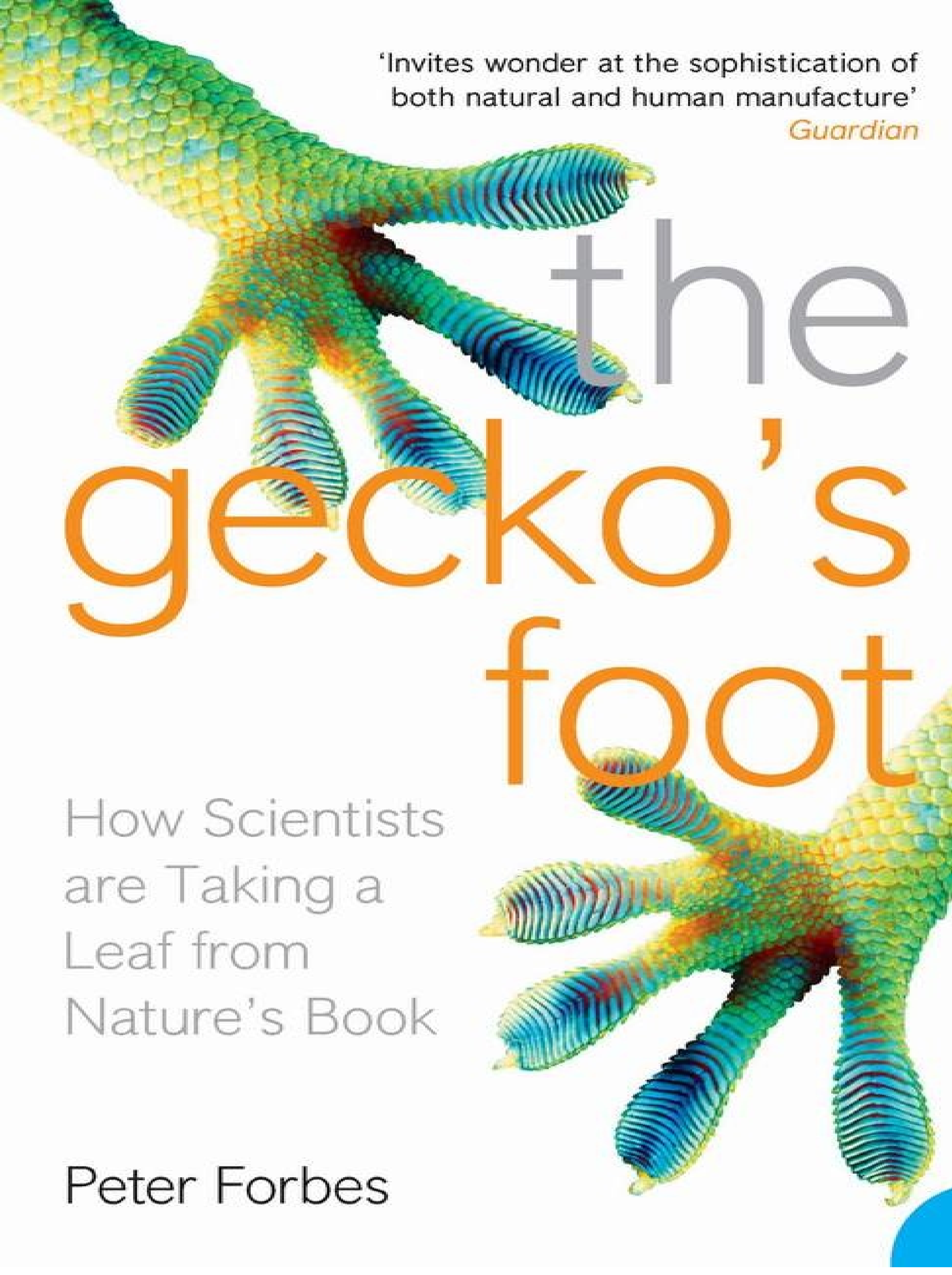
'Invites wonder at the sophistication of both natural and human manufacture'
Guardian

the gecko's foot

How Scientists are Taking a Leaf from Nature's Book



Peter Forbes

The Gecko's Foot

How Scientists are Taking a Leaf from Nature's Book

Peter Forbes

HARPER PERENNIAL
London, New York, Toronto and Sydney

In memory of my father
Leonard Harry Forbes (1916–1991)

Table of Contents

CHAPTER ONE
Something New Under the Sun

These *Atom-Worlds* found out, I would despise Colombus, and his vast Discoveries.
RICHARD LEIGH (1649–1728), 'Greatness in Little '

'Nature' is one of our great good words. To do things naturally, to go with the flow, to feel that we ar in harmony with the principle that has sustained life on the planet for, according to our best guesses, more than three and a half billion years: all of these are natural (that word again) aspirations. But when we think of how we actually live – by means of technology – we feel 'unnatural': all our activities seem to involve forcing nature to do things she would otherwise not have done. We fear tha perhaps we are a rogue species: the first one to have broken the bounds of nature.

These psychological feelings may or may not reflect the reality of our situation but there is no doubt that our technology and nature's are radically different. Our planes do not fly like birds and insects; although we travel faster than a cheetah, by muscle power alone we are much slower.

Many scientists now believe that it is possible for us to close the gap between our technology an nature. Bio-inspiration is the new science that seeks to use nature's principles to create things that evolution never achieved. To do this has entailed understanding nature at a new level – a tiny realm, far beneath our vision, and beneath the threshold of even the best optical microscopes.

Throughout human history human beings have been prejudiced creatures, and perhaps we were once biologically programmed to be that way. Despite this, we have learnt to cast aside narrow chauvinisms one by one and to embrace a broader view of our place in the scheme of things. But one set of blinkers remains: as adults we are creatures of a certain dimension – mostly 1.5–1.8 m tall – an we cannot help seeing things much smaller or larger than ourselves as remote from our experience. Apparently, we are deeply and stubbornly sizist.

The general acceptance, from the 17th century on, that the Earth was merely a planet of the Sun was supposed to have humbled our human pretensions. And the subsequent awareness of the vast distances of the universe, the number of stars (and, potentially, planets) and the minor-star status of the Sun were supposed to have increased this humiliation. The truth is, it is the things nearest to us that matter most. When we are ill in bed with flu, our horizon shrinks to our own body. And when we are bounding with health, it is pleasure on our own scale that we chase after. The universe can go run itself.

But this book is mostly about small things, not large, and they often seem even more distant tha the black holes and supernovae of the deep universe. We find it quite hard to understand that minute creatures such as fleas and midges are fully functional, with a nervous system, a brain, a heart, and al the apparatus of life. In fact, life begins way below the threshold of human vision, and the intricately structured apparatus on which life depends – DNA, proteins and countless other molecules – is much smaller still.

For most of human history we have fabricated the devices we need on our own scale from simpl materials, especially the metals such as iron, copper, zinc and tin. These are chemical elements and they are the same stuff all the way through – billions of atoms packed together like snooker balls in a frame, and then another layer on top, and so on *ad infinitum*. Biological materials, such as wood and cotton, have a much more complicated structure than metals and the intimate molecular structure of these materials was unknown until the 20th century. They were presented to us, more or less ready to use, and we used them without knowing what they were made from.

