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Nanotechnology Applications in Environment Management

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ABSTRACT: Nanotechnology was defined by the National Nanotechnology Initiative as the manipulation of matter with at least one dimension sized from 1 to 100 nanometers (nm). At this scale, commonly known as the nanoscale, surface area and quantum mechanical effects become important in describing properties of matter. The definition of nanotechnology is inclusive of all types of research and technologies that deal with these special properties. It is therefore common to see the plural form "nanotechnologies" as well as "nanoscale technologies" to refer to the broad range of research and applications whose common trait is size.[1] An earlier description of nanotechnology referred to the particular technological goal of precisely manipulating atoms and molecules for fabrication of macroscale products, also now referred to as molecular nanotechnology.

KEYWORDS-nanotechnology, environment, nanoscale, molecular, research

I. INTRODUCTION

Nanotechnology as defined by size is naturally broad, including fields of science as diverse as surface science, organic chemistry, molecular biology, semiconductor physics, energy storage,[3][4] engineering,[5] microfabrication,[6] and molecular engineering.[7] The associated research and applications are equally diverse, ranging from extensions of conventional device physics to completely new approaches based upon molecular self-assembly,[8] from developing new materials with dimensions on the nanoscale to direct control of matter on the atomic scale.

Scientists currently debate the future implications of nanotechnology. Nanotechnology may be able to create many new materials and devices with a vast range of applications, such as in nanomedicine, nanoelectronics, biomaterials energy production, and consumer products. On the other hand, nanotechnology raises many of the same issues as any new technology, including concerns about the toxicity and environmental impact of nanomaterials,[9] and their potential effects on global economics, as well as speculation about various doomsday scenarios. These concerns have led to a debate among advocacy groups and governments on whether special regulation of nanotechnology is warranted.

The concepts that seeded nanotechnology were first discussed in 1959 by physicist Richard Feynman in his talk There's Plenty of Room at the Bottom, in which he described the possibility of synthesis via direct manipulation of atoms.

The term "nano-technology" was first used by Norio Taniguchi in 1974, though it was not widely known. Inspired by Feynman's concepts, K. Eric Drexler used the term "nanotechnology" in his 1986 book Engines of Creation: The Coming Era of Nanotechnology, which proposed the idea of a nanoscale "assembler" which would be able to build a copy of itself and of other items of arbitrary complexity with atomic control. Also in 1986, Drexler co-founded The Foresight Institute (with which he is no longer affiliated) to help increase public awareness and understanding of nanotechnology concepts and implications.

The emergence of nanotechnology as a field in the 1980s occurred through convergence of Drexler's theoretical and public work, which developed and popularized a conceptual framework for nanotechnology, and high-visibility experimental advances that drew additional wide-scale attention to the prospects of atomic control of matter. In the 1980s, two major breakthroughs sparked the growth of nanotechnology in the modern era. First, the invention of the scanning tunneling microscope in 1981 which enabled visualization of individual atoms and bonds, and was successfully used to manipulate individual atoms in 1989. The microscope's developers Gerd Binnig and Heinrich Rohrer at IBM Zurich Research Laboratory received a Nobel Prize in Physics in 1986.[10][11] Binnig, Quate and Gerber also invented the analogous atomic force microscope that year.

Second, fullerenes were discovered in 1985 by Harry Kroto, Richard Smalley, and Robert Curl, who together won the 1996 Nobel Prize in Chemistry.[12][13] C_{60} was not initially described as nanotechnology; the term was used regarding subsequent work with related carbon nanotubes (sometimes called graphene tubes or Bucky tubes) which suggested

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potential applications for nanoscale electronics and devices. The discovery of carbon nanotubes is largely attributed to Sumio Iijima of NEC in 1991,[14] for which Iijima won the inaugural 2008 Kavli Prize in Nanoscience.

In the early 2000s, the field garnered increased scientific, political, and commercial attention that led to both controversy and progress. Controversies emerged regarding the definitions and potential implications of nanotechnologies, exemplified by the Royal Society's report on nanotechnology.[15] Challenges were raised regarding the feasibility of applications envisioned by advocates of molecular nanotechnology, which culminated in a public debate between Drexler and Smalley in 2001 and 2003.[16]

Meanwhile, commercialization of products based on advancements in nanoscale technologies began emerging. These products are limited to bulk applications of nanomaterials and do not involve atomic control of matter. Some examples include the Silver Nano platform for using silver nanoparticles as an antibacterial agent, nanoparticle-based transparent sunscreens, carbon fiber strengthening using silica nanoparticles, and carbon nanotubes for stain-resistant textiles.[17][18]

Governments moved to promote and fund research into nanotechnology, such as in the U.S. with the National Nanotechnology Initiative, which formalized a size-based definition of nanotechnology and established funding for research on the nanoscale, and in Europe via the European Framework Programmes for Research and Technological Development.

By the mid-2000s new and serious scientific attention began to flourish. Projects emerged to produce nanotechnology roadmaps[19][20] which center on atomically precise manipulation of matter and discuss existing and projected capabilities, goals, and applications.

Fundamental concepts

Nanotechnology is the science and engineering of functional systems at the molecular scale. This covers both current work and concepts that are more advanced. In its original sense, nanotechnology refers to the projected ability to construct items from the bottom up, using techniques and tools being developed today to make complete, high-performance products.

One nanometer (nm) is one billionth, or 10^{-9}, of a meter. By comparison, typical carbon-carbon bond lengths, or the spacing between these atoms in a molecule, are in the range 0.12–0.15 nm, and a DNA double-helix has a diameter around 2 nm. On the other hand, the smallest cellular life-forms, the bacteria of the genus Mycoplasma, are around 200 nm in length. By convention, nanotechnology is taken as the scale range 1 to 100 nm following the definition used by the National Nanotechnology Initiative in the US. The lower limit is set by the size of atoms (hydrogen has the smallest atoms, which are approximately a quarter of a nm kinetic diameter) since nanotechnology must build its devices from atoms and molecules. The upper limit is more or less arbitrary but is around the size below which the phenomena not observed in larger structures start to become apparent and can be made use of in the nano device.[21] These new phenomena make nanotechnology distinct from devices which are merely miniaturised versions of an equivalent macroscopic device; such devices are on a larger scale and come under the description of microtechnology.[22]

To put that scale in another context, the comparative size of a nanometer to a meter is the same as that of a marble to the size of the earth.[23] Or another way of putting it: a nanometer is the amount an average man's beard grows in the time it takes him to raise the razor to his face.[23]

Two main approaches are used in nanotechnology. In the "bottom-up" approach, materials and devices are built from molecular components which assemble themselves chemically by principles of molecular recognition.[24] In the "top-down" approach, nano-objects are constructed from larger entities without atomic-level control.[25]

Areas of physics such as nanoelectronics, nanomechanics, nanophotonics and nanoionics have evolved during the last few decades to provide a basic scientific foundation of nanotechnology.

