Chapter 1

What is Light? The Mystery Continues

You're reading these words under natural or artificial light, light that seems so ordinary that you take it for granted. Yet although light surrounds us, it is anything but ordinary. Its ancient role in the universe and its unique properties make it remarkable. Equally remarkably, light's science-fictionish behavior — such as its dual nature as wave and quantum particle and its ability to be teleported — can be applied in daily use and in advanced technology. Light also plays a continuing role in culture and in fantasy, from ancient myths to contemporary science fiction. All this has roots in humanity's long study of light.

To fully appreciate light's universal nature and how we use it today, let your mental vision roam beyond your immediate surroundings. Visualize our planet, then look beyond it to the Moon, the Sun, and the other bodies in our solar system; then further out to the stars, to the galaxies, and finally to the entire universe.

Light exists everywhere you turn your attention in our imaginary tour, part of it visible to human eyes, much of it detectible only by instruments. Some originates from a hot object such as an incandescent bulb or a star. Some is reflected from things on our world or off it: the pages of this book, a cloud, the planet Venus. And some has existed almost since the universe began, for light derives directly from the energy that filled the universe at the Big Bang. That explosion of reality began the cosmos 14 billion years ago with incredibly high temperatures. Among other things, those early conditions generated photons, the packets of energy that constitute particles of light.

It's not just that light is an ancient part of the universe. Light was also involved in the beginnings of matter. In the universe today, matter comes as a hundred different atomic elements and in sizes ranging from subatomic particles to stars and galaxies. It also comes in a variety of forms: as plasmas, that is, hot gases inside stars; as cooler gases between stars and in planetary atmospheres; in liquid form like the water and hydrocarbons found on Earth and elsewhere in the solar system; and as solids, like the rock and metal that make up planets and asteroids.

Different threads in the growth of the universe contributed to this diversity, among them, the evolution of light. When the universe was only a fraction of a nanosecond old, photons formed, along with other elementary particles such as quarks. According to Einstein's theory of relativity, energy and matter can change into each other, and so when photons collided, they turned into elementary particles with mass; for instance, electrons and their anti-matter partners, positrons. This may seem surprising, for we perceive light as pure and ethereal, beautiful in its intangibility. Yet even weighty materials, even dense metals such as lead or gold, can ultimately trace their origins back to light. The elementary particles that were formed from energy eventually combined into atoms, which in turn made the variety of matter that we know.

However, not all the light from the Big Bang became matter. Some, called the cosmic background radiation, still exists and travels throughout the universe. It is invisible to the eye but can be detected in any direction that we point our instruments. The distribution and wavelengths of this light are strong evidence that the Big Bang occurred.

Long before we knew this much about light, natural philosophers theorized about its nature. Light has always been important to humanity, starting with its reappearance each dawn as the sun rose. Ancient societies recognized that significance in their religious observances and in their gods of light and of the sun, such as Ra and Aten of the ancient Egyptians and Helios of the ancient Greeks. Some early thinkers, too, were drawn to consider light's properties. The Greek philosophers, forerunners of modern scientists, observed light and drew conclusions about its nature, some correct and some incorrect.

Around 300 BCE, for instance, the Greek mathematician Euclid, the "father of geometry," treated light rays as moving in straight lines, which is correct except near very large bodies like stars — but that was not known until millennia later, when Einstein's relativity predicted the effect and measurements confirmed it. On the other hand, some Greek pre-scientists such as the philosopher Empedocles (most famous for his theory of the Four Elements: Earth, Air, Fire, and Water) seemed to believe that human vision is enabled when a "visual ray" emerges from the eye to reach out to an object. Now we know that light must enter the eye to activate vision, and that nothing is emitted from the eye as part of the visual process.

Later thinkers, such as Aristotle and the Arab optical scientist Ibn al-Haitham or Alhazen, corrected some of the earlier misapprehensions and extended our knowledge of light. By the 17th century, tools and ideas were in place to begin the quantitative scientific study of light. Isaac Newton, perhaps the greatest scientist who ever lived, did so in 1665 when he examined the spectrum of sunlight dispersed by a glass prism that he had bought at a fair.

