1. Introduction to Nanotechnology

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A biological system can be exceedingly small. Many of the cells are very tiny, but they are very active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvelous things – all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small which does what we want – that we can manufacture an object that maneuvers at that level.

(From the talk *There's Plenty of Room at the Bottom*, delivered by Richard P. Feynman at the annual meeting of the American Physical Society at the California Institute of Technology; Pasadena, December 29, 1959).

1.1 Nanotechnology – Definition and Examples

Nanotechnology literally means any technology on a nanoscale that has applications in the real world. Nanotechnology encompasses the production and application of physical, chemical, and biological systems at scales ranging from individual atoms or molecules to submicron dimensions, as well as the integration of the resulting nanostructures into larger systems. Nanotechnology is likely to have a profound impact on our economy and society in the early 21st century, comparable to that of semiconductor technology, information technology, or cellular and molecular biology. Science and technology research in nanotechnology promises breakthroughs in areas such as materials and manufacturing, nanoelectronics, medicine and healthcare, energy, biotechnology, information technology, and national security. It is widely felt that nanotechnology will be the next Industrial Revolution.

Nanometer-scale features are mainly built up from their elemental constituents. Examples include chemical synthesis, spontaneous self-assembly of molecular clusters (molecular self-assembly) from simple reagents in solution, biological molecules (e.g., DNA) used as building blocks for production of three-dimensional nanostructures, and quantum dots (nanocrystals) of arbitrary diameter (about $10–10^5$ atoms). The definition of a nanoparticle is an aggregate of atoms bonded together with a radius between 1 and 100 nm. It typically consists of $10–10^5$ atoms. A variety of vacuum deposition and nonequilibrium-plasma chemistry techniques are used to produce layered nanocomposites and nanotubes. Atomically controlled structures are produced using molecular-beam epitaxy and organometallic vapor-phase epitaxy. Micro- and nanosystem components are fabricated using top-down lithographic and nonlithographic fabrication techniques and range in size from micro- to nanometers. Continued improvements in lithography for use in the production of nanocomponents have resulted in line widths as small as 10 nm in experimental prototypes. The nanotechnology field, in addition to the fabrication of nanosystems, provides impetus for the development of experimental and computational tools.

The discovery of novel materials, processes, and phenomena at the nanoscale and the development of new experimental and theoretical techniques for research provide fresh opportunities for the development of innovative nanosystems and nanostructured materials. The properties of materials at the nanoscale can be very different from those at a larger scale. When the dimension of a material is reduced from a large size, the properties remain the same at first, then small changes occur, until finally when the size drops below 100 nm, dramatic changes in properties can occur. If only one length of a three-dimensional nanostructure is of nanodimension, the structure is referred to as a quantum well; if two sides are of nanometer length, the structure is referred to as a quantum wire. A quantum dot has all three dimensions in the nano range. The term *quantum* is associated with these three types of nanostructures because the changes in properties arise from the quantum-mechanical nature of physics in the domain of the ultrasmall. Materials can

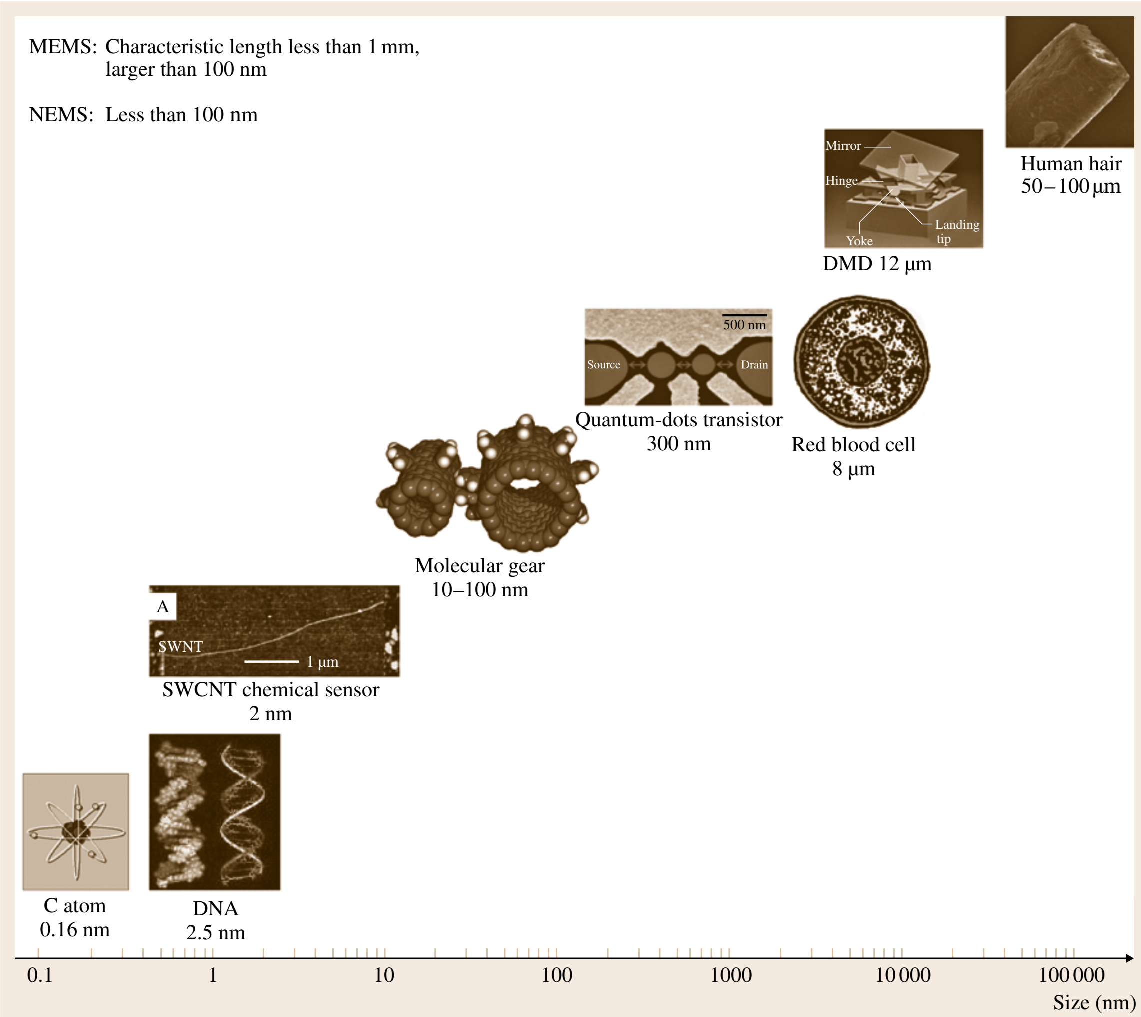


Fig. 1.1 Dimensions of MEMS/NEMS and BioNEMS in perspective. Examples shown are a single-walled carbon nanotube (SWCNT) chemical sensor [1.1], molecular dynamic simulations of carbon-nanotube-based gears [1.2], quantum-dot transistor obtained from [1.3], and digital microdevice (DMD) obtained from www.dlp.com. For comparison, dimensions and weights of various biological objects found in nature are also presented

Table 1.1 Characteristic dimensions and weights in perspective

Characteristic dimensions in perspective	
NEMS characteristic length	< 100 nm
MEMS characteristic length	< 1 mm and > 100 nm
SWCNT chemical sensor	≈ 2 nm
Molecular gear	≈ 10 nm
Quantum-dot transistor	300 nm
Digital micromirror	12 000 nm
Individual atoms	Typically a fraction of a nm in diameter
DNA molecules	≈ 2.5 nm wide
Biological cells	In the range of thousands of nm in diameter
Human hair	≈ 75 000 nm in diameter
Weight in perspective	
NEMS built with cross-sections of about 10 nm	As low as 10^{-20} N
Micromachine silicon structure	As low as 1 nN
Eyelash	≈ 100 nN
Water droplet	≈ 10 µN

be nanostructured for new properties and novel performance. This field is opening new avenues in science and technology.

