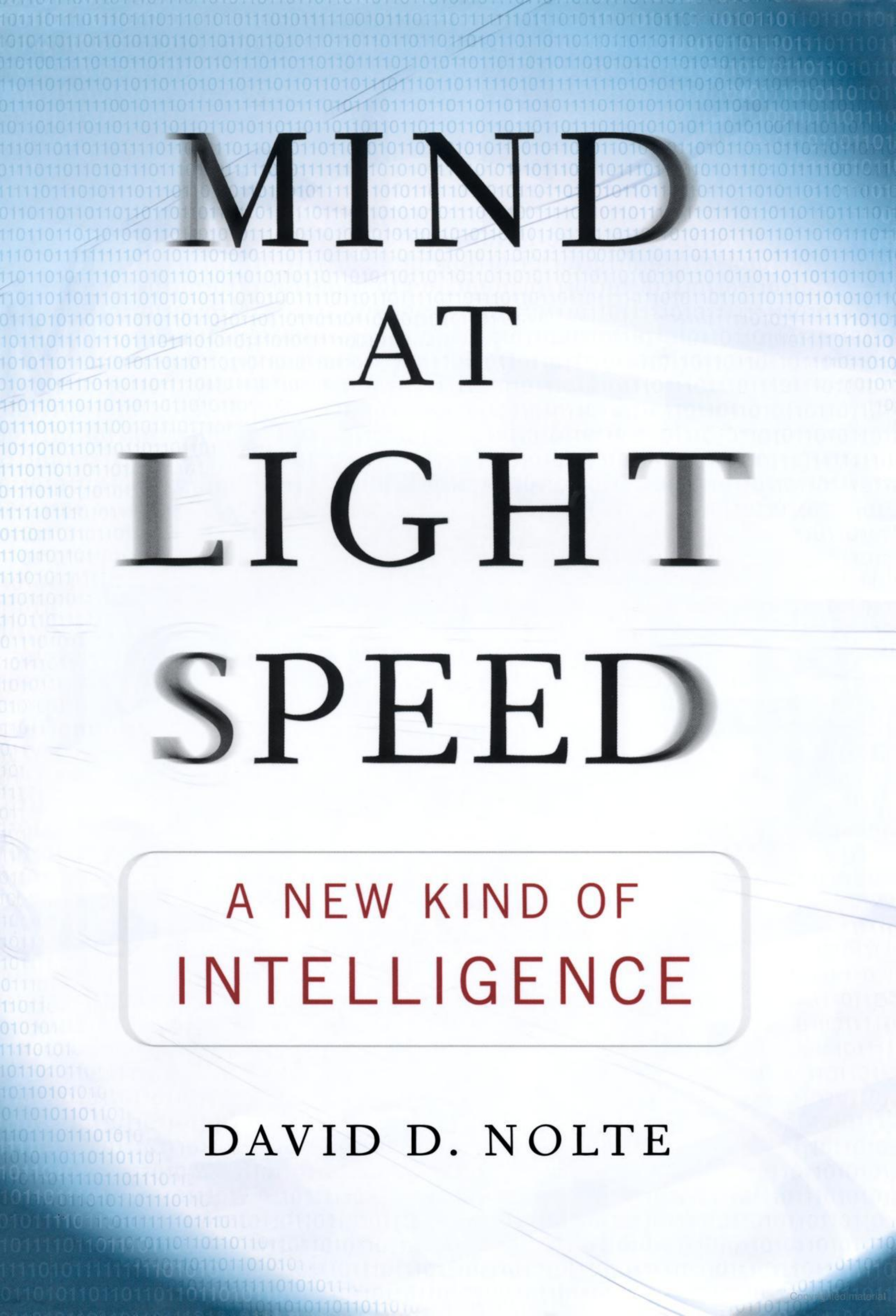

MIND AT LIGHT SPEED

A NEW KIND OF INTELLIGENCE

DAVID D. NOLTE

Mind at Light Speed

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CONTENTS

PREFACE

Light is the quintessential messenger. It travels faster than anything else can travel. It weighs nothing, and costs almost as little to make. A million rays of light carrying a thousand colors can travel along with each other or through each other without interacting, carrying data and commands between millions of locations. This capability is called the parallelism of light, and it represents massive communication and computational power. With it, machines of light will do a million things at once.

Indeed, visual information is streaming into our eyes and hitting our retinas at a rate over a billion bits per second. The need to feed the information-hungry eyes is one of the principal forces driving the exponential growth of information carried by the optical Internet. The desire for ever more sophisticated visual content puts demands on the Internet that can be solved only by using the parallelism of light moving in transparent glass fibers.

The optical revolution that began at the end of the twentieth century was launched by the human eye, but it will move far beyond serving simple human senses. The power of parallelism is the basis of whole new classes of machines of light. These will become ever faster. But faster intelligence is not a revolution—it is just more of the same. The real revolution will come when all-optical intelligence distributes itself over optical networks with light controlling light. The net will have a multiplicity of interconnections that rivals the complexity contained in human minds.

This book is a journey. It begins with the oldest (yet the most sophisticated) machine of light: the human eye. It ends by exploring the quantum optical computers that will be realized late in this new century. To reach that end it will take three generations of machines of light, which I introduce in chapter 2. The first is the Optoelectronic Generation that we are using now, supporting the optical Internet. The second is the All-Optical Generation, when light will control light and images become the units of information. The third and last is the Quantum Optical Generation, when quantum effects that defy classical logic will be used to transport (even teleport) quantum information and perform "uncomputable" computations in the wink of an eye.

What will these machines of light look like? How will they manipulate information? Will they have intelligence? These are some of the questions that I ask when exploring the structure of visual intelligence in chapter 3.

The neural networks of the human eye and brain are the most sophisticated image-processing machines that we know. They provide the starting point for artificial networks in optical machines. Detecting spatial features in a crowded scene is one of the simplest things our eyes and mind can do, yet it is one of the most challenging problems to artificial intelligence. Why? Our neurons are so slow. Our rate of reading is millions of times slower than the processing rates of our simple PCs. How can such slow machines as our minds perform so well? These questions are explored through chapters 4 and 5.

Which raises a tantalizing question: What if machines of light could tap into the parallelism of light without being hampered by human limitations? This is the challenge for the three generations of the machines of light. The Optoelectronic Generation, supporting the bandwidth explosion on the Internet, is described in chapter 6, followed by the migration to optical intelligence, described in chapter 7, when information as light controls light and intelligence on the Internet becomes distributed over more intelligent nodes than there are neurons in the human brain. What kind of intelligence will that represent?

To tap fully the parallelism of light requires that images become the units of information. What if the bit, a simple yes-no, is replaced by an entire image as the "unit" of information? In such machines, one image will tell another image what to do. Chapter 8 describes holographic machines that store information optically inside brilliantly clear crystals and that dream visually.

At the apex of optical evolution driven by parallelism will be the quantum optical computer. Nothing we have ever experienced can prepare us for the astronomical shift that quantum technology represents. What will become possible when quantum neural networks connect together through quantum teleportation across the Quantum Internet? The entire network will become a macroscopic quantum wavefunction. Will it be conscious?

