Prologue

Imagine

The year Greta Garbo died of kidney failure in New York was the year I made up my mind to become a nanotechnologist. I was seventeen and Greta had me under her spell. Watching *Mata Hari,* I was beguiled, more devoted and unsuspecting than an ensnared Russian lieutenant. Mesmerized by the undulations of her hips, I wondered: Must I be content with just the dream of her? We knew so much about matter, more still about Greta, so why must it be absurd to imagine returning her to life? Not clone her, but construct her. Synthesize her, build her and bring her to life from the atom up. Merge elements, transforming chemical into human form.

The necessary ingredients were at my disposal. Ample visual account was available describing Greta's detailed structure—her architecture and furnishings. Vestiges of silver oxide particles passed or masked light, retelling the projection of her shape. Her voice reverberated in my memory. Lionel Barrymore must have had the presence of mind to record the smell of her hair swooshing under his nose. Her blueprints must be available for download: I could upload my lips to her cheek.

Greta lives on in matter as well as in memory. Now, fifteen years after her death, her particles still surround us. Elemental

Garbonium wafts through the air we breathe. Back then, Greta's molecules were organized into a complex, elegantly coordinated superstructure. Proteins manufactured from the blueprint of her delicious DNA put muscle, fat, and liver in their splendid places. Oxygen and glucose fed hot red blood, giving Greta energy, life … enchantment.

No, Greta was not gone. It was just that her atoms were in all the wrong places, spread around the earth, but still somewhere in the material world. I wanted Greta back, integral. Her every sensory endowment was archived and in the air were suspended the very elements which, appropriately arranged, had given her life. So why was I not dancing with Greta Garbo?

Living beings may be the most striking examples of the power of atoms, suitably organized, to yield a striking range of behavior, but they are not the only ones. Glass blocks bounce and bend light. Plastics flex while titanium bicycle frames gird. Hair coils and structural steel supports. Semiconductors conduct waves of electrons in harmonious concert. What if we could pick a property—bulletproofness, cancer-cell destructiveness—and specify and generate the molecules, and from these the materials, needed to implement our dream?

Some might seek to save lives using this astonishing power: create a device, fully integrated with the blood flow of the diabetic patient, to monitor and maintain blood sugar levels as in a healthy subject. Screen and filter cells continually for dangerous mutations. Remove pollutants from the air in our cities. Others might dream of taking lives: create new bullets so hard and streamlined that they could penetrate today's bulletproof vests. Build minuscule unmanned planes densely packed with explosives to bomb buildings. Engineer viruses that kill only the blue-eyed. Some might envision improving quality of life: create an active, hydrogen-powered muscle-suit that amplifies strength and finesse. Paint the walls of a room such that they display the real-time image of another place located far across the ocean, visually and aurally merging two homes separated by thousands of miles and obviating costly and polluting travel. Some might dream of improving their lives at others' expense: creating wireless tracking devices, microphones or cameras the size of dust, and puffing such imperceptible powders onto unsuspecting victims: e-stalking.

But enough fantasy—let's come back down to earth. Could we turn our dreams of tailoring matter to our needs into reality? It seems a tall order. We first need to measure: know which properties we experience and which atomic configurations a material possesses. Sense hair's bendiness and identify the atoms, molecules, and superstructures of which it is composed. Then we'd need to understand, trace out in full the relationships between structure and function. How does collagen's twist yield hair curly or straight? Next we'd need to invert the problem: place an order for hair not curly, but veering 90° to the southwest after each inch-long straightaway, and then specify the molecules to make it work its magic. Finally, we'd need to manufacture our molecules and induce them to curve as needed. They'd have to do the same thing every time, or, better yet, we'd need to architect them such that the occasional modest slip-up didn't ruin the overall effect. Here biological systems would inspire us at every turn, their every instance of an organism, each leaf and snail, not imperfect, only unique.

But today we analyze better than we synthesize, and that's the crux of the problem. Scientists deconstruct matter into its elemental constituents, but we are not yet able to trace out fully the links between the molecular—the nanoscopic—and the macroscopic realities we all encounter day by day. We can know the details of chemical composition intimately yet still not fully grasp how function arises from structure. Sequencing the human genome has not pinpointed the Garbo Allure gene. Height, disposition, and predilection are instead sprawled across abstruse molecules of DNA. For now, Garbonics remains a humanity, not a science.