The microscope and telescope were both invented in the 17th century but it was the telescope th made the most impact. The telescope was always trained on some big new frontier – bigger ships, bigger factories, bigger armies – so it was something of a shock when the celebrated physicist Richar Feynman, in a talk of characteristic bravado given to the American Physical Society in 1959, announced that '[There's plenty of room at the bottom]'. By this he meant that even as we ran out of personal space in our human-scale world, there was a paradoxically spacious untapped domain in which our minds could roam, one that was beneath the threshold of our vision. This was the nanorealm, in which objects are between one billionth and one millionth of a metre in size. Feynman suggested that this realm had room enough to do many things of great interest, and that life was already doing them, if only we could see what was going on:

> This fact…that enormous amounts of information can be carried in an exceedingly small space…is, of course, well known to the biologists…All this information…whether we have brown eyes, or whether we think at all, or that in the embryo the jawbone should first develop with a little hole in the side so that later a nerve can grow through it…all this information is contained in a very tiny fraction of the cell in the form of long-chain DNA molecules in which approximately 50 atoms are used for one bit of information about the cell.
>
> It is very easy to answer many of the fundamental biological questions; you just *look at the thing!* You will see the order of bases in the chain; you will see the structure of the microsome. Unfortunately, the present microscope sees at a scale which is just a bit too crude. Make the microscope one hundred times more powerful, and many problems of biology would be made very much easier.

It must have seemed crazy to many at the time. Feynman blithely asserted that the whole of the *Encyclopaedia Britannica* could be stored on the head of a pin. Now we can believe this because even if we have not quite got it down to a pinhead, we are not far off with our electronic disk-storage systems. But the micro-electronics revolution was only the first stage of the drive into micro-space. A the time, Feynman looked to biology to make his point because he knew that nature did her most intricate work on a tiny scale. But he also knew that most of the detail was tantalizingly out of reach.

A gecko climbs a vertical glass wall sure-footedly; when it reaches the ceiling it steps onto it an continues, upside-down, without difficulty. From the other side of the glass you can see transverse bands of tissues crossing its feet that alternately grip and release in a mini Mexican wave across the surface of the foot. A leaf of the sacred lotus unfurls in muddy water; as it rises, all the mud rolls off as if magnetically repelled, leaving a pristine surface. From a quarter of a mile away you can see the brilliant blue wings of a *Morpho rhetenor* butterfly; they are not just blue – they shimmer with an iridescent sparkle – but analysis reveals no blue pigment in the wings. That same *Morpho* butterfly takes off and jinks through the air, changing direction abruptly; until 1996, scientists were at a loss t understand how insects like this could fly. According to the well-tried aerodynamic theories that took a Jumbo into the air or flew Concorde at twice the speed of sound, insects did not generate enough lif to fly, but fly they do. And when a heavy insect thuds into a spider's web constructed from filaments about one tenth the diameter of human hair, the web distorts, brings the fly to a standstill and then returns to its original shape, the fly held fast in its sticky capture threads. Human engineering sugges that even if such a gossamer structure could catch an insect, it ought to fling it out again in recoil.

~~These creatures obviously possess skills and attributes beyond conventional engineering.~~ But if we could find out how they achieve what they do, and learn how to utilize their techniques, it would extend our capabilities unimaginably. But the mechanisms behind these feats were hidden in structures so tiny that no microscope could observe them, and their chemical structures were so complex they defeated all attempts at analysis. As for creating man-made substances with the same properties: it was out of the question.

The dramatic powers of adhesion, self-cleaning, optical wizardry, tough elasticity and aerodynamics shown by these creatures are all highly prized by technologists. Scientists have long admired nature's engineering skills. Indeed, the precision of some of nature's gadgets takes the breat away: the stinging cells of jellyfishes; the jet engines of squids and cuttlefish; the marine creatures (and the land-based fireflies) that produce light without any heat. But there was no simple way of translating natural mechanisms into technical equivalents.

Nature was thought to use an entirely different set of principles to those of the engineer. Nature was soft and wet, worked at room temperature, and made her gadgets out of incredibly complex substances. While the human engineer instinctively reaches for metals to heat and beat into shape, nature goes for proteins that are grown inside living cells at body temperature. A single protein molecule is made from hundreds or thousands of smaller component molecules, virtually all of whic have to be in precisely the right place for the protein to work.[*] A protein molecule is first made as a long chain and then it folds up precisely into a three-dimensional ball, like a piece of wet origami.

Nanotechnology has brought nature and engineering far closer together. If Feynman's 1959 talk is seen as the beginning of nano-technology, natural mechanisms were taken to be the epitome of the science right from the beginning. And now we don't just stare at creatures in amazement, wondering 'How do they do it?' Thanks to genetic engineering and a host of new techniques, we can now start tc unravel nature's nanoengineering and produce engineered equivalents for it. This is bio-inspiration.

What makes bio-inspiration possible is the miracle that nature's mechanisms do not have to be 'alive' to work. In the 19th century, there was a doctrine known as 'vitalism' which held that all livir things had a magical property – the *élan vital* – that could not be reduced to material science. Even th waste products of living things were thought to be fundamentally different from mineral substances. The doctrine began to crumble in 1828 when the waste product urea was made in the laboratory from two ordinary chemicals of mineral origin. Thereafter, the idea of vitalism suffered blow after blow and now no scientist seriously believes that living things are, in a material sense, any more than the chemicals that comprise them. The property of life derives from the enormous complexity of the way the chemicals are organized, and not from an *élan vital*; some of the principles of this organization will become clear as the book proceeds.

Many of nature's most ingenious systems can continue to work outside living cells, in a test tub and can be directed to work in novel ways to suit our purposes. For instance, in 1997 it was discovere that, although proteins will never meet such substances in the living cell, in the laboratory they can bind to inorganic materials such as gold and silver. Not only that but new proteins can be engineered that can bind to all the materials used to make computer chips. And since proteins are structured on a much smaller scale than silicon chips, they could act as templates for smaller microchips – nanochip

Proteins have active centres, nooks and crannies precisely fashioned so that only one specific chemical can fit into them. When, in the whirling fluids of the cell, the one and only right chemical happens to come along, it becomes tightly bound to the protein. In living cells, proteins bind some chemicals, let others pass through pores, and, in general, regulate the traffic within the cell and facilitate chemical reactions. The full implications of this are spelt out in Chapter 6 but for now the ~~point is that we have come so far from vitalism that the old division between living and non-living~~ substances is breaking down – we can engineer hybrids between the two.

That there are no new frontiers is a weary cliché of our time: the ancient thrill of unspoiled plac on Earth has given way to the fact of life that people can and do fly anywhere anytime. The dream of new worlds in space has retreated in the face of the barrenness of the Moon and Mars; the glorious new dawn of modernism in the Arts in the early 20th century led only to the stylistic emporium of postmodernism in which any retro style could be taken up again for a few years, given a whirl, then dropped. The decadence and satiation of our world is only too apparent. Scientifically, we have gone very deep – into the nucleus of the atom and the genetic code of all life – so what can be left to discover?

Bio-inspiration is a genuine new frontier. It is a growing body of techniques for making materia with novel and startling properties: surfaces such as paint and glass that clean themselves, fabrics tha exhibit shimmering colour despite having no coloured pigments, fibres tougher (weight for weight) than nylon or steel based on spider silk, dry adhesives based on the microstructure of the gecko's foo

It is not just a new frontier because these properties are startling but because they have somethi in common. The mechanisms of most of these effects are caused by physical structures of a certain size: from one billionth of a metre up to one millionth of a metre (fig. 1.1). This is the nanoregion an the structures nature builds at this level we can call nature's nanostructures. Until recently, the nanorealm remained relatively inaccessible to science and this may seem strange since scientists are able to manipulate subatomic particles millions of times smaller. And chemistry, a precise science with a growing inventory of more than 24 million discrete substances, operates at the size range just *below* the nanoscale.

The key to this paradox is that there is a huge gap between what we can *infer* about the size of atoms and molecules (and their even smaller constituents – protons, electrons and the like) by elegantly indirect experiments in chemistry and physics, and what we can *see* with the aid of a microscope. The ability of microscopes to magnify the smallest features has improved immensely since their invention in the late 17th century but there is a limit that is set by the properties of light itself.

When light hits objects patterned at just below one thousandth of a millimetre (1 micrometre or 1,000 nanometres) strange things begin to happen to it. This is because light itself is patterned on the same dimension. Light is a wave motion, with the peaks of the waves repeating at just below the 1 micrometre mark. When the waves meet patterns of a similar size, they bounce off in ways that blur the picture. This is known as interference and in itself it plays an important role in bio-inspiration (*se* Chapter 5).