These are questions raised on our journey from hieroglyphics, one of the first optical languages invented at the dawn of civilization, to the holographic quantum computers of the new century. Plug in your eyes.

1 The Glass Bead Game

Visual Knowledge

> THIS SAME ETERNAL IDEA, WHICH FOR US HAS BEEN EMBODIED IN THE GLASS BEAD GAME, HAS UNDERLAIN EVERY MOVEMENT OF MIND . . . WITH THE DREAM OF PAIRING THE LIVING BEAUTY OF THOUGHT AND ART WITH THE MAGICAL EXPRESSIVENESS OF THE EXACT SCIENCES.
>
> Hermann Hesse, *The Glass Bead Game, 1942*

Our lives are filled with images. Every day we see signals, read signs, and learn symbols. We find our way with maps, look for news and bargains in newspapers, calculate our bills and taxes. We turn printed music into wonderful sounds, often without conscious effort. Icons fill our churches, synagogues, and mosques, dot our computer screens, and are sprawled on billboards, on clothing and advertisement pages. Architecture and art conspire to fill our views with meaningful shapes and form. Pictures capture an instant in time, while movies and video entertain us with visual motion. We live in a visual world, full of information transmitted by light.

Writing is the verbal made visual, put into physical form as combinations of letters incised in clay or stone, or on a printed page, or on a computer screen. We understand the words as we see them because the visual impressions on our retinas ultimately connect with the language centers of our human brain. Similar mental processes occur for mathematics and music. Mathematical symbols represent something specific, some thought or quantity, or a relationship between abstract concepts. Notes on a score represent pitch and duration. We see the symbols, visually, and we know what they represent. But how do we know?

More neurons are used to transmit visual sensory information to the brain than for any of the other senses. The retina, the light-sensitive layer at the back of the eye, has a special status above all other sensory organs as a direct extension and outgrowth of the brain itself. In the early fetus, portions of the nascent forebrain extend forward to develop eventually into the eyes and retinas. The mature retina is composed of multiple interconnected layers of neurons that take the images coming into the eye and begin to analyze them for spatial relationships. After the retina performs considerable neural computation, the visual information is coded into electrochemical impulses that are the language of the brain and of intelligence. This all happens before the signals are even transmitted to the visual cortex of the brain. Thus, we already have intelligence in our eyes. Natural selection has driven the evolution of organisms that have sophisticated image acquisition and analysis capabilities because the visual image is an information format with significant advantages for survival. None of the other senses can give the type of explicit spatial information that eye and vision can, especially the ability to provide information about distant predators or prey. What is it about the image that makes it so informative?

A visual image such as a picture is a parallel data structure. That is, all points in the picture or scene either emit, transmit, or reflect light all at the same time—in parallel. A single square centimeter of a picture has well over a million points of light, all emitting together. When the image falls on the retina, a million micron-size receptive fields in the retina process and send information simultaneously to the brain. The parallel data rate on the optic nerve is over 1 megabyte per second—comparable to the data transfer rate of a computer hard drive. By considerable contrast, during oral communication the ear receives words one at a time—that is, serially—at the rate of only a few bytes per second. The parallel processing capability of the eyes, and their highly advanced structure and function, far exceeds the information speed that the serial mode of speech and ears can offer.

Is a picture worth a thousand words? What information is conveyed when a picture is seen compared to when a thousand words are read? Images carry texture and form, and above all provide spatial relationships "at a glance." They present a whole world to which language can only allude. Inevitably, we must ask: How can we better use the advantages of light and image?

THE GLASS BEAD GAME

The search for a universal language of visual symbols that can express the essence and subtleties of all knowledge has had a long and energetic history since the English philosopher Sir Francis Bacon (1561–1626) first suggested such a project. One of the early proponents of universal visual languages was the brilliant and influential German philosopher Gottfried Wilhelm Leibniz (1646–1716), who envisioned a universal "character" that could express all knowledge and act as an instrument of discovery to uncover new concepts and truths. At the time, hints that a universal language might be possible came from the growing awareness of Chinese character writing, as well as the rediscovery of Egyptian hieroglyphic writing. The opening up of the Far East and the growing infatuation with Egyptian artifacts presented European scholars with a treasure of mind-expanding possibilities. There was an impression (albeit false) that the hieroglyphs represented things directly, and were divorced from the peculiarities of the spoken language. The existence of these forms of writing was cited as proof that a universal language was possible, which could impart ideas and concepts directly (visually) through written characters. The difficulty was in finding an efficient means to do this.

Leibniz outlined the goals of the project in his *Dissertatio de arte combinatoria* of 1666. Many of his activities related to the project, even his development of the calculus. He corresponded extensively with Johann Bernoulli (1667–1748), a co-inventor of the calculus, to discuss fine points of notation, striving to find the most consistent and efficient set of visual symbols to express the calculus. The standardized notation we use today for calculus was contributed almost exclusively by Leibniz, superseding the English physicist Isaac Newton's (1643–1727) clumsy notation developed at the same time. But Leibniz was unable to find the time in a busy life to tackle the problem of a more general universal language. Others took up the call.

In the Twentieth Century, the psychologist Carl Jung (1875–1961) strove for universality with his symbols of transformation, and in an altogether different sphere the English logician and philosopher Bertrand Russell (1872–1970) and the English mathematician and logician Alfred North Whitehead (1861–1947) strove for the same thing with the symbolic logic they developed.

Yet the most imaginative picture of the potential of light and image was painted by the twentieth century Nobel Prize winning novelist Hermann Hesse (1877–1962). The novel *Die Glasperlenspiel* (The Glass Bead Game) was the last novel of the author and led to his receiving the Nobel prize in literature in 1946. Hermann Hesse was born in 1877 in the southern German town of Calw by the edge of the Black Forest. As a young man, he developed a voracious appetite for literature as he worked in bookshops in Tübingen and later in Basel, Switzerland. Always a loner and outsider, he immersed himself in books and began a literary career. His first novel, published in 1904 when he was twenty-seven years old, was *Peter Camenzind.* This novel brought the unknown writer rapid fame and won for him the Bauernfeld Prize of Vienna. He married Maria Bernoulli (of the famous mathematical Bernoulli family) the same year. The following years brought more literary success as Hesse explored the inner turmoil of his youth in his literature.

Hesse became acquainted with the theories of Carl Jung, which had a profound influence on his life and writing. In particular, Hesse was fascinated by Jung's ideas concerning dreams and universal symbols. As more novels followed, including *Demian, Siddhartha, Steppenwolf,* and *The Journey to the East,* Hesse's writing progressively looked inward, with increasing emphasis on symbolism and vivid imagery. The culmination of his inward growth appeared in 1942, at the age of sixty-five, with *Das Glasperlenspiel (The Glass Bead Game).*

The novel describes a utopian intellectual community called the Order, which occupies itself with the study and playing of the Glass Bead Game. This monastic community exists in some future time, in a country named Castilia that is dedicated solely to the purposes of the Order and of the Game. The story of the Game, and in particular of Joseph Knecht, the Master of the Game, known as the Magister Ludi, unfolds through the narrative of a fictitious biographer.

