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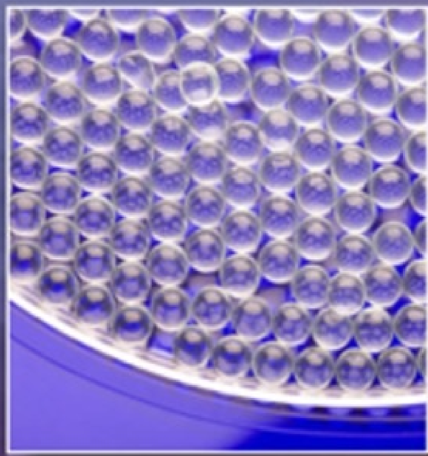
Jeremy J. Ramsden



NANOTECHNOLOGY

An Introduction

Table of Contents

Front Matter

Nanotechnology: An Introduction

Micro & Nano Technologies Series		
Published Titles		
9780815515739	Francois Leonard	*Physics of Carbon Nanotube Devices* (2009)
9780815515784	Mamadou Diallo, Jeremiah Duncan, Nora Savage, Anita Street & Richard Sustich	*Nanotechnology Applications for Clean Water* (2009)
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9780080964478	Jeremy Ramsden	*Nanotechnology: An Introduction* (2011)
Forthcoming Titles		
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Nanotechnology: An Introduction

Jeremy Ramsden

Cranfield University

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Dedication

…Kicsinyben rejlik a nagy,

Olyan sok a tárgy, s létünk oly rövid.

IMRE MADÁCH

Preface

There are already hundreds of books in print on nanotechnology in English alone, at all levels up that of the advanced researcher and ranging in coverage from detailed accounts of increment improvements in existing microtechnologies to far-reaching visionary approaches toward producti nanosystems. Furthermore, not only do many old-established scientific journals in the fields physics and chemistry now carry nanotechnology sections, but numerous scientific journals dedicat solely to nanotechnology have appeared and new ones are launched each year. In addition, a flood commercially oriented reports about present and future nanotechnology markets is constantly bei produced; these are often weighty documents comprising a thousand pages or more, whose reliabili is difficult to assess, since even if they make use of publicly available data, the processing of tho data in order to arrive at predictions is typically carried out using unrevealed algorithms.

Faced with this huge and burgeoning literature, the newcomer to the field, who may well have a stro background in one of the traditional disciplines such as physics, mechanical or electrical engineerin chemistry or biology, or who may have been working on microelectromechanical systems (MEM (also known as microsystems technology, MST), is likely to feel confronted with a somewhat chaot and colorful scene from which it is often difficult to extract meaning. The goal of this book is tackle that problem by presenting an overview of the entire field, focusing on key essentials, wi which the reader will be able to erect his or her own personal scaffold on which the amazingly diver plethora of detailed information emerging from countless laboratories all over the world can structured into some kind of coherent order. The emphasis is therefore on concepts; any attempt complement this by capturing all the latest specific discoveries and inventions in nanotechnolog other than illustratively, would almost immediately become out of date; the aim of this book mig briefly be stated as being "to make sense of nanotechnology"—to explain things thoroughly enough be intelligible while still remaining introductory.

The book itself is structured around a robust anatomy of the subject. Following a basic introducti (Chapter 1), which includes a brief history of the subject, careful consideration is given to t meaning of the nanoscale (Chapter 2), on which everything else is dependent, since nanotechnolog can most simply (but cryptically) be defined as "technology (or engineering) at the nanoscale". Th chapter in itself constitutes a succinct summary of the entire field. Chapter 3 is devoted to interfac forces, which govern key aspects of behavior at the nanoscale. Chapter 4 covers the nano/bio interfa which plays a fundamental role in the continuing evolution of nanotechnology, and Chapter 5 dea with the demanding issues of metrology in nanotechnology, which have also strongly influenc nanofabrication technology. In this chapter, the metrology of the nano/bio interface is covered detail, since this is one of the newest and least familiar parts of the field. Nanomaterials (both nan objects and nanostructured materials) are covered in Chapter 6—except carbon nanomaterials (a devices), which merit a separate chapter (9). Nanoscale devices of all kinds (except those based carbon)—mainly information processors and transducers, including sensors are the topic of Chapter and strategies for their fabrication are covered in Chapter 8, devoted to the three fundament approaches towards achieving nanoscale manufacture (nanofacture), namely the top–down metho rooted in ultraprecision engineering and semiconductor processing, the bottom-to-bottom approa that is closest to the original concept of nanotechnology (the molecular assembler), and the bottom– (self-assembly) methods that have been powerfully inspired by processes in the living worl Problems of materials selection, design and so forth are treated in Chapter 10, especially how to de with vastification; that is, the vast numbers of components in a nanosystem and the almost inevitab occurrence of defective ones. Chapter 11 is devoted to bionanotechnology, defined as th incorporation of biomolecules into nanodevices. The final chapter (12) deals with the impacts nanotechnology: technical, economic, social, psychological and ethical. Each chapter is provided wi a succinct summary at the end as well as suggestions for further reading. A glossary nanotechnology neologisms is appended, along with a list of the most common abbreviations.