Larger to smaller: a materials perspective

Several phenomena become pronounced as the size of the system decreases. These include statistical mechanical effects, as well as quantum mechanical effects, for example the "quantum size effect" where the electronic properties of solids are altered with great reductions in particle size. This effect does not come into play by going from macro to micro dimensions. However, quantum effects can become significant when the nanometer size range is reached, typically at distances of 100 nanometers or less, the so-called quantum realm. Additionally, a number of physical (mechanical, electrical, optical, etc.) properties change when compared to macroscopic systems. One example is the increase in surface area to volume ratio altering mechanical, thermal and catalytic properties of materials.

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Diffusion and reactions at nanoscale, nanostructures materials and nanodevices with fast ion transport are generally referred to nanoionics. Mechanical properties of nanosystems are of interest in the nanomechanics research. The catalytic activity of nanomaterials also opens potential risks in their interaction with biomaterials.

Materials reduced to the nanoscale can show different properties compared to what they exhibit on a macroscale, enabling unique applications. For instance, opaque substances can become transparent (copper); stable materials can turn combustible (aluminium); insoluble materials may become soluble (gold). A material such as gold, which is chemically inert at normal scales, can serve as a potent chemical catalyst at nanoscales. Much of the fascination with nanotechnology stems from these quantum and surface phenomena that matter exhibits at the nanoscale.[26]

Simple to complex: a molecular perspective

Modern synthetic chemistry has reached the point where it is possible to prepare small molecules to almost any structure. These methods are used today to manufacture a wide variety of useful chemicals such as pharmaceuticals or commercial polymers. This ability raises the question of extending this kind of control to the next-larger level, seeking methods to assemble these single molecules into supramolecular assemblies consisting of many molecules arranged in a well defined manner.

These approaches utilize the concepts of molecular self-assembly and/or supramolecular chemistry to automatically arrange themselves into some useful conformation through a bottom-up approach. The concept of molecular recognition is especially important: molecules can be designed so that a specific configuration or arrangement is favored due to non-covalent intermolecular forces. The Watson–Crick basepairing rules are a direct result of this, as is the specificity of an enzyme being targeted to a single substrate, or the specific folding of the protein itself. Thus, two or more components can be designed to be complementary and mutually attractive so that they make a more complex and useful whole.

Such bottom-up approaches should be capable of producing devices in parallel and be much cheaper than top-down methods, but could potentially be overwhelmed as the size and complexity of the desired assembly increases. Most useful structures require complex and thermodynamically unlikely arrangements of atoms. Nevertheless, there are many examples of self-assembly based on molecular recognition in biology, most notably Watson–Crick basepairing and enzyme-substrate interactions. The challenge for nanotechnology is whether these principles can be used to engineer new constructs in addition to natural ones.

Molecular nanotechnology: a long-term view

Molecular nanotechnology, sometimes called molecular manufacturing, describes engineered nanosystems (nanoscale machines) operating on the molecular scale. Molecular nanotechnology is especially associated with the molecular assembler, a machine that can produce a desired structure or device atom-by-atom using the principles of mechanosynthesis. Manufacturing in the context of productive nanosystems is not related to, and should be clearly distinguished from, the conventional technologies used to manufacture nanomaterials such as carbon nanotubes and nanoparticles.

When the term "nanotechnology" was independently coined and popularized by Eric Drexler (who at the time was unaware of an earlier usage by Norio Taniguchi) it referred to a future manufacturing technology based on molecular machine systems. The premise was that molecular-scale biological analogies of traditional machine components demonstrated molecular machines were possible: by the countless examples found in biology, it is known that sophisticated, stochastically optimized biological machines can be produced.

It is hoped that developments in nanotechnology will make possible their construction by some other means, perhaps using biomimetic principles. However, Drexler and other researchers[27] have proposed that advanced nanotechnology, although perhaps initially implemented by biomimetic means, ultimately could be based on mechanical engineering principles, namely, a manufacturing technology based on the mechanical functionality of these components (such as gears, bearings, motors, and structural members) that would enable programmable, positional assembly to atomic specification.[28] The physics and engineering performance of exemplar designs were analyzed in Drexler's book Nanosystems: Molecular Machinery, Manufacturing, and Computation.[2]

In general it is very difficult to assemble devices on the atomic scale, as one has to position atoms on other atoms of comparable size and stickiness. Another view, put forth by Carlo Montemagno,[29] is that future nanosystems will be hybrids of silicon technology and biological molecular machines. Richard Smalley argued that mechanosynthesis are impossible due to the difficulties in mechanically manipulating individual molecules.

This led to an exchange of letters in the ACS publication Chemical & Engineering News in 2003.[30] Though biology clearly demonstrates that molecular machine systems are possible, non-biological molecular machines are today only in

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their infancy. Leaders in research on non-biological molecular machines are Alex Zettl and his colleagues at Lawrence Berkeley Laboratories and UC Berkeley.[31] They have constructed at least three distinct molecular devices whose motion is controlled from the desktop with changing voltage: a nanotube nanomotor, a molecular actuator,[32] and a nanoelectromechanical relaxation oscillator.[33] See nanotube nanomotor for more examples.

An experiment indicating that positional molecular assembly is possible was performed by Ho and Lee at Cornell University in 1999. They used a scanning tunneling microscope to move an individual carbon monoxide molecule (CO) to an individual iron atom (Fe) sitting on a flat silver crystal, and chemically bound the CO to the Fe by applying a voltage.