The Game is an idealized version of the universal language envisioned by Leibniz. The narrator tells how the fictitious originator of the Game "invented for the Glass Bead Game the principles of a new language, a language of symbols and formulas, in which mathematics and music played an equal part, so that it became possible to combine astronomical and musical formulas, to reduce mathematics and music to a common denominator." Within this Game, abstract concepts are represented by a set of glass beads, or icons. The visual and spatial arrangement of these beads by players allows all aspects of human knowledge to be related one to another: mathematics to art, music to astronomy, philosophy to architecture, and infinite combinations of these. The winner of the Game was the player who succeeded in weaving the most striking or surprising connections and themes among seemingly disparate concepts. Though fanciful, the Glass Bead Game is a model for the visual representation of knowledge.

A quote from Leibniz in 1678, three centuries before, evokes the spirit of the Game: "The true method should furnish us with an Ariadne's thread, that is to say, with a certain sensible and palpable medium, which will guide the mind as do the lines drawn in geometry and the formulas for operations, which are laid down for the learner in arithmetic." It is easy to imagine Leibniz as the Magister Ludi conducting a sublime Glass Bead Game, the players forming threads of colored glass beads, this one representing a theorem of logic, that one an astronomical observation, and between them a musical theme branching to a mathematical formula—all interrelated, all sharing common forms that span the breadth of human knowledge condensed into symbols.

The importance of the Glass Bead Game is not the physical implementation of a set of rules that defines a game. In fact, Hesse was careful never to describe the actual rules by which the Game was played. Furthermore, it must be admitted that universal language schemes (and there have been many) all have failed by being too cumbersome and naive. However, the profound idea at the heart of the Glass Bead Game is that symbols and rules can be visual and that knowledge can be represented and manipulated visually. The Glass Bead Game is an allegory of a new optical language, the language of light and image needed to run the architecture of the future machines of light. This book explores those machines in which the language of the Glass Bead Game is about to become a reality.

THE HUMAN BOTTLENECK

The measure of any technology is the degree to which we live better by it. This may be posited as the principal thesis of technological humanism. One way that we live better is by reassigning human tasks to alternative agents. James Bailey, in his book *After Thought,* writes about successive stages of reassignment of human tasks. In the first stage, we reassigned our muscle tasks to animals. Horses provided transportation and oxen pulled our carts.

Thus, this stage is not the revolution that some make it out to be. Mathematical computation is noticeably sped up by machines, but the calculations themselves remain the same as we would do by hand. The speed of solution has increased beyond human capability, but the structure has not. The real revolution is beginning only now as the reassigned mind tasks evolve beyond human design by using adaptive and genetic algorithms that change their own structure in response to changing inputs, without human intervention. Such algorithms have the potential to evolve into intelligent systems with no human analog—possibly evolving beyond human comprehension.

Part of this revolution in intelligent model building is the current interest in artificial neural networks based loosely on the structures of biological systems. Scientists have analyzed how the functions of the brain are distributed over neurons, and are trying to translate those structures into electronic or photonic models. Networks of nodes and their interconnections mimic some of the structure of biological networks of neurons and their synapses. However, it is an open question whether mimicking the brain's structure is sufficient to produce an "intelligent" system. Biological model building is still in an early stage of development, with significant work ahead. Furthermore, basing intelligence on the biological neurological model may not be the best solution. Newer, non-biological technologies (such as optical technology) may have more to offer.

Optical technology is primed to change intelligent model building. The advantage of the optical computer is its massive parallelism. For a digital computer, the unit of information is the binary unit, known as the "bit." For every tick of the internal clock, only a handful of bits are processed even in the most advanced electronic computers. The bit does not carry much weight: only a "yes" or "no" answer. In some types of optical computer, on the other hand, the unit of information is an image. For every tick of the internal clock, the entire image, with all the information in it, is processed all at once. The parallelism of the image improves the data rate enormously.

If the single advantage of optical computers were in parallel processing, then it would still not be the revolution. Higher data rates may mean more computing power but they do not represent expanded function. Optical computers promise something more. They promise abstract and associative "reasoning," based on images and symbols that exist within a language of spatial and spectral (color) relationships. For an optical computer, a picture may well be worth *more* than a thousand words. A picture may be the program that tells the computer what functions it must perform and what concepts must be employed.

The rudimentary and specialized optical computers built so far in the laboratory are not the flexible, programmable machines that will be able to make conjectures and leaps of imagination. Some of the current limitations have been in materials and in technology. More importantly, a fundamental new architecture must be designed for the next-generation machines of light. The new architecture will need a new language in which to express itself. It must be an optical language, where images are like words and the grammar is made up of visual projections and associations; we will need something akin to the language of the Glass Bead Game.

THE ARCHITECTURE OF LIGHT

Three basic themes are crucial to understanding our own intelligence and how we can go beyond with the next-generation machines of light. First, all manners of human communication, whether audible through speaking and listening, whether visual through writing and reading or the use of sign language by the deaf, or whether tactile through the use of Braille, share a common rate for comprehension that is limited by biological physiology. I call this the Human Comprehension Bottleneck. All communication channels must pass through the same cognitive centers of the brain to provide the ability to make informed decisions.

Second, images and words cannot be equivalent (even when considering the same written and spoken word), because the visual and auditory channels use different media that initially access different parts of the brain. Specifically, the visual channel is a massively parallel data channel which has unique attributes and advantages that far outstrip verbal and serial communication—if only they can be accessed. I call this the Parallel Advantage of Light and Image.

Third, and finally, the biological and physiological limitations underlying the Human Comprehension Bottleneck need not be machine limitations. We can build machines that can perform functions that we cannot. Speed alone is not such an advance. Rather, new machine architectures will utilize information in ways that go beyond human capabilities. This process of searching for new visual architectures based on a visual language of spatial and spectral relationships may allow machines to find new ways of thinking that utilize the Parallel Advantage of Light and Image. That new computational structure will be the Architecture of Light, the guiding principal that shapes the three generations of the machines of light.

2 Three Generations of Machines of Light

The Paradigm

> I CAN PROMISE YOU FOUR WORKS, THE FIRST OF WHICH I WILL SOON BE ABLE TO SEND YOU. . . . IT DEALS WITH RADIATION AND THE ENERGY CHARACTERISTICS OF LIGHT AND IS VERY REVOLUTIONARY, AS YOU WILL SEE. . . .
>
> *Albert Einstein, 1905*

We are already running at light speed. Pick up a telephone and your voice is carried as pulses of light (for at least part of the journey) along delicate strands of glass. The revolution in fiber-optic telecommunications was a rapid one, taking only a little over two decades at the end of the twentieth century to replace most long-haul copper wire with over 100 million kilometers of fiber that, in some places, led all the way to the home. Go to the store, and laser scanners read the universal product code (UPC) and immediately adjust the inventory. Play your CDs, and a tiny laser reads millions of bits that represent full symphonies, reconstructing nearly perfect sound. Watch your DVD movies, and the laser reads billions of bits that are sent to your TV or computer screen, where active pixels modulate light so fast that the separate frames blend into an apparent continuum of motion.