Today we can marvel at Nature's glorious creations, but when it comes to designing our own using Nature's Lego blocks, we are all thumbs. Had we the benefit of an atom-by-atom plan of Greta's lush three-dimensional architecture, resolved with nanometer scale bar, we would still be unable to erect her. Both conceptually and chemically, we can neither fully explain nor build the links between the bottom—the arrangement of atoms that constitute matter—and the top—complexity, subtlety, function, and dysfunction. As we experience it today, macroscopic reality wends its way mysteriously out of nanoscopic form.

This is where nanotechnology comes in. Nanotechnologists have as their goal to design and build matter to order, specified by a functional requirement. Nanotechnology is coordinated movement, a choreographed dance among atoms and molecules to achieve a desired effect. It harmonizes within Nature's own set of rules to coax matter to assemble into new forms. The resulting materials exhibit striking beauty when viewed in an electron or optical microscope, often even with the naked eye. Their purpose: to produce breakthroughs in medicine, energy, and information.

Nanotechnology is not a new science. For four billion years, Nature has organized atoms into simple molecules; molecules into proteins; proteins and sugars and fats into complex societies of cells; and cells into the life that surrounds us. Nature builds using a finite array of atomic elements, the periodic table. She is rigorously disciplined, limiting herself to a small set of simple, but powerful, rules. Physics is simple but subtle, quantum mechanics pioneer Paul Ehrenfest used to say. With a modest set of elements deployed subject to rigorous rules, Nature invents limitless variety, beauty, form, and purpose.

For centuries scientists have exploited Nature's ready-made molecular assembly line. We have linked molecules to form long, perfect polymer chains with predictable properties, creating Tupperware and rubber tires. We have introduced lumps of imperfect, impure material into a vacuum chamber, let atoms evaporate, and grow from them strikingly perfect crystals of defined shape, size, and orientation. We have controlled how these designer materials produce light, conduct electricity, and respond to the touch.

Nanotechnology is an intersection—a confluence at the heart of contemporary science. It is where the latest breakthroughs in chemistry, physics, and biology merge, mix with engineering and medicine, and produce chips, diagnoses, and therapies that no sequestered specialist would generate. Nanotechnology produces convergent thinking when representatives of various mind-sets meet, learn one another's languages, and gather the ideas that result when paradigms collide.

Specialization evolved as a necessary response to science's rapid rise in the Renaissance. The tree of knowledge diverged into separate branches: chemistry, physics, biology. In the last century, each branch spread into twigs—biochemistry into pharmacology, drug discovery, pharmacotoxicity. Now the culture of research in the scientific, engineering and medical communities is undergoing a second renaissance. Researchers out in the twigs are recognizing that they all are connected to—nourished by—the same trunk. Mechanical engineers, are using nanometer-sized probes to pull on biochemists' proteins, studying their remarkable tensile properties. Electrical engineers are working with biologists to grow not just circuits, but cells, on a silicon chip. Information theorists are learning more about their field by observing with awe the native capacity of DNA to correct errors during transcription. Fundamental scientists, once focused narrowly on the quest for understanding in its purest form, are taking pride in changing people's lives through their research. Where once this rendered science impure, now it makes it personally as well as profoundly relevant. For their part, engineering and medical researchers are not waiting for scientific breakthroughs to mature into completely understood, fully controlled technologies before beginning to use them to create new therapies, diagnostic tools, and communications devices.

If we had a comprehensive understanding of how a given molecular form results in observable function, could we then construct materials, perfect down to the placement of atoms, which fit our structural requirements? In their techniques of building matter to a specification, nanotechnologists were once divided into two camps, the top-downs and the bottom-ups. "Top" lies at the summit of the hierarchy of function: the useful purpose endowed by a macroscopic property, the desired goal. "Bottom" refers to the smallest material-size scale imaginable, the realm of the atoms and molecules. Top-down and bottom-up nanotechnologists are both matchmakers for atoms and molecules, but they use different tactics.