Nanomaterials

The nanomaterials field includes subfields which develop or study materials having unique properties arising from their nanoscale dimensions.[36]

- Interface and colloid science has given rise to many materials which may be useful in nanotechnology, such as carbon nanotubes and other fullerenes, and various nanoparticles and nanorods. Nanomaterials with fast ion transport are related also to nanoionics and nanoelectronics.
- Nanoscale materials can also be used for bulk applications; most present commercial applications of nanotechnology are of this flavor.
- Progress has been made in using these materials for medical applications; see Nanomedicine.
- Nanoscale materials such as nanopillars are sometimes used in solar cells which combats the cost of traditional silicon solar cells.
- Development of applications incorporating semiconductor nanoparticles to be used in the next generation of products, such as display technology, lighting, solar cells and biological imaging; see quantum dots.
- Recent application of nanomaterials include a range of biomedical applications, such as tissue engineering, drug delivery, antibacterials and biosensors.[37][38][39][40][41]

Bottom-up approaches

These seek to arrange smaller components into more complex assemblies.

- DNA nanotechnology utilizes the specificity of Watson–Crick basepairing to construct well-defined structures out of DNA and other nucleic acids.
- Approaches from the field of "classical" chemical synthesis (Inorganic and organic synthesis) also aim at designing molecules with well-defined shape (e.g. bis-peptides[42]).
- More generally, molecular self-assembly seeks to use concepts of supramolecular chemistry, and molecular recognition in particular, to cause single-molecule components to automatically arrange themselves into some useful conformation.
- Atomic force microscope tips can be used as a nanoscale "write head" to deposit a chemical upon a surface in a desired pattern in a process called dip pen nanolithography. This technique fits into the larger subfield of nanolithography.
- Molecular Beam Epitaxy allows for bottom up assemblies of materials, most notably semiconductor materials commonly used in chip and computing applications, stacks, gating, and nanowire lasers.

Top-down approaches

These seek to create smaller devices by using larger ones to direct their assembly.

- Many technologies that descended from conventional solid-state silicon methods for fabricating microprocessors are now capable of creating features smaller than 100 nm, falling under the definition of nanotechnology. Giant magnetoresistance-based hard drives already on the market fit this description,[43] as do atomic layer deposition (ALD) techniques. Peter Grünberg and Albert Fert received the Nobel Prize in Physics in 2007 for their discovery of Giant magnetoresistance and contributions to the field of spintronics.[44]
- Solid-state techniques can also be used to create devices known as nanoelectromechanical systems or NEMS, which are related to microelectromechanical systems or MEMS.

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- Focused ion beams can directly remove material, or even deposit material when suitable precursor gasses are applied at the same time. For example, this technique is used routinely to create sub-100 nm sections of material for analysis in Transmission electron microscopy.
- Atomic force microscope tips can be used as a nanoscale "write head" to deposit a resist, which is then followed by an etching process to remove material in a top-down method.

Functional approaches

These seek to develop components of a desired functionality without regard to how they might be assembled.

- Magnetic assembly for the synthesis of anisotropic superparamagnetic materials such as recently presented magnetic nano chains.[24]
- Molecular scale electronics seeks to develop molecules with useful electronic properties. These could then be used as single-molecule components in a nanoelectronic device.[45] For an example see rotaxane.
- Synthetic chemical methods can also be used to create synthetic molecular motors, such as in a so-called nanocar.

Biomimetic approaches

- Bionics or biomimicry seeks to apply biological methods and systems found in nature, to the study and design of engineering systems and modern technology. Biomineralization is one example of the systems studied.
- Bionanotechnology is the use of biomolecules for applications in nanotechnology, including use of viruses and lipid assemblies.[46][47] Nanocellulose, a nanopolymer often used for bulk-scale applications, is a green material that has gained interests in nanotechnology and green chemistry owing to its useful properties such as abundance, high aspect ratio, good mechanical properties, renewability, and biocompatibility.[48]

Speculative

These subfields seek to anticipate what inventions nanotechnology might yield, or attempt to propose an agenda along which inquiry might progress. These often take a big-picture view of nanotechnology, with more emphasis on its societal implications than the details of how such inventions could actually be created.

- Molecular nanotechnology is a proposed approach which involves manipulating single molecules in finely controlled, deterministic ways. This is more theoretical than the other subfields, and many of its proposed techniques are beyond current capabilities.
- Nanorobotics centers on self-sufficient machines of some functionality operating at the nanoscale. There are hopes for applying nanorobots in medicine.[49][50] Nevertheless, progress on innovative materials and methodologies has been demonstrated with some patents granted about new nanomanufacturing devices for future commercial applications, which also progressively helps in the development towards nanorobots with the use of embedded nanobioelectronics concepts.[51][52]
- Productive nanosystems are "systems of nanosystems" which will be complex nanosystems that produce atomically precise parts for other nanosystems, not necessarily using novel nanoscale-emergent properties, but well-understood fundamentals of manufacturing. Because of the discrete (i.e. atomic) nature of matter and the possibility of exponential growth, this stage is seen as the basis of another industrial revolution. Mihail Roco, one of the architects of the USA's National Nanotechnology Initiative, has proposed four states of nanotechnology that seem to parallel the technical progress of the Industrial Revolution, progressing from passive nanostructures to active nanodevices to complex nanomachines and ultimately to productive nanosystems.[53]
- Programmable matter seeks to design materials whose properties can be easily, reversibly and externally controlled though a fusion of information science and materials science.
- Due to the popularity and media exposure of the term nanotechnology, the words picotechnology and femtotechnology have been coined in analogy to it, although these are only used rarely and informally.

Dimensionality in nanomaterials

Nanomaterials can be classified in 0D, 1D, 2D and 3D nanomaterials. The dimensionality play a major role in determining the characteristic of nanomaterials including physical, chemical and biological characteristics. With the decrease in dimensionality, an increase in surface-to-volume ratio is observed. This indicate that smaller dimensional nanomaterials have higher surface area compared to 3D nanomaterials. Recently, two dimensional (2D) nanomaterials are extensively investigated for electronic, biomedical, drug delivery and biosensor applications.

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II. DISCUSSION

There are several important modern developments. The atomic force microscope (AFM) and the Scanning Tunneling Microscope (STM) are two early versions of scanning probes that launched nanotechnology. There are other types of scanning probe microscopy. Although conceptually similar to the scanning confocal microscope developed by Marvin Minsky in 1961 and the scanning acoustic microscope (SAM) developed by Calvin Quate and coworkers in the 1970s, newer scanning probe microscopes have much higher resolution, since they are not limited by the wavelength of sound or light.

The tip of a scanning probe can also be used to manipulate nanostructures (a process called positional assembly). Feature-oriented scanning methodology may be a promising way to implement these nanomanipulations in automatic mode.[54][55] However, this is still a slow process because of low scanning velocity of the microscope.

