LIVES IN PHYSICS

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Contents

INTRODUCTION[1]

Science has developed with constantly-accelerating speed

40,000 years ago, our hunter-gatherer ancestors were making paintings of the animals that they hunted on the walls of the caves in which they lived. Only a blink of an eye later on the vast time-scale of evolutionary history, they were speculating about the existence of atoms. After another brief tick of the evolutionary clock, humans had invented the atomic bomb.

Genetic evolution contrasted with cultural evolution

Humans, like all animals and plants, transmit genetic information to future generations by means of the DNA and RNA macromolecules. The slow process of genetic evolution takes place through the genetic lottery, in which characteristics from one parent or the other are transmitted to the next generation in a random way. Also, random mutations of the parents DNA or RNA sometimes occur. Natural selection ensures that when these random variations are favorable, they survive, while if they are unfavorable they are discarded. Most mutations result in very early spontaneous abortions of which the mother is not even conscious.

Genetic evolution is a very slow process. Genetically we are almost identical with our hunter-gatherer ancestors of 40,000 years ago; but cultural evolution has changed our way of like beyond recognition.

Although other animals have languages, the amazing linguistic abilities of humans exceed these by many orders of magnitude. The acquisition of humans' unique linguistic abilities seems to have occurred about 100,000-200,000 years ago. I have discussed a possible genetic mechanism for this abrupt change in another book, *Languages and Classification*, (2917)[2].

The highly developed langnguages of our species initiated our lightning-like cultural evolution, which has completely outpaced genetic evolution, and allowed humans to grow from a few million hunter-gatherers to a population of more than seven billion, to which a billion are being added every decade. Today we are so numerous that humans threaten to destroy the global environment by the sheer weight of numbers.

[1]This book makes use of articles and book chapters that I have previously written on subjects related to the history of physics, but a great deal of new material has been added.

[2]http://eacpe.org/about-john-scales-avery/

Acceleration of cultural evolution

Human cultural evolution began to accelerate with the invention and spread of agriculture. It began to move faster still with the invention of writing, followed by paper, ink, printing, and printing with movable type. In our own time, with transistors, microelectronics, the Internet, cell phones, Skype, and Wikipedia, cultural evolution has exploded into a constantly-morphing world-changing force.

Institutional and cultural inertia

If we look more closely at cultural evolution, we can see that it is divided into two main parts, with different rates of change. Science and technology are changing with breathtaking and constantly accelerating speed, while laws, economic practices, education, religion, ethics and political structures change more slowly. The contrast between these two rates of change has severely stressed and endangered modern human society.

For example, we still preserve the concept of the absolutely sovereign nation-state, but instantaneous global communications and economic interdependence, and all-destroying modern weapons have made this concept a dangerous anachronism. As another example, we can think of our fossil-fuel-based economic system which has been made anachronistic by the urgent need to halt CO_2 emissions before feedback loops take over and make human efforts to avoid catastrophic climate change futile. As a third example, we can think of social practices, such as child marriage in Africa, which lead to very high birth rates and the threat of future famine. We urgently need new ethical, educational, legal, social and political systems which will be appropriate to our new science and technology.

Tribalism and the institution of war

Compared with cultural evolution of all kinds, genetic evolution is extremely slow. Genetically and emotionally, we are almost identical to our hunter-gatherer ancestors, who lived in small tribes, competing with other tribes for territory on the grasslands of Africa. Thus it is not surprising that inherited human nature contains an element of what might be called “tribalism” - the tendency to be kind and loyal to members of one’s own group, and sometimes murderously hostile towards outsiders that are perceived as threats. The willingness of humans to sacrifice their own lives in defense of their group is explained by population genetics, which regards the group rather than the individual as the unit upon which the Darwinian forces of natural selection act.

Because human emotions contain this tendency towards tribalism, the military-industrial complexes of our modern world, and their paid political servants, find it easy to persuade citizens that they are threatened by this or that outside nation, and that obscenely large military budgets are justified.

Today the world spends 1.7 trillion dollars each year on armaments, an almost unimaginably large amount of money. It is the huge river of money that drives and perpetuates the institution of war. But today, the threat of a thermonuclear war is one of the two existential threats to human civilization and the biosphere, the other being the threat of catastrophic climate change.

Physicists have known sin

J. Robert Oppenheimer, the leader of the Los Alamos project that constructed the first nuclear bomb, said, "In some sort of crude sense which no vulgarity, no humor, no overstatement can quite extinguish, the physicists have known sin; and this is a knowledge which they cannot lose." He also said, "If atomic bombs are to be added as new weapons to the arsenals of a warring world, or to the arsenals of the nations preparing for war, then the time will come when mankind will curse the names of Los Alamos and Hiroshima. The people of this world must unite or they will perish.".

Science and democracy

It matters a great deal whether the results of science and technology are used constructively or whether they are used in way that harm human society or the environment. In a democracy, decisions decisions of this kind ought to be made by all of the voters. It is therefore important that a qualitative understanding of science should be part of everyone's education.

I hope that this book will contribute to the goal of making the history of physics and its social impact available to a wide audience. I have tried to tell the story through the lives of a few of the people who have contributed importantly to the development of physics, not in an exhaustive way, but rather letting the lives of few researchers stand for many others who could equally well have been chosen. I hope that you will enjoy the book.

Chapter 1

THE ATOMISTS

1.1 Leucippus, Democritus and the concept of atoms

What is permanent, and what changes?

In the 5th century B.C. there was a great deal of discussion among the Greek philosophers about whether there is anything permanent in the universe. Heraclitus (540 B.C. - 475 B.C.) maintained that *everything* is in a state of flux. Parmenides (540 B.C. - c. 470 B.C.) maintained that on the contrary *nothing* changes - that all change is illusory. Leucippus (490 B.C. - c. 420 B.C.) and his student Democritus (470 B.C. - c. 380 B.C.), by a lucky chance, hit on what a modern scientist would regard as very nearly the correct answer.

According to Democritus, if we cut an apple in half, and then cut the half into parts, and keep on in this way for long enough, we will eventually come down to pieces which cannot be further subdivided. Democritus called these ultimate building blocks of matter “atoms”, which means “indivisible”. He visualized the spaces between the atoms as being empty, and he thought that when a knife cuts an apple, the sharp edge of the blade fits into the empty spaces between the atoms and forces them apart.

Democritus believed that each atom is unchanged in the processes which we observe with our senses, where matter seems to change its form. However, he believed that the atoms are in a state of constant motion, and that they can combine with each other in various ways, thus producing the physical and chemical changes which we observe in nature. In other words, each atom is in itself eternal, but the way in which the atoms combine with each other is in a state of constant flux because of the motion of the atoms.

This is very nearly the same answer which we would give today to the question of which things in the universe are permanent and which change. Of course, the objects which we call “atoms” *can* be further subdivided, but if Democritus were living today he would say that we have merely made the mistake of calling the wrong things “atoms”. We should really apply the word to fundamental particles such as quarks, which cannot be further subdivided.

In discussing which things in the universe are permanent and which change, we would also add, from our modern point of view, that the fundamental laws of the universe are permanent. In following these unchanging laws, matter and energy constantly alter their configuration, but the basic laws of nature remain invariant. For example, the configuration of the planets changes constantly, but these constant changes are governed by Newton's laws of motion, which are eternal.

Parmenides' challenge

The Stanford Encyclopedia of Philosophy describes the doctrines of the atomists as follows:

Ancient sources describe atomism as one of a number of attempts by early Greek natural philosophers to respond to the challenge offered by Parmenides. Despite occasional challenges, this is how its motivation is generally interpreted by scholars today. Parmenides had argued that it is impossible for there to be change without something coming from nothing. Since the idea that something could come from nothing was generally agreed to be impossible, Parmenides argued that change is merely illusory. In response, Leucippus and Democritus, along with other Presocratic pluralists such as Empedocles and Anaxagoras, developed systems that made change possible by showing that it does not require that something should come to be from nothing. These responses to Parmenides suppose that there are multiple unchanging material principles, which persist and merely rearrange themselves to form the changing world of appearances. In the atomist version, these unchanging material principles are indivisible particles, the atoms: the atomists are often thought to have taken the idea that there is a lower limit to divisibility to answer Zeno's paradoxes about the impossibility of traversing infinitely divisible magnitudes. Reconstructions offered by Wardy (1988) and Sedley (2008) argue, instead, that atomism was developed as a response to Parmenidean arguments.

The atomists held that there are two fundamentally different kinds of realities composing the natural world, atoms and void. Atoms, from the Greek adjective atomos or atomon, 'indivisible,' are infinite in number and various in size and shape, and perfectly solid, with no internal gaps. They move about in an infinite void, repelling one another when they collide or combining into clusters by means of tiny hooks and barbs on their surfaces, which become entangled. Other than changing place, they are unchangeable, ungenerated and indestructible. All changes in the visible objects of the world of appearance are brought about by relocations of these atoms: in Aristotelian terms, the atomists reduce all change to change of place. Macroscopic objects in the world that we experience are really clusters of these atoms; changes in the objects we see - qualitative changes or growth, say - are caused by rearrangements or additions to the atoms composing them. While the atoms are eternal, the objects compounded out of them are not. Clusters of atoms moving in the infinite void come to form kosmoi or worlds as a result of a circular motion that gathers atoms up into a whirl, creating clusters within it; these kosmoi

are impermanent. Our world and the species within it have arisen from the collision of atoms moving about in such a whirl, and will likewise disintegrate in time.

1.2 Opposition from Plato and Aristotle

Of the various ancient philosophers, Democritus is the one who comes closest to our modern viewpoint. However, the ideas of Democritus were too advanced for his contemporaries. Although Democritus was not actually thrown into prison for his beliefs, they aroused considerable hostility. According to Diogenes Laertius, Plato dislike the ideas of Democritus so much that he wished that all of his books could be burned. (Plato had his wish! None of the seventy-two books of Democritus has survived.) Aristotle also argued against atomism, and because of the enormous authority which was attached to Aristotle's opinions, atomism almost disappeared from western thought until the time of John Dalton (1766 - 1844).

1.3 Epicurus and Lucretius

That the ideas of Democritus did not disappear entirely was due to the influence of Epicurus (341 B.C. - 270 B.C.), who made mechanism and atomism the cornerstones of his philosophy. The Roman poet Lucretius (95 B.C. - 55 B.C.) expounded the philosophy of Epicurus in a long poem called *De Natura Rerum* (On the Nature of Things). During the middle ages, this poem disappeared completely, but in 1417, a single surviving manuscript was discovered. The poem was then published, using Gutenberg's newly-invented printing press, and it became extremely popular. Thus, the idea of atoms was not entirely lost, and after being revived by John Dalton, it became one of the cornerstones of modern science.

Figure 1.1: **A painting depicting Democritus. He was sometimes called "the laughing philosopher" because of his belief in a cheerful attitude towards life.**

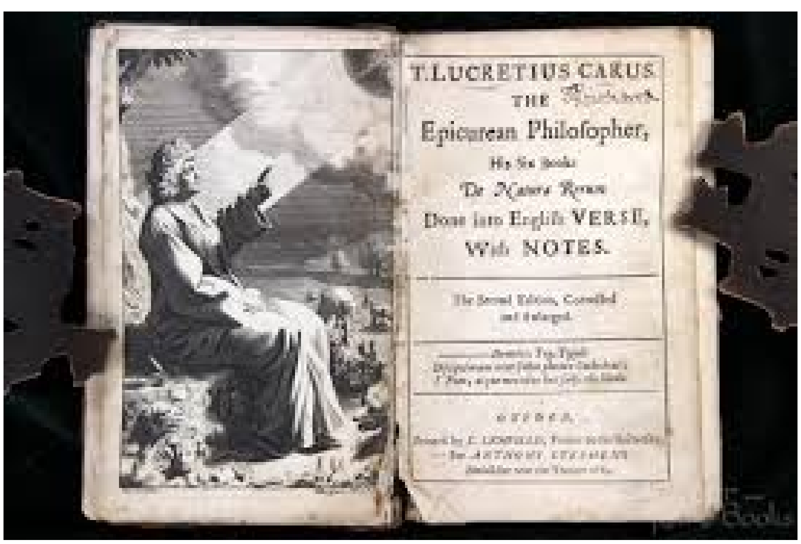

Figure 1.2: **An English translation of *De Natura Rerum.***

Suggestions for further reading

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Chapter 2

ARCHIMEDES

2.1 Heiron's crown

Archimedes was the greatest mathematician of the Hellenistic Era. In fact, together with Newton and Gauss, he is considered to be one of the greatest mathematicians of all time.

Archimedes was born in Syracuse in Sicily in 287 B.C.. He was the son of an astronomer, and he was also a close relative of Hieron II, the king of Syracuse. Like most scientists of his time, Archimedes was educated at the Museum in Alexandria, but unlike most, he did not stay in Alexandria. He returned to Syracuse, probably because of his kinship with Hieron II. Being a wealthy aristocrat, Archimedes had no need for the patronage of the Ptolemys.

Many stories are told about Archimedes: For example, he is supposed to have been so absent-minded that he often could not remember whether he had eaten. Another (perhaps apocryphal) story has to do with the discovery of "Archimedes Principle" in hydrostatics. According to the story, Hieron had purchased a golden crown of complex shape, and he had begun to suspect that the goldsmith had cheated him by mixing silver with gold. Since Hieron knew that his bright relative, Archimedes, was an expert in calculating the volumes of complex shapes, he took the crown to Archimedes and asked him to determine whether it was made of pure gold (by calculating its specific gravity). However, the crown was too irregularly shaped, and even Archimedes could not calculate its volume.

While he was sitting in his bath worrying about this problem, Archimedes reflected on the fact that his body seemed less heavy when it was in the water. Suddenly, in a flash of intuition, he saw that the amount by which his weight was reduced was equal to the weight of the displaced water. He leaped out of his bath shouting *"Eureka! Eureka!"* ("I've found it!") and ran stark naked through the streets of Syracuse to the palace of Hieron to tell him of the discovery.

The story of Hieron's crown illustrates the difference between the Hellenistic period and the classical period. In the classical period, geometry was a branch of religion and philosophy. For aesthetic reasons, the tools which a classical geometer was allowed too use were restricted to a compass and a straight-edge. Within these restrictions, many problems

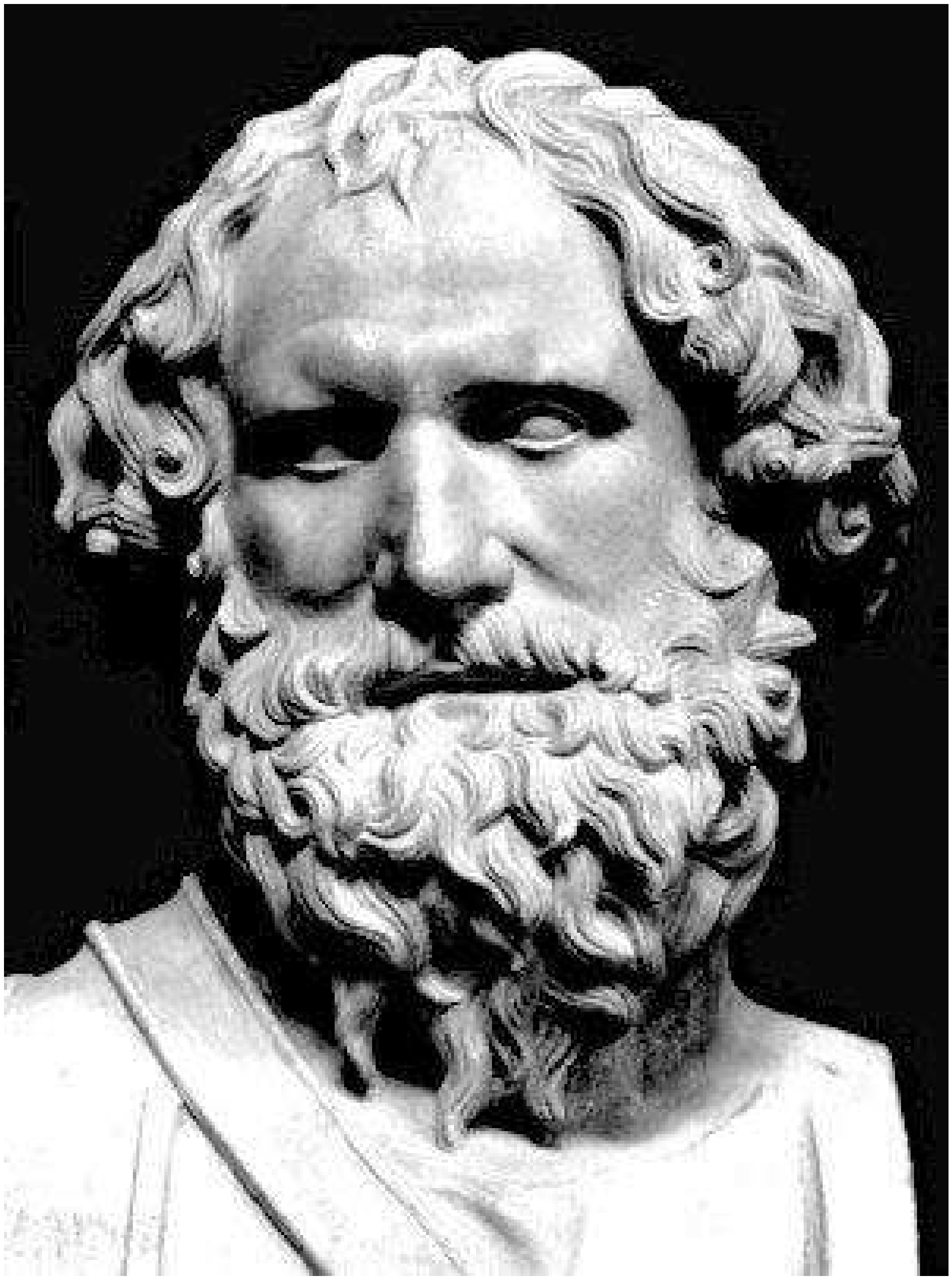

Figure 2.1: **A statue of Archimedes (287 BC - 212 BC**. He invented both differential and integral calculus almost two milenia before Newton, but he was unable to teach his methods to his contemporaries.

are insoluble. For example, within the restrictions of classical geometry, it is impossible to solve the problem of trisecting an angle. In the story of Hieron's crown, Archimedes breaks free from the classical restrictions and shows himself willing to use every conceivable means to achieve his purpose.

One is reminded of Alexander of Macedon who, when confronted with the Gordian Knot, is supposed to have drawn his sword and cut the knot in two! In a book *On Method*, which he sent to his friend Eratosthenes, Archimedes even confesses to cutting out figures from paper and weighing them as a means of obtaining intuition about areas and centers of gravity. Of course, having done this, he then derived the areas and centers of gravity by more rigorous methods.

