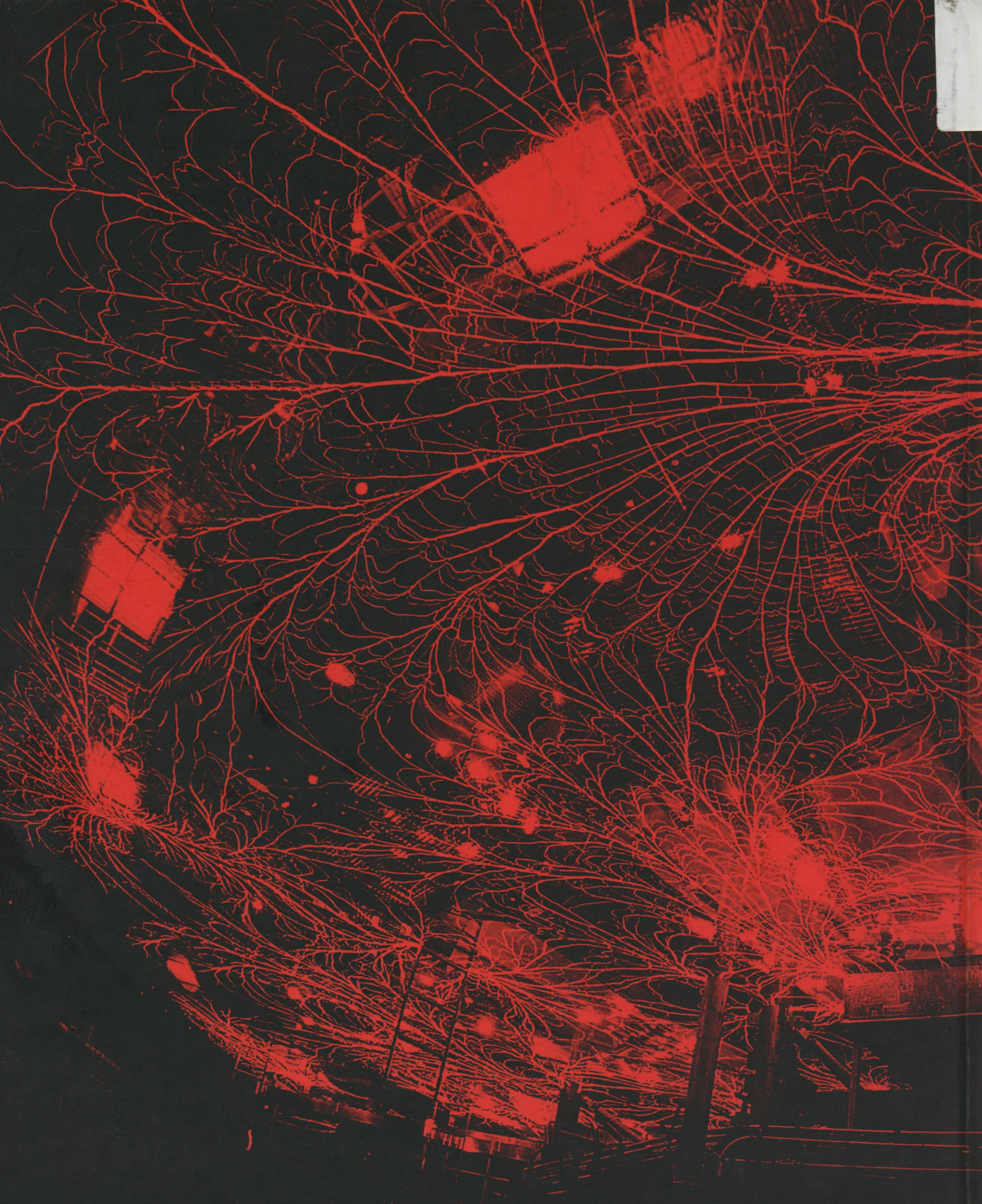

Editor: Eric Himmel
Designer: Ellen Nygaard Ford

Library of Congress Cataloging-in-Publication Data

Suplee, Curt.
Physics in the twentieth century / Curt Suplee ; edited by Judy R. Franz and John S. Rigden
p. cm.
Includes index.
ISBN 0-8109-4364-6
1. Physics—Popular works. I. Franz, Judy R. II. Rigden, John S. III. Title.
QC24.5.S86 1999
530—dc21 98-41306