Newton concluded that light is made of "corpuscles" or individual particles, although the modern idea of the photon was still centuries away. His view remained the definitive understanding of light until scientist and polymath Thomas Young conducted a series of experiments beginning around 1801. In the most crucial of these, the famous "double slit" experiment, he passed light from a single source through two slits and recombined the two beams on a screen. The result was a series of alternating bright and dark bands. These absolutely could not be explained by Newton's corpuscles, which could add to give a result that was brighter than from one beam, but could never subtract to give an absence of light. Both bright and dark regions could appear, however, if light came in waves.

Unlike particles, waves are extended in space with alternating peaks and troughs. Lay two waves atop each other so that peaks match peaks and troughs match troughs, and "constructive interference" yields a new wave stronger than either of the originals. But shift one wave so that its peaks line up with the valleys of the other and you have "destructive interference," where the waves cancel each other to leave no activity or intensity at all. These phenomena explained the light and dark regions in the double slit experiment, and so Young's results seemed to establish that light is made of waves, not particles — though unlike the rise and fall of water in an ocean wave, exactly what was undulating in a light wave was then unknown.

The answer came in the 1860s from the Scottish physicist James Clerk Maxwell. His brilliant mathematical analysis of electricity and magnetism, known as Maxwell's equations, showed that when an electrical charge changes its motion — that is, accelerates — it produces an electromagnetic wave that travels through space. The connection to light came when Maxwell calculated the speed at which the wave would propagate and found it equal to the known speed of light. That had been accurately measured by then as close to today's accepted value of very nearly 300,000 kilometers per second (km/sec) or 186,000 miles/sec, a number that comes up so often that it has its own special symbol "*c*," supposedly to represent "constant."

By the end of the 19th century, it was clear that light is an electromagnetic wave defined by its wavelength, the distance between two successive peaks; or equally its frequency, how many peaks you count per second as a light wave travels past you (if you know one, you know the other because their product is equal to *c*). But new experiments were casting doubt on the wave theory. Measurements on the light emitted by a hot object, and on the photoelectric effect — where light impinging on a metal plate releases electrons — produced results that disagreed with how waves should behave.

In the 1890s, the German physicist Max Planck found that the problems with light from a hot body could be resolved if the energies in the process were emitted in discrete units or "quanta." In 1905, Albert Einstein took the idea further when he explained the photoelectric effect by showing that light itself comes in discrete packets of energy. These light quanta were later named "photons." Planck and Einstein both won Nobel Prizes, in 1918 and 1921, respectively, for these insights that gave birth to quantum mechanics.

Like Dr. Frankenstein's creature, Einstein's creation was remarkable but troublesome to its creator and others. Though the photon explained the photoelectric effect, it was at odds with the wave theory of light, and Einstein himself was never fully comfortable with the quantum nature of the universe. Nevertheless, starting in the 1920s, other scientists successfully developed quantum theory and applied it to matter as well as light. Theorists also went on to examine the physics of photons and electrons to produce quantum electrodynamics (QED), the quantum theory of electromagnetism. This work led to the 1965 Nobel Prize in Physics for Richard Feynman, Julian Schwinger and Sin-Itiro Tomonaga.

Einstein also extended our knowledge of light in a different way, through his theories of special and general relativity from 1905 and 1915 respectively. Special relativity shows that the speed of light is absolute; that is, unlike anything else in the universe, an observer measures a light speed of 300,000 km/sec no matter in what direction or how fast the observer or light source is moving. This differs from ordinary life. For instance, the driver of a car traveling at 60 mph measures the speed of a second car, traveling alongside at 60 mph, as zero relative to himself; but as Einstein himself noted, an observer on a light wave measures the speed of a second adjacent light wave as 300,000 km/sec, not zero. Another startling conclusion from special relativity is that nothing material can go faster than light, the fastest thing in the universe.

General relativity brought further understanding of how light behaves. Along with special relativity, the theory gives spacetime — the three spatial dimensions integrated with the fourth dimension of time — a central physical role in the workings of the universe. Gravity is explained as a distortion in spacetime due to the presence of mass. That distortion affects light, so a light ray no longer necessarily travels in a straight line, but traverses a curved path called a geodesic near a large object like a star. In extreme cases, a region of spacetime can become so warped that it traps light, that is, the region becomes a black hole.

