CHAPTER ONE

RÖNTGEN'S INHERITANCE

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"In the history of Science, nothing is more true than that the discoverer, even the greatest discoverer, is but the descendant of his scientific forefathers; he is always essentially the product of the age in which he is born." Thus British physicist Sylvanus P. Thompson addressed the Roentgen Society in London on 5 November 1897. We are celebrating the centennial of one of the most famous events in scientific history: Roentgen’s discovery of X rays. It is not unreasonable to ask what led to this remarkable event. Certainly Roentgen did not create X rays out of nothing. What was his inheritance—what had his scientific forefathers bequeathed to him? What equipment, knowledge, perceptions, physical principles, and experience did Roentgen have to work with? How was he shaped by his times? What were his characteristics as a scientist and a man, and what concepts did he bring with him to the laboratory at Würzburg?

Roentgen, very much a product of the nineteenth century, was influenced by the tide of developments in science, technology, philosophy, economics, politics, and religion. This chapter examines some of these developments not only in physics, but in the other areas as well, since physics was very much influenced by them. Because the principal focus of this chapter is on physics as Roentgen inherited it and on the world as he saw it, greater emphasis will be placed on developments in Germany, although of course many countries contributed to the amazing progress made in that century. This chapter is not a biography of Roentgen, but it attempts to give the reader some flavor of what it was like to live and work in those times, what state of affairs Roentgen inherited, and what people and events most influenced him.

GENERAL OBSERVATIONS ABOUT THE NINETEENTH CENTURY

Mark Twain once noted that the most profound development in the nineteenth century was the general realization that a new idea could have value. If there was an underlying theme to the time, it was this: a willingness to accept new ideas. Soon new ideas were being actively sought out, with tremendous progress in intellectual curiosity and the means to satisfy it, along with some false starts. It has been claimed that the nineteenth century saw more changes in human life and thinking
than had been achieved in the previous two thousand years. By the end of the century Western civilization had completed (or at least thought it had completed) its final conquest of the entire world. Alfred Russel Wallace, who with Darwin formulated the theory of evolution by natural selection, called the 1800s "The Wonderful Century." Revamped universities placed greater stress than ever before on new ideas and fostered research and innovation. Scientific journals and societies began to spread information throughout the Western world; scientists could take part in a communications network hitherto undreamed of.

At the same time, scientists of the early nineteenth century had a very limited comprehension of physical principles, compared with the standards of today's college students. They were baffled by phenomena we now take for granted. They lacked the mathematical, statistical, and computational tools that would have saved years of work and might have allowed them to progress further in their thinking (for example, standard deviation and variance were not introduced until 1920; until then scientists could speak only of means and mean deviations).

They were often constrained, whether by custom or necessity, to work alone or with only one or two others, with meager support and many demands on their time. Communication of new knowledge was slow and awkward, especially at the beginning of the nineteenth century, and many scientists wound up duplicating or even contradicting one another's work. Despite all this, the scientists of the 1800s emerge as some of the most innovative, perceptive, and productive scientists of all time.

The form of science as we know it today was forged in the laboratories of the nineteenth century, both in universities and in industry. Goal-oriented research, the quest for inventions or discoveries to fill practical needs, was sired by the Industrial Revolution and born in the factories of England, where machines were developed to manufacture things the hand was too slow or too weak to make, and in the chemical laboratories of early nineteenth-century Germany, where synthetic dyes such as aniline were developed to overcome the need for importing natural dyes such as indigo. Pure science, research for its own sake, was never abandoned, but the public grew to expect more and more from scientists in practical accomplishments that would make their lives easier or safer.

The attitude of scientists and the general public toward science in the latter half of the 1800s was that, if properly developed and harnessed, science could yield only benefits and blessings for mankind (Fig. 1.1). It was only in the
twentieth century, beginning with the use of Nobel's invention, dynamite, in war that the neutrality of science toward the well-being of humanity became apparent: it could kill as well as heal, destroy as well as build. This facet of science was not at all part of its nineteenth-century image.

Harvard's I. Bernard Cohen described how science and technology mushroomed in the nineteenth century:

Industry became increasingly based on science, especially organic and inorganic chemistry, electromagnetism, and animal and plant biology. A science-based technology introduced new forms of human communications—notably the telegraph and telephone—that constituted a revolution in the affairs of men and nations. And, at the same time, the veil of man's ignorance was torn aside to reveal the composition of stars; the origins and descent of man; the evolution of plants and animals; the constitution of matter; the age and formation of the earth; the interconvertibility of natural forces and forms of energy; the laws of electricity and magnetism; and the seemingly all-embracing electromagnetic theory of light. It was in the nineteenth century that science developed into a fully recognized profession, with regular posts and the support system of established research laboratories with paid assistants and technicians. Symbolic of this new status was the conscious invention of the term 'scientist' by William Whewell in 1841.

One recurring and fascinating theme that has lasted from the earliest times to the present is the idea of transmutation. In its most familiar expression it is changing some common metal into gold, perhaps with the help of a "philosopher's stone." But it has taken many other expressions: incurably sick people could become well, perhaps with the help of (in spite of?) some arcane potion; Jekyll could become Hyde; an ape could become a man with the help of evolution; desert could become farmland with the help of water; dinosaurs could be changed into oil; electricity could become magnetism and vice versa; and chemicals could be changed into other chemicals in bewildering profusion. The possibility that X could legitimately become Y under the right circumstances became a driving force among scientists, who no longer saw the object X as being inherently and forever X, as Aristotle had seen it, but potentially Y or, who knows, even Z.

Scientists of the nineteenth century must have been concerned about their image. They were always depicted in illustrations of the time as immaculately dressed, solemn, often hirsute men who
were never seen to wear protective aprons or eye shields. Evidently they carried out their experiments in the same clothes they would wear to weddings or to church. Popular magazines of the late nineteenth and early twentieth centuries showed that even small boys who conducted scientific experiments invariably did so wearing ties (Fig. 1.2).

The Legacy of the Industrial Revolution: Practicality

The Industrial Revolution caused one of the most profound changes in the course of history. Beginning in Great Britain toward the end of the eighteenth century and receiving a boost from some of the new ideas of the French Revolution, it produced an ever-increasing demand for ideas and techniques with practical results (read "marketable"). The Industrial Revolution saw the transformation of sources of energy from animate (horses) to inanimate (steam), the substitution of the precise reproducibility of machines for the variability of humans, the division of production into individual tasks to be performed in factories by machines operated by humans, the development of entirely new materials (steel, novel chemicals), and the gradual shift of the populations of Europe from agrarian to urban (Fig. 1.3).

The effect of this revolution on science also was profound. For the first time there was a real need for a systematic application of new knowledge to more efficient production in industry. For many scientists this meant that their chances of getting support for their research was greater if they could come up with a practical application for the results. It is interesting to note that, while Röntgen was an heir both to this notion of industrial practicality in science and to a certain Teutonic inclination to useful application, he was personally disinclined to pursue the myriad possibilities suggested by his discovery of X rays (see Chapter 2).

The Industrial Revolution taught people that they were more powerful than they had thought. They could control their environment far more than had been possible before. Where were the limits? This heady insight was reflected in literature; the excitement of thinking beyond the usual bounds of thought, as in the pioneering science fiction of writers such as Jules Verne and Edgar Allan Poe, discussed below.

As might be expected, the revolution had an effect on universities: it created many new technical jobs requiring special training that only a university or technical college could give. Universities completed their transition from their earliest mission, to educate priests and monks beyond the level of the

Fig. 1.3 A typical factory during the Industrial Revolution. There was a great exodus of farm workers, most of whom became factory workers. (Author's collection)
monastery, to their more or less current mission, to prepare people for the society in which they will work and live, with opportunities for broader education for those who wish it. This was the mission of the university in Röntgen's time, and it profoundly affected not only his own education but his career as an academician.

