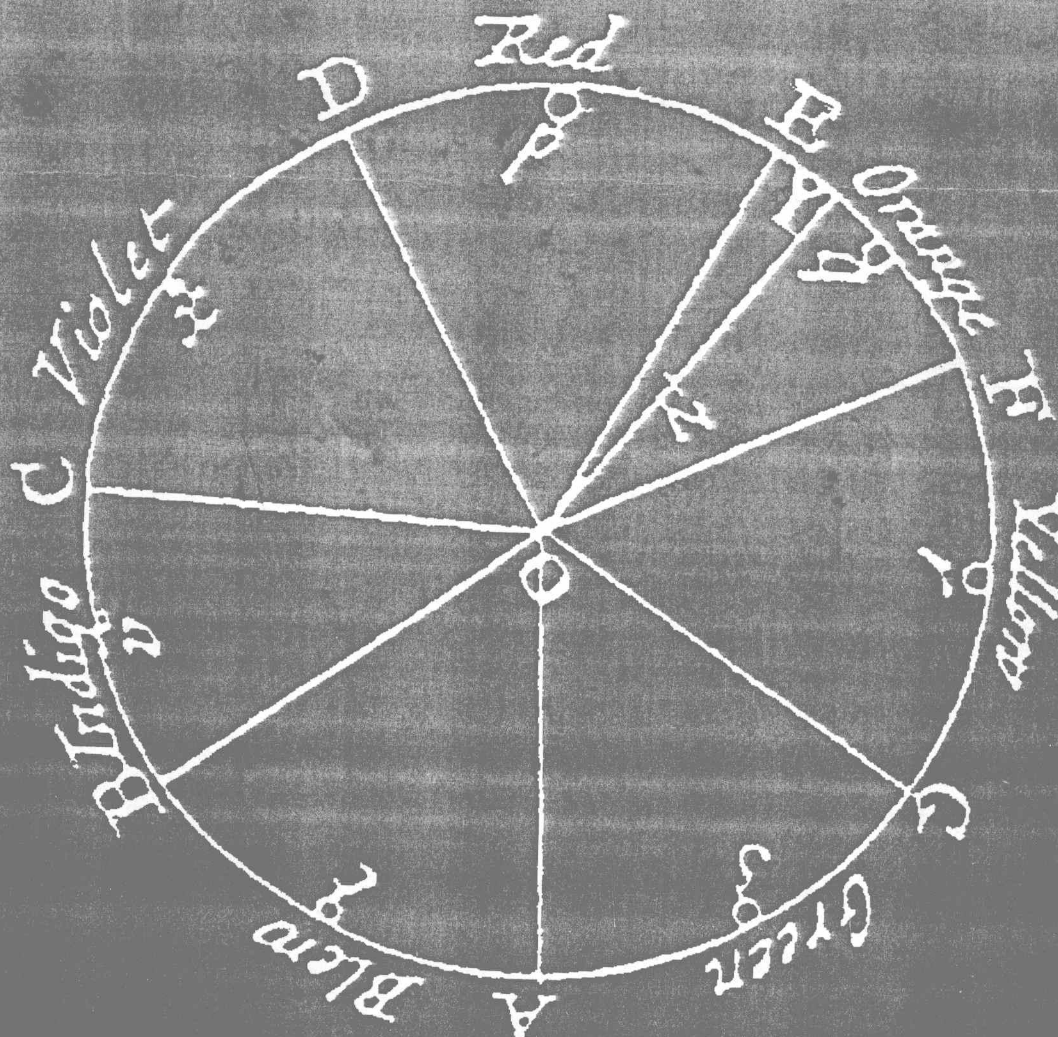
VISION AND The Biology Of Seeing

By Margaret Livingstone Foreword By David Hubel

VISION AND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THE BIOLOGY OF SEEING

BY MARGARET LIVINGSTONE

FOREWORD BY DAVID HUBEL

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Endpapers: The scintillating grid illusion (see page 56).