2.2 Invention of differential and integral calculus

One of Archimedes' great contributions to mathematics was his development of methods for finding the areas of plane figures bounded by curves, as well as methods for finding the areas and volumes of solid figures bounded by curved surfaces. To do this, he employed the "doctrine of limits". For example, to find the area of a circle, he began by inscribing a square inside the circle. The area of the square was a first approximation to the area of the circle. Next, he inscribed a regular octagon and calculated its area, which was a closer approximation to the area of the circle. This was followed by a figure with 16 sides, and then 32 sides, and so on. Each increase in the number of sides brought him closer to the true area of the circle.

Archimedes also circumscribed polygons about the circle, and thus he obtained an upper limit for the area, as well as a lower limit. The true area was trapped between the two limits. In this way, Archimedes showed that the value of pi lies between 223/71 and 220/70.

Sometimes Archimedes' use of the doctrine of limits led to exact results. For example, he was able to show that the ratio between the volume of a sphere inscribed in a cylinder to the volume of the cylinder is 2/3, and that the area of the sphere is 2/3 the area of the cylinder. He was so pleased with this result that he asked that a sphere and a cylinder be engraved on his tomb, together with the ratio, 2/3.

Another problem which Archimedes was able to solve exactly was the problem of calculating the area of a plane figure bounded by a parabola. In his book *On method*, Archimedes says that it was his habit to begin working on a problem by thinking of a plane figure as being composed of a very large number of narrow strips, or, in the case of a solid, he thought of it as being built up from a very large number of slices. This is exactly the approach which is used in integral calculus .

Archimedes must really be credited with the invention of both differential and integral calculus. He used what amounts to integral calculus to find the volumes and areas not only of spheres, cylinders and cones, but also of spherical segments, spheroids, hyperboloids and paraboloids of revolution; and his method for constructing tangents anticipates differential calculus.

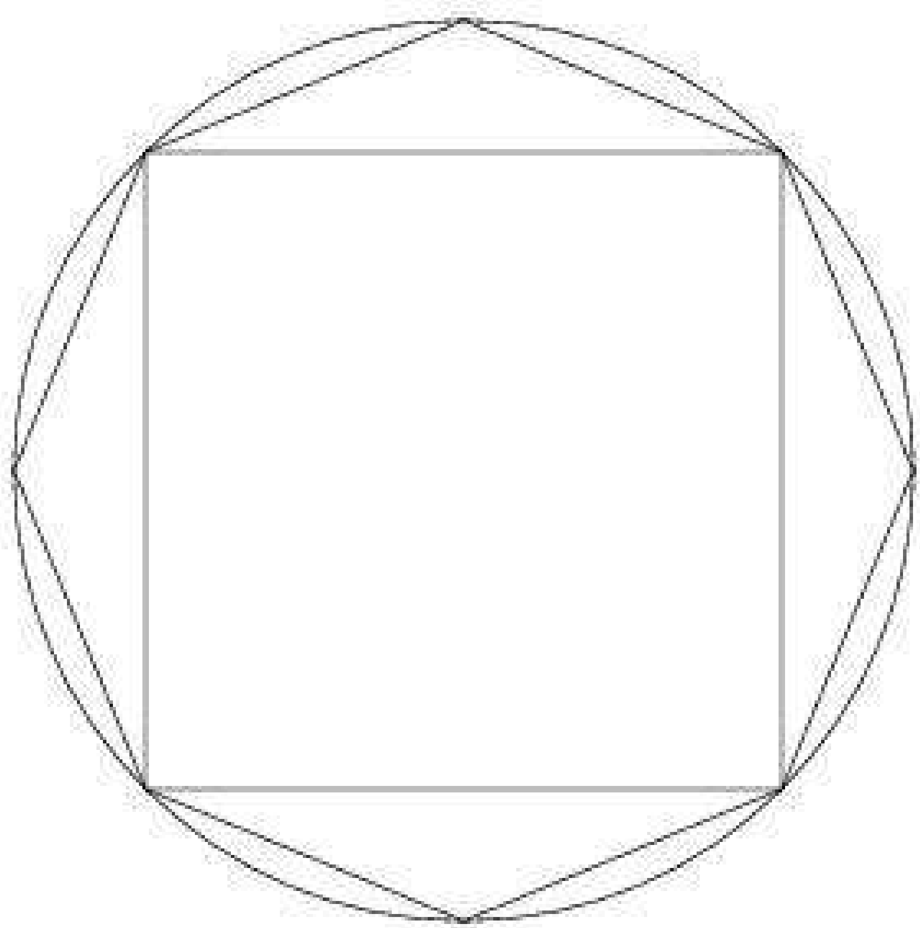

Figure 2.2: **This figure illustrates one of the ways in which Archimedes used his doctrine of limits to calculate the area of a circle. He first inscribed a square within the circle, then an octagon, then a figure with 16 sides, and so on. As the number of sides became very large, the area of these figures (which he could calculate) approached the true area of the circle.**

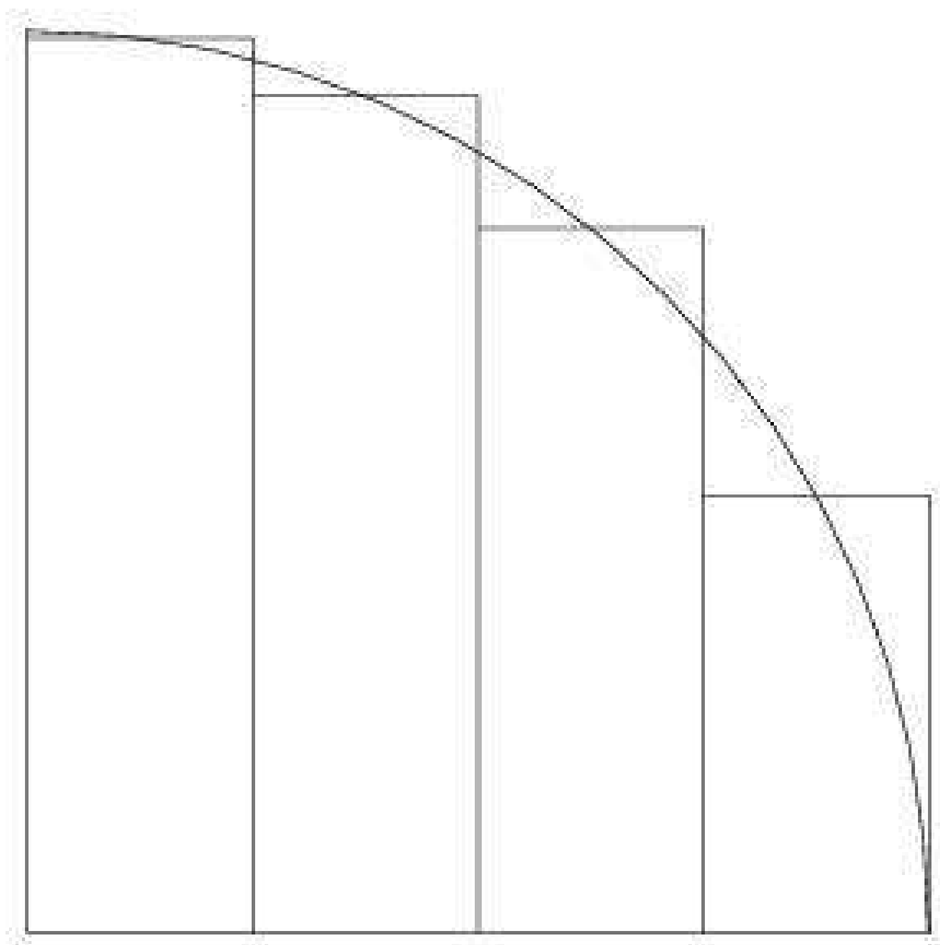

Figure 2.3: **Here we see another way in which Archimedes used his doctrine of limits. He could calculate the areas of figures bounded by curves by dividing up these areas into a large number of narrow strips. As the number of strips became very large, their total area approached the true area of the figure.**

Unfortunately, Archimedes was unable to transmit his invention of the calculus to the other mathematicians of his time. The difficulty was that there was not yet any such thing as algebraic geometry. The Pythagoreans had never recovered from the shock of discovering irrational numbers, and they had therefore abandoned algebra in favor of geometry. The union of algebra and geometry, and the development of a calculus which even non-geniuses could use, had to wait for Descartes, Fermat, Newton and Leibniz.

2.3 Statics and hydrostatics

Archimedes was the father of statics (as well as of hydrostatics). He calculated the centers of gravity of many kinds of figures, and he made a systematic, quantitative study of the properties of levers. He is supposed to have said: "Give me a place to stand on, and I can move the world!" This brings us to another of the stories about Archimedes: According to the story, Hieron was a bit sceptical, and he challenged Archimedes to prove his statement by moving something rather enormous, although not necessarily as large as the world. Archimedes good-humoredly accepted the challenge, hooked up a system of pulleys to a fully-loaded ship in the harbor, seated himself comfortably, and without excessive effort he singlehandedly pulled the ship out of the water and onto the shore.

Archimedes had a very compact notation for expressing large numbers. Essentially his system was the same as our own exponential notation, and it allowed him to handle very large numbers with great ease. In a curious little book called *The Sand Reckoner*, he used this notation to calculate the number of grains of sand which would be needed to fill the universe. (Of course, he had to make a crude guess about the size of the universe.) Archimedes wrote this little book to clarify the distinction between things which are very large but finite and things which are infinite. He wanted to show that nothing finite - not even the number of grains of sand needed to fill the universe - is too large to be measured and expressed in numbers. *The Sand Reckoner* is important as an historical document, because in it Archimedes incidentally mentions the revolutionary heliocentric model of Aristarchus, which does not occur in the one surviving book by Aristarchus himself.

In addition to his mathematical genius, Archimedes showed a superb mechanical intuition, similar to that of Leonardo da Vinci. Among his inventions are a planetarium and an elegant pump in the form of a helical tube. This type of pump is called the "screw of Archimedes", and it is still in use in Egypt. The helix is held at an angle to the surface of the water, with its lower end half-immersed. When the helical tube is rotated about its long axis, the water is forced to flow uphill!

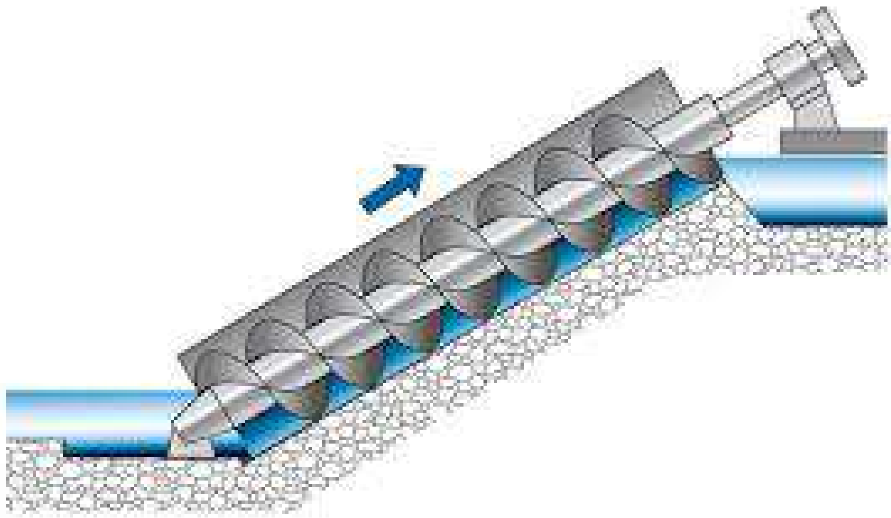

Figure 2.4: **Archimedes' screw, the helical pump which he invented, is still in use today.**

2.4 Don't disturb my circles!

His humanity and his towering intellect brought Archimedes universal respect, both during his own lifetime and ever since. However, he was not allowed to live out his life in peace; and the story of his death is both dramatic and symbolic:

In c. 212 B.C., Syracuse was attacked by a Roman fleet. The city would have fallen quickly if Archimedes had not put his mind to work to think of ways to defend his countrymen. He devised systems of mirrors which focused the sun's rays on the attacking ships and set them on fire, and cranes which plucked the ships from the water and overturned them.

In the end, the Romans hardly dared to approach the walls of Syracuse. However, after several years of siege, the city fell to a surprise attack. Roman soldiers rushed through the streets, looting, burning and killing. One of them found Archimedes seated calmly in front of diagrams sketched in the sand, working on a mathematical problem. When the soldier ordered him to come along, the great mathematician is supposed to have looked up from his work and replied: "Don't disturb my circles." The soldier immediately killed him.

The death of Archimedes and the destruction of the Hellenistic civilization illustrate the fragility of civilization. It was only a short step from Archimedes to Galileo and Newton; only a short step from Eratosthenes to Columbus, from Aristarchus to Copernicus, from Aristotle to Darwin or from Hippocrates to Pasteur. These steps in the cultural evolution of mankind had to wait nearly two thousand years, because the brilliant Hellenistic civilization was destroyed, and Europe was plunged back into the dark ages.

Figure 2.5: **Machines used by Archimedes to defend Syracuse against the Roman attack.**

Figure 2.6: **"The death of Archimedes", a painting by Thomas Degeorge.**

Figure 2.7: **The Great Library of Alexandria was partially burned during an attack by Julius Caesar in 48 BC. Much of the library survived, but during the Roman period which followed, it declined through neglect. With the destruction of the advanced Hellenistic civilization, much knowledge was lost. Had it survived, the history of human culture and science would have been very different.**

Suggestions for further reading

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Chapter 3

GALILEO

3.1 Experimental physics

Galileo Galilei was born in Pisa in 1564. He was the son of Vincenzo Galilei, an intellectual Florentine nobleman whose fortune was as small as his culture was great. Vincenzo Galilei was a mathematician, composer and music critic, and from him Galileo must have learned independence of thought, since in one of his books Vincenzo wrote: "It appears to me that those who try to prove a assertion by relying simply on the weight of authority act very absurdly." This was to be Galileo's credo throughout his life. He was destined to demolish the decayed structure of Aristotelian physics with sledgehammer blows of experiment.

Vincenzo Galilei, who knew what it was like to be poor, at first tried to make his son into a wool merchant. However, when Galileo began to show unmistakable signs of genius, Vincenzo decided to send him to the University of Pisa, even though this put a great strain on the family's financial resources.

At the university and at home, Galileo was deliberately kept away from mathematics. Following the wishes of his father, he studied medicine, which was much better paid than mathematics. However, he happened to hear a lecture on Euclid given by Ostilio Ricci, a friend of his father who was Mathematician at the court of the Grand Duke Ferdinand de' Medici.

Galileo was so struck by the logical beauty and soundness of the lecture that he begged Ricci to lend him some of the works of Euclid. These he devoured in one gulp, and they were followed by the works of Archimedes. Galileo greatly admired Archimedes' scientific method, and he modeled his own scientific method after it.

After three years at the University of Pisa, Galileo was forced to return home without having obtained a degree. His father had no more money with which to support him, and Galileo was unable to obtain a scholarship, probably because his irreverent questioning of every kind of dogma had made him unpopular with the authorities. However, by this time he had already made his first scientific discovery.

According to tradition, Galileo is supposed to have made this discovery while attending a service at the Cathedral of Pisa. His attention was attracted to a lamp hung from the

Figure 3.1: **Galileo became interested in the pendulum when he watched a lamp swinging in a cathedral. In 1602, he began experiments with pendulums, and discovered that the period is not affected by the amplitude.**

vault, which the verger had lighted and left swinging. As the swings became smaller, he noticed that they still seemed to take the same amount of time. He checked this by timing the frequency against his pulse. Going home, he continued to experiment with pendula. He found that the frequency of the oscillations is independent of their amplitude, provided that the amplitude is small; and he found that the frequency depends only on the length of the pendulum.

Having timed the swings of a pendulum against his pulse, Galileo reversed the procedure and invented an instrument which physicians could use for timing the pulse of a patient. This instrument consisted of a pendulum whose length could be adjusted until the swings matched the pulse of the patient. The doctor then read the pulse rate from the calibrated length of the pendulum. Galileo's pulse meter was quickly adopted by physicians throughout Europe. Later, the famous Dutch physicist, Christian Huygens (1629-1695), developed Galileo's discovery into the pendulum clock as we know it today.

While he was living at home after leaving the University of Pisa, Galileo invented a balance for measuring specific gravity, based on Archimedes' Principle in hydrostatics.

Through his writings and inventions, particularly through his treatise on the hydrostatic balance, Galileo was becoming well known, and at the age of 26 he was appointed Professor of Mathematics at the University of Pisa. However, neither age nor the dignity of his new title had mellowed him. As a professor, he challenged authority even more fiercely than he had done as a student. He began systematically checking all the dogmas of Aristotle against the results of experiment.

Aristotle had asserted that the speed of a falling object increased according to its weight: Thus, according to Aristotle, an object ten times as heavy as another would fall ten times as fast. This idea was based on the common experience of a stone falling faster than a feather.

Galileo realized that the issue was being complicated by air resistance. There were really two questions to be answered: 1) How would a body fall in the absence of air? and 2) What is the effect of air resistance? Galileo considered the first question to be the more fundamental of the two, and in order to answer it, he experimented with falling weights made of dense materials, such as iron and lead, for which the effect of air resistance was reduced to a minimum.

According to Galileo's student and biographer, Viviani, Galileo, wishing to refute Aristotle, climbed the Leaning Tower of Pisa in the presence of all the other teachers and philosophers and of all the students, and "by repeated experiments proved that the velocity of falling bodies of the same composition, unequal in weight, does not attain the proportion of their weight as Aristotle assigned it to them, but rather that they move with equal velocity." (Some historians doubt Viviani's account of this event, since no mention of it appears in other contemporary sources.)

Galileo maintained that, in a vacuum, a feather would fall to the ground like a stone. This experiment was not possible in Galileo's time, but later it was tried, and Galileo's prediction was found to be true.

Galileo realized that falling bodies gain in speed as they fall, and he wished to find a quantitative law describing this acceleration. However, he had no good method for measuring very small intervals of time. Therefore he decided to study a similar process which was slow enough to measure: He began to study the way in which a ball, rolling down an inclined plane, increases in speed.

Describing these experiments, Galileo wrote:

"..Having placed the board in a sloping position... we rolled the ball along the channel, noting , in a manner presently to be described, the time required to make the descent. We repeated the experiment more than once, in order to measure the time with an accuracy such that the deviation between two observations never exceeded one-tenth of a pulse beat"

"Having performed this operation, and having assured ourselves of its reliability, we now rolled the ball only one quarter of the length of the channel, and having measured the time of its descent, we found it precisely one-half the former. Next we tried other distances, comparing the time for the whole length with that for the half, or with that for two-thirds or three-fourths, or indeed any fraction. In such experiments, repeated a full hundred times, we always found that the spaces traversed were to each other as the squares of the times..."