The primary readership is expected to be engineers and scientists who have previously been workin in other fields but are considering entering the nano field and wish to rapidly acquire an appreciatio of its vocabulary, possibilities and limitations. The secondary readership is anyone curious abo nanotechnology, including undergraduates and professionals in other fields. The book should als appeal to those less directly connected with science and engineering, such as insurers and lawyer whose activities are very likely to be connected with nanotechnology in the future, and trader commodity brokers and entrepreneurs in general dissatisfied with remaining in ignorance of th technology that they are making use of. It is designed to equip the reader with the ability to cogent appraise the merits or otherwise of any piece of nanotechnology that may be reported in one form another.

It is a distinct characteristic of nanotechnology that many of its features draw heavily from existin work in chemistry, physical chemistry, physics and biology. Hence, there is relatively little domain specific knowledge associated with nanotechnology. Most of the themes in this book are covered great detail in specialist literature that may not exclusively or even overtly be associated wi nanotechnology. It seems, therefore, that nanotechnology is most aptly globally characterized as a attitude or mindset, comprising above all the desire both to understand the world at the atomic lev and to create objects of beauty and utility by controlling matter at that level. Unlike the science of th subatomic level, however, nanotechnology necessarily concerns itself with superatomic levels as wel since the ultimate objects of its creation must be macroscopic in order to be of use to humanit Hence, problems of emergent properties also form a part of nanotechnology.

The uniqueness of this book resides in its unifying viewpoint that draws many disparate pieces knowledge together to create novel technologies. These nanotechnologies are in turn united by th distinctive attitude associated with nanotechnology.

Nanotechnology is inseparably associated with the emergence of qualitatively different behavior wh a quantitative difference, namely increasing smallness, becomes great enough: one might call this Hegelian viewpoint of nanotechnology. Phenomena that are merely modified *pari passu* wi diminishing size without any qualitative change should not, therefore, strictly rank as nanotechnolog This viewpoint avoids the pitfall of having to group practically all of physics, chemistry and biolog under nanotechnology because of too vague a definition.

Inevitably, the author of a book of this nature is greatly indebted to countless colleagues an correspondents both at Cranfield and throughout the world. It would be invidious to mention som without mentioning all, and they are too numerous for the latter, but I hope that in this era of voluminous research literature their inputs are adequately reflected in the reference list.

Jeremy J. Ramsden

Cranfield

Chapter 1. What is Nanotechnology?

Chapter Contents

Nanotechnology is defined in various ways; a selection of already-published definitions is given, from which it may be perceived that a reasonable consensus already exists more formal concept system for nanotechnology is developed, in which care is taken to use the terms consistently. Nanotechnology is also defined ostensively (i.e., what obje already in existence are called “nano”?), and by its history. The role of biology is introduced as providing a living proof-of-principle for the possibility of nanotechnology; has been of historical importance and continues to provide inspiration. Motivations for nanotechnology are summarized.

Keywords: definitions, concept system, ontology, history, ultraprecision engineering, semiconductor processing, nanoparticles, biology, motivation, miniaturization

Nanotechnology is above all a mindset, a way of thinking about the world that is rooted in atomical precise perception. As such, it represents the apotheosis of man's ceaseless urge to understand th world and use that understanding for practical purposes. Well synonymized as “atomically precis technology”, it encapsulates the vision of building “our earthly estate” atom-by-atom, controllin architecture, composition and hence physical properties with atomic resolution. “Hard nanotechnologists promote a future world in which every artifact (and even food) can be constructe atom-by-atom from a feedstock such as acetylene, requiring in addition only energy and instruction A more pragmatic view accepts that there are many intermediate stages in which partially atomical precise construction can improve existing artifacts and create new ones. Similarly, the resolute aim “hard” nanotechnologists is to create productive nanosystems (PN) working with atomic precision- the nanoscale assemblers that would execute the instructions and build everything we need from th bottom upwards, whereas a more pragmatic view accepts that while in principle everything can b reproduced and many things imitated via atom-by-atom assembly, in many cases the improvement properties or performance would be negligible and a hybrid approach will best serve the needs humanity. This is particularly likely to be the case for large artifacts (such as human dwellings airplanes) and for relatively complex products such as food, which can be quite easily grow naturally.

In this chapter we shall first look at the basic definitions for nanotechnology, and sketch a conce system (“ontology”) for the field. It is also possible to define nanotechnology ostensively, accordin

to what is already generally considered to be nanotechnology, and extended by what is envisaged i
the ~~future. A further way of defining it is through its history. We also briefly look at the relatio~~n o
nanotechnology to biology, which has been a powerful paradigm for convincing engineers th
nanotechnology is possible—nanobiotechnology and bionanotechnology form the topics of subseque
Chapter 4 and Chapter 11 respectively). General motivations for nanotechnology are considere
—"Why nanotechnology?" Attention is drawn to the appended list of neologisms associated wi
nanotechnology (Appendix, p. 247).