Published in 1999 by Harry N. Abrams, Incorporated, New York

Printed and bound in Japan

Harry N. Abrams, Inc.
100 Fifth Avenue
New York, N.Y. 10011
www.abramsbooks.com

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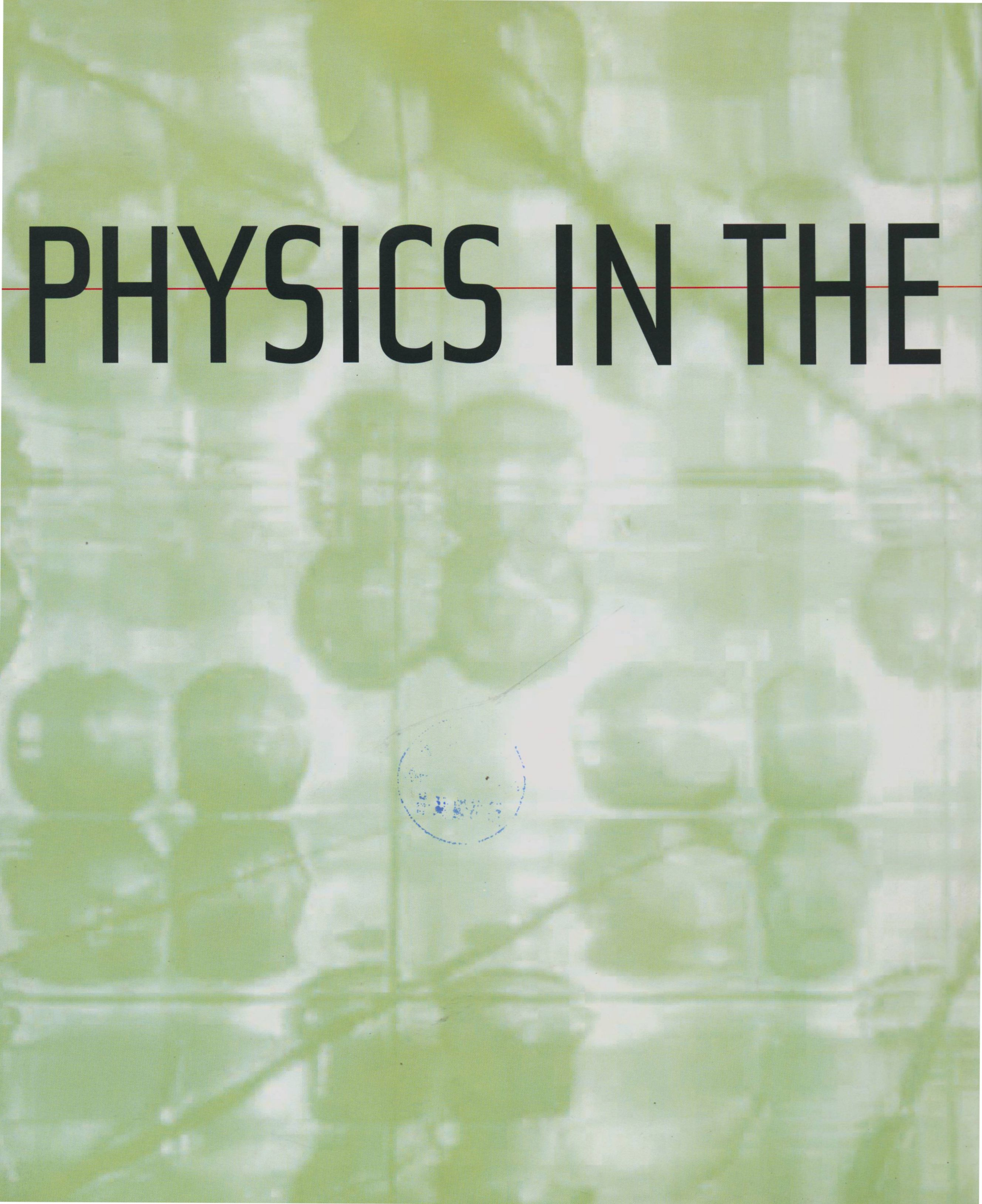

20TH CENTURY

Curt Suplee

Edited by Judy R. Franz
and John S. Rigden

Harry N. Abrams, Inc., Publishers
in association with
the American Physical Society and
the American Institute of Physics

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INTRODUCTION

The twentieth century dawned on an era of exuberant confidence in the power of science and technology to explain the world and to improve the human condition. For scientists and non-scientists alike, that optimism was well founded. The Victorian period had witnessed an incessant parade of scientific and technological astonishments. Thanks to progress in thermodynamics, heat engines—including the newfangled internal combustion engine—had imbued industry with new power. Factories thundered. Railroads roared. Airships cruised the skies. Automobiles hit the road.