All these activities belong to the first generation of the machines of light, the Optoelectronic Generation (shown in the figure, p. 13), which uses electrons to generate photons, and photons to generate electrons, converting back and forth to use the best advantages of each. We are well into this generation. It began in 1960 with the invention of the laser and later merged with silicon electronics to sustain the Information Age and the Internet's ever-increasing demand for more data at higher speeds. Optical fibers draw ever closer to the home, where video on demand will become commonplace and fibers will enter directly into personal computers. Inside those computers, information will no longer be entirely electronic, but will include optical data streams—first connecting circuit board to circuit board and eventually chip to chip—forming hybrid optoelectronic processors where light and electronics perform separate functions, each using its own talents: electronics for fast logic (still digital), and light for the collection, dispersal, and routing of data.

The second generation of the machines of light is beginning now at the turn of the twenty-first century. This is the All-Optical Generation, which forgoes electronics and uses light to control light. All-optical fiber-optic communication networks will use laser beams to modulate other laser beams, sharing information and directing each other to different destinations depending on the information encoded on the light beams. Information will be stored in three-dimensional volumes as minuscule changes in the optical properties of holographic memory crystals. The vast three-dimensional storage capabilities of such crystals will further enhance our ability to access astronomical amounts of information at the instant we want it. With all this information to sift through, specialized optical computers will go beyond serial digital information and use the Advantage of Light and Image to manipulate and filter information as parallel images at speeds inaccessible to electronics.

The third generation of the machines of light will be the Quantum Optical Generation, which relies on the unusual physics of quanta, the smallest units of mass and energy. This generation will use the quantum nature of the photon to encode quantum bits (called qubits) that have no classical analog. By using qubits, quantum cryptography will make it possible to send information over optical fibers perfectly immune to eavesdropping by third-party information pirates. Harness quantum parallelism to solve problems in minutes that would otherwise occupy classical computers for the age of the universe will make classical cryptography obsolete by using parallelism to factor large prime numbers on which classical encryption is based. Such developments will further drive information transmission and communication into the secure quantum optical regime. Perhaps by the end of the twenty-first century, all information will be in quantum qubits, and the classical bit will be as archaic as a telegraph key is to us today.

These three generations are worthy descendants of the quintessential machine of light born of natural evolution—the eye. The eyes are themselves intelligent. There are more neurons and neural connections within light did little more than cast light—passively illuminating the dark. After that time, light has increasingly *done* things, actively participating in optical machines.

The properties of lasers that have drawn popular attention are their brightness and fine focus. Laser beam weapons are a favorite attention-getter of technology reporters. As recently as the Strategic Defense Initiative (also known as "Star Wars"), laser beams were touted as directed energy weapons that would shoot down enemy missiles. However, these popular notions of lasers are neither realistic nor even relevant to their actual unique attributes that have fueled the optics revolution. Lasers have two special properties that are not commonly experienced and that make them truly revolutionary. First, they generate "coherent" light; and second, they are quantum devices.

What is "coherent" light and how is it useful? Coherence is a way of describing how multiple waves add together, such as the addition of one light wave to another. The crowning achievement of electrodynamics in the nineteenth century by the English physicist James Clerk Maxwell (1831–1879) was the realization that light is composed of intimately interlinked electric and magnetic fields that propagate as waves through space. The electric fields in the waves induce magnetic fields that in turn reinduce electric fields. This give-and-take between electric energy and magnetic energy sustains itself as a freely traveling disturbance (wave) that propagates indefinitely (unless it interacts with matter).

Electromagnetic waves can have any wavelength. We use waves with wavelengths of centimeters to heat our food in microwave ovens. We feel the radiated warmth of the Sun as infrared waves with wavelengths of only a fraction of a millimeter. Visible light is composed of electromagnetic waves with wavelengths of about half a micron (1 micron is one millionth of a meter). Ultraviolet light at wavelengths shorter than that burns our skin at the beach, even on overcast days. Doctors and dentists use electromagnetic waves with wavelengths that are a thousand times smaller (or only the size of single atoms) to look through our bodies using X-rays. The furthest reaches of space are measured by astronomers reading the discrete pulses of gamma rays with wavelengths the size of atomic nuclei.

All these waves behave quite differently and interact with matter in seemingly unrelated ways. You cannot feel the "warmth" of X rays, but you feel the warmth of the Sun. You cannot see intense infrared or ultraviolet energy, but you can navigate by dim moonlight. You cannot put metal in a microwave oven without generating sparks, but you use metallic mirrors every day in bright sunlight. The only difference between these very different waves is their wavelength; in all other aspects, the physics of these waves is identical. But let us return to visible light.

We see light in the visible range of the electromagnetic spectrum. The wavelengths that excite the retina in human eyes vary from about 0.4 microns (violet) to 0.7 microns (red). Green light, with a wavelength of around 0.5 microns, is near the center of the visible spectrum. It is no accident that precisely this band of wavelengths from the Sun is most efficiently transmitted through the Earth's atmosphere. Wavelengths longer than red and shorter than violet are attenuated by water vapor or ozone in the air and do not make it down to the Earth's surface in appreciable intensities. Only the visible light makes it through. Our retinas have evolved to be sensitive to the colors that are brightest at the Earth's surface and that form our "rainbow" spectrum.

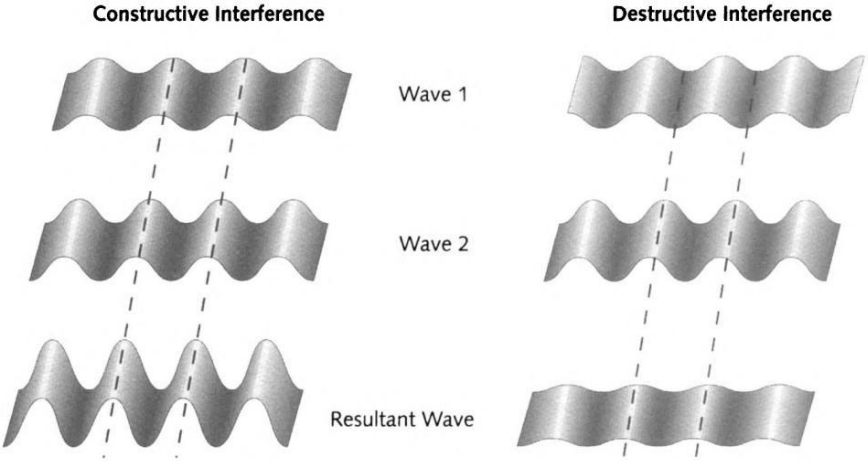
When we look at light in this visible spectral bandwidth, we see intensity, but we cannot see coherence. For instance, when you look at a red light bulb on a Christmas tree, and compare it with the red laser beam of a checkout laser scanner, they may seem more or less the same. But there is a major difference. And it is one of coherence.

Although it is difficult to illustrate coherent light waves, coherent waves of other kinds are quite common and easily visualized. If you throw a stone into a smooth pond, it generates regular circular wavefronts that propagate outward from the point where the stone disappeared. The wave is composed of several crests separated by troughs with a regular spacing between them. These waves are coherent because all the water molecules on the surface of the pond experience the same regular periodic motion as the wave passes by.