1.1. Definitions and Concepts

1.1.1. Working Definitions

The simplest definition of nanotechnology is "technology at the nanoscale". The various definitio
currently circulating can be reasonably accurately thus paraphrased. Obviously, this definition is n
intelligible in the absence of a further definition, namely that of the nanoscale. Furthermor
definitions of components of nanotechnology, such as "nanofiber", also refer to the nanoscale; indee
every word starting with "nano", which we can generically write as "nanoX", can be defined
"nanoscale X". Therefore, unless we define "nanoscale", we cannot therefore properly defi
nanotechnology. A rational attempt to do so is made in Chapter 2. Here we note that provisionally, th
nanoscale is considered to cover the range from 1 to 100 nm. Essentially this is a consensus without
strong rational foundation.

A slightly longer but still succinct definition of nanotechnology is simply "engineering with atom
precision", or "atomically precise technology" (APT). However, this definition does not explicit
include the aspects of "fundamentally new properties" or "novel" and "unique" that nanotechnologis
usually insist upon, wishing to exclude existing artifacts that happen to be small. These aspects a
encapsulated by the US National Nanotechnology Initiative's declaration that "the essence
nanotechnology is the ability to work at the molecular level, atom-by-atom, to create large structur
with fundamentally new molecular organization … nanotechnology is concerned with materials an
systems whose structures and components exhibit novel and significantly improved physica
chemical, and biological properties, phenomena, and processes due to their nanoscale size"[123].

The US Foresight Institute gives "nanotechnology is a group of emerging technologies in which th
structure of matter is controlled at the nanometer scale to produce novel materials and devices th
have useful and unique properties". Function is stressed in: "the design, synthesis, characterizati
and application of materials, devices and systems that have a functional organization in at least o
dimension on the nanometer scale". This is emphasized even more strongly in "nanotechnolog
pertains to the processing of materials in which structure of a dimension of less than 100 nm
essential to obtain the required functional performance"[36].

In all such definitions, there is the implicit meaning that, as for any technology, the end result must b
of practical use. A dictionary definition of nanotechnology is "the design, characterization, productio
and application of materials, devices and systems by controlling shape and size in the nanoscale"[1
An alternative definition from the same dictionary is "the deliberate and controlled manipulatio
precision placement, measurement, modeling and production of matter in the nanoscale in order
create materials, devices, and systems with fundamentally new properties and functions"[1]. Th
emphasis on control is particularly important: it is this that distinguishes nanotechnology fro
chemistry, with which it is often compared. In the latter, motion is essentially uncontrolled an

random, within the constraint that it takes place on the potential energy surface of the atoms ar
molecules under consideration. In order to achieve the desired control, a special, nonrandom *eutact*
environment needs to be available. How eutactic environments can be practically achieved is st
being vigorously discussed. Finally, a definition of nanotechnology attempting to be comprehensive
“the application of scientific knowledge to measure, create, pattern, manipulate, utilize or incorpora
materials and components in the nanoscale”. This underlines the idea of nanotechnology as th
consummation of Stage 4 in the sequence of technological revolutions that marks the development
human civilization (Table 12.1 in Chapter 12).

It is sometimes debated whether one should refer to “nanotechnology” or “nanotechnologies”. Th
argument in favor of the latter is that nanotechnology encompasses many distinctly different kinds
technology. But there seems to be no reason not to use “nanotechnology” in a collective sense, sinc
the different kinds are nevertheless all united by striving for control at the atomic scale. Both tern
are, in fact, legitimate. When one wishes to emphasize diverse applications, the plural form
appropriate. The singular term refers above all to the mindset or attitude associated with th
technology.

1.1.2. Towards a Concept System for Nanotechnology

Objects are perceived or conceived. The properties of an object (which may be common to a set
objects) are abstracted into characteristics. Essential characteristics (feature specifications) typical
falling into different categories (e.g., shape, color) are combined as a set to form a concept; this
how objects are abstracted into concepts, and the set of essential characteristics that come together
a unit to form a concept is called the intension. The set of objects abstracted into a concept is calle
the extension. Delimiting characteristics distinguish one concept from another. Concepts are describe
in definitions and represented by designations. The set of designations constitutes the terminolog
Concepts are organized into concept systems. A concept system is often called an ontology (whic
literally means the science of being, but lately is often used in a more restricted sense, namely that
the study of categories).

Figure 1.1 shows (part of) an ontology for nanotechnology. To the right of the diagram one ha
products—an axis of tangible objects in order of increasing complexity: *materials*, *devices an*
systems. To the left of the diagram one has processes. Note the relationships between *metrology* an
fabrication (nanomanufacturing, usually abbreviated to nanofacture, also called atomically preci
manufacturing, APM) and devices. An atomic force microscope is used to measure nanoscale feature
every measuring instrument is necessarily a device; and pushing nano-objects around with a needle
the basis of bottom-to-bottom fabrication (see Section 8.3).