These results from the theory of relativity are far from obvious or intuitive, yet Einstein's theories correctly describe the behavior of light, of gravity, and of the universe. Similarly, the photon picture and QED are highly successful in predicting the behavior of light and its interaction with matter. There's no doubt that the quantum nature of light is real, and photons take their place among the other elementary particles like quarks and electrons that make up the universe. Yet light also displays characteristic wave features such as constructive and destructive interference, and much of its behavior can be described by the theory of electromagnetic waves.

Along with the unusual aspects of relativity, this dual wave–particle nature of light is hard to accept. No one has ever brought the paradoxical elements of the duality fully under one theoretical umbrella. It is startling, and humbling, that after brilliant and sustained efforts over centuries to grasp the essence of light, we still do not understand how it embodies these two utterly different pictures.

Fortunately, incomplete understanding is no barrier to technological application. Scientists know how to use each half of the wave–particle duality as appropriate, and also how to apply relativistic principles. Without knowledge of general relativity, the worldwide global positioning system would be inaccurate; without theories of photons and quantum mechanics in general, we would not have conceived and invented many devices central to our technological society, such as computer chips, light emitting diodes, and lasers.

Nevertheless, the wave–particle duality of light is an aspect of quantum weirdness — one of those quantum phenomena that has no counterpart in human experience and perceptions and so seems inexplicable. The Heisenberg Uncertainty Principle is another strange feature. This states that there are certain combinations of physical properties, for instance the position and momentum of a small particle, that can't be simultaneously measured to a desired accuracy because the measurement process changes the properties. Any attempt to determine the position of a photon or electron adds energy to the particle, which changes its momentum, thus foiling the measurement of the momentum at the same time. This limitation is effective only at the small scales where quantum physics applies, and so we never experience it in daily life.

There is also the matter of superposition. In classical physics, a particle like an electron or photon has a single specific value for any of its physical properties. For instance, to pick a property useful for photon applications, a photon's electric field can be oriented or "polarized" along either a vertical or horizontal direction. But in quantum physics, that electric field has a probability of being oriented in either direction. It is not definitively vertical or horizontal until its direction is actually measured. Before the measurement, the photon is said to be in a "superposition" of states, with its field simultaneously vertical and horizontal — which seems to echo a famous bit of advice ascribed to baseball player and philosopher Yogi Berra: "When you come to a fork in the road, take it." Physicists are not entirely happy with this baffling image, but they accept it because it turns out to correctly describe the world around us.

Even more perplexing than quantum uncertainty and superposition is the exceedingly odd phenomenon called entanglement, which Einstein himself called "spooky." Consider two photons that were once closely associated, but have since been physically separated by being sent down two different paths. Select one of the two and measure its properties. Apparently instantaneously, the other changes in response even if it is many kilometers away, as if knowledge of their physical states passes from one to the other by an unknown process. This is akin to the classic science fiction idea of teleportation, as when Scotty on the starship *Enterprise* beams people and things across intervening gulfs of space. But entanglement is a real, serious, and growing research topic, an idea that has moved out of fantasy into science and potentially into new quantum technologies of computing and telecommunication.

The connection between quantum entanglement and teleportation is just one link between science fiction and the science of light. The speed of light is another, for its role as the universal speed limit hugely affects science fiction. Distances in the universe are so enormous that even if a spacecraft could travel at 300,000 km/sec — infinitely faster than NASA rockets actually move — it would require years to millennia to reach the stars outside our solar system. But science fiction writers want their characters to travel freely between stars and through galaxies, so they invent fictional ways to travel FTL, that is, faster than light. That's the origin of *Star Trek's* "warp drive" and other similar imaginary spacecraft propulsion systems. The idea is that the spaceship engines somehow distort spacetime to create a "hyperspace" that allows speeds greater than *c*, or that constitutes a cosmic shortcut or "wormhole" through which the spaceship can effectively travel faster than light.

Though general relativity does in fact predict the possibility of drastically changed spacetime in black holes and wormholes, and though there is strong evidence that black holes exist, there isn't as yet any firm idea of how to build a warp drive. But that hasn't stopped the quest to find ways to exceed the speed of light, which raises questions full of scientific interest: Are there loopholes in relativity? Has the value of *c* ever changed in the history of the universe? If something could go faster than light, how would it behave?

