FRITZ ALLHOFF, PATRICK LIN
AND DANIEL MOORE

WHAT IS NANOTECHNOLOGY AND WHY DOES IT MATTER?

FROM SCIENCE TO ETHICS

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Fritz Allhoff, Patrick Lin,
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What Is Nanotechnology and Why Does It Matter?

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Preface

New and emerging technologies both excite and worry us – academics, policy-makers, businesses, investors, ethicists, journalists, futurists, humanitarians, the global public – and nanotechnology today is certainly a flashpoint for irrational exuberance and fears. By definition, there is a knowledge gap during the nascent stages of any new technology, and nanotechnology is no exception: researchers and engineers are still learning about nanoscience and its applications. But, in the meantime, hope and hype naturally and irresistibly fill this vacuum of information.

In nanotechnology, we find an entire range of speculative possibilities, from limitless life to the end of days. Depending on whom you ask, nanotechnology is predicted to help solve the world's energy and hunger issues. Or it can help us easily ride into orbit on a space elevator or evolve into cybernetic beings. Or by playing with this fire – by manipulating the basic building blocks of nature – nanotechnology may scorch the earth and fulfill a prophecy of Armageddon. We may finally cause our own undoing by unleashing a powerful technology that we do not yet fully understand and thus may not be able to control.[1]

So which is it: will nanotechnology usher in a bright era for humanity, or its reckless demise? Or perhaps neither: nanotechnology could be much ado about nothing, given the admittedly humdrum products it enables today from longer-lasting tennis balls to stain-resistant pants. Of course, none of us knows the answer, despite a continuous flood of predictions. But what

[1] In addition to forthcoming discussion in this book, see Fritz Allhoff, Patrick Lin, James Moor, and John Weckert (eds), *Nanoethics: The Social and Ethical Implications of Nanotechnology* (Hoboken, NJ: John Wiley & Sons, 2007). See also Fritz Allhoff and Patrick Lin (eds), *Nanotechnology and Society: Current and Emerging Ethical Issues* (Dordrecht: Springer, 2008).

we do know is that nanotechnology is rapidly entering the marketplace today, and ongoing research reveals risks (e.g., environmental and health harms) as well as fantastical innovations (e.g., invisibility cloaks and 'smart dust'). It is also becoming clear that nanotechnology has the potential to profoundly change the world, even if today's products are uninspired and only incrementally better than previous ones. Therefore, understanding what nanotechnology is and why it matters is the first step in a roadmap toward our future: it is the next generation for industries, financial markets, research labs, headlines, and our everyday lives.

In this book, we hope to tame the riot of speculation with an informed and balanced look at nanotechnology and its issues. To that end, this book is organized in three units. First, we discuss the science behind nanotechnology, including the nanoscale, tools of the trade, nanomaterials, and applied nanotechnology. In the second unit, we provide a general framework to evaluate the particular ethical and social issues that nanotechnology raises (which are then covered in the third unit); for instance, we will discuss the different ways to understand risk, regulation, and fairness in the use and dissemination of nanotechnology. In the third unit, we dedicate chapters to some of the most urgent and contentious applications of nanotechnology: environment, military, privacy, medicine, and enhancement. In choosing this list, we have focused on near- and mid-term issues rather than more speculative ones – such as life extension, space exploration, and molecular manufacturing – though these latter are mentioned when appropriate. We should also note that given the unusually broad range of issues that arise in connection with the social and ethical implications of nanotechnology, we have made specific choices regarding our coverage; to this end, we have focused on core scientific and philosophical issues and ones on which we are qualified to write. Other important topics – such as existing (and potential) laws and regulations, economic impacts, and so on – can be pursued elsewhere by the interested reader.

While all of the chapters were the result of collaboration, one or other of us bore the primary responsibility for each. Having one scientist and two philosophers on the project undoubtedly makes it stronger and, while our disciplinary backgrounds undoubtedly come through, we hope the presentation and styles are well integrated; editing a project like this takes as long as writing it! Some of the chapters have extended scientific or philosophical primers, which we include for those with less background and/or for pedagogical reasons as this book stands for various course adoptions. Those with the relevant professional training can certainly skip these discussions.

New technologies are not easy to understand, nor are the public policy questions they engender. Therefore, we commend you, the reader, not only for your patience in sorting through these issues, but also for your foresight in recognizing how essential nanotechnology will be to society and our collective futures.

We further thank the institutions and organizations with which the authors are – or have been during time of writing – affiliated for their support: The Australian National University's Centre for Applied Philosophy and Public Ethics, California Polytechnic State University (San Luis Obispo), Dartmouth College, Georgia Institute of Technology, IBM, The Nanoethics Group, University of Oxford's Future of Humanity Institute, and Western Michigan University.