Micro- and nanosystems include micro/nanoelectromechanical systems (MEMS/NEMS). MEMS refers to microscopic devices that have a characteristic length of less than 1 mm but more than 100 nm and that combine electrical and mechanical components. NEMS refers to nanoscopic devices that have a characteristic length of less than 100 nm and that combine electrical and mechanical components. In mesoscale devices, if the functional components are on the micro- or nanoscale, they may be referred to as MEMS or NEMS, respectively. These are referred to as intelligent miniaturized systems, comprising sensing, processing, and/or actuating functions and combining electrical and mechanical components. The acronym MEMS originated in the USA. The term commonly used in Europe is *microsystem technology* (MST), and in Japan the term *micromachines* is used. Another term generally used is micro/nanodevices. The terms MEMS/NEMS are also now used in a broad sense and include electrical, mechanical, fluidic, optical, and/or biological function. MEMS/NEMS for optical applications are referred to as micro/nanooptoelectromechanical systems (MOEMS/NOEMS). MEMS/NEMS for electronic applications are referred to as radiofrequency MEMS/NEMS (RF-MEMS/RF-NEMS). MEMS/NEMS for biological applications are referred to as bioMEMS/bioNEMS.

To put the dimensions of MEMS/NEMS and BioNEMS in perspective, see Fig. 1.1 and Table 1.1. Individual atoms are typically a fraction of a nanometer in diameter, DNA molecules are about 2.5 nm wide, biological cells are in the range of thousands of nm in diameter, and human hair is about 75 µm in diameter. The smallest length of BioNEMS shown in the figure is about 2 nm, NEMS ranges in size from 10 to 300 nm, and the size of MEMS is 12 000 nm. The mass of a micromachined silicon structure can be a low as 1 nN, and NEMS can be built with mass as low as 10^{-20} N with cross-sections of about 10 nm. In comparison, the mass

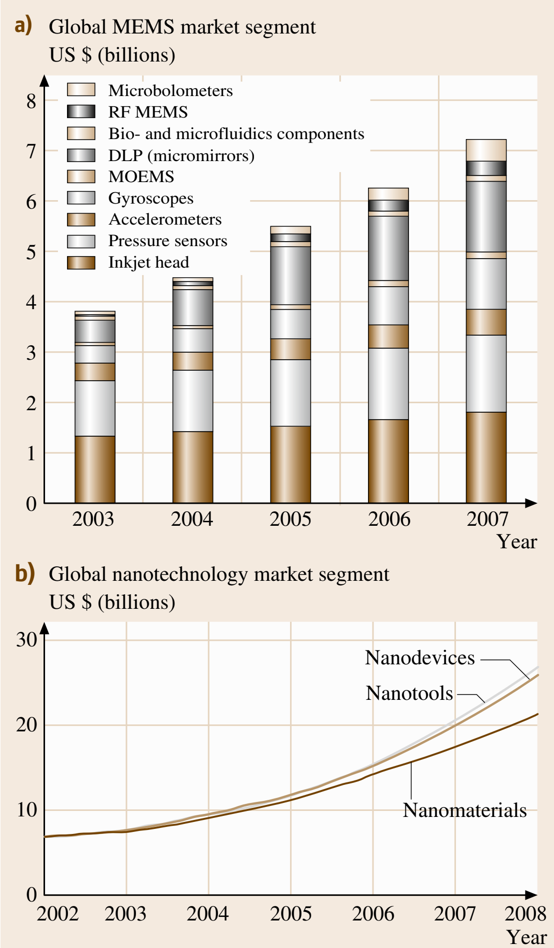


Fig. 1.2 Global MEMS and nanotechnology market segments (DLP – digital light processing)

of a drop of water is about 10 μN, and the mass of an eyelash is about 100 nN.

MEMS/NEMS and BioMEMS/BioNEMS are expected to have a major impact on our lives, comparable to that of semiconductor technology, information technology, or cellular and molecular biology [1.4, 5]. MEMS/NEMS and BioMEMS/BioNEMS are used in electromechanical, electronics, information/communication, chemical, and biological applications. The MEMS industry in 2004 was worth about US$ 4.5 billion, with a projected annual growth rate of 17% (Fig. 1.2) [1.6]. The NEMS industry was worth about US$ 10 billion in 2004, mostly in nanomaterials (Fig. 1.2) [1.7]. Growth of Si-based MEMS/NEMS may slow down and that of nonsilicon MEMS may pick up during the next decade. It is expected to expand in this decade, for nanomaterials and biomedical applications as well as nanoelectronics or molecular electronics. For example, miniaturized diagnostics could be implanted for early diagnosis of illness. Targeted drug-delivery devices are under development. Due to the enabling nature of these systems and because of the significant impact they can have on both commercial and defense applications, industry as well as federal governments have taken special interest in seeing growth in this field nurtured. MEMS/NEMS and BioMEMS/BioNEMS are the next logical step in the *silicon revolution*.

1.2 Background and Research Expenditures

On December 29, 1959 at the California Institute of Technology, Nobel Laureate *Richard P. Feynman* gave a talk at the Annual Meeting of the American Physical Society that has become one of the 20th century's classic science lectures, entitled *There's Plenty of Room at the Bottom* [1.8]. He presented a technological vision of extreme miniaturization in 1959, several years before the word *chip* became part of the lexicon. He talked about the problem of manipulating and controlling things on a small scale. Extrapolating from known physical laws, Feynman envisioned a technology using the ultimate toolbox of nature, building nanoobjects atom by atom or molecule by molecule. Since the 1980s, many inventions and discoveries in the fabrication of nanoobjects have been testaments to his vision. In recognition of this reality, the National Science and Technology Council (NSTC) of the White House created the Interagency Working Group on Nanoscience, Engineering, and Technology (IWGN) in 1998. In a January 2000 speech at the same institute, President W. J. Clinton talked about the exciting promise of *nanotechnology* and the importance of expanding research in nanoscale science and technology more broadly. Later that month, he announced in his State of the Union Address an ambitious US$ 497 million federal, multiagency National Nanotechnology Initiative (NNI) in the fiscal year 2001 budget, and made the NNI a top science and technology priority [1.9, 10]. The objective of this initiative was to form a broad-based coalition in which academia, the private sector, and local, state, and federal governments work together to push the envelop of nanoscience and nanoengineering to reap nanotechnology's potential social and economic benefits.

