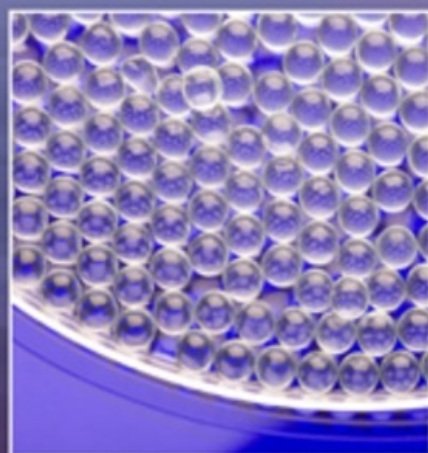




Jeremy J. Ramsden



# NANOTECHNOLOGY

An Introduction

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## Nanotechnology: An Introduction

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# Dedication

*...Kicsinyben rejlik a nagy,*

*Olyan sok a tárgy, s létünk oly rövid.*

IMRE MADÁCH



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## Preface

There are already hundreds of books in print on nanotechnology in English alone, at all levels up to that of the advanced researcher and ranging in coverage from detailed accounts of incremental improvements in existing microtechnologies to far-reaching visionary approaches toward productive nanosystems. Furthermore, not only do many old-established scientific journals in the fields of physics and chemistry now carry nanotechnology sections, but numerous scientific journals dedicated solely to nanotechnology have appeared and new ones are launched each year. In addition, a flood of commercially oriented reports about present and future nanotechnology markets is constantly being produced; these are often weighty documents comprising a thousand pages or more, whose reliability is difficult to assess, since even if they make use of publicly available data, the processing of that 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 strong background in one of the traditional disciplines such as physics, mechanical or electrical engineering, chemistry or biology, or who may have been working on microelectromechanical systems (MEMS) (also known as microsystems technology, MST), is likely to feel confronted with a somewhat chaotic and colorful scene from which it is often difficult to extract meaning. The goal of this book is to tackle that problem by presenting an overview of the entire field, focusing on key essentials, with which the reader will be able to erect his or her own personal scaffold on which the amazingly diverse plethora of detailed information emerging from countless laboratories all over the world can be structured into some kind of coherent order. The emphasis is therefore on concepts; any attempt to complement this by capturing all the latest specific discoveries and inventions in nanotechnology other than illustratively, would almost immediately become out of date; the aim of this book might briefly be stated as being “to make sense of nanotechnology”—to explain things thoroughly enough to be intelligible while still remaining introductory.

The book itself is structured around a robust anatomy of the subject. Following a basic introduction ([Chapter 1](#)), which includes a brief history of the subject, careful consideration is given to the meaning of the nanoscale ([Chapter 2](#)), on which everything else is dependent, since nanotechnology can most simply (but cryptically) be defined as “technology (or engineering) at the nanoscale”. This chapter in itself constitutes a succinct summary of the entire field. [Chapter 3](#) is devoted to interfacial forces, which govern key aspects of behavior at the nanoscale. [Chapter 4](#) covers the nano/bio interface, which plays a fundamental role in the continuing evolution of nanotechnology, and [Chapter 5](#) deals with the demanding issues of metrology in nanotechnology, which have also strongly influenced nanofabrication technology. In this chapter, the metrology of the nano/bio interface is covered in detail, since this is one of the newest and least familiar parts of the field. Nanomaterials (both nanoscale objects and nanostructured materials) are covered in [Chapter 6](#)—except carbon nanomaterials (and devices), which merit a separate [chapter \(9\)](#). Nanoscale devices of all kinds (except those based on carbon)—mainly information processors and transducers, including sensors are the topic of [Chapter 7](#) and strategies for their fabrication are covered in [Chapter 8](#), devoted to the three fundamental approaches towards achieving nanoscale manufacture (nanofabrication), namely the top-down method rooted in ultraprecision engineering and semiconductor processing, the bottom-to-bottom approach that is closest to the original concept of nanotechnology (the molecular assembler), and the bottom-up (self-assembly) methods that have been powerfully inspired by processes in the living world. 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 inevitable occurrence of defective ones. [Chapter 11](#) is devoted to bionanotechnology, defined as the incorporation of biomolecules into nanodevices. The final [chapter \(12\)](#) deals with the impacts of nanotechnology: technical, economic, social, psychological and ethical. Each chapter is provided with a succinct summary at the end as well as suggestions for further reading. A glossary of 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 working in other fields but are considering entering the nano field and wish to rapidly acquire an appreciation of its vocabulary, possibilities and limitations. The secondary readership is anyone curious about nanotechnology, including undergraduates and professionals in other fields. The book should also appeal to those less directly connected with science and engineering, such as insurers and lawyers whose activities are very likely to be connected with nanotechnology in the future, and traders, commodity brokers and entrepreneurs in general dissatisfied with remaining in ignorance of the technology that they are making use of. It is designed to equip the reader with the ability to cogently appraise the merits or otherwise of any piece of nanotechnology that may be reported in one form or another.