But imagine a lake during a fierce summer squall. The surface of the lake is choppy and chaotic. Crests and troughs abound, but with no regular patterns. Waves are present in all sizes and heights, some as big as a boat, others as small as a drop of rain. All the water molecules experience simultaneous, but unrelated motion. If you watch a navigation buoy or a float on a fishing line in this turmoil, it has no discernible regular pattern of movement. That is incoherence. The light from a light bulb is like storm waves on a lake. The bulb emits many different wavelengths into random directions with random crests and troughs (in the electric or magnetic fields that constitute the light waves). In contrast, light from a laser is coherent, like the ripples across a still pond, with regular and periodic oscillations.

Coherence in a light wave is important because of the way that waves can add together to give strips of bright intensity separated by dark bands. This is called interference, as shown in the Coherent Interference figure. Coherent interference can be either constructive or destructive when waves add together. When crests line up, the interference is constructive and the resultant wave amplitude is larger than the individual waves. When crests line up with troughs, the resultant wave is smaller. In all three generations of the machines of light, the coherence of light, particularly the coherence of laser light, is the key to optical control of light. For instance, simply by changing the distance through which one light beam travels relative to another beam (by changing the position of a mirror, let's say), the waves can be brought from constructive interference (that generates bright fringes) to destructive interference (that produces darkness). This allows the intensity of the observed light to depend on the relative path lengths, and hence allows sensitive control of light intensity.

This is the principle upon which your compact disc (CD) works. On the compact disc there are billions of very small pits that are a digital representation of recorded sound. The depth of the pit is about one quarter of a wavelength of the laser light that is used to read the CD. When laser light



COHERENT INTERFERENCE

shines on the pit, part of the light travels to the bottom of the pit and is reflected back, while part of the light reflects off the surface surrounding the pit. The light that went into the pit and back has a total path length that is a half-wavelength longer than the light that reflected off the surface surrounding the pit. When these two waves are combined, they are exactly out of phase with each other by half a wavelength (the crest of one lines up with the trough of the other). This condition leads to destructive interference of the combined wave (a decrease in the light intensity) that is detected as a drop in intensity by a light detector in the CD player. Successive drops in intensity as the laser beam scans over the pits become ones and zeros that are used to give nearly perfect reconstruction of the initial sound—all based on coherent interference of the laser light.

That is just one example of the importance of coherent interference for optical applications. In virtually all of the machines of light, the coherence of light plays a key role in how the machine functions. In machines of the first generation, the interference is used to control intensities of light. In machines of the second generation, coherence is used to cause one light beam to modulate the intensity or phase of a second light beam, that is, provide a means for light to control light without the need for electronics. In machines of the third generation, coherence is more profound. In quantum optical machines, the coherence regulates the probabilities of detecting photons (quanta of light) in one photodetector over another. But the quantum properties of light are important for more than just the machines of the third generation. Even for the machines of the first and second generations, the quantum nature of light is essential for the generation of coherent light by lasers. We therefore need to understand something of the quantum world.

THE QUANTUM WORLD

Quantum mechanics is the physics of the smallest units of mass and energy (from the Latin *quantum*, meaning "unit"). Together with the theory of relativity, it was part of the scientific revolution around 1900 that one hundred years later is still called "modern physics." The tag has stuck because quantum mechanics is still as strange as the day it was born. No one, not even physicists, is altogether comfortable with it.

When we think of elementary particles, such as the electrons and protons and neutrons that make up atoms, we must give up the mechanical intuition of our everyday world and consider possibilities that violate our conceptions of reality. Motion is no longer understandable as a trajectory. Particles on this scale do not move like a baseball batted into left field. For an electron in an atom, all trajectories are simultaneously possible. And if you try to measure which trajectory is actually taken, then you irreversibly perturb the system so that it no longer has the same condition it had before you made the observation.

Measuring properties of a quantum particle is like using flamingos as the croquet mallets in Lewis Carroll's *Alice's Adventures in Wonderland.* No sooner do you think you have one part of the flamingo in the right shape to serve as a mallet than it bends somewhere else. Even if you prepare an electron with the greatest care to be in a very specific state, you may know precisely where it is, but you will have absolutely no knowledge of which direction it is moving. And if you try to measure which direction it is moving in, you will disturb the electron in the process, and will no longer know precisely where it is.

Even beyond these frustrations of quantum physics, there is a fundamentally different way in which physical reality is described in the quantum world. All quantum events are described as probabilities rather than as actual events with definite outcomes. For a long time, scientists believed it was necessary for science to make deterministic predictions that did not involve probabilities. That stopped being the case about a century ago. If we consider a single radioactive nucleus, we cannot tell when the nucleus will decay. We can state that there is a probability of such-and-such a percent that it will decay in the next second. But if it survives that second, the chances of surviving the next second are exactly the same, and the same beyond that, and so on. Just as many coin flips can land heads-up in a sequence, it is also possible for a nucleus to live much longer than expected. But if you have just such a nucleus that has lived far longer than expected, the chances that it will decay in the next second are just the same as for the second right after the nucleus was born.

This intrinsic unknowability of quantum mechanics has struck many very smart physicists as a serious flaw. Even Einstein (1879–1955), who was most responsible for establishing the quantum nature of light, believed that the inability of quantum mechanics to tell exactly when an event would take place was the consequence of an incomplete theory rather than an irreducible uncertainty. In describing how an atom emits a quantum of

But Einstein approached the problem of black body radiation from an entirely different perspective. In his simple paper with the complicated title "On a Heuristic Viewpoint Concerning the Production and Transformation of Light," he made no assumptions about the physical interaction of light with electrons, but instead asked simply what the thermodynamic properties of electromagnetic radiation would be when confined inside a black body cavity. By applying statistics to the problem, he was led to the inescapable conclusion that radiation "behaves with respect to thermal phenomena as if it were composed of independent energy quanta." In other words, his "heuristic viewpoint" was that thermal radiation could be explained if the light were composed of discrete quanta of energy—as if light were composed of quantum particles, which seemed to defy the wave nature of light demonstrated thoroughly in the nineteenth century. The beauty of this early paper, which was published when Einstein was still relatively an unknown, was that it made no assumptions about the interaction of light with matter, as Planck had. Instead, the quantum theory of light was a consequence of simple statistical arguments.

This paper brought Einstein his greatest criticisms as well as his greatest rewards. Planck rejected it outright. For many years, it was considered by the top physicists of the day to be Einstein's greatest blunder. Even so, Einstein remained steadfast in his conviction of the validity of his light-quantum. At the First Solvay Congress, held in Brussels in 1911, Einstein was the first to speak after Planck made his presentation to the gathered scientists. Einstein criticized Planck's application of physical laws that were not necessary if one admitted the existence of the quantum of light. This harsh attack on Planck was returned when Einstein was nominated for a research professorship in the Prussian Academy of Sciences in 1913. Planck wrote: "That he may sometimes have missed the target of his speculations, as for example, in his hypothesis of light quanta, cannot really be held against him." Nonetheless, Planck supported the nomination.