Various techniques of nanolithography such as optical lithography, X-ray lithography, dip pen nanolithography, electron beam lithography or nanoimprint lithography were also developed. Lithography is a top-down fabrication technique where a bulk material is reduced in size to nanoscale pattern.

Another group of nanotechnological techniques include those used for fabrication of nanotubes and nanowires, those used in semiconductor fabrication such as deep ultraviolet lithography, electron beam lithography, focused ion beam machining, nanoimprint lithography, atomic layer deposition, and molecular vapor deposition, and further including molecular self-assembly techniques such as those employing di-block copolymers. The precursors of these techniques preceded the nanotech era, and are extensions in the development of scientific advancements rather than techniques which were devised with the sole purpose of creating nanotechnology and which were results of nanotechnology research.[56]

The top-down approach anticipates nanodevices that must be built piece by piece in stages, much as manufactured items are made. Scanning probe microscopy is an important technique both for characterization and synthesis of nanomaterials. Atomic force microscopes and scanning tunneling microscopes can be used to look at surfaces and to move atoms around. By designing different tips for these microscopes, they can be used for carving out structures on surfaces and to help guide self-assembling structures. By using, for example, feature-oriented scanning approach, atoms or molecules can be moved around on a surface with scanning probe microscopy techniques.[54][55] At present, it is expensive and time-consuming for mass production but very suitable for laboratory experimentation.

In contrast, bottom-up techniques build or grow larger structures atom by atom or molecule by molecule. These techniques include chemical synthesis, self-assembly and positional assembly. Dual polarisation interferometry is one tool suitable for characterisation of self assembled thin films. Another variation of the bottom-up approach is molecular beam epitaxy or MBE. Researchers at Bell Telephone Laboratories like John R. Arthur. Alfred Y. Cho, and Art C. Gossard developed and implemented MBE as a research tool in the late 1960s and 1970s. Samples made by MBE were key to the discovery of the fractional quantum Hall effect for which the 1998 Nobel Prize in Physics was awarded. MBE allows scientists to lay down atomically precise layers of atoms and, in the process, build up complex structures. Important for research on semiconductors, MBE is also widely used to make samples and devices for the newly emerging field of spintronics.

However, new therapeutic products, based on responsive nanomaterials, such as the ultradeformable, stress-sensitive Transfersome vesicles, are under development and already approved for human use in some countries.[57]

As of August 21, 2008, the Project on Emerging Nanotechnologies estimates that over 800 manufacturer-identified nanotech products are publicly available, with new ones hitting the market at a pace of 3–4 per week.[18] The project lists all of the products in a publicly accessible online database. Most applications are limited to the use of "firstgeneration" passive nanomaterials which includes titanium dioxide in sunscreen, cosmetics, surface coatings,[58] and some food products; Carbon allotropes used to produce gecko tape; silver in food packaging, clothing, disinfectants and household appliances; zinc oxide in sunscreens and cosmetics, surface coatings, paints and outdoor furniture varnishes; and cerium oxide as a fuel catalyst.[17]

Further applications allow tennis balls to last longer, golf balls to fly straighter, and even bowling balls to become more durable and have a harder surface. Trousers and socks have been infused with nanotechnology so that they will last longer and keep people cool in the summer. Bandages are being infused with silver nanoparticles to heal cuts faster.[59] Video game consoles and personal computers may become cheaper, faster, and contain more memory thanks to nanotechnology.[60] Also, to build structures for on chip computing with light, for example on chip optical quantum information processing, and picosecond transmission of information.[61]

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Nanotechnology may have the ability to make existing medical applications cheaper and easier to use in places like the general practitioners' offices and at homes.[62] Cars are being manufactured using nanomaterials in such ways that car parts require fewer metals during manufacturing and less fuel to operate in the future.[63]

Scientists are now turning to nanotechnology in an attempt to develop diesel engines with cleaner exhaust fumes. Platinum is currently used as the diesel engine catalyst in these engines. The catalyst is what cleans the exhaust fume particles. First, a reduction catalyst is employed to take nitrogen atoms from NOx molecules in order to free oxygen. Next the oxidation catalyst oxidizes the hydrocarbons and carbon monoxide to form carbon dioxide and water.[citation needed] Platinum is used in both the reduction and the oxidation catalysts.[64] Using platinum though, is inefficient in that it is expensive and unsustainable. Danish company InnovationsFonden invested DKK 15 million in a search for new catalyst substitutes using nanotechnology. The goal of the project, launched in the autumn of 2014, is to maximize surface area and minimize the amount of material required. Objects tend to minimize their surface energy; two drops of water, for example, will join to form one drop and decrease surface area. If the catalyst's surface area that is exposed to the exhaust fumes is maximized, efficiency of the catalyst is maximized. The team working on this project aims to create nanoparticles that will not merge. Every time the surface is optimized, material is saved. Thus, creating these nanoparticles will increase the effectiveness of the resulting diesel engine catalyst—in turn leading to cleaner exhaust fumes—and will decrease cost. If successful, the team hopes to reduce platinum use by 25%.[65]

Nanotechnology also has a prominent role in the fast developing field of Tissue Engineering. When designing scaffolds, researchers attempt to mimic the nanoscale features of a cell's microenvironment to direct its differentiation down a suitable lineage.[66] For example, when creating scaffolds to support the growth of bone, researchers may mimic osteoclast resorption pits.[67]

Researchers have successfully used DNA origami-based nanobots capable of carrying out logic functions to achieve targeted drug delivery in cockroaches. It is said that the computational power of these nanobots can be scaled up to that of a Commodore 64.[68]

An area of concern is the effect that industrial-scale manufacturing and use of nanomaterials would have on human health and the environment, as suggested by nanotoxicology research. For these reasons, some groups advocate that nanotechnology be regulated by governments. Others counter that overregulation would stifle scientific research and the development of beneficial innovations. Public health research agencies, such as the National Institute for Occupational Safety and Health are actively conducting research on potential health effects stemming from exposures to nanoparticles.[69][70]

Some nanoparticle products may have unintended consequences. Researchers have discovered that bacteriostatic silver nanoparticles used in socks to reduce foot odor are being released in the wash.[71] These particles are then flushed into the waste water stream and may destroy bacteria which are critical components of natural ecosystems, farms, and waste treatment processes.[72]