It is a distinct characteristic of nanotechnology that many of its features draw heavily from existing 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 in great detail in specialist literature that may not exclusively or even overtly be associated with nanotechnology. It seems, therefore, that nanotechnology is most aptly globally characterized as an attitude or mindset, comprising above all the desire both to understand the world at the atomic level and to create objects of beauty and utility by controlling matter at that level. Unlike the science of the subatomic level, however, nanotechnology necessarily concerns itself with superatomic levels as well, since the ultimate objects of its creation must be macroscopic in order to be of use to humanity. 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 of knowledge together to create novel technologies. These nanotechnologies are in turn united by the distinctive attitude associated with nanotechnology.

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

Inevitably, the author of a book of this nature is greatly indebted to countless colleagues and correspondents both at Cranfield and throughout the world. It would be invidious to mention some 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?

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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. A 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 objects 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; it 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 atomically precise perception. As such, it represents the apotheosis of man's ceaseless urge to understand the world and use that understanding for practical purposes. Well synonymized as “atomically precise technology”, it encapsulates the vision of building “our earthly estate” atom-by-atom, controlling architecture, composition and hence physical properties with atomic resolution. “Hard” nanotechnologists promote a future world in which every artifact (and even food) can be constructed 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 atomically precise construction can improve existing artifacts and create new ones. Similarly, the resolute aim of “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 the bottom upwards, whereas a more pragmatic view accepts that while in principle everything can be reproduced and many things imitated via atom-by-atom assembly, in many cases the improvement in properties or performance would be negligible and a hybrid approach will best serve the needs of humanity. This is particularly likely to be the case for large artifacts (such as human dwellings or airplanes) and for relatively complex products such as food, which can be quite easily grown naturally.

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

to what is already generally considered to be nanotechnology, and extended by what is envisaged for the future. A further way of defining it is through its history. We also briefly look at the relation of nanotechnology to biology, which has been a powerful paradigm for convincing engineers that nanotechnology is possible—nanobiotechnology and bionanotechnology form the topics of subsequent [Chapter 4](#) and [Chapter 11](#) respectively). General motivations for nanotechnology are considered—“Why nanotechnology?” Attention is drawn to the appended list of neologisms associated with 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 definitions currently circulating can be reasonably accurately thus paraphrased. Obviously, this definition is not intelligible in the absence of a further definition, namely that of the nanoscale. Furthermore, definitions of components of nanotechnology, such as “nanofiber”, also refer to the nanoscale; indeed every word starting with “nano”, which we can generically write as “nanoX”, can be defined as “nanoscale X”. Therefore, unless we define “nanoscale”, we cannot therefore properly define nanotechnology. A rational attempt to do so is made in [Chapter 2](#). Here we note that provisionally, the 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 atomic precision”, or “atomically precise technology” (APT). However, this definition does not explicitly include the aspects of “fundamentally new properties” or “novel” and “unique” that nanotechnologists usually insist upon, wishing to exclude existing artifacts that happen to be small. These aspects are encapsulated by the US National Nanotechnology Initiative's declaration that “the essence of nanotechnology is the ability to work at the molecular level, atom-by-atom, to create large structures with fundamentally new molecular organization ... nanotechnology is concerned with materials and systems whose structures and components exhibit novel and significantly improved physical, 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 the structure of matter is controlled at the nanometer scale to produce novel materials and devices that have useful and unique properties”. Function is stressed in: “the design, synthesis, characterization and application of materials, devices and systems that have a functional organization in at least one dimension on the nanometer scale”. This is emphasized even more strongly in “nanotechnology pertains to the processing of materials in which structure of a dimension of less than 100 nm is 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 be of practical use. A dictionary definition of nanotechnology is “the design, characterization, production 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 manipulation, precision placement, measurement, modeling and production of matter in the nanoscale in order to create materials, devices, and systems with fundamentally new properties and functions”[\[1\]](#). The emphasis on control is particularly important: it is this that distinguishes nanotechnology from chemistry, with which it is often compared. In the latter, motion is essentially uncontrolled and