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Unit I

What Is Nanotechnology?

1

The Basics of Nanotechnology

1.1 Definitions and Scales

Before delving into the depths of nanotechnology and nanoscale science, we should be clear what we mean when we use terms such as 'nanotechnology,' 'nanoscience,' and 'nanoscale.' It is a basic nomenclature, used to describe certain attributes of certain systems, and such nomenclatures are typically designed to eliminate confusion and encourage accurate communication among those discussing the system. To be sure, there will be several other variants of words with the prefix 'nano-' used in this book and it is important to make sure that we have our meanings straight if any sort of meaningful discussion is possible.

The prefix 'nano-' is derived from the Greek word *nannos*, meaning "very short man." Most of the measurement prefixes used today originate from Greek and Latin words used in measurements. For example, 'kilo-' is from the Greek word *khilioi* meaning "one thousand" and 'milli-' is from the Latin word *mille* meaning "one thousand." Greek and Latin words for numbers cover the everyday level of measurements from one-thousandth to one thousand. Beyond that, it gets interesting. To describe one billion (1,000,000,000) of something we use the prefix 'giga-' which is from the Greek word *gigas* meaning "giant." We also get the word "gigantic" from this root. On the other end of the spectrum, to describe one millionth (0.000 001) we use the prefix 'micro-' from the Greek word *mikros* meaning "small." To describe one trillionth (0.000 000 000 001) we use the prefix 'pico-' from the Spanish word *pico*, which can mean both a "beak" and a "small quantity." These prefixes are extremely useful when discussing very large or very small values. For example, we could refer to the radius of the Earth at its equator as being 6,378,100 meters, but it is more useful (and requires less effort) to refer to it as 6,378.1 kilometers. The most common scientific prefixes and their derivations are shown in Table 1.1.

Table 1.1 Etymology of scientific prefixes

Prefix	*Language of origin*	*Word*	*Meaning of word*	*Value*
Zetta	Latin	Septem	Seven	$(10^3)^7 = 10^{21}$
Exa	Greek	Hexa	Six	$(10^3)^6 = 10^{18}$
Peta	Greek	Penta	Five	$(10^3)^5 = 10^{15}$
Tera	Greek	Teras	Monster	10^{12}
Giga	Greek	Gigas	Giant	10^9
Mega	Greek	Megas	Great	10^6
Kilo	Greek	Khilioi	One thousand	10^3
Hecto	Greek	Hekaton	One hundred	10^2
Deca	Greek	Deka	Ten	10^1
Deci	Latin	Decem	Ten	10^{-1}
Centi	Latin	Centum	One hundred	10^{-2}
Milli	Latin	Mille	One thousand	10^{-3}
Micro	Greek	Mikros	Small	10^{-6}
Nano	Greek	Nannos	Dwarf	10^{-9}
Pico	Spanish	Pico	Beak, small quantity	10^{-12}
Femto	Danish	Femten	Fifteen	10^{-15}
Atto	Danish	Atten	Eighteen	10^{-18}
Zepto	Latin	Septem	Seven	$(10^{-3})^7 = 10^{-21}$

At its root, the prefix 'nano-' refers to a scale of size in the metric system. 'Nano' is used in scientific units to denote one-billionth (0.000 000 001) of the base unit. For example, it takes one billion nanoseconds to make a second. In everyday practical use, the term 'nanosecond' is not very useful in describing time accurately. Imagine discussing time in these terms: we would say things like "dinner will be ready in 300,000,000,000 nanoseconds." Instead, the term 'nanosecond' is mainly used to refer to a very short period of time. (A nanosecond is to a second as one second is to approximately 30 years.)

When we are talking about *nano*technology, we are talking about a scale – an order of magnitude – of size, or length. We are making a reference to objects that are sized on a scale that is relevant when we discuss *nanometers* (nm). Using this terminology makes it easier to discuss the size of objects that are the main attraction in nanotechnology, namely atoms. If we were to describe the size of atoms and molecules in feet or meters, we would have to say that a hydrogen atom (the smallest atom) is 7.874×10^{-10} feet or 2.4×10^{-10} meters. Instead, we can use nanometers and say that the hydrogen atom is 0.24 nm.

The nanoscale, then, is the size scale at which nanotechnology operates. Though we have a lower limit on this scale size (the size of one atom), pinning down an upper limit on this scale is more difficult. A useful and well-accepted convention is that for something to exist on the nanoscale, at least one of its dimensions (height, width, or depth) must be less than about 100 nanometers. In fact, it is these limits to the nanoscale that the National Nanotechnology Initiative (NNI) uses for its definition of nanotechnology: "Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nm, where unique phenomena enable novel applications."[1] To this, it is useful to add two other statements to form a complete definition. First, nanotechnology includes the forming and use of materials, structures, devices, and systems that have unique properties because of their small size. Also, nanotechnology includes the technologies that enable the control of materials at the nanoscale.