The validity of the quantum theory of light was finally confirmed ten years after Einstein's "revolutionary" paper. The definitive experiments were performed by the American physicist Robert Millikan (1868–1953) on the "photoelectric effect" in 1915. This is an effect where light shining on a metal ejects electrons from the metal surface. In Einstein's 1905 paper, he had specifically used his light-quantum theory to predict that the kinetic energy of the emitted electron would be linearly proportional to the frequency of the light. When Millikan began his experiments, it was ostensibly to put the controversy about Einstein's light-quantum to rest by finally proving the error in Einstein's thinking. Instead, Millikan's experimental data on the photoelectron energy matched perfectly Einstein's theory. Millikan's incredulity was reflected in his words as he described the results of his experiment: "I shall not attempt to present the basis for such an assumption, for as a matter of fact, it had almost none at the time."

In 1921, Einstein won the Nobel Prize in Physics specifically for his quantum theory of light—not for his relativity theory. Although both special and general relativity had been largely accepted by this time, the Nobel Committee was struck most by the far-reaching importance of the quantum theory of light as a revolution in the sciences of mankind that affected photochemistry and photobiology, with potential technological benefits. But perhaps even more important was the effect on physical philosophy with its introduction of the wave/particle duality paradox that has occupied philosophers of science to this day. Planck, though credited as the originator of the quantum hypothesis, could not make a clean break with classical physics; Einstein did. His theory of the light-quantum was the first rigorous quantum theory. It was made at a time when the wave nature of light had been firmly established. To claim that light was a particle was audacious and potentially catastrophic for a young scientist who had not yet made his name. Yet Einstein made his claim and forever altered physical theory. His initial assessment of his "revolutionary" idea indeed proved correct.

HOW LASERS WORK

Einstein had not waited for validation of his 1905 paper to continue work on the quantum theory of light. His most important paper on the topic was published in 1917, only a year after he published his paper on the theory of gravitation. Where his first work on light-quanta was "heuristic," this new work was definitive. It remains a classic in the literature of physics to this day, and also laid the groundwork for the laser. In this paper he described how atoms absorb and emit light. Quantum mechanics comes into play in these processes in several ways.

Because electrons are quantum particles, their energies are restricted to discrete values inside matter. These discrete energies are determined by the wavelike properties of the electrons, and are called energy "states" or energy "levels." When an electron jumps from a higher energy state to a lower energy state, it generates a light quantum or photon. The energy of the photon is exactly equal to the difference in energy between the two energy states that the electron occupies before and after its quantum transition. In a laser, all the atoms are identical, and the electrons in the laser all have the same energy states. Therefore, a photon emitted by any one of the electrons will have exactly the same energy as the photons emitted from other electrons as they jump from the excited states to lower states. So all the photons generated in the material have the same energy, and hence the same wavelength.

Having lots of photons with the same wavelength gives laser light extremely "pure" color, but that alone is not sufficient to make the light coherent. This requires yet another quantum process. When a photon is generated in a laser material, it propagates past other electrons that are in their higher energy states. The photon then stimulates one of these electrons to make a transition from the higher to the lower energy level and emit a photon. This induced photon has the same energy as the first photon. But in addition, this second photon has the special property that it will be exactly in-phase with the first photon. In-phase means that the peaks and troughs of the electric fields from the second photon exactly line up with the peaks and troughs of the first photon, that is, they interfere constructively. These two photons are now coherent with each other, having exactly the same energy and same phase. The process of stimulated emission, introduced by Einstein in his 1917 paper, is clearly a means of getting two photons for one—in other words, a means to amplify light. But there is a fundamental barrier to getting just any collection of atoms to amplify light. This barrier has to do with the way that electrons occupy energy levels when the atoms are in thermal equilibrium.

Thermal equilibrium is a condition of a physical system that is achieved when the system has been allowed to sit unperturbed for a long time. When you put a container of warm tap water in the refrigerator, it takes some time for the temperature of the water to approach the temperature of the inside of the refrigerator. But once it has, its temperature no longer changes. It is said to be in thermal equilibrium. Systems that are in thermal equilibrium are, in some sense, "boring." This is because their properties are in steady state. Nothing is changing—macroscopically. However, on the microscopic level, the molecules of the system are moving and jostling about, colliding with each other at surprising speeds. For instance, the molecules of air surrounding you at this instant are striking your body at an average speed over 1,000 miles per hour. This would seem like a violent attack, if it were not for the light mass of the air molecules. In fact, this incessant bombardment on your skin is nothing other than air pressure.

Despite the microscopic violence, when the air is in thermal equilibrium, even at temperatures much higher than room temperature, most of the molecules are in their lowest energy state, called their ground state. Only a fraction of the electrons in the gas atoms will be in excited states. Therefore, even though a photon might stimulate the emission of a second photon from one atom, both of the photons are likely to be absorbed by the more numerous atoms in their ground states. In thermal equilibrium, the process of absorption wins out over the process of emission, and no amplification of light can occur. This fundamental fact seemed to make the likelihood of a light amplifier highly improbable.

One of the great scientific breakthroughs of the twentieth century was the nearly simultaneous yet independent realization by several researchers around 1951 (by Charles H. Townes (1915–) of Columbia University, by Joseph Weber (1919–2000) of the University of Maryland, and by Alexander M. Prokhorov (1916–) and Nikolai G. Basov (1922–) at the Lebedev Institute in Moscow) that clever techniques and novel apparatuses could be used to produce collections of atoms that had more electrons in excited states than in ground states. Such a situation is called a population inversion. If this situation could be attained, then a single photon would stimulate the emission a second photon, which in turn would stimulate two additional electrons to emit two identical photons to give a total of four photons—and so on. Clearly, this process turns a single photon into a host of photons, all with identical energy and phase.

Charles Townes and his research group were the first to succeed in 1953 in producing a device based on ammonia molecules that could work as an intense source of coherent photons. The initial device did not amplify visible light, but amplified microwave photons that had wavelengths of about 3 centimeters. They called the process "microwave amplification by stimulated emission of radiation," hence the acronym MASER. Despite the significant breakthrough that this invention represented, the devices were very expensive and difficult to operate. The maser did not revolutionize technology, and some even quipped that the acronym stood for "Means of Acquiring Support for Expensive Research." The maser did, however, launch a new field of study, called quantum electronics, that was the direct descendant of Einstein's 1917 paper. Most importantly, the existence and development of the maser became the starting point for a device that could do the same thing for light.

The race to develop an optical maser (later to be called laser, for "light amplification by stimulated emission of radiation") was intense. Many groups actively pursued this holy grail of quantum electronics. Most believed that it was possible, which made its invention merely a matter of time and effort. The race was won by Theodore H. Maiman (1927–) at Hughes Research Laboratory in Malibu, California, in 1960. He used a ruby crystal that was excited into a population inversion by an intense flash tube (like a flash bulb) that had originally been invented for flash photography. His approach was amazingly simple—blast the ruby with a high-intensity pulse of light and see what comes out—which explains why he was the first. Most other groups had been pursuing much more difficult routes because they believed that laser action would be difficult to achieve.