As far as microscopy goes, though, this is simply a nuisance. With the light microscope we can see living cells and some of their contents – bacteria, spermatozoa, etc – but not the complicated larg molecules that make up these structures.

Microscopy and chemistry began at more or less the same time in the late 17th century and closing the gap between them has been a long and tortuous business. At first, chemistry had nothing t do with size. The initial job was to identify which substances could not be broken down into anythin simpler – these are the elements such as hydrogen, carbon, oxygen, nitrogen, sulphur. It was a matte of speculation as to what was the smallest possible part of an element. The best theory going at the time was the Atomic Theory that suggested that elements were composed of millions of identical tin billiard-ball-like particles. For centuries, this was purely a theory. No one knew how large atoms we or if they really existed at all.

~~But, in the late 19th century, thanks to work on the pressure of gases,[*] it became possible to~~ estimate the size of these ‘atoms’ (by now most scientists accepted that they existed). The first accurate figure for the size of individual atoms was made in 1908. Atoms are very small – in fact the are just off the nanoscale. A typical small atom such as carbon is about 0.3 nm (nanometre) in diameter.

So, if atoms were less than 1 nm in size and the smallest object you could see with a microscope was 1,000 nm, what existed in this Blind Zone? To try to understand how much we were missing, imagine being able to see objects, say, up to 1 cm but nothing more until you get to 10 m. Most of what we make and live with lies within this range (micro-electronics excepted). The equivalent for nature is the region ten million times smaller – and this zone was inaccessible to us.

Peering into this realm in the early 1960s, we were as blind as the moles in a fable by the Czech immunologist and poet Miroslav Holub: his poem ‘Brief reflection on cats growing in trees’ imagine the moles trying to make sense of the world. Lookouts emerged at different times of day to report on the way things were above ground. The first scout saw a bird on a tree: ‘birds grow on trees’, he reported; the second found mewing cats in the branches: ‘cats grow on trees, not birds’. The conflict worried one of the elders, so up he went:

By then it was night and all was pitch-black.

Both schools are mistaken, the venerable mole declared.
Birds and cats are optical illusions produced
by the refraction of light. In fact, things above

Were the same as below, only the clay was less dense and
the upper roots of the trees were whispering something,
but only a little.

‘Things above were the same as things below’, or vice versa in our case. We had only our knowledge of chemistry at the bottom and the world of visible objects at the top to guide us. When w look around we can see only such objects as can be seen with eyes like ours. We make use of materia that we can grasp and manipulate to make objects on a scale that suits creatures around 1.5–1.8 m tal We may not like to think of ourselves as being as cramped in our perception as the moles, but on the scale of the universe, from quarks to galaxies, we are. In the scale of things, we are trillions of times larger than the smallest things known, evanescent subatomic particles, and trillions of times smaller than the largest cosmological objects known.

What exists in the Blind Zone are large molecules of complex non-random chemical compositic that are assembled to make the working structures of the cell: pumps and engines and factories for making everything the cells need, including copies of themselves. The contents of the Blind Zone comprise nature’s nanotechnology. And these are the nanomachines and structures we wish to harnes for our own purposes.

But how could the gap be closed? How could we see nature’s nanomachines at work? The answe was to nibble at the problem from both ends. As chemists gained in confidence throughout the 19th century, the chemical structures of some of the molecules used by living things began to be deduced: sugars, for instance, and the amino acids that are the ingredients of the fabulously complicated proteins. And as the 20th century progressed, the structures of larger and larger natural molecules were worked out.

Although the limitations of light microscopy were unbridgeable, even in theory, new techniques of investigation became available. By far the most important new investigative technique in the mid-20th century was the use of X-rays; with a wavelength thousands of times smaller than that of light (*see* fig. 5.2, page 105), these allow us to penetrate deep into molecules such as proteins. When X-ray hit molecules they produce complex reflection patterns that mirror the actual structure of the molecules themselves. Strangely, this reflection of X-rays is exactly the same property that sets a limit to light microscopy. The result of an X-ray analysis is not a photograph in the conventional sense. When X-rays hit a crystalline substance they are scattered in a regular geometric fashion and the patterns produced give information about the position of the atoms in the crystal. So this is not a picture so much as the result of complex mathematical analysis of data.

And it was a combination of chemistry and X-ray analysis that led to the greatest biological breakthrough of the 20th century, the elucidation of the double helix of DNA. The chemistry of DNA had already shown that it was composed of certain known substances: sugars and four different bases with these bases, intriguingly, seeming to be paired. In any DNA sample, from whatever source, there was always as much adenine as thymine and as much cytosine as guanine. With this knowledge, it wa possible for Watson and Crick to interpret the X-ray picture and to deduce the double helical structur

From the 1950s onwards, this technique – the combination of chemistry and X-ray analysis – allowed scientists to work out the structure of many significant biological molecules, especially proteins. However, X-ray techniques are limited by the fact that the specimen has to be a crystal, and many biological molecules cannot be crystallized. And also, we want to *see* the larger structures that the molecules make up.

In a sense, the beginning of a sustained interest in the nanorealm can be dated precisely, for it was on 29 December 1959 that Richard Feynman gave *that* talk. Feynman's was a rallying call and it was heeded first in solid-state physics, as the relentless development of ever smaller and more integrated electronic circuits began. Finally, the better microscope requested by Feynman did arrive and biologists were allowed a glimpse into the nanoworld. This was the scanning electron microscop (SEM), invented in 1965 by Cambridge Instruments after decades of pioneering work at Cambridge University. Since then, many more advanced electronic instruments, such as the atomic force microscope, have followed, and a battery of different techniques can be brought to bear on natural structures. Ron Fearing, fabricator of gecko tape and micro air vehicles at Berkeley, University of California, talks of the 'psychological barrier that was broken in the sixties with micro-machining, th atomic force microscope coming along. Before, people would have looked at these structures and sai "Oh, that's too small to know what's going on".'

The SEM was a big breakthrough and it has had huge consequences for bio-inspiration. The pictures revealed by the SEM look like engineering of an exquisite kind. The organs of minute insect and the parts of plants are revealed as wonderfully tooled artefacts. Bio-inspirationists constantly hav to track back and forth between the nanorealm and the everyday scale of things. According to the Russian novelist and serious amateur lepidopterist Vladimir Nabokov in *Speak, Memory*, this is an intrinsically artistic activity:

> There is, it would seem, in the dimensional scale of the world a kind of delicate meeting place between imagination and knowledge, a point arrived at by diminishing large things and enlarging small ones, that is intrinsically artistic.

When the first pictures were seen, the question of how nature achieved these wonders of micro-engineering was completely off the agenda – scientists could only goggle at the structures. But now we know a lot more about how nature creates such shapes. *The Gecko's Foot* is the story of how we a closing in on this last frontier of natural exploration.

The nanoworld is like a complex jigsaw puzzle in three dimensions. We try to piece it together b viewing it with different magnifications and techniques. Behind the picture we can see with the unaided eye, there is another picture we have to zoom in on with the light microscope; behind that is more detailed picture that we need the electron microscope to see; beyond that is the picture revealed by X-rays; and there are new types of microscope, such as the atomic tunnelling microscope, that all add information to the puzzle. To add to this, our knowledge of chemistry also sheds light on the three-dimensional structure. By combining all the information, we come to a picture that begins to approach completeness.

In retrospect, it seems curious that we have been ignorant for so long about *how nature makes stuff*. While we are pretty good at making intricate structures ourselves, when it comes to the miracle of the human body our role in the construction process is crude andlumbering. Anne Stevenson's poem '[The Spirit is too Blunt an Instrument]' makes this point:

> The spirit is too blunt an instrument
> to have made this baby.
> Nothing so unskilful as human passions
> could have managed the intricate
> exacting particulars…
>
> Observe the distinct eyelashes and sharp crescent
> fingernails, the shell-like complexity
> of the ear, with its firm involutions
> concentric in miniature to minute
> ossicles. Imagine the
> infinitesimal capillaries, the flawless connections
> of the lungs, the invisible neural filaments…

So, if not the spirit, what is nature's organizing principle? How does nature create intricate structures There is still much to learn and our own attempts at mimicking these processes are fumbling, but we are now on the trail.