Though we have established that the 'nano-' in 'nanotechnology' signifies a particular scale, it is important to get a good idea of what that scale is – that is, what size the nanoscale is in relation to our everyday experience. There are several analogies that we can use to explain the size of a nanometer in relation to sizes that are more commonly known. For example, it takes 50,000 nm to make up the width of a single strand of human hair. Another example is as follows: a nanometer compared to the size of a meter is roughly of the same proportion as a golf ball compared to the size of the Earth. Perhaps the best way to illustrate the nanometer scale is by describing the range of length scales from the centimeter down to the nanoscale. An ant is on the order of 5 mm (10^{-3} meters) in size. The head of a pin is 1–2 mm. A dust mite is 200 µm (10^{-6} meters) in size. A human hair is about half the size of a dust mite, 100 µm wide. The red blood cells that flow in our veins are about 8 µm in diameter. Even smaller than that, the ATP synthase of our cells is 10 nm (10^{-9}) in diameter. The size of the double helix of DNA on the nanoscale is about 2 nm wide. Finally, atoms themselves are typically less than a nanometer in size and are sometimes spoken about in terms of angstroms (10^{-10} meters).

1.2 The Origins of Nanotechnology

Nanotechnology, like any other successful technology, has many founders. In one sense, the very field of chemistry has been working on nanotechnology since its inception, as have materials science, condensed physics, and solid state physics. The nanoscale is not really all that new. But investigating and designing with a specific eye on the nanoscale is new – and revolutionary.

The term 'nanotechnology' can be traced back to 1974. It was first used by Norio Taniguchi in a paper entitled "On the Basic Concept of 'Nano-Technology'."[2] In this paper, Taniguchi described nanotechnology as

[1] "What is Nanotechnology?" National Nanotechnology Initiative. Available at http://www.nano.gov/html/facts/whatIsNano.html (accessed October 11, 2008).

[2] Norio Taniguchi, "On the Basic Concept of Nanotechnology," *Proceedings of the International Conference of Production Engineering, London, Part II*. British Society of Precision Engineering, 1974.

the technology that engineers materials at the nanometer level. However, nanotechnology's history predates this. Traditionally, the origins of nanotechnology are traced back to a speech given by Richard Feynman at the California Institute of Technology in December 1959 called "There's Plenty of Room at the Bottom."[3] In this talk, Feynman spoke about the principles of miniaturization and atomic-level precision and how these concepts do not violate any known law of physics. He proposed that it was possible to build a surgical nanoscale robot by developing quarter-scale manipulator hands that would build quarter-scale machine tools analogous to those found in machine shops, continuing until the nanoscale is reached, eight iterations later. As we will see, this is not exactly the path that nanotechnology research has actually followed.

Feynman also discussed systems in nature that achieve atomic-level precision unaided by human design. Furthermore, he laid out some precise steps that might need to be taken in order to begin work in this uncharted field.[4] These included the development of more powerful electron microscopes, key tools in viewing the very small. He also discussed the need for more fundamental discovery in biology and biochemistry. Feynman concluded this talk with a prize challenge. The first challenge was to take "the information on the page of a book and put it on an area 1/25,000 smaller in linear scale, in such a manner that it can be read by an electron microscope."[5] The second challenge was to make "an operating electric motor – a rotary electric motor which can be controlled from the outside and, not counting the lead-in wires, is only 1/64 inch cube."[6] He ended the talk by saying "I do not expect that such prizes will have to wait very long for claimants."[7] He was right about one of the prizes: the motor was built fairly quickly and by a craftsman using tools available at the time. However, it was not until 1985 that a graduate student at Stanford named Tom Newman reduced the first paragraph of Charles Dickens' *A Tale of Two Cities* to 1/25,000 its size.

In his paper on the basic concept of nanotechnology, Taniguchi developed Feynman's ideas in more detail. Taniguchi stated, " 'Nano-technology' is the production technology to get the extra high accuracy and ultra fine dimensions, i.e., the preciseness and fineness of the order of 1 nm

[3] Richard P. Feynman, "There's Plenty of Room at the Bottom," *Journal of Microelectromechanical Systems* 1 (1992): 60–6.

[4] Physicists, especially, had not explored this field much. Most physicists at the time were focused on high-energy physics, probing into the atom to look at quarks and subnuclear reactions, astrophysics, or nuclear physics. Much of what fell in between was left to chemists and engineers, as many of the fundamental equations in this area of the natural world were believed to be explained already.

[5] Feynman, "There's Plenty of Room," p. 66.

[6] Ibid.

[7] Ibid.