Pages 2–3: Jean-Auguste-Dominique Ingres. *Princess Albert de Broglie, née Joséphine-Eléonore-Marie-Pauline de Galard de Brassac de Béarn (1825–1860).* 1853. Oil on canvas, 21.3 x 90.8 cm. The Metropolitan Museum of Art, Robert Lehman Collection

TO MY SONS,
David, Dwight, and Bevil

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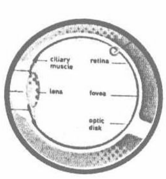

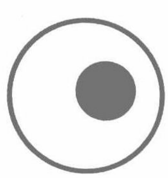

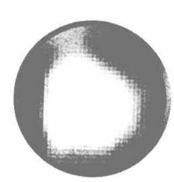

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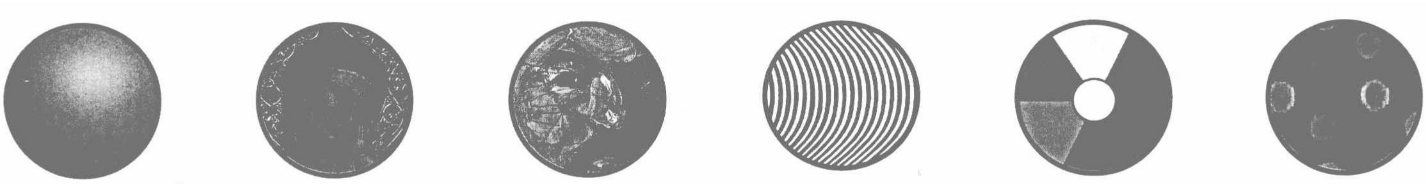


MARGARET LIVINGSTONE and I have been colleagues for over twenty-five years. We collaborated, like a team of horses pulling a sled, for the first fifteen years, and since about 1990 we have worked independently in adjacent laboratories, sharing graduate students and postdoctoral fellows, and carrying on a continuous dialogue about our science. Given Marge's longstanding interest in art and its relation to visual neurobiology, it has been natural for her to ask whether what we have learned about visual science in the last few decades can lead to a deeper understanding of the visual arts. Her work in vision has covered all the main aspects of visual neurobiology, including movement, depth perception, color, and form.

Over the last fifty years our knowledge of how the brain interprets the information it receives from the eyes has made huge strides, largely because for the first time we have had the tools to ask the appropriate questions. Among these tools are the microelectrode, which allows us to listen in on the activity of single cells in the brain; electronic apparatus that lets us amplify and record these signals; and new techniques in neuroanatomy, which make it possible to know how the cells are interconnected. We now know, in broad outline if not in full detail, how the brain begins to deal with the basic components of vision. Our appreciation of the visual arts can only be deepened by such knowledge. In the future, visual neurobiology will enhance art in much the same way as a knowledge of bones and muscles has for centuries enhanced the ability of artists to portray the human body.

This relationship between art and present-day science would be just a vague and unrealistic dream if visual neurobiology were a subject so abstract and highly evolved as to be out of reach for someone not thoroughly trained in science and mathematics. Luckily our science is not abstruse, in the way that relativity or quantum mechanics is. I have never had the least doubt that given two hours I could make anyone with a good high-school education fully aware of the main accomplishments of the last half-century of visual science. I once gave a private lecture in neurobiology to Françoise Gilot (of Picasso fame) and from her questions it was clear that she fully grasped everything I was saying, including concepts such as receptive fields and complex cells. The possibility of communicating our science to our friends and neighbors is exhilarating, and in many ways I feel sorry for my friends in physics, whose lives must be relatively lonely.

Given how easy it is to convey these ideas, it seems unfortunate that people in general and artists in particular should be so insulated from them. This is largely our fault for not taking more time to communicate, and perhaps for assuming that the ideas will not be comprehensible to those outside our field. Here are two examples of things most people don't know: In an article having to do with weaving I once read that a yellow warp plus a blue weft gives a green cloth—even though since Newton's time, in the 1600s, we have known that what you get is white or gray. And most people seem to regard a charcoal drawing or a black-and-white movie as something artificial and out of the reach of our normal experience, whereas our vision in dim light *is* black-and-white, and consequently color blindness *is* part of everyday—or everynight—experience.