To understand why the realm of bio-inspiration is such a *terra incognita*, something really new under the sun, we need to look at the two great currents of 20th-century science. So powerful were these two prongs of attack that many people were dazzled into thinking that they revealed all we needed to know about the material world. These sciences were nuclear physics and molecular biology Both ignored the multiplicity of the natural world – the several million species of living creatures (some estimates go as high as 30 million or more), all with different shapes, sizes, habits and curious adaptations; the more than 24 million known chemical combinations of the 92 natural elements; the architecture of matter in the honeycombs of the beehive, the fantastic filigree forms of the radiolarians of the ocean, and the interlocking spirals of a sunflower head. These were cast aside in th search for the ultimate, universal components and principles of matter (physics) and the chemical un and mechanism of genetic inheritance in biology.

The idea behind these quests was that if successful, they would somehow explain everything els And, of course, they *were* successful. Nuclear physics uncovered the unexpected power of nuclear forces and molecular biology determined the mechanism of inheritance: a precise sequence that has a chemical form (the DNA molecule) but which functions as a code for the synthesis of proteins, nature's prime functional substances.

But, dramatically brilliant as these sciences were, they left enormous gaps. They did not begin t explain complex forms of nature, nor did they determine the composition of these forms. What the physics and biology obscured was the fact that to create functioning organs, the fundamental building blocks of atoms and molecules have to be synthesized into large structures whose properties cannot really be explained by a knowledge of which molecules compose them. The biologist Helen Ghiradel wrote in 1991, just before the bio-inspired explosion:

> Many of us working in biological fields have perhaps unconsciously assumed that small things must be simple, at least more accessible to human understanding than those on a human scale. This may not be the case, and indeed, the further we investigate the more complexity we seem to find.

When, as a schoolboy in the early 1960s, I became fascinated by chemistry, what I wanted to know was: What are familiar objects made of? How is a tiny insect engineered from biological materials? What is the chemical structure of wood? What, in chemical terms, is a spider's web? In *The Periodic Table*, Primo Levi beautifully expressed this chemist's lust to know the fabric of the world:

> Everything around us was a mystery pressing to be revealed: the old wood of the benches, the sun's sphere beyond the window panes and the roofs, the vain flight of the pappus down in the June air. Would all the philosophers and all the armies of the world be able to construct this little fly?

But, at the time, chemistry had no answers to these questions. Whenever such structures and substances were mentioned in textbooks, the explanations petered out in sentences such as: 'The hardness of the insect skeleton is due to the chitin being impregnated with another substance, called sclerotin or cuticulin; but not much is known about it chemically.' There were some successes in getting close to nature. Nylon, for instance, invented in 1937, imitated the chemical bond of natural protein fibres, but natural proteins such as wool, silk and spider silk were known to be much more complex than nylon. While the nylon molecule has the same chemical unit, linked nose to tail thousands of times, natural silks have different amino acid units, linked nose to tail in a complex non random pattern. Despite a concerted effort over the last 20 years to determine the structure of, and replicate, spider silk, it is still not fully understood.

Although science has been successful in uncovering things not directly known to our senses, the mindset required to solve the problems of nuclear physics and genetic inheritance tends to be impatient of such questions as: What lies between the molecular realm and the objects we can see? The great early 20th-century nuclear physicist Sir Ernest Rutherford notoriously used to say that 'all science is either physics or stamp collecting'. But our new science has arisen largely from the very stamp collecting Rutherford despised – descriptive biology, investigations of the habits of strange creatures, comparative studies of the microstructures of leaves.

For a Rutherford, these meanders off the central pathway were expected to be explained fully by the fundamental laws of physics. And when his kind of particle physics was at the forefront in the mid-20th century, there were no techniques available to investigate larger-scale phenomena.

~~The atoms of physics and chemistry are very small~~ ~~(about one ten billionth of a metre in~~ diameter) and until 1971 this was far too small for any kind of microscope to see. Their size and properties were inferred from experiments on much larger quantities than single atoms: 1 gram of carbon contains about fifty thousand million million million atoms (usually written 5×10^{22} to avoid the cum-bersomeness of the expression). It was the triumph of chemistry that it was not necessary to see these tiny atoms in order to synthesize millions of new compounds whose precise structure is known.

This chemistry of inference, working in the dark, so to speak, was the chemistry I was taught at school in the 1960s – experiments were carried out with simple substances, stuff you could grasp and whose properties were clear. I might bubble carbon dioxide through limewater, say; the result was a white precipitate of solid matter. I could filter and dry this and the result would be calcium carbonate the chemical that chalk and limestone are made of. Running parallel to this palpable experience, the books would give you an equation for their reaction, in this case:

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$$

Like mathematical equations, these equations always balance because they represent the reactions between individual atoms and molecules, and nothing is ever lost in a chemical reaction. There is one calcium atom, four oxygens, two hydrogens, and one carbon on both sides of the equation. What happened in my test tube was this reaction, between individual calcium hydroxide and carbon dioxide molecules. And it was happening billions of times over to make enough of this substance for it to be visible to my eyes.

I chose this reaction as an example because the simple minerals of school chemistry, such as calcium carbonate and silicon dioxide, turn out to be capable of forming structures of architectural complexity in living systems, many of which are to be found in the deep oceans. The extreme conditions to be found there – intense pressure and little light, the dispersed nature of prey, the single medium of water – have inspired some ingenious devices. The romance of the oceans is epitomized b the Venus flower basket, a sea sponge and a baroque extravaganza of mineral basketwork so ornate that Joanna Aizenberg, the biomineralization expert at Bell Labs, who is studying it for its fibre-optical properties, cannot yet see how such a structure can grow from an egg. A new frontier indeed! To its beauty and mystery have now been added the fact that it possesses in the long hairs that surround the base of its latticework some brilliantly effective fibre-optic filaments. These, in human engineering terms, are the conduits used for high-capacity telephone and internet lines. The Venus flower basket has evolved these structures to manipulate what little light there is on the sea floor (at least we think it has – as with much else about the creature, biologists are not entirely sure).

Then there are the brittlestars, with primitive eyes that focus light through exquisitely engineere lenses made from single crystals of calcium carbonate (*see* Chapter 5). In these creatures, the crystallization of calcium carbonate is directed by proteins and this is one of the prime routes being explored in bio-inspiration: to direct the formation of engineered structures of minerals such as calcium carbonate and silica, using proteins, as nature does.

But simple chemistry was inadequate to explain how proteins organize minerals to produce thes complex forms. Proteins are, unlike calcium carbonate, very large molecules. The molecular weight o $CaCo_3$ is 100 D (D stands for 'Dalton' and is a measure of the relative mass of atoms and molecules, hydrogen being 1 Dalton) but a protein can contain thousands of different amino acid building blocks in one molecule, and the molecular weight might be 300,000 D.

~~Although attempts to derive engineering solutions from natural mechanisms have only begun~~ to be made in the last 15 years, earlier biologists came close to guessing their potential. Sir Alistair Hardy, in *The Open Sea* (1956), repeatedly marvelled at natural mechanisms as feats of engineering. This is Hardy on the stinging hairs found on many jellyfish:

> It is not a living thing; it is a dead structure, an elaborate tool made ready for work – and made to perfection – by the semi-fluid living substance of the cell. Here is something to wonder at, for it looks as if it were designed.