Public deliberations on risk perception in the US and UK carried out by the Center for Nanotechnology in Society found that participants were more positive about nanotechnologies for energy applications than for health applications, with health applications raising moral and ethical dilemmas such as cost and availability.[73]

Experts, including director of the Woodrow Wilson Center's Project on Emerging Nanotechnologies David Rejeski, have testified[74] that successful commercialization depends on adequate oversight, risk research strategy, and public engagement. Berkeley, California is currently the only city in the United States to regulate nanotechnology;[75] In 2008, Cambridge, Massachusetts considered enacting a similar law,[76] but ultimately rejected it.[77]

Health and environmental concerns

Nanofibers are used in several areas and in different products, in everything from aircraft wings to tennis rackets. Inhaling airborne nanoparticles and nanofibers may lead to a number of pulmonary diseases, e.g. fibrosis.[78] Researchers have found that when rats breathed in nanoparticles, the particles settled in the brain and lungs, which led to significant increases in biomarkers for inflammation and stress response[79] and that nanoparticles induce skin aging through oxidative stress in hairless mice.[80][81]

A two-year study at UCLA's School of Public Health found lab mice consuming nano-titanium dioxide showed DNA and chromosome damage to a degree "linked to all the big killers of man, namely cancer, heart disease, neurological disease and aging".[82]

A Nature Nanotechnology study suggests some forms of carbon nanotubes – a poster child for the "nanotechnology revolution" – could be as harmful as asbestos if inhaled in sufficient quantities. Anthony Seaton of the Institute of Occupational Medicine in Edinburgh, Scotland, who contributed to the article on carbon nanotubes said "We know that

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some of them probably have the potential to cause mesothelioma. So those sorts of materials need to be handled very carefully."[83] In the absence of specific regulation forthcoming from governments, Paull and Lyons (2008) have called for an exclusion of engineered nanoparticles in food.[84] A newspaper article reports that workers in a paint factory developed serious lung disease and nanoparticles were found in their lungs.[85][86][87][88]

Regulation

Calls for tighter regulation of nanotechnology have occurred alongside a growing debate related to the human health and safety risks of nanotechnology.[89] There is significant debate about who is responsible for the regulation of nanotechnology. Some regulatory agencies currently cover some nanotechnology products and processes (to varying degrees) – by "bolting on" nanotechnology to existing regulations – there are clear gaps in these regimes.[90] Davies (2008) has proposed a regulatory road map describing steps to deal with these shortcomings.[91]

Stakeholders concerned by the lack of a regulatory framework to assess and control risks associated with the release of nanoparticles and nanotubes have drawn parallels with bovine spongiform encephalopathy ("mad cow" disease), thalidomide, genetically modified food,[92] nuclear energy, reproductive technologies, biotechnology, and asbestosis. Andrew Maynard, chief science advisor to the Woodrow Wilson Center's Project on Emerging Nanotechnologies, concludes that there is insufficient funding for human health and safety research, and as a result there is currently limited understanding of the human health and safety risks associated with nanotechnology.[93] As a result, some academics have called for stricter application of the precautionary principle, with delayed marketing approval, enhanced labelling and additional safety data development requirements in relation to certain forms of nanotechnology.[94]

The Royal Society report[15] identified a risk of nanoparticles or nanotubes being released during disposal, destruction and recycling, and recommended that "manufacturers of products that fall under extended producer responsibility regimes such as end-of-life regulations publish procedures outlining how these materials will be managed to minimize possible human and environmental exposure" (p. xiii).

The Center for Nanotechnology in Society has found that people respond to nanotechnologies differently, depending on application – with participants in public deliberations more positive about nanotechnologies for energy than health applications – suggesting that any public calls for nano regulations may differ by technology sector.[73]

III. RESULTS

As the world's energy demand continues to grow, the development of more efficient and sustainable technologies for generating and storing energy is becoming increasingly important. According to Dr. Wade Adams from Rice University, energy will be the most pressing problem facing humanity in the next 50 years and nanotechnology has potential to solve this issue.[1] Nanotechnology, a relatively new field of science and engineering, has shown promise to have a significant impact on the energy industry. Nanotechnology is defined as any technology that contains particles with one dimension under 100 nanometers in length. For scale, a single virus particle is about 100 nanometers wide.

People in the fields of science and engineering have already begun developing ways of utilizing nanotechnology for the development of consumer products. Benefits already observed from the design of these products are an increased efficiency of lighting and heating, increased electrical storage capacity, and a decrease in the amount of pollution from the use of energy. Benefits such as these make the investment of capital in the research and development of nanotechnology a top priority.

Commonly used nanomaterials in energy

An important sub-field of nanotechnology related to energy is nanofabrication, the process of designing and creating devices on the nanoscale. The ability to create devices smaller than 100 nanometers opens many doors for the development of new ways to capture, store, and transfer energy. Improvements in the precision of nanofabrication technologies are critical to solving many energy related problems that the world is currently facing.

Graphene-based materials

There is enormous interest in the use of graphene-based materials for energy storage. The research on the use of graphene for energy storage began very recently, but the growth rate of relative research is rapid.[2]

Graphene recently emerged as a promising material for energy storage because of several properties, such as low weight, chemical inertness and low price. Graphene is an allotrope of carbon that exists as a two-dimensional sheet of carbon atoms organized in a hexagonal lattice. A family of graphene-related materials, called "graphenes" by the

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research community, consists of structural or chemical derivatives of graphene.[2] The most important chemically derived graphene is graphene oxide (defined as single layer of graphite oxide,[3] Graphite oxide can be obtained by reacting graphite with strong oxidizers, for example, a mixture of sulfuric acid, sodium nitrate, and potassium permanganate[4]) which is usually prepared from graphite by oxidization to graphite oxide and consequent exfoliation. The properties of graphene depend greatly on the method of fabrication. For example, reduction of graphene oxide to graphene results in a graphene structure that is also one-atom thick but contains a high concentration of defects, such as nanoholes and Stone–Wales defects.[5] Moreover, carbon materials, which have relatively high electrical conductivity and variable structures are extensively used in the modification of sulfur. Sulfur–carbon composites with diverse structures have been synthesized and exhibited remarkably improved electrochemical performance than pure sulfur, which is crucial for battery design.[6][7][8][9] Graphene has great potential in the modification of a sulfur cathode for high performance Li-S batteries, which has been broadly investigated in recent years.[2]