What probably never could have been foreseen, except by a science fiction reader or writer, is that researchers could also have become fascinated by light that is not fast but slow, creeping along at a few kilometers per hour and even brought to a full stop. In 1999, physicist Lene Vestergaard Hau, working at Harvard and the Rowland Institute in Cambridge, Massachusetts, used a new state of matter called a Bose–Einstein condensate (its creation was the subject of a Nobel Prize in Physics in 2001) to bring light down to the speed of a bicycle and then later to a dead halt.

Startling as it is to visualize a light ray moving at a snail's pace, at least two science fiction writers considered the meaning of slow light long before it became a subject for research. John Stith's novel *Redshift Rendezvous* (1990) postulated a hyperspace in which light is slowed by a factor of 30,000 to 10 m/sec, and worked out in careful detail the implications for daily life. Much earlier, in his well-known short story "Light of Other Days" from 1966, the Irish science fiction writer Bob Shaw proposed a way to make light crawl far more slowly than a ponderous glacier, then went on to explore what this could mean in human terms. (Both efforts were nominated for prestigious science fiction writing awards).

We are nowhere near creating any sort of hyperspace in which light might slow down, and the slow light in "Light of Other Days" seemed like pure fantasy when the story was written. Now after Hau's breakthrough and the work of other scientists, slow light can be made on demand; but it might seem a mere lab curiosity and even regressive, for after all, light's high speed is important for its applications. Whether as radio and television waves, or as infrared pulses traveling through optical fiber networks, light rapidly carries voice, music, images and data throughout the world. Certain applications, such as the global positioning system that orients a person or vehicle on the earth's surface, would not work well if light were substantially slower than it is. But although light's high speed is valuable, slow and stopped light can also lead to new applications in computing and telecommunications.

That isn't the end, though, of the manipulation of light speed. The same techniques that make light slow down can be used to do two astounding things: speed up pulses of light beyond *c*, and make light run backward, in the sense that the peak of a pulse leaves a given medium *before* entering it. These results seem like science fiction, not to mention that they seem to violate the relativistic speed limit and the universal principle of causality, that causes precede effects. Fortunately, careful consideration shows that so-called fast light and backwards light don't damage any fundamental theories; but these effects do show that the difference between science fiction and the science of light isn't always easy to determine.

Another way that light enters fantasy is in the wide use of lasers in science fiction. The power of concentrated light was recognized long before lasers were invented. In what is probably more legend than truth, there is an unsubstantiated story that around the year 212 BCE, Archimedes used curved mirrors to focus sunlight and set afire the wooden ships of an invading Roman fleet. A modern replication of this event shows that even if the enemy ships had obligingly held still to give the sunbeam time to heat them, the weapon would not have worked. Nevertheless, it shows that the ancients were well aware of the damage that light could do.

Millennia later, the power of concentrated light took on a more modern appearance in H. G. Wells' story from 1898, *The War of the Worlds*. In it, invaders from Mars deploy laser-like, invisible, but destructive heat rays. Ever since, lasers have been the armament of choice in many science fiction sagas, from the ray guns wielded by Buck Rogers and Flash Gordon, to an anti-weapon ray generated by the robot Gort in the film *The Day the Earth Stood Still* (1951), to the gargantuan Death Star laser that obliterates an entire planet in the original *Star Wars* (1977).

These fictional devices foreshadowed their real world versions. The carbon dioxide or CO_2 laser, invented in 1964, produces an invisible infrared beam like Wells' heat ray (as I got to know first-hand, having once been scarred by a CO_2 laser in my own lab). Laser space weapons were part of the Strategic Defense Initiative (SDI, also known as Star Wars) proposed by President Ronald Reagan in 1983. The plan was to place powerful X-ray lasers in orbit around the earth to destroy incoming nuclear-tipped missiles. The scheme came to nothing because of problems in developing the lasers and because the fall of the Soviet Union eliminated a major threat, but the military continues to develop other laser weaponry.

Despite the emphasis on weapons, lasers can also do constructive things. Low to medium power lasers send information over optical fiber networks, read bar codes in retail transactions, and perform surgery and other medical tasks. At higher powers, lasers can potentially provide clean energy for general use, although so far, only in science fiction. In the films *Chain Reaction* (1996) and *Spider-Man 2* (2004), lasers initiate hydrogen fusion, the process where hydrogen nuclei merge into helium and release energy.