"For the measurement of time, we employed a large vessel of water placed in an elevated position. To the bottom of this vessel was soldered a pipe of small diameter giving a thin jet of water, which we collected in a small glass during the time of each descent... The water thus collected was weighed after each descent on a very accurate balance. The differences and ratios of these weights gave us the differences and ratios of the times, and with such an accuracy that although the operation was repeated many, many times, there was no appreciable discrepancy in the results"

These experiments pointed to a law of motion for falling bodies which Galileo had already guessed: The acceleration of a falling body is constant; the velocity increases in linear proportion to the time of fall; and the distance traveled increases in proportion to the square of the time.

Extending these ideas and experiments, Galileo found that a projectile has two types of motion superimposed: the uniformly accelerated falling motion just discussed, and, at the same time, a horizontal motion with uniform velocity. He showed that, neglecting air resistance, these two types of motion combine to give the projectile a parabolic trajectory.

Galileo also formulated the principle of inertia, a law of mechanics which states that in the absence of any applied force, a body will continue at rest, or if in motion, it will continue indefinitely in uniform motion. Closely related to this principle of inertia is the principle of relativity formulated by Galileo and later extended by Einstein: Inside a closed room, it is impossible to perform any experiment to determine whether the room is at rest, or whether it is in a state of uniform motion.

For example, an observer inside a railway train can tell whether the train is in motion by looking out of the window, or by the vibrations of the car; but if the windows were covered and the tracks perfectly smooth, there would be no way to tell. An object dropped in a uniformly-moving railway car strikes the floor directly below the point from which it was dropped, just as it would do if the car were standing still.

The Galilean principle of relativity removed one of the objections which had been raised against the Copernican system. The opponents of Copernicus argued that if the earth really were in motion, then a cannon ball, shot straight up in the air, would not fall back on the cannon but would land somewhere else. They also said that the birds and the clouds would be left behind by the motion of the earth.

In 1597, Kepler sent Galileo a copy of his *Mysterium Cosmographicum*. Galileo read the introduction to the book, which was the first printed support of Copernicus from a professional astronomer, and he replied in a letter to Kepler:

"...I shall read your book to the end, sure of finding much that is excellent in it. I shall do so with the more pleasure because I have for many years been an adherent of the Copernican system, and it explains to me the causes of many of the phenomena of nature which are quite unintelligible on the commonly accepted hypothesis."

"I have collected many arguments in support of the Copernican system and refuting the opposite view, which I have so far not ventured to make public for fear of sharing the fate of Copernicus himself, who, though he acquired immortal fame with some, is yet to an infinite multitude of others (for such is the number of fools) an object of ridicule and derision. I would certainly publish my reflections at once if more people like you existed; as they don't, I shall refrain from publishing."

Kepler replied urging Galileo to publish his arguments in favor of the Copernican system:

"...Have faith, Galileo, and come forward! If my guess is right, there are but few among the prominent mathematicians of Europe who would wish to secede from us, for such is the force of truth." However, Galileo left Kepler's letter unanswered, and he remained silent concerning the Copernican system.

By this time, Galileo was 33 years old, and he had become Professor of Mathematics at the University of Padua. His Aristotelian enemies at the University of Pisa had succeeded in driving him out, but by the time they did so, his fame had become so great that he was immediately offered a position at three times the salary at Padua.

The move was a very fortunate one for Galileo. Padua was part of the free Venetian Republic, outside the power of the Inquisition, and Galileo spent fifteen happy and productive years there. He kept a large house with a master mechanic and skilled craftsmen to produce his inventions (among which was the thermometer). His lectures were attended by enthusiastic audiences, sometimes as large as two thousand; and he had two daughters and a son with a Venetian girl.

3.2 The telescope

In 1609, news reached Galileo that a Dutch optician had combined two spectacle lenses in such a way as to make distant objects seem near. Concerning this event, Galileo wrote:

"A report reached my ears that a certain Fleming had constructed a spyglass by means of which visible objects, though very distant from the eye of the observer, were distinctly seen as if nearby. Of this truly remarkable effect, several experiences were related, to which some persons gave credence while others denied them."

"A few days later the report was confirmed to me in a letter from (a former pupil) at Paris; which caused me to apply myself wholeheartedly to inquire into the means by which I might arrive at the invention of a similar instrument. This I did shortly afterward through deep study of the theory of refraction."

"First I prepared a tube of lead at the ends of which I fitted two glass lenses, both plane on one side, while on the other side one was spherically convex and the other concave. Then, placing my eye near the concave lens, I perceived objects satisfactorally large and near, for they appeared three times closer and nine times larger than when seen with the naked eye alone."

"Next I constructed another more accurate instrument, which represented objects as enlarged more than sixty times. Finally, sparing neither labor nor expense, I succeeded in constructing for myself an instrument so excellent that objects seen through it appeared nearly one thousand times larger and over thirty times closer than when regarded with our natural vision."

Galileo showed one of his early telescopes to his patrons, the Signoria of Venice. Writing of this, Galileo says:

"Many noblemen and senators, though of advanced age, mounted to the top of one of the highest towers to watch the ships, which were visible through my glass two hours before they were seen entering the harbor; for it makes a thing fifty miles off as near and clear as if it were only five."

The senate asked Galileo whether he would give the city a similar instrument to aid in its defense against attack by sea. When he did this, they immediately doubled his salary,

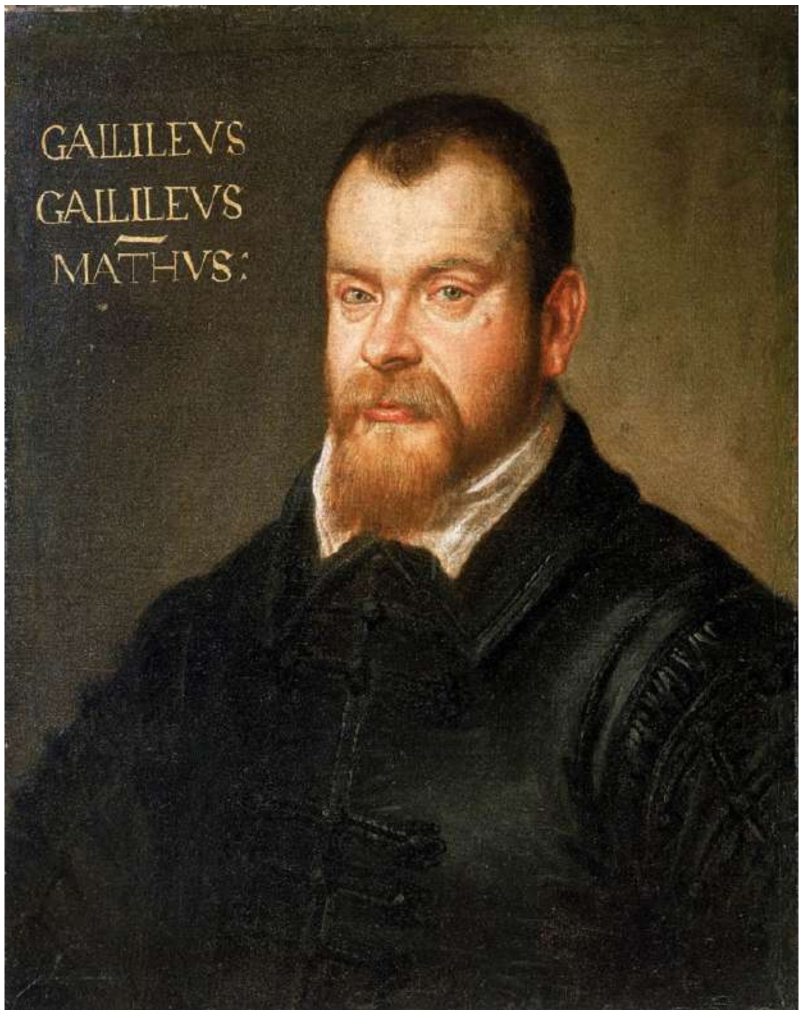

Figure 3.2: **Galileo Galilei in a portrait by Domenico Tintoretto.**

Figure 3.3: **Galileo demonstrates the telescope.**

and they confirmed him in his position for life.

After perfecting the telescope as much as he could, Galileo turned it towards the moon, the planets and the stars. He made a series of revolutionary discoveries which he announced in a short booklet called *Siderius Nuncius*, (The Sidereal Messenger). The impact of this booklet was enormous, as can be judged by the report of Sir Henry Wotton, the British Ambassador to Venice:

"Now touching the occurents of the present", Sir Henry wrote, "I send herewith to His Majesty the strangest piece of news (as I may justly call it) that he has ever yet received from any part of the world; which is the annexed book (come abroad this very day) of the Mathematical Professor at Padua, who by the help of an optical instrument (which both enlargeth and approximateth the object) invented first in Flanders and bettered by himself, hath discovered four new planets rolling around the sphere of Jupiter, besides many other unknown fixed stars; likewise the true cause of the *Via Lactae* (Milky Way), so long searched; and lastly that the moon is not spherical but endued with many prominences, and, which is strangest of all, illuminated with the solar light by reflection from the body of the earth, as he seemeth to say. So as upon the whole subject, he hath overthrown all former astronomy.."

"These things I have been so bold to discourse unto your Lordship, whereof here all corners are full. And the author runneth a fortune to be either exceeding famous or exceeding ridiculous. By the next ship your Lordship shall receive from me one of the above instruments, as it is bettered by this man."

Wherever Galileo turned his powerful telescope, he saw myriads of new stars, so utterly outnumbering the previously known stars that mankind's presumption to know anything at all about the universe suddenly seemed pitiful. The Milky Way now appeared as a sea of stars so numerous that Galileo despaired of describing them in detail. The vastness of the universe as postulated by Nicolas Copernicus and Gordiano Bruno (one ridiculed and the other burned alive) was now brought directly to Galileo's senses. In fact, everywhere he looked he saw evidence supporting the Copernican system and refuting Aristotle and Ptolemy.

The four moons of Jupiter, which Galileo had discovered, followed the planet in its motion, thus refuting the argument that if the earth revolved around the sun, the moon would not be able to revolve around the earth. Also, Jupiter with its moons formed a sort of Copernican system in miniature, with the massive planet in the center and the four small moons circling it, the speed of the moons decreasing according to their distance from Jupiter.

Galileo discovered that the planet Venus has phase changes like the moon, and that these phase changes are accompanied by changes in the apparent size of the planet. Copernicus had predicted that if the power of human vision could be improved, exactly these changes in the appearance of Venus would be observed. Galileo's observations proved that Venus moves in an orbit around the sun: When it is on the opposite side of the sun from the earth, it appears small and full; when it lies between the earth and the sun, it is large and crescent.

Galileo also observed mountains on the moon. He measured their height by observing the way in which sunlight touches their peaks just before the lunar dawn, and he found some of the peaks to be several miles high. This disproved the Aristotelian doctrine that the moon is a perfect sphere, and it established a point of similarity between the moon and the earth.

Galileo observed that the dark portion of the moon is faintly illuminated, and he asserted that this is due to light reflected from the earth, another point of similarity between the two bodies. Generally speaking, the impression which Galileo gained from his study of the moon is that it is a body more or less like the earth, and that probably the same laws of physics apply on the moon as on the earth.

All these observations strongly supported the Copernican system, although the final rivet in the argument, the observation of stellar parallax, remained missing until the 19th century. Although he did not possess this absolutely decisive piece of evidence, Galileo thought that he had a strong enough basis to begin to be more open in teaching the Copernican system. His booklet, *Siderius Nuncius* had lifted him to an entirely new order of fame. He had seen what no man had ever seen before, and had discovered new worlds. His name was on everyone's lips, and he was often compared to Columbus.

3.3 Still it moves!

In 1610, Galileo left Padua to take up a new post as Mathematician to the court of the Medicis in Florence; and in the spring of 1611, he made a triumphal visit to Rome. Describing this visit, Cardinal del Monte wrote: "If we were living under the ancient Republic of Rome, I really believe that there would have been a column on the Capital erected in Galileo's honor!" The Pope received Galileo in a friendly audience, and Prince Cesi made him a member of the Academia dei Lincei.

The Jesuit astronomers were particularly friendly to Galileo. They verified his observations and also improved some of them. However, Galileo made many enemies, especially among the entrenched Aristotelian professors in the universities. He enjoyed controversy (and publicity), and he could not resist making fools of his opponents in such a way that they often became bitter personal enemies.

Not only did Galileo's law describing the acceleration of falling bodies contradict Aristotle, but his principle of inertia contradicted the Aristotelian dogma, *omne quod movetur ab alio movetur* - whatever moves must be moved by something else. (The Aristotelians believed that each planet is moved by an angel.) Galileo also denied Aristotle's teaching that generation and decay are confined to the sphere beneath the orbit of the moon.

Although Galileo was at first befriended and honored by the Jesuit astronomers, he soon made enemies of the members of that order through a controversy over priority in the discovery of sunspots. In spite of this controversy, Galileo's pamphlet on sunspots won great acclaim; and Cardinal Maffeo Barberini (who later became Pope Urban VIII) wrote to Galileo warmly praising the booklet.

In 1613, the Medicis gave a dinner party and invited Professor Castelli, one of Galileo's students who had become Professor of Mathematics at Pisa. After dinner, the conversation turned to Galileo's discoveries, and the Grand Duchess Christina, mother of Duke Cosimo de' Medici, asked Castelli his opinion about whether the motion of the earth contradicted the Bible.

When this conversation was reported to Galileo, his response was to publish a pamphlet entitled *Letter to Castelli*, which was later expanded into a larger pamphlet called *Letter to the Grand Duchess Christina*. These pamphlets, which were very widely circulated, contain the following passage:

"...Let us grant, then, that Theology is conversant with the loftiest divine contemplation, and occupies the regal throne among the sciences by this dignity. By acquiring the highest authority in this way, if she does not descend to the lower and humbler speculations of the subordinate sciences, and has no regard for them because they are not concerned with blessedness, then her professors should not arrogate to themselves the authority to decide on controversies in professions which they have neither studied nor practiced. Why this would be as if an absolute despot, being neither a physician nor an architect, but knowing himself free to command, should undertake to administer medicines and erect buildings according to his whim, at the grave peril of his poor patients' lives, and the speedy collapse of his edifices..."

Galileo's purpose in publishing these pamphlets was to overcome the theological objections to the Copernican system. The effect was exactly the opposite. The *Letter to Castelli* was brought to the attention of the Inquisition, and in 1616 the Inquisition prohibited everyone, especially Galileo, from holding or defending the view that the earth turns on its axis and moves in an orbit around the sun.

Galileo was silenced, at least for the moment. For the next eighteen years he lived unmolested, pursuing his scientific research. For example, continuing his work in optics, he constructed a compound microscope.

In 1623, marvelous news arrived: Cardinal Maffeo Barberini had been elected Pope. He was a great intellectual, and also Galileo's close friend. Galileo went to Rome to pay his respects to the new Pope, and he was received with much warmth. He had six long audiences with the Pope, who showered him with praise and gifts. The new Pope refused to revoke the Inquisition's decree of 1616, but Galileo left Rome with the impression that he was free to discuss the Copernican system, provided he stayed away from theological arguments.

Galileo judged that the time was right to bring forward his evidence for the Copernican cosmology; and he began working on a book which was to be written in the form of a Platonic dialogue. The characters in the conversation are Salivati, a Copernican philosopher, Sagredo, a neutral but intelligent layman, and Simplicio, a slightly stupid Aristotelian, who always ends by losing the arguments.

The book, which Galileo called *Dialogue on the Two Chief World Systems*, is a strong and only very thinly veiled argument in favor of the Copernican system. When it was published in 1632, the reaction was dramatic. Galileo's book was banned almost immediately, and the censor who had allowed it to be printed was banished in disgrace. When the agents of the Inquisition arrived at the bookstores to confiscate copies of the *Dialogue*, they found that the edition had been completely sold out.

The Pope was furious. He felt that he had been betrayed. Galileo's enemies had apparently convinced the Pope that the character called Simplicio in the book was a caricature of the Pope himself! Galileo, who was seventy years old and seriously ill, was dragged to Rome and threatened with torture. His daughter, Maria Celeste, imposed severe penances and fasting on herself, thinking that these would help her prayers for her father. However, her health was weak, and she became ill.

Meanwhile, Galileo, under threat of torture, had renounced his advocacy of the motion of the earth. According to tradition, as he rose from his knees after the recantation he muttered *"Eppur si muove!"*, ("Still it moves!"). It is unlikely that he muttered anything of the kind, since it would have been fatally dangerous to do so, and since at that moment, Galileo was a broken man. Nevertheless, the retort which posterity has imagined him to make remains unanswerable. As Galileo said, before his spirit was broken by the Inquisition, "...It is not in the power of any creature to make (these ideas) true or false or otherwise than of their own nature and in fact they are."

Galileo was allowed to visit the bedside of his daughter, Marie Celeste, but in her weak condition, the anxiety of Galileo's ordeal had been too much for her. Soon afterward, she died. Galileo was now a prisoner of the Inquisition. He used his time to write a book on his lifelong work on dynamics and on the strength of material structures. The manuscript of this book, entitled *Two New Sciences*, was smuggled out of Italy and published in Holland.

When Galileo became blind, the Inquisition relaxed the rules of his imprisonment, and he was allowed to have visitors. Many people came to see him, including John Milton, who was then 29 years old. One wonders whether Milton, meeting Galileo, had any premonition of his own fate. Galileo was already blind, while Milton was destined to become so. The two men had another point in common: their eloquent use of language. Galileo was a many-sided person, an accomplished musician and artist as well as a great scientist. The impact of his ideas was enhanced by his eloquence as a speaker and a writer. This can be seen from the following passage, taken from Galileo's *Dialogue*, where Sagredo comments on the Platonic dualism between heavenly perfection and earthly corruption:

"...I cannot without great wonder, nay more, disbelief, hear it being attributed to natural bodies as a great honor and perfection that they are impassable, immutable, inalterable, etc.; as, conversely, I hear it esteemed a great imperfection to be alterable, generable and mutable. It is my opinion that the earth is very noble and admirable by reason of the many different alterations, mutations and generations which incessantly occur in it. And if, without being subject to any alteration, it had been one vast heap of sand, or a mass of jade, or if, since the time of the deluge, the waters freezing that covered it, it had continued an immense globe of crystal, whereon nothing had ever grown, altered or changed, I should have esteemed it a wretched lump of no benefit to the Universe, a mass of idleness, and in a word, superfluous, exactly as if it had never been in Nature. The difference for me would be the same as between a living and a dead creature."

"I say the same concerning the moon, Jupiter and all the other globes of the Universe. The more I delve into the consideration of the vanity of popular discourses, the more empty and simple I find them. What greater folly can be imagined than to call gems, silver and gold noble, and earth and dirt base? For do not these persons consider that if there were as great a scarcity of earth as there is of jewels and precious metals, there would be no king who would not gladly give a heap of diamonds and rubies and many ingots of gold to purchase only so much earth as would suffice to plant a jasmine in a little pot or to set a tangerine in it, that he might see it sprout, grow up, and bring forth such goodly leaves, fragrant flowers and delicate fruit?"