**POLITICS, WAR, AND THE ECONOMY**

The Germany into which Röntgen was born was still recovering from a series of major calamities. The nineteenth century, like any other century in modern European history, was one of profound changes, wars, and upheavals. But a catastrophic war two centuries earlier—the Thirty Years' War (1618–1648)—had made an indelible mark on Germany. Even in the 1800s Germany was still recovering from the war, one many believe to have been the most thoroughly devastating in European history. Territorial, religious, and dynastic tensions triggered a pancontinental conflict in which German, Austrian, Hungarian, Italian, and Spanish princes fought one another, backed by powers including France, Sweden, Denmark, and England, not to mention the Catholic and Protestant churches, each of whom used the princes as power surrogates. The war swept through Germany again and again.

At the end of the war—after eighty major battles—Germany had lost a quarter of its population, some four or five million. Tens of thousands of villages had been destroyed, comprising a third of all houses in Germany. Agriculture was especially hard hit, and starva
tion was rampant. As a final blow, in the 1630s the plague swept away more than half of the surviving inhabitants in many areas of Germany.

One of the many results of this war was the division of Germany into a predominately Catholic south and Protestant north, a situation which prevails today. In many ways one sees the sequelae of the Thirty Years' War in the Germany of the present, and certainly Röntgen and his ancestors must have felt the repercussions of it. Röntgen's paternal ancestors settled in Wuppertal shortly after the war ended, and his maternal ancestors moved from what is now northern Italy to Holland about the same time, possibly because their Protestant beliefs were no longer tolerated.

Given this background, it is understandable that the Röntgens felt no unseverable roots in Germany, although they had lived in Lennep (Rhineland) for a century and a half. As German roots went, this was not especially long time. The family moved to Holland when Wilhelm was three, and later his parents followed him to Strasbourg and to Giessen. Röntgen's own mobility—seven career moves—was, and still is, unusual in German academia (Fig. 1.4). Perhaps one can trace Röntgen's mobility not only to his insecurity at not having had all the traditional academic credentials but also to his family's acceptance of mobility following its own resettlements.
The nineteenth century also saw its share of wars. Countless local conflicts developed from the continual quarrels over power among the numerous German states, territories, and cities; on the eve of the French Revolution "Germany" could hardly form a unified political position, because by that time the old German nation of the Holy Roman Empire had disintegrated into no fewer than 1,790 independent states. Napoleon swept through this conglomerate, conquered it in a series of bloody battles, and reorganized it into a smaller number of states under his protection. The southern and western German states formed the Rhine League and, following the French lead, a national assembly was created: the church and the aristocracy lost their power and privileges to a new central governing body elected by the people at large.

The Napoleonic Code, a set of guidelines for rational lawmakers, was put into effect in France, western Germany, and other areas under French control in 1804–1806. The code reflects influences of the American Revolution: all citizens were equal; primogeniture, hereditary nobility, and class privileges were done away with; there was separation of church and state; and freedom of person, freedom of contract, and inviolability of private property became fundamental principles upon which to create laws.

The newly created German states chafed under Napoleon's rule, and the idea of a unified, all-German state gained support. In the Battle of Leipzig (1813) many German soldiers in Napoleon's Confederation of the Rhine troops deserted and joined forces with the Prussians. What was left of Napoleon's Grand Armee after his calamitous winter campaign in Russia was defeated by this new German alliance. This was probably the inception of Germany as we know it today, though final confederation was blocked by the powerful states that wanted to retain autonomy, and the German states continued to be a loose coalition of dynasties. Nevertheless there was a new sense of German identity, reflected in music (Beethoven, Schumann, Wagner) and poetry (Goethe, Heine).

Unification proceeded along non-political lines: the states agreed on a free-trade alliance, an extensive transportation system, and a unified postal service. But this economic progress was thwarted by the effects of the Industrial Revolution, which hit Germany hard. In the 1830s and 1840s thousands of skilled craftsmen were thrown out of work by machines that could do the work better, faster, and cheaper. The liberation of the peasants required farm owners to cede a portion of their land, but neither farmers nor peasants could operate the smaller plots profitably, so that both became farm laborers and, with the collapse of agriculture, the industrial proletariat. Probably one of the best-known products of that stormy era was Karl Marx (1818–1883), protagonist of the Communist movement, which made more headway in other countries in Europe than it did in his native Germany. The Revolution of 1848 brought about a final ratification of the Napoleonic Code, along with the legalization of trade unions and a number of social reforms that bore striking resemblances to the American Bill of Rights.

In 1862 consummate politician Otto von Bismarck (1815–1898), a supporter of the emperor and himself a prince, was appointed prime minister of Prussia under Emperor Wilhelm I (1797–1888). Bismarck's unification of all of the northern German states threatened France and led to the War of 1870, in which the southern German states sided with Prussia. After the war Bismarck consolidated and isolated this union (1871). Wilhelm I was proclaimed emperor of Germany. Even so, it remained a confederation of kingdoms (Prussia, Bavaria, Saxony, Württemberg), grand duchies, principalities, and Hanseatic cities.

Röntgen was born in 1845 in Lennep, a town in the Rhine League, just twenty years after the first introduction of the Napoleonic Code, which would drastically alter German politi-
cal, social, economic, and family life. The ideals of equality and brotherhood that he espoused from childhood came naturally to him, although had he been born a century earlier, his life and attitudes would possibly have been quite different. Röntgen’s patriotism was part of him from the beginning, even though he spent most of his first twenty-five years outside his homeland. His return to Germany in 1870, when his mentor August Kundt took him to Würzburg for a brief time, coincided with the Franco-Prussian War and the establishment of the German Empire. It was a time when German national pride was on the rise. For the remainder of his life Röntgen showed intense loyalty to the country of his birth, even though in a sense it was not the same country.

Astronomy, Biology, Geology: Humans and Their Place in the Universe

Astronomy can lay claim to being the first science to progress through government grants, and this from antiquity onward. By the nineteenth century it was known that stars were separated from the earth and from one another by vast distances, and the universe was immensely larger than had been thought. The situation of human beings in the universe had to be reconsidered; for that matter so did God’s place. God was no longer the overseer of a comfortably intimate universe, the stars just out of reach, but of a measureless expanse of space which, as would soon be discovered, consisted mainly of emptiness. In the nineteenth century two fundamental astronomical tools were introduced, spectroscopy and photography, enabling astronomers to study the chemical nature of stars (Fig. 1.5). The discovery that the spectra of atoms in the sun and in distant stars were essentially the same as those on earth—though puzzlingly shifted—meant that even though the universe was inconceivably large, the laws of physics known on earth would apply anywhere. The universe must have seemed a little more intimate then. Perhaps it gave some reassurance to physicists that their explanations of phenomena would be valid not only on earth but throughout the universe.

Biology was a stepchild of science until Darwin, and even after him it continued for a long time to consist of collections of things in the private or university possession of the independently wealthy; only they could afford to travel to where the interesting specimens were to be found. Biologists of the day were people who went out into the...
wilderness and found things and gave them names. But the impact that Darwin's theory of evolution had on people's view of themselves can hardly be overstated (Fig. 1.6). The theory was vigorously challenged, but its adherents found themselves suddenly kin to all other life on earth, a vision that had profound effects on society. Now biology no longer had to be merely a descriptive science; one could form hypotheses regarding evolution (of necessity a posteriori) and test them by studying how different species had adapted to changing environments.

Geology had a peculiar fascination about it that attracted many good minds; it had both practical and philosophical aspects. One could return from a field trip not only with valuable information about natural resources, but with new speculations about the origin of the earth. For a long time geology was mainly descriptive mineralogy, which, like biology, consisted largely of personal collections rather than basic principles. Fossils of ancient creatures turned the evolution-oriented public mind to the question of our origins; astronomy and biology raised the same question and, like geology, yielded no clear answer. But anticipation had heightened. With better scientific tools we would surely unlock the riddle of our place in the universe, or so the public sentiment seemed to suggest. Advances in astronomy, biology, and geology had intensified the public's expectations of science.

Röntgen maintained a lively interest in other branches of science throughout his career. His close friends included scientists representing botany (Enderlin, von Sachs), biology (Boveri), physiology (Fick), histology (von Kölliker), mathematics (Prym), chemistry (Tafel), as well as several physicians.