Electrical energy, though not yet widespread, promised to transform the nature of daily life. In motors and generators, it would relax the toll on human muscle; in electric lights, it would vanquish darkness itself. Radio waves had been observed for over ten years, telephone communication was becoming possible, and the first Morse code signals were about to cross the Atlantic. Physicists were beginning to understand the nature of that most evanescent substance, light, as a form of electromagnetic radiation. Its speed of 186,300 miles per second had been confirmed to an excellent approximation.

Civilization had every apparent reason to bask in a sense of gathering comprehension of—and thus encroaching dominion over—the objects and energies in the universe. And most educated people shared some of the burgeoning excitement the poet Tennyson felt when he described himself as an "heir of all the ages, in the foremost files of time," content to "[l]et the great world spin forever down the ringing grooves of change."

Beneath it all lay the orderly, predictable, and reassuring cosmos as depicted by Isaac Newton, still imperturbably intact after nearly three hundred years of progress. Newton's classical mechanics—the science of the transfer of forces and the response of matter to those forces—had been refined and extended, but remained the preeminently successful instrument for understanding the way nature worked. By the end of the nineteenth century, writes physics historian Andrew Whitaker, those laws "were held to be among the greatest human achievements, indeed the very greatest strictly scientific achievement, and practically a direct revelation of divine intent." So in 1900, "it seemed unthinkable that they could be challenged."

Nonetheless, strange, unsettling new phenomena were observed in laboratories in Europe and America. Perhaps the most mysterious developments were in the field of radiation, where oddities abounded. Negative electrodes were seen to emit bizarre emanations called "cathode rays." Something called the "X-ray" had just been revealed—a kind of beam that could pass through solid matter almost unimpeded. Equally baffling was the newly discovered process called "radioactivity," in which certain substances appeared to give off an inexplicable form of radiation that could fog a photographic plate.

At the outset of the twentieth century, no scientific topic was more exciting than the newly discovered phenomenon of radioactivity. And no one did more to further the understanding of that mysterious process than Marie and Pierre Curie, shown here shortly before Pierre's untimely death in 1906. Their landmark work—including discovery of the elements polonium and radium—forced a broad rethinking of fundamental principles and made it possible for physicists to investigate the structure of the atom.

Researchers were about to discover that these entities obeyed rules very different from those that governed classical objects such as billiard balls or planets orbiting the sun. In fact, as science began to examine nature at smaller and smaller scales, it soon became clear that a whole new set of concepts would be required to account for a growing body of problems—especially the vexing question of how to determine the energy content of electromagnetic waves. Scientists could begin to explain why a piece of metal placed in a forge glowed red when it emitted long-wavelength radiation; but theory demanded that it should also emit a large amount of radiation at shorter wavelengths, and that

was plainly not the case. And whereas British theorist James Clerk Maxwell had devised an elegant set of equations to describe the wave properties of light, it sometimes behaved in a seemingly unwavelike manner.

Moreover, many scientists still believed that light, like any other wave, needed a medium in which to propagate. Thus the Earth and all other celestial bodies must be surrounded by, and pass through, a hypothetical fluid called the lumeniferous ether. Maxwell insisted that "there can be no doubt that the interplanetary and interstellar spaces are not empty, but are occupied by a material substance or body which is certainly the largest, and probably the most uniform body of which we have any knowledge." However, a cunning and highly accurate experiment conducted by American physicists Albert Michelson and Edward Morley in 1887 found absolutely no evidence of this ghostly medium.

Similarly, although the upstart science of electricity was producing marvels, very little was known about what electricity actually *is*, or what physically happens when a current flows. The electron, nature's chief communicator of negative charge, had been discovered in 1897. But what this "atom of electricity" did, and how it was related to the overall configuration of atoms, was beyond the current state of science.

So was the structure of the atom itself—if, in fact, such things really existed. The hypothetical notion of a single, indivisible atomic unit had been used pragmatically in chemistry to determine the ratios in which various elements combine and statistically in thermodynamics to calculate the motion of large arrays of matter such as gases. But at the end of the nineteenth century, no one was quite sure what atoms *were*, or how they were built. Nor did they understand the physical nature of the bonds that linked atom to atom and gave the periodic table such valuable predictive power. And scientists could not yet even imagine the factors governing the intimate, intricate relationships between atomic behavior and the macroscopic properties of materials—a field that would become the modern discipline of condensed-matter physics.

On the macroscopic scale, there was considerable disagreement over the age of the sun and the Earth. Such grand figures as Hermann von Helmholtz and William Thomson (Lord Kelvin) had theorized that the source of the sun's heat was gravitational collapse of its mass. They calculated that the Earth and its star could not be too much older than 20 to 40 million years.

However, that figure was drastically at odds with the measurements of geologists and paleontologists, who pointed out that some terrestrial surface features such as the Grand Canyon would have taken more than 25 million years to form. But no one could be reasonably certain how long anything had lasted because there was no acceptable benchmark for dating materials of such stupendous ages. And none would be found until physicists began to understand how radioactive elements break down over precise and predictable time scales.