Silicon-based nano semiconductors

Silicon-based nano semiconductors have the most useful application in solar energy and it also has been extensively studied at many places, such as Kyoto University. They utilize silicon nanoparticles in order to absorb a greater range of wavelengths from the electromagnetic spectrum. This can be done by putting many identical and equally spaced silicon rods on the surface. Also, the height and length of spacing have to be optimized for reaching the best results. This arrangement of silicon particles allows solar energy to be reabsorbed by many different particles, exciting electrons and resulting in much of the energy being converted to heat. Then, the heat can be converted to electricity. Researchers from Kyoto University have shown that these nano-scale semiconductors can increase efficiency by at least 40%, compared to the regular solar cells.[10]

Nanocellulose-based materials

Cellulose is the most abundant natural polymer on earth. Currently, nanocellulose-based mesoporous structures, flexible thin films, fibers, and networks are developed and used in photovoltaic (PV) devices, energy storage systems, mechanical energy harvesters, and catalysts components. Inclusion of nanocellulose in those energy-related devices largely raises the portion of eco-friendly materials and is very promising in addressing the relevant environmental concerns. Furthermore, cellulose manifests itself in the low cost and large-scale promises.[11]

Nanostructures in energy

One-dimensional nanomaterials

One-dimensional nanostructures have shown promise to increase energy density, safety, and cycling-life of energy storage systems, an area in need of improvement for Li-ion batteries. These nanostructures are mainly used in battery electrodes because of their shorter bi-continuous ion and electron transport pathways, which results in higher battery performance.[12]

Additionally, 1D nanostructures are capable of increasing charge storage by double layering, and can also be used on supercapacitors because of their fast pseudocapacitive surface redox processes. In the future, novel design and controllable synthesis of these materials will be developed much more in-depth. 1D nanomaterials are also environmentally friendly and cost-effective.[13]

Two-dimensional nanomaterials

The most important feature of two dimensional nanomaterials is that their properties can be precisely controlled. This means that 2D nanomaterials can be easily modified and engineered on nanostructures. The interlayer space can also be manipulated for nonlayered materials, called 2D nanofluidic channels. 2D nanomaterials can also be engineered into porous structures in order to be used for energy storage and catalytic applications by applying facile charge and mass transport.[14]

2D nanomaterials also have a few challenges. There are some side effects of modifying the properties of the materials, such as activity and structural stability, which can be compromised when they are engineered. For example, creating some defects can increase the number of active sites for higher catalytic performance, but side reactions may also happen, which could possibly damage the catalyst's structure. Another example is that interlayer expansion can lower the ion diffusion barrier in the catalytic reaction, but it can also potentially lower its structural stability. Because of this, there is a tradeoff between performance and stability. A second issue is consistency in design methods. For example, heterostructures are the main structures of the catalyst in interlayer space and energy storage devices, but these structures may lack the understanding of mechanism on the catalytic reaction or charge storage mechanisms. A deeper understanding of 2D nanomaterial design is required, because fundamental knowledge will lead to consistent

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and efficient methods of designing these structures. A third challenge is the practical application of these technologies. There is a huge difference between lab-scale and industry-scale applications of 2D nanomaterials due to their intrinsic instability during storage and processing. For example, porous 2D nanomaterial structures have low packing densities, which makes them difficult to pack into dense films. New processes are still being developed for the application of these materials on an industrial scale.[14]

Applications

Lithium-sulfur based high-performance batteries

The Li-ion battery is currently one of the most popular electrochemical energy storage systems and has been widely used in areas from portable electronics to electric vehicles.[15][16] However, the gravimetric energy density of Li-ion batteries is limited and less than that of fossil fuels. The lithium sulfur (Li-S) battery, which has a much higher energy density than the Li-ion battery, has been attracting worldwide attention in recent years.[17][18] A group of researches from the National Natural Science Foundation of China (Grant No. 21371176 and 21201173) and the Ningbo Science and Technology Innovation Team (Grant No. 2012B82001) have developed a nanostructure-based lithium-sulfur battery consisting of graphene/sulfur/carbon nano-composite multilayer structures. Nanomodification of sulfur can increase the electrical conductivity of the battery and improve electron transportation in the sulfur cathode. A graphene/sulfur/carbon nanocomposite with a multilayer structure (G/S/C), in which nanosized sulfur is layered on both sides of chemically reduced graphene sheets and covered with amorphous carbon layers, can be designed and successfully prepared. This structure achieves high conductivity, and surface protection of sulfur simultaneously, and thus gives rise to excellent charge/discharge performance. The G/S/C composite shows promising characteristics as a high performance cathode material for Li-S batteries.[19]

Nanomaterials in solar cells

Engineered nanomaterials are key building blocks of the current generation solar cells.[20] Today's best solar cells have layers of several different semiconductors stacked together to absorb light at different energies but still only manage to use approximately 40% of the Sun's energy. Commercially available solar cells have much lower efficiencies (15-20%). Nanostructuring has been used to improve the efficiencies of established photovoltaic (PV) technologies, for example, by improving current collection in amorphous silicon devices,[21] plasmonic enhancement in dye-sensitized solar cells,[22] and improved light trapping in crystalline silicon.[23] Furthermore, nanotechnology could help increase the efficiency of light conversion by utilizing the flexible bandgaps of nanomaterials,[24] or by controlling the directivity and photon escape probability of photovoltaic devices.[25] Titanium dioxide (TiO_2) is one of the most widely investigated metal oxides for use in PV cells in the past few decades because of its low cost, environmental benignity, plentiful polymorphs, good stability, and excellent electronic and optical properties.[26][27][28][29][30] However, their performances are greatly limited by the properties of the TiO_2 materials themselves. One limitation is the wide band gap, making TiO_2 only sensitive to ultraviolet (UV) light, which just occupies less than 5% of the solar spectrum.[31] Recently, core–shell structured nanomaterials have attracted a great deal of attention as they represent the integration of individual components into a functional system, showing improved physical and chemical properties (e.g., stability, non-toxicity, dispersibility, multi-functionality), which are unavailable from the isolated components.[32][33][34][35][36][37][38][39][40] For TiO_2 nanomaterials, this core–shell structured design would provide a promising way to overcome their disadvantages, thus resulting in improved performances.[41][42][43] Compared to sole TiO_2 material, core–shell structured TiO_2 composites show tunable optical and electrical properties, even new functions, which are originated from the unique core–shell structures.[31]