**MYSTERY OF ACTION AT A DISTANCE; THE LUMINIFEROUS ETHER**

Scientists throughout the ages have been mystified by the fact that objects interact with each other even though there is no apparent intervening medium (objects, for example, such as magnets, the sun and the earth, the earth and the moon). Even today the connection is not entirely clear. It was a very hot topic in the 1800s and influenced Röntgen in his attempt to understand the nature of cathode rays.

The Greek philosopher Thales of Miletus (640? B.C.-546 B.C.) is generally credited with being the first to study action at a distance systematically. He noticed that a sample of iron ore from a town called Magnesia caused pieces of iron (but, oddly enough, nothing else) to move toward it. He found that the attraction persisted even if he interposed a thin sheet of wood or even bronze. How did the force get through air or through obstacles? Thales postu-
Wilhelm Röntgen’s discovery of X rays in 1895 was both a serendipitous event and the result of his informed participation in a strong tradition of scientific inquiry. (Courtesy of the Center for the American History of Radiology, Reston, Va.)
lated that the iron ore must have some kind of life or soul. Thales is also credited with discovering that amber (in Greek, *elektron*), when rubbed, attracts certain objects to it, and was therefore also alive. History tends to look for neat packages and may have assigned Thales both discoveries on that basis, but if Thales was indeed the first to investigate both electricity and magnetism, he stands among the most remarkable of men.

The puzzle persisted through the ages. Astrologers were unable to explain the influence planets and zodiacal figures had on people. How were some planets friendly and others unfriendly? When astronomers found that planets and stars were at enormous distances from us and from one another, and that zodiacal constellations are really chance groupings of unrelated stars, astrology suffered a remarkable decline. Still, in their movements the sun, earth, and moon appeared to influence one another. How? Newton postulated the concept of gravity and gained acceptance for it through his correct mathematical predictions of the movement of the heavenly bodies. This is an important point: scientists believed Newton because he was able to predict, not because he was some great authority or because he had arrived at his conclusions through metaphysics or intuition. Europe was beginning to distance itself from Aristotle.

But just how does Newton’s gravitation travel from one celestial body to another? There must be a carrier, some matrix that transmits these forces. Such a matrix was postulated: it was weightless and did not affect any of the senses; it pervaded everything; and it was called the *ether* (Greek for “clear upper air”). The search for the ether, the matrix of the universe, occupied some of the greatest minds in history. At the end of the nineteenth century most leading scientists still believed in the ether model of the universe and attempted to fit their findings into it.

The ether was believed to be the medium that carried light (hence the name *luminiferous ether*). Was the ether a gas, a liquid, or a solid? That planets could move through it with ease meant it had to be an extremely rarefied gas. Were light waves transverse or longitudinal? The discovery that light could be polarized meant that light consisted of transverse waves, and hence the ether must be a solid, because transverse waves can move only through solids or along liquid surfaces. Moreover, to explain all known phenomena it had to be both an extremely rarefied gas and at the same time a solid more rigid than steel. Perhaps there was yet another state of matter as yet undiscovered.

The English physicist Sir William Crookes (1832–1919) did seminal work on cathode rays in the 1880s. Unable to classify them, he referred to them as a “fourth state of matter” (Fig. 1.7). This caused considerable excitement among physicists, who were trying to resolve the nature of the ether and hoped that cathode rays would somehow explain everything. Röntgen was pursuing this line of investigation when he discovered X rays. After his discovery it was hotly debated whether X rays and cathode rays were vibrations in the ether and whether either form of radiation could be used to demonstrate the existence of the ether. Questions along this line
occupied much of the productive careers of scientists such as Crookes, Lenard, Thompson, and others. Investigation of the ether seemed to raise more questions than it answered. It was left to physicists Michelson and Morley in 1887 to show that there is no ether wind and hence no ether. Their results were so contrary to common knowledge that they were not accepted for many years. Even though their experiments were done in 1887, it is doubtful that Röntgen would have been influenced by them. He remained a believer in the ether and framed all of his interpretations accordingly.

**INSTRUMENTATION AND THE IMPORTANCE OF MEASUREMENT**

In the seventeenth century the development of the telescope and the microscope showed that there were immensely complex worlds, small ones as well as large, which had been previously hidden from view. The human body was no longer the all-sufficient instrument that it had seemed to be. As instrumentation developed, people learned of sounds they could never hear, colors they could never see, and vibrations they could never feel. Instrumentation became the extension of the human body and of the human mind, carrying it to realizations of the inconceivably large and the inconceivably small. The nineteenth century saw advanced technology, developed for the Industrial Revolution, bring about striking improvements in scientific instruments. These extended the finite world of our senses into the infinite world of reality.

Scientists developed a keener appreciation of accurate, dependable instrumentation and of precise observations and an even greater appreciation for the instrument makers whose craft shaped the direction of their science. Nowhere did the importance of this craft become more evident than in the latter part of the nineteenth century, when the discoveries of Tesla, Edison, Crookes, Dewar, Lenard, Faraday, and many others depended critically on instrumentation they had designed and, in some cases, constructed. This was the age of instrument makers.

An excellent example of a great idea that failed because of a lack of adequate instrumentation is the analytical engine of Charles Babbage (1792–1871), the forerunner of the modern computer. In 1834 Babbage designed a fully programmable mechanical calculator, complete with memory, branched instructions, loops, and punched cards. Because the analytical engine was operated by delicate mechanical parts, it required components made with the utmost precision, and, unfortunately for Babbage, the best instrument makers of the day did not have the technology to produce parts with the required tolerances. Babbage and his workers set about making all the parts by hand, but hand-crafting the myriad parts proved to be too complex a task. Babbage did not live to see his analytical engine constructed, but later in the nineteenth century, when high-precision tooling had been developed, someone else built it, and it worked.

With precise instrumentation came precise measurements. Scientists made fundamental discoveries based on numerical measurements more precise than those of their predecessors; examples are the discovery of the planet Neptune by accurate measurements of the orbit of Uranus (1846), Fizeau's terrestrial measurement of the velocity of light (1849), and the famous Michelson-Morley experiment showing there is no ether wind (1887). Perhaps the essence of this stress on accurate measurements was summed up in an oft-quoted remark by Sir William Thomson (later Lord Kelvin) in 1883:

> When you can measure what you are speaking about and express it in numbers you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be.

Sir William was widely admired and respected. This particular remark strengthened the resolve of physical sci-
entists to obtain their measurements with the utmost care, because they wanted their work to be counted as true science. But the natural sciences (biology, natural history, etc.) offered limited opportunities for measurements, and precise measurements were often irrelevant anyway, since biological variability played such an important role (Fig. 1.8). Biological scientists began to feel excluded, and physical scientists questioned whether the life-oriented sciences were really sciences at all—a controversy that continues to this day with regard to fields such as psychology, economics, and the social sciences. At any rate, it had become clear that one standard of good science was good measurement.

**THE AMATEUR SCIENTIST**

Early in the nineteenth century science was largely a hobby enjoyed by gentlemen of independent means. There were very few professional scientists, although professionals like doctors and engineers often set out on scientific pursuits in their leisure time. As time progressed and better instruments were developed, the fascinations of astronomy, microscopy, and other sciences appealed to a wider audience. By the mid-1800s good instrumenta-

tion was available not only to the professional scientists but to amateurs as well. With a little money an amateur could obtain a microscope, a telescope, or a set of cathode ray tubes as good as those of the most eminent professors. Amateur scientists made significant contributions to our knowledge of astronomy, electricity and magnetism, chemistry, medicine, and many other fields, and they continue to do so to this day.

British scientists were an interesting group, largely because so many of them, even the most famous ones, were amateurs who did science as a hobby—a gentleman’s hobby—and as scientists were often prolific and influential. Some well-known amateur British scientists were Darwin (theory of evolution), Babbage (concept and first model of the computer), and Joule (equivalence of heat and other forms of energy). Perhaps one reason for the proliferation of amateur scientists was the lack of institutions supporting research positions; ironically, in the capital-rich birthplace of the Industrial Revolution, there was little money for development.