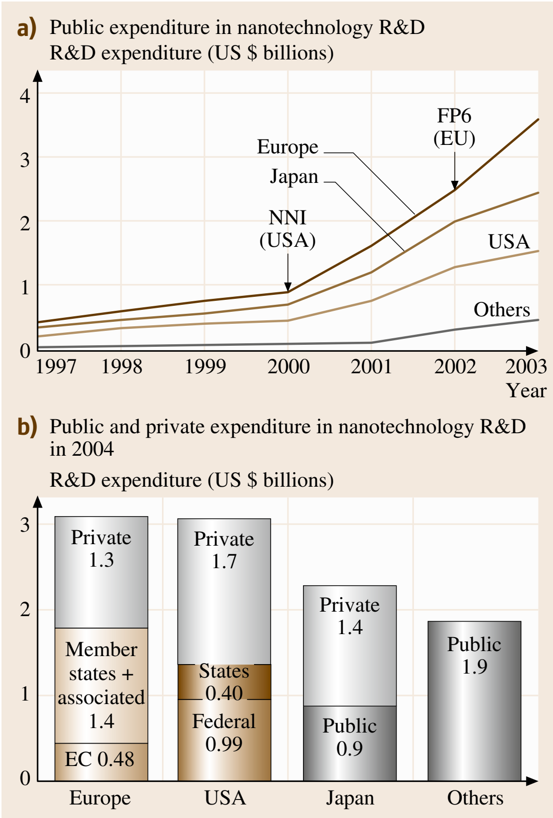


Fig. 1.3a,b Breakdown of expenditure in nanotechnology R&D **(a)** around the world (source: European Commission, 2003), and **(b)** by public and private resources in 2004 (source: European Commission, 2005; figures for private sources based upon data from Lux Research)

Funding in the USA has continued to increase. In January 2003, the US Senate introduced a bill to establish a National Nanotechnology Program. On December 3, 2003, President George W. Bush signed into law the 21st Century Nanotechnology Research and Development Act. This legislation put into law programs and activities supported by the National Nanotechnology Initiative. The bill gave nanotechnology a permanent home in the federal government and authorized US$ 3.7 billion to be spent in the 4 year period beginning in October 2005 for nanotechnology initiatives at five federal agencies. The funds would provide grants to researchers, coordinate research and development (R&D) across five federal agencies [the National Science Foundation (NSF), the Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), the National Institute of Standards and Technology (NIST), and the Environmental Protection Agency (EPA)], establish interdisciplinary research centers, and accelerate technology transfer into the private sector. In addition, the Departments of Defense (DOD), Homeland Security, Agriculture, and Justice as well as the National Institutes of Health (NIH) also fund large R&D activities. They currently account for more than one-third of the federal budget for nanotechnology.

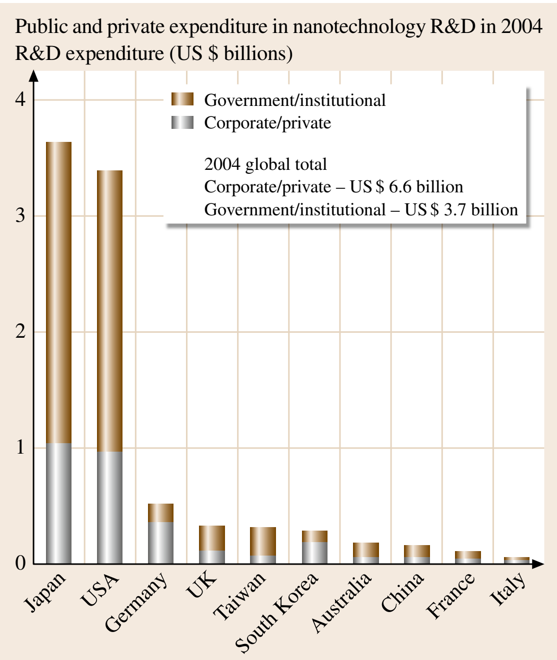


Fig. 1.4 Breakdown of public and private expenditures in nanotechnology R&D in 2004 in various countries (after [1.7])

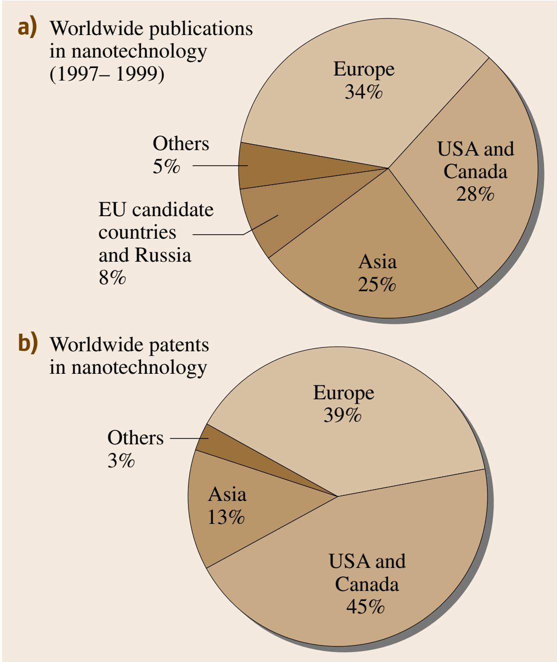
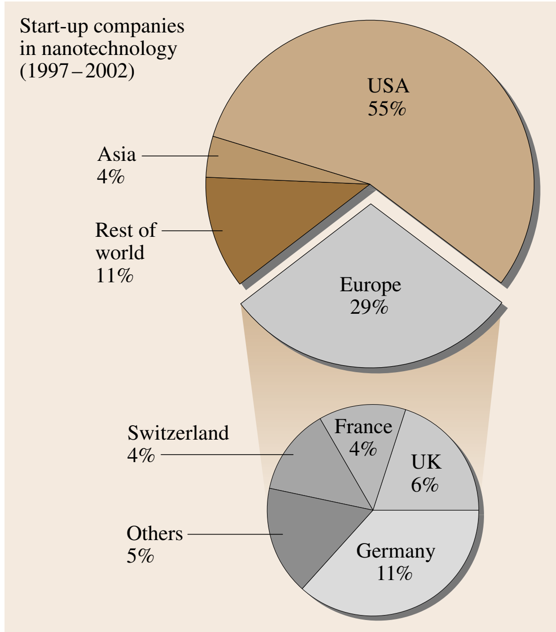


Fig. 1.5a,b Breakdown of **(a)** worldwide publications and **(b)** worldwide patents (source: European Commission, 2003)

The European Union (EU) made nanosciences and nanotechnologies a priority in the Sixth Framework Program (FP6) in 2002 for the period 2003–2006. There were also small dedicated funds in FP4 and FP5 before. FP6 was tailored to help better structure European research and to cope with the strategic objectives set out in Lisbon in 2000. Japan identified nanotechnology as one of its main research priorities in 2001. The funding levels increased sharply from US$ 400 million in 2001 to around US$ 950 million in 2004. In 2003, South Korea embarked upon a 10 year program with around US$ 2 billion of public funding, and Taiwan has committed around US$ 600 million of public funding over 6 years. Singapore and China are also investing on a large scale. Russia is well funded as well.