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

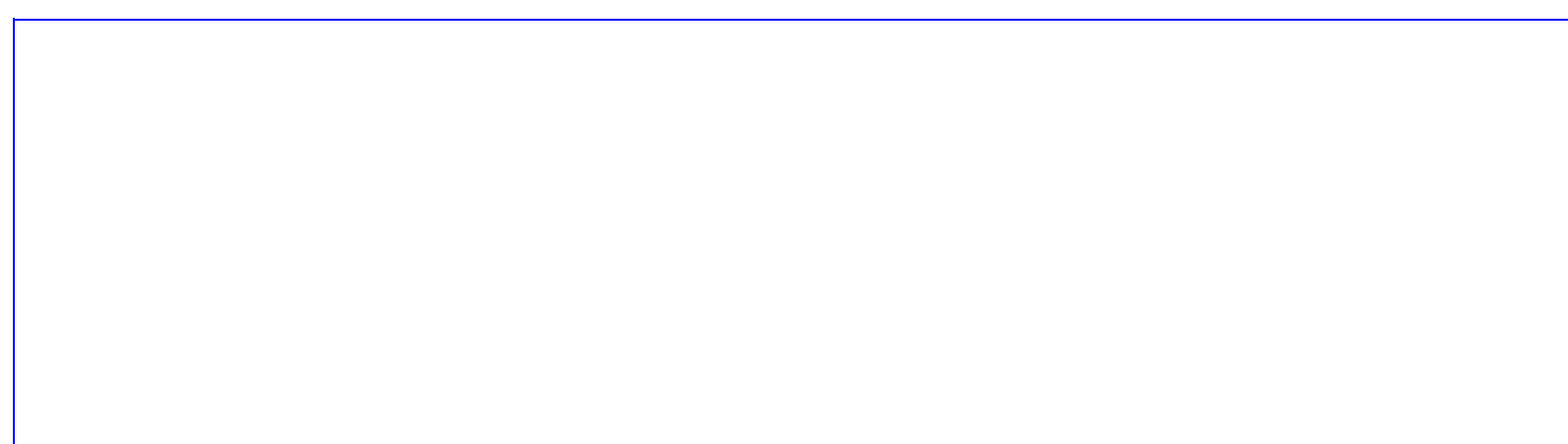
It is sometimes debated whether one should refer to “nanotechnology” or “nanotechnologies”. The argument in favor of the latter is that nanotechnology encompasses many distinctly different kinds of technology. But there seems to be no reason not to use “nanotechnology” in a collective sense, since the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

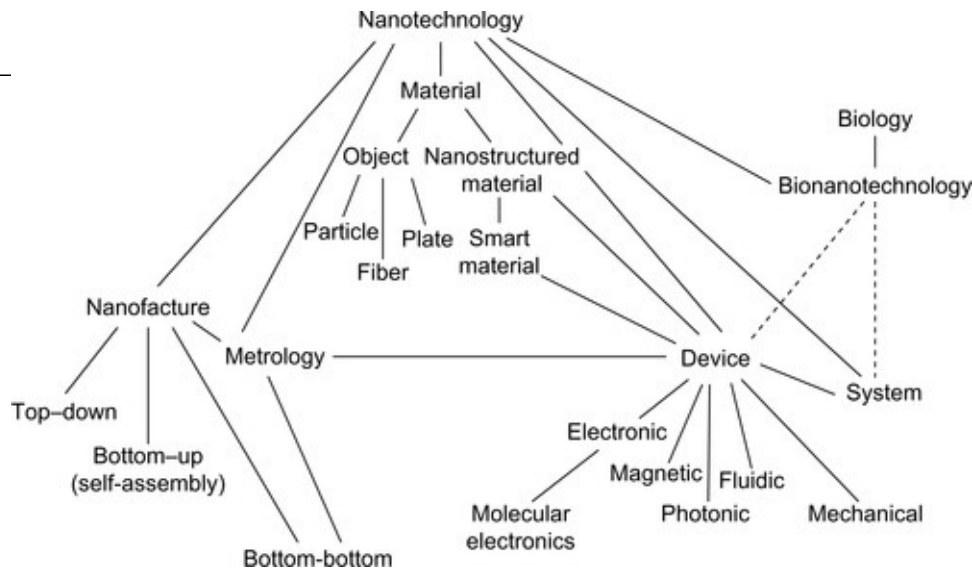
### 1.1.2. Towards a Concept System for Nanotechnology