But of all the subjects of physical science, perhaps none epitomized the late-nineteenth-century paradox of enormous progress and lingering incomprehension as much as the cosmos. An intelligent, well-educated person gazing up at the night sky in 1900 would have known about planetary orbits and other gravitationally bound systems around our sun, a bit about comets, and a fair amount about ways astronomers characterized and catalogued visible objects in the heavens.

No one had begun to understand why stars shine, or how they are arranged in the heavens, or how far away they are. In fact, there was no suitable approximation of the size of the universe (though some adventurous minds had postulated its scope at a few light years), or any idea of how it might be moving or evolving on grand scales. Many observers believed that our galaxy, the Milky Way, *was* the universe.

Within a few decades, all of that would change forever, as revolutionary discoveries altered thousands of years of human history in an accelerating expansion of knowledge that continues to this hour. At the largest scales, Einstein's theory of relativity utterly destroyed the traditional views of space and time. Space, the world learned to its shock, warped and buckled in the presence of mass. Time was not a universal constant; from Earth's perspective, it ran at completely different rates in different locations.

At the smallest scale, traditional thinking turned out to be practically useless. Exploring the uncharted realm of matter and energy at atomic dimensions, physicists found that nature follows an entirely unexpected and wholly different set of principles from the familiar Newtonian systems. Particles—unlike things in the dependable, predictable world of everyday objects—do not have a definite position or other characteristics. In fact, many physicists would argue, they do not "exist" in the conventional sense at all unless they are observed!

Matter can become energy; energy can turn into matter. Light is neither a particle nor a wave; it is both, or either, at different times. Even the emptiest vacuum is seething with activity as particles pop into and out of existence. Elements transform themselves into other elements by splitting or fusing, releasing energy of unimaginable magnitude. Electrons travel through materials according to complex but comprehensible causes and sometimes do so without encountering any resistance.

As the new knowledge of atomic and subatomic entities grew, scientists found ways to apply it to objects as small as the circuits on computer chips and as large as the violent death spasms of giant stars. As early as 1905, Ernest Rutherford would marvel, "The rapidity of this advance has seldom, if ever, been equaled in the history of science."

In 1999, those sentiments are just as accurate. The world as it is now understood differs more dramatically from the Victorian view than the science of Galileo, Copernicus, and Newton differed from that of Aristotle. By the end of this century of wonder, physics would transform nearly every aspect of daily life. It would also permanently alter our vision of reality, the universe we inhabit, and our peculiar and enigmatic place in it.

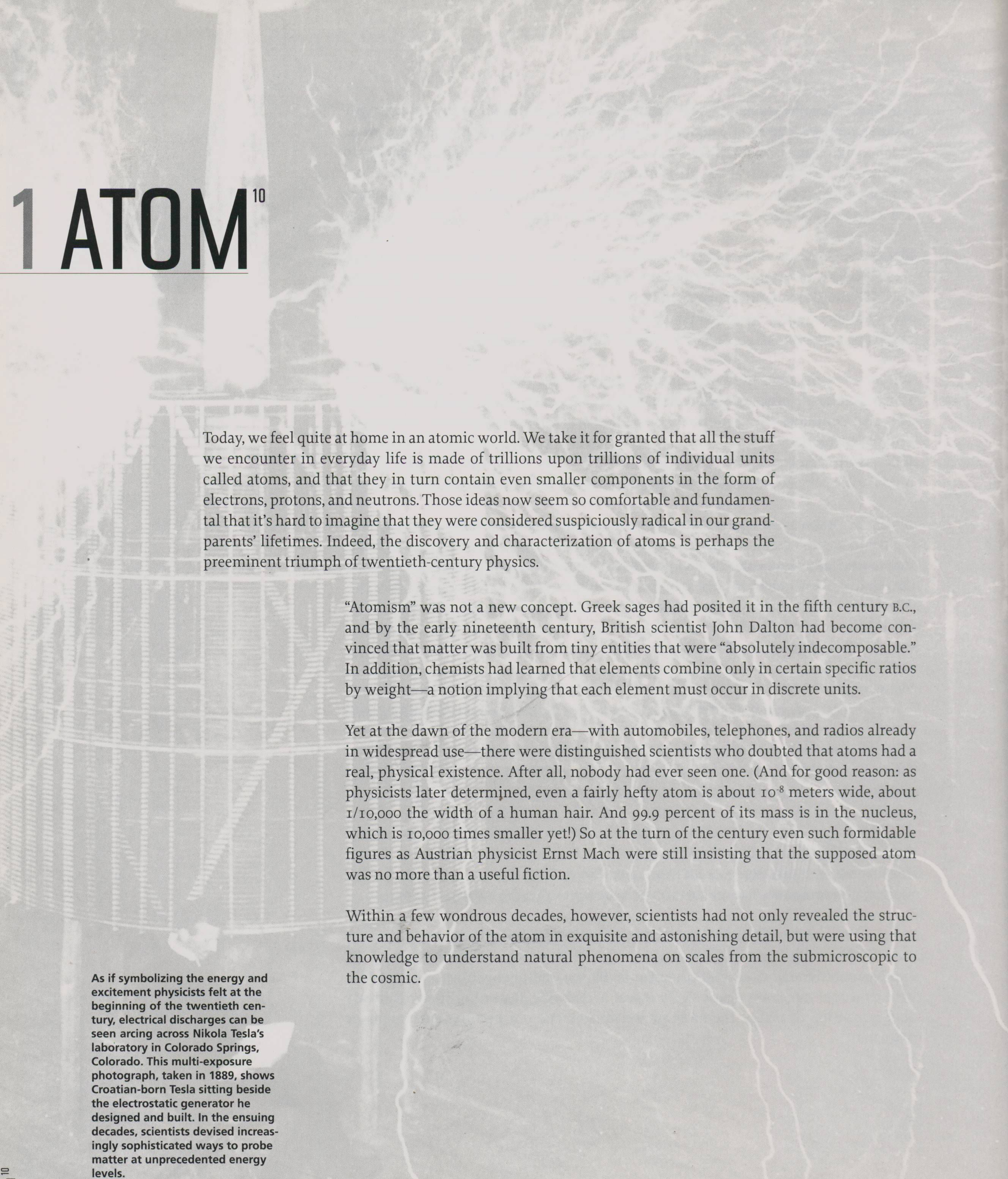
1 ATOM[10]