Figure 1.3a shows the public expenditure breakdown of nanotechnology R&D around the world, with about US$ 5 billion in 2004, coming approximately equally from the USA, Japan, and Europe. Next we compare public expenditure on a per-capita basis. The average expenditures per capita for the USA, the EU-

Fig. 1.6 Breakdown of start-up companies around the world (1997–2002) (source: CEA, Bureau d'Etude Marketing) ▶



25, and Japan are about US$ 3.7 billion, US$ 2.4 billion, and US$ 6.2 billion, respectively [1.11]. Figure 1.3b shows the breakdown of expenditure in 2004 by public and private sources, with more than US$ 10 billion spent in nanotechnology research. Two-thirds of this came from corporate and private funding. Private expenditure in the USA and Japan was slightly larger than that from public sources, whereas in Europe it was about one-third. Figure 1.4 shows the public and private expenditure breakdown in 2004 in various countries. Japan and USA had the largest expenditure, followed by Germany, Taiwan, South Korea, the UK, Australia, China, France, and Italy. Figure 1.5 shows a breakdown of worldwide publications and patents. USA and Canada led, followed by Europe and Asia. Figure 1.6 shows the breakdown in start-up companies around the world (1997–2002). Entrepreneurship in USA is clearly evident, followed by Europe.

1.3 Lessons from Nature (Biomimetics)

The word nanotechnology is a relatively new word, but it is not an entirely new field. Nature has gone through evolution over the 3.8 billion years since life is estimated to have appeared on Earth. Nature has many materials, objects, and processes which function from the macroscale to nanoscale [1.9]. Understanding the functions provided by these objects and processes can guide us to imitate and produce nanomaterials, nanodevices, and processes. Biologically inspired design, adaptation or derivation from nature is referred to as *biomimetics*, a term coined by the polymath Otto Schmitt in 1957. Biomimetics is derived from the Greek word *biomimesis*. Other terms used include bionics, biomimicry, and biognosis. The term biomimetics is relatively new; however, our ancestors looked to nature for inspiration and the development of various materials and devices many centuries ago [1.12, 13]. There are a large number of objects, including bacteria, plants, land and aquatic animals, seashells, and spider web, with properties of commercial interest. Figure 1.7 provides an overview of various objects from nature and their selected functions. Figure 1.8 shows a montage of some examples from nature, which serve as the inspiration for various technological developments.

The flagella of bacteria rotate at over 10 000 rpm [1.14]. This is an example of a biological molecular machine. The flagella motor is driven by the proton flow caused by the electrochemical potential differences across the membrane. The diameter of the bearing is about 20–30 nm, with an estimated clearance of ≈ 1 nm.

Several billions years ago, molecules began organizing into complex structures that could support life. Photosynthesis harnesses solar energy to support plant life. Molecular ensembles present in plant leaves, which include light-harvesting molecules such as chlorophyll, arranged within the cells (on the nanometer to micrometer scales), capture light energy and convert it into the chemical energy that drives the biochemical machinery of plant cells. Live organs use chemical energy in the body. This technology is being exploited for solar energy applications.

Some natural surfaces, including the leaves of water-repellent plants such as lotus, are known to be superhydrophobic and self-cleaning due to hierarchical roughness (microbumps superimposed with nanostructure) and the presence of a wax coating [1.15–19]. Roughness-induced superhydrophobic

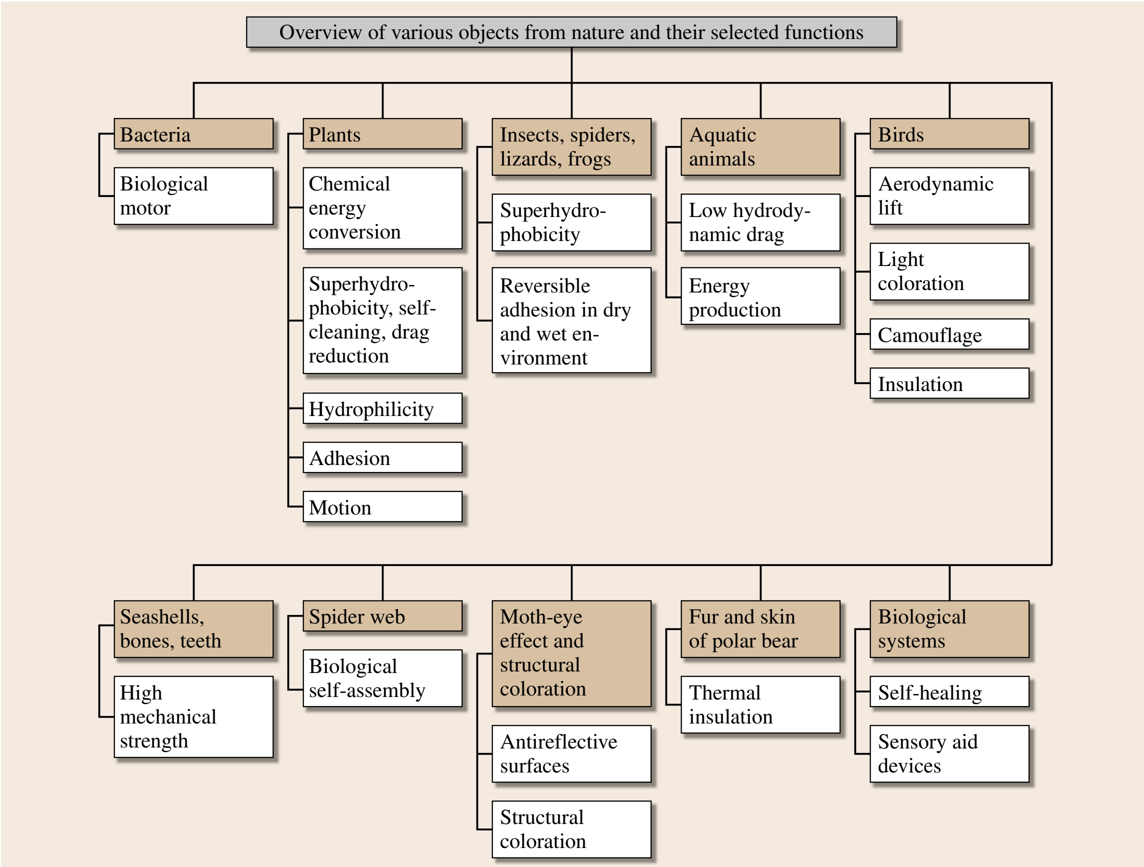


Fig. 1.7 Overview of various objects from nature and their selected function (after [1.13])

and self-cleaning surfaces are of interest in various applications, including self-cleaning windows, windshields, exterior paints for buildings and navigation ships, utensils, roof tiles, textiles, and applications requiring a reduction of drag in fluid flow, e.g., in micro/nanofluidics. Superhydrophobic surfaces can also be used for energy conversion and conservation [1.20]. Nonwetting surfaces also reduce stiction at contacting interfaces in machinery [1.21, 22].

The leg attachment pads of several creatures, including many insects (e.g., beetles and flies), spiders, and lizards (e.g., geckoes), are capable of attaching to a variety of surfaces and are used for locomotion [1.23]. Biological evolution over a long period of time has led to the optimization of their leg attachment systems. The attachment pads have the ability to cling to different smooth and rough surfaces and detach at will [1.24, 25]. This dynamic attachment ability is referred to as reversible adhesion or smart adhesion. Replication of the characteristics of gecko feet would enable the development of a superadhesive polymer tape capable of clean, dry adhesion which is reversible [1.25–27]. (It should be noted that common manmade adhesives such as tape or glue involve the use of wet adhesives that permanently attach two surfaces.) The reusable gecko-inspired adhesives have the potential for use in everyday objects such as tapes, fasteners, and toys, and in high technology such as microelectronic and space applications. Replication of the dynamic climbing and peeling ability of geckoes could find use in the treads of wall-climbing robots. Incidentally, *Velcro* was invented based on the action of the hooked seeds of the burdock plant [1.28].