Top-down nanotechnologists emerged from electrical engineering, the field that gave us the astonishing success of microelectronics in the second half of the twentieth century. Well before we accessed the nanometer, electrical engineers were systematically working their way down from the goal of producing a versatile, efficient, fast-computational engine, to specifying and manipulating matter, forming shapes of metal and semiconductors that, once connected, constituted the million-transistor integrated circuits inside our laptops. As of the 1960s, computer chips have been built using lithography, screen-printing that has allowed us to imprint forms as small as 100 nanometers. One-hundredth of a cell. One-thousandth of a human hair. One-ten-millionth the diameter of an elusive celluloid seductress like Greta Garbo.

From this tradition of top-down premeditated arrangement of matter emerged an early approach to nanotechnology. Fear catalyzed the process: would the powerful economic engine of information technology grind to a halt when engineers could not build circuits smaller than conventional lithography could imprint? Breakthroughs were needed to control morsels of matter smaller than 100 nanometers—though still much bigger than individual atoms and molecules. Engineers needed to develop the ability to craft matter on the nanoscale.

Long before the integrated circuit revolution, physicist Richard Feynman, the surfing, womanizing winner of the 1965 Nobel Prize in Physics, articulated what became the ultimate dream of the top-down camp. He gave his name to a family of—appropriately—sperm-like diagrams that describe fundamental interactions among elementary particles. He addressed the 1959 annual meeting of the American Physical Society in a talk titled "There's Plenty of Room at the Bottom." Feynman proved that, from the laws of physics and the known properties of matter, the entire twenty-four volumes of the *Encyclopaedia Britannica* could feasibly be written on the head of a pin. Four decades after Feynman's talk, Gerd Binnig and Heinrich Rohrer of the IBM Zürich Research Laboratory wrote the word *IBM,* atom by atom, using the scanning tunneling microscope for which they had won the 1986 Nobel Prize in physics. Had they kept writing, they could comfortably have fit the encyclopedia onto the tip—not the head—of their pin. Macropaedia, Micropaedia? Nanopaedia.

But does meticulous, self-conscious atom-arranging bring us closer to Greta Garbo? To push around carbon, oxygen, and nitrogen atoms to form 50 kilograms of luxurious closet-Swede is a major enterprise. The math tells the story:

{Mass of Greta Garbo ~ 50 kg} ÷ {Mass per carbon atom ~ 2×10^{-23} grams} = 2×10^{27} atoms to be arranged

Assemble a billion billion billion atoms? Even a team of twenty graduate students working full throttle—Igor and Sergei will each take a leg if Tung-Wah handles hands—could not hope to execute the project in the five years of a doctoral dissertation. That it would take longer than I am willing to wait is only a fraction of the problem. Would you trust an engineer to design Greta Garbo? When top-down atom-pushers design devices, circuits, and systems, they insist on explicit nanometer-scale control over what they will build. Intel engineers in ultra-clean fabrication facilities dress in canary-yellow spacesuits to prevent a single particle from alighting on your computer chip. There is centralized planning of every nanoacre. If one transistor goes off the grid, the computational engine grinds to a halt: the authorities insist upon rigid perfection.

In contradistinction, Nature builds imperfect things that work perfectly. Each maple leaf is atomically unique, but incontrovertibly a member of its class. Nature has no flaws, only miracles. Thus inspired, the new generation of nanotechnologists seeks to learn from and exploit self-organization of matter. Nobel laureate Jean-Marie Lehn spoke of the sociology of molecules: once we know how each molecule behaves, and how it interacts with its fellow citizens, we can predict the communities these molecules will form. From knowledge of the rules each molecule obeys, we can predict the emergence of the structure and function of a material—a molecular society and, ultimately, a material culture. Beating heart muscle. Pollutant-filtering molecular sponges. Energy-harvesting solar cells.

Let us embark upon a journey into the world of nanotechnology. Let us see how far we have come in persuading Nature to fashion matter after our needs, in using refined control over atoms, electrons, and photons to better human existence. Let us examine how the latest breakthroughs are revolutionizing human health, environment, and information. Humbled before Nature's achievements, let us inquire as to our own limitations, and contemplate what responsibilities arise in the face of our newfound abilities.