The basic structure of nearly all lasers is the same, from Maiman's first device to the ultra-high-tech lasers found in laboratories today. A laser consists of a laser gain medium placed between two mirrors in a structure called an optical resonantor or an optical cavity. One of the mirrors has perfect reflection, but the other, called the output coupler, transmits a small fraction of light. An external energy source pumps the atoms in the gain medium into a population inversion in their excited states. Photons that are emitted spontaneously in the direction of the mirrors stimulate the emission of additional photons. When the pumping rate is too weak, most photons are lost either through the output coupler or to absorption in the laser medium, and the laser light cannot build up inside the cavity. But once the pumping rate passes a threshold, known as the lasing threshold, the chance of stimulating photons exceeds the chance of losing photons, and the light builds up as the photons bounce back and forth between the mirrors. The intensity of the light coming from a laser as a function of the pumping rate is therefore zero up to the threshold rate, after which it increases extremely rapidly. When the laser is lasing, the light inside the cavity is very intense, and what we see emitted from a laser is only the small fraction allowed out by the output coupler.

Inside the laser cavity, all the photons share the same phase if the wavelength of the photons is equal to an integer number of half-wavelengths. If two different wavelengths satisfy this condition, each wavelength is called a laser mode and represents a resonance of the laser cavity; hence the term laser resonator that is used synonymously with laser cavity. All the pho-

problem in transmitting light through the atmosphere is atmospheric attenuation. For the same reasons that you can barely see a mile on a humid day in the summertime, or even a few feet through dense fog, laser light cannot penetrate further than we can see. What was needed to tap the potential of light for communication was a way of sequestering the light away from atmospheric variability. One approach is to confine light in special pipes—light pipes—that allow the light to travel unimpeded over vast distances. These light pipes are glass fibers.

FIBER OPTICS

Sending light down thin strands of glass is easy because once light is inside a circular fiber of glass, it cannot escape. The light rays experience a process known as total internal reflection. This means that light propagating inside the fiber is completely reflected by the surface rather than being allowed to exit into the surrounding air. Total internal reflection is critical if the light intensity is not to diminish as it moves along the fiber.

Total internal reflection is not limited to light in glass fibers. Anyone spending much time in a swimming pool or snorkeling in a calm lake can experience total internal reflection. It is best observed when wearing swimmer's goggles or a facemask. When you are underwater, look up at the surface of the water and try to look through to the trees standing on the shoreline, or the beach chairs surrounding the swimming pool. You will notice a cone of angles (relative to the vertical) where you can see objects above the water, but beyond those angles you instead see simply a reflection of the underwater. The angle at which you can no longer see past the surface is the critical angle. All light rays traveling at angles beyond that critical angle are totally internally reflected. The same process occurs inside glass fibers. Those light rays that make angles greater than the critical angle are trapped forever to travel down the fiber, making bounce after bounce. Light can travel long distances without losing intensity. Guiding light down a fiber couldn't be easier.

Despite the simple physics of total internal reflection, the early technological challenges were severe. Problems arise from many physical processes that attenuate light intensity. For instance, if the surface of the glass fiber is not perfectly smooth, light can be reflected off the roughness, allowing it to escape. In addition, all glass has impurities that absorb light.

If you look at a thick piece of glass, you will probably notice a greenish color to it. The green color is caused by absorption of red light by impurities in the glass. The roughness of the surface and the absorption severely limit the distances that light can travel down ordinary glass fibers.

In the early days of fiber-optic research, shortly after 1960, scientists could not send light 100 meters without losing nearly all of its intensity. The first breakthrough came in 1966, with the suggestion by researchers in England that a light-guiding core of high-density glass could be surrounded with an outer cladding of lower-density glass. The lower-density cladding still allowed total internal reflection, while shielding the guided light from the rough surface of the fiber. This clad fiber solved one of the impediments to getting light to travel long distances; but there was still the problem of absorption by impurities in glass.

The second breakthrough came in 1970, when researchers at Corning showed that, by using a special fabrication technique called chemical vapor deposition (CVD), the fibers could be made very pure to minimize the absorption. They showed that light intensity in the fiber would drop 99 percent over 1 kilometer. Though this sounds like a big drop in intensity, it was a critical threshold toward which everyone had been working. With this degree of transparency, a fiber system could have a repeater (a photodetector that receives the signal, and a laser that relaunches it down the next segment of fiber) spaced as far as 1–2 kilometers apart. This was a magic number because it was the same repeat distance that was being used by electronic transmission. If it was good enough for telephone wires, it should be good enough for fibers.

In one of the famous coincidences of science and technology, another 1970 breakthrough formed the last critical component in fiber-optic communication systems. Although intense research on fiber-optic communication had been launched in the early 1960s by the invention of the laser, by early 1970 there was still no laser source that could be used in a fiber system. All the reliable lasers at that time were too large and expensive to operate in the many repeater stations that were necessary to regenerate the optical signals every 2 kilometers or so.

Semiconductor lasers, which had been invented in 1963, had the advantage that they were extremely small and inexpensive, but until 1970 they had never operated continuously at room temperature without burning out. As with all the major laser discoveries of the 1960s, a fierce race began to find the right semiconductor structure to achieve continuous laser action at room temperature. Three groups were leading the race: Bell Laboratories, RCA, and the Lebedev Institute in the USSR. The Bell Labs team won the race for the continuously operating room-temperature diode laser during the Memorial Day weekend in late May 1970. They published their results within a month of the Corning announcement of their low-loss fibers. All the components of a complete light wave communication system were now in place. All that remained was development and real-world trials.

The development of fiber-optic communication systems represents one of the fastest R&D tracks in history for taking inventions out of the laboratory and turning them into commercial systems. Within five years, the expected lifetime-to-failure rate of the room-temperature semiconductor lasers had been extended to about a century (compared with the lifetime of only several minutes for the first room-temperature laser). During the same time, advances in fiber technology further reduced the loss of light in fibers. The first field trial was conducted by the Bell System in 1976 in Atlanta, Georgia, and the first commercial systems were put in place separately by GTE and Bell in 1977 in Santa Monica, California, and in Chicago. By 1980, large-scale commercialization of fiber-optic systems was well underway. The time from the first practical components to commercial success had only taken ten years.

Those ten years began a revolution that continues today. Indeed, it proceeds at an ever-increasing rate driven by the machines of light. The first generation of these machines, born with the diode laser and optical fiber, uses electronics and optics together. The second generation dispenses with electronics, and it is just beginning at the dawn of the twenty-first century. The third generation, which harnesses quantum optics, has not quite begun—but it will. The three generations of the machines of light are the technologies that will support the new kind of intelligence based on light. Let's take a closer look at each generation.

THE FIRST GENERATION: OPTOELECTRONICS

Light and electronics are already on intimate terms. Electrons can generate light, and light can be absorbed by electrons. In optoelectronic machines of light, light and electrons perform separate tasks: electrons perform control, while photons carry information. This division of labor is determined by their different physical properties. For instance, each electron has a charge that causes it to strongly attract or repel other charged electrons. This property makes them candidates for control operations. In a field-effect transistor, electrons are the gatekeepers for a channel through which an electric current flows. Change the number of electrons that are in the gate, and this allows or prevents the flow of electrons through that channel. The control of charge by charge is natural and powerful, and it drives the electronics age.