Behind this you feel the lurking suspicion that *we* ought to be able to design such a structure. In this case, we haven't yet done so but the action of biological springs like the jellyfish's sting is definitely on the bio-inspired agenda. Hardy has the true spirit of bio-inspiration before its time. My second-hand copy of *The Open Sea: The World of Plankton* (*The Open Sea* is in two volumes, one on the world of plankton, the other on fishes) has an interesting history. It is stamped inside: 'MoD Library Services: withdrawn from stock.' These days, the Ministry of Defence is a principal funder of work i bio-inspiration. I hope they have bought a new copy.

Bio-inspiration has an appeal denied to other cutting-edge sciences. Firstly, it involves some attractive creatures, adding an extra dimension to the allure of butterflies, geckos, lotus plants and th like. Then there is the utility of the products – this is a technology, not science for science's sake. Bio inspired solutions are often comprehensible in a way that much science is not: they involve structure whose functions are clear, even if they need a microscope to see them. Finally, some subjects of bio-inspiration are amenable to kitchen-table experimentation, as this book will demonstrate.

Inevitably with a new subject, there is some uncertainty about the boundaries of bio-inspiration. Scientists working in bio-inspiration generally fall into one of two camps: biomechanics or materials science. Biomechanics is concerned with large-scale mechanisms, such as how insects fly, materials science with fine-scale structure and chemical composition. It is worth remembering that, historicall these two disciplines come from very different traditions. The materials scientists prefer the term 'biomimetics' for this new subject but the biomechanics don't like this because it suggests to them a slavish copying of nature (*mimesis* = 'copying'). When he lectures, Professor Bob Full, the ebullient master of animal locomotion at Berkeley, University of California, even has a slide with a big red slash through the word: 'Biomimetics? No,' he says, 'Bio-inspiration is the way to do it.' In an important sense Full is right. Scientists try to unravel nature's mechanisms, but technologists use whatever will work. Bio-inspired technical products will almost certainly not mimic the actual materials used by nature. The self-cleaning Lotus-Effect® (*see* Chapter 2) is the most advanced of these techniques in terms of coming to market, with several products available, but it does not use th actual substances found in lotus leaves.

It is worth thinking about how nature and the human engineer went about producing their structures before we reached this point of rapprochement at which engineers are eager to learn from nature. Design in nature and in engineering are achieved by totally opposite methods. The human engineer can start from scratch, designing on paper something never seen before and then assemblin the parts until it is all connected up and ready to go. For example, for birds to reach their present sublime level of design, it has taken millions of years of evolution. In the 1940s, aeroplanes made th abrupt jump of moving to jet engines from piston engines that drive propellers. The jet engine was perfected by Frank Whittle between its invention in 1928 and the first flight in 1941. If nature had wanted to evolve towards something similar there would have been an intermediate creature that cou still fly by the old method while the new one was developing.

Bob Full makes the point like this: ‘If I told you to take my ‘84 Toyota and make it the fastest c possible using any material that you have, you could make a pretty fast car if you could replace 20 things. But you can’t throw away the whole genome and start from scratch. That’s a pretty heavy compromise.’

Put like this, it would seem that the human engineer holds all the aces. If, as a designer, nature i hobbled in this way, surely the human engineer ought to win hands down? But, despite her apparent constraints, nature has still produced devices for which engineers would give their eyeteeth. With regard to flight, for example, human aviation is impressive but in terms of manoeuvrability, the fly leaves a modern jet fighter standing, being able to turn a right angle at speed in only one twentieth of second.

We are fortunate that we can have it both ways, using nature when it has developed structures w can adapt, while at the same time retaining the engineer’s radical risk-taking advantage over evolution’s necessarily conservative processes.

There are times when it seems that bio-inspiration should be called ‘technomimetics’: only too often physicists, engineers or chemists invent something; biologists then discover that nature has already invented it (often hundreds of millions of years before), but the phenomenon itself was not known until discovered by the technologists! Obvious examples are echo-location in bats and sonar i whales and dolphins: before ultrasound was invented scientists could have dissected bats for eternity and still not understood their echo-location mechanism.

The most dramatic recent example has been the photonic crystal: a nanostructured crystal that will enable light to be guided at fantastic speeds through the crystal to create pathways in which information can be stored and manipulated. The photonic crystal was predicted as a theoretical possibility by physicists in 1987, first created technically in 1991, and discovered in butterflies and marine creatures in the late 1990s. In other areas, biological discovery has led to technical invention in the true spirit of bio-inspiration. In fact, in the case of the Lotus-Effect, once the biological effect was established – that some plant leaves have a micro-structure that produces highly developed wate repellency and self-cleaning – it was realized that physicists had produced a general theory to accour for this 50 years earlier, but its importance had not been recognized. Now, super-water repellency is respectable subject in many physics and materials science laboratories where you won’t find a leaf o any kind.

Bio-inspiration is not a narrow discipline. Origami was once thought merely to be an amusing game, nothing to do with science. Then mathematicians realized that it could be interesting to them, a branch of topology: the maths of shapes. Origami is used by nature because some structures such as leaves and wings need to be folded. Now whenever human engineers want to deploy structures (erect something that is usually kept folded), they look at the ways nature uses origami.

Although Primo Levi, the great Italian writer and chemist who died in 1987, did not live long enough to see the birth of bio-inspiration, he did have an abiding interest in the natural world. He was especially fascinated by insects and in his essays (*Other People’s Trades*) he said of beetles:

> These small flying fortresses, these portentous little machines, whose instincts were programmed one hundred million years ago, have nothing at all to do with us, they represent a totally different solution to the survival problem.

But beetles, like every other major group in the natural world, *do* have something to offer us. The flashing light of the firefly (a beetle despite the name) is caused by a chemical reaction that produces almost no heat and this has been mimicked to produce biomedical diagnostic tests. The Oxford zoologist Andrew Parker has discovered a desert beetle that has a novel way of capturing the sparse water that comes its way and this too will have technical applications.

And what of the bombardier beetle, a creature that seems to have anticipated many of the principles of human rocketry? It has a powerful defence mechanism that involves directing a hot irritant spray in the direction of an attacker. The chemical propellant for the spray turns out to be hydrogen peroxide, a well-known human rocket fuel. The peroxide is mixed with hydroquinones in a 'reaction chamber'; the reaction is hot (80°C) and the gases produced result in an explosive exhaust. The reaction chamber can be swivelled like a rocket motor to point towards the attacker. The whole business sounds far more like human technology than a natural creature. The more we know about beetles the more they seem to be little compendia of bio-inspirational properties.

Bio-inspiration can work across the whole size spectrum but there is no doubt that most of the work presently being carried out is in the former Blind Zone, the nanoregion. The idea that the properties of things as experienced by us derive from tiny structures goes back a very long way: back to the 5th-century-BC Greek philosophers Democritus and Leucippus who proposed the atomic theor of matter. Their ideas are known to us through the exuberant epic poem *De Rerum Natura* by the Roman poet Lucretius (*c.* 100–*c.* 55 BC). Lucretius would have loved bio-inspiration. He tried to answer fundamental questions: What is the world made of? Can matter be created or destroyed? Are conscious beings made of conscious stuff? How does life renew itself? And despite three centuries o modern science that would have astonished Lucretius, many everyday things remained unexplained until recently. As he makes clear in *De Rerum Natura*, he was aware of the mystery of nature's tiny functioning organs:

> How small can anything be? We know of creatures
> So tiny they would seem to disappear
> If they were less than half their present size.
> How big do you suppose their livers are?
> Their hearts? The pupils of their eyes? Their toes?
> Pretty minute you must admit.

Lucretius believed that the underlying particles of the material world could not have the same properties that appear to our eyes. They *had* to be colourless, odourless and tasteless (and lacking consciousness). It was a subtle idea; you might think that if you kept chopping something up until it was very small it would be the same all the way through – just smaller – but it was Lucretius's intuition (I refer to this as the Lucretian Leap) that, at the smallest scale, things just had to be different. In this sense, Lucretius and his forebears were the first nanotechnologists, although the subject had only a notional existence in their imaginations.

