Frontiers in Nanoscale Science, Engineering, and Technology

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Abstract

Science is being enhanced towards the better understanding of the physics, chemistry, biology, sensors, computation, actuators, adaptation, interaction, and coordination of particles at the atomic, molecular, and supramolecular levels through the steady advancements in nanoscale science, engineering, and technology. The technology itself is beginning to be developed at the most elementary level, while engineering models, devices, and systems need to be designed and developed at a much higher pace to be able to exploit more rapidly the almost incredible benefits in wide areas of application including biological and medical, miniaturized electronics and its manufacturing, space and defense to mention a few. The foundations of this fascinating field together with a selective choice of key current and future applications and challenges are examined.

Keywords: Atomic Force Microscope (ATM), carbon nanotubes (CNT), lab-on-a-chip (LOC), molecular electronics, nanoanalytics, nanoclinics, nanodevices, nanoelectronics, nano electromechanical systems (NEMS), nanomechanics , nanomedicine, nanoparticles, nanorobotics, Scanning Tunneling Microscope (STM).

Introduction

Novel applications are being enabled by the study of matter – with the intention of understanding and controlling it – at scales in the orders of magnitude 1–100 nm, i.e., at nanoscale. For that purpose, matter needs to be imaged, measured, modeled, and manipulated. The physical, chemical, and biological properties that emerge in nanoscale materials tend to be atypical w.r.t. what we are used to at larger scales.

There is a vast amount of literature in this emergent field. With no intention to be exhaustive, some key references are provided. For example, book publications include among several others (Drexler, 1987), an early, visionary book with future projections of nanotechnology, and more recently, a handbook of nanotechnology (Bhushan, 2006), the foundations of its nanophysics (Wolf, 2006), a handbook of MEMS/NEMS (Micro/Nano Electro Mechanical Systems) (Leondes, 2006), nanotechnology in biology and medicine (Vo-Dinh, 2007), molecular building blocks (Mansoori, George, Assoufid, & Zhang, 2007), a treatment of nanoelectronics (Mitin, Kochelap, & Stroscio, 2008), a handbook of nanomedicine (Jain,

2008), a treatment of nanochemistry (Ozin, Arsenault, & Cademartiri, 2009), and nanotechnology for chemical and biological defense (Kosal, 2009).

In the U.S., a multi-agency effort, the National Nanotechnology Initiative (NNI) (NCST, 2009), with 25 agencies participating, is being coordinated by the National Council of Science and Technology (NCST) with an investment of approx. $12 billion since its inception in FY2001, of which alone in 2010 $1.64 billion are planned to be invested, see the major participating agencies and a subdivision by 8 investment categories or program component areas (PCAs) in Table 1 to achieve 4 major goals:

1. Advance a world-class nanotechnology R&D program,
2. Foster the transfer of new technologies into products for commercial and public benefit,
3. Develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology, and
4. Support responsible development of nanotechnology.

Table 1 U.S. National Nanotechnology Initiative (NNI) 2010 Budget (NCST)

Planned 2010 Agency Investments by Program Component Area (dollars in millions)									
	Fundamental Phenomena & Processes	Nanomaterials	Nanoscale Devices & Systems	Instrument Research, Metrology, & Standards	Nano-manufacturing	Major Research Facilities & Instr. Acquisition	Environment, Health, and Safety	Education & Societal Dimensions	NNI Total
NSF	154.7	80.4	43.8	18.5	22.5	38.5	29.9	34.7	423.0
DOD	174.8	61.6	100.6	4.6	14.2	21.0	1.7		378.5
DOE	103.2	82.4	12.8	35.1	4.9	109.6	2.9	0.5	351.4
DHHS (NIH)	48.8	45.2	169.3	5.5	0.7	38.2	17.3	0.6	325.6
DOC (NIST)	21.1	7.5	14.4	19.4	10.7	11.4	6.0		90.5
EPA	0.2	0.2	0.2				17.1		17.7
NASA	1.8	9.5	5.3						16.6
DHHS (NIOSH)							12.4		12.4
DHS		6.5	4.9		0.3				11.7
USDA (FS)	2.0	1.4	0.7	1.1	0.2				5.4
USDA (CSREES)	0.4	0.6	1.5		0.1		0.4	0.3	3.3
DOT (FHWA)		1.5	1.0						2.5
DOJ	0.1		0.1		0.1				0.4
TOTAL	**507.1**	**296.8**	**354.6**	**84.2**	**53.7**	**218.7**	**87.7**	**36.1**	**1,639.0**

Foundations

One nm (10^{-9} m) is one billionth of a meter. Nano science, engineering, and technology handle matter at the scale of 1—100 nm, that is, at the level of atoms, molecules, and supramolecular structures. To perceive the dimensions in which nano science, engineering, and technology are to operate, we compare some known relevant objects providing their approximate measures. For example, the width of human hair measures about 70,000 nm, whereas an aspirin molecule measures 1 nm. In between we have a red blood cell (2,500 nm), bacterium (1,000 nm), a vesicle in a cell (200 nm), virus (100 nm),

exosomes, i.e., nanovesicles shed by dendritic cells (65—100 nm), proteins (1—20 nm), ribosome (2—4 nm), DNA (width 2.5 nm), amino acid, e.g., tryptophan, the largest one (1.2 nm, longest measurement). Subnanometric objects include a base pair in human genome (0.4 nm) and an individual atom (0.25 nm). Figure 1 shows natural and man-made objects in comparison.