The trial of Galileo cast a chill over the intellectual atmosphere of southern Europe, and it marked the end of the Italian Renaissance. However, the Renaissance had been moving northward, and had produced such figures as Dürer and Gutenberg in Germany, Erasmus and Rembrandt in Holland, and Shakespeare in England. In 1642, the same year during which Galileo died in Italy, Isaac Newton was born in England.

Suggestions for further reading

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Chapter 4

NEWTON

4.1 Descartes

Until the night of November 10, 1619, algebra and geometry were separate disciplines. On that autumn evening, the troops of the Elector of Bavaria were celebrating the Feast of Saint Martin at the village of Neuberg in Bohemia. With them was a young Frenchman named René Descartes (1596-1659), who had enlisted in the army of the Elector in order to escape from Parisian society. During that night, Descartes had a series of dreams which, as he said later, filled him with enthusiasm, converted him to a life of philosophy, and put him in possession of a wonderful key with which to unlock the secrets of nature.

The program of natural philosophy on which Descartes embarked as a result of his dreams led him to the discovery of analytic geometry, the combination of algebra and geometry. Essentially, Descartes' method amounted to labeling each point in a plane with two numbers, x and y. These numbers represented the distance between the point and two perpendicular fixed lines, (the coordinate axes). Then every algebraic equation relating x and y generated a curve in the plane.

Descartes realized the power of using algebra to generate and study geometrical figures; and he developed his method in an important book, which was among the books that Newton studied at Cambridge. Descartes' pioneering work in analytic geometry paved the way for the invention of differential and integral calculus by Fermat, Newton and Leibniz. (Besides taking some steps towards the invention of calculus, the great French mathematician, Pierre de Fermat (1601-1665), also discovered analytic geometry independently, but he did not publish this work.)

Analytic geometry made it possible to treat with ease the elliptical orbits which Kepler had introduced into astronomy, as well as the parabolic trajectories which Galileo had calculated for projectiles.

Descartes also worked on a theory which explained planetary motion by means of "vortices"; but this theory was by no means so successful as his analytic geometry, and eventually it had to be abandoned.

Descartes did important work in optics, physiology and philosophy. In philosophy, he

Figure 4.1: **Portrait of René Descartes, after Frans Hals.**

is the author of the famous phrase *"Cogito, ergo sum"*, "I think; therefore I exist", which is the starting point for his theory of knowledge. He resolved to doubt everything which it was possible to doubt; and finally he was reduced to knowledge of his own existence as the only real certainty.

René Descartes died tragically through the combination of two evils which he had always tried to avoid: cold weather and early rising. Even as a student, he spent a large portion of his time in bed. He was able to indulge in this taste for a womblike existence because his father had left him some estates in Brittany. Descartes sold these estates and invested the money, from which he obtained an ample income. He never married, and he succeeded in avoiding responsibilities of every kind.

Descartes might have been able to live happily in this way to a ripe old age if only he had been able to resist a flattering invitation sent to him by Queen Christina of Sweden. Christina, the intellectual and strong-willed daughter of King Gustav Adolf, was determined to bring culture to Sweden, much to the disgust of the Swedish noblemen, who considered that money from the royal treasury ought to be spent exclusively on guns and fortifications. Unfortunately for Descartes, he had become so famous that Queen Christina wished to take lessons in philosophy from him; and she sent a warship to fetch him from Holland, where he was staying. Descartes, unable to resist this flattering attention from a royal patron, left his sanctuary in Holland and sailed to the frozen north.

The only time Christina could spare for her lessons was at five o'clock in the morning, three times a week. Poor Descartes was forced to get up in the utter darkness of the bitterly cold Swedish winter nights to give Christina her lessons in a draughty castle library; but his strength was by no means equal to that of the queen, and before the winter was over he had died of pneumonia.

4.2 Newton

On Christmas day in 1642 (the year in which Galileo died), a recently widowed woman named Hannah Newton gave birth to a premature baby at the manor house of Woolsthorpe, a small village in Lincolnshire, England. Her baby was so small that, as she said later, "he could have been put into a quart mug", and he was not expected to live. He did live, however, and lived to achieve a great scientific synthesis, uniting the work of Copernicus, Brahe, Kepler, Galileo and Descartes.

When Isaac Newton was four years old, his mother married again and went to live with her new husband, leaving the boy to be cared for by his grandmother. This may have caused Newton to become more solemn and introverted than he might otherwise have been. One of his childhood friends remembered him as "a sober, silent, thinking lad, scarce known to play with the other boys at their silly amusements".

As a boy, Newton was fond of making mechanical models, but at first he showed no special brilliance as a scholar. He showed even less interest in running the family farm, however; and a relative (who was a fellow of Trinity College) recommended that he be sent to grammar school to prepare for Cambridge University.

When Newton arrived at Cambridge, he found a substitute father in the famous mathematician Isaac Barrow, who was his tutor. Under Barrow's guidance, and while still a student, Newton showed his mathematical genius by inventing the binomial theorem.

In 1665, Cambridge University was closed because of an outbreak of the plague, and Newton returned for two years to the family farm at Woolsthorpe. He was then twenty-three years old. During the two years of isolation, Newton developed his binomial theorem into the beginnings of differential calculus.

Newton's famous experiments in optics also date from these years. The sensational experiments of Galileo were very much discussed at the time, and Newton began to think about ways to improve the telescope. Writing about his experiments in optics, Newton says:

"In the year 1666 (at which time I applied myself to the grinding of optic glasses of other figures than spherical), I procured me a triangular prism, to try therewith the celebrated phenomena of colours. And in order thereto having darkened my chamber, and made a small hole in the window shuts to let in a convenient quantity of the sun's light, I placed my prism at its entrance, that it might thereby be refracted to the opposite wall."

"It was at first a very pleasing divertisment to view the vivid and intense colours produced thereby; but after a while, applying myself to consider them more circumspectly, I became surprised to see them in an oblong form, which, according to the received laws of refraction I expected should have been circular."

Newton then describes his crucial experiment. In this experiment, the beam of sunlight from the hole in the window shutters was refracted by two prisms in succession. The first prism spread the light into a rainbow-like band of colors. From this spectrum, he selected a beam of a single color, and allowed the beam to pass through a second prism; but when light of a single color passed through the second prism, the color did not change, nor was the image spread out into a band. No matter what Newton did to it, red light always remained red, once it had been completely separated from the other colors; yellow light remained yellow, green remained green, and blue remained blue.

Newton then measured the amounts by which the beams of various colors were bent by the second prism; and he discovered that red light was bent the least. Next in sequence came orange, yellow, green, blue and finally violet, which was deflected the most. Newton recombined the separated colors, and he found that together, they once again produced white light.

Concluding the description of his experiments, Newton wrote:

"...and so the true cause of the length of the image (formed by the first prism) was detected to be no other than that light is not similar or homogenial, but consists of *deform rays, some of which are more refrangible than others*."

"As rays of light differ in their degrees of refrangibility, so they also differ in their disposition to exhibit this or that particular colour... To the same degree of refrangibility ever belongs the same colour, and to the same colour ever belongs the same degree of refrangibility."

"...The species of colour and the degree of refrangibility belonging to any particular sort of rays is not mutable by refraction, nor by reflection from natural bodies, nor by any other cause that I could yet observe. When any one sort of rays hath been well parted from those of other kinds, it hath afterwards obstinately retained its colour, notwithstanding my utmost endeavours to change it."

During the plague years of 1665 and 1666, Newton also began the work which led to his great laws of motion and universal gravitation. Referring to the year 1666, he wrote:

"I began to think of gravity extending to the orb of the moon; and having found out how to estimate the force with which a globe revolving within a sphere presses the surface of the sphere, from Kepler's rule of the periodical times of the planets being in a sesquialternate proportion of their distances from the centres of their orbs, I deduced that the forces which keep the planets in their orbs must be reciprocally as the squares of the distances from the centres about which they revolve; and thereby compared the force requisite to keep the moon in her orb with the force of gravity at the surface of the earth, and found them to answer pretty nearly."

"All this was in the plague years of 1665 and 1666, for in those days I was in the prime of my age for invention, and minded mathematics and philosophy more than at any time since."

Galileo had studied the motion of projectiles, and Newton was able to build on this work by thinking of the moon as a sort of projectile, dropping towards the earth, but at the same time moving rapidly to the side. The combination of these two motions gives the moon its nearly-circular path.

From Kepler's third law, Newton had deduced that the force with which the sun attracts a planet must fall off as the square of the distance between the planet and the sun. With great boldness, he guessed that this force is *universal*, and that every object in the universe attracts every other object with a gravitational force which is directly proportional to the product of the two masses, and inversely proportional to the square of the distance between them.

Newton also guessed correctly that in attracting an object outside its surface, the earth acts as though its mass were concentrated at its center. However, he could not construct the proof of this theorem, since it depended on integral calculus, which did not exist in 1666. (Newton himself invented integral calculus later in his life.)

In spite of the missing proof, Newton continued and "...compared the force requisite to keep the moon in her orb with the force of gravity at the earth's surface, and found them to answer pretty nearly". He was not satisfied with this incomplete triumph, and he did not show his calculations to anyone. He not only kept his ideas on gravitation to himself, (probably because of the missing proof), but he also refrained for many years from publishing his work on the calculus. By the time Newton published, the calculus had been invented independently by the great German mathematician and philosopher, Gottfried Wilhelm Leibniz (1646-1716); and the result was a bitter quarrel over priority. However, Newton did publish his experiments in optics, and these alone were enough to make him famous.

In 1669, Newton's teacher, Isaac Barrow, generously resigned his post as Lucasian Professor of Mathematics so that Newton could have it. Thus, at the age of 27, Newton became the head of the mathematics department at Cambridge. He was required to give eight lectures a year, but the rest of his time was free for research.

Newton's prism experiments had led him to believe that the only possible way to avoid blurring of colors in the image formed by a telescope was to avoid refraction entirely. Therefore he designed and constructed the first reflecting telescope. In 1672, he presented a reflecting telescope to the newly-formed Royal Society, which then elected him to membership.

Meanwhile, the problems of gravitation and planetary motion were increasingly discussed by the members of the Royal Society. In January, 1684, three members of the Society were gathered in a London coffee house. One of them was Robert Hooke (1635-1703), author of *Micrographia* and Professor of Geometry at Gresham College, a brilliant but irritable man. He had begun his career as Robert Boyle's assistant, and had gone on to do important work in many fields of science. Hooke claimed that he could calculate the motion of the planets by assuming that they were attracted to the sun by a force which diminished as the square of the distance.

Listening to Hooke were Sir Christopher Wren (1632-1723), the designer of St. Paul's Cathedral, and the young astronomer, Edmund Halley (1656-1742). Wren challenged Hooke to produce his calculations; and he offered to present Hooke with a book worth 40 shillings if he could prove his inverse square force law by means of rigorous mathematics. Hooke tried for several months, but he was unable to win Wren's reward.

Meanwhile, in August, 1684, Halley made a journey to Cambridge to talk with Newton, who was rumored to know very much more about the motions of the planets than he had revealed in his published papers. According to an almost-contemporary account, what happened then was the following:

"Without mentioning his own speculations, or those of Hooke and Wren, he (Halley) at once indicated the object of his visit by asking Newton what would be the curve described by the planets on the supposition that gravity diminished as the square of the distance. Newton immediately answered: an Ellipse. Struck with joy and amazement, Halley asked how he knew it? 'Why', replied he, 'I have calculated it'; and being asked for the calculation, he could not find it, but promised to send it to him."

Newton soon reconstructed the calculation and sent it to Halley; and Halley, filled with enthusiasm and admiration, urged Newton to write out in detail all of his work on motion and gravitation. Spurred on by Halley's encouragement and enthusiasm, Newton began to put his research in order. He returned to the problems which had occupied him during the plague years, and now his progress was rapid because he had invented integral calculus. This allowed him to prove rigorously that terrestrial gravitation acts as though all the earth's mass were concentrated at its center. Newton also had available an improved value for the radius of the earth, measured by the French astronomer Jean Picard (1620-1682). This time, when he approached the problem of gravitation, everything fell into place.

By the autumn of 1684, Newton was ready to give a series of lectures on dynamics, and he sent the notes for these lectures to Halley in the form of a small booklet entitled *On the Motion of Bodies*. Halley persuaded Newton to develop these notes into a larger book, and with great tact and patience he struggled to keep a controversy from developing between Newton, who was neurotically sensitive, and Hooke, who was claiming his share

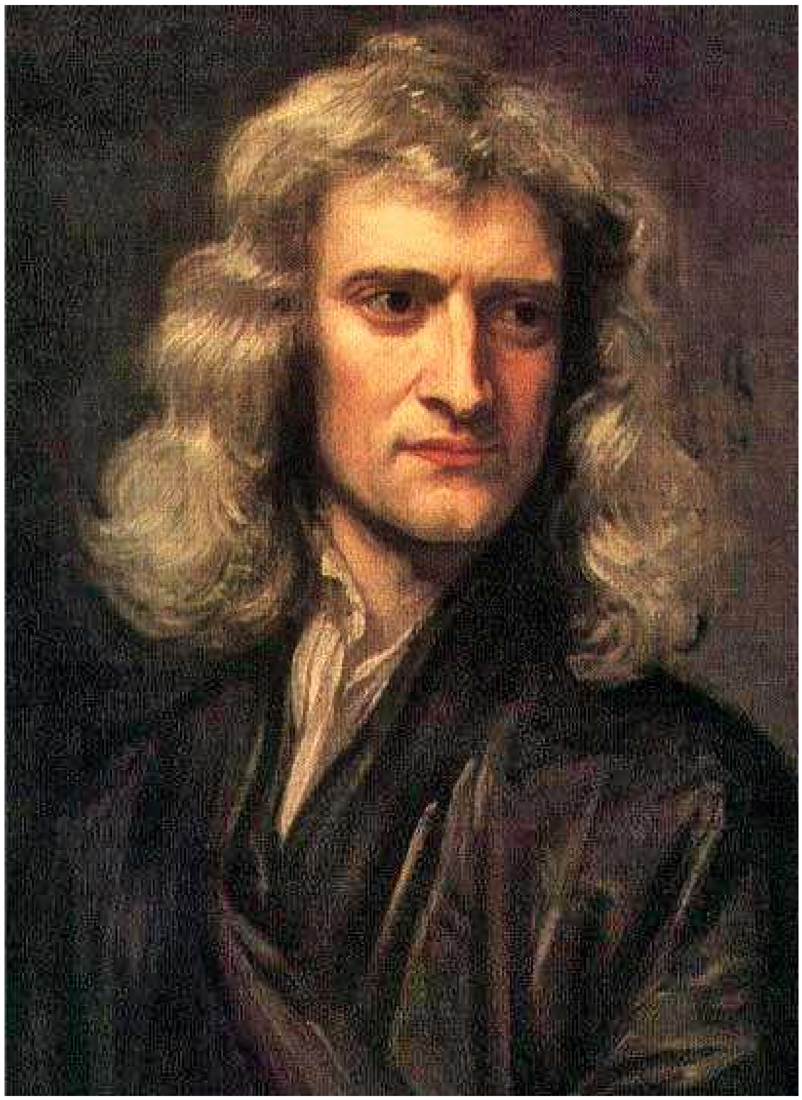

Figure 4.2: **Portrait of Isaac Newton (1642-1727) by Sir Godfrey Kneller.**

of recognition in very loud tones, hinting that Newton was guilty of plagiarism.

Although Newton was undoubtedly the greatest physicist of all time, he had his shortcomings as a human being; and he reacted by striking out from his book every single reference to Robert Hooke. The Royal Society at first offered to pay for the publication costs of Newton's book, but because a fight between Newton and Hooke seemed possible, the Society discretely backed out. Halley then generously offered to pay the publication costs himself, and in 1686 Newton's great book was printed. It is entitled *Philosophae Naturalis Principia Mathematica*, (The Mathematical Principles of Natural Philosophy), and it is divided into three sections.

The first book sets down the general principles of mechanics. In it, Newton states his three laws of motion, and he also discusses differential and integral calculus (both invented by himself).

In the second book, Newton applies these methods to systems of particles and to hydrodynamics. For example, he calculates the velocity of sound in air from the compressibility and density of air; and he treats a great variety of other problems, such as the problem of calculating how a body moves when its motion is slowed by a resisting medium, such as air or water.

The third book is entitled *The System of the World*. In this book, Newton sets out to derive the entire behavior of the solar system from his three laws of motion and from his law of universal gravitation. From these, he not only derives all three of Kepler's laws, but he also calculates the periods of the planets and the periods of their moons; and he explains such details as the flattened, non-spherical shape of the earth, and the slow precession of its axis about a fixed axis in space. Newton also calculated the irregular motion of the moon resulting from the combined attractions of the earth and the sun; and he determined the mass of the moon from the behavior of the tides.

Newton's *Principia* is generally considered to be the greatest scientific work of all time. To present a unified theory explaining such a wide variety of phenomena with so few assumptions was a magnificent and unprecedented achievement; and Newton's contemporaries immediately recognized the importance of what he had done.

The great Dutch physicist, Christian Huygens (1629-1695), inventor of the pendulum clock and the wave theory of light, travelled to England with the express purpose of meeting Newton. Voltaire, who for reasons of personal safety was forced to spend three years in England, used the time to study Newton's *Principia*; and when he returned to France, he persuaded his mistress, Madame du Chatelet, to translate the *Principia* into French; and Alexander Pope, expressing the general opinion of his contemporaries, wrote a famous couplet, which he hoped would be carved on Newton's tombstone:

"Nature and Nature's law lay hid in night.

God said: 'Let Newton be!', and all was light!"

The Newtonian synthesis was the first great achievement of a new epoch in human thought, an epoch which came to be known as the "Age of Reason" or the "Enlightenment". We might ask just what it was in Newton's work that so much impressed the intellectuals of the 18th century. The answer is that in the Newtonian system of the world, the entire evolution of the solar system is determined by the laws of motion and by the positions and velocities of the planets and their moons at a given instant of time. Knowing these, it is possible to predict all of the future and to deduce all of the past.

The Newtonian system of the world is like an enormous clock which has to run on in a predictable way once it is started. In this picture of the world, comets and eclipses are no longer objects of fear and superstition. They too are part of the majestic clockwork of the universe. The Newtonian laws are simple and mathematical in form; they have complete generality; and they are unalterable. In this picture, although there are no miracles or exceptions to natural law, nature itself, in its beautiful works, can be regarded as miraculous.

Newton's contemporaries knew that there were other laws of nature to be discovered besides those of motion and gravitation; but they had no doubt that, given time, all of the laws of nature would be discovered. The climate of intellectual optimism was such that many people thought that these discoveries would be made in a few generations, or at most in a few centuries.

