additional area where policymakers could have a significant impact is in bridging the gap between the scientific community and makers of computational hardware. Frequent changes in computing architectures can lead to a loss of productivity for researchers because code must be constantly updated. Improved collaboration with hardware manufacturers and other providers of computing resources could ensure scientific needs are better aligned with advances in computing technology, enhancing overall research efficiency.

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