De Rerum Natura gives us, in a language all can understand, a passionate explanation of the way things are. Indeed, it is unfortunate that modern science has not proved amenable to the Lucretian treatment. But bio-inspiration is remarkably Lucretian in spirit. It answers simple bold questions about aspects of nature: Why is the lotus leaf always clean? How does the gecko walk upside down? How can a spider's web be stronger than steel? How can a fly of little brain be more manoeuvrable than a Eurofighter?

The answers to these questions are also Lucretian. Lucretius constantly argues that the *causes* of the ~~effects that we see are different in kind to the effects. This could almost be the first law of bio-~~ inspiration: the tidiest surfaces are the roughest at the nanolevel; the structures that cause the colour of the peacock's tail are *not* coloured; the hairs on the feet of the gecko are *not* sticky.

Take silk, a byword for slinkiness. But what is the gorgeous crackle it makes when you rub it against itself (known as 'scrooping') and what causes the colour changes when dyed silks are viewed from different angles? Early synthetic silks did not have these properties because the fibres were smooth and of rounded section. But under the SEM a natural silk fibre will be observed to have micro-structured rough edges – not at all what might be expected from the feel of it. When, in the 1980s, Japanese textile manufacturers realized this, at last they were able to make close synthetic copies of natural silks: they called them *Shin-Gosen* ('New Feel').

Lucretius was not the only poet whose imagination was caught by these natural phenomena. In his poem 'Greatness in Little', the 17th-century English poet Richard Leigh was intrigued by tiny things, long before such a fascination could be satisfied. At one point he bursts into praise of minuteness itself:

> Ah, happy littleness! That art thus blest,
> That greatest glories aspire to seem least.
>
> Even those installed in a higher sphere,
> The higher they are raised, the less appear…

Bio-inspiration usually works at the nanolevel, but that does not make it synonymous with nanotechnology. Most nanotechnology is not bio-inspired; it is the province of materials technology, comprising things like smaller electronic components and nanoparticles in cosmetics and systems for delivering targeted doses of drugs. Another name for bio-inspiration makes clear the distinction: bio-inspiration is 'nature's nanotechnology'.

What is especially interesting about nanotechnology and bio-inspiration is the existence of hybrid technologies – systems in which one part comes from technical nanotechnology and the other part from natural mechanisms. Our minds are attuned to an 'animal, vegetable, mineral' classification system and we generally assume that anything will belong to just one of these categories. One of the most dramatic discoveries of bio-inspiration is that technical components can be incorporated into natural systems.

Although cells never meet silicon chips or other electronics materials (which have only existed for 30–40 years) in nature, natural proteins can stick to silicon and other electronics materials and in doing so create structures on a much finer scale than would be possible for the technical materials alone.

Engineers make things by heating, beating and hacking them into shape; chemists make things by cooking up the ingredients; nature makes things through the DNA in the genes. The plan of every creature that exists is at some stage just a coded blueprint strung out along the double helix of DNA. Nature's way is by far the most subtle, accurate and fine scaled. It can be seen as a combination of engineering and chemistry. DNA is a chemical but it also has architecture – the double helix – and the substances DNA makes – proteins – also have architecture. They are both chemicals and pieces of nanoengineering.

To exploit DNA's design potential, bio-inspirationists use hybrid techniques of genetic engineering and silicon-chip fabrication. This may trouble some people – but nature does not recognize the division between organic and inorganic: gorgeous *inorganic* mineral shell structures ar produced under *organic* control. The rigid organic/inorganic divide is a product of the human mind, more specifically that of chemists who have put the labels 'Organic' and 'Inorganic' over the doors o departments which used to have very little to do with each other.

When I put it to Mehmet Sarikaya, the passionate advocate of this new hybrid technology, that some would see a Frankenstein element in it, he said: 'There will be more good happening than bad because human beings are fundamentally good people. What's at the back of this scientist's mind is: Can I have an impact on the early detection of cancer? Can I have an impact on assembling nanofibre for new nano-molecular devices? That's what we have in mind, that's why we work.'

Although bio-inspiration is still largely unfamiliar to a wide public, nanotechnology has already attained a certain notoriety. The idea is abroad that there is something inherently dangerous in the nanorealm. Michael Crichton's bestseller *Prey* (2002) imagines self-replicating nanorobots escaping from human control, learning rapidly and becoming ruthless predators. What lies behind this fantasy and does it have any credibility?

We have always lived in a nanoworld – our bodies and those of all living things are composed o biological nanomachines, and the dust in the air, pollen grains, smoke from all forms of combustion, contain nanoparticles – but like M. Jourdain in Molière's *Le Bourgeois Gentilhomme*, who was astonished to discover that he had been speaking prose all his life, we have only just woken up to the fact. And this has caused panic in some quarters. The idea behind *Prey* came from Eric Drexler's *Engines of Creation* (1986), which first put nanotechnology into the public arena. Drexler suggested that nano-technology would spawn self-replicating systems that might get out of control, thus swamping the world with a 'grey goo' of synthetic nanomaterial.

The idea of 'grey goo' took on a life of its own; it was resurrected in 2003 by Prince Charles in a speech warning of the dangers of nano-technology. But, in 2004, Drexler set the record straight, in ar article co-written with Chris Phoenix of the Centre for Responsible Nanotechnology, saying:

> Nanotechnology-based fabrication systems can be thoroughly non-biological and safe: such systems need have no ability to move about, use natural resources, or undergo incremental mutation. Moreover, self-replication is unnecessary; the development and use of highly productive systems of nanomachinery (nanofactories) need not involve the construction of autonomous self-replicating nanomachines.

Of course, the nanotechniques of bio-inspiration *are* biological but, when you look at what these techniques are, you will see that there is no way that their products could reproduce themselves and get out of control.

Even if nanotechnology is not going to swamp the world, many people remain concerned about some aspects of it. In 2004, the Royal Society and the Royal Academy of Engineering published a report on its benefits and possible dangers. The report stressed that while it would be wise to be wary of ingesting nano*particles* and releasing them to the environment without tests to ascertain what effects these substances can have, nano*structures* are a different matter. Nano*particles* are potentially dangerous on two counts: being so small they can enter cells by routes forbidden to larger particles and because they have such a large surface area relative to their volume their chemical and electrical properties are enhanced, which raises the possibility that they could trigger damaging reactions withi the cell. There is no reason to fear *solid* objects structured at the nanolevel: the world is full of solid nanostructures. All living things, including us, are necessarily nanostructured – made from atoms ~~which have to be assembled into nanostructures before they can make up anything large enough~~ to be seen.

The possibility of a hysterical reaction to things nano really came home to me when I visited the glassmakers Pilkington in St Helens, Merseyside, to discuss Activ™, their new self-cleaning glass, described in Chapter 2. Activ glass has a very thin coating on the surface that gives it self-cleaning properties. This coating is less than 20 nm thick. Kevin Sanderson, one of Activ's inventors, told me that they had received worried telephone calls asking, 'Are these nanoparticles on my Activ glass window going to fly off the surface and do me harm?' In fact, the nanolayer is bonded very strongly t the glass underneath, it is harder than glass and will last as long as the window does.

As for nanoparticles, there have always been and always will be nanoparticles in the environment: they are called dust. All forms of combustion produce huge clouds of them. The air in the London Underground is full of nanoparticles and some of them may even be carbon nanotubes, th most famous nanoparticle, created by the action of electric sparks from the live rails. It seems likely that the concern about nanoparticles being added to sunscreens and cosmetics will lead to new research on our *total* exposure to nanoparticles – from car exhausts and the Underground, to bonfires and barbecues.