Nanoparticle fuel additives

Nanomaterials can be used in a variety of ways to reduce energy consumption. Nanoparticle fuel additives can also be of great use in reducing carbon emissions and increasing the efficiency of combustion fuels. Cerium oxide nanoparticles have been shown to be very good at catalyzing the decomposition of unburnt hydrocarbons and other small particle emissions due to their high surface area to volume ratio, as well as lowering the pressure within the combustion chamber of engines to increase engine efficiency and curb NO_x emissions.[44] Addition of carbon nanoparticles has also successfully increased burning rate and ignition delay in jet fuel.[45] Iron nanoparticle additives to biodiesel and diesel fuels have also shown a decrease in fuel consumption and volumetric emissions of hydrocarbons by 3-6%, carbon monoxide by 6-12% and nitrogen oxides by 4-11% in one study.[46]

Environmental and health impacts of fuel additives

While nanomaterials can increase energy efficiency of fuel in several ways, a drawback of their use lies in the effect of nanoparticles on the environment. With cerium oxide nanoparticle additives in fuel, trace amounts of these toxic

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particles can be emitted within the exhaust. Cerium oxide additives in diesel fuel have been shown to cause lung inflammation and increased bronchial alveolar lavage fluid in rats.[44] This is concerning, especially in areas with high road traffic, where these particles are likely to accumulate and cause adverse health effects. Naturally occurring nanoparticles created by the incomplete combustion of diesel fuels are also large contributors to toxicity of diesel fumes. More research needs to be conducted to determine whether the addition of artificial nanoparticles to fuels decreases the net amount of toxic particle emissions due to combustion.[44]

Economic benefits

The relatively recent shift toward using nanotechnology with respect to the capture, transfer, and storage of energy has and will continue to have many positive economic impacts on society. The control of materials that nanotechnology offers to scientists and engineers of consumer products is one of the most important aspects of nanotechnology and allows for efficiency improvements of a variety of products. More efficient capture and storage of energy by use of nanotechnology may lead to decreased energy costs in the future, as preparation costs of nanomaterials becomes less expensive with more development.

A major issue with current energy generation is the generation of waste heat as a by-product of combustion. A common example of this is in an internal combustion engine. The internal combustion engine loses about 64% of the energy from gasoline as heat and an improvement of this alone could have a significant economic impact.[47] However, improving the internal combustion engine in this respect has proven to be extremely difficult without sacrificing performance. Improving the efficiency of fuel cells through the use of nanotechnology appears to be more plausible by using molecularly tailored catalysts, polymer membranes, and improved fuel storage.

In order for a fuel cell to operate, particularly of the hydrogen variant, a noble-metal catalyst (usually platinum, which is very expensive) is needed to separate the electrons from the protons of the hydrogen atoms.[48] However, catalysts of this type are extremely sensitive to carbon monoxide reactions. In order to combat this, alcohols or hydrocarbons compounds are used to lower the carbon monoxide concentration in the system. Using nanotechnology, catalysts can be designed through nanofabrication that limit incomplete combustion and thus decrease the amount of carbon monoxide, improving the efficiency of the process.

IV. CONCLUSION

The National Nanotechnology Initiative (NNI) is a research and development initiative which provides a framework to coordinate nanoscale research and resources among United States federal government agencies and departments.

Mihail C. Roco proposed the initiative in a 1999 presentation to the White House under the Clinton administration.[2][3][4][5][6] The NNI was officially launched in 2000 and received funding for the first time in FY2001.[7]

President Bill Clinton advocated nanotechnology development. In a 21 January 2000 speech [1] at the California Institute of Technology, Clinton stated that "Some of our research goals may take twenty or more years to achieve, but that is precisely why there is an important role for the federal government."

President George W. Bush further increased funding for nanotechnology. On 3 December 2003 Bush signed into law the 21st Century Nanotechnology Research and Development Act (Pub. L.Tooltip Public Law (United States) 108–153 (text) (PDF)), which authorizes expenditures for five of the participating agencies totaling $3.63 billion over four years.[2]. This law is an authorization, not an appropriation, and subsequent appropriations for these five agencies have not met the goals set out in the 2003 Act. However, there are many agencies involved in the Initiative that are not covered by the Act, and requested budgets under the Initiative for all participating agencies in Fiscal Years 2006 – 2015 totaled over $1 billion each.

In February 2014, the National Nanotechnology Initiative released a Strategic Plan outlining updated goals and "program component areas" [3]," as required under the terms of the Act. This document supersedes the NNI Strategic Plans released in 2004 and 2007.

The NNI's budget supplement proposed by the Obama administration for Fiscal Year 2015 provides $1.5 billion in requested funding. The cumulative NNI investment since fiscal year 2001, including the 2015 request, totals almost $21 billion. Cumulative investments in nanotechnology-related environmental, health, and safety research since 2005 to 2015 total nearly $900 million. The Federal agencies with the largest investments are the National Institutes of Health, National Science Foundation, Department of Energy, Department of Defense, and the National Institute of Standards and Technology.[8]

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The NNI received increased support for emerging technologies during the Trump administration and a special focus on clean energy and mitigating climate change during the Biden administration. NNI cumulative investment by 2022 inclusive reached $40 billion, and nanotechnology has become pervasive in material, energy and biosystem related discoveries and applications [9] (https://www.tvworldwide.net/NNI-Retrospective/VideoId/2111/nni-retrospective-video-creating-a-national-initiative-trailer-3-min).

Goals

The four primary goals of NNI are:[10]

1. Advance a world-class nanotechnology research and development program;
2. Foster the transfer of new technologies into products for commercial and public benefits;
3. Develop and sustain educational resources, a skilled workforce, and a dynamic infrastructure and toolset to advance nanotechnology;
4. Support responsible development of nanotechnology.

Initiatives

Nanotechnology Signature Initiatives

Nanotechnology Signature Initiatives (NSIs) spotlight areas of nanotechnology where significant advances in nanoscale science and technology can be made with the focus and cooperation of participating agencies. NSIs accelerate research, development, and application of nanotechnology in these critical areas.[11]

As of December 2020, the current NSIs are:[11]

- NSI: Water Sustainability through Nanotechnology – Nanoscale Solutions for a Global-Scale Challenge,
- NSI: Nanotechnology for Sensors and Sensors for Nanotechnology – Improving and Protecting Health, Safety, and the Environment,
- NSI: Sustainable Nanomanufacturing - Creating the Industries of the Future,
- NSI: Nanoelectronics for 2020 and Beyond.