However, the property that makes electrons excellent at control also makes them troublesome messengers. When you want to send information from one place to another, you don't want other pieces of information getting mixed into the signal. If electrons are carrying the information, then other electrons, carrying other messages in the same device, will exert a force on the signal carriers. This leads to a problem known as cross-talk, as on a telephone call when you hear another conversation going on at the same time as your own. With myriads of electrons around (they are constituents of all matter), it is hard to keep them from affecting each other.

Photons, in contrast to electrons, are perfect messengers. Photons have no charge, and pass through each other unaffected. You can take two lasers and cross their intense beams in air, and nothing happens. They travel at the speed of light, and they can travel with a hundred other signals without ever affecting each other. Therefore, fiber optics offers more than just sending information over large distances; the information, when it gets to where it is going, is clear and uncorrupted by electromagnetic interference.

But whereas photons win out over electrons in terms of communication, electrons have the advantage of extremely small size compared to the size of a photon. The photon has a wavelength that is typically around 1 micron, which can roughly be identified with the "size" of the photon. But electrons, when considered as quantum particle waves, have their own characteristic wavelengths less than 1 nanometer—more than a hundred times smaller than light.

The small size of electronic devices directly affects the speed needed for computation. Put simply, smaller electronic devices have smaller distances between them, which take shorter times for signals to travel. The American physicist Richard Feynman (1918–1988) made the point in 1959 that there was plenty of room at the bottom of the size scale to keep pushing the computation rates upward by decreasing the size of the electronic components. After half a century of acceleration in computation rates, there is still room down there.

But being small and fast is not enough to be useful. For logic operations to be insensitive to fluctuations, which can be thought of as static or white noise, strong interactions are needed. Electrons satisfy this requirement and therefore are given the tasks of control and logic in optoelectronic computer chips. In addition, communication among single-electron devices must continue to use electrons as the messengers. At the small scale of 10 nanometers, they are the only possible messenger because the wavelength of light (even short-wavelength ultraviolet light) is around 300 nanometers—thirty times larger. Clearly, light has no role to play at such small scales.

However, a crossover length can be identified that separates the roles of photons from electrons. For distances larger than the crossover length, photons are better than electrons for data communication. Even now, communications between computers are relying more on fiber optics. The length scale for this crossover is currently on the order of a meter; gigabit ethernet is used to connect up system-area networks of separate computers. But the length scale is shrinking as new optical technology opens up areas previously reserved for electrons. Optics will soon be making incursions into the computer boxes themselves to port information back and forth from board to board on the centimeter-length scale. Pushing this trend even farther will bring light onto single computer boards, and eventually into the chips themselves, where light will span millimeter-length scales. Even at this small scale, there appears to be plenty of room at the bottom to push light to work at even smaller distances, possibly even down to the size of the wavelength of light, around 1 micrometer.

At the engineering limit of these kinds of machines, photons and electrons will be inextricably entwined in a three-dimensional optoelectronic architecture. In such machines of the first generation, the distinction between electronics and optics will be blurred. However, electrons will continue to perform the switching functions, while photons will be the fleet-footed messengers. Electrons will generate the messengers and impress information onto the light beams, while light will generate electrons at the appropriate destinations. Light will continue to be used passively to transmit information from one place to another (just as it does in the inforagates through a non-linear medium. The laser beams are no longer *independent,* but have become *interdependent.*

The technological value of all-optical interaction is clear. Light is controlling light without involving electronics. In some cases, the efficiency of the process approaches 100 percent. And no time is lost, because the light always stays in the form of photons that travel at the speed of light. This may sound too good to be true. If all-optical control is so great, and if non-linear optics was born only a year after the laser, why aren't our systems all-optical today? Why are routing switches still optoelectronic? There are various reasons. Some are economic, while others involve the physics of non-linear optics.

First, electronics is, has been, and will continue to be the fundamental controller in all information and computing systems. The strong electrostatic interactions among electrons will always make them the best choice for control. Second, electronics can be very fast. Just look at the processor speed of your desktop computer. Is it a gigahertz processor? That is pretty fast. And through most of the time of fiber-optic development, telecommunication rates have been traditionally lower than a gigahertz. It is only at the turn of the twenty-first century that the vision-driven hunger for Internet bandwidth is demanding ever higher data rates that outstrip electronic capabilities. Electronic speeds generally die out above 40 gigahertz, while Internet use is demanding terahertz bandwidth. Therefore, it is only in the past few years that the fiber-optical communication rates have needed to push beyond electronic capabilities. The call for all-optical networks is something that arose only in the late 1990s and could never have been foreseen in the 1960s.

Finally, there is the physics of non-linear optics and the challenges faced by the control of light by light. In that first paper in 1961 on second harmonic generation in quartz, the efficiency of the process was about 1 part in 100 million. This number pales in comparison to the 70 percent efficiency for optoelectronic conversion. Admittedly, first tries are never best tries, and today it is possible to achieve nearly 100 percent efficiency for light generation and control through non-linear optics. But again, there is a catch. Achieving these high efficiencies usually requires very high light intensities that can burn or melt a crystal if the beam shines for too long. Applications therefore must use short-lived but intense laser pulses to achieve high instantaneous intensities, but with a lot of dead time between pulses to let things cool.

Researchers in non-linear optics are always dealing with these kinds of trade-offs that allow one type of desired performance to be achieved at the cost of another. But the frustrations of dealing with such trade-offs dissolve before clever engineering. Already, high efficiencies at steady light intensities are already available, and laser intensities in some applications can be weaker than the intensity of light in a dimly lit room, yet still allow strong control of other light beams. These advances, combined with the new need for photonic Internet data rates that outstrip electronic capabilities, are driving the second generation of the machines of light. There is still considerable room for advancement before the all-optical network becomes a reality, but new optical materials are opening up unexpected possibilities. One type of solid medium is particularly amenable to non-linear light interactions: glass. In one of those happy coincidences of technology and physics, optical fibers happen to be ideal media for the interaction of light with light—for several reasons.

First, light can be focused down to very small areas when it is launched into the fiber. For instance, the core of a single-mode fiber is less than 8 microns in diameter. When light is focused down to such a small area, the resultant intensity can be very large, even if the total power is small. The light inside a fiber therefore has surprisingly high intensity—which is just the condition necessary for strong non-linear interactions.

Second, light beams contained in fibers can interact over large distances of 100 kilometers. Even if the optical non-linearities in glass are small, the small interactions between beams can accumulate over the long distances and become large effects. Many types of fiber non-linearities have been studied, and multiple demonstrations have been performed in which light beams control other light beams inside the fiber, even performing operations such as switching, which is one of the critical all-optical logic functions that must be developed for routing and switching in all-optical networks.

Third, fibers can be fabricated containing special impurities, such as atoms of the rare earth element erbium. These fibers are called erbium-doped fibers, and they have an extremely important property: if they are illuminated with light having a wavelength near 1 micron, they will amplify separate beams at wavelengths around 1.5 microns. The 1.5 micron wavelength is a magic wavelength for fiber-optic communications because that is where fibers have their lowest absorption. This combination of low loss with the ability to amplify the light signals has made erbium fiber ampli-