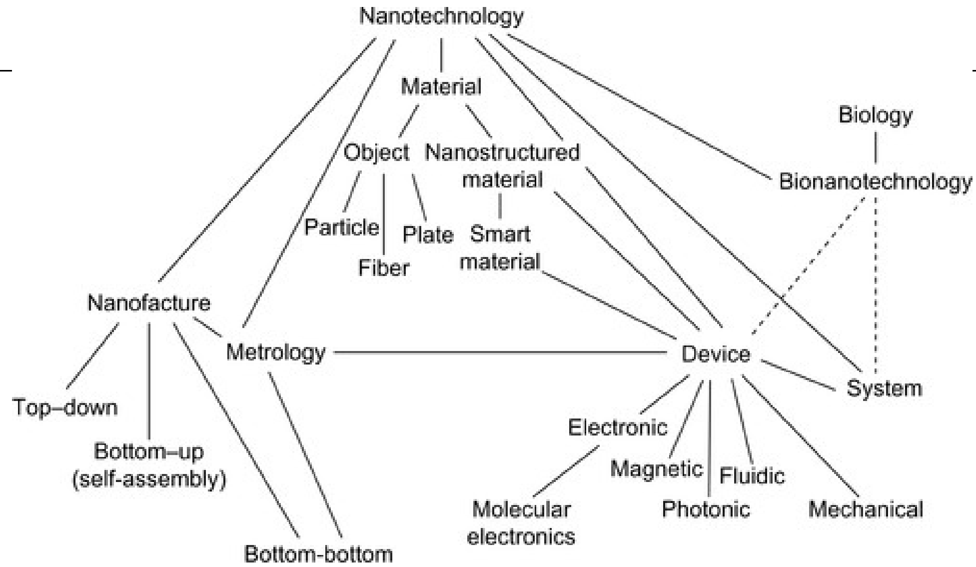

Figure 1.1 A concept system (ontology) for nanotechnology. Most of the terms would normally be prefixed by "nano" (e.g., nanometrology, nanodevice). A dashed lin merely signifies that if the superordinate concept contributes, then the prefix must indicate that (e.g., bionanodevice, bionanosystem). Biology may also have some input nanomanufacture (nanofacture), inspiring, especially, self-assembly processes. Not shown on the diagram is what might be called "conceptual nanotechnology", or perha better (since it is itself a concept), "virtual nanotechnology", which means the (experimental and theoretical) scrutiny of engineering (and other, including biological) process at the nanoscale in order to understand them better; that is, the mindset or attitude associated with nanotechnology.

Especially the leaves of the tree might be associated with some ambiguity regarding their extension For example, devices can be characterized by the nature of their working medium: electrons, photon etc. Yet many devices involve more than one medium: for example, nanoelectro*mechanical* devic are being intensively researched as a way of achieving electronic switching; opto*electronic* control a popular way of achieving photonic switching; and photochemistry in miniaturized reactors involv both nanophotonics and nanofluidics.

Table 1.1 describes a few of the concepts and their intensions and extensions. At the time of writin the terminology of nanotechnology is still being intensively debated within national standar organizations as well supranational bodies such as the Comité Européen de Normalisation (CEN) an the International Standards Organization (ISO), hence no attempt has been made to be comprehensiv here.

Table 1.1 Some nano concepts and their intensions and extensions

Intension	Concept	Extension
One or more external dimensions in the nanoscale	Nano-object	Graphene, fullerene
One or more geometrical features in the nanoscale	Nanomaterial	A nanocomposite
Automaton with information storage and/or processing embodiments in the nanoscale	Nanodevice	Single electron transistor

1.2. An Ostensive Definition of Nanotechnology

An ostensive definition of current nanotechnology can be constructed from the most popular topi (Table 1.2), essentially extensions in the sense of Section 1.1.2.

Table 1.2 Table of the relative importance (ranked by numbers of occurrences of words in the titles of papers presented at the Nano2009 Conference in Houston, Texas) of nanotechnology terms and applications

Rank	Term	Number of occurrences
1	Carbon, CNT	1
2	Nanoparticle, nanocrystal	1
3	Energy	
4	(Nano)material	
5	Nanotube	
6	(Nano)composite	
7	(Bio)sensor	
8	Water	

9	Device	
10	Nanowire	
11	Assembly	
12	Silicon	
13	Zinc (oxide)	
14	Titanium (oxide)	
15	Quantum	
16	Silica	
17	Phage	
18	Bio	
19	Photovoltaic	
20	Nanorod	
21	Graphene	
22	Nanopore	
23	Silver	

A number of inferences can be drawn from this table, including the preeminence of carbon as nanomaterial, the nanoparticle as a nano-object, and energy, composites (materials) and sensors applications. Interestingly, "water" features highly on the list. The reasons for this will be appare from reading Section 3.8.

A very simple (albeit privative) ostensive definition of nanotechnology is "If you can see it (includin with the aid of an optical microscope), it's not nano", referring to the fact that any object below 10 nm in size is below the Abbe limit for optical resolution using any visible wavelength (equation 5.2 A nanoplate, however, would only be invisible if oriented exactly parallel to the line of sight.

1.3. A Brief History of Nanotechnology

Reference is often made to a lecture given by Richard Feynman in 1959 at Caltech [56]. Entitl "There's Plenty of Room at the Bottom", it expounds his vision of machines making the componen for smaller machines (a familiar enough operation at the macroscale), themselves capable of makin the components for yet smaller machines, and simply continuing the sequence until the atomic real is reached. Offering a prize of $1000 for the first person to build a working electric motor with overall size not exceeding 1/64th of an inch, Feynman was dismayed when not long afterwards student, William McLellan, presented him with a laboriously hand-assembled (i.e., using th technique of the watchmaker) electric motor of conventional design that nevertheless met th specified criteria.