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

[Figure 1.1](#) shows (part of) an ontology for nanotechnology. To the right of the diagram one has products—an axis of tangible objects in order of increasing complexity: *materials*, *devices* and *systems*. To the left of the diagram one has processes. Note the relationships between *metrology* and *fabrication* (nanomanufacturing, usually abbreviated to nanofabrication, also called atomically precise manufacturing, APM) and devices. An atomic force microscope is used to measure nanoscale features; every measuring instrument is necessarily a device; and pushing nano-objects around with a needle is 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 line merely signifies that if the superordinate concept contributes, then the prefix must indicate that (e.g., bionanodevice, bionanosystem). Biology may also have some input into nanomanufacture (nanofabrication), inspiring, especially, self-assembly processes. Not shown on the diagram is what might be called “conceptual nanotechnology”, or perhaps better (since it is itself a concept), “virtual nanotechnology”, which means the (experimental and theoretical) scrutiny of engineering (and other, including biological) processes 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, photons, etc. Yet many devices involve more than one medium: for example, nanoelectromechanical devices are being intensively researched as a way of achieving electronic switching; optoelectronic control is a popular way of achieving photonic switching; and photochemistry in miniaturized reactors involves both nanophotonics and nanofluidics.

[Table 1.1](#) describes a few of the concepts and their intensions and extensions. At the time of writing, the terminology of nanotechnology is still being intensively debated within national standards organizations as well as supranational bodies such as the Comité Européen de Normalisation (CEN) and the International Standards Organization (ISO), hence no attempt has been made to be comprehensive 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 topics ([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 a nanomaterial, the nanoparticle as a nano-object, and energy, composites (materials) and sensors as applications. Interestingly, “water” features highly on the list. The reasons for this will be apparent from reading [Section 3.8](#).

A very simple (albeit privative) ostensive definition of nanotechnology is “If you can see it (including with the aid of an optical microscope), it's not nano”, referring to the fact that any object below 100 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 [\[56\]](#). Entitled “There's Plenty of Room at the Bottom”, it expounds his vision of machines making the components for smaller machines (a familiar enough operation at the macroscale), themselves capable of making the components for yet smaller machines, and simply continuing the sequence until the atomic realm is reached. Offering a prize of \$1000 for the first person to build a working electric motor with an overall size not exceeding 1/64th of an inch, Feynman was dismayed when not long afterwards a student, William McLellan, presented him with a laboriously hand-assembled (i.e., using the technique of the watchmaker) electric motor of conventional design that nevertheless met the specified criteria.

A similar idea was proposed at around the same time by Marvin Minsky: “Clearly it is possible to 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 is concentrated on “printing” or evaporation through masks. This is surely attractive; in one operation one can print thousands of elements. But an alternative, equally attractive, has been ignored. Imagine small machines fabricating small elements at kilocycle rates. (The speed of small mechanical devices is extremely high.) Again, one can hope to make thousands of elements per second. But the generality of the mechanical approach is much greater since there are many structures that do not lend themselves easily to laminar mask construction”[\[118\]](#). One wonders whether Feynman and Minsky had previously read Robert A. Heinlein's short story “Waldo”, which introduces this idea (it was published in the August 1942 issue of “Astounding” magazine under the pseudonym Anscombe MacDonald).

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

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

However, the idea of a minute device intervening at the level of elementary particles was conceived almost a hundred years earlier by James Clerk Maxwell when he conceived his “demon” of selectively allowing molecules to pass through a door, thereby entangling physics with information. Perhaps Maxwell should be considered as the real father of nanotechnology. The demon was described in Maxwell's *Theory of Heat* first published in 1871, but had already been mentioned in earlier 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 in 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 rather inefficient means of pumping water out of mines to an industrially useful and even self-propelling technology was only possible once machining tolerance had improved to enable pistons to slide within cylinders without leaking.