Every new technology creates fear and resistance, but as far as it is known at all, bio-inspiration has had a good press to date. It has an eco-friendly feel to it, unlike the more hard-edged nanotechnology; but once its connection to nanotechnology becomes known – that bio-inspiration is mostly nanoscale technology – it will be damned by some through association. So it is important to stress that there is nothing wrong with nanotechnology *per se.*

But if nanotechnology induces fear in some people, in science it is also a buzzword: play the nanocard and you unlock the funders' purse strings. As a result, a lot of people have suddenly discovered that, in reality, they are doing nanotechnology. Physicist Andre Geim tells of engineers 'who never make anything smaller than 1 metre in diameter and now they're doing nanotechnology because they can *position* their things to within 1 nanometre accuracy!' As Geim says, 'Adam and Ev were nanotechnologists, they created everything from sperm, from DNA!'

Bio-inspiration arrives at a time when there is organicism in the air, especially with regard to architecture and design. The theme of Expo 2005, held in Aichi, Japan, from March to September 2005, was 'Nature's Wisdom'. Organicism is abroad in both the *Zeitgeist* of general culture and in materials science and there are connections between large-scale bio-inspired architecture and bio-inspired materials. Many architects want to design smart buildings and to use the new bio-inspired materials. The first really commercial application of bio-inspiration is in paint for the exteriors of buildings, using the Lotus-Effect, closely followed by Pilkington's self-cleaning Activ™ glass. And i other bio-inspired materials are not yet ready, there is no law against including organic curves in the shape of a building.

In September 2003, the *Zoomorphic* exhibition at the Victoria and Albert Museum recognized this new tendency in architecture, with structures based on many creatures, from sea sponges to dinosaurs. The archetypal figure is the Spanish engineer and architect Santiago Calatrava, creator of the Athens Olympic Stadium. Calatrava's buildings and bridges exhibit creaturely gestures rather tha mimicking specific creatures: there are moth-like antennae, forest canopy train-shed roofs, reptilian snouts, a whale's tail (or bird of prey's wings). After the turbulent history of architectural styles sinc the early 20th-century modernist revolution, organic architecture seems an attractive option. It uses the same materials as hi-tech architecture, and both organic and hi-tech architectures have their roots in geometry. Indeed, the key to all bio-inspiration is that nature and human artefacts are acted upon b the ~~same forces and they occupy the same three-dimensional world. And this is why similar solutions~~ are possible in each.

Alongside the architecture, in cars such as the Vauxhall Tigra, Ford Ka, Volkswagen New Beetl and the latest Nissan Micra, recent car design has also shown itself leaning towards organicism. The idea behind these cars is to be *expressive*: they sit unusually on the road, with the tail up, and the headlights styled as eyes, giving the impression of a face. These are cars whose moods you can read. In the case of the Vauxhall Tigra, the first of the breed, there is a resemblance to the warning display of an eyed hawkmoth – which is appropriate, because the hawkmoth displays large eye patterns on its wings, trying to look like a much larger and fiercer creature; similarly, the Tigra is a tame little Cors dressed up to be racy. Whether or not there is a *functional* reason for such large-scale organic structures (and often there is not) they belong to the new worldview that bio-inspiration has ushered in.

While writing this book, I have found myself watching insects in the garden far more closely. In fact, I wonder if I ever really noticed them before, other than on the increasingly rare occasions that a butterfly flew in. A sudden flurry in the corner of my eye and a garden spider is binding an already unrecognizable insect. Hoverflies punctuate the air around the *Coreopsis*. Two cabbage whites lurch across the garden in a mating dance. I realize that one of the reasons I used to be impervious to this micro-choreography is that it all seemed so impenetrable. How on earth did they do it? But, increasingly, we know, or if not, we know *how* we are going to know in a few years' time. Welcome t an Aladdin's cave of bio-inspired materials and devices.

CHAPTER TWO
The Great Sacred Lotus Cleans Up

Though buried deep
In the slime of the pool,
Unstained and untouched
You come forth to the world
Glorious in beauty,
Pure and serene:
Yet in your innocence
Oft you deceive us
Transforming the dew
On your life-giving leaves Into sparkling gems!

GONNOSKé KOMAI, 'To the Lotus-Bloom'

'Nooks and crannies harbour dirt,' we have always been told: a piece of folk wisdom scientists woulc not have bothered to dispute until some 15 years ago. But the self-cleaning powers of the sacred lotus plant – recognized and sanctified thousands of years ago in the East – have turned this on its head. Th lotus's secret is that its surface is *rough* at the micro- and nanolevels. It is almost embarrassing that such an elemental discovery should have waited so long to be made, but it has opened up for human use a new field of self-cleaning surfaces, utilizing the Lotus-Effect®.

Water skitters off a lotus leaf like drops of mercury – it doesn't spread and the globules it forms are highly spherical. So water doesn't last long on a lotus leaf. As for dirt, it seems to have a greater affinity for water than for the leaf so when it rains it is simply washed off.

There is a school of thought that science has still to rediscover the greater wisdom of the Ancients. In the case of the lotus, they are right. In ancient Eastern cultures, the lotus's immaculate emergence from muddy water was more than noticed: the plant became a symbol of the triumph of enlightenment over the dross of earthly life. So deeply does the lotus pervade Indian, Chinese and Japanese consciousness that the name is a byword for, and a guarantor of, purity. The most famous Buddhist chant, *Om mani padme hum*, translates as 'Behold! The jewel in the lotus', and the classic Buddhist texts are known collectively as the Threefold Lotus Sutra. The quest for spiritual cleanlines that runs through Buddhism derives from the lotus's example, so much so that images of cleaning recur in the texts:

> The Law is like water that washes off dirt. As a well, a pond, a stream, a river, a valley stream, a ditch, or a great sea, each alike effectively washes off all kinds of dirt, so the law-water effectively washes off the dirt of all delusions of living beings.
>
> *Innumerable Meaning Sutra*

While researching this book, I experienced my own lotus epiphany. I had flown from San Francisco t Seattle, and was en route from the airport to the University of Washington campus. It was a long day my trip was almost at an end and I was tired and anxious. I had to change buses in the middle of

Seattle’s downtown subway system. I emerged in the middle of Chinatown and walked into the neare café ~~for a bite to eat. In the middle of the counter, staring up at me, were lotus cakes. I ate one –~~ it tasted rather like chestnut – and a Proustian madeleine feeling came over me, although this was not for the recollection of time past but a kind of blessing on the future of my enterprise. I had risen fron the underworld of the subway system, in which the route to enlightenment – Washington University campus – was temporarily lost. The notion of sweetness

arising from dross is such a powerful one that once you know of the lotus you cannot help but refer to it: hence its omnipresence in East and South Asian cultures.

In the West, appreciation of the lotus is more aesthetic than spiritual: ‘No more stately plant adorns our gardens than lotuses,’ is a typical statement from an early 20th-century horticultural book on the water lilies.* Concerning the flowers, the book goes on: ‘These great blossoms are among the noblest products of the vegetable world. They fairly glow in the morning sunlight.’ With flowers 20–30 cm across, some of the leaves sit on the water, as water lily leaves do, and some stand 1 m from th surface. The water that collects on them is tossed back into the lake by the wind. In size they are dwarfed by the largest water lily, the *Victoria regia* from the Amazon, which was first brought to flower in England by Joseph Paxton in 1849, but the grace conferred by the lotus’s exceptional purity more than compensates for that. (Incidentally, *Victoria regia* also has a role in the development of bio-inspiration; Paxton, as the engineer of the Crystal Palace in 1851, was much influenced by its structure; *see* Chapter 9.)

I was not sure whether I had ever seen a lotus before I became interested in the Lotus-Effect: water lilies of course, but had some of these been lotuses? I went to the Botanic Gardens at Kew, London, to find out for myself. Lotus plants die down every year and in cultivation are replanted fror the runners that spread from the rhizomes rooted in the mud. At Kew in April they had plants of a variety of the American lotus, ‘Perry’s Giant Sunburst’, growing in tanks next to water lilies. Although it had a name redolent of out-of-town garden centres, nevertheless it was a real lotus: the leaves had that bluish bloom you see on some cabbage leaves. Dropping water on the lotus leaves wa like dropping mercury on the table. The water drops gleamed with internal reflection and skittered around like quicksilver (fig. 2.1).