Today, we feel quite at home in an atomic world. We take it for granted that all the stuff we encounter in everyday life is made of trillions upon trillions of individual units called atoms, and that they in turn contain even smaller components in the form of electrons, protons, and neutrons. Those ideas now seem so comfortable and fundamental that it's hard to imagine that they were considered suspiciously radical in our grandparents' lifetimes. Indeed, the discovery and characterization of atoms is perhaps the preeminent triumph of twentieth-century physics.

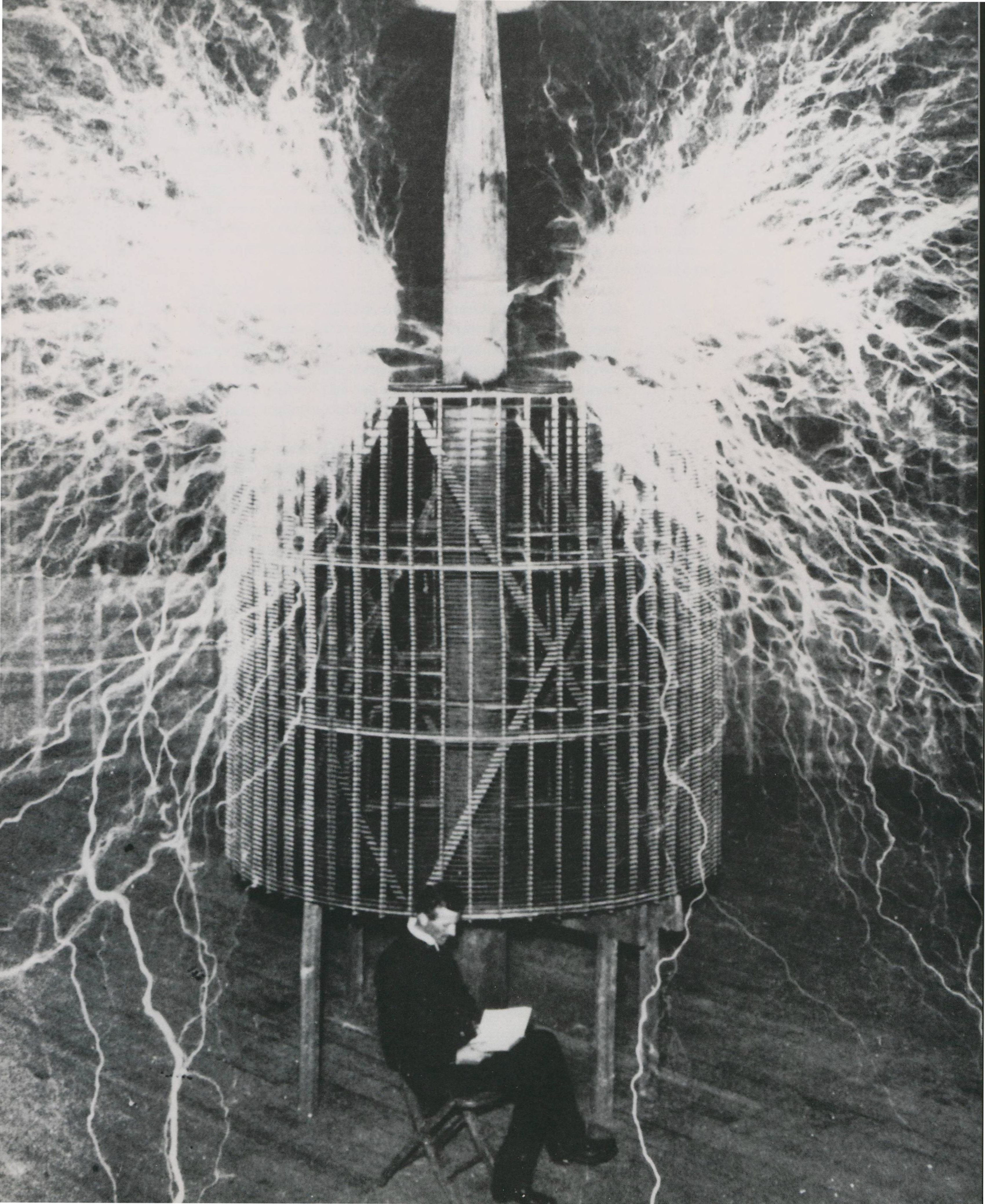
"Atomism" was not a new concept. Greek sages had posited it in the fifth century B.C., and by the early nineteenth century, British scientist John Dalton had become convinced that matter was built from tiny entities that were "absolutely indecomposable." In addition, chemists had learned that elements combine only in certain specific ratios by weight—a notion implying that each element must occur in discrete units.