In 1704, Newton published a book entitled *Opticks*, expanded editions of which appeared in 1717 and 1721. Among the many phenomena discussed in this book are the colors produced by thin films. For example, Newton discovered that when he pressed two convex lenses together, the thin film of air trapped between the lenses gave rise to rings of colors ("Newton's rings"). The same phenomenon can be seen in the in the colors of soap bubbles or in films of oil on water.

In order to explain these rings, Newton postulated that "..every ray of light in its passage through any refracting surface is put into a transient constitution or state, which in the progress of the ray returns at equal intervals, and disposes the ray at every return to be easily transmitted through the next refracting surface and between the returns to be easily reflected from it."

Newton's rings were later understood on the basis of the wave theory of light advocated by Huygens and Hooke. Each color has a characteristic wavelength, and is easily reflected when the ratio of the wavelength to the film thickness is such that the wave reflected from the bottom surface of the film interferes constructively with the wave reflected from the top surface. However, although he ascribed periodic "fits of easy reflection" and "fits of easy transmission" to light, and although he suggested that a particular wavelength is associated with each color, Newton rejected the wave theory of light, and believed instead that light consists of corpuscles emitted from luminous bodies.

Newton believed in his corpuscular theory of light because he could not understand on the basis of Huygens' wave theory how light casts sharp shadows. This is strange, because in his *Opticks* he includes the following passage:

"Grimaldo has inform'd us that if a beam of the sun's light be let into a dark room through a very small hole, the shadows of things in this light will be larger than they ought to be if the rays went on by the bodies in straight lines, and that these shadows have three parallel fringes, bands or ranks of colour'd light adjacent to them. But if the hole be enlarg'd, the fringes grow broad and run into one another, so that they cannot be distinguish'd"

After this mention of the discovery of diffraction by the Italian physicist, Francesco

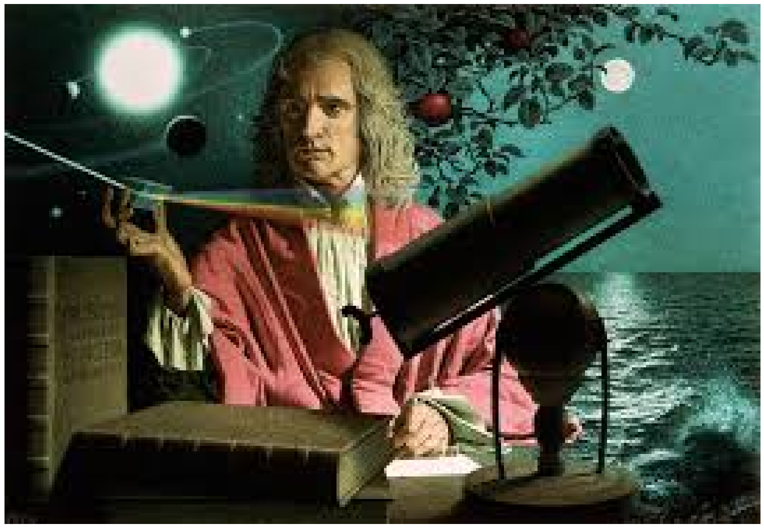

Figure 4.3: **Newton: "I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."**

Maria Grimaldi (1618-1663), Newton discusses his own studies of diffraction. Thus, Newton must have been aware of the fact that light from a very small source does not cast completely sharp shadows!

Newton felt that his work on optics was incomplete, and at the end of his book he included a list of "Queries", which he would have liked to have investigated. He hoped that this list would help the research of others. In general, although his contemporaries were extravagant in praising him, Newton's own evaluation of his work was modest. "I do not know how I may appear to the world", he wrote, "but to myself I seem to have been only like a boy playing on the seashore and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

4.3 Huygens and Leibniz

Meanwhile, on the continent, mathematics and physics had been developing rapidly, stimulated by the writings of René Descartes. One of the most distinguished followers of Descartes was the Dutch physicist, Christian Huygens (1629-1695).

Huygens was the son of an important official in the Dutch government. After studying mathematics at the University of Leiden, he published the first formal book ever written about probability. However, he soon was diverted from pure mathematics by a growing interest in physics.

In 1655, while working on improvements to the telescope together with his brother

Figure 4.4: **Christian Huygens (1629-1695).**

and the Dutch philosopher Benedict Spinoza, Huygens invented an improved method for grinding lenses. He used his new method to construct a twenty-three foot telescope, and with this instrument he made a number of astronomical discoveries, including a satellite of Saturn, the rings of Saturn, the markings on the surface of Mars and the Orion Nebula.

Huygens was the first person to estimate numerically the distance to a star. By assuming the star Sirius to be exactly as luminous as the sun, he calculated the distance to Sirius, and found it to be 2.5 trillion miles. In fact, Sirius is more luminous than the sun, and its true distance is twenty times Huygens' estimate.

Another of Huygens' important inventions is the pendulum clock. Improving on Galileo's studies, he showed that for a pendulum swinging in a circular arc, the period is not precisely independent of the amplitude of the swing. Huygens then invented a pendulum with a modified arc, not quite circular, for which the swing was exactly isochronous. He used this improved pendulum to regulate the turning of cog wheels, driven by a falling weight; and thus he invented the pendulum clock, almost exactly as we know it today.

In discussing Newton's contributions to optics, we mentioned that Huygens opposed Newton's corpuscular theory of light, and instead advocated a wave theory. Huygens believed that the rapid motion of particles in a hot body, such as a candle flame, produces a wave-like disturbance in the surrounding medium; and he believed that this wavelike disturbance of the "ether" produces the sensation of vision by acting on the nerves at the back of our eyes.

In 1678, while he was working in France under the patronage of Louis XIV, Huygens composed a book entitled *Traité de la Lumiere*, (Treatise on Light), in which he says:

"...It is inconceivable to doubt that light consists of the motion of some sort of matter. For if one considers its production, one sees that here upon the earth it is chiefly engendered by fire and flame, which undoubtedly contain bodies in rapid motion, since they dissolve and melt many other bodies, even the most solid; or if one considers its effects, one sees that when light is collected, as by concave mirrors, it has the property of burning as fire does, that is to say, it disunites the particles of bodies. This is assuredly the mark of motion, at least in the true philosophy in which one conceives the causes of all natural effects in terms of mechanical motions..."

"Further, when one considers the extreme speed with which light spreads on every side, and how, when it comes from different regions, even from those directly opposite, the rays traverse one another without hindrance, one may well understand that when we see a luminous object, it cannot be by any transport of matter coming to us from the object, in the way in which a shot or an arrow traverses the air; for assuredly that would too greatly impugn these two properties of light, especially the second of them. It is in some other way that light spreads; and that which can lead us to comprehend it is the knowledge which we have of the spreading of sound in the air."

Huygens knew the velocity of light rather accurately from the work of the Danish astronomer, Ole Rømer (1644-1710), who observed the moons of Jupiter from the near and far sides of the earth's orbit. By comparing the calculated and observed times for the moons to reach a certain configuration, Rømer was able to calculate the time needed for light to propagate across the diameter of the earth's orbit. In this way, Rømer calculated the velocity of light to be 227,000 kilometers per second. Considering the early date of this first successful measurement of the velocity of light, it is remarkably close to the accepted modern value of 299,792 kilometers per second. Thus Huygens knew that although the speed of light is enormous, it is not infinite.

Huygens considered the propagation of a light wave to be analogous to the spreading of sound, or the widening of the ripple produced when a pebble is thrown into still water. He developed a mathematical principle for calculating the position of a light wave after a short interval of time if the initial surface describing the wave front is known. Huygens considered each point on the initial wave front to be the source of spherical wavelets, moving outward with the speed of light in the medium. The surface marking the boundary between the region outside all of the wavelets and the region inside some of them forms the new wave front.

If one uses Huygens' Principle to calculate the wave fronts and rays for light from a point source propagating past a knife edge, one finds that a part of the wave enters the shadow region. This is, in fact, precisely the effect which was observed by both Grimaldi and Newton, and which was given the name "diffraction" by Grimaldi. In the hands of Thomas Young (1773-1829) and Augustin Jean Fresnel (1788-1827), diffraction effects later became a strong argument in favor of Huygens' wave theory of light.

(You can observe diffraction effects yourself by looking at a point source of light, such as a distant street lamp, through a piece of cloth, or through a small slit or hole. Another type of diffraction can be seen by looking at light reflected at a grazing angle from a phonograph record. The light will appear to be colored. This effect is caused by the fact that each groove is a source of wavelets, in accordance with Huygens' Principle. At certain angles, the wavelets will interfere constructively, the angles for constructive interference being different for each color.)

Interestingly, modern quantum theory (sometimes called wave mechanics) has shown that *both* Huygens' wave theory of light and Newton's corpuscular theory contain aspects of the truth! Light has both wave-like and particle-like properties. Furthermore, quantum theory has shown that small particles of matter, such as electrons, also have wave-like properties! For example, electrons can be diffracted by the atoms of a crystal in a manner exactly analogous to the diffraction of light by the grooves of a phonograph record. Thus the difference of opinion between Huygens and Newton concerning the nature of light is especially interesting, since it foreshadows the wave-particle duality of modern physics.

Among the friends of Christian Huygens was the German philosopher and mathematician Gottfried Wilhelm Leibniz (1646-1716). Leibniz was a man of universal and spectacular ability. In addition to being a mathematician and philosopher, he was also a lawyer, historian and diplomat. He invented the doctrine of balance of power, attempted to unify the Catholic and Protestant churches, founded academies of science in Berlin and St. Petersberg, invented combinatorial analysis, introduced determinants into mathematics, independently invented the calculus, invented a calculating machine which could multiply and divide as well as adding and subtracting, acted as advisor to Peter the Great and originated the theory that "this is the best of all possible worlds" (later mercilessly satirized by Voltaire in *Candide*).

Leibniz learned mathematics from Christian Huygens, whom he met while travelling as an emissary of the Elector of Mainz. Since Huygens too was a man of very wide interests, he found the versatile Leibniz congenial, and gladly agreed to give him lessons. Leibniz continued to correspond with Huygens and to receive encouragement from him until the end of the older man's life.

In 1673, Leibniz visited England, where he was elected to membership by the Royal Society. During the same year, he began his work on calculus, which he completed and published in 1684. Newton's invention of differential and integral calculus had been made much earlier than the independent work of Leibniz, but Newton did not publish his discoveries until 1687. This set the stage for a bitter quarrel over priority between the admirers of Newton and those of Leibniz. The quarrel was unfortunate for everyone concerned, especially for Leibniz himself. He had taken a position in the service of the Elector of Hanover, which he held for forty years. However, in 1714, the Elector was called to the throne of England as George I. Leibniz wanted to accompany the Elector to England, but was left behind, mainly because of the quarrel with the followers of Newton. Leibniz died two years later, neglected and forgotten, with only his secretary attending the funeral.

Figure 4.5: **Portrait of Gottfried Wilhelm Leibniz by J.F. Wentzel.**

4.4 The Bernoullis and Euler

Among the followers of Leibniz was an extraordinary family of mathematicians called Bernoulli. They were descended from a wealthy merchant family in Basel, Switzerland. The head of the family, Nicolas Bernoulli the Elder, tried to force his three sons, James (1654-1705), Nicolas II (1662-1716) and John (1667-1748) to follow him in carrying on the family business. However, the eldest son, James, had taught himself the Leibnizian form of calculus, and instead became Professor of Mathematics at the University of Basel. His motto was *"Invicto patre sidera verso"* ("Against my father's will, I study the stars").

Nicolas II and John soon caught their brother's enthusiasm, and they learned calculus from him. John became Professor of Mathematics in Gröningen and Nicolas II joined the faculty of the newly-formed Academy of St. Petersberg. John Bernoulli had three sons, Nicolas III (1695-1726), Daniel (1700-1782) and John II (1710-1790), all of whom made notable contributions to mathematics and physics. In fact, the family of Nicolas Bernoulli the Elder produced a total of nine famous mathematicians in three generations!

Daniel Bernoulli's brilliance made him stand out even among the other members of his gifted family. He became professor of mathematics at the Academy of Sciences in St. Petersberg when he was twenty-five. After eight Russian winters however, he returned to his native Basel. Since the chair in mathematics was already occupied by his father, he was given a vacant chair, first in anatomy, then in botany, and finally in physics. In spite of the variety of his titles, however, Daniel's main work was in applied mathematics, and he has been called the father of mathematical physics.

One of the good friends of Daniel Bernoulli and his brothers was a young man named Leonhard Euler (1707-1783). He came to their house once a week to take private lessons from their father, John Bernoulli. Euler was destined to become the most prolific mathematician in history, and the Bernoullis were quick to recognize his great ability. They persuaded Euler's father not to force him into a theological career, but instead to allow him to go with Nicolas III and Daniel to work at the Academy in St. Petersberg.

Euler married the daughter of a Swiss painter and settled down to a life of quiet work, producing a large family and an unparalleled output of papers. A recent edition of Euler's works contains 70 quarto volumes of published research and 14 volumes of manuscripts and letters. His books and papers are mainly devoted to algebra, the theory of numbers, analysis, mechanics, optics, the calculus of variations (invented by Euler), geometry, trigonometry and astronomy; but they also include contributions to shipbuilding science, architecture, philosophy and musical theory!

Euler achieved this enormous output by means of a calm and happy disposition, an extraordinary memory and remarkable powers of concentration, which allowed him to work even in the midst of the noise of his large family. His friend Thiébault described Euler as sitting "..with a cat on his shoulder and a child on his knee - that was how he wrote his immortal works".

In 1771, Euler became totally blind. Nevertheless, aided by his sons and his devoted scientific assistants, he continued to produce work of fundamental importance. It was his habit to make calculations with chalk on a board for the benefit of his assistants, although he himself could not see what he was writing. Appropriately, Euler was making such computations on the day of his death. On September 18, 1783, Euler gave a mathematics lesson to one of his grandchildren, and made some calculations on the motions of balloons. He then spent the afternoon discussing the newly-discovered planet Uranus with two of his assistants. At five o'clock, he suffered a cerebral hemorrhage, lost consciousness, and died soon afterwards. As one of his biographers put it, "The chalk fell from his hand; Euler ceased to calculate, and to live".

In the eighteenth century it was customary for the French Academy of Sciences to propose a mathematical topic each year, and to award a prize for the best paper dealing with the problem. Léonard Euler and Daniel Bernoulli each won the Paris prize more than ten times, and they share the distinction of being the only men ever to do so. John Bernoulli is said to have thrown his son out of the house for winning the Paris prize in a year when he himself had competed for it.

Euler and the Bernoullis did more than anyone else to develop the Leibnizian form of calculus into a workable tool and to spread it throughout Europe. They applied it to a great variety of problems, from the shape of ships' sails to the kinetic theory of gasses. An example of the sort of problem which they considered is the vibrating string.

In 1727, John Bernoulli in Basel, corresponding with his son Daniel in St. Petersberg, developed an approximate set of equations for the motion of a vibrating string by considering it to be a row of point masses, joined together by weightless springs. Then Daniel boldly passed over to the continuum limit, where the masses became infinitely numerous and small.

The result was Daniel Bernoulli's famous wave equation, which is what we would now call a partial differential equation. He showed that the wave equation has sinusoidal solutions, and that the sum of any two solutions is also a solution. This last result, his superposition principle, is a mathematical proof of a property of wave motion noticed by Huygens. The fact that many waves can propagate simultaneously through the same medium without interacting was one of the reasons for Huygens' belief that light is wave-like, since he knew that many rays of light from various directions can cross a given space simultaneously without interacting. Because of their work with partial differential equations, Daniel Bernoulli and Léonard Euler are considered to be the founders of modern theoretical physics.

4.5 Political philosophy of the Enlightenment

The 16th, 17th and 18th centuries have been called the "Age of Discovery", and the "Age of Reason", but they might equally well be called the "Age of Observation". On every side, new worlds were opening up to the human mind. The great voyages of discovery had revealed new continents, whose peoples demonstrated alternative ways of life. The telescopic exploration of the heavens revealed enormous depths of space, containing myriads of previously unknown stars; and explorations with the microscope revealed a new and marvelously intricate world of the infinitesimally small.

In the science of this period, the emphasis was on careful observation. This same emphasis on observation can be seen in the Dutch and English painters of the period. The great Dutch masters, such as Jan Vermeer (1632-1675), Frans Hals (1580-1666), Pieter de Hooch (1629-1678) and Rembrandt van Rijn (1606-1669), achieved a careful realism in their paintings and drawings which was the artistic counterpart of the observations of the pioneers of microscopy, Anton van Leeuwenhoek and Robert Hooke. These artists were supported by the patronage of the middle class, which had become prominent and powerful both in England and in the Netherlands because of the extensive world trade in which these two nations were engaged.

Members of the commercial middle class needed a clear and realistic view of the world in order to succeed with their enterprises. (An aristocrat of the period, on the other hand, might have been more comfortable with a somewhat romanticized and out-of-focus vision, which would allow him to overlook the suffering and injustice upon which his privileges were based.) The rise of the commercial middle class, with its virtues of industriousness, common sense and realism, went hand in hand with the rise of experimental science, which required the same virtues for its success.

In England, the House of Commons (which reflected the interests of the middle class), had achieved political power, and had demonstrated (in the Puritan Rebellion of 1640 and the Glorious Revolution of 1688) that Parliament could execute or depose any monarch who tried to rule without its consent. In France, however, the situation was very different.

After passing through a period of disorder and civil war, the French tried to achieve order and stability by making their monarchy more absolute. The movement towards absolute monarchy in France culminated in the long reign of Louis XIV, who became king in 1643 and who ruled until he died in 1715.

The historical scene which we have just sketched was the background against which the news of Newton's scientific triumph was received. The news was received by a Europe which was tired of religious wars; and in France, it was received by a middle class which was searching for an ideology in its struggle against the *ancien régime*.

To the intellectuals of the 18th century, the orderly Newtonian cosmos, with its planets circling the sun in obedience to natural law, became an imaginative symbol representing rationality. In their search for a society more in accordance with human nature, 18th century Europeans were greatly encouraged by the triumphs of science. Reason had shown itself to be an adequate guide in natural philosophy. Could not reason and natural law also be made the basis of moral and political philosophy? In attempting to carry out this program, the philosophers of the Enlightenment laid the foundations of psychology, anthropology, social science, political science and economics.