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

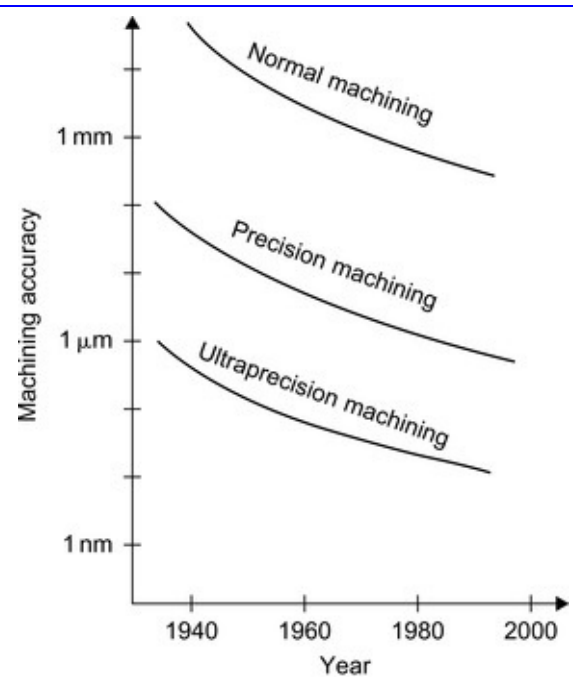


Figure 1.2 The evolution of machining accuracy (after Norio Taniguchi).

### 1.3.2. *Semiconductor Processing qua Microtechnology*

The trend in ultraprecision engineering is mirrored by relentless miniaturization in the semiconductor

processing industry. The history of the integrated circuit could perhaps be considered to start in 1901 when Bose patented the galena crystal for receiving electromagnetic waves, followed by Picard's 1902 patent for a silicon crystal. The thermionic valve and the triode were invented respectively by Fleming (in 1904) and de Forest (in 1906), which became the basis of logic gates, reaching zenith with the ENIAC, which contained about 20,000 valves. The invention of the point contact transistor in 1947 by Bell Laboratories essentially rendered the thermionic valve obsolete, but the first commercial use of transistors only occurred in 1953 (the Sonotone 1010 hearing aid), the first transistor radio appearing one year later. Meanwhile the idea of an integrated circuit had been proposed by Dummer at the Royal Signals Research Establishment (RSRE) in 1952, but (presumably) he was not allowed to work on it because what was then a government establishment, and the first actual example was realized by Kilby in 1959 at Texas Instruments, closely followed by Noyce at Fairchild in the following year. It is interesting to recall that the Apollo flight computer ("Block II") used for the first moon landing in 1969 was designed in 1964 (the year before Moore's law was first proposed), used resistor-transistor logic (RTL) and had a clock speed of 2 MHz. Intel introduced the first microprocessor, with about 2000 transistors, in 1971, the year in which the pioneering "LE-120A Handy" pocket calculator was launched in Japan. It took another decade before the IBM personal computer appeared (1981); the Apple II had already been launched in 1977. By 2000, we had the Pentium 4 chip with about  $1.2 \times 10^9$  transistors fabricated with 180 nm process technology. In contrast, today's dual core Intel Itanium chip has about  $1.7 \times 10^9$  transistors (occupying an area of about  $50 \times 20$  mm) with a gate length of 90 nm. A 45 nm transistor can switch  $3 \times 10^{11}$  times per second—this is about 100 GHz. Experiments with graphene-based devices achieve more than a THz. Despite the extraordinarily high precision and fabrication called for in such devices, modern integrated circuits are reliable enough for spacecraft (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 180 nm process technology costs about \$100,000, rising to one million dollars for 45 nm technology. Despite the huge costs of the plant, cost per chip continues to fall relentlessly: for example, a mobile 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 transistors that can be fabricated in parallel on a single chip, has been well documented; structures with features of a few tens of nanometers in size capable of being examined in an electron microscope were reported as long ago as 1960; device structures with dimensions less than 100 nm were already being reported in 1972, with 25 nm achieved in 1979. Incidentally, the lower size limit for practical semiconductor circuits is considered to be 20 nm; smaller sizes, hence higher transistor number densities per unit area, will only be achievable using three-dimensional design or quantum logic ([Section 7.3](#)). Thus we see that since the beginning of nanotechnology—identifying this with the conception of Maxwell's demon—nanotechnology has been intimately connected with information science and technology.