Yet at the dawn of the modern era—with automobiles, telephones, and radios already in widespread use—there were distinguished scientists who doubted that atoms had a real, physical existence. After all, nobody had ever seen one. (And for good reason: as physicists later determined, even a fairly hefty atom is about 10^{-8} meters wide, about 1/10,000 the width of a human hair. And 99.9 percent of its mass is in the nucleus, which is 10,000 times smaller yet!) So at the turn of the century even such formidable figures as Austrian physicist Ernst Mach were still insisting that the supposed atom was no more than a useful fiction.

Within a few wondrous decades, however, scientists had not only revealed the structure and behavior of the atom in exquisite and astonishing detail, but were using that knowledge to understand natural phenomena on scales from the submicroscopic to the cosmic.



As if symbolizing the energy and excitement physicists felt at the beginning of the twentieth century, electrical discharges can be seen arcing across Nikola Tesla's laboratory in Colorado Springs, Colorado. This multi-exposure photograph, taken in 1889, shows Croatian-born Tesla sitting beside the electrostatic generator he designed and built. In the ensuing decades, scientists devised increasingly sophisticated ways to probe matter at unprecedented energy levels.



Electrons

The first convincing clue was the discovery of the electron—or, as it was then known, the "cathode ray." In the mid-nineteenth century, scientists had found that if electrodes were placed in a vacuum tube, the negative pole, or cathode, appeared to emit some strange form of radiation. By the 1890s, voltage generators had become powerful enough, and vacuum conditions good enough, that this effect could be observed in detail. But no one knew what it *was.*

Many Continental researchers were betting that it was indeed radiation. German physicist Heinrich Hertz had shown that cathode rays could penetrate a thin metal foil, which was very ray-like behavior. Moreover, X-rays and radioactivity had just been discovered, and mysterious sorts of radiation suddenly seemed to be cropping up almost monthly. But some British physicists had suspected for years that the rays were actually streams of an unknown kind of particles carrying negative electrical charges.

One of the physicists was Joseph John (J. J.) Thomson, son of a Manchester bookseller, who in 1884 had been elected as director of Cambridge University's famed Cavendish Laboratory. In the mid-1890s, he set out to examine the phenomenon using a then-high-tech apparatus designed by Sir William Crookes. The device was in many ways no different from a modern television set: in a sealed glass tube from which most of the air had been pumped to create a vacuum, the cathode emitted its rays in straight lines that made sections of the glass near the cathode glow brightly, just as a TV "electron gun" shoots particles at a glass screen coated with phosphors.

Thanks to the laws governing the interaction of charges and fields—worked out in the nineteenth century by British physicists Michael Faraday, James Clerk Maxwell, and others—Thomson knew that if cathode rays were actually streams of charged particles, they should be deflected by electric and magnetic fields. The direction in which the beam was bent would reveal the type of charge, and the amount of the deflection would depend on the size of the charge and the speed of the particles.