This is not to say that we now have a sufficiently deep or incisive understanding of visual science to explain why a Vermeer is superior to an everyday newspaper cartoon. Our knowledge of visual science is rudimentary; it goes as far as three or four stages of visual cortex, whereas we know that there are at least several dozen further stages in the occipital lobes alone, none of which are yet explored. We know about some of the early building blocks of vision, much more than we did fifty years ago, but we still have no idea of what happens in the brain when we recognize a hat, a safety pin, or a boat, or when we look at a painting that has intense emotional content. But we are beginning to understand some elementary things fairly well: why yellow plus blue light makes white, why equiluminant colors shimmer, why a black object remains black whether seen in dim light or on the beach.

The book you are about to read answers some of these questions. It also makes the point that art depends ultimately on our brains and that by understanding what goes on in our brains when we look at a work of art we can hope to deepen our appreciation of both the art and the science. That the two are so separated is an artificial product of the way our knowledge is subdivided in academic circles. One of the purposes of this book is to overcome the separation, and no one is more capable of starting the process than Margaret Livingstone.

David Hubel

I AM A NEUROPHYSIOLOGIST. I spend my time investigating why some nerve cells in our visual systems are sensitive to color whereas others are not. In the process I have become particularly interested in something that artists have been aware of for a very long time: that color and luminance (or lightness) carry different kinds of visual information.

The elements of art have long been held to be color, shape, texture, and line. But an even more fundamental distinction is between color and luminance. Color (in addition to reproducing objects' surface properties) can convey emotion and symbolism, but luminance (what you see in a black-and-white photograph) alone defines shape, texture, and line. Pablo Picasso described it aptly in a letter to the poet Guillaume Apollinaire: "Colors are only symbols; reality is to be found in lightness alone."

While most people are comfortable talking about color, luminance—even though it is more fundamental—seems less familiar. Given two patches of gray, it is easy to say which is lighter, but given two colors, it is often difficult to make such a distinction. Artists, however, must learn to distinguish differences in luminance independent of color. "If one is not able to distinguish the difference between a higher tone and a lower tone, one probably should not make music. If a parallel conclusion were to be applied to color, almost everyone would prove incompetent for its proper use," wrote artist and art teacher Josef Albers. "Very few are able to distinguish higher and lower light intensity (usually called higher and lower value) between different hues.... Only a minority can distinguish the lighter from the darker within close intervals when obscured by contrasting hues or by different color intensities."

In this book I will explore luminance and color, from the physics of light to information processing in the brain. Then I will examine how the neurophysiological differences between the color and luminance pathways can elucidate the different roles color and luminance play in art. The research I've been involved in shows that color and luminance do carry quite different kinds of visual information, and those differences can explain how color and luminance can play such different roles in art. Throughout, I will analyze how various works of art reflect different properties of our visual system. I will draw most heavily from the work of Impressionist artists because they developed many techniques whose effects derive from the parallel architecture of our visual systems.

Of course our visual systems do not process color and luminance separately in order to see illusions in art, but rather for evolutionary reasons. Other scientific observations about the way our brains work can explain such things as why a concept like "line" is so fundamental in art, when in natural scenes there are no lines.

We will explore these—and many other phenomena related to light and vision as well as color and luminance—in the chapters that follow.

TWO PEOPLE, Bevil Conway and Sharon AvRutick, contributed substantially to this book. Bevil was my graduate student and is now a postdoctoral fellow. He is an artist and a scientist, a rare combination; many of the ideas, or clarifications of ideas, in this book arose from discussions I had with him. Sharon edited this book. If you tore up all the pages, tossed the fragments in the air, and then read them as you picked them up, you'd have some idea of what she started with. All the dashes are hers. Thanks to Helene Silverman for doing such a wonderful job with the layout.