Many aquatic animals can move in water at high speeds with low energy input. Drag is a major hindrance to movement. Most shark species move through water with high efficiency and maintain buoyancy. Through its ingenious design, their skin turns out to be an essen-

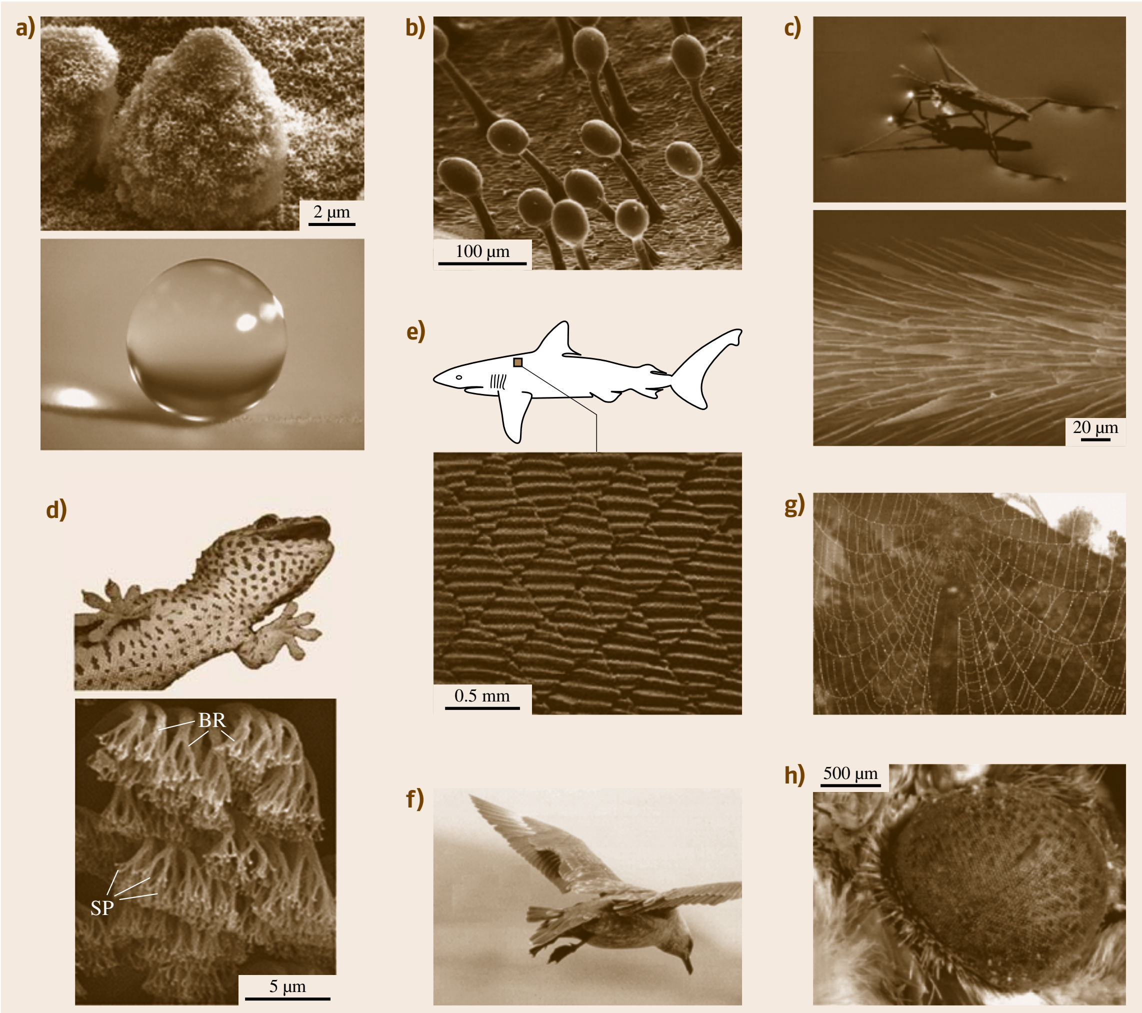


Fig. 1.8a–h Montage of some examples from nature: **(a)** lotus effect [1.30], **(b)** glands of carnivorous plant that secrete adhesive to trap insects [1.17], **(c)** water strider walking on water [1.31], **(d)** gecko foot exhibits reversible adhesion [1.32] (BR – branch, SP – spatula), **(e)** scale structure of shark reduces drag [1.33], **(f)** wings of a bird in landing approach, **(g)** spider web made of silk material [1.12], **(h)** moth's eyes are antireflective [1.34]

tial aid to this behavior by reducing friction drag and autocleaning ectoparasites from their surface [1.29]. The very small individual tooth-like scales of shark skin, called dermal denticles, are ribbed with longitudinal grooves, which result in water moving very efficiently over their surface. The scales also minimize the collection of barnacles and algae. Speedo created the whole-body swimsuit called Fastskin, modeled on shark skin, for elite swimming. Boat, ship, and aircraft manufacturers are trying to mimic shark skin to reduce friction drag and minimize the attachment of organisms to their bodies. In addition, mucus on the skin of aquatic animals, including sharks, acts as an osmotic barrier against the salinity of seawater and protects the creature from parasites and infections. It also acts as a drag-reducing agent. Artificial derivatives of fish mucus (polymer additives) are used to propel crude oil in the Alaska pipeline. The compliant skin of dolphins allows them to swim at high speed. By interacting with the water flowing over the body's surface it stabilizes the flow and delays the transition to turbulence. Dolphins possess an optimum shape for drag reduction of submerged bodies. Submarines use the shape of dolphins. The streamlined form of boxfish (*Ostracion meleagris*) has inspired Mercedes Benz's bionic concept car with low aerodynamic drag. The beak of the kingfisher was used to model the nose cone of the Japanese Shinkansen bullet train. Power is generated by the scalloped edges of a humpback whale, and this design is exploited for wind turbine blades.

Bird feathers make the body water repellant, and movable flaps create wing and tail for aerodynamic lift during flying [1.29]. Birds and butterflies create brilliant hues by refracting light through millions of repeated structures that bend light to make certain colors. Seashells are natural nanocomposites with a laminated structure and exhibit superior mechanical properties. Spider web consists of silk fiber which is very strong. The materials and structures used in these objects have led to the development of various materials and fibers with high mechanical strength. Moth eyes have a multifaceted surface on the nanoscale and are structured to reduce reflection. This antireflective design led to the discovery of antireflective surfaces [1.35].

A remarkable property of biological tissues is their ability for self-healing. In biological systems, chemical signals released at the site of a fracture initiate a systemic response that transports repair agents to the site of an injury and promotes healing. Various artificial self-healing materials are being developed [1.36]. Human skin is sensitive to impact, leading to purple-colored marks in areas that are hit. This idea has led to the development of coatings indicating impact damage [1.12]. Another interesting and promising idea involves the application of an array of sensors to develop an *artificial nose* or an *artificial tongue*.

Other lessons from nature include the wings of flying insects, abalone shell with high-impact ceramic properties, strong spider silk, ultrasonic detection by bats, infrared detection by beetles, and silent flying of owls because of frayed feathers on the edges of their wings.