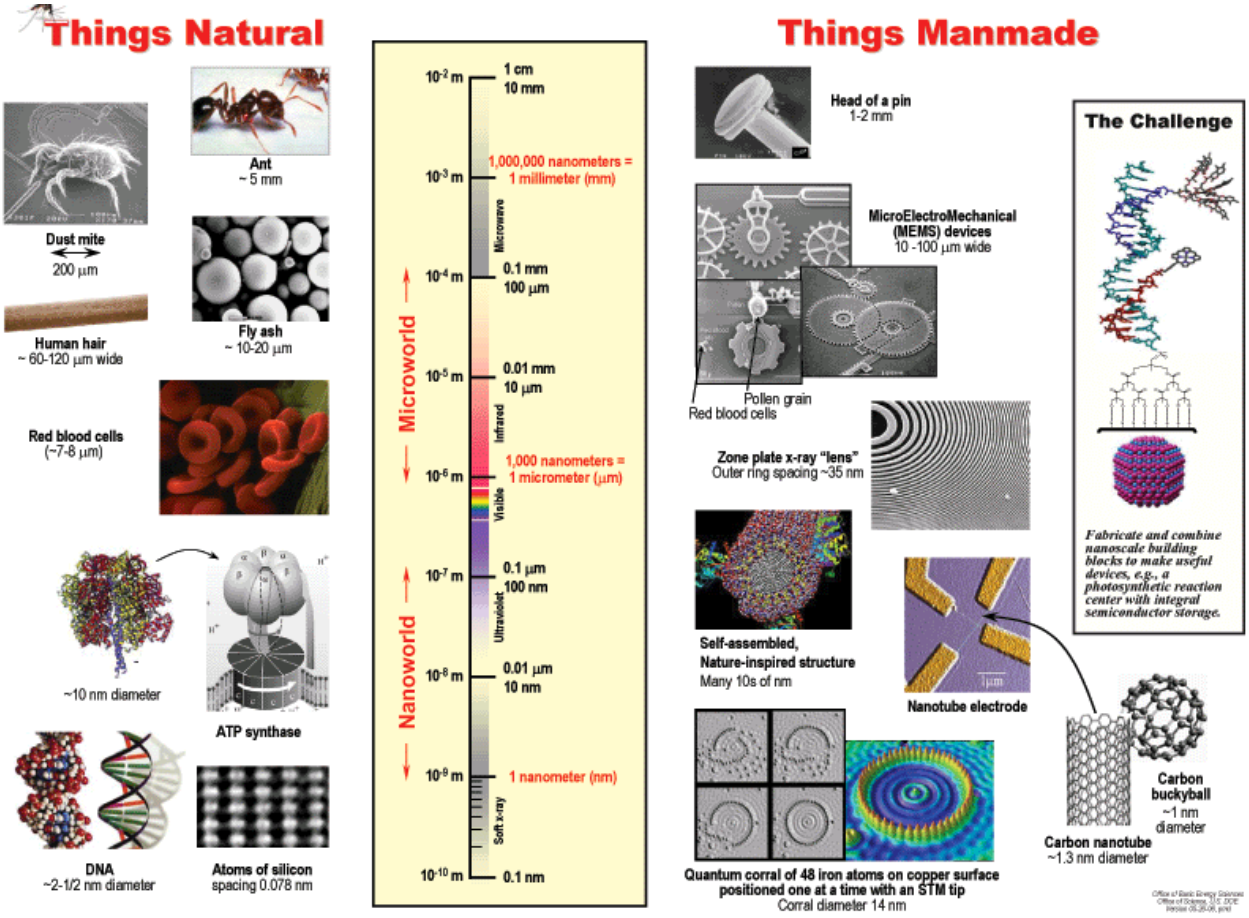

Figure 1 The Scale of Things (DOE)

The Scanning Tunneling Microscope (STM) was invented in the 1980's (Binnig & Rohrer, 1986). It is widely used to obtain atomic-scale surface images. It provides a three-dimensional profile of the surface used to characterize surface roughness, to detect surface defects, and to determine the size and conformation of molecules and aggregates on the surface. The STM is based on the tunnel effect of quantum mechanics due to particles' behavior governed by the Schrödinger's wave equation (Schrödinger, 1926), which describes how the quantum state of physical systems varies in time. The tunnel effect was first discovered in nuclear physics by the theory of alpha decay of a nucleus via tunneling (Gamov, 1928).

When a conducting sharp tip is brought fairly near to a metallic or semiconducting, extremely clean surface, a bias between the two objects: surface and tip, allows electrons to tunnel through the vacuum between them. That is, the STM probes the density of states of a material using tunneling current. For

low voltages, this current is a function of the local density of states (LDOS) at the Fermi level of the sample. As the probe passes over the surface, current variations are converted into an image.

Good STM lateral and depth resolutions are considered to be 0.1 nm and 0.01 nm respectively. The environments in which the STM can be used include ultra high vacuum as well as air and other liquids and gases. The temperature can range from approximately zero degrees Kelvin to a few hundred degrees Celsius. The STM is considered in the meantime a standard tool of nanoanalytics. Figure 2 shows a Scanning Tunneling Microscope (STM), a block diagram of its system components, and a 35 nm x 35 nm STM image of single substitutional Chromium (Cr) impurities – shown as small bumps - in the iron (Fe) surface.

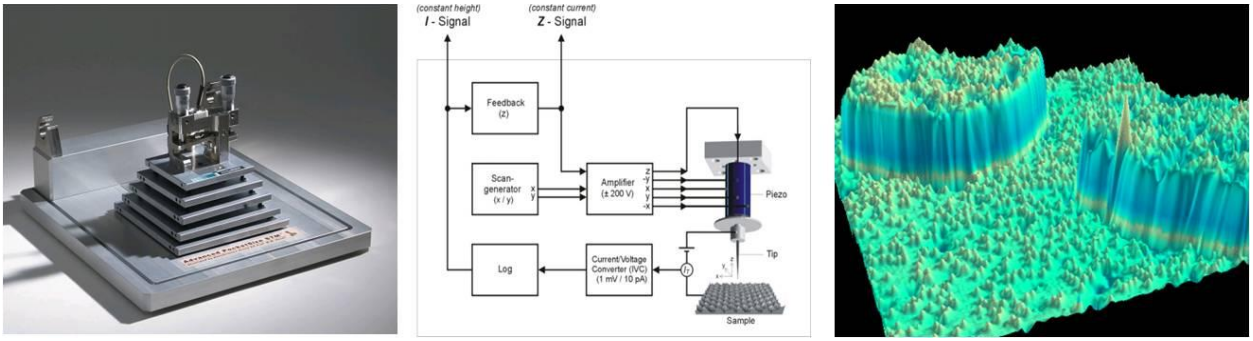

Figure 2 Scanning Tunneling Microscope (STM) (LMU)

Certain chemical elements exhibit allotropism: these elements can exist in more than one form, each form is called an allotrope of that element. More specifically, they can exist in different structural modifications of the element, i.e., the element's atoms are bonded together in different manners in different allotropes. For example, two common allotropes of Carbon (Ca) are diamond and graphit, whose atoms are arranged in a tetrahedral lattice and in hexagonal lattice sheets respectively. Element allotropism is similar to compound polymorphism, it does not affect the state of matter: solid, fluid, gas.

One relevant family of allotropes for the emergent field of nanotechnology is the fullerene (Kroto, Heath, O'Brien, Curl, & Smalley, 1985), a family of carbon allotropes, which are molecules entirely composed of carbon. They take different forms: plane, cylinder, sphere, ellipsoid. See Figure 3 (left) for an example of fullerene. A spherical fullerene is called buckyball, Figure 3 (middle). A cylindrical fullerene is called buckytube or carbon nanotube (CNT), Figure 3 (right).