John Shearman, Roy Perkinson, Elizabeth Panzer, and Michael Fisher kept me from making more stupid mistakes about art history than I have. Wade Regehr and David Hubel caught some of the mistakes I made about science. Thanks to Eric Himmel for making me read Gombrich. The Mind Brain Behavior Initiative made it possible for Bevil and me to go to Paris and measure the luminance of the sun in *Impression Sunrise.*

Special thanks to Mei Tseng.

1:

FIAT LUX: LET THERE BE LIGHT

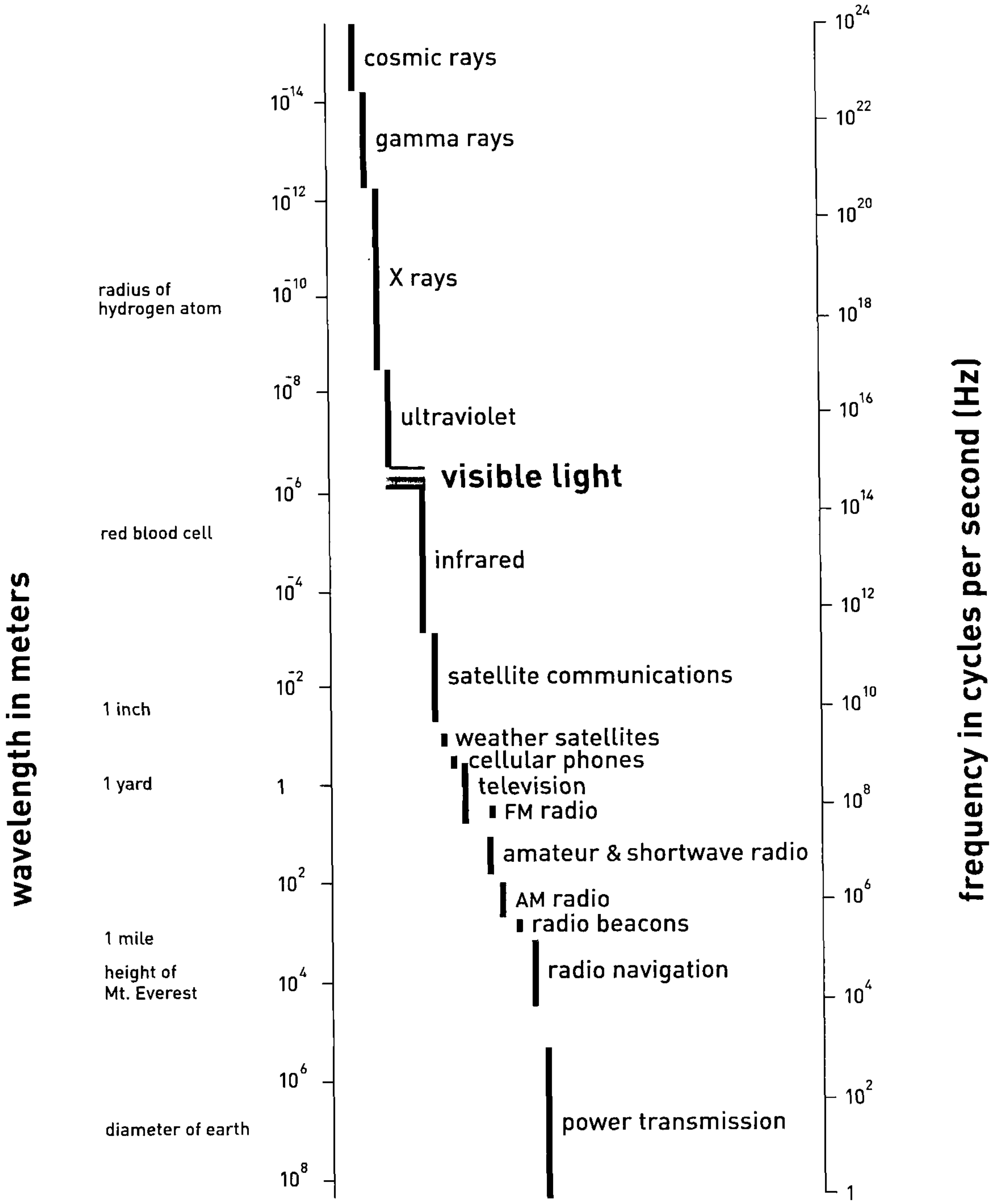
Opposite: The electromagnetic spectrum comprises all energy that moves at the speed of light. In this diagram wavelength and frequency of the electromagnetic spectrum are on the left and right axes, respectively. The different classes of energy are indicated for each region of the spectrum, with some familiar items for length comparison (left). Visible light is a relatively narrow region of the entire electromagnetic spectrum.