A similar idea was proposed at around the same time by Marvin Minsky: "Clearly it is possible have complex machines the size of a flea; probably one can have them the size of bacterial cells consider contemporary efforts towards constructing small fast computers. The main line of attack concentrated on "printing" or evaporation through masks. This is surely attractive; in one operatio one can print thousands of elements. But an alternative, equally attractive, has been ignored. Imagin small machines fabricating small elements at kilocycle rates. (The speed of small mechanical devic is extremely high.) Again, one can hope to make thousands of elements per second. But the generali of the mechanical approach is much greater since there are many structures that do not len themselves easily to laminar mask construction"[118]. One wonders whether Feynman and Minsk had previously read Robert A. Heinlein's short story "Waldo", which introduces this idea (it wa published in the August 1942 issue of "Astounding" magazine under the pseudonym Anso MacDonald).

Here we find the germ of the idea of the assembler, a concept later elaborated by Eric Drexler. Th assembler is a universal nanoscale assembling machine, capable not only of making nanostructur

materials, but also other machines (including copies of itself). The first assembler would have to b
laboriously built atom-by-atom, but once it was working numbers could evidently grow exponentiall
and when a large number became available, universal manufacturing capability, hence the nano-er
would have truly arrived (see also Chapter 8).

However, the idea of a minute device intervening at the level of elementary particles was conceive almost a hundred years earlier by James Clerk Maxwell when he conceived his "demon" f selectively allowing molecules to pass through a door, thereby entangling physics with informatio Perhaps Maxwell should be considered as the real father of nanotechnology. The demon was describe in Maxwell's *Theory of Heat* first published in 1871, but had already been mentioned in earli correspondence of his.

1.3.1. Ultraprecision Engineering

It could well be said that the history of technological advance is the history of ever finer tolerances machining metals and other materials. A classic example is the steam engine: James Watt's high pressure machine that paved the way for the technology to move from a cumbersome and rath inefficient means of pumping water out of mines to an industrially useful and even self-propellin technology was only possible once machining tolerance had improved to enable pistons to slide with cylinders without leaking.

An approach to the nanoscale seemingly quite different from the Heinlein–Feynman–Minsky–Drexl vision of assemblers starts from the microscopic world of precision engineering, progressively scalin down to ultraprecision engineering (Figure 1.2). The word "nanotechnology" was itself coined b Norio Taniguchi in 1974 to describe the lower limit of this process [159]. He referred to "atomic b machining".

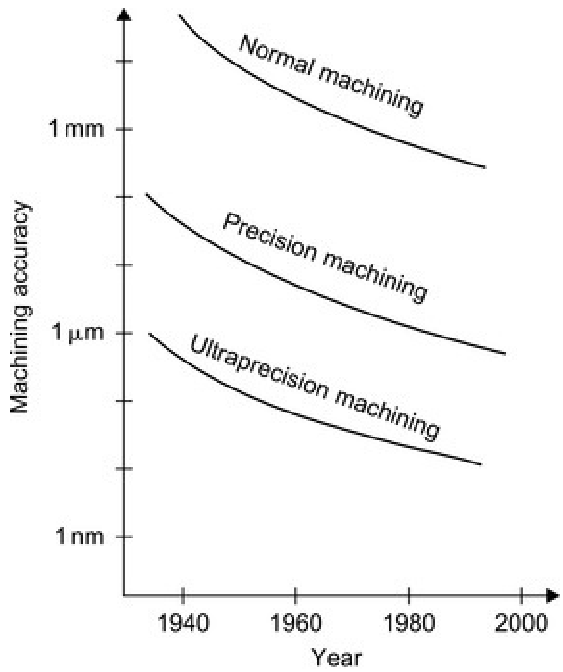

Figure 1.2 The evolution of machining accuracy (after Norio Taniguchi).

1.3.2. Semiconductor Processing qua Microtechnology

The trend in ultraprecision engineering is mirrored by relentless miniaturization in the semiconduct processing industry. The history of the integrated circuit could perhaps be considered to start in 190 when Bose patented the galena crystal for receiving electromagnetic waves, followed by Picard's 190 patent for a silicon crystal. The thermionic valve and the triode were invented respectively by Flemin (in 1904) and de Forest (in 1906), which became the basis of logic gates, reaching zenith with th ENIAC, which contained about 20,000 valves. The invention of the point contact transistor in 1947 Bell Laboratories essentially rendered the thermionic valve obsolete, but the first commercial use transistors only occurred in 1953 (the Sonotone 1010 hearing aid), the first transistor radio appearin one year later. Meanwhile the idea of an integrated circuit had been proposed by Dummer at the Roy Signals Research Establishment (RSRE) in 1952, but (presumably) he was not allowed to work on it what was then a government establishment, and the first actual example was realized by Kilby in 195 at Texas Instruments, closely followed by Noyce at Fairchild in the following year. It is interesting recall that the Apollo flight computer ("Block II") used for the first moon landing in 1969 wa designed in 1964 (the year before Moore's law was first proposed), used resistor–transistor log (RTL) and had a clock speed of 2 MHz. Intel introduced the first microprocessor, with about 200 transistors, in 1971, the year in which the pioneering "LE-120A Handy" pocket calculator wa launched in Japan. It took another decade before the IBM personal computer appeared (1981); th Apple II had already been launched in 1977. By 2000, we had the Pentium 4 chip with about 1.2 × 10 transistors fabricated with 180 nm process technology. In contrast, today's dual core Intel Itanium ch has about 1.7×10^9 transistors (occupying an area of about 50 × 20 mm) with a gate length of 90 nm A 45 nm transistor can switch 3×10^{11} times per second—this is about 100 GHz. Experiment graphene-based devices achieve more than a THz. Despite the extraordinarily high precisio fabrication called for in such devices, modern integrated circuits are reliable enough for spacecra (for example) to use commercial off-the-shelf (COTS) devices. The fabrication plants are not cheap- Intel's 2008 China facility is reputed to have cost $\$2.5 \times 10^9$: a mask alone for a chip made using 18 nm process technology costs about $100,000, rising to one million dollars for 45 nm technolog Despite the huge costs of the plant, cost per chip continues to fall relentlessly: for example, a mobi phone chip cost about $20 in 1997, but only $2 in 2007.