CNTs are macromolecules made of carbon atoms arranged in a cage-like sheet of hexagons with the shape of tiny hollow cylinders that can reach lengths of 1mm and diameters of 0.4nm—100^{+}nm, depending on how many concentric tubes they are made of. There are metallic and semiconducting CNTs depending on the tube geometry. CNTs can be Single Wall Carbon Nanotubes (SWCNTs) or Multiwall Carbon Nanotubes (MWCNTs). MWCNTs were discovered (Iijima, 1991) before SWCNTs (Iijima & Ichihashi, 1993).

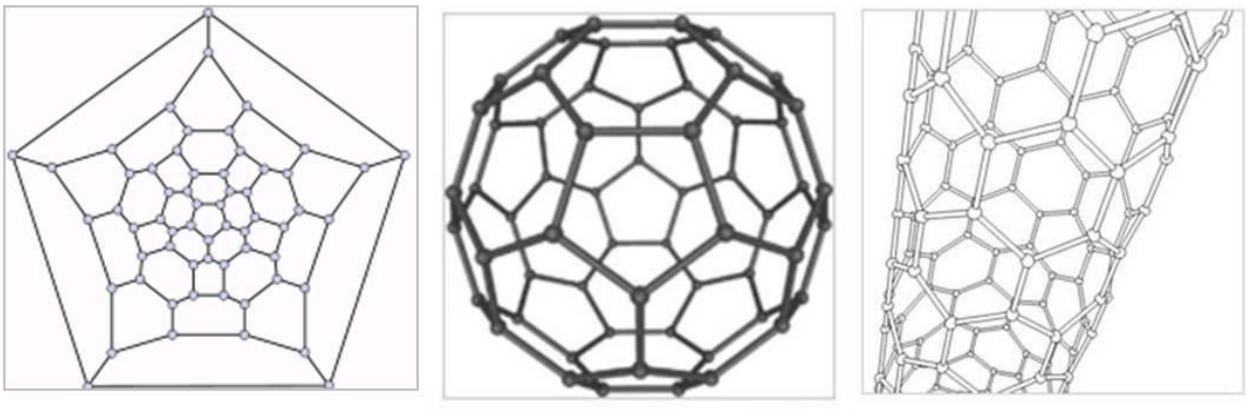

Figure 3 Fullerene, Buckyball, Nanotube

Currently, the silicon process technology is transitioning to structures with a minimum diameter of 90 nm. SWCNTs' diameters measure 0.4—5 nm. While copper begins to melt at a current density of approximately 10^7A/cm², semiconducting SWCNTs can withstand current densities of up to 10^{10}A/cm². Nanotube production processes are relatively inexpensive, which further stresses the attractiveness to apply this technology.

Applications

To satisfy the current-carrying capability in the semiconductor industry, measured by the transconductance, CNTs would need to be configured in parallel, since a single CNT with a 1 nm-diameter could deliver 24 µA in a prototype. For example, an Infineon's nanotube power transistor prototype with 400 parallel CNTs was developed to deliver 2 mA at 2.4 V, capable of driving LEDs and small motors.

Figure 4 (left) shows the schematic cross section of IBM's single-wall Carbon Nanotube Field Effect Transistor (CNTFET) (Wind, Appenzeller, Martel, Derycke, & Avouris, 2002), resembling the structure of a conventional metal-oxide-semiconductor field-effect-transistor (MOSFET). With this top-gate design, the independent gating of each transistor is achievable, enabling the fabrication of complementary metal-oxide-semiconductor (CMOS) circuits with simpler design and less power consumption.

Figure 4 (right) shows Infineon's nanotube field-effect transistor (FET) with a channel length of 18 nm. A controlled process allowed to grow CNTs, each measuring 0.7—1.1 nm in diameter. At a supply voltage of only 0.4 V, the nanotube transistor can deliver currents of 15^+ µA, which represents 10 times higher current density than the one of silicon. The natural extension of these developments is growing semiconducting CNTs in wafers and replacing current planar microelectronics by appropriate three-dimensional technology.

Figure 5 (left) shows carbon monoxide molecules (5 nm by 5 nm purple region) precisely positioned on a copper surface (yellow). The dark dimples in the surface display a molecular hologram made of molecular position density and created by a scanning tunneling microscope (STM). Information can be stored at unprecedented densities by using electrons to encode data. Once encoded in this region, the

information can be read out using scanning tunneling spectroscopy. In the example shown, two pages of information – pages in a data cube– are retrieved. Two energy levels (red, blue) are shown for reading the density of electron states.

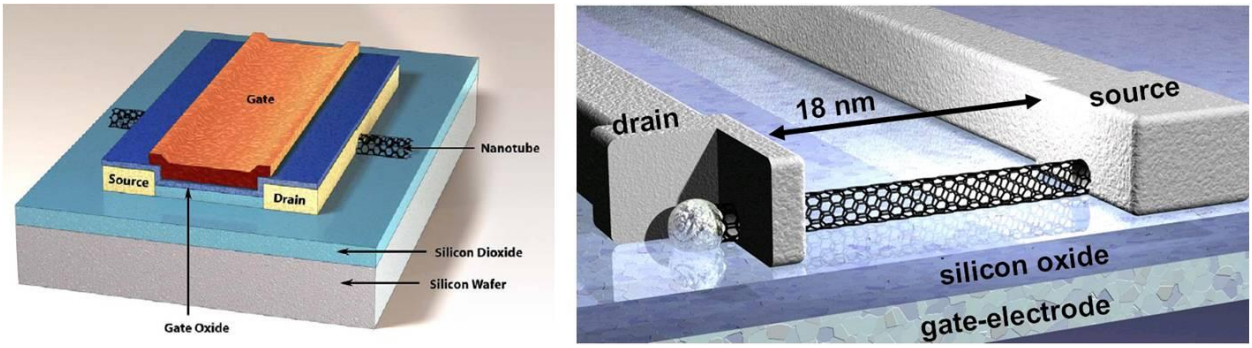

Figure 4 Nanotube Transistors (IBM, Infineon)

To continue with the miniaturization of semiconductor elements, new lithography processes need to be developed, with Extreme UltraViolet (EUV) and X-ray light (Luther & Bachmann, 2009). To manufacture semiconductor structure widths smaller than 32 nm, EUV lithography is one alternative. Figure 5 (right) shows the basic principle of EUV lithography for chip production using x-ray mirrors. The use of radiation in those spectral areas demands the development of reflection layers with high precision requirements. X-ray mirrors consist of 100s to 1000s of individual layers, each with a width of 0.5 to 20 nm. The goal is to develop manufacturing facilities that solve the associated challenges at the intersection between nanotechnology and optics.