In the real world, hydrogen fusion has been pursued for 60 years as a clean, practical power source. One current effort employs lasers far more powerful than those in *Chain Reaction* and *Spider-Man 2*. It is underway at the world's most energetic laser installation, the National Ignition Facility at the Lawrence Livermore Laboratory in California. This huge, arena-size complex is designed to deliver brief pulses of ultraviolet light carrying hundreds of terawatts of power into a small capsule containing hydrogen, in the hope of initiating a fusion reaction.

At the opposite extreme are devices devoted to making light at the lowest possible levels, one or two photons at a time, to study quantum entanglement and provide photons for quantum communication and computing. Single photons can be produced from single atoms or from quantum dots. These are very small semiconductor structures typically a few nanometers in dimension, that is, no more than a few dozen atoms across — so small that their properties are defined by quantum physics. Taken together, the light from the immense National Ignition Facility and a single photon from a quantum dot represent "extreme light," from ultrahigh power to the lowest power level short of zero.

Another area where science fiction has led the way, and the science of light follows, is invisibility. The magical power to make things and people disappear has a long literary and cultural history. It is used to make a point in Plato's *Republic* and it appears in early Teutonic mythology. This particular magic has been popular in fantasy fiction too, and remains compelling in modern times: think of the Ring of Power in *The Lord of the Rings*, which confers invisibility, and the Invisibility Cloak in the Harry Potter stories.

A different approach that replaces magic with science is represented by the H. G. Wells story "The Invisible Man" (1897), which describes the benefits and drawbacks of invisibility and sketches out a scientific method for achieving it. Another early story, "The Shadow and the Flash" (1903) by Jack London, gives an alternate scientific basis for making a person invisible. Probably the most famous nonmagical invisibility apparatus in science fiction is the "cloaking device" in the *Star Trek* series that can hide an entire spacecraft, apparently by bending light so that it curves around the spaceship.

Echoing these fictional approaches, scientists are finding real ways to manipulate light so as to make people and objects invisible. The oldest technique is camouflage, first widely used in World War I. With modern technology, it goes beyond the familiar desert or forest patterns on soldiers' uniforms to make a subject appear transparent as glass and hence invisible. A second approach, stealth technology that renders aircraft virtually invisible to radar, began in the 1970s. The latest method, called "cloaking" as in *Star Trek*, redirects light rays around an object so that the light appears undisturbed by anything real. This technique uses artificial "metamaterials" that give new ways to control light rays. Unlike technology that reflects quantum weirdness, these approaches to invisibility use classical electromagnetic wave theory and can be applied to other kinds of waves, including sound waves, water waves, and seismic waves from earthquakes.

Indeed, a tour of the science of light is a tour of physics and technology, from the quantum world to the macrocosmic universe, from highly abstract theory to everyday applications, from old established ideas like Maxwell's equations to the cutting edge of modern science — and beyond it into speculative regions. It's striking that although the technology of light is embedded in our daily lives, much of it — especially many breakthroughs of the last 10 or 20 years — arises from the counterintuitive theories of quantum physics and relativity. Here are five important conclusions of these theories that will appear as we examine light:

1. Relativity I: Light in vacuum is the fastest thing in the universe. Nothing with mass and no information transfer can exceed that speed.
2. Relativity II: The path that light traverses follows geodesics in spacetime, whose shape is determined by nearby mass or energy; or to put it another way, light is affected by gravity.
3. Quantum weirdness I: Light is dual in nature, acting as particle or wave depending on the experiment.
4. Quantum weirdness II: A photon exists in a superposition of states until a measurement is actually made.

5. Quantum weirdness III: Photons can be entangled, so that a change in one of an entangled pair is instantly reflected in the other no matter what the distance between them.

These ideas and their consequences lie outside direct, visceral human experience and so they carry an air of mystery and fantasy that makes them easy to incorporate into speculative fiction. And truly, the line between speculation and fiction on the one hand, and the real science of light on the other, is blurred: sometimes the science fiction leads directly to the science, and sometimes the real science develops so rapidly that it outstrips the fiction.

In the remainder of this book, we'll look at both the real and the fantastic to see how they intertwine, beginning with a fundamental question about light: why does it move so very fast?