**THE POPULARIZATION OF SCIENCE**

Once found only in universities and monasteries, scientific knowledge began to be a public commodity in the early 1800s. The essence of scientific investigation is that results are independent of the observer (a principle later challenged by relativity); anyone performing a well-defined experiment should get the same results. With the proliferation of scientific journals and magazines, any amateur scientist could read what some leading figure had done and, with appropriate resources, repeat the process and perhaps even improve on it.

The first scientific journal in Europe was the *Transactions of the Royal Society*, which appeared in London in 1664. Because there were few scientists as such, many of them amateurs, the journal served both professional and popular science. The first periodical dedicated to the dissemination of scientific articles to the general public was probably *Der Naturforscher [The Scientist]*, which was
published in Leipzig and enjoyed only a brief existence (1747–1748). It was soon succeeded by Physikalische Beleuchtungen [Physics Amusements] (Berlin), which ran from 1751 to 1757. Both were published by the enterprising Christian Mylius.10 In the United States the first general science publication was Scientific American (1845). Science did a good job of marketing itself: in the mid-1800s a rash of museums, planetariums, arboretums, and other scientific showcases cropped up all over the Western world to stimulate and satisfy the curiosity of the public. The Crystal Palace Exhibition in London in 1851 was the first world’s fair to feature advances in science, and it was followed soon after by the Paris Exhibition in 1855 (Fig. 1.9). Every world’s fair since then has featured science.

The increasing public interest in science was reflected in fictional literature as well. Jules Verne (1828–1905), a French novelist, produced three blockbusters in rapid succession: A Journey to the Center of the Earth (1864), From the Earth to the Moon (1865), and Twenty Thousand Leagues Under the Sea (1870). Verne anticipated rockets and space travel, the submarine, the aqualung, and television. His books had a profound influence on lay scientific thinking. The excitement of these new frontiers in thought probably induced many people to take up careers in science.

Interestingly enough, two of the first full-length science-fiction stories based on assumptions that were realistic in terms of scientific knowledge of the day were written by none other than Edgar Allan Poe (1809–1849): “The Unparalleled Adventure of One Hans Pfaall” (1835), a curious mixture of science fiction, satire, and humor, about a balloon voyage to the moon; and the more serious “The Narrative of Arthur Gordon Pym” (1838), about a sea voyage to the then unknown Antarctica, which had first been sighted only eighteen years earlier. Other works by Poe also reveal his fascination with the role of logic and ratiocination in developing a good story line. In contrast to Jules Verne, Poe’s stories did not so much influence public support of science as reflect an increasing public interest in it.

**SCIENCE AND RELIGION**

History smiles at the acceptance that science finds in most churches today. Since antiquity there has been tension between organized religion and science, which offered alternative, plausible,
objective explanations that in many cases threatened or even replaced traditional teachings. Gradually the tensions eased. Education and knowledge, once available only at monasteries, were being dispersed freely by the universities. Especially in Germany, the Reformation encouraged people to think more independently; naturally this influenced scientists. One could pursue independent scientific inquiry and remain in the fold of the church. In understanding the lives of scientists in the 1800s it is important to remember that most of them (with some notable exceptions) were basically religious men and women, who looked on their science as explaining divine actions rather than repudiating them. This was also true of Röntgen, who, like others, had benefited from the church’s acceptance of independent scientific inquiry.

Churches in the early 1800s grew uneasy with the accelerating growth of science. What would science do to religion, illuminate it or eliminate it? The tensions peaked in 1859 with the introduction of the theory of evolution by Darwin and Wallace. Many scientists who accepted the theory found themselves faced with a dilemma: disavow the theory or leave the church. Today, more than a hundred years later, there is a generally accepted duality, and the early animosity the church leveled against at least this branch of science has almost completely vanished, although some traces remain.

Increasing public interest in science probably influenced the church, primarily Protestants, to consider the bridge-building idea that “theology is a progressive science, capable of continued development in the light of newly discovered facts, and of gradual adaptation to changing phases of our knowledge of the physical universe.” Toward the end of the nineteenth century a gradual reconciliation eased tensions; churches welcomed scientists once again.

Röntgen was born into a moderately religious Lutheran family. His grandfather, Johann Heinrich Röntgen, was an elder of the Lutheran church in Lennep, his birthplace. Röntgen the scientist saw divine order in the natural world; in biographer W. Robert Nitsche’s words, he was “convinced of an absolutely ordered existence of all things. Creation was not an accidental or happenstance occurrence, but a magnificent process of precise orderliness. Man did not discover anything that did not already exist; each discovery was merely a phenomenon he had failed to recognize earlier.” The softening of theological views of science had probably paved the way for him to believe this without apology. Röntgen was quite tolerant of other religions, once suggesting that it would not harm his Protestant friends to become more familiar with Catholic views.

Science and Philosophy

Even with the best intentions, scientists have difficulty separating their observations and analyses from the basic frames of mind they bring to their science. The nineteenth century offered its scientists several conflicting philosophies, each of which gave its followers a special frame of reference from which to view the world. Although generalizations are hazardous (including this one), it is still worth noting that English, French, and German scientists of the early 1800s were by no means a cohesive, unified group, working with the same basic assumptions. Each was influenced to a greater or lesser degree by the philosophical environment that had nurtured an interest in science in the first place.

Following Alexander Pope’s dictum that “the proper study of mankind is man,” the proper study of nature became close observation, careful measurement, exhaustive record keeping and lists, and the synthesis of empirical observations into theories. Empiricism and careful inductive reasoning characterize much of British science in the 1800s, an era that saw Great Britain make great advances in electricity and magnetism, optics, chemistry, and biology.

By contrast the French built on their enviable reputation as mathematicians. Lagrange, Laplace, Poisson, and Pas-
(philosophy of life). Kantians were wary of relying too much on inductive reasoning and in general made cautious use of mathematics. Kantians also learned to distrust their senses or at least the messages their senses brought them. They attempted to form comprehensive theories that united various disciplines and recognized, for example, that the concept of energy was a unifying one and that different types of energy might have some relationship that could allow one form to be converted into another. Some of these concepts proved to be useful in freeing the mind from certain preconceptions, such as the widely held belief that electricity and magnetism were fundamentally different and unrelated. The Kantian influence was strongest in the early 1800s and by the latter part of the century had faded considerably. It is interesting to note, with regard to Röntgen, that he had no conceptual difficulty in relating his new kind of radiation to other forms of radiation and did so with little recourse to mathematics.

Röntgen may have been influenced by the teachings of Kant, perhaps through his mentors. Kant taught his followers that our experience may influence how we interpret our own sensory input and even our reasoning, that both have their limitations, and we should not place too much faith in either. Röntgen, throughout most of his career, was instrument-oriented, relying less on subjective observation than on objective measurements. In some of his observations he knew he was limited to some extent by his color-blindness, but this did not seem to have placed any limitations on his achievements. Röntgen had at least one occasion to disbelieve both his senses and his reason. His odd behavior at the time of the discovery of X rays (see Chapter 2) indicates that he feared that some subjective, perceptual problem on his part might be at work, that the amazing results in his darkened laboratory might be chimerical.
DETERMINISM

An increasing sense of human power and of the capabilities of the individual gave scientists a greater hope that they could predict and ultimately control natural phenomena. Furthermore, it was becoming more obvious that many processes that had hitherto been considered exclusively divine in reality had roots in natural processes that could be studied, measured, described, and in some cases, predicted. Examples are Wöhler's synthesis of urea (1828), proving that a "life force" was not essential to organic substances; Darwin's theory of evolution (1859), and the logic of natural selection as a rational explanation for the diversity of species; the realization of the age of the earth in terms of billions of years, and the techniques for estimating the age of samples of it; and the progress made in mechanics, especially in the matting of physics and mathematics to predict the position and state of motion of complex systems.

As the tools of science developed, mainly in physics and chemistry, scientists found they were gaining a significant element of control over the phenomena they were observing. There was no leap of knowledge, only a gradual shift from emphasis on understanding through observation and description to understanding through control and prediction. As scientists were increasingly able to identify the factors influencing phenomena and alter them one by one in a controlled fashion, physics and chemistry began the remarkable crescendo of technical progress that characterized the nineteenth century.