The relentless diminution of feature size, and the concomitant increase of the number of transisto that can be fabricated in parallel on a single chip, has been well documented; structures with features few tens of nanometers in size capable of being examined in an electron microscope were reported long ago as 1960; device structures with dimensions less than 100 nm were already being reported 1972, with 25 nm achieved in 1979. Incidentally, the lower size limit for practical semiconducto circuits is considered to be 20 nm; smaller sizes, hence higher transistor number densities per un area, will only be achievable using three-dimensional design or quantum logic (Section 7.3). Thus w see that since the beginning of nanotechnology—identifying this with the conception of Maxwell demon—nanotechnology has been intimately connected with information science and technology.

1.3.3. Nanoparticles

If we define nanotechnology ostensively, we have to concede a very long history: there is eviden that PbS nanocrystals were the goal of a procedure used since Greco-Roman times to color hair blac [164]. Nanoparticulate gold has a long history, not least in medicine (see Section 4.2). The Flemis glassmaker John Utynam was granted a patent in 1449 in England for making stained gla incorporating nanoparticulate gold; and the Swiss medical doctor and chemist von Hohenhei (Paracelsus) prepared and administered gold nanoparticles to patients suffering from certain ailmen in the early 16th century; a modern equivalent is perhaps the magnetic nanoparticles proposed f therapeutic purposes. The secret of the extraordinarily advanced metallurgical features of Damasc swords made more than 400 years ago has recently been found to be carbon nanotubes embedded the blades [146].

With such a long history, it is perhaps hardly surprising that at present they represent almost the on part of nanotechnology with commercial significance. The fabrication of different kinds nanoparticles by chemical means seems to have been well established by the middle of the 19 century (e.g., Thomas Graham's method for making ferric hydroxide nanoparticles [63]). Wolfgar Ostwald lectured extensively on the topic in the early 20th century in the USA, and wrote up th lectures in what became a hugely successful book, *Die Welt der vernachlässigten Dimensionen*. Ma universities had departments of colloid science (sometimes considered as physics, sometimes chemistry), at least up to the middle of the 20th century, then slowly the subject seemed to fall out fashion, until its recent revival as part of nanotechnology. The field somewhat overlapped that heterogeneous catalysis, in which it was well known, indeed almost obvious, that specific activi (i.e., per unit mass) tended to increase with increasing fineness of division.

1.4. Biology as Paradigm

When Feynman delivered his famous lecture [56] it was already well known that the smallest viab unit of life was the cell, which could be less than a micrometer in size. It was surmised that cel contained a great deal of machinery at smaller scales, which has since been abundantly evidence through the work of molecular biologists. Examples of these machines are molecule carriers (e.g hemoglobin), enzymes (heterogeneous catalysts), rotary motors (e.g., those powering bacteri flagella), linear motors (e.g., muscle), pumps (e.g., transmembrane ion channels), and multi-enzym complexes carrying out more complicated functions then simple reactions (e.g., the proteasome f degrading proteins, or the ribosome for translating information encoded as a nucleic acid sequen into a polypeptide sequence). When Drexler developed his explicit schema of nanoscale assemble allusion to nanoscale biological machinery was explicitly made as a “living proof-of-principl demonstrating the feasibility of artificial devices constructed at a similar scale [43].