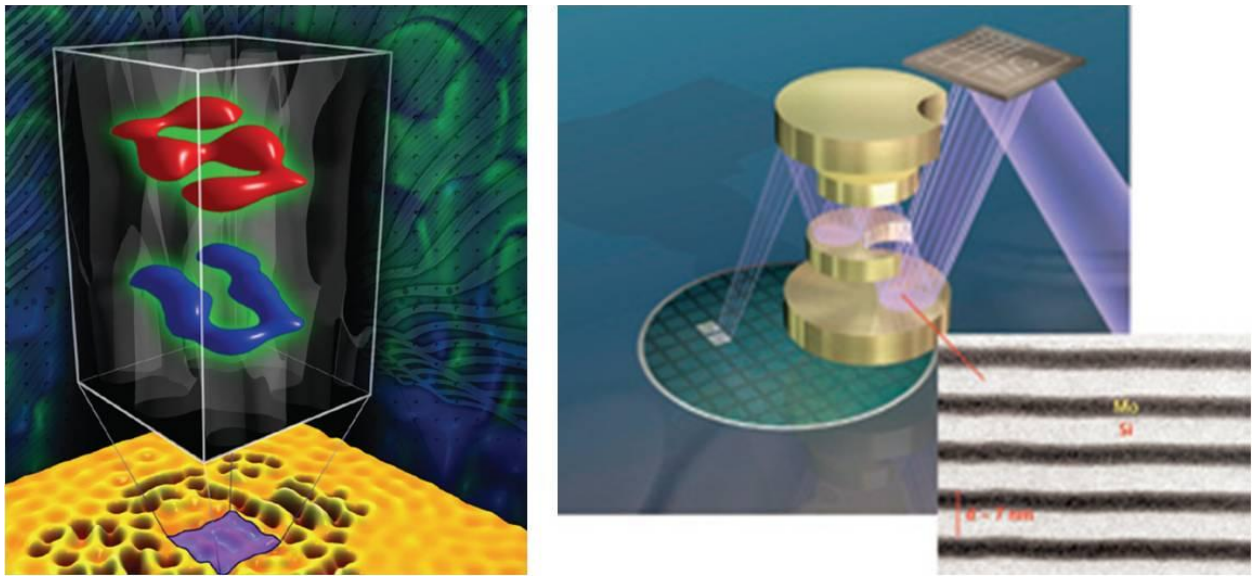

Figure 5 Subatomic Information Storage (NNI) and Extreme UltraViolet (EUV) Lithography for Chip Production (BMBF)

Alone in medicine (nanomedicine) potential applications are innumerable and include nanodiagnostics, nanotechnology-based drugs, regenerative and transplantation medicine, nanorobotic treatments, implants, minimally invasive surgery using catheters. Interrelated technologies are outlined in Figure 6.

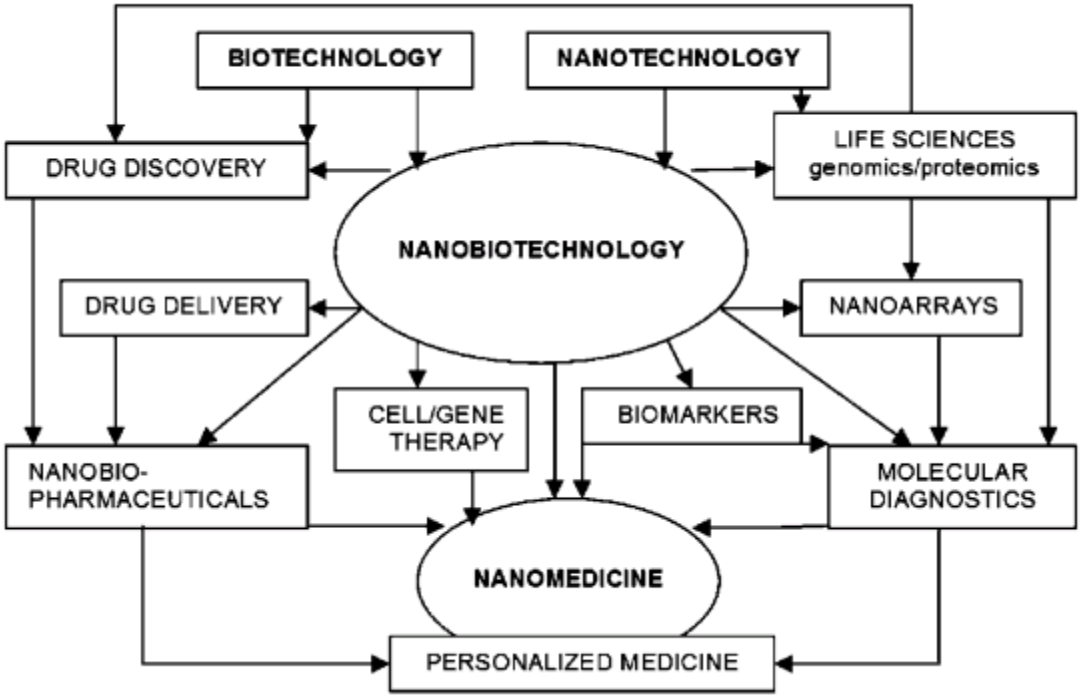

Figure 6 Interrelated Nanotechnologies (Jain, 2008)

The therapy of diseases, in particular of cancer, is being dramatically changed through the introduction of nanoscale devices. They are envisioned as customizable, target drug delivery vehicles carrying large doses of chemotherapeutic agents or therapeutic genes only to malignant cells and sparing healthy cells, thus avoiding the side effects of most of the current cancer therapies. Dendrimers (spherical, branched polymers), silica-coated micelles, ceramic nanoparticles, and cross-linked liposomes have all shown to be able to be targeted to cancer cells.

The targeting can be done by attaching monoclonal antibodies or cell-surface receptor ligands that bind specifically to molecules on the cancer cell surfaces, such as the high-affinity folate receptor and luteinizing hormone releasing hormone (LH-RH), or molecules unique to endothelial cells that become co-opted by malignant cells. Another focus of effort is the construction of robust smart nanostructures that can detect malignant cells in vivo and identify their location in the body, kill the malignant cells, and confirm back having done the job.

This latter effort seeks to implement modularity and multifunctionality at the operational level to create flexible, modifiable functional building blocks that can fulfill - when put together - all particular requirements of a given clinical situation. There are good examples of this in biology, e.g., a set of proteins, each with a specific chemical functionality, can make up a virus capsule and create a multifunctional nanodelivery vehicle for genetic material. A multifunctional nanoparticle that can be targeted to cancer cells using receptor ligands is shown in Figure 7 (left).

