

## INTRODUCTION

### INFINITIES IN A GRAIN OF SAND

This book is an invitation to take the plunge into the infinitely small, to stay there — “at the bottom” — and play with a single atom or a single molecule. In our day-to-day lives we never encounter such objects individually, because they are too small to be grasped one by one. So how big is an atom? Rather than talking about its dimensions — one ten-billionth of a meter, or ten millionths of a millimeter — another approach is to consider how big it would be if you, the reader of this book, were the size of the Earth. In that case, an atom would be a tiny ball one millimeter across. And if the atom were as big as a room, you would be tall enough to touch the Sun. So an atom is invisible not only to the naked eye, but even to our most powerful optical microscopes.

In 1981, a new microscope was invented: the so-called scanning tunneling microscope (STM), which can provide an image of a single atom or a single molecule on a computer screen. However, as far back as the 1950s, “electron” microscopes had shown images of atoms on a phosphorescent screen. What is different about the STM is that its minute tip can now also touch a single atom at a time, and move it at will. Usually, when we touch something, the billions of atoms in our fingers come into “contact” with the billions of atoms in the object. But the tip of the STM is so sharp that it allows us to touch a single atom and even to assemble new atomic architectures atom by atom. The tip becomes an extension of the scientist’s or engineer’s finger.

The result is that the STM is revolutionizing our relationship with matter. With this microscope as a tool, a different technological method has emerged, in which ever-larger edifices are constructed atom by atom and “monumentalized” until each embodies a minute but functioning machine. It is a bottom-up approach to machine construction, the reverse of miniaturization.

Suppose, for instance, that we wanted to make a cube a million times smaller than a grain of sand, with edges one nanometer — i.e. one billionth of a meter — long. To build this nanocube, we would have to put together around sixty atoms one by one. This can be done with the STM, and this bottom-up technology of atom-by-atom construction is called “nanotechnology.” In the top-down approach of miniaturization, we would have to remove 100 billion billion atoms to make the same nanocube from a cube that started out with edges one centimeter long.

In essence, therefore, nanotechnology is a technology that is sparing with material resources. Over the years, however, the definition has become more elastic. Nanotechnology has become “nanotechnologies,” which are no longer just concerned with the atom-by-atom manipulation of matter, but also encompass all the techniques used to make “small objects” with a precision measured in nanometers, even though they bring billions of atoms — rather than just a few — into play.

How did we get from nanotechnology, with its focus on sustainable development, to the “catch-all” nanotechnologies we see today? This shift, which we will describe in the first chapter, is the result of complex political maneuverings involving vested interests, money and competition. Within the space of a few years, nanotechnology was diverted from its initial purpose. Today’s nanotechnologies, which employ the same technological principles as before the invention of the STM, push miniaturization to its limits and flirt with the nanometric scale. They have produced extraordinary devices a few tens of nanometers in size, but small as they are, these devices still contain several thousand atoms. We will describe these minimarvels in Chapter 2, which will retrace the key episodes in the adventure of miniaturization, a process often wrongly equated with nanotechnology.

In Chapter 3, we tell the true story of nanotechnology. Physicists have long dreamed of working with single atoms or molecules. With the STM, that dream has become a reality. They can now access a single molecule and study it as if by touch. The exploration of this material world at the bottom is only in its infancy. Physicists want to know whether the phenomena observed at this scale obey the laws we know or will force us to rethink our understanding of physics.

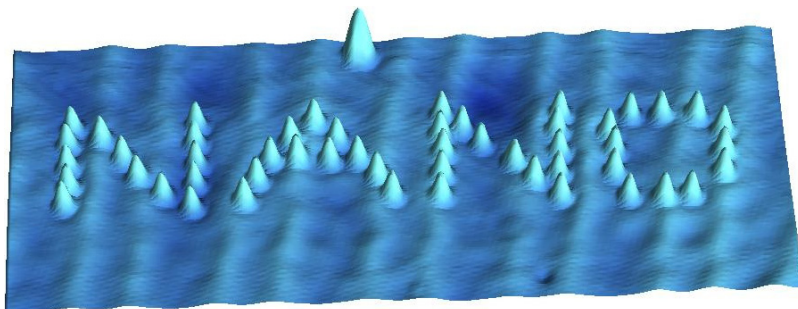
With the STM, it is in principle possible to build every kind of possible or conceivable molecular structure atom by atom. True, there is nothing new about synthesizing new molecules. Hundreds are produced every day in laboratories for use in colorings or drugs. However, these new molecules are manufactured by the billion (a single drop of water contains more than 1500 billion billion molecules!), whereas the molecule constructed at the tip of the STM is a single entity.

Equipped with the STM, physicists and chemists have an opportunity to design new molecules, to produce the tiniest of nanomachines, such as mechanical devices or computers. This bottom-up approach is promising: the workings of fantastic little machines made up of a single molecule have already been studied, and in Chapter 4 we will see what the next generations of such machines may look like.

One day, it will probably be possible to assemble larger structures, for example molecules from the living world such as DNA, together with proteins and membranes to enfold them. However, once this molecular apparatus has been assembled, what will happen? Does life lie at the end of monumentalization? Our fascination with life belongs to the sphere of the sacred. Where, in the monumental mass of atoms that constitute a cell, is the essence of life to be found? In Chapter 5, we will consider whether the fantasy of recreating life from nonliving matter has any chance of becoming a reality.

Nanotechnologies raise other disconcerting questions. Is there a risk that nanomachines could break free from our control? Might they be poisonous or damaging to the environment? Nanotechnologies arouse heated debate, but beyond that they raise questions about scientific progress, about the balance between the benefits and the risks of their applications. In Chapter 6, we will summarize these debates and consider whether there is anything to fear in the exploitation of the infinitely small.

The purpose of this book is to describe what nanotechnologies really are, and to consider their scientific and technical consequences. To do this, we need to rediscover the urge to know, which is such a characteristic feature of the human mind. We are more accustomed to directing that questing spirit toward stars and galaxies, toward the immensely large. But there are infinities too in a grain of sand.



Scanning-tunneling-microscope image of 51 gold atoms (plus one unidentified atom) deposited on the surface of a gold crystal. In this picture, the atoms look like small bumps 0.15 nanometers high (nanometer: one millionth of a millimeter). Each of the gold atoms has been moved by the tip of the microscope to write "NANO." The positioning precision is 0.05 nanometers and the smallest distance between two atoms of gold in the letters is 1.2 nanometers. This atom-by-atom image was produced for this book on a Createc low temperature microscope by Soe We-Hyo and Carlos Manzano, researchers in the "Atom Technology" group at the IMRE Institute of Singapore's A\*STAR agency, headed by the author. Real size of the image: 10 nanometers  $\times$  30 nanometers.