YOU MAY BE SURPRISED, or perhaps chagrined, to find that this book about art begins with a chapter on physics. This book is actually about the science of vision—the process of receiving and interpreting light reflected from objects—and what it can tell us about how artists achieve various effects. To enable you to get the most from what I've written, this first chapter will refresh your knowledge about the nature of light, what makes colored objects colored, and how different ways of generating light can produce vastly different mixtures of wavelengths. As the nineteenth-century English physicist Thomas Young said, "The nature of light is a subject of no material importance to the concerns of life or to the practice of the arts, but it is in many other respects extremely interesting."

LIGHT

As early as the fifth century BC the Greeks recognized that there had to be some kind of link between the eye and objects seen. The nature of this link (which we now know is light), along with the most basic facts about vision, however, eluded people for thousands of years. Some schools of thought held that there was an emission, or fire, emanating from the eye that traveled to and palpated the object seen. Others favored the inverse: that objects seen emitted a substance that traveled into the eye. And a third faction suggested that both sorts of emissions existed; when they met, it was said, vision resulted. In the fourth century BC Aristotle rejected the idea of a visual fire emanating from the eye, because, he asked, "If vision were produced by means of a fire emitted by the eye,

THE ELECTROMAGNETIC SPECTRUM



Opposite: The sun and a fluorescent light produce different amounts of energy at different wavelengths of visible light. Sunlight is broadband (consisting of a wide range of wavelengths), while fluorescent light consists of narrow peaks of light, corresponding to the emission peaks of the electrically excited compounds inside the glass tubes. These two very different compositions of wavelengths both look white to us because our eyes have only a small number of kinds of light-activated receptors.

like the light emitted by a lantern, why then are we not able to see in the dark?"

The Arab physicist Alhazen in around AD 1000 concluded from experimental observations that light actually travels into the eye. The first observation was that "the eye, when looking at a very strong light, feels pain and may be damaged." The second was that the eye registers an afterimage after looking at a bright light. Nevertheless, five hundred years later, at the time of Leonardo da Vinci, the idea that rays emanate from the eye to palpate the viewed object was still prevalent enough that Leonardo objected, "It is impossible that the eye should send the power of vision outside itself through visual rays, because, on opening the eye from whence such rays must depart, the power of vision could not reach out to the object without a lapse of time. This being so, the rays could not climb in a month to the height of the sun, when the eye wished to see it."

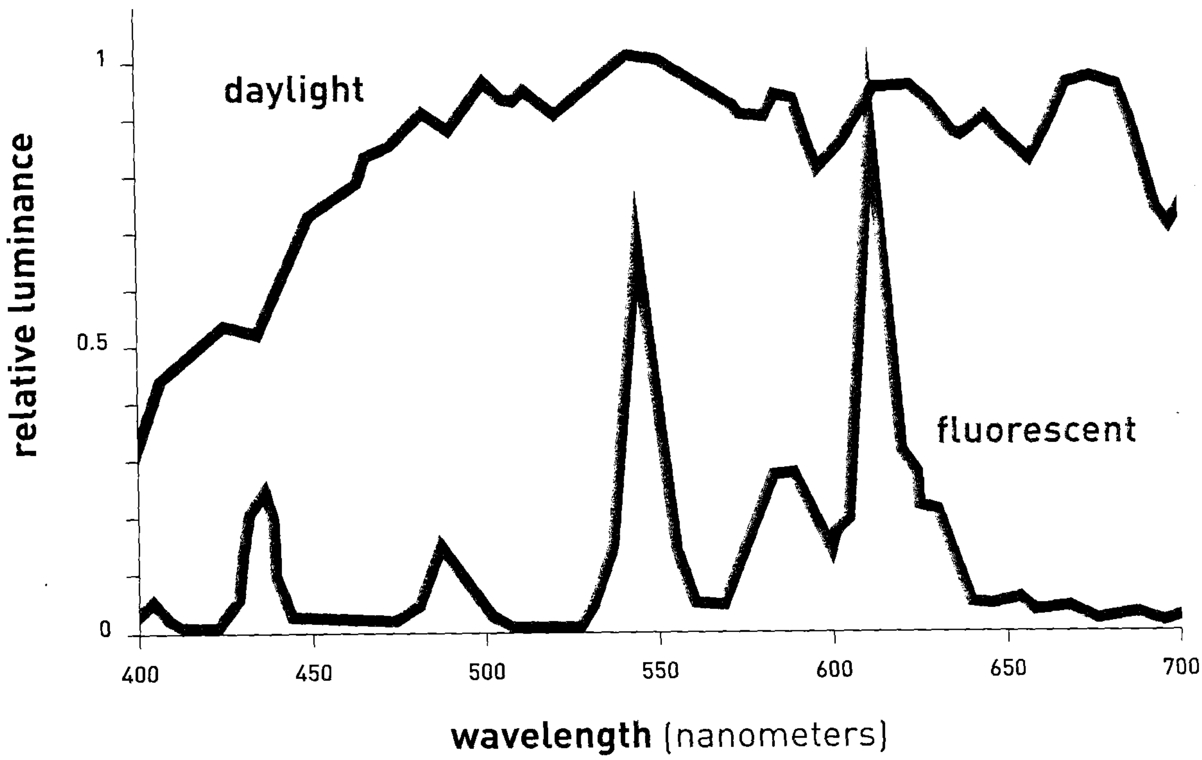
In 1604 Johannes Kepler first elaborated the modern idea that light is emitted by sources like the sun and is then reflected from objects into the eye. He thought that light is intrinsically colorless but is "broken" and becomes colored when it encounters a colored object. His contemporary Galileo nevertheless felt that no one yet really understood the nature of light. "I have always considered myself unable to understand what light was," he said, "so much so that I would readily have agreed to spend the rest of my life in prison with only bread and water if only I could have been sure of reaching the understanding that seems so hopeless to me."

A major leap in the understanding of light came in 1672 with the work of Isaac Newton. He darkened a room by closing his window shutter, and then he made a small hole in the shutter. He put a triangular piece of glass in the sunbeam passing through the hole and discovered that such a prism divides white light into various colors, which he called "variously refrangible" (that is, they were bent to a greater or lesser degree by the prism). He discovered that the color of a beam of light is a permanent feature of that light; it cannot be further broken into some other color. He also discovered that colored lights can be recombined to yield white light.

The nature of light was hotly disputed in Newton's time, in particular the question of whether it was formed of particles or waves. Some of Newton's results, such as the variable bending of different colors of light by prisms, suggested that light had characteristics of waves, but the fact that light does not bend around obstacles in the manner of sound or water waves was thought to favor a particulate nature. Newton, sensibly, presented evidence supporting both hypotheses and tried not to be definitive. Still, in his great work *Opticks*, published in 1704, he came down marginally in favor of the particle ("corpuscule") theory of light, and he proposed that the different colors of light have different masses. Though Newton had reservations about his conclusion, because of his stature, the corpuscular theory reigned supreme for a hundred years.

The ascendance of the wave theory, however, was eventually brought on partly by experiments Newton himself had performed. In 1802 Thomas Young carefully pointed out that despite Newton's ultimate preference for the corpuscular theory, he had recognized that light must have some characteristics of "undulations" or must somehow induce "vibrations" in the "æther" it passed through. Newton had extended observations first made by Robert Hooke (the inventor of the compound microscope) on the brilliant colors often seen in thin films of water or oil and found that the colors varied systematically with the thickness of the film. Young argued that this indicated that light was

WAVELENGTHS IN DAYLIGHT AND FLUORESCENT LIGHT



wavelike in character. In 1802 it was almost sacrilegious to suggest that Newton, who by that point was synonymous with the particulate theory, might have been wrong about something. Despite the fact that Young lauded Newton throughout his treatise, the wave hypothesis was initially very unpopular. British statesman Henry Brougham harshly reviewed Young's ideas: "It is difficult to deal with an author whose mind is filled with a medium of so fickle and vibratory a nature . . . ; We now dismiss . . . the feeble lucubrations of this author, in which we have searched without success for some traces of learning, acuteness, and ingenuity, that might compensate his evident deficiency in the powers of solid thinking." But in the end Young's logic prevailed. By the mid-nineteenth century other scientists had provided strong evidence that light consists of waves.

In 1905 Albert Einstein postulated that the wave theory of light might be incomplete, and that light has some characteristics of particles after all. He proposed that there are indivisible units (or quanta) of light energy, which we now call photons, and that these bits of energy travel in a wavelike manner. Quantum mechanics is a mathematical explanation of how electromagnetic radiation can have both wavelike and particle-like characteristics. Fortunately we don't need quantum mechanics in order to explain the phenomena we shall discuss in this book.

The most basic question about light—what is it made of?—also was not settled until the nineteenth century, when the great theoretical physicist James Clerk Maxwell finally deduced that light is just one part of a huge continuous spectrum of electromagnetic radiation. All electromagnetic radiation, including light, travels through a vacuum at exactly the same characteristic speed of 186,000 miles per second. Visible light is not qualitatively distinguishable in any way from the rest of the spectrum. It shares many characteristics with X rays and microwaves. The only reason it is so special to us is that we have receptors in our eyes that are selectively responsive to just its range of wavelengths, wavelengths between 370 and 730 nanometers (0.00000037 to 0.00000073 meters).

Electromagnetic radiation, including light, is emitted when charged particles, like electrons, move. The wavelengths emitted can cover a wide range or be very specific. Applying heat is one way to create electromagnetic radiation; the hotter objects get, the shorter the wavelengths emitted. If you heat up a piece of metal, it gives off shorter and shorter wavelengths until around 1000° F, at which point it begins to emit visible light. You may have noticed that light from a lamp on a dimmer switch looks reddish (longer wavelength) when it is turned down low, and bluer (shorter wavelength) when you turn it up. You may also have seen that you can set the "white point" on a computer monitor by defining it as a temperature.

A different way atoms can emit radiation is when specific electrons are bumped from one energy level to another. This can happen when free electrons, like ones from an electric current, collide with the electrons already present in a compound like neon or mercury vapor. When the electrons jump back down to their resting state, they emit a photon of a particular wavelength.

These two ways of creating electromagnetic radiation result in different kinds of light: incandescence and luminescence. Incandescence is the production of light by heated materials: the sun, fire, and tungsten lamps (regular lightbulbs) produce incandescent light. Fluorescent lights, fireflies, televisions, computer monitors, and lasers produce luminescent light, which results from specific excitation and emission of electrons and is a lower-temperature reaction. Since incandescence is the result of heat, a nonselective process, incandescent light is nonselective, containing many wavelengths. Luminescence, on the other hand, tends to be more specific. The photon emitted when an electron drops back into an unexcited state usually has a characteristic wavelength, so the light emitted is usually a single color. Different compounds undergoing excitation/emission processes release different characteristic wavelengths of light.

White light can be created equally well by incandescent and luminescent light sources. The multiple wavelengths of incandescent light mix together, as do the narrow emission peaks of fluorescent light, and both appear white.