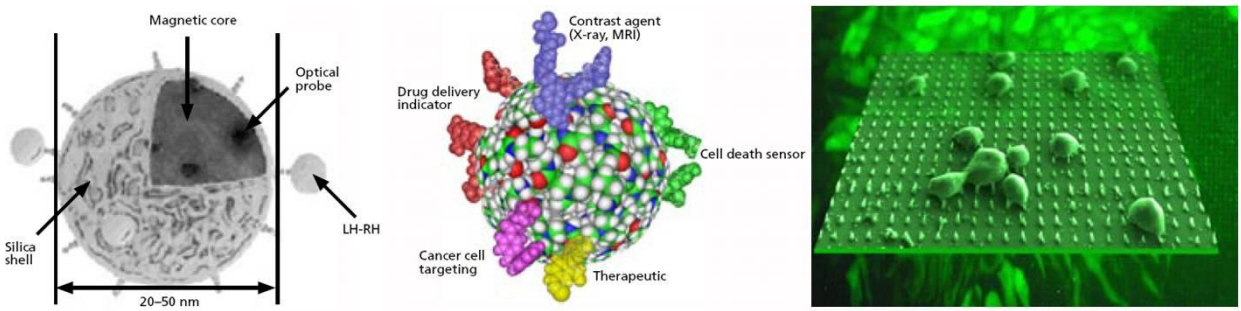

Figure 7 Nanoscale Platforms in Cancer Nanotechnology (NCI)

Synthetic materials have been also turned into multifunctional nanodevices or nanoclinics. Multifunctional modularity can be delivered by dendrimers, spherical polymers of uniform molecular weight made from branched monomers, with a radius of 1 – 10 nm. For example, a folate was attached to a single dendrimer. The folate targets the high-affinity folate receptor of some malignant cells, the indicator fluorescein, and either of the anticancer drugs methotrexate or paclitaxel.

The receptor-positive cells were folated and labeled for fluorescent detection as in vitro and in vivo experiments showed. As a fluorescent indicator of cell death was linked to the dendrimer, evidence was found that the therapeutic compound had been not only delivered to its target cell, but also had produced the desired effect. Dendrimer-based products are being prepared for clinical trial and to subsequently treat varieties of cancer. A dendrimer as a versatile nanoscale platform is shown in Figure 7 (middle).

Modern molecular biology is being linked to the physical sciences and engineering through nanotechnology. Among others, biomolecules and assemblies are being studied by materials scientists, sophisticated nanoscale tools are being designed and developed by engineers. As a result of these efforts, a variety of nanodevices are being created of different type and size, each one with particular characteristics. For example, a CNT array is shown in Figure 7 (right), which provides an addressable platform for probing intact, living cells.

A closely related area to nanomedicine is nanorobotics (Freitas Jr., 2005). In the near term, nanomedicine can use nanoscale-structured materials and simple nanodevices to interact with biological systems, for example. Mid term, more remarkable advances in molecular medicine and biotics will become available in biotechnology including microbiological biorobots and engineered organisms. Long term, physicians will be able to conquer human disease, ill-health, and aging using molecular machine systems and nanorobots.

Figure 8 (left) shows a therapeutic nanosome model, the Dynamic Nano-Platform (DNP), a core nanodevice with interchangeable components that provide considerable flexibility in targeting, imaging, and treatment of cancer and cardiovascular disease indications. Proposed technology extensions might incorporate magnetic and optical control as well as contrast elements to enable a number of functions from biological sensing to targeted photo dynamic cancer therapy.

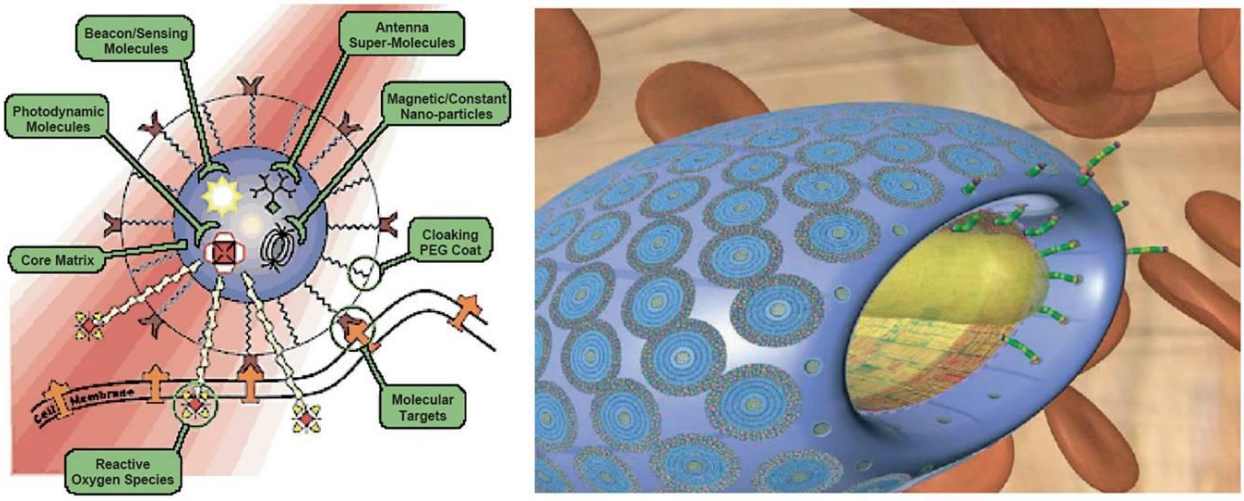

Figure 8 Nanosome (Molecular Therapeutics) and Microbivore (Freitas Jr., 2005)

Figure 8 (right) shows a microbivore, a microscopic artificial white cell designed to destroy microbiological pathogens in the human bloodstream making use of a digest and discharge protocol. The dimensions of this oblate spheroidal nanomedical device are as follows: 3.4 and 2.0 microns for the major and minor axis respectively, its gross volume and dry mass are 12.1 micron^3 and 12.2 picograms respectively, the power consumption is up to 200 picowatt.

As an example of the curing power of microbivores, they would completely eliminate septicemic infections in minutes to hours in comparison to weeks to months when natural phagocytic defenses act, even aided by antibiotics. That is because microbivores can entirely digest trapped microbes at a maximum throughput of 2 micron^3 of organic material per 30-second cycle and be approximately 1,000 times faster than natural or antibiotic-assisted biological phagocytic defenses.