1.4 Applications in Different Fields

Science and technology continue to move forward in making the fabrication of micro/nanodevices and systems possible for a variety of industrial, consumer, and biomedical applications [1.37, 38]. A variety of MEMS devices have been produced, and some are in commercial use [1.39–48]. A variety of sensors are used in industrial, consumer, defense, and biomedical applications. Various micro/nanostructures and micro/nanocomponents are used in microinstruments and other industrial applications such as micromirror arrays. The largest *killer* MEMS applications include accelerometers (some 90 million units installed in vehicles in 2004), silicon-based piezoresistive pressure sensors for manifold absolute pressure sensing for engines and for disposable blood pressure sensors (about 30 million and 25 million units, respectively), capacitive pressure sensors for tire pressure measurements (about 37 million units in 2005), thermal inkjet printheads (about 500 million units in 2004), micromirror arrays for digital projection displays (about US$ 700 million revenue in 2004), and optical cross-connections in telecommunications. Other applications of MEMS devices include chemical/biosensors and gas sensors, microresonators, infrared detectors and focal-plane arrays for Earth observation, space science, and missile defense applications, picosatellites for space applications, fuel cells, and many hydraulic, pneumatic, and other consumer products. MEMS devices are also being pursued for use in magnetic storage systems [1.49], where they are being developed for supercompact and ultrahigh-recording-density magnetic disk drives.

NEMS are produced by nanomachining in a typical top–down approach and bottom–up approach, largely relying on nanochemistry [1.50–56]. Examples of NEMS include microcantilevers with integrated sharp nanotips for scanning tunneling microscopy (STM) and atomic force microscopy (AFM), quantum corrals formed using STM by placing atoms one by one, AFM cantilever arrays for data storage, AFM tips for nanolithography, dip-pen lithography for printing molecules, nanowires, carbon nanotubes, quantum wires (QWRs), quantum boxes (QBs), quantum-dot transistors, nanotube-based sensors, biological (DNA) motors, molecular gears formed by attaching benzene molecules to the outer walls of carbon nanotubes, devices incorporating nm-thick films [e.g., in giant magnetoresistive (GMR) read/write magnetic heads and magnetic media] for magnetic rigid disk drives and magnetic tape drives, nanopatterned magnetic rigid disks, and nanoparticles (e.g., nanoparticles in magnetic tape substrates and magnetic particles in magnetic tape coatings).

Nanoelectronics can be used to build computer memory using individual molecules or nanotubes to store bits of information, molecular switches, molecular or nanotube transistors, nanotube flat-panel displays, nanotube integrated circuits, fast logic gates, switches, nanoscopic lasers, and nanotubes as electrodes in fuel cells.

BioMEMS/BioNEMS are increasingly used in commercial and defense applications [1.57–63]. They are used for chemical and biochemical analyses (biosensors) in medical diagnostics (e.g., DNA, RNA, proteins, cells, blood pressure and assays, and toxin identification) [1.63, 64], tissue engineering [1.65], and implantable pharmaceutical drug delivery [1.66, 67]. Biosensors, also referred to as biochips, deal with liquids and gases. There are two types of biosensors. A large variety of biosensors are based on micro/nanofluidics. Micro/nanofluidic devices offer the ability to work with smaller reagent volumes and shorter reaction times, and perform analyses multiple times at once. The second type of biosensors includes micro/nanoarrays which perform one type of analysis thousands of times. Micro/nanoarrays are a tool used in biotechnology research to analyze DNA or proteins to diagnose diseases or discover new drugs. Also called DNA arrays, they can identify thousands of genes simultaneously [1.60]. They include a microarray of silicon nanowires, roughly a few nm in size, to selectively bind and detect even a single biological molecule, such as DNA or protein, by using nanoelectronics to detect the slight electrical charge caused by such binding, or a microarray of carbon nanotubes to electrically detect glucose.

After the tragedy of September 11, 2001, concern about biological and chemical warfare has led to the development of handheld units with bio- and chemical sensors for detection of biological germs, chemical or nerve agents, and mustard agents, and chemical precursors to protect subways, airports, water supplies, and the population at large [1.68].

BioMEMS/BioNEMS are also being developed for minimal invasive surgery, including endoscopic surgery, laser angioplasty, and microscopic surgery. Other applications include implantable drug-delivery devices (micro/nanoparticles with drug molecules encapsulated in functionalized shells for site-specific targeting applications) and a silicon capsule with a nanoporous membrane filled with drugs for long-term delivery.

1.5 Various Issues

There is an increasing need for a multidisciplinary, system-oriented approach to the manufacture of micro/nanodevices which function reliably. This can only be achieved through the cross-fertilization of ideas from different disciplines and the systematic flow of information and people among research groups. Common potential failure mechanisms for MEMS/NEMS requiring relative motion that need to be addressed in order to increase their reliability are: adhesion, friction, wear, fracture, fatigue, and contamination [1.21, 22, 69, 70]. Surface micro/nanomachined structures often include smooth and chemically active surfaces. Due to the large surface area to volume ratio in MEMS/NEMS, they are particularly prone to stiction (high static friction) as part of normal operation. Fracture occurs when the load on a microdevice is greater than the strength of the material. Fracture is a serious reliability concern, particularly for brittle materials used in the construction of these components, since it can immediately or would eventually lead to catastrophic failures. Additionally, debris can be formed from the fracturing of microstructures, leading to other failure processes. For less brittle materials, repeated loading over a long period of time causes fatigue that can also lead to the breaking and fracturing of the device. In principle, this failure mode is relatively easy to observe and simple to predict. However, the materials properties of thin films are often not known, making fatigue predictions error prone.

Many MEMS/NEMS devices operate near their thermal dissipation limit. They may encounter hot spots that may cause failures, particularly in weak structures such as diaphragms or cantilevers. Thermal stressing and relaxation caused by thermal variations can create material delamination and fatigue in cantilevers. When exposed to large temperature changes, as experienced in the space environment, bimetallic beams will also experience warping due to mismatched coefficients of thermal expansion. Packaging has been a big problem. The contamination that probably happens in packaging and during storage also can strongly influence the reliability of MEMS/NEMS. For example, a dust particle that lands on one of the electrodes of a comb drive can cause catastrophic failure. There are no MEMS/NEMS fabrications standards, which make it difficult to transfer fabrication steps in MEMS/NEMS between foundries.

Obviously, studies of the determination and suppression of active failure mechanisms affecting this new and promising technology are critical to high reliability of MEMS/NEMS and are determining factors for successful practical application.

Adhesion between a biological molecular layer and the substrate, referred to as *bioadhesion*, and reduction of friction and wear of biological layers, biocompatibility, and biofouling for BioMEMS/BioNEMS are important.

Mechanical properties are known to exhibit a dependence on specimen size. Mechanical property evaluation of nanoscale structures is carried out to help design reliable systems since good mechanical properties are of critical importance in such applications. Some of the properties of interest are: Young's modulus of elasticity, hardness, bending strength, fracture toughness, and fatigue life. Finite-element modeling is carried out to study the effects of surface roughness and scratches on stresses in nanostructures. When nanostructures are smaller than a fundamental physical length scale, conventional theory may no longer apply, and new phenomena emerge. Molecular mechanics is used to simulate the behavior of a nanoobject.