At present, probably the most practically useful manifestation of the biological nanoparadigm is sel assembly. In simple form, self-assembly is well known in the nonliving world (for exampl crystallization). This process does not, however, have the potential to become a feasible industri technology for the general-purpose construction of nanoscale objects, because size limitation is n intrinsic to it. Only when highly regular structures need to be produced (e.g., a nanoporous membran or a collection of monosized nanoparticles) can the process parameters be set to generate an outcon of a prespecified size. Nature, however, has devised a more sophisticated process, known to enginee as programmable self-assembly, in which every detail of the final structure can be specified advance by using components that not only interlock in highly specific ways but are also capable changing their structure upon binding to an assembly partner in order to block or facilitat respectively, previously possible or impossible interlocking actions. Inspiration for harnessi programmable self-assembly arose from the work of virologists who noticed that pre-assembl components (head, neck, legs) of bacteriophage viruses would further assemble spontaneously into functional virus merely upon mixing and shaking in a test-tube. This “shake and bake” approa appeared to offer a manufacturing route to nanodevices obviating: (1) the many difficulties involv in making Drexlerian assemblers, which would appear to preclude their realization in the near futu and (2) the great expense of the ultrahigh precision “top–down” approach, whether via UPMT semiconductor processing. Even if assemblers are ultimately realized, it might be most advantageo to use them to assemble sophisticated “nanoblocks”, designed to self-assemble into final macroscop objects (see Section 8.3.2). In other words, self-assembly's greatest potential utility will probably ari as a means to bridge the size gap between the nanoscopic products of assemblers and the macroscop artifacts of practical use for humans. Self-assembly is covered in detail in Chapter 8.

1.5. Why Nanotechnology?

Nanotechnology is associated with at least three distinct advantages:

1. It offers the possibility of creating materials with novel combinations of properties.
2. Devices in the nanoscale need less material to make them, use less energy and oth consumables, their function may be enhanced by reducing the characteristic dimensions, and the may have an extended range of accessibility.
3. It offers a universal fabrication technology, the apotheosis of which is the personal nanofactory.

The burgeoning worldwide activity in nanotechnology cannot be explained purely as a rational attem to exploit “room at the bottom”, however. Two other important human motivations are doubtless als playing a role. One is simply “it hasn't been done before”—the motivation of the mountaine ascending a peak previously untrodden. The other is the perennial desire to “conquer nature Opportunities for doing so at the familiar macroscopic scale have become very limited, partly becau so much has already been done—in Europe, for example, there are hardly any marshes left to drain rivers left to dam, historically two of the most typical arenas for “conquering nature”—and part because the deleterious effects of such “conquest” are now far more widely recognized, and the fe remaining undrained marshes and undammed rivers are likely nowadays to be legally protected natu reserves. But the world at the bottom, as Feynman picturesquely called it, is uncontrolled and large unexplored. On a more prosaic note, nanotechnology may already offer immediate benefit for existi products through substitution or incremental improvement (Figure 1.3). The space industry has constant and heavily pressing requirement for making payloads as small and lightweight as possibl Nanotechnology is ideally suited to this end user—provided the nanomaterials, devices and systen can be made sufficiently reliable (see Chapter 10).

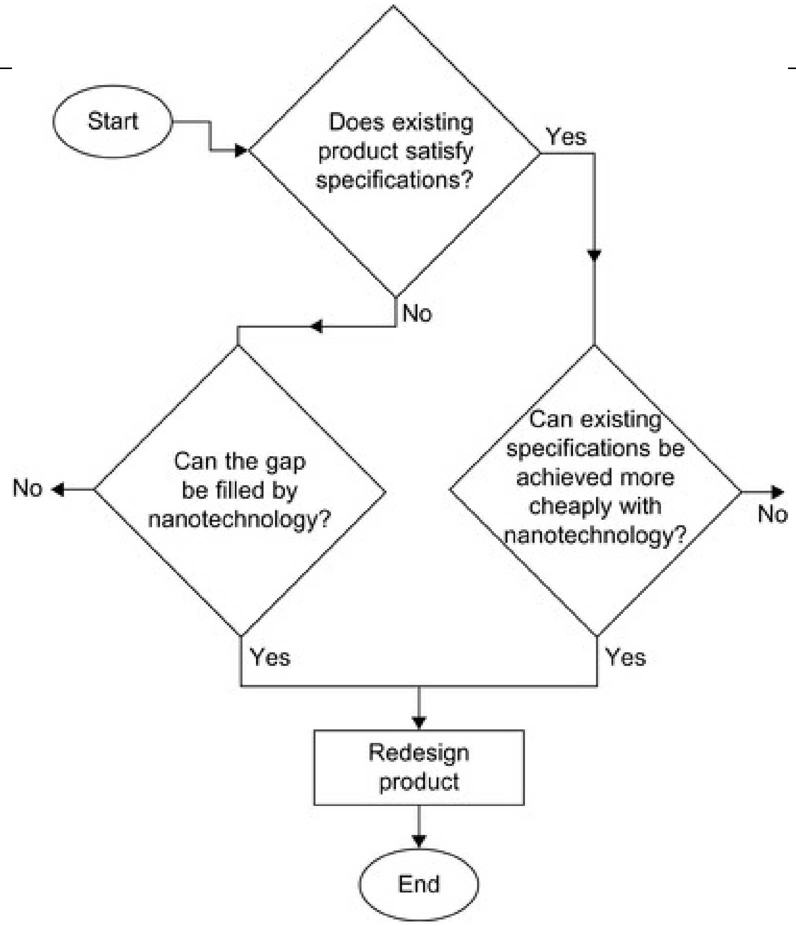

Figure 1.3 Flow chart to determine whether nanotechnology should be introduced into a product.

1.5.1. Novel Combinations of Properties

There are two ways of creating nanomaterials. One is by adding nano-objects (nanoadditives) to matrix. For example, organic polymer matrices incorporating carbon nanotubes can be light and ve strong, or transparent and electrically conducting. The other is by fabricating materials *de novo*, ator by-atom.