During the nanorobot operation, the target bacterium is bound to the surface of the bloodborne microbivore via species-specific reversible binding sites. Macrophages release biologically active compounds during bacteriophagy in contrast to microbivores that only release biologically inactive effluent. The microbivores use a digest and discharge protocol similar to the internalization and digestion process practiced by natural phagocytes, with the difference that the artificial process is much faster and cleaner.

Figure 9 (left) shows a nanorobotic architecture in an epidemic control application (Cavalcanti, Shirinzadeh, Zhang, & Luiz C. Kretly, 2008), which provides high precision pervasive biomedical monitoring with real time data transmission and enables in vivo real time prognosis of a biohazard infection. Figure 9 (right) shows the three-dimensional simulation of nanorobots efficiently detecting alpha-NAGA signals in the bloodstream, with the integrated system retrieving information about a person infected with influenza.

The outlined nanorobot architecture for medical defense promises to prevent an aggressive pandemic disease from an outbreak, helping the public health sector to save lives and decrease high medical costs, enabling a real time quarantine action. When the alpha-NAGA, detected by the electrochemical sensor,

reaches a concentration of 3 µl, the corresponding nanorobot is activated to emit an electromagnetic signal backpropagated to the monitoring integrated platform. To suppress noise distortion and enhance resolution, plans call for at least 100 nanorobots per individual emitting a higher proteomic signal transduction as strong evidence of influenza contamination.

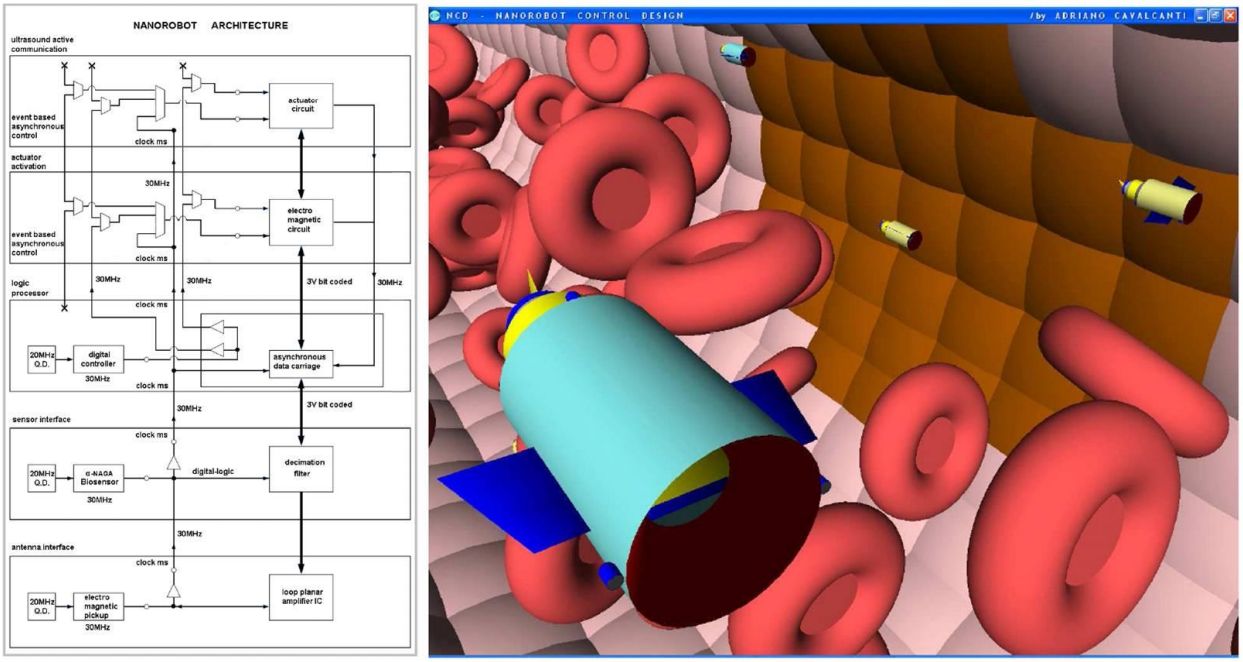

Figure 9 Architecture and Simulation of a Medical Nanorobot for Biohazard Defense (Cavalcanti et al, 2008)

Applications in space environments are also diverse and include the construction of a space elevator using carbon nanotubes (CNTs) and the utilization of nanotechnology program elements: nanoelectronics and computing, sensors, and structural materials in the Jupiter's Europa submarine depicted in Figure 10. Let us examine the space elevator concept in further detail. The basic idea was delivered already over a century ago in (Tsiolkovsky, 1895) as a compression-based tower structure to launch payloads into orbit without a rocket. The tower was to be built from the ground up to geostationary orbit, i.e., to an altitude of 35,790 km. The elevator would attain orbital velocity at the top and so would the payload released at the tower's top, i.e., the payload would remain in geostationary orbit.

A more realistic tension or tether structure was proposed in (Artsutanov, 1960). More recent advancements have been published for instance in (Edwards & Westling, 2003) and (Smitherman Jr., 2006). A geostationary satellite would be used as the base from which to deploy the cable structure downward. Using a counterweight, the cable can be lowered from geostationary orbit to the surface of Earth. Because the counterweight was extended from the satellite away from Earth, the center of gravity of the cable is kept motionless relative to Earth.

The specific strength = strength per density and the unit Yuri, defined as 1 Yuri = 1 Pa/(kg/m3), are used to provide the strength requirement for the material to be used for constructing the space elevator

cable or ribbon. CNT simulations and practical measurements show a cap of 40 to 50 MYuri for the specific strength of individual nanotubes, which is sufficient to build the space elevator.