NSIs are dynamic and are retired as they achieve their specified goals or develop an established community they no longer require the spotlight provided as a NSI. Retired NSIs are:[11]

- NSI: Nanoelectronics for 2020 and Beyond,
- NSI: Nanotechnology for Solar Energy Collection and Conversion - Contributing to Energy Solutions for the Future,
- NSI: Nanotechnology Knowledge Infrastructure - Enabling National Leadership in Sustainable Design.

Nanotechnology-Inspired Grand Challenges

A nanotechnology-inspired grand challenge (GC) is an ambitious goal that utilizes nanotechnology and nanoscience to solve national and global issues. The first and current GC was announced in October 2015 after receiving input and suggestions from the public. As of December 2020, the grand challenge is:[12]

- A Nanotechnology-Inspired Grand Challenge for Future Computing: Create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain.

Participating Federal Agencies and Departments

Departments and agencies with nanotechnology R&D budgets:

- Consumer Product Safety Commission (CPSC)
- Department of Commerce (DOC)
  - Bureau of Industry and Security (BIS)
  - Economic Development Administration (EDA)

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  - National Institute of Standards and Technology (NIST)
  - U.S. Patent and Trademark Office (USPTO)
- Department of Defense (DOD)
- Department of Energy (DOE)
- Department of Health and Human Services (DHHS)
  - Food and Drug Administration (FDA)
  - National Institutes of Health (NIH)
  - National Institute of Occupational Safety and Health (NIOSH)
- Department of Homeland Security (DHS)
- Department of Transportation (DOT)
  - Federal Highway Administration (FHWA)
- Environmental Protection Agency (EPA)
- National Aeronautics and Space Administration (NASA)
- National Science Foundation (NSF)
- U.S. Department of Agriculture (USDA)
  - Agricultural Research Services (ARS)
  - Forest Service (FS)
  - National Institute of Food and Agriculture (NIFA)

Other participating departments and agencies:

- Department of Education (DOEd)
- Department of the Interior
  - U.S. Geological Survey (USGS)
- Department of Justice (DOJ)
  - National Institute of Justice (NIJ)
- Department of Labor (DOL)
  - Occupation Safety and Health Administration (OSHA)
- Department of State (DOS)
- Department of the Treasury (DOTreas)
- Intelligence Community (IC)
- Nuclear Regulatory Commission (NRC)
- U.S. International Trade Commission (USITC)

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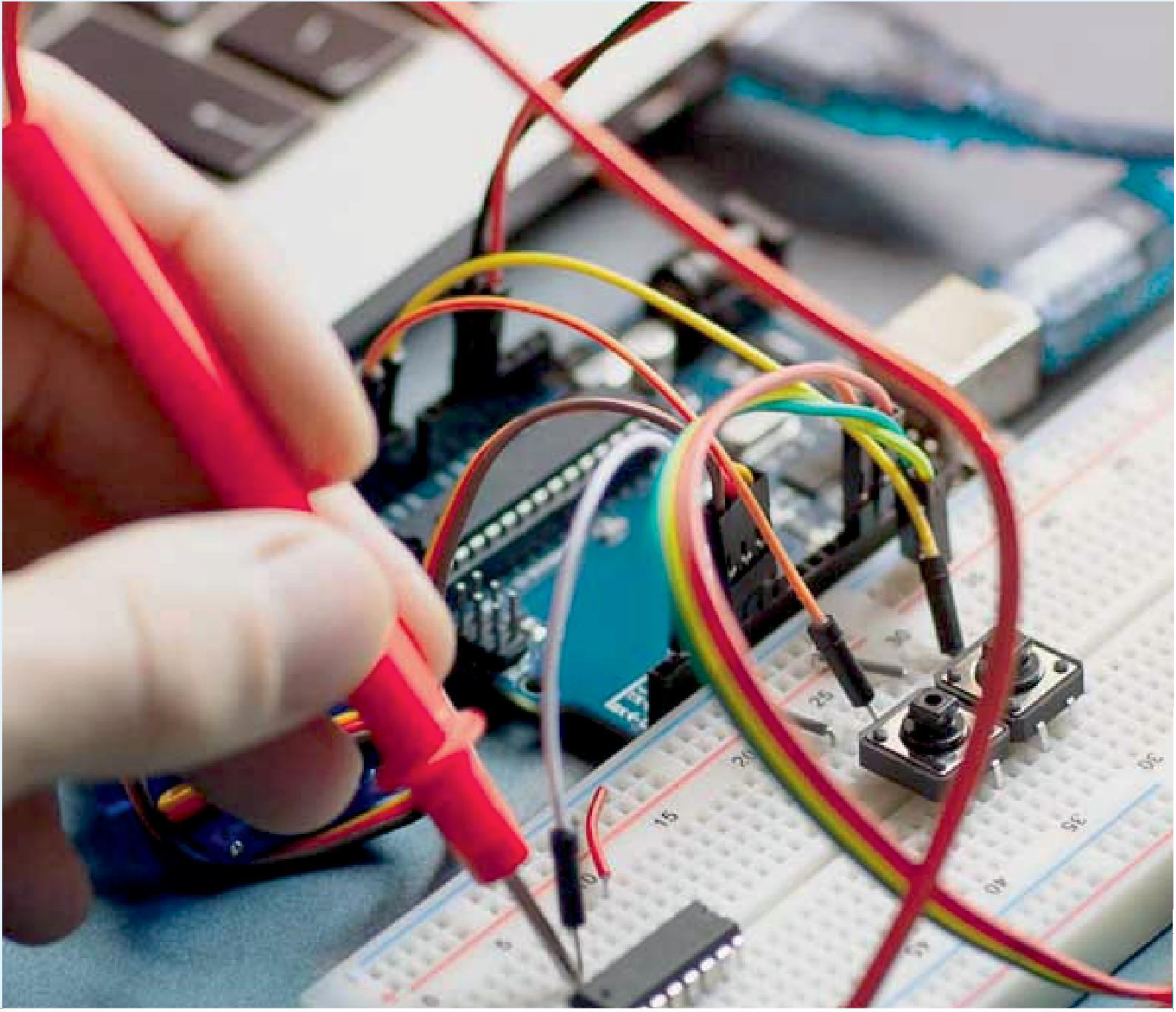

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