Along this line the French mathematician Pierre Laplace (1749–1827) wrote:

Given for one instant an intelligence which could comprehend all the forces by which nature is animated and the respective positions of the beings which compose it, if moreover this intelligence were vast enough to submit these data to analysis, it would embrace in the same formula both the movements of the largest bodies in the universe and those of the lightest atom; to it nothing would be uncertain, and the future as the past would be present to its eyes.16

Laplace's vision was one of absolute determinism through mechanics, if one could somehow know all positions and all velocities at once, one could predict all future events as well as reconstruct all past ones. It was a vision more of mathematical understanding than of control, but it spoke clearly for the deterministic view.

In 1865 German physicist Gustav Robert Kirchhoff (1824–1887) wrote:

The highest object at which the natural sciences are constrained to aim, but which they will never reach, is the determination of the forces which are present in nature, and of the state of matter at any given moment—in one word, the reduction of all the phenomena of nature to mechanics.17

Increasing reliance on the principle of determinism assured scientists that if their experiment was valid, any other experimenter doing it the same way should get the same results. It is difficult to comprehend, from our present perspective, how scientists could think any other way. But to scientists in the early 1800s it was not at all obvious that if they knew the factors that constituted the cause, they should be able to vary the effect at will by varying the causal factors. Perhaps there was a sort of Darwinian selection at work: those scientists who relied on their own capacity to identify causative factors and test their hypotheses by experiment proved to be successful, while those who looked on effects as being brought about by divine influence or unknowable forces were not.

The effect of this principle on physicists was itself predictable. The field of mechanics flourished. Physicists took their cue from the chemists, who developed formulas and recipes with which anyone could prepare any number of desired chemicals by following the directions. It is interesting to track the articles in scientific journals from the beginning of the nineteenth century to the end of it. There was a definite trend away from merely descriptive and speculative narratives to more experimental
details, giving readers all the information needed to reconstruct the experiment. Readers had full faith that, if the experiment was repeated as written, the same results would be obtained.

As a physics professor Röntgen was widely respected for his skill in preparing and carrying out demonstrations successfully, a skill that seemed to elude even some of the most gifted scientists. In his articles Röntgen often played the role of the lecturer who had to put on some form of demonstration. He wrote several "how to" articles for lecturers, for example his 1883 paper "On an Apparatus for the Lecture Demonstration of Poiseuille's Law." In his classic 1895 article on X rays Röntgen used a style more like that of someone describing how to set up a demonstration than of a physicist trying to investigate a problem; in this article Röntgen never stated the problem that got him going in the first place or the original purpose of his experimental setup.

The growth of determinism in science was not without its tensions. Churches claimed that man was trying to usurp God's place and explain God away. Religious scientists—most of the leading scientists of that era were devout—resolved the divisiveness by maintaining that God does not play tricks or manipulate experiments; science is merely a rational explanation of God's works, and experiment is its proof; science shows how God operates. In support of this they pointed to the fact that the laws of physics apply everywhere, all the time, and to all persons equally, whereas if God had some special purpose in influencing the outcome of experiments directly, this would not be the case.

Determinism was validated in medicine when the germ theory of disease was substantiated, largely by Louis Pasteur (1822–1895), in the 1870s. The root causes of some hitherto unexplainable diseases could be studied and potential treatments tested in the laboratory instead of in the dying patient. At last sickness and death were not absolute mysteries; there was a rationale and a hope that understanding the cause would pave the way to the cure. This philosophy still holds today. Determinism in medicine was the vision of God sharing power with mankind. Perhaps it was God's will that a microbe strike a patient down, but perhaps it was also God's will that scientists should conquer the microbe and cure the patient. Proof that even disease was the effect of an identifiable cause strengthened the resolve of many scientists to find the causes of as many phenomena as they could.

**SCIENCE AND THE EUROPEAN UNIVERSITIES**

Röntgen's life, from his teen years, was centered in the university as an institution. From early life he saw himself as a scientist or engineer of some sort and knew that the university was the only pathway for him; the role that institution played in his life can hardly be overstated. His determination to attend caused him a great deal of difficulty, but he made it, and his entire career was played out at one university or another. Because they were so central to his self-image, it is worth looking at the development of universities up to Röntgen's time.

Universities, as a continuous institution in Western society, are second in longevity only to the Roman Catholic Church. By the mid-nineteenth century many universities found themselves facing a dilemma: should they use their resources to maintain traditional classical education or diversify their curricula to teach new and practical technologies?

It is remarkable how great an effect the French Revolution had on the subsequent development of universities in Europe. It showed that an old order could be completely overthrown and replaced—the old idea of transmutation again. French universities were reorganized to serve the needs of the people (i.e. the state), and the teaching of science and technology found a high priority. "Liberty" increasingly allowed the politicization of universities and fostered student movements with social and political missions. The professor could no longer count on students' acceptance as
a matter of form; he had to earn it.\textsuperscript{19} Röntgen was to benefit from this student freedom in his professorial years at Giessen and Würzburg, when students demonstrated their respect and affection for him in many ways.

The scholar-brothers Wilhelm and Alexander von Humboldt (Fig. 1.10) reshaped the German university system with their concept of a “free university,” one that fostered self-expression and personal freedom, where professors were free to teach as they saw fit without constraints from the state, religious organizations, or other sponsoring institutions (\textit{Lernfreiheit}), and students were free to choose their own studies and live independently of the university (\textit{Lernfreiheit}).\textsuperscript{20} In 1809 they founded the University of Berlin; by 1840 it was the largest university among all the German states. Their concept of a free university was not supported by succeeding ministers of education, but the idea caught on, and when Röntgen taught at Giessen (1879–1888) and Würzburg (1888–1900) he found a degree of academic freedom he had not known before but that was very much to his liking.

In Germany the expense of higher education limited it to the wealthy and powerful for all practical purposes, so that desirable positions requiring higher education were in effect reserved for the upper classes. Education had become somewhat of a social barrier. Willis Rudy explains that:

The cost of a higher education in Germany by 1885 ranged from four thousand to eight thousand marks, while the yearly salary of a primary school teacher averaged only fifteen hundred marks. In that year 7.5 million attended the German primary schools, 238,000 were at the secondary schools, and a mere 27,000 were in attendance at all the universities of Germany.\textsuperscript{21}

The scientific laboratory had existed from the earliest days of organized inquiry, but until the French Revolution had never been particularly associated with universities. In the early 1800s university laboratories appeared in France, England, and Germany, some for teaching and others for research. The German universities were the first to integrate these two concepts into a combined research and educational program leading to a doctorate, similar to the system we have today. Probably the first to accomplish this was chemist Justus Liebig at Giessen in the 1850s. When Röntgen joined the faculty there in 1879 the integrated research-teaching principle was well established, as it was in Würzburg when he moved there in 1888.

To understand the climate in the German university of the nineteenth century it is helpful to understand the concept of \textit{Bildung}. This concept
embodies education, discipline, character, self-improvement, and scholarly, moral, and emotional maturity. It expresses the idea of man as an image (Bild) of his idealized society. Knowledge alone was an insufficient goal for the scholar. The Humboldt s took this a step further and promoted the concept of allgemeine Bildung, or Bildung for everyone, not directed to a particular need of either the individual or the society, but rather Bildung for its own sake. As Alexander von Humboldt wrote, “Insight into universal nature provides an intellectual delight and sense of freedom that no blows of fate and no evil can destroy.”

JOURNALS AND SOCIETIES

As the invention of the printing press revolutionized communication by giving the written language a vehicle for widespread dispersion, the development of the scientific journal revolutionized science by creating, for the first time, a community of scientists. As communication among scientists became easier through the development of scientific societies, journals, and international meetings, each country contributed its strengths to the gradual development of a more ecumenical European model of the sciences. The felicitous combination of mathematical principles, the philosophical tools of deductive and inductive reasoning, and the realization of the importance of accurate measurement provided the nourishment science had been waiting for. During the nineteenth century theories and mathematical models were developed and tested by experiment in chemistry, biology, physics, and even geology, with the result that all these fields advanced as they never had before.