Since it is usually more expensive to create nanosized rather than microsized matter, one needs justify the expense of downscaling the additives: as matter is divided ever more finely, certa properties become qualitatively different (see Chapter 2). As examples, the optical absorptic spectrum of silicon vapor is quite different from that of a silicon crystal, even though the vapor ar crystal are chemically identical; when a crystal becomes very small, the melting point falls and the may be a lattice contraction (i.e., the atoms move closer together)—these are well understoc consequences of Laplace's law, and may be useful for facilitating a sintering process. If the radius the crystal is smaller than the Bohr radius of the electron in the bulk solid, the electron is confined ar has a higher energy than its bulk counterpart; the optical absorption and fluorescent emission spect shift to higher energies. Hence, by varying the crystal radius, the optical absorption and emissic wavelengths can be tuned. Chemists have long known that heterogeneous catalysts are more active they are more finely divided. This is a simple consequence of the fact that the reaction takes place the interface between the solid catalyst and the rest of the reaction medium. Hence, for a given ma the finer the division the greater the surface area. This is not in itself a qualitative change, although an industrial application there may be a qualitative transition from an uneconomic to an econom process.

1.5.2. Device Miniaturization: Functional Enhancement

The response time of a device usually decreases with decreasing size. Information carriers have le far to diffuse, or travel ballistically, and the resonant frequency of oscillators increases (Section 2.7)

Clearly the quantity of material constituting a device scales roughly as the cube of its line dimension. Its energy consumption in operation may scale similarly. In the macroscopic world mechanical engineering, however, if the material costs are disregarded, it is typically more expensi to make something very small; for example, a watch is more expensive than a clock, for equivale timekeeping precision. On the other hand when things become very large, as in the case of the clo familiarly known as Big Ben for example, costs again start to rise, because special machinery may needed to assemble the components, and so on. We shall return to the issue of fabrication in Chapt 8.

Performance (expressed in terms of straightforward input–output relations) *may* thus be enhanced reducing the size, although the enhancement does not always continue *ad libitum*: for mo microelectromechanical systems (MEMS) devices, such as accelerometers, performance is degrad by downscaling below the microscale (Section 10.8), and the actual size of the devices currently mas produced for actuating automotive airbags already represents a compromise between economy material, neither taking up too much space nor weighing two much, and still-acceptable performan On the other hand processor speed of VLSI chips is increased through miniaturization, sin components are closer together and electrons have to traverse shorter distances.

Miniaturization may enable new domains of application by enhancing device accessibility. In oth words, functionality may be enhanced by reducing the size. A typical example is the cellular (mobil phone. The concept was developed in the 1950s at Bell Labs, but the necessary circuitry would ha occupied a large multistorey building using the then current thermionic valve technology and, henc only became practical with large-scale circuit integration. Similarly, it would not be practicable equip mass-produced automobiles with macroscopic accelerometers with a volume of about one lit and weighing several kilograms.

Functional enhancement also applies to materials. The breaking strain of a monolithic materi typically increases with diminishing size (see, e.g., Section 2.7). This is usually because, for a giv probability of occurrence of defects per unit volume, a smaller volume will inevitably contain few defects. This advantage may be countered if the surface itself is a source of defects because of t increased preponderance of surface (Section 2.2).

Fabrication procedures may also be enhanced by miniaturization: any moving parts involved assembly will be able to operate at much higher frequencies than their macroscopic counterparts. Ne difficulties are, however, created: noise and surfaces. The random thermal motion of atoms plays much more deleteriously influential role than at the macroscale, where it can normally be neglecte The concept of the eutactic environment was introduced partly to cope with this problem. Bottom–u self-assembly, of course, requires noise to drive it; it is amplified up to constructive macroscop expression by virtue of special features of the components being assembled. The preponderance surfaces at the nanoscale, which can act as attractors for contamination and so forth, is probably be solved by appropriate energetic engineering of the surfaces (Section 3.2).

1.5.3. A Universal Fabrication Technology

Such a technology is usually considered to be based on nanoscale assemblers (i.e., person nanofactories). They would enable most artifacts required by humans to be made out of a simp feedstock such as acetylene together with a source of energy (see Section 8.3). Note that there is a intermediate level of technological achievement in which objects are constructed with atom precision, but without the need for construction equipment to be itself in the nanoscale (e.g., usin current tip-based ultramicroscope technology and its derivatives). Nanofabrication (nanomanufactu or nanofacture) represents the ultimate in modularity. Using nanoblocks, purity, the bane of specialt chemical manufacturing, especially pharmaceuticals, is no longer as issue—extraneous molecules a simply ignored by the fabrication system.

1.6. Summary

Nanotechnology is defined in various ways; a selection of already published definitions is given, fro which it may be perceived that a reasonable consensus already exists. A more formal concept syste is developed, in which care is taken to use the terms consistently. Nanotechnology is also define ostensively (i.e., what objects already in existence are called “nano”?) and by its history. The role biology is introduced as providing a living proof-of-principle for the possibility of nanotechnolog this has been of historical importance and continues to provide inspiration. Motivations f nanotechnology are summarized.

1.7 Further Reading

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