### **1.3.3. Nanoparticles**

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If we define nanotechnology ostensively, we have to concede a very long history: there is evidence that PbS nanocrystals were the goal of a procedure used since Greco-Roman times to color hair black ([164](#)). Nanoparticulate gold has a long history, not least in medicine (see [Section 4.2](#)). The Flemish glassmaker John Utynam was granted a patent in 1449 in England for making stained glass incorporating nanoparticulate gold; and the Swiss medical doctor and chemist von Hohenheim (Paracelsus) prepared and administered gold nanoparticles to patients suffering from certain ailments in the early 16th century; a modern equivalent is perhaps the magnetic nanoparticles proposed for

therapeutic purposes. The secret of the extraordinarily advanced metallurgical features of Damascus swords made more than 400 years ago has recently been found to be carbon nanotubes embedded in the blades [146].

With such a long history, it is perhaps hardly surprising that at present they represent almost the only part of nanotechnology with commercial significance. The fabrication of different kinds of nanoparticles by chemical means seems to have been well established by the middle of the 19th century (e.g., Thomas Graham's method for making ferric hydroxide nanoparticles [63]). Wolfgang Ostwald lectured extensively on the topic in the early 20th century in the USA, and wrote up his lectures in what became a hugely successful book, *Die Welt der vernachlässigten Dimensionen*. Many universities had departments of colloid science (sometimes considered as physics, sometimes as chemistry), at least up to the middle of the 20th century, then slowly the subject seemed to fall out of fashion, until its recent revival as part of nanotechnology. The field somewhat overlapped that of heterogeneous catalysis, in which it was well known, indeed almost obvious, that specific activity (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 viable unit of life was the cell, which could be less than a micrometer in size. It was surmised that cells contained a great deal of machinery at smaller scales, which has since been abundantly evidenced 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 bacterial flagella), linear motors (e.g., muscle), pumps (e.g., transmembrane ion channels), and multi-enzyme complexes carrying out more complicated functions than simple reactions (e.g., the proteasome for degrading proteins, or the ribosome for translating information encoded as a nucleic acid sequence into a polypeptide sequence). When Drexler developed his explicit schema of nanoscale assemblers, an allusion to nanoscale biological machinery was explicitly made as a “living proof-of-principle” 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 self-assembly. In simple form, self-assembly is well known in the nonliving world (for example, crystallization). This process does not, however, have the potential to become a feasible industrial technology for the general-purpose construction of nanoscale objects, because size limitation is not intrinsic to it. Only when highly regular structures need to be produced (e.g., a nanoporous membrane or a collection of monosized nanoparticles) can the process parameters be set to generate an outcome of a prespecified size. Nature, however, has devised a more sophisticated process, known to engineers as programmable self-assembly, in which every detail of the final structure can be specified in advance by using components that not only interlock in highly specific ways but are also capable of changing their structure upon binding to an assembly partner in order to block or facilitate, respectively, previously possible or impossible interlocking actions. Inspiration for harnessing programmable self-assembly arose from the work of virologists who noticed that pre-assembled components (head, neck, legs) of bacteriophage viruses would further assemble spontaneously into a functional virus merely upon mixing and shaking in a test-tube. This “shake and bake” approach appeared to offer a manufacturing route to nanodevices obviating: (1) the many difficulties involved in making Drexlerian assemblers, which would appear to preclude their realization in the near future, and (2) the great expense of the ultrahigh precision “top-down” approach, whether via UPMT or semiconductor processing. Even if assemblers are ultimately realized, it might be most advantageous