The Lotus-Effect’s discoverer, Professor Wilhelm Barthlott, Director of the Nees-Institute for Biodiversity at Bonn, Germany, is unusual in pursuing parallel careers as a research botanist and as a patent-holding industrial inventor working closely with many industrial partners. ‘Technology transfer’ is a buzz phrase in universities these days, as governments try to kickstart economic growth by applying university expertise to the commercial world. The Lotus-Effect is a model of how it should be done.

Wilhelm Barthlott had no intention of becoming a technologist. He is a benign, avuncular and energetic man with bristling bottlebrush hair and a moustache that perhaps evoke some of plants he encounters. He has made a particular study of cacti and his interest in biodiversity stemmed from visits to Madagascar, where many of the plants are unique to the island. As often happens in life, Barthlott found the Lotus-Effect when he was looking for something else. Evolution was his obsessic and in those days – before the emergence of molecular biology in the early 1960s – evolutionary

relationships were studied purely by comparing the anatomy of creatures, especially their micro anatomy: pollen grains for example. So Barthlott spent a lot of time at the microscope.

But then the scanning electron microscope (SEM) arrived that was to transform his work and would ultimately lead to his discovery of the Lotus-Effect. The SEM, which came onto the market in 1965, uses television-style scanning to produce richly contoured images with the appearance of 3-D.

With the SEM, a wonderland of fine structure, as detailed as any architect's fantasy, came into view. The surface of plants is a strange other-worldly terrain. The outer surface does not consist of living cells but a non-living shell, the cuticle, covered in layers of waxes of varied composition. Sometimes the waxes are deposited on the surface in bizarre shapes (fig. 2.2). Through the microscop these structures often look more like animals than plants: *Virola surinamensis* seems to have miniature starfish nestling on a bed of waxy bobbles; the surface of *Colletia cruciata* resembles nothing so much as Anthony Gormley clay figurines, lolling about on the leaf; and *Williamodendron quadrilocellatum* has little piles of wax rings that could be a new form of pasta. Then there are miraculous architectural sweeps – the seed coat of *Lychnis viscaria* has plates that lock together like the tessellations of an Escher drawing. (Chapter 9 explores how structures like this have become important sources of inspiration for contemporary architects.) But most plants have bobbles like miniature topiary yew trees, with a frosting of waxy crystals on top.*

For a while, Barthlott was engrossed in the sheer beauty of these structures, but then something unexpected emerged. Specimens must be cleaned to be looked at in detail – at very high levels of magnification, contaminants can ruin the picture. But, in 1974, Barthlott realized that certain plants never seemed to need cleaning and that these, under the microscope, were always the ones with the roughest surfaces.

This was the beginning of a trail that was to take Barthlott far from his comparative studies of t structure of plants (although he is still highly productive in this field), into the world of technical production of a new invention. The full impact of the self-cleaning effect crept up on Barthlott over a long period: the early work, he says, was 'purely descriptive, without measurements'. He believed he had discovered something important in botany but 'it never occurred to me that it could be somethin new to physicists and materials scientists'.

So what is happening on the rough surfaces of those leaves? The self-cleaning effect depends on the relative 'wettability' of a leaf. Wettability is something we all recognize but scientifically it is something quite specific. On wettable surfaces, water drops are severely flattened and the contact angle that water makes with the surface of the leaf is very low (fig. 2.3). On a highly non-wetting surface, water forms near-spherical drops and the contact angle is very high – almost 180°.

When a surface has many tiny bumps, and these bumps are formed from a water-repellent substance, water drops 'sit' on top of the bumps, cushioned by the air in the space beneath them. The area of contact between the water and the surface is dramatically reduced by these bumps. The curiou properties of an array of bumps in providing a cushion for an object sitting on them is demonstrated by the 'magic' illusion of the Fakir-on-the-Bed-of-Nails. The mystery of how the fakir can bear to lie on the bed of nails is no mystery at all.

In a standard demonstration of the 'fakir effect', about 1,000 nails are punched through a plank big enough to lie on. Not only is it possible for a person to lie on the board, another board can be pile on top to create a sandwich, a breeze block placed on the recumbent's chest, and the block smashed with a hammer. (The only danger to the victim – and to the block smasher – is flying debris: goggles must *always* be worn in this experiment.) The weight of the body distributed over the 1,000 nails doe not exert enough force at the points to puncture the skin, although we intuitively feel that nails, however many there are, *must* be painful.

To translate from the large-scale world of the fakir down to the lotus surface: water drops sit on the points of the bumps, with the compression of the air in the cavities giving extra buoyancy. The self-cleaning effect occurs because when dirt lands on the surface it also has few points of contact. When rain falls, the dirt adheres to the water far better than it adheres to the surface and is carried of with the water, which rolls easily over the bumps (fig. 2.4).

In Barthlott's studies, the self-cleaning effect was most noticeable in the sacred lotus (*Nelumbo nucifera*). The plant had not been easy to cultivate in Germany but when Barthlott became Director o the Bonn Botanic Garden he set about providing himself with good specimens. Around 1988, Barthlo identified the lotus as the best exponent of the art of self-cleaning; it was a magical completion of an ancient story.

Given the mythical status of the lotus it would have been reasonable to assume that the effect wa peculiar to the plant, or at least to plant leaves of the lotus type. But Barthlott realized that the effect was a physical one and absolutely generic: *any* surface with bobbles of the right size, made from a water-repellent substance, would exhibit the same self-cleaning effect.

By 1988, Barthlott knew there was a technical product in view and he set out to interest the big chemical companies: 'the tribes along the Rhine', he calls them, 'those global players' (these are the major German chemical companies such as Bayer, Hoechst, BASF, Degussa). He had a party trick: h would squeeze some glue onto a leaf and show that it rolled off, leaving no trace behind. The hard-nosed industrialists refused to believe it. At first they assumed his glue was doctored and produced a tube of their own. The result was the same.

Surface-coatings specialists could not accept that they had anything to learn from plants: they said, 'Oh, it's something to do with living things.' After five years of frustration at the lack of industrial interest, Barthlott realized that he needed a technical demonstration of the self-cleaning effect, so he created the 'honey spoon', with a home-made micro-rough siliconized surface. When dipped into a honey pot, these spoons shed their entire load when tipped, leaving nothing behind (fig. 2.5). But this was a demonstration, not yet a technical product: 'It was very difficult to attach the lotu surface in a stable way, so all our home-made technical surfaces were not really intended for use. However, these first surfaces were a breakthrough: as soon as we could show them to industrial partners they were convinced. A living plant with even better properties did not have the same impact.'

Barthlott showed that not only could a botanist become a technical inventor but also that this botanist had fine PR antennae. He felt that the process needed something shorter and pithier to describe it than 'Self-cleaning Materials with Nanostructured Surfaces'. So, in 1992, Barthlott established the name Lotus-Effect® as a label for self-cleaning products. The lotus flower was the best example of the effect so lotus it had to be. Even so, at the time he did not realize quite how apt the name was:

> When I gave a talk to Indian students in '95 at the Humboldt Institute, they came to me afterwards and said: 'It's a symbol of purity in our religion'.
>
> I said, 'I know.'
>
> 'Do you know why?' they said. I had thought it was something esoteric – because Buddha hid under the leaves to protect himself, something like that – but no: you can find Chinese and Sanskrit poems describing the lotus, how it unfolds its leaves from dirt and muck, completely clean.

The Lotus-Effect officially entered the canon of Western inventions in July 1994 when Barthlott applied for a patent. Then, in 1997, came the classic summing up of the Lotus-Effect itself: 'Purity o the sacred lotus, or escape from contamination in biological surfaces.' This paper disclosed the Lotus Effect in full: the biology, the physics, the implications for plant ecology and the technical