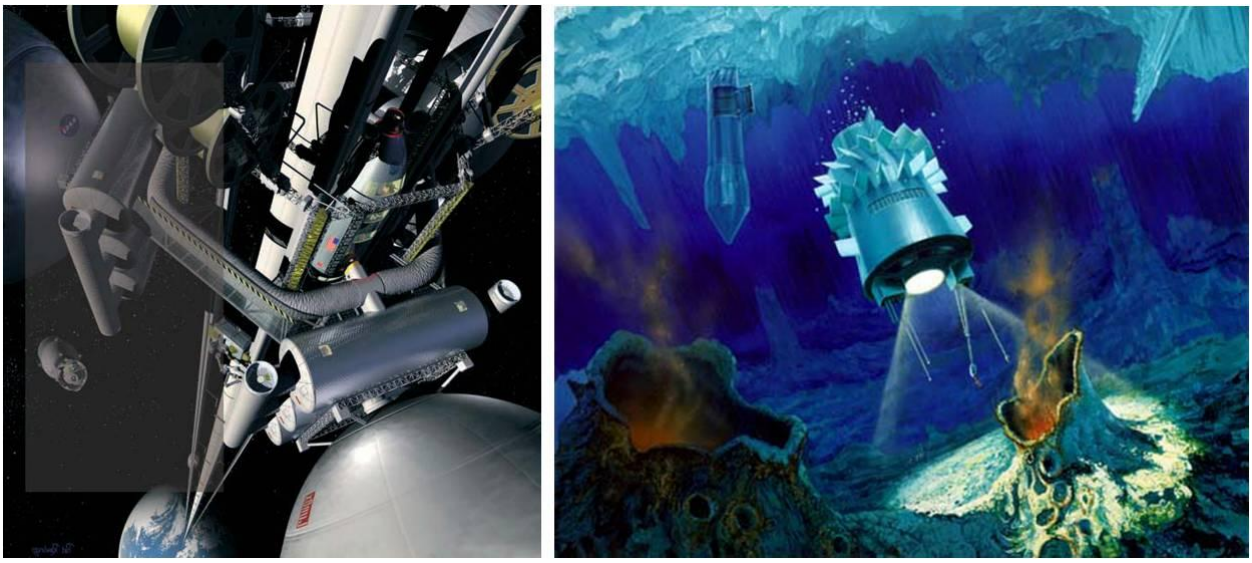

Figure 10 Nanotechnology in Space (NASA)

Estimates for the construction of a functioning space elevator in the form of a 100,000 kilometer tall assembly, which allows a train to transport payloads into orbit include a budget of $ 10 – 15 Billion and a construction time of 12 years like in the plans of the Japanese government (Ohno, 2008). The most compelling reason to build a space elevator is the dramatic cost reduction to deploy payloads into orbit it would provide: from currently $20,000/kg to $250/kg.

The three left images in Figure 11 show the current concept of a space elevator as a carbon nanotube ribbon stretching some 100 000 km from Earth to space. The elevator will be anchored to an offshore sea platform near the equator in the Pacific Ocean, and to a small counterweight in space. Mechanical lifters will move up and down the ribbon, carrying such items as satellites, solar power systems, and people into space. A climber is shown being beamed up the carbon nanotube ribbon. The track and roller climber system presses onto the ribbon and provides traction for movement up and down the tether. The circular base consists of photovoltaic cells and receives power from a laser beaming station on the surface below.

Figure 11 (rightmost) shows a Mars elevator concept with design options advantageous w.r.t the utilization of rocket systems, for example, of space stations and habitats. An initial Mars elevator design includes a power beaming system using inflatable solar concentrators, a deployment scenario minimizing the propulsion requirements, an overall system with modules on each end of the ribbon, a self anchoring module on the lower end of the ribbon, a power beaming, propulsion, and capture system at the upper, and an anchor location on Olympus Mons to avoid both the moons and the dust storms.

Figure 11 Space Elevators for Earth and Mars (ESA, NASA)

Challenges

Very often, challenges pertain scaling down structures that have been discovered to the next level of miniaturization to become truly nanoscale structures keeping in mind that not every discovery needs to be reduced to nanoscale to become applicable. For example, in a military application setting, when soldiers have potentially been exposed to chemical or biological weapons, a disposable or implantable portable device could be extremely helpful, which is able to automatically and almost instantaneously test a tiny blood sample.

Figure 12 shows the design and development towards a fully portable Lab-On-a-Chip (LOC) that utilizes micropumps allowing high-speed flows through microchannels and requiring only battery power. Two established approaches to design LOCs are to mechanically force fluid through microchannels or via capillary electro-osmosis, where flow is driven by an electric field across the chip. Neither one of them is capable of offering portability.

Instead of placing electrodes at each end of the channel, as in capillary electro-osmosis, a substantially lowered alternating current (AC) voltage is applied at closely spaced microelectrode arrays on the channel floor. Tiny electrodes with raised steps generate opposing slip velocities at different heights, the combined push of the fluid in one direction improves the flow rate almost twenty times and generates fast mm/s flows, comparable to pressure-driven systems, and attainable with only battery voltages.

Figure 12 (left) shows the simulation of three-dimensional (3-D) AC electro-osmosis and liquid flowing around stepped electrodes. The fluid can be fast pumped through microchannels by its conveyor belt. The 3-D, AC electro-osmotic pump consists of interdigitated stepped gold microelectrodes on a glass substrate, see Figure 12 (right). Beyond the military, the portable blood analysis device has extensive applicability in civilian medicine. Other LOC applications include DNA testing and antigens screening.

Specific challenges are attached to specific applications, that is just a standard rule. To get an overall flavor of the issues involved while remaining specific, let us analyze the challenge areas in the NCI's cancer nanotechnology plan: prevention and control of cancer, early detection and proteomics, imaging diagnostics, multifunctional therapeutics, quality of life enhancement in cancer care, and interdisciplinary training. In each of those six areas but the last one, nanodevices need to be engineered

to meet the corresponding challenges. For example, one challenge per area, for the prevention and control of cancer, nanoscale devices need to be developed that can deliver cancer prevention agents.

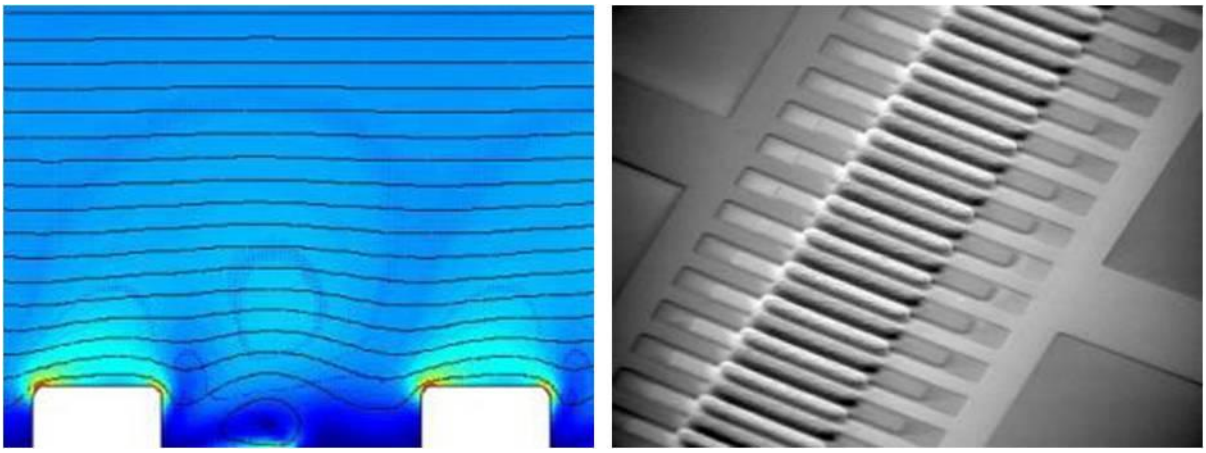

Figure 12 Fully Portable Lab-On-a-Chip (LOC) with 3-D AC Electro-Osmotic µPump (MIT ISN)