One of the earliest and most influential of these philosophers was John Locke (1632-1705), a contemporary and friend of Newton. In his *Second Treatise on Government*, published in 1690, John Locke's aim was to refute the doctrine that kings rule by divine right, and to replace that doctrine by an alternative theory of government, derived by reason from the laws of nature. According to Locke's theory, men originally lived together without formal government:

"Men living together according to reason," he wrote, "without a common superior on

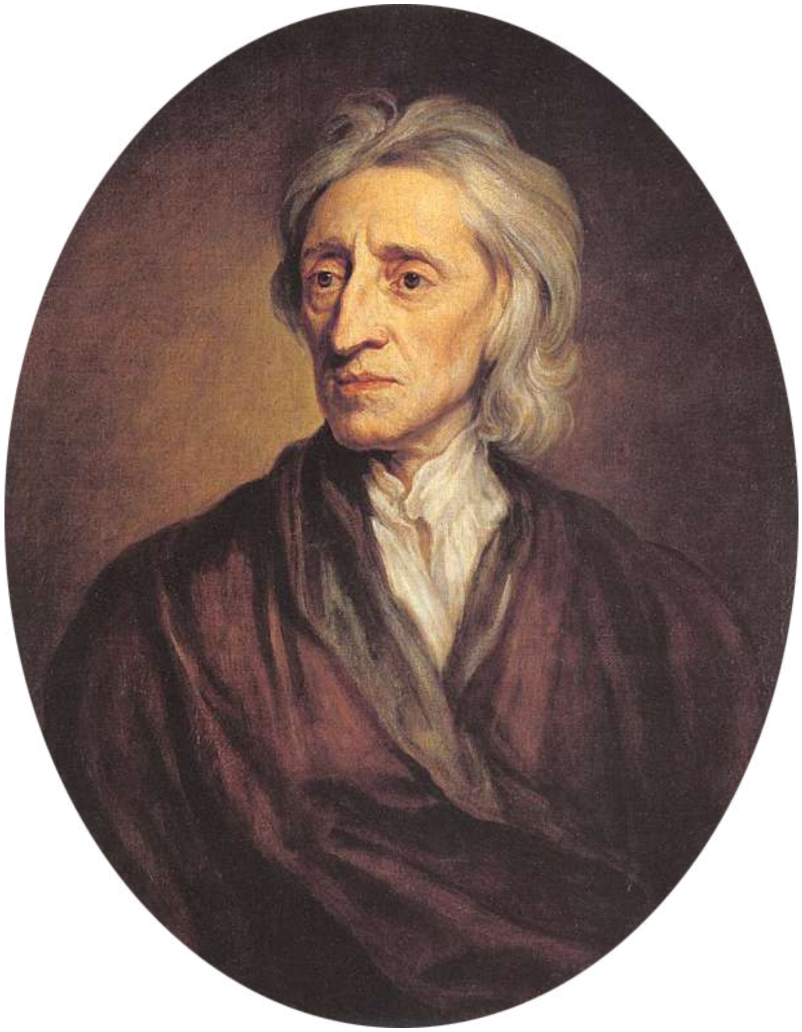

Figure 4.6: **Portrait of John Locke, by Sir Godfrey Kneller.**

earth with authority to judge between them, is properly the state of nature... A state also of equality, wherein all the power and jurisdiction is reciprocal, no one having more than another; there being nothing more evident than that creatures of the same species, promiscuously born to all the same advantages of nature and the use of the same facilities, should also be equal amongst one another without subordination or subjection..."

"But though this be a state of liberty, yet it is not a state of licence... The state of nature has a law to govern it, which obliges every one; and reason, which is that law, teaches all mankind who will but consult it, that being equal and independent, no one ought to harm another in his life, health, liberty or possessions."

In Locke's view, a government is set up by means of a social contract. The government is given its powers by the consent of the citizens in return for the services which it renders to them, such as the protection of their lives and property. If a government fails to render these services, or if it becomes tyrannical, then the contract has been broken, and the citizens must set up a new government.

Locke's influence on 18th century thought was very great. His influence can be seen, for example, in the wording of the American Declaration of Independence. In England, Locke's political philosophy was accepted by almost everyone. In fact, he was only codifying ideas which were already in wide circulation and justifying a revolution which had already occurred. In France, on the other hand, Locke's writings had a revolutionary impact.

Credit for bringing the ideas of both Newton and Locke to France, and making them fashionable, belongs to Francois Marie Arouet (1694-1778), better known as "Voltaire". Besides persuading his mistress, Madame de Chatelet, to translate Newton's *Principia* into French, Voltaire wrote an extremely readable commentary on the book; and as a result, Newton's ideas became highly fashionable among French intellectuals. Voltaire lived with Madame du Chatelet until she died, producing the books which established him as the leading writer of Europe, a prophet of the Age of Reason, and an enemy of injustice, feudalism and superstition.

The Enlightenment in France is considered to have begun with Voltaire's return from England in 1729; and it reached its high point with the publication of of the *Encyclopedia* between 1751 and 1780. Many authors contributed to the *Encyclopedia*, which was an enormous work, designed to sum up the state of human knowledge.

Turgot and Montesquieu wrote on politics and history; Rousseau wrote on music, and Buffon on natural history; Quesnay contributed articles on agriculture, while the Baron d'Holbach discussed chemistry. Other articles were contributed by Condorcet, Voltaire and d'Alembert. The whole enterprise was directed and inspired by the passionate faith of Denis Diderot (1713-1784). The men who took part in this movement called themselves *"philosophes"*. Their creed was a faith in reason, and an optimistic belief in the perfectibility of human nature and society by means of education, political reforms, and the scientific method.

The *philosophes* of the Enlightenment visualized history as a long progression towards the discovery of the scientific method. Once discovered, this method could never be lost; and it would lead inevitably (they believed) to both the material and moral improvement of society. The *philosophes* believed that science, reason, and education, together with the principles of political liberty and equality, would inevitably lead humanity forward to a new era of happiness. These ideas were the faith of the Enlightenment; they influenced the French and American revolutions; and they are still the basis of liberal political belief.

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Chapter 5

GALVANI AND VOLTA

5.1 Benjamin Franklin's kite experiment

The Wikipedia article about Franklin states that he was "...an American polymath and one of the Founding Fathers of the United States. Franklin was a leading author, printer, political theorist, politician, freemason, postmaster, scientist, inventor, humorist, civic activist, statesman, and diplomat. As a scientist, he was a major figure in the American Enlightenment and the history of physics for his discoveries and theories regarding electricity. As an inventor, he is known for the lightning rod, bifocals, and the Franklin stove, among other inventions. He founded many civic organizations, including the Library Company, Philadelphia's first fire department and the University of Pennsylvania.

"Franklin earned the title of 'The First American' for his early and indefatigable campaigning for colonial unity, initially as an author and spokesman in London for several colonies. As the first United States Ambassador to France, he exemplified the emerging American nation. Franklin was foundational in defining the American ethos as a marriage of the practical values of thrift, hard work, education, community spirit, self-governing institutions, and opposition to authoritarianism both political and religious, with the scientific and tolerant values of the Enlightenment."

Benjamin Franklin's famous kite experiment created a vogue for experiments in electricity. It is possible that the name of Frankenstein, the scientist who creates life using a lightning flash in Mary Shelly's novel, is derived from Bengimin Franklin's name. Many laboratories in Europe began to have devices for generating static electricity, and these machines could produce miniature lightning flashes.

Figure 5.1: **A portrait of Benjamin Franklin by Joseph Duplessis, 1778.**

Figure 5.2: **Franklin's kite experiment, as visualized by the artist Benjamin West, who added some cherubs. Franklin's kite experiment led him to invent the lightning rod. His other inventions included bifocal glasses, the glass harmonica and the Franklin stove. In science, Franklin was an early supporter of the wave theory of light; and he made important contributions to demographics, the study of ocean currents and the theory of electricity. He discovered the principle of conservation of electrical charge and constructed a multiple plate capacitor.**

5.2 Galvani's argument with Volta

While Dalton's atomic theory was slowly gaining ground in chemistry, the world of science was electrified (in more ways than one) by the discoveries of Franklin, Galvani, Volta, Ørsted, Ampère, Coulomb and Faraday.

A vogue for electrical experiments had been created by the dramatic experiments of Benjamin Franklin (1706-1790), who drew electricity from a thundercloud, and thus showed that lightning is electrical in nature. Towards the end of the 18th century, almost every scientific laboratory in Europe contained some sort of machine for generating static electricity. Usually these static electricity generators consisted of a sphere of insulating material which could be turned with a crank and rubbed, and a device for drawing off the accumulated static charge. Even the laboratory of the Italian anatomist, Luigi Galvani (1737-1798), contained such a machine; and this was lucky, since it led indirectly to the invention of the electric battery.

In 1771, Galvani noticed that some dissected frog's legs on his work table twitched violently whenever they were touched with a metal scalpel while his electrostatic machine was running. Since Franklin had shown lightning to be electrical, it occurred to Galvani to hang the frog's legs outside his window during a thunderstorm. As he expected, the frog's legs twitched violently during the thunderstorm, but to Galvani's surprise, they continued to move even after the storm was over. By further experimentation, he found that what made the frog's legs twitch was a closed electrical circuit, involving the brass hook from which they were hanging, and the iron lattice of the window.

Galvani mentioned these experiments to his friend, the physicist Alessandro Volta (1745-1827). Volta was very much interested, but he could not agree with Galvani about the source of the electrical current which was making the frog's legs move. Galvani thought that the current was "animal electricity", coming from the frog's legs themselves, while Volta thought that it was the two different metals in the circuit which produced the current.

The argument over this question became bitter, and finally destroyed the friendship between the two men. Meanwhile, to prove his point, Volta constructed the first electrical battery. This consisted of a series of dishes containing salt solution, connected with each other by bridges of metal. One end of each bridge was made of copper, while the other end was made of zinc. Thus, as one followed the circuit, the sequence was: copper, zinc, salt solution, copper, zinc, salt solution, and so on.

Volta found that when a closed circuit was formed by such an arrangement, a steady electrical current flowed through it. The more units connected in series in the battery, the stronger was the current. He next constructed a more compact arrangement, which came to be known as the "Voltaic pile". Volta's pile consisted of a disc of copper, a disc of zinc, a disc of cardboard soaked in salt solution, another disc of copper, another disc of zinc, another disc of cardboard soaked in salt solution, and so on. The more elements there were in the pile, the greater was the electrical potential and current which it produced.

The invention of the electric battery lifted Volta to a peak of fame where he remained for the rest of his life. He was showered with honors and decorations, and invited to demonstrate his experiments to Napoleon, who made him a count and a senator of the

Figure 5.3: **Alisandro Volta.**

Figure 5.4: **Luigi Galvani.**

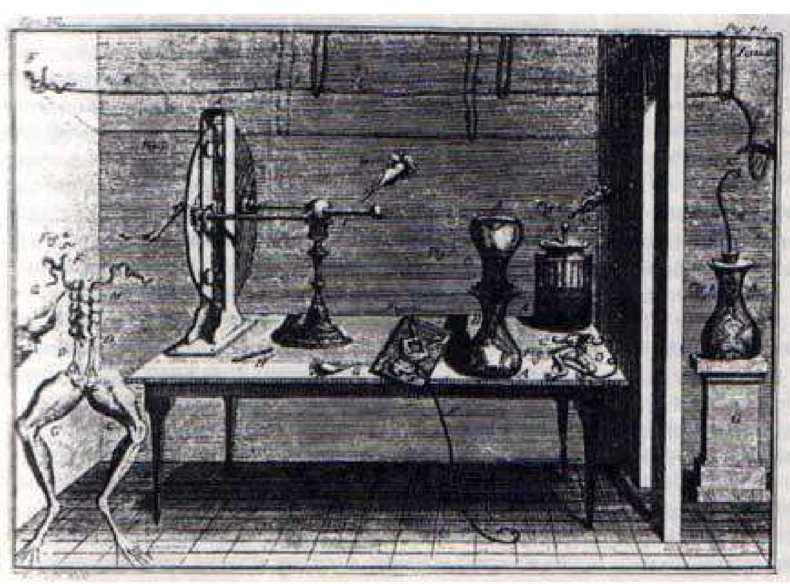

Figure 5.5: **The apparatus used by Galvani.**

Figure 5.6: **Hans Christian Ørsted (1777-1851).**

Kingdom of Lombardy. When Napoleon fell from power, Volta adroitly shifted sides, and he continued to receive honors as long as he lived.

News of the Voltaic pile spread like wildfire throughout Europe and started a series of revolutionary experiments both in physics and in chemistry. On March 20, 1800, Sir Joseph Banks, the President of the Royal Society, received a letter from Volta explaining the method of constructing batteries. On May 2 of the same year, the English chemist, William Nicholson (1755-1815), (to whom Banks had shown the letter), used a Voltaic pile to separate water into hydrogen and oxygen.

Shortly afterwards, the brilliant young English chemist, Sir Humphrey Davy (1778-1829), constructed a Voltaic pile with more than two hundred and fifty metal plates. On October 6, 1807, he used this pile to pass a current through molten potash, liberating a previously unknown metal, which he called potassium. During the year 1808, he isolated barium, strontium, calcium, magnesium and boron, all by means of Voltaic currents.

5.3 Ørsted, Ampère and Faraday

In 1819, the Danish physicist, Hans Christian Ørsted (1777-1851), was demonstrating to his students the electrical current produced by a Voltaic pile. Suspecting some connection between electricity and magnetism, he brought a compass needle near to the wire carrying the current. To his astonishment, the needle turned from north, and pointed in a direction perpendicular to the wire. When he reversed the direction of the current, the needle pointed in the opposite direction.

Ørsted's revolutionary discovery of a connection between electricity and magnetism was extended in France by André Marie Ampère (1775-1836). Ampère showed that two parallel wires, both carrying current, repel each other if the currents are in the same direction, but they attract each other if the currents are opposite. He also showed that a helical coil of wire carrying a current produces a large magnetic field inside the coil; and the more turns in the coil, the larger the field.

Suggestions for further reading

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Chapter 6

FARADAY AND MAXWELL

The electrochemical experiments of Davy, and the electromagnetic discoveries of Ørsted and Ampère, were further developed by the great experimental physicist and chemist, Michael Faraday (1791-1867). He was one of ten children of a blacksmith, and as a boy, he had little education. At the age of 14, he was sent out to work, apprenticed to a London bookbinder. Luckily, the bookbinder sympathized with his apprentice's desire for an education, and encouraged him to read the books in the shop (outside of working hours). Faraday's favorites were Lavoisier's textbook on chemistry, and the electrical articles in the Encyclopedia Britannica.

In 1812, when Michael Faraday was 21 years old, a customer in the bookshop gave him tickets to attend a series of lectures at the Royal Institution, which were to be given by the famous chemist Humphry Davy. At that time, fashionable London socialites (particularly ladies) were flocking to the Royal Institution to hear Davy. Besides being brilliant, he was also extremely handsome, and his lectures, with their dramatic chemical demonstrations, were polished to the last syllable.

Michael Faraday was, of course, thrilled to be present in the glittering audience, and he took careful notes during the series of lectures. These notes, to which he added beautiful colored diagrams, came to 386 pages. He bound the notes in leather and sent them to Sir Joseph Banks, the President of the Royal Society, hoping to get a job related to science. He received no reply from Banks, but, not discouraged, he produced another version of his notes, which he sent to Humphry Davy.

Faraday accompanied his notes with a letter saying that he wished to work in science because of "the detachment from petty motives and the unselfishness of natural philosophers". Davy told him to reserve judgement on that point until he had met a few natural philosophers, but he gave Faraday a job as an assistant at the Royal Institution.

In 1818, Humphry Davy was knighted because of his invention of the miner's safety lamp. He married a wealthy and fashionable young widow, resigned from his post as Director of the Royal Institution, and set off on a two-year excursion of Europe, taking Michael Faraday with him. Lady Davy regarded Faraday as a servant; but in spite of the humiliations which she heaped on him, he enjoyed the tour of Europe and learned much from it. He met, and talked with, Europe's most famous scientists; and in a sense, Europe was his university.

Returning to England, the modest and devoted Faraday finally rose to outshine Sir Humphry Davy, and he became Davy's successor as Director of the Royal Institution. Faraday showed enormous skill, intuition and persistence in continuing the electrical and chemical experiments begun by Davy.

In 1821, a year after H.C. Ørsted's discovery of the magnetic field surrounding a current-carrying wire, Michael Faraday made the first electric motor. His motor was simply a current-carrying wire, arranged so that it could rotate around the pole of a magnet; but out of this simple device, all modern electrical motors have developed. When asked what use his motor was, Faraday replied: "What use is a baby?"

Ørsted had shown that electricity could produce magnetism; and Faraday, with his strong intuitive grasp of the symmetry of natural laws, believed that the relationship could be reversed. He believed that magnetism could be made to produce electricity. In 1822, he wrote in his notebook: "Convert magnetism to electricity". For almost ten years, he tried intermittently to produce electrical currents with strong magnetic fields, but without success. Finally, in 1831, he discovered that a *changing* magnetic field would produce a current.

Faraday had wrapped two coils of wire around a soft iron ring; and he discovered that at precisely the instant when he started a current flowing in one of the coils, a momentary current was induced in the other coil. When he stopped the current in the first coil, so that the magnetic field collapsed, a momentary current in the opposite direction was induced in the second coil.

Next, Faraday tried pushing a permanent magnet in and out of a coil of wire; and he found that during the time when the magnet was in motion, so that the magnetic field in the coil was changing, a current was induced in the coil. Finally, Faraday made the first dynamo in history by placing a rotating copper disc between the poles of a magnet. He demonstrated that when the disc rotated, an electrical current flowed through a circuit connecting the center with the edge. He also experimented with static electricity, and showed that insulating materials become polarized when they are placed in an electric field.

Faraday continued the experiments on electrolysis begun by Sir Humphry Davy. He showed that when an electrical current is passed through a solution, the quantities of the chemical elements liberated at the anode and cathode are directly proportional to the total electrical charge passed through the cell, and inversely proportional to the valence of the elements. He realized that these laws of electrolysis supported Dalton's atomic hypothesis, and that they also pointed to the existence of an indivisible unit of electrical charge.

Faraday believed (correctly) that light is an electromagnetic wave; and to prove the connection of light with the phenomena of electricity and magnetism, he tried for many years to change light by means of electric and magnetic fields. Finally, towards the end of his career, he succeeded in rotating the plane of polarization of a beam of light passing through a piece of heavy glass by placing the glass in a strong magnetic field. This phenomenon is now known as the "Faraday effect".