The societal, ethical, political, and health/safety implications of nanotechnology are also attracting major attention [1.11]. One of the prime reasons is to avoid some of the public skepticism that surrounded the debate over biotechnology advances such as genetically modified foods, while at the same time dispelling some of the misconceptions the public may already have about nanotechnology. Health/safety issues need to be addressed as well. For example, one key question is what happens to nanoparticles (such as buckyballs or nanotubes) in the environment and whether they are toxic in the human body, if digested.

1.6 Research Training

With the decreasing number of people in Western countries going into science and engineering and the rapid progress being made in nanoscience and nanotechnology, the problem of ensuring a trained workforce is expected to become acute. Education and training are essential to produce a new generation of scientists, engineers, and skilled workers with the flexible and interdisciplinary R&D approach necessary for rapid progress in the nanosciences and nanotechnology [1.71]. The question is being asked: is the traditional separation of academic disciplines into physics, chemistry, biology, and various engineering disciplines meaningful at the nanolevel? Generic skills and entrepreneurship are needed to transfer scientific knowledge into products. Scientists and engineers in cooperation with relevant experts should address the societal, ethical, political, and health/safety implications of their work for society at large.

To increase the pool of students interested in science and technology, science needs to be projected to be exciting at the high-school level. Interdisciplinary curricula relevant for nanoscience and nanotechnology need to be developed. This requires the revamping of education, the development of new courses and course material including textbooks [1.47, 56, 70, 72–74] and instruction manuals, and the training of new instructors.

1.7 Organization of the Handbook

This Handbook integrates knowledge from the fabrication, mechanics, materials science, and reliability points of view. Organization of the Handbook is straightforward. The Handbook is divided into nine parts. The first part of the book includes an introduction to nanostructures, micro/nanofabrication, methods, and materials. The second part introduces various MEMS/NEMS and BioMEMS/BioNEMS devices. The third part introduces scanning probe microscopy. The fourth part provides an overview of bio/nanotribology and bio/nanomechanics, which will prepare the reader to understand the interface reliability in industrial applications. The fifth part provides an overview of molecularly thick films for lubrication. The sixth part focuses on the emerging field of biomimetics, in which one mimics nature to develop products and processes of interest. The seventh part focuses on industrial applications, and the eighth part focuses on micro/nanodevice reliability. The final part focuses on technological convergence from the nanoscale as well as social, ethical, and political implications of nanotechnology.

References

1.1 R.J. Chen, H.C. Choi, S. Bangsaruntip, E. Yenilmex, X. Tang, Q. Wang, Y.L. Chang, H. Dai: An investigation of the mechanisms of electrode sensing of protein adsorption on carbon nanotube devices, J. Am. Chem. Soc. **126**, 1563–1568 (2004)

1.2 D. Srivastava: Computational nanotechnology of carbon nanotubes. In: *Carbon Nanotubes: Science and Applications*, ed. by M. Meyyappan (CRC, Boca Raton 2004) pp. 25–36

1.3 W.G. van der Wiel, S. De Franceschi, J.M. Elzerman, T. Fujisawa, S. Tarucha, L.P. Kauwenhoven: Electron transport through double quantum dots, Rev. Mod. Phys. **75**, 1–22 (2003)

1.4 Anonymous: *Microelectromechanical Systems: Advanced Materials and Fabrication Methods* (National Academy Press, Washington 1997), NMAB-483

1.5 M. Roukes: Nanoelectromechanical systems face the future, Phys. World **14**, 25–31 (2001)

1.6 J.C. Eloy: *Status of the MEMS Industry* (Yole Developpement, Lyon 2005), presented at SPIE Photonics West, San Jose (2005)

1.7 S. Lawrence: Nanotech grows up, Technol. Rev. **108**(6), 31 (2005)

1.8 R.P. Feynman: There's plenty of room at the bottom, Eng. Sci. **23**, 22–36 (1960), http://www.zyvex.com/nanotech/feynman.html

1.9 I. Amato: *Nanotechnology* (2000), http://www.ostp.gov/nstc/html/iwgn/iwgn.public.brochure/welcome.htm or http://www.nsf.gov/home/crssprgm/nano/nsfnnireports.htm

1.10 Anonymous: *National Nanotechnology Initiative* (2000), http://www.ostp.gov/nstc/html/iwgn.fy01budsuppl/nni.pdf or http://www.nsf.gov/home/crssprgm/nano/nsfnnireports.htm

1.11 Anonymous: *Towards a European Strategy for Nanotechnology* (European Commission Research Directorate General, Brussels 2004)

1.12 Y. Bar-Cohen (Ed.): *Biomimetics – Biologically Inspired Technologies* (CRC, Boca Raton 2005)

1.13 B. Bhushan: Biomimetics: Lessons from nature – An overview, Philos. Trans. R. Soc. Lond. Ser. A **367**, 1445–1486 (2009)

1.14 C.J. Jones, S. Aizawa: The bacterial flagellum and flagellar motor: Structure, assembly, and functions, Adv. Microb. Physiol. **32**, 109–172 (1991)

1.15 B. Bhushan, Y.C. Jung: Wetting, adhesion and friction of superhydrophobic and hydrophilic leaves and fabricated micro-/nanopatterned surfaces, J. Phys. D **20**, 225010 (2008)

1.16 K. Koch, B. Bhushan, W. Barthlott: Diversity of structure, morphology, and wetting of plant surfaces, Soft Matter **4**, 1943–1963 (2008)

1.17 K. Koch, B. Bhushan, W. Barthlott: Multifunctional surface structures of plants: An inspiration for biomimetics (invited), Prog. Mater. Sci. **54**, 137–178 (2009)

1.18 M. Nosonovsky, B. Bhushan: *Multiscale Dissipative Mechanisms and Hierarchical Surfaces: Friction, Superhydrophobicity, and Biomimetics* (Springer, Berlin, Heidelberg 2008)

1.19 M. Nosonovsky, B. Bhushan: Roughness-induced superhydrophobicity: A way to design non-adhesive surfaces, J. Phys. D **20**, 225009 (2008)

1.20 M. Nosonovsky, B. Bhushan: Multiscale effects and capillary interactions in functional biomimetic surfaces for energy conversion and green engineering, Philos. Trans. R. Soc. Lond. Ser. A **367**, 1511–1539 (2009)

1.21 B. Bhushan: *Principles and Applications of Tribology* (Wiley, New York 1999)

1.22 B. Bhushan (Ed.): *Introduction to Tribology* (Wiley, New York 2002)

1.23 S. Gorb (Ed.): *Attachment Devices of Insect Cuticle* (Kluwer, Dordrecht 2001)

1.24 K. Autumn, Y.A. Liang, S.T. Hsieh, W. Zesch, W.P. Chan, T.W. Kenny, R. Fearing, R.J. Full: Adhesive force of a single gecko foot-hair, Nature **405**, 681–685 (2000)

1.25 B. Bhushan: Adhesion of multi-level hierarchical attachment systems in gecko feet, J. Adhes. Sci. Technol. **21**, 1213–1258 (2007)

1.26 A.K. Geim, S.V. Dubonos, I.V. Grigorieva, K.S. Novoselov, A.A. Zhukov, S.Y. Shapoval: Microfabricated adhesive mimicking gecko foot-hair, Nat. Mater. **2**, 461–463 (2003)