Perhaps it was especially fitting that Germany was to take the initiative in forming the first interdisciplinary association for the advancement of science. Prior to 1870 there was no Germany as such; what is now Germany was then a loosely knit, unstable, often feuding cluster of kingdoms and duchies. Despite the support that German scientists received from their political or industrial patrons, there was no national unity. Travel from one German duchy to another was often inconvenient, even risky, and the borders could be unpredictable. But German scientists felt the need for a unifying society. The first association for the advancement of science was formed by a group of German-speaking scientists in Leipzig (Saxony) in 1822, and was called the Deutsche Naturforschers Versammlung (German Scientific Association, in effect the Association of German-speaking Nature-researchers) (Fig. 1.11). The German association was followed quickly by the British Association for the Advancement of Science (1831) and the American Association for the Advancement of Science (1842).

These societies (a multitude of them were formed throughout Europe) played an essential role in propagating ideas and information. Their journals, of course, also played a key role. In this regard it is interesting to consider what almost absolute power was held by the scientific editors of the day. They alone, without benefit of editorial panels or peer reviewers, decided which of the submitted articles would be published and which rejected. Editors often solicited and published scientific articles promoting certain viewpoints and not infrequently wrote such articles themselves. It should be stressed that these were editor-written scientific articles as opposed to editorials.

Scientific journals were often called by the name of the current editor; thus, in Germany, the Annalen der Physik (Annals of Physics) was variously referred to as Poggendorff’s Journal, Drude’s Journal, and Wiedemann’s Journal, depending on who was editor at the time. This jumble, a historian’s nightmare, reflects the smaller numbers and closer camaraderie of scientists in those days.

The network of scientific journals was an inheritance Röntgen especially appreciated; he read them avidly. Otto Glasser, in his biography of Röntgen, noted the contrast between his eagerness to read and reluctance to write:
That Röntgen was able to work successfully on so many problems in different branches of physics was due to his tremendous knowledge of the literature, and often until late into the night he read in order to keep himself informed on current publications. His devoted application to the study of physics and his good honest workmanship in the research laboratory produced excellent results. Only with the greatest effort, however, could he force himself to write down his observations for publication. His interest was quickly transferred to other experiments, and often he became so absorbed in these that he did not care about publishing the results of earlier investigations.23

Even so, Röntgen managed to make his contribution to the scientific literature with fifty-eight articles, the majority of them in Annalen der Physik. It is an indication of his stature in physics that he published in that prestigious journal thirty-seven of the forty-eight articles he wrote before his 1895 discovery.

The scientific societies, especially the Leipzig society, did more than act as forums for the exchange of scientific ideas. They were open not only to the top scientists of the day, but to anyone with a serious interest in science. By attracting middle-level scientists and even some dedicated lay scientists to their meetings, they scored magnificently in public relations. At last a nonscientist with a genuine interest could attend a scientific meeting and rub shoulders with heroes—and for the first time find out how they looked and spoke. Public support for scientific research had never been so strong. Governments began to see practical advantages in supporting scientists. Encouraged by collegial experiences in their societies, scientists began working in groups more than before, except at the highest levels, where most of the top scientists continued to publish under sole authorship through the end of the nineteenth century.

ON THE NATURE OF LIGHT

Throughout the 1800s a recurring topic of investigation in physics was the unexplained nature of light. Was it particles or waves? Sometimes it behaved like one, sometimes like the other. One wag suggested that light was particles on Mondays, Wednesdays, and Fridays and waves on Tuesdays, Thursdays, and Saturdays, with Sundays off. Radiation below the red end of the spectrum (infrared radiation) had been detected by its effect on thermometers, and radiation above the violet end (ultraviolet radiation) had been detected by its chemical effect on silver nitrate. So even though the concept of an electromagnetic spectrum had not yet been born, it was generally accepted that infrared and ultraviolet were forms of light. In 1886 Hertz added his “electric waves,” but as of 1895 no other part of what we now know as the electromag-
The corpuscular theory of light from the Middle Ages and probably derived much of its support from the mechanistic view of the universe that had been so successful. In the 1700s it had become obvious that the property of matter that most determined its behavior was mass. It would therefore seem self-evident that light consisted of incredibly tiny particles having correspondingly tiny masses. But the theory had its problems: how could corpuscles pass through glass so easily?

The wave theory of light had been developed by the English scientist Robert Hooke (1635–1703), who published it in 1665. In 1690 the Dutch scientist Christian Huygens (1629–1695) used it to explain reflection and refraction and formulated the principle, still used today, that each point on a wave front is the source of a new wave front.

But the corpuscular theory held its ground. The work of Hooke and Huygens seemed hypothetical and mathematical, without solid evidence to back it up. The corpuscular theory seemed reasonable, compatible with how things worked in the universe. Scientists were searching for some definitive experiment that would resolve the matter.

The simple but convincing experiment of the English physicist and physician Thomas Young (1773–1829) should have settled the issue. Young began the century in 1801 with a simple experiment to decide whether light consisted of waves or particles. He reasoned that if light consisted of waves it might behave like sound waves or like surface waves on water and exhibit the property of interference. Particles would not. (Young assumed that the waves would be longitudinal rather than transverse. Well, he got most other things right. Later Röntgen postulated that X rays might be longitudinal waves in the ether, unlike light waves which by then were known to be transverse.)

Young let light shine through a narrow slit onto a flat surface containing two closely spaced, parallel, narrow slits in such a way that the light beams passing through the two slits overlapped on a screen. If light consisted of particles, the overlap should be uniform and roughly twice as bright as the rest of the screen. If light consisted of waves, the constructive and destructive interference of the waves from the two slits should form a pattern of parallel bright and dark bands. As any physics student knows, Young found the latter, which could be explained only by the wave model; the particle model was stumped (Fig. 1.13).

By simple geometry Young was able to measure the wavelength of the light in his experiment, which he reported as being approximately one fifty-thousandth of an inch. This translates to roughly 500 nanometers; we know now that the visible spectrum extends from 400 to 700 nanometers, so Young's 1801 measurement was right on the mark. He also studied the colored interference rings exhibited by thin films of oil, which Isaac Newton

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<th>Known in 1835</th>
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<td>long radio waves</td>
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Fig. 1.12: Even in the late 1800s very little of the electromagnetic spectrum had been discovered. Only light, near ultraviolet, near infrared, and "electric oscillations" (Hertz's radio waves) were known. (Author's collection.)
Volta (1745–1827) developed the electric cell (battery) in 1800 (Fig. 1.14). It was a unique invention. Volta's electric cell (alternating layers of zinc and copper, separated by salt water) provided, for the first time, a steady source of flowing electricity (current).

The effect of Volta's battery on the development of science in the 1800s can hardly be exaggerated. It provided employment for physicists, chemists, and engineers for decades. It made possible a number of great discoveries and developments (Fig. 1.15). In 1806 the English chemist Humphrey Davy (1778–1829) used a powerful voltaic pile (battery) to separate sodium from a salt solution, an enterprise that until then had been impossible. He did the same with potassium, barium, calcium, strontium, and magnesium. His able assistant, Michael Faraday (1791–1867), developed these achievements into an organized science: electrochemistry. In 1820 the Danish physicist Hans Christian Ørsted (1777–1851) found that an electric current flowing through a wire could deflect a nearby compass needle, thereby making a first link between electricity and magnetism: electricity can produce magnetism. The French physicist André-Marie Ampère (1775–1836) lost no time in carrying this link further and giving it a mathematical foundation. He reasoned that if electricity and magnetism have some properties in common, perhaps a wire carrying a current would behave as if it had a north pole and a south pole. He found it did (1820); a wire carrying a current in one direction repels another wire carrying a current in the same direction, and attracts it when the current is reversed: electricity is like magnetism. In 1831 Michael Faraday discovered that changing the magnetic flux through a conducting circuit induces a current in it: magnetism can produce electricity.