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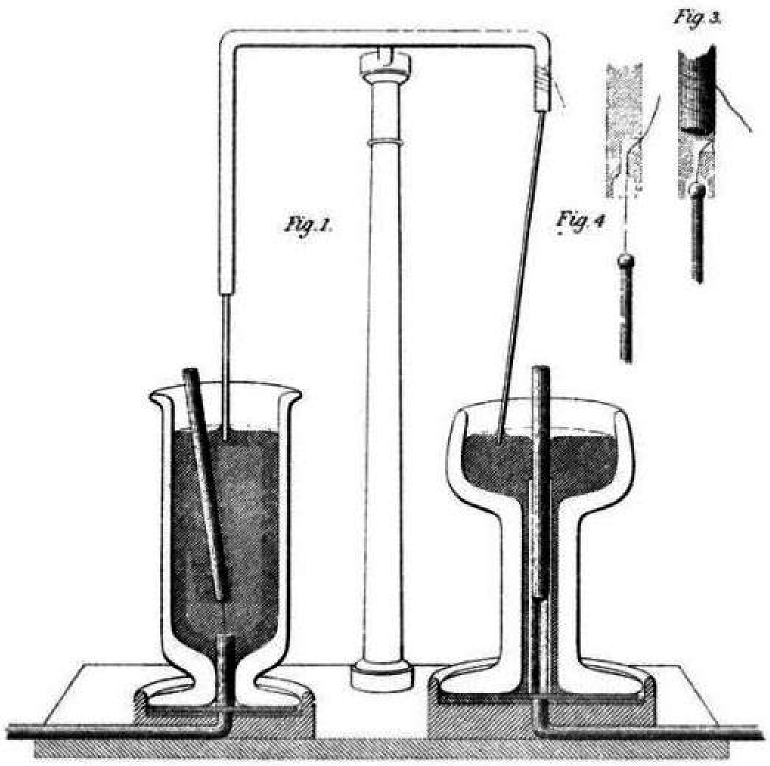

Figure 6.1: **Faraday's experiment showing that an electric current could produce mechanical rotation in a magnetic field. This was the first electric motor! On the right side of the figure, a current-carrying rod rotates about a fixed magnet in a pool of mercury. On the left, the rod is fixed and the magnet rotates.**

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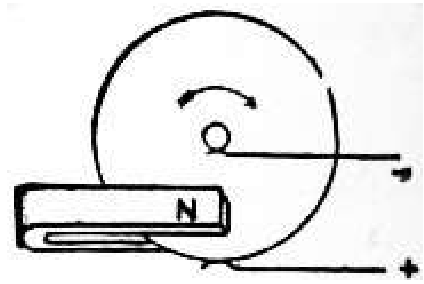

Figure 6.2: **Faraday also showed that a copper disc, rotating between the poles of a magnet could produce an electric current.**

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Because of his many contributions both to physics and to chemistry (including the discovery of benzene and the first liquefaction of gases), and especially because of his contributions to electromagnetism and electrochemistry, Faraday is considered to be one of the greatest masters of the experimental method in the history of science. He was also a splendid lecturer. Fashionable Londoners flocked to hear his discourses at the Royal Institution, just as they had flocked to hear Sir Humphrey Davy. Prince Albert, Queen Victoria's husband, was in the habit of attending Faraday's lectures, bringing with him Crown Prince Edward (later Edward VII).

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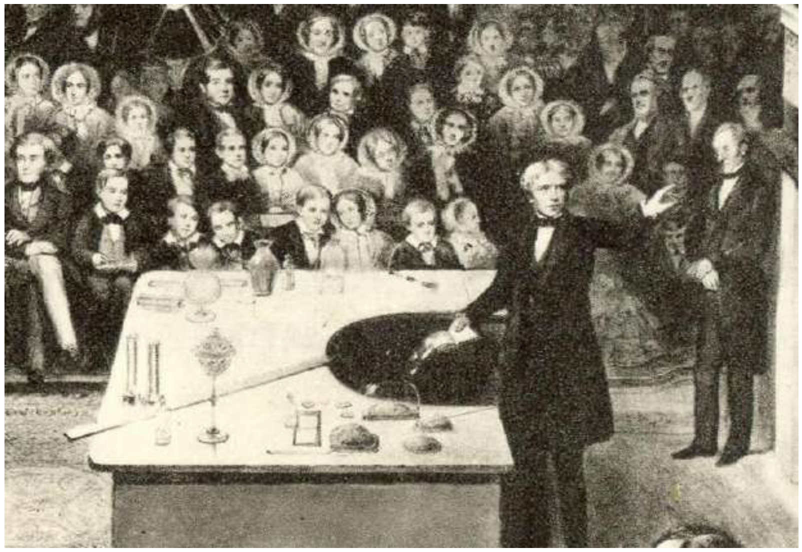

Figure 6.3: **A Christmas lecture at the Royal Institution by Michael Faraday.**

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As Faraday grew older, his memory began to fail, probably because of mercury poisoning. Finally, his unreliable memory forced him to retire from scientific work. He refused both an offer of knighthood and the Presidency of the Royal Society, remaining to the last the simple, modest and devoted worker who had first gone to assist Davy at the Royal Institution.

6.1 Maxwell and Hertz

Michael Faraday had no mathematical training, but he made up for this lack with his powerful physical intuition. He visualized electric and magnetic fields as "lines of force" in the space around the wires, magnets and electrical condensers with which he worked. In the case of magnetic fields, he could even make the lines of force visible by covering a piece of cardboard with iron filings, holding it near a magnet, and tapping the cardboard until the iron filings formed themselves into lines along the magnetic lines of force.

In this way, Faraday could actually see the magnetic field running from the north pole of a magnet, out into the surrounding space, and back into the south pole. He could also see the lines of the magnetic field forming circles around a straight current-carrying wire. Similarly, Faraday visualized the lines of force of the electric field as beginning at the positive charges of the system, running through the intervening space, and ending at the negative charges.

Meanwhile, the German physicists (especially the great mathematician and physicist, Johann Karl Friedrich Gauss (1777-1855)), had utilized the similarity between Coulomb's law of electrostatic force and Newton's law of gravitation. Coulomb's law states that the force between two point charges varies as the inverse square of the distance between them - in other words, it depends on distance in exactly the same way as the gravitational force. This allowed Gauss and the other German mathematicians to take over the whole "action at a distance" formalism of theoretical astronomy, and to apply it to electrostatics.

Faraday was unhappy with the idea of action at a distance, and he expressed his feelings to James Clerk Maxwell (1831-1879), a brilliant young mathematician from Edinburgh who had come to visit him. The young Scottish mathematical genius was able to show Faraday that his idea of lines of force did not in any way contradict the German conception of action at a distance. In fact, when put into mathematical form, Faraday's picture of lines of force fit beautifully with the ideas of Gauss.

During the nine years from 1864 to 1873, Maxwell worked on the problem of putting Faraday's laws of electricity and magnetism into mathematical form. In 1873, he published *A Treatise on Electricity and Magnetism*, one of the truly great scientific classics. Maxwell achieved a magnificent synthesis by expressing in a few simple equations the laws governing electricity and magnetism in all its forms. His electromagnetic equations have withstood the test of time; and now, a century later, they are considered to be among the most fundamental laws of physics.

Maxwell's equations not only showed that visible light is indeed and electromagnetic wave, as Faraday had suspected, but they also predicted the existence of many kinds of invisible electromagnetic waves, both higher and lower in frequency than visible light. We now know that the spectrum of electromagnetic radiation includes (starting at the low-frequency end) radio waves, microwaves, infra-red radiation, visible light, ultraviolet rays, X-rays and gamma rays. All these types of radiation are fundamentally the same, except that their frequencies and wave lengths cover a vast range. They all are oscillations of the electromagnetic field; they all travel with the speed of light; and they all are described by Maxwell's equations.

Maxwell's book opened the way for a whole new category of inventions, which have had a tremendous impact on society. However, when the *Treatise on Electricity and Magnetism* was published, very few scientists could understand it. Part of the problem was that the scientists of the 19th century would have liked a mechanical explanation of electromagnetism.

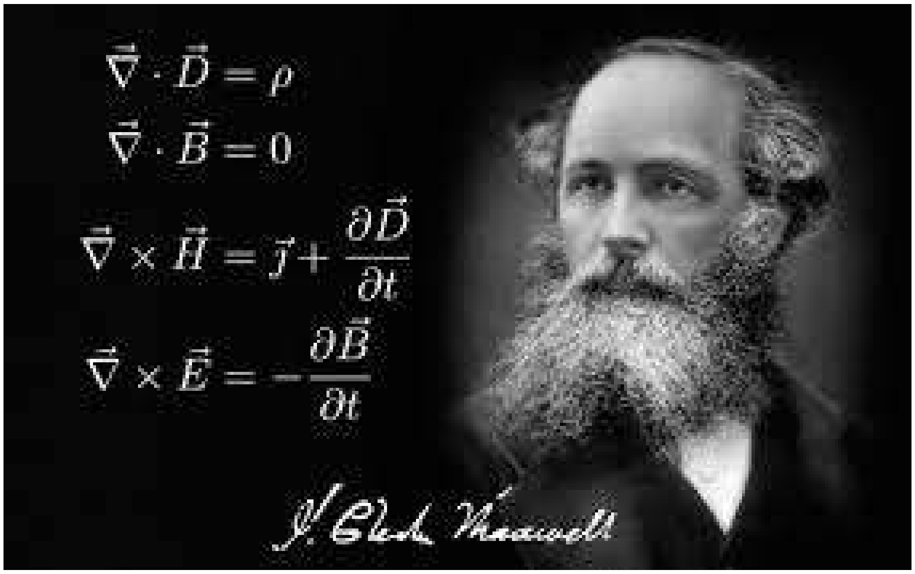

Figure 6.4: **James Clerk Maxwell (1831-1879).**

Figure 6.5: **Heinrich Hertz (1857-1894).**

6.2 History of the electrical telegraph

Many people contributed to the development of the telegraph. Here is a timeline showing some important events:

1774	Georges-Louis Le Sage (26 separate wires)
1800	Alessandro Volta invents the electric pile
1809	Samuel Thomas von Sömmering (up to 35 wires for letters and numerals)
1816	Francis Ronalds demonstrates an electrostatic telegraph at Hammersmith
1820	H.C. Ørsted discovers that an electric current produces a magnetic field
1821	André Marie Ampere suggests telegraph using a galvanometer
1828	Joseph Henry invents an improved electromagnet
1830	Joseph Henry demonstrates magnetic telegraph to Albany Academy
1832	Baron Schilling von Canstatt's 16-key transmitting device (binary system)
1833	C.F. Gauss and W. Weber install 1200-meter-long telegraph in Göttingen
1835	C.F. Gauss installs a telegraph along a German railway line
1835	Joseph Henry and Edward Davy invent electrical relay
1836	David Alter's telegraph system in America
1837	Edward Davy demonstrates his telegraph system in Regents Park
1837	Samuel Morse develops and patents recording telegraph
1837	W.F. Cooke and C. Wheatstone patent the first commercial telegraph
1838	Morse and his assistant Alfred Vale develop Morse code
1840	Charles Wheatstone's ABC system could be used by an unskilled operator
1846	Royal Earl House develops and patents letter printing telegraph
1855	David Edward Hughes invents a printing telegraph using a spinning type wheel
1861	Overland telegraph connects east and west coasts of the United States

Figure 6.6: **An early telegraph key**

Figure 6.7: **A girl operating an early telegraph**

Figure 6.8: **Professor Samuel F.B. Morse (1791-1872). For many years, most telegraph systems throughout the world made use of Morse code, which allowed messages to be sent over a single wire.**

6.3 The transatlantic cable

The first durable translantic cable was laid in 1866 by Isambard Kingdom Brunel's unprecedentedly large ship, the Great Eastern. Brunel had pioneered many engineering innovations, including the Great Western Railway, the first tunnel under a navigable river, and the first propeller-driven ocean-going iron steamship, the SS Great Britain. launched in 1843. He had realized that in order to carry enough coal for a transatlantic crossing, a ship had to be very large, since water resistance to be overcome is proportional to surface area, while the amount of coal (and cargo) that can be carried is proportional to volume. As a ship becomes larger, the ratio of volume to surface increases.

At first, transatlantic telegraphic transmissions were extremely slow, because the designers of the cable had not realizer that for efficient signal transmission the ratio of the cable's inductance to capacitance had to be correctly adjusted.

The first message sent was "Directors of Atlantic Telegraph Company, Great Britain, to Directors in America: Europe and America are united by telegraph. Glory to God in the highest; on earth peace, good will towards men." The second message was from Queen Victoria to President Buchanan of the United States, expressing the hope that the cable link would prove to be "an additional link between the nations whose friendship is founded on their common interest and reciprocal esteem." Buchanan replied that "it is a triumph more glorious, because far more useful to mankind, than was ever won by conqueror on the field of battle. May the Atlantic telegraph, under the blessing of Heaven, prove to be a bond of perpetual peace and friendship between the kindred nations, and an instrument destined by Divine Providence to diffuse religion, civilization, liberty, and law throughout the world."

Public enthusiasm for the transatlantic cable was enormous. In New York, 100 guns were fired, the streets were decorated with flags, and church bells were rung.

Figure 6.9: **Landing of the Atlantic Cable of 1866, Heart's Content, Newfoundland, a painting by by Robert Charles Dudley.**

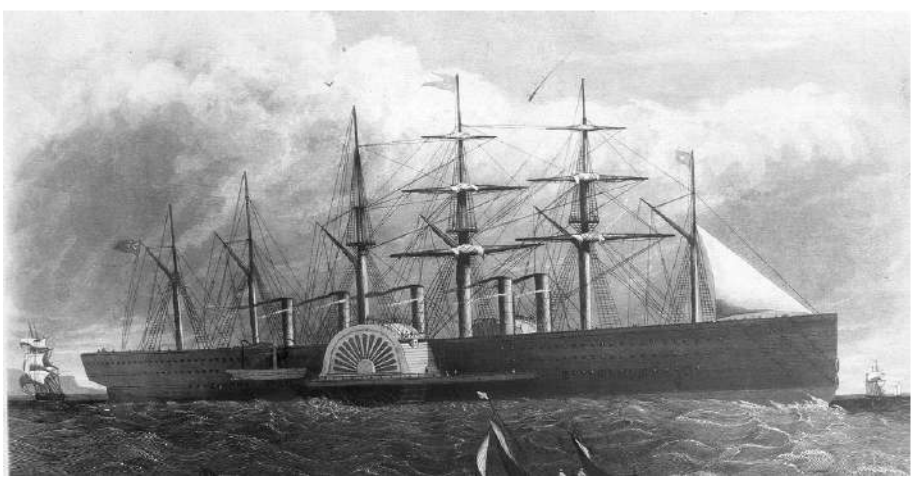

Figure 6.10: **Under Sir James Anderson, the Great Eastern laid 4,200 kilometers (2,600 mi) of the 1865 transatlantic telegraph cable. Under Captains Anderson and then Robert Halpin, from 1866 to 1878 the ship laid over 48,000 kilometers (30,000 mi) of submarine telegraph cable including from Brest, France to Saint Pierre and Miquelon in 1869, and from Aden to Bombay in 1869 and 1870.**

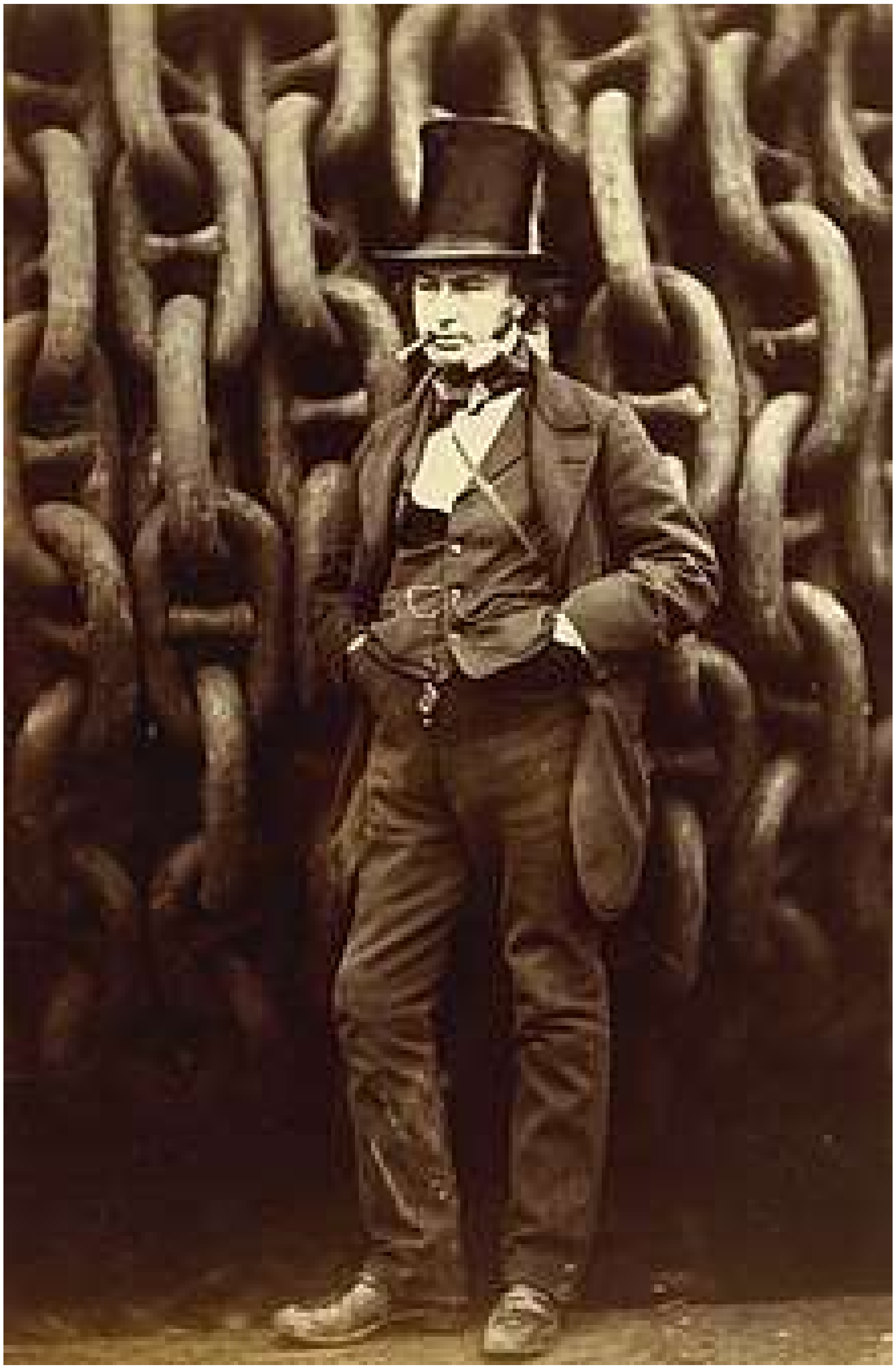

Figure 6.11: **The great 19th century engineer, Isambard Kingdom Brunel (1806-1959), beside the launching chain of the Great Eastern.**

6.4 Marconi

The waves detected by Hertz were, in fact, radio waves; and it was not long before the Italian engineer, Guglielmo Marconi (1874-1937), turned the discovery into a practical means of communication. In 1898, Marconi used radio signals to report the results of the boat races at the Kingston Regatta, and on December 12, 1901, using balloons to lift the antennae as high as possible, he sent a signal across the Atlantic Ocean from England to Newfoundland.