1.27 B. Bhushan, R.A. Sayer: Surface characterization and friction of a bio-inspired reversible adhesive tape, Microsyst. Technol. **13**, 71–78 (2007)

1.28 S.A. Velcro: Improvements in or relating to a method and a device for producing velvet type fabric, Switzerland Patent 721338 (1995)

1.29 D.W. Bechert, M. Bruse, W. Hage, R. Meyer: Fluid mechanics of biological surfaces and their technological application, Naturwissenschaften **87**, 157–171 (2000)

1.30 B. Bhushan, Y.C. Jung, K. Koch: Micro-, nano-, and hierarchical structures for superhydrophobicity, self-cleaning, and low adhesion, Philos. Trans. R. Soc. Lond. Ser. A **367**, 1631–1672 (2009)

1.31 X.F. Gao, L. Jiang: Biophysics: Water-repellent legs of water striders, Nature **432**, 36 (2004)

1.32 H. Gao, X. Wang, H. Yao, S. Gorb, E. Arzt: Mechanics of hierarchical adhesion structures of geckos, Mech. Mater. **37**, 275–285 (2005)

1.33 W.E. Reif: *Squamation and Ecology of Sharks*, Courier Forschungsinst. Senckenberg, Vol. 78 (Schweizerbart, Stuttgart 1985)

1.34 J. Genzer, K. Efimenko: Recent developments in superhydrophobic surfaces and their relevance to

marine fouling: A review, Biofouling **22**, 339–360 (2006)
1.35 C.G. Bernhard, W.H. Miller, A.R. Möller: The insect corneal nipple array: A biological, broad-band impedance transformer that acts as a antireflection coating, Acta Physiol. Scand. **63**, 1–79 (1965)
1.36 J.P. Youngblood, N.R. Sottos: Bioinspired materials for self-cleaning and self-healing, MRS Bulletin **33**, 732–738 (2008)
1.37 Anonymous: *Small Tech 101 – An Introduction to Micro and Nanotechnology* (Small Times, 2003)
1.38 M. Schulenburg: *Nanotechnology – Innovation for Tomorrow's World* (European Commission Research Directorate General, Brussels 2004)
1.39 R.S. Muller, R.T. Howe, S.D. Senturia, R.L. Smith, R.M. White: *Microsensors* (IEEE, New York 1991)
1.40 I. Fujimasa: *Micromachines: A New Era in Mechanical Engineering* (Oxford Univ. Press, Oxford 1996)
1.41 W.S. Trimmer (Ed.): *Micromachines and MEMS, Classical and Seminal Papers to 1990* (IEEE, New York 1997)
1.42 B. Bhushan: *Tribology Issues and Opportunities in MEMS* (Kluwer, Dordrecht 1998)
1.43 G.T.A. Kovacs: *Micromachined Transducers Sourcebook* (WCB McGraw-Hill, Boston 1998)
1.44 M. Elwenspoek, R. Wiegerink: *Mechanical Microsensors* (Springer, Berlin Heidelberg 2001)
1.45 S.D. Senturia: *Microsystem Design* (Kluwer, Boston 2000)
1.46 T.R. Hsu: *MEMS and Microsystems: Design and Manufacture* (McGraw-Hill, Boston 2002)
1.47 M. Madou: *Fundamentals of Microfabrication: The Science of Miniaturization*, 2nd edn. (CRC, Boca Raton 2002)
1.48 A. Hierlemann: *Integrated Chemical Microsensor Systems in CMOS Technology* (Springer, Berlin Heidelberg 2005)
1.49 B. Bhushan: *Tribology and Mechanics of Magnetic Storage Devices*, 2nd edn. (Springer, Berlin Heidelberg 1996)
1.50 K.E. Drexler: *Nanosystems: Molecular Machinery, Manufacturing and Computation* (Wiley, New York 1992)
1.51 G. Timp (Ed.): *Nanotechnology* (Springer, New York 1999)
1.52 M.S. Dresselhaus, G. Dresselhaus, P. Avouris: *Carbon Nanotubes – Synthesis, Structure, Properties, and Applications* (Springer, Berlin Heidelberg 2001)
1.53 E.A. Rietman: *Molecular Engineering of Nanosystems* (Springer, Berlin, Heidelberg 2001)
1.54 W.A. Goddard, D.W. Brenner, S.E. Lyshevski, G.J. Iafrate (Eds.): *Handbook of Nanoscience, Engineering,and Technology* (CRC, Boca Raton 2002)
1.55 H.S. Nalwa (Ed.): *Nanostructured Materials and Nanotechnology* (Academic, San Diego 2002)
1.56 C.P. Poole, F.J. Owens: *Introduction to Nanotechnology* (Wiley, New York 2003)
1.57 A. Manz, H. Becker (Eds.): *Microsystem Technology in Chemistry and Life Sciences*, Top. Curr. Chem., Vol. 194 (Springer, Berlin, Heidelberg 1998)
1.58 J. Cheng, L.J. Kricka (Eds.): *Biochip Technology* (Harwood, Philadephia 2001)
1.59 M.J. Heller, A. Guttman (Eds.): *Integrated Microfabricated Biodevices* (Marcel Dekker, New York 2001)
1.60 C. Lai Poh San, E.P.H. Yap (Eds.): *Frontiers in Human Genetics* (World Scientific, Singapore 2001)
1.61 C.H. Mastrangelo, H. Becker (Eds.): *Microfluidics and BioMEMS*, Proc. SPIE, Vol. 4560 (SPIE, Bellingham 2001)
1.62 H. Becker, L.E. Locascio: Polymer microfluidic devices, Talanta **56**, 267–287 (2002)
1.63 A. van der Berg (Ed.): *Lab-on-a-Chip: Chemistry in Miniaturized Synthesis and Analysis Systems* (Elsevier, Amsterdam 2003)
1.64 P. Gravesen, J. Branebjerg, O.S. Jensen: Microfluidics – A review, J. Micromech. Microeng. **3**, 168–182 (1993)
1.65 R.P. Lanza, R. Langer, J. Vacanti (Eds.): *Principles of Tissue Engineering*, 2nd edn. (Academic, San Diego 2000)
1.66 K. Park (Ed.): *Controlled Drug Delivery: Challenges and Strategies* (American Chemical Society, Washington 1997)
1.67 P.Å. Öberg, T. Togawa, F.A. Spelman: *Sensors in Medicine and Health Care* (Wiley, New York 2004)
1.68 M. Scott: MEMS and MOEMS for national security applications, Proc. SPIE **4980**, xxxvii–xliv (2003)
1.69 B. Bhushan: *Handbook of Micro/Nanotribology* (CRC, Boca Raton 1999)
1.70 B. Bhushan (Ed.): *Nanotribology and Nanomechanics – An Introduction*, 2nd edn. (Springer, Berlin, Heidelberg 2008)
1.71 Anonymous: Current status and future needs, Proc. Workshop Res. Train. Nanosci. Nanotechnol. (European Commission Research Directorate General, Brussels 2005)
1.72 M. Di Ventra, S. Evoy, J.R. Heflin: *Introduction to Nanoscale Science and Technology* (Springer, Berlin Heidelberg 2004)
1.73 A. Hett: *Nanotechnology – Small Matter, Many Unknowns* (Swiss Reinsurance Company, Zurich 2004)
1.74 M. Köhler, W. Fritzsche: *Nanotechnology* (Wiley, New York 2004)