The theoretical work of the Scottish physicist James Clerk Maxwell (1831–1879) had a profound effect on the perception of electricity and magnetism. In a classic 1865 article he distilled what was then known about electricity and magnetism into his famous four equations,
and summed them up: "We have strong reason to conclude that light itself (including radiant heat, and other radiations if any) is an electromagnetic disturbance in the form of waves." 25

Maxwell’s observations showed conclusively that electricity and magnetism were inseparably related, as others had suspected in the past, and that one should speak of electromagnetic radiation rather than of electricity and magnetism, the latter terms being useful only to stress different aspects of a unitary phenomenon. Maxwell showed that any oscillating electric charge should produce electromagnetic waves traveling at the speed of light. He showed further that the wavelength of the waves was inversely related to the frequency of vibrations (though he stopped short of saying just what it was that vibrated) and that the relationship could be expressed by \( v = \frac{c}{\lambda} \), where \( c \) = the velocity of light, \( v \) = frequency of vibration, and \( \lambda \) = wavelength.

Perhaps Maxwell’s most mind-expanding idea, and one that affected Röntgen, was to show that, at least mathematically, there was no limit to how large or how small these electromagnetic frequencies could be. Light was just one form of electromagnetic radiation; Maxwell predicted there could be many other forms. This was an open invitation to find them.
These predictions were not realized until seven years after his death, when the German physicist Heinrich Rudolph Hertz (Fig. 1.16) discovered what are now called radio waves, the first of many new waves predicted by Maxwell. In 1886 Hertz set up an electric circuit producing a spark across a known gap between two electrodes; this was his oscillating electric charge. To detect the resulting electromagnetic radiation, Hertz used a loop of wire with an identical gap some distance away. Sure enough, Hertz observed sparks in the “receiver” loop, providing strong support for Maxwell’s theory. This was the first experimental demonstration of a hitherto unknown but predicted form of electromagnetic radiation and gave physicists their first glimpse into the potentially immense scope it could have. What as yet unknown forms of electromagnetic radiation awaited discovery?

Cathode Rays

Cathode rays had been first noted by the German physicist Julius Plücker (1801–1868) during experiments with Geissler tubes, evacuated glass tubes into which two electrodes had been sealed. Their original purpose had been to show the beautiful color effects of various gases when ionized by the passage of an electric current through them (Fig. 1.17). Plücker noted a greenish luminescence near the cathode, and with higher voltage across the tube the luminescence shifted to the glass wall opposite the cathode. He noted also that neither the color of the luminescence nor its intensity depended on what metal the cathode was made of, nor what gas was in the tube, just as long as it had a good vacuum; hence it was an electrical phenomenon and not a chemical one. Plücker supported this view by showing that a magnet deflected the beam. On the basis of this observation it was widely held that cathode rays must be some sort of charged particles.

But cathode rays traveled in straight lines, cast sharp shadows, and were unaffected by electric fields or gravity. These characteristics suggested that they were waves. (We now know that the cathode rays were traveling so fast—about one-tenth the speed of light—that neither electric fields nor gravity would exert an effect observable with equipment then available.) But they were charged, there was no doubt of that. Could there be such a thing as charged waves?

The English physicist Crookes was intrigued by cathode rays and invented a tube of his own to study them (Fig. 1.18). He popularized cathode rays through his writings and lectures, in which he made good use of the brilliant luminescence they induce in many substances (inorganic salts, glasses, diamonds). He showed that the rays could exert pressure against light objects sealed inside the tubes. Even Crookes could not resolve whether they were particles or waves. Since they were not solid, liquid, or gas, he called them a
"fourth state of matter." Crookes, a confirmed mystic, also attempted to make a link between these mysterious radiations and the occult; history has forgiven him for this by ignoring the writings of his last few years.

THE ELECTRON AND THE ATOM

Ever since Democritus proposed in 430 B.C. that all matter was made up of basic tiny, indivisible units which he called atoms (uncuttable or indivisible), scientists had been waiting for the day when someone would take a photograph of an atom or somehow prove there really were such things. In the 1800s it was obvious that this possibility was getting closer, because the scale of accurate observations was becoming smaller and smaller. The microscopes available at the time did not show atoms, but perhaps a better one might.

Meanwhile, in the field of chemistry, Michael Faraday (1791–1867) had found that an electric current can be made to flow through certain solutions (which he called electrolytes, "electricity set loose"), but not through others (non-electrolytes). He soon found that chemical changes occurred in the electrolytes after electricity had passed through them, and that elements could be separated from their compounds this way. Some formed on the negative electrode (cations) and some on the positive one (anions). Faraday also found that the same electric current that produced exactly one gram-atom of copper (from copper chloride, CuCl) produced exactly one-half gram-atom of zinc (from ZnCl₂). Faraday reasoned that because each atom (whatever that was) of copper can bond with one atom of chlorine, but each atom of zinc binds with two atoms of chlorine, the amount of electricity required to make a gram-atom must involve some sort of fundamental integral unit, which later came to be called the faraday. One faraday produced one gram-atom of an element. Notice that Faraday was a chemist. Atomic theory was mainly the province of chemistry in those days; physicists showed little interest in it, although they were interested in what the basic atomic structure might be. The chemical applications seemed to them to be too complex, too utilitarian.

Faraday's work formed the first firm bond between electricity and chemistry, and showed that there was some link between the fundamental unit of electricity (which had not yet been identified) and the fundamental unit of matter (the atom, which had not yet been found). There was a need for a name for the fundamental unit of electricity, and the Irish physicist George Stoney (1820–1911) gave it in 1881: the electron, which he named after the
Greek word for amber, for its property of storing static electricity (the early work of Thales of Miletus had meanwhile been rediscovered). No one had seen an electron, much less an atom, but having the terms gave scientists a language with which to talk.

There were many attempts to isolate atoms, to define them, to photograph them. Röntgen had an "oil drop experiment" of his own. In 1890 he took an interesting approach to measuring an upper limit to atomic size: he placed a small drop of oil of known volume on a water surface and allowed it to spread out until it formed a layer one molecule thick. The boundaries of the oil drop were outlined by chalk dust. If the volume V and the area A are known, the thickness of the molecule is \( V/A \). This gave an upper limit to the thickness of an atom. Röntgen's measurements yielded a molecular diameter between \( 5.6 \times 10^{-8} \) and \( 1.8 \times 10^{-7} \) centimeters (cm.).

Much was learned about both atoms and electrons through research with cathode rays. In 1894 the German physicist Philipp Lenard (Fig. 1.19) devised an instrument for studying cathode rays that revealed their nature more than ever before; it was a cathode ray tube with a very thin aluminum window at one end, through which the cathode rays could pass into the air outside the tube or even into another observation chamber (Fig. 1.20). In this way one could study cathode rays independently from the vacuum and electric fields in which they were created. Lenard found that the cathode rays were extremely tiny particles. The tiny particles had a negative charge, as had been known before by their magnetic deflection, but Lenard found that they also had an incredibly small mass, roughly one one-thousandth the mass of a hydrogen atom (off by a factor of 1.8 by today's values, not bad for the times, and not bad considering the infinitesimal mass of an electron: \( 9.1 \times 10^{-28} \) grams). Thus Lenard found and characterized the electron that George Stoney had named thirteen years earlier.

Scientists suddenly realized they had been working with electrons all along and had not realized it. Electric currents were really nothing more than electrons in motion, and as long as the electrons remained inside the wire there was no way they could be observed as such. But once out in the open they behaved as individual particles, and their nature could be studied more closely. From the fact that cathode rays could penetrate several centimeters of air Lenard concluded that atoms or molecules must be made up mainly of empty space. He also showed why we had not yet observed atoms: they are too small, having diameters on the order of \( 10^{-8} \) cm. Lenard did not publish his findings until 1903. Three years later the British physicist Ernest Rutherford (1871–1937), on the basis of the scattering of alpha rays in gold foil, proposed a more accurate model.