In 1904, a demonstration of a voice-carrying radio apparatus developed by Fessenden was the sensation of the St. Louis World's Fair; and in 1909, Marconi received the Nobel Prize in physics for his development of radio communications. In America, the inventive genius of Alexander Graham Bell (1847-1922) and Thomas Alva Edison (1847-1931) turned the discoveries of Faraday and Maxwell into the telephone, the electric light, the cinema and the phonograph.

Figure 6.12: **Marconi's wireless telegraph**

6.5 Alexander Graham Bell

Alexander Graham Bell (1847-1922) is credited with inventing the first workable telephone, but in addition, his inventions and scientific work reached many other fields. Bell was born in Edinburgh, Scotland, where his father. Professor Alexander Melville Bell, worked in phonetics, a branch of linguistics that studies the sounds of human speech and their physical properties. Alexander Graham Bell's grandfather and his two brothers also worked in this field.

At the age of 12, Alexander Graham Bell invented a dehusking machine that was used for many years to prepare grain to be milled into flour. As a reward, the local mill owner and gave young Bell the materials and workshop that he needed to work on other inventions.

Motivated not only by the fact that so many of his family members worked in phonetics but also by his mother's gradually increasing deafness, Bell began experiments on the mechanical reproduction of sound. When he was 19, a report on Bell's work in this field was sent to Alexander Ellis[1]. Ellis informed Bell that very similar work had been done in Germany by Hermann von Helmholtz. Unable to read German, Bell studied a French translation of the work of von Helmholtz. He later said:

"Without knowing much about the subject, it seemed to me that if vowel sounds could be produced by electrical means, so could consonants, so could articulate speech. I thought that Helmholtz had done it ... and that my failure was due only to my ignorance of electricity. It was a valuable blunder ... If I had been able to read German in those days, I might never have commenced my experiments!"

When Bell was 23, he and his family moved to Canada because several family members were threatened with tuberculosis[2]. They hoped that Canada's climate would help their struggles with the disease. Two years later Bell moved to Boston, Massachusetts, where he opened his School of Vocal Physiology and Mechanics of Speech. Among his numerous students was Helen Keller.

Because the late nights and overwork resulting from combining electrical voice transmission experimentation with teaching was affecting his health, Bell decided to keep only two students, 6 year old Georgie Sanders and 15 year old Mable Hubbard. Georgie Sanders' wealthy father provided Bell with free lodging and a laboratory. Mable was a bright and attractive girl, ten years younger than Bell, and she later became his wife.

At that time, in 1874, the telegraph was becoming more and more commercially important, and William Orton, the President of the Western Union telegraph company had hired Thomas Edison and Elisha Gray to invent a method for sending multiple messages over the same wire. When Bell confided to the wealthy fathers of his two pupils that he was working on a method to send multiple voice messages over the same wire, the two fathers supported Bell's race with Edison and Gray to be first with a practical method and a patent.

[1]later portrayed as Henry Higgins in Shaw's play *Pygmalion*

[2]Both of Bell's brothers eventually died of tuberculosis.

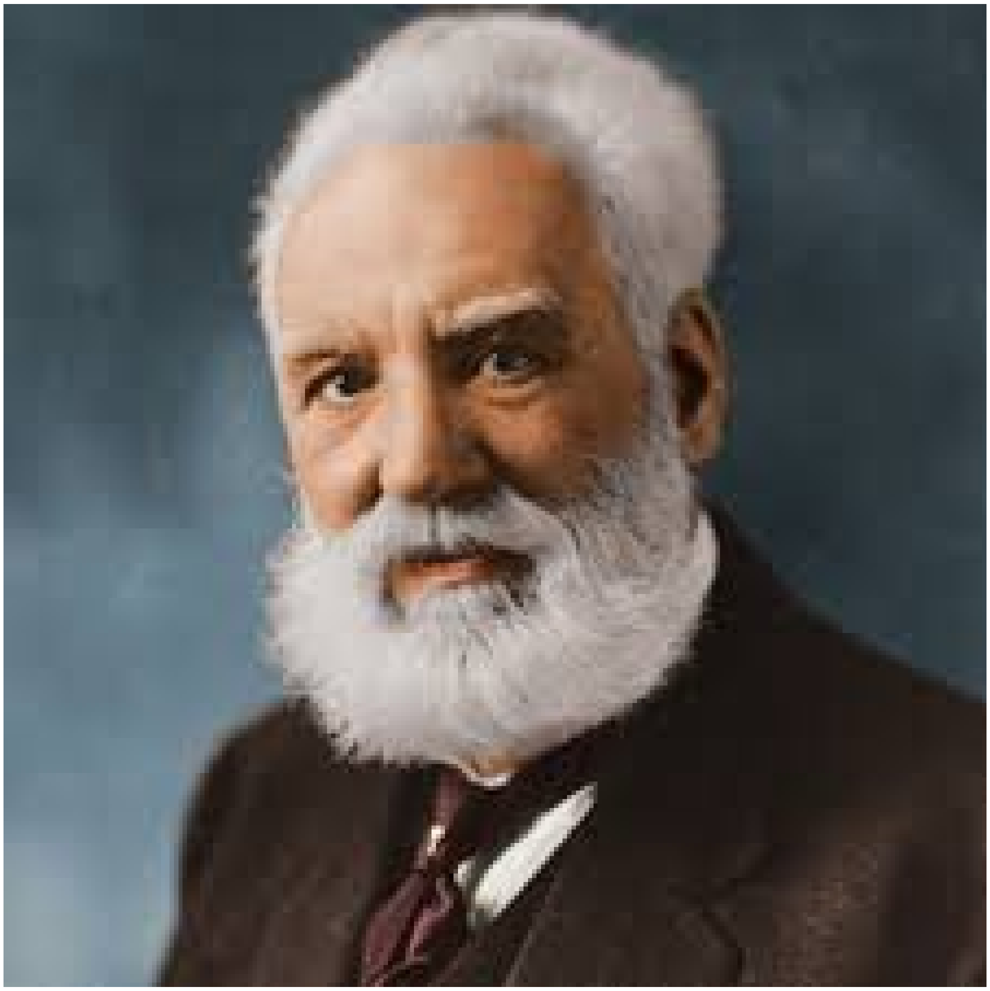

Figure 6.13: **Alexander Graham Bell (1847-1922).**

In the same year, Bell happened to meet Thomas A. Watson, an experienced designer of electrical machines. With the financial help of Sanders and Hubbard, Bell hired Watson as his assistant. In 1876, Bell spoke the first intelligible words over his newly invented telephone: "Mr. Watson, come here. I need you." That same year U.S. and U.K patents were granted to Bell, but a somewhat similar patent application from Elisha Gray had arrived almost simultaneously, initiating a controversy over priority.

Bell and his supporters offered to sell another patent which covered their method for sending multiple messages over the same telegraph wire to Western Union for $100,000, but the offer was refused. Two years later the President of Western Union said that if he could obtain the patent for $25,000,000, he would consider it a bargain, but by that time, the Bell Telephone Company no longer wished to sell.

Although Bell is best known for the telephone, his interests were very wide According to Wikipedia,

Bell's work ranged "unfettered across the scientific landscape" and he often went to *bed voraciously reading the Encyclopedia Britannica, scouring it for new areas of interest. The range of Bell's inventive genius is represented only in part by the 18 patents granted in his name alone and the 12 he shared with his collaborators. These included 14 for the telephone and telegraph, four for the photophone, one for the phonograph, five for aerial vehicles, four for "hydroairplanes", and two for selenium cells. Bell's inventions spanned a wide range of interests and included a metal jacket to assist in breathing, the audiometer to detect minor hearing problems, a device to locate icebergs, investigations on how to separate salt from seawater, and work on finding alternative fuels.*

Bell worked extensively in medical research and invented techniques for teaching speech to the deaf. During his Volta Laboratory period, Bell and his associates considered impressing a magnetic field on a record as a means of reproducing sound. Although the trio briefly experimented with the concept, they could not develop a workable prototype. They abandoned the idea, never realizing they had glimpsed a basic principle which would one day find its application in the tape recorder, the hard disc and floppy disc drive, and other magnetic media.

Bell's own home used a primitive form of air conditioning, in which fans blew currents of air across great blocks of ice. He also anticipated modern concerns with fuel shortages and industrial pollution. Methane gas, he reasoned, could be produced from the waste of farms and factories. At his Canadian estate in Nova Scotia, he experimented with composting toilets and devices to capture water from the atmosphere. In a magazine interview published shortly before his death, he reflected on the possibility of using solar panels to heat houses.

As of today, the Bell Laboratories, funded by the Bell Telephone Company, has produced 13 Nobel Prize winners. Most notably, the 1956 Nobel Prize in Physics was shared by Bell Laboratory scientists John Bardeen, Walter Brattain, and William Shockley for the invention of the transistor, a device that has made the astonishing modern stages of the information explosion possible.

Even Maxwell himself, in building up his ideas, made use of mechanical models, "..replete with ropes passing over pulleys, rolled over drums, pulling weights, or at times comprising tubes pumping water into other elastic tubes which expanded and contracted, the whole mass of machinery noisy with the grinding of interlocked gear wheels". In the end, however, Maxwell abandoned as unsatisfactory the whole clumsy mechanical scaffolding which he had used to help his intuition; and there is no trace of mechanical ideas in his final equations. As Synge has expressed it, "The robust body of the Cheshire cat was gone, leaving in its place only a sort of mathematical grin".

Lord Kelvin (1824-1907), a prominent English physicist of the time, was greatly disappointed because Maxwell's theory could offer no mechanical explanation for electromagnetism; and he called the theory "a failure - the hiding of ignorance under the cover of a formula". In Germany, the eminent physicist, Hermann von Helmholtz (1821-1894), tried hard to understand Maxwell's theory in mechanical terms, and ended by accepting Maxwell's equations without ever feeling that he really understood them.

In 1883, the struggles of von Helmholtz to understand Maxwell's theory produced a dramatic proof of its correctness: Helmholtz had a brilliant student named Heinrich Hertz (1857-1894), whom he regarded almost as a son. In 1883, the Berlin Academy of Science offered a prize for work in the field of electromagnetism; and von Helmholtz suggested to Hertz that he should try to win the prize by testing some of the predictions of Maxwell's theory.

Hertz set up a circuit in which a very rapidly oscillating electrical current passed across a spark gap. He discovered that electromagnetic waves were indeed produced by this rapidly-oscillating current, as predicted by Maxwell! The waves could be detected with a small ring of wire in which there was a gap. As Hertz moved about the darkened room with his detector ring, he could see a spark flashing across the gap, showing the presence of electromagnetic waves, and showing them to behave exactly as predicted by Maxwell.

The waves detected by Hertz were, in fact, radio waves; and it was not long before the Italian engineer, Guglielmo Marconi (1874-1937), turned the discovery into a practical means of communication. In 1898, Marconi used radio signals to report the results of the boat races at the Kingston Regatta, and on December 12, 1901, using balloons to lift the antenae as high as possible, he sent a signal across the Atlantic Ocean from England to Newfoundland.

In 1904, a demonstration of a voice-carrying radio apparatus developed by Fessenden was the sensation of the St. Louis World's Fair; and in 1909, Marconi received the Nobel Prize in physics for his development of radio communications. In America, the inventive genius of Alexander Graham Bell (1847-1922) and Thomas Alva Edison (1847-1931) turned the discoveries of Faraday and Maxwell into the telephone, the electric light, the cinema and the phonograph.

6.6 A revolution in communication

The modern communication revolution began with the prediction of electromagnetic waves by James Clerk Maxwell, their discovery by Heinrich Hertz, Marconi's wireless telegraph messages across the Atlantic, and the invention of the telephone by Alexander Graham Bell. Radio and television programs were quick to follow. Today cell phones and Skype allow us to talk across vast distances with little effort and almost no expense. The Internet makes knowledge universally and instantly available.

Suggestions for further reading

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3. E.T. Whittaker, *A History of the Aether and Electricity*, Cambridge University Press (1953).
4. D.K.C. Macdonald, *Faraday, Maxwell and Kelvin*, Heinemann, London (1964).
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Chapter 7

EINSTEIN

"The unleashed power of the atom has changed everything except our ways of thinking, and thus we drift towards unparalleled catastrophes."

"I don't know what will be used in the next world war, but the 4th will be fought with stones."

Albert Einstein (1879-1955)

Besides being one of the greatest physicists of all time, Albert Einstein was a lifelong pacifist, and his thoughts on peace can speak eloquently to us today. We need his wisdom today, when the search for peace has become vital to our survival as a species.

7.1 Family background

Albert Einstein was born in Ulm, Germany, in 1879. He was the son of middle-class, irreligious Jewish parents, who sent him to a Catholic school. Einstein was slow in learning to speak, and at first his parents feared that he might be retarded; but by the time he was eight, his grandfather could say in a letter: "Dear Albert has been back in school for a week. I just love that boy, because you cannot imagine how good and intelligent he has become."

Remembering his boyhood, Einstein himself later wrote: "When I was 12, a little book dealing with Euclidean plane geometry came into my hands at the beginning of the school year. Here were assertions, as for example the intersection of the altitudes of a triangle in one point, which, though by no means self-evident, could nevertheless be proved with such certainty that any doubt appeared to be out of the question. The lucidity and certainty made an indescribable impression on me."

When Albert Einstein was in his teens, the factory owned by his father and uncle began to encounter hard times. The two Einstein families moved to Italy, leaving Albert alone and miserable in Munich, where he was supposed to finish his course at the gymnasium. Einstein's classmates had given him the nickname "Beidermeier", which means something like "Honest John"; and his tactlessness in criticizing authority soon got him into trouble. In Einstein's words, what happened next was the following: "When I was in the seventh grade at the Lutpold Gymnasium, I was summoned by my home-room teacher, who expressed the wish that I leave the school. To my remark that I had done nothing wrong, he replied only, 'Your mere presence spoils the respect of the class for me'."

Einstein left gymnasium without graduating, and followed his parents to Italy, where he spent a joyous and carefree year. He also decided to change his citizenship. "The over-emphasized military mentality of the German State was alien to me, even as a boy", Einstein wrote later. "When my father moved to Italy, he took steps, at my request, to have me released from German citizenship, because I wanted to be a Swiss citizen."

The financial circumstances of the Einstein family were now precarious, and it was clear that Albert would have to think seriously about a practical career. In 1896, he entered the famous Zürich Polytechnic Institute with the intention of becoming a teacher of mathematics and physics. However, his undisciplined and nonconformist attitudes again got him into trouble. His mathematics professor, Hermann Minkowski (1864-1909), considered Einstein to be a "lazy dog"; and his physics professor, Heinrich Weber, who originally had gone out of his way to help Einstein, said to him in anger and exasperation: "You're a clever fellow, but you have one fault: You won't let anyone tell you a thing! You won't let anyone tell you a thing!"

Einstein missed most of his classes, and read only the subjects which interested him. He was interested most of all in Maxwell's theory of electro-magnetism, a subject which was too "modern" for Weber. There were two major examinations at the Zürich Polytechnic Institute, and Einstein would certainly have failed them had it not been for the help of his loyal friend, the mathematician Marcel Grossman.

Grossman was an excellent and conscientious student, who attended every class and took meticulous notes. With the help of these notes, Einstein managed to pass his examinations; but because he had alienated Weber and the other professors who could have helped him, he found himself completely unable to get a job. In a letter to Professor F. Ostwald on behalf of his son, Einstein's father wrote: "My son is profoundly unhappy because of his present joblessness; and every day the idea becomes more firmly implanted in his mind that he is a failure, and will not be able to find the way back again."

From this painful situation, Einstein was rescued (again!) by his friend Marcel Grossman, whose influential father obtained for Einstein a position at the Swiss Patent Office: Technical Expert (Third Class). Anchored at last in a safe, though humble, position, Einstein married one of his classmates. He learned to do his work at the Patent Office very efficiently; and he used the remainder of his time on his own calculations, hiding them guiltily in a drawer when footsteps approached.

In 1905, this Technical Expert (Third Class) astonished the world of science with five papers, written within a few weeks of each other, and published in the Annalen der Physik. Of these five papers, three were classics: One of these was the paper in which Einstein applied Planck's quantum hypothesis to the photoelectric effect. The second paper discussed "Brownian motion", the zig-zag motion of small particles suspended in a liquid and hit randomly by the molecules of the liquid. This paper supplied a direct proof of the validity of atomic ideas and of Boltzmann's kinetic theory. The third paper was destined to establish Einstein's reputation as one of the greatest physicists of all time. It was entitled "On the Electrodynamics of Moving Bodies", and in this paper, Albert Einstein formulated his special theory of relativity. Essentially, this theory maintained that all of the fundamental laws of nature exhibit a symmetry with respect to rotations in a 4-dimensional space-time continuum.

7.2 Special relativity theory

The theory of relativity grew out of problems connected with Maxwell's electromagnetic theory of light. Ever since the wavelike nature of light had first been demonstrated, it had been supposed that there must be some medium to carry the light waves, just as there must be some medium (for example air) to carry sound waves. A word was even invented for the medium which was supposed to carry electromagnetic waves: It was called the "ether".

By analogy with sound, it was believed that the velocity of light would depend on the velocity of the observer relative to the "ether". However, all attempts to measure differences in the velocity of light in different directions had failed, including an especially sensitive experiment which was performed in America in 1887 by A.A. Michelson and E.W. Morley.

Even if the earth had, by a coincidence, been stationary with respect to the "ether" when Michelson and Morley first performed their experiment, they should have found an "ether wind" when they repeated their experiment half a year later, with the earth at the other side of its orbit. Strangely, the observed velocity of light seemed to be completely independent of the motion of the observer!

In his famous 1905 paper on relativity, Einstein made the negative result of the Michelson-Morley experiment the basis of a far-reaching principle: He asserted that no experiment whatever can tell us whether we are at rest or whether we are in a state of uniform motion. With this assumption, the Michelson-Morley experiment of course had to fail, and the measured velocity of light had to be independent of the motion of the observer.

Einstein's Principle of Special Relativity had other extremely important consequences: He soon saw that if his principle were to hold, then Newtonian mechanics would have to be modified. In fact, Einstein's Principle of Special Relativity required that *all* fundamental physical laws exhibit a symmetry between space and time. The three space dimensions, and a fourth dimension, ict, had to enter every fundamental physical law in a symmetrical way. (Here i is the square root of -1, c is the velocity of light, and t is time.)

When this symmetry requirement is fulfilled, a physical law is said to be "Lorentz-invariant" (in honor of the Dutch physicist H.A. Lorentz, who anticipated some of Einstein's ideas). Today, we would express Einstein's principle by saying that every fundamental physical law must be Lorentz-invariant (i.e. symmetrical in the space and time coordinates). The law will then be independent of the motion of the observer, provided that the observer is moving uniformly.

Einstein was able to show that, when properly expressed, Maxwell's equations are already Lorentz-invariant; but Newton's equations of motion have to be modified. When the needed modifications are made, Einstein found, then the mass of a moving particle appears to increase as it is accelerated. A particle can never be accelerated to