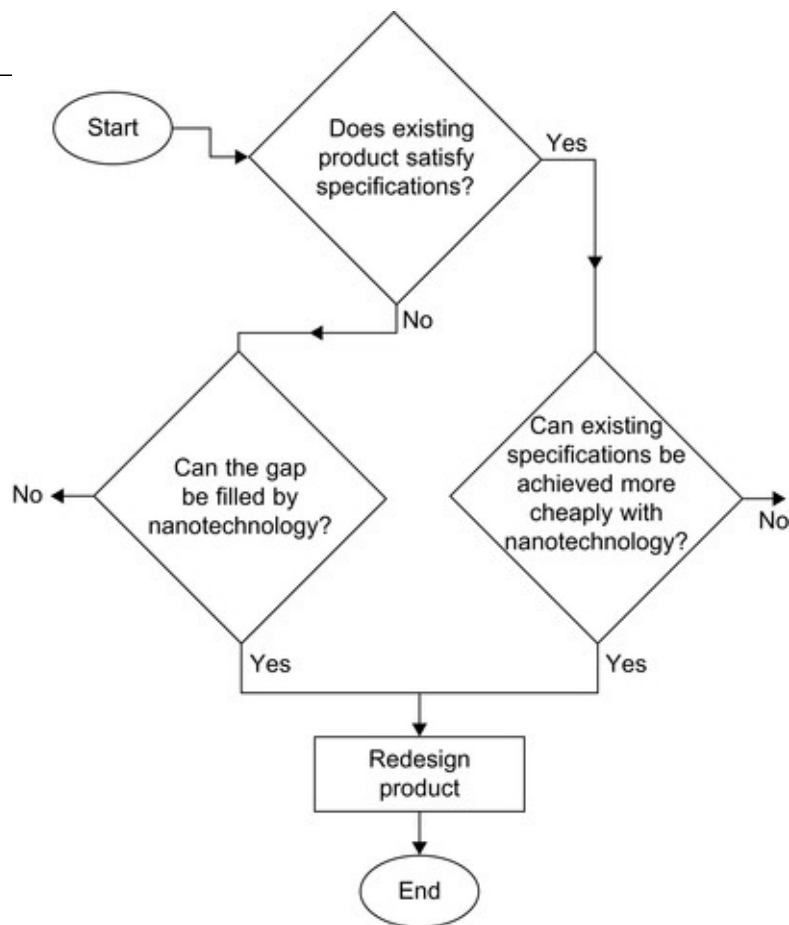
to use them to assemble sophisticated “nanoblocks”, designed to self-assemble into final macroscopic objects (see [Section 8.3.2](#)). In other words, self-assembly's greatest potential utility will probably arise as a means to bridge the size gap between the nanoscopic products of assemblers and the macroscopic 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 other consumables, their function may be enhanced by reducing the characteristic dimensions, and they 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 attempt to exploit “room at the bottom”, however. Two other important human motivations are doubtless also playing a role. One is simply “it hasn't been done before”—the motivation of the mountaineer 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 because 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 partly because the deleterious effects of such “conquest” are now far more widely recognized, and the few remaining undrained marshes and undammed rivers are likely nowadays to be legally protected natural reserves. But the world at the bottom, as Feynman picturesquely called it, is uncontrolled and largely unexplored. On a more prosaic note, nanotechnology may already offer immediate benefit for existing products through substitution or incremental improvement ([Figure 1.3](#)). The space industry has a constant and heavily pressing requirement for making payloads as small and lightweight as possible. Nanotechnology is ideally suited to this end user—provided the nanomaterials, devices and systems 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 a matrix. For example, organic polymer matrices incorporating carbon nanotubes can be light and very strong, or transparent and electrically conducting. The other is by fabricating materials *de novo*, atom-by-atom.

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

### 1.5.2. Device Miniaturization: Functional Enhancement

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The response time of a device usually decreases with decreasing size. Information carriers have less time to 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 linear dimension. Its energy consumption in operation may scale similarly. In the macroscopic world of mechanical engineering, however, if the material costs are disregarded, it is typically more expensive to make something very small; for example, a watch is more expensive than a clock, for equivalent timekeeping precision. On the other hand when things become very large, as in the case of the clock tower familiarly known as Big Ben for example, costs again start to rise, because special machinery may be needed to assemble the components, and so on. We shall return to the issue of fabrication in [Chapter 8](#).

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

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

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

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

### 1.5.3. A Universal Fabrication Technology

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

## 1.6. Summary

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. A more formal concept system is developed, in which care is taken to use the terms consistently. Nanotechnology is also defined ostensively (i.e., what objects 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; this has been of historical importance and continues to provide inspiration. Motivations for nanotechnology are summarized.

## 1.7 Further Reading

Broers, A.N., Limits of thin-film microfabrication, *Proc. R. Soc. Lond. A* **416** (1988) 1–142.

Drexler, K.E., *Engines of Creation*. (1986) Anchor Books/Doubleday, New York.

Drexler, K.E., *Nanosystems: Molecular Machinery, Manufacturing, and Computation*. (1992) Wiley-Interscience.

Maruyama, K.; Nori, F.; Vedral, V., The physics of Maxwell's demon and information, *Rev. Mod. Phys.* **81** (2009) 1–23.

Ostwald, W., *Die Welt der vernachlässigten Dimensionen*. (1914) Steinkopff, Dresden.

Zsigmondy, R.; Thiessen, P.A., *Das kolloide Gold*, Akademische Verlagsgesellschaft. (1925) Leipzig

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