Previous attempts to demonstrate this effect had failed. But Thomson surmised that the fields might have been too weak. Using improved induction coils and a better vacuum, he found that he could bend the beams, causing the glow to shift to a different part of the tube. In 1897, he wrote, "I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter." He had also been able to determine the ratio of the mass to the charge. Though he could calculate neither quantity separately, it appeared likely that the mass was shockingly scant—around 1/1,000 that of the positively charged hydrogen ion, which had been approximated by chemists and was "the smallest mass hitherto recognized as being capable of a separate existence."

(More than a decade would pass before American physicist Robert Millikan was able to determine the new particle's charge accurately. First he noted how fast tiny oil droplets fell in air. Then he induced an electric charge on the droplets that would push them in the opposite direction and measured how much charge was necessary to propel them upward. His data came out in multiples of a single, presumably minimal charge. In

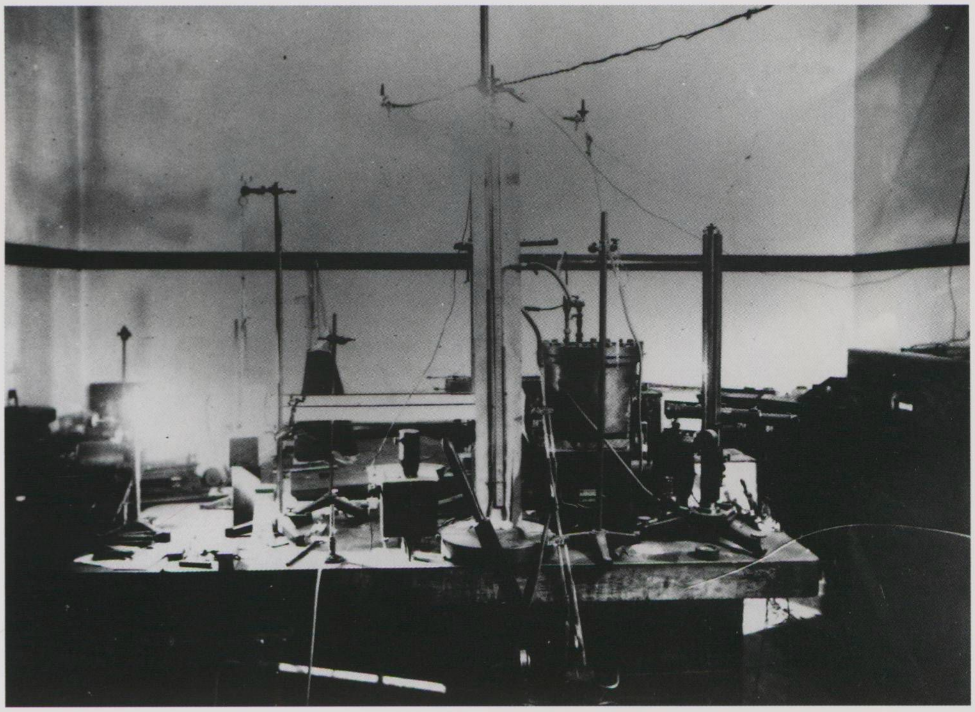
1909, he determined this quantity to within a few percentage points of the currently accepted value. Once he had established the charge, he could calculate the mass, which would prove to be 1/1,837 that of the hydrogen nucleus.)

Thomson had called his particle a "corpuscle." But the name that stuck had been invented in 1891 by his Irish contemporary G. Johnstone Stoney: "electron." Its discovery jolted science into a new way of imagining the composition of matter—and suddenly raised several serious questions.