For early detection and proteomics, implantable, biofouling-indifferent molecular sensors need to be developed that can detect cancer-associated biomarkers. The biomarkers can then be collected for ex vivo analysis or analyzed in situ, and the results need to be transmitted wirelessly to the physician. For imaging diagnostics, nanoscale devices need to be engineered that are capable of addressing the biological and evolutionary diversity of the multiple cancer cells that make up a tumor of an individual.

For multifunctional therapeutics, we need to design and develop smart therapeutic devices capable of controlling the spatial and temporal release of therapeutic agents while monitoring the agents effectiveness. And finally, for quality of life enhancement in cancer care, nanoscale devices need to be engineered that can optimally deliver medications for treating chronic anticancer therapy conditions including pain, nausea, loss of appetite, depression, and difficulty breathing.

We now examine the state of the art and challenges of nanomechanical instrumentation, see, e.g., the corresponding chapter in (Postek & Hocken, 2004). Widely used nanodevices will require nanomechanical measurements that are rapid, accurate, predictive, well-understood, and representative of the device's environment in real time. Instrumentation and metrology for nanomechanics focus on both state of the art practice as well as gaps in technology for achieving accurate, repeatable measurements of the mechanical performance of nanostructured materials in devices and systems. Table 2 presents a summary of the state of the art in nanomechanical instrumentation.

As we can see in Table 3, there are many challenges that we have to address successfully to create the necessary nanomechanical instrumentation and metrology in support of the nanotechnology industry and its commercialization. These challenges involve the development of standards and calibration methods, accurate predictive modeling tools and reliable, fast, multifunctional quantitative instrumentation.

Table 2 Nanomechanical Instrumentation - State of the Art (NIST)

Instrumentation	Accuracy	Sensitivity	Resolution	Precision	Compatibility with Different Material Systems
Scanning Probe Microscopes	• Greatest challenge • Calibration-dependent • Tip and surface damage contributes to poor accuracy	• Piconewton to nanonewton range • Can be enhanced through chemical modification of the tip	• Subnanometer • Dependent on scanning mode and sharpness of tip	• Dependent on cantilever, environment, and scanner performance	• Limited to materials with $E > 10^9$ Pa
Instrumented Indentation Testing	• Large uncertainties at small forces and displacements • Model-dependent results	• Nanonewton to millinewton range • Can be enhanced by harmonic oscillation	• Large tips not conducive to nanoscale measurements	• Highly dependent on tip shape knowledge	• Limited to materials with $E > 10^6$ Pa
Tribometers and Nanoscratch Testers	• Real area of contact determination is the major limitation • Higher requirements in rigidity because lateral resistance can be large • Force sensors are more sensitive than instrumented indentation testing but less than scanning probe microscopes	• Nanonewton to millinewton range • Vibration and environmental factors affect results significantly • Large variety of tips and cantilever designs	• Depends on tip sizes • Most tips are suitable for microscale measurements • Advanced diamond tips can get below 50 nm radius	• Depth of penetration during sliding can be controlled only to several nanometers • Dependent on environmental control and vibration isolation	• Limited by surface roughness at nanometer scale • Materials limited by tip hardness and system stiffness

To examine one area of challenges in further detail, we take the area of integration of multiple techniques. Primarily, we need to possess the ability to probe nanoscale deformation, image it, and understand the physical and chemical processes events occurring in real time. Only partial information about nanoscale deformation can be individually recovered using nanoindentation equipment, Atomic Force Microscope (ATM), and surface force apparatus. This particular challenge can be met by using integrated, multifunctional measurements.

Technical challenges include more specifically using various probes focusing with high spatial resolution on a single location, and spatial and temporal synchronization of the data gathered by the different probes. Integration tasks among probes include the areas of software, I/O compatibility, and control languages.

Table 3 Nanomechanical Challenges (NIST)

Metrology	Challenges/Barriers
Standards and Calibration	• Traceable force and displacement calibration • International collaboration to establish common standards • Methodologies based on reliable data and models • Machine-independent standards • Understanding of nanometer scale surface forces and contact mechanics • Wide experimental dynamic range
Nano-mechanical Modeling of Experiments	• Modeling—computational power, intelligent data storage and mining, length of model development time, capturing physics • Experiment—ability to fabricate and characterize testing fixtures, manufacture and characterize samples; accuracy and traceability for experiments; ability to position/manipulate samples
Integration of Multiple Techniques	• *In situ* probes for imaging, manipulation, chemical bonding and orientation detection at atomic/molecular resolution • Spatial resolution when focusing on a single event • Integration of software, input/output compatibility, control languages • Synchronization of time and position information
High-Throughput Automated Measurements	• Sample preparation—speed, automation, yield, quality, size, conditioning, and material specific issues (polymers, metals, ceramics, glasses, electronics) • Calibration—robust probes, periodic reference specimens or characterizations • Analysis/testing schemes—lack of wide range of testing environments (temperature, frequency); lack of models to describe complex nanoscale mechanical behavior; lack of high-speed methodologies; lack of well-characterized nanoscale probes
Instrument Development	• Tip wear, control, cm to nm positioning • Decoupled lateral and vertical force sensors • Lack of lateral or vertical force calibration standards • Multiple operating mechanisms and environments required for mechanical property measurements • Non-linearity of actuators/sensors • Thermal drift • Quantitative mechanical property mapping is typically a slow, point-by-point process
Measurement Under Real Application Conditions	• Real area of contact • Surface treatments • Robustness • Application-compatible materials • Real-time measurement capabilities • Sub-element specific testing (e.g., interfaces)

Conclusions

After examining the foundations of nanoscale science, engineering, and technology, some of the most salient current and future applications and challenges were discussed. The variety of applications and the entire impact in broad fields of science and engineering are remarkable with many more engineering systems in need to be designed and developed to accelerate the revenue of nanotechnology. An analysis

of the multiple domain-specific challenges confirms that heavy human and financial investment is needed. With a focused approach, all of them can be systematically mastered.

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