**RÖNTGEN'S ANCILLARY EQUIPMENT: PUMPS, COILS, FLUORS, AND FILMS**

For his experiments with cathode ray tubes Röntgen also needed a good vacuum pump, an induction coil with interrupter (a device to convert low-voltage direct current to high-voltage alternating or pulsating current), and a fluorescent substance to detect the cathode rays. Ultimately he would use photographic film to capture the images. The vacuum pump was needed to evacuate...
the cathode ray tube, because cathode rays were known to travel only a few centimeters through air but to travel freely through a vacuum. An induction coil was needed to provide the high voltage that created the cathode rays. The induction coil needed alternating or pulsating current; only direct current from batteries was available in those days, so it was "chopped" by a vibrating metal reed into pulsating current that drove the induction coil (a high voltage transformer). The high voltage output was typically 10,000 to 25,000 volts at a current of a few milliamperes. Röntgen was fortunate in being the head of a well-supported physics department; he was in a position to order what he needed. He used a Raps vacuum pump, a Ruhmkorff induction coil with a Deprez interrupter, and a screen of barium platinocyanide.

Vacuum Pump

The nature of a vacuum has puzzled scientists ever since Aristotle, who concluded that there could be no such thing for the following reason: a stone falls through air faster than through water; the thinner the substance through which it falls, the faster it falls. In a vacuum (i.e., an infinitely thin substance) the rock would fall with an infinite velocity. This is clearly impossible, therefore a vacuum cannot exist. From this arose the dictum, "Nature abhors a vacuum." It seems strange that scientists through the centuries continued to hang on to this concept; it was the work of Galileo, Torricelli, and most convincingly of Otto von Guericke and his Magdeburg hemispheres (1654) that finally convinced scientists that not only could a vacuum exist, man could create one. It was von Guericke, one of Röntgen's "Aristotle-bashers," (see Chapter 2) who constructed the first practical vacuum pump. Later Heinrich Geissler (1814–1879), a Bonn glassblower (of Geissler tube fame), invented the mercury pump, making it possible to evacuate cathode ray tubes down to 0.0002 millimeters of mercury, the highest vacuum used by Röntgen. The pump Röntgen used was a Raps pump, a type of mercury pump. Even with the best pumps of the day it took from one to four days to evacuate a cathode ray tube sufficiently for operation.

Induction Coil

The high-voltage induction coil Röntgen used was developed by Heinrich Daniel Ruhmkorff (1803–1877). Born Rühmkorff in Hanover, Germany, he deferentially dropped the umlaut when he moved to Paris. The 1851 model Ruhmkorff coil produced sparks 5 cm. long in air. By the time Röntgen obtained one it could make sparks 15 cm. long. It was the standard source for high voltage in Röntgen's time.

Fluorescent Screen

Röntgen's use of barium platinocyanide as a fluorescent (fluorescing material) to detect cathode rays was a stroke of luck. He could not have foreseen that...
this substance was fluorescent to both cathode rays and X rays, while "keton," the fluor used by Lenard in his earlier experiments, fluoresced under cathode rays but not under X rays. Thus if Röntgen had carried out Lenard's experiments to the letter, he might have missed the discovery completely.

Barium platinocyanide was first prepared by the German chemist Gmelin in 1822. Its unusual optical properties and brilliant fluorescence under ultraviolet, and later under cathode, rays attracted attention, and it was often used in physics demonstrations. It is not clear why Röntgen was using it instead of keton; he had both on hand. The critical role it played in his discovery is discussed more fully elsewhere.31,32

**Photography**

Röntgen had not planned to use photography in setting up his experiment, but it came to play a vital role in documenting his results. It is well known that the French inventor Louis Daguerre (1789–1851) introduced the photographic process we use today.33 By 1895 photography was widely used by both scientists and amateurs to document the results of experiments and natural observations. Röntgen, however, rarely used photography in his experiments or publications. Most of his work during the six weeks after his discovery of X rays depended on visual observations made with the fluorescent barium platinocyanide screen. He did document several of his observations photographically, as an objective proof of his claims. Röntgen may have had the photographic materials on hand because he was "following the experiments of Lenard," and Lenard had noted that cathode rays exposed the photographic plate and had suggested documenting cathode ray work photographically. There is no question that photography played a key role in spreading the fame of Röntgen's discovery; without pictures there would have been no wildfire (Fig. 1.21).

There was one other reason Röntgen had occasion to document his observations photographically, which has been mentioned earlier: his first sighting of the bones in his own hand. Such an utterly preposterous observation made him wonder whether he had lost his reason and was suffering from hallucinations. This thought shook him to the core. But when he took an X-ray photograph of his wife Bertha's hand, she also saw the bones. The photograph terrified her, but reassured him; she had seen the bones, and he was not hallucinating.

**1890: Has Science Gone as Far as It Can Go?**

Toward the latter part of the nineteenth century there was a curious and unexpected development in science: it seemed to be losing steam. The copious proliferation of new knowledge was being systematized. As of 1890 seventy-five elements were known, well over half of them having been discovered in that century. Thousands of stars had been catalogued, and many of the mysteries of our existence on earth had been cleared away. In physics James Clerk Maxwell had reduced essentially all the known principles of electricity and magnetism to four fundamental equations, from which all others could be derived. Around 1880 there came a sense of slowing down, of having attained some exalted goal that gave little promise of any higher goals. Looking back to the beginning of their century, scientists must indeed have enjoyed a great feeling of satisfaction at the immense progress that had been made.

Between 1880 and 1895 physicists began to worry about the future of their field. Röntgen biographer Shapiro expressed their outlook:

This was an era when physicists, Röntgen among them, might well have concluded that all the basic laws of nature had already been discovered and that nothing remained but to complete the tables listing the properties of materials and extend the precision of measurements to the next decimal place.34

Nobel physicist Karl Siegbahn looked back on the self-satisfied complacency, the sense of accomplishment and completeness of that era:

Towards the end of the last century physical science had arrived at a picture of the natural phenomena and their interplay which was apparently very satisfactory and to a certain extent complete. Everything seemed to fit well
into a mechanical conception of the universe, including electric, magnetic and optical phenomena. It was hardly expected that there would be any revolutionary innovations.55

Nobel physicist Albert A. Michelson made what turned out to be a singularly unprophectic remark at the dedication ceremony of the Ryerson Physical Laboratory at the University of Chicago in 1894:

The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote...Our future discoveries must be looked for in the sixth place of decimals.56

Nor did Michelson leave it at that. He communicated his sense of discouragement to a scientific gathering in 1895, the very year in which Röntgen was to make his discovery:

While it is never safe to affirm that the future of physical science has no marvels in store, it seems probable that most of the great underlying principles have been firmly established, and that further advances are to be sought chiefly in the rigorous application of these principles.57

Röntgen himself did not escape the feeling that things were slowing down. In 1888 he wrote to Hertz, who had been asked to succeed him at Göttingen:

During the last few years the number of students in the practical courses has decreased somewhat, probably because the outlook is gloomy for the future of natural scientists and mathematicians.58

To be sure, there were many important discoveries in the years 1880-1895, but they did not seem to give many physicists the vision of distant horizons waiting to be explored. Certainly when Röntgen set up his famous experiment in 1895 he was intending to pursue the "rigorous application of these principles" and was not expecting to plow new ground. Yet that ground was rich with scientific, technological, and philosophical treasures waiting to be inherited.

REFERENCES

This work was supported, in part, by a United States Senior Scientist Award from the Alexander von Humboldt Foundation, Bonn, Federal Republic of Germany.

1 One of the most enjoyable challenges in writing about historic events is looking forward from the perspective of the historic figure in his own time, trying to ignore all knowledge that was gained subsequently. It is easier to look back on a discovery from a modern perspective than it is to put oneself in another century and try to imagine what limited intellectual and physical tools the scientist of those times had to work with. In other words it is easier to walk in their knowledge than to walk in their ignorance; easier to know what they knew than to not know what they did not know. To this end the reader is asked to forget all knowledge that was revealed after 1895.

2 Quoted by Otto Glosner in his article, "The Genealogy of the Roentgen Rays," A.J.R. 30 (1933):180. The classic article is required reading for understanding Röntgen's scientific forefathers.


4 Röntgen made only veiled comments about his own reaction to what must have been an eerie discovery—the living bones of his own hand. Even later in life he was reluctant to discuss the discovery in any but the most austere and removed terms.


6 Barzel, R. Fragen an die deutsche Geschichte [Questions on German History] (Bonn: Bundestag Press and Information Center, 1984).