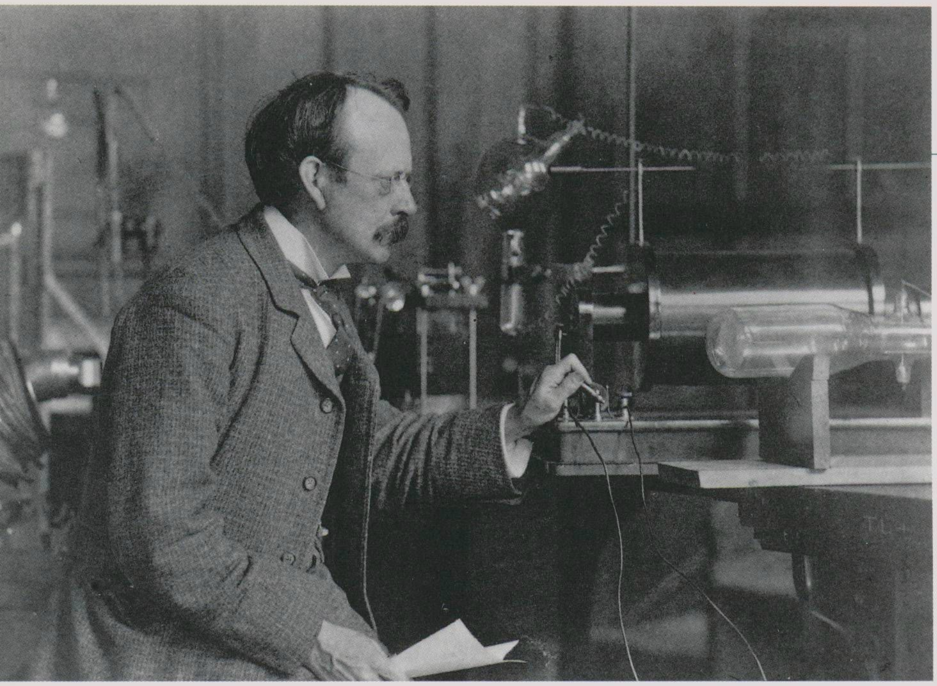
For one thing, if atoms existed, they were supposed to be the smallest elementary units of matter. But here was something thousands of times smaller. And it couldn't be the atom itself. Scientists had long known that, if there were such things as atoms, they were electrically neutral, although they could be made to take on a positive charge (that is, become ions) if exposed to enough energy. Today, we understand that the energy dislodges one or more electrons, leaving the ionized atom with a net positive charge from the protons in its nucleus.

At the end of the nineteenth century, however, all Thomson knew was that if the electron was negative, something in the atom had to carry a corresponding positive charge. But what was it? And how were the charges arranged?

Various ingenious models were proposed. But early in the twentieth century the favored conception was the one endorsed by Thomson: an atom was a composite in which a number of electrons are imbedded in a wad of undifferentiated positive matter "like raisins in a pudding." This agreeable notion didn't last long.

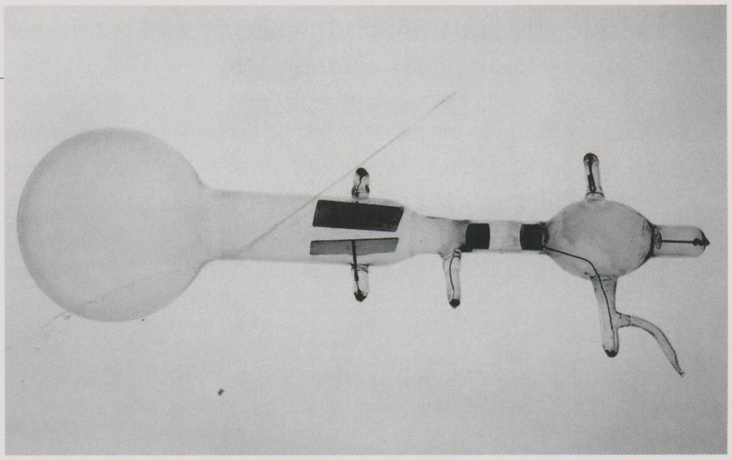


This is the device built and used by Robert Millikan in 1913 to determine the electrical charge of the electron. By measuring the speed with which electrically charged droplets of oil fell through electric fields of various strengths, Millikan arrived at a result that differs by less than 3 percent from the current accepted value.



British physicist J. J. Thomson ushered in a new era of subatomic physics by discovering the electron in 1897. Here he is shown in the 1890s with the apparatus he used to determine the ratio of the electron's electrical charge to its mass.

This device, designed by Thomson, was crucial to his experiments. Air was pumped out of the glass enclosure so that electrons (then known as "cathode rays") would not collide with gas molecules. The negatively charged cathode at the far right generated electrons that were accelerated toward a positively charged plate with a slit in it. Some electrons passed through the slit, and proceeded at about one-tenth the speed of light toward the large bulb at the left, where the beam made a luminous spot when it collided with the glass at far left. As the electrons passed by two more electrodes, mounted on the top and bottom of the glass just before the large bulb, they were deflected from side to side. The amount of deflection depended on the voltage between the two electrodes. By applying a magnetic field from outside coils (not shown) that exactly balanced the deflection, Thomson was able to find the essential ratio between the charge and mass of the electron. Once the charge was known, the mass could be calculated.



A century after Thomson's experiments, the successor to his cathode-ray bulb is the modern particle detector, which takes millions of measurements in a fraction of a second to determine the mass, charge, and other characteristics of various particles. This detector, shown in construction at the Stanford Linear Accelerator Center in California, surrounds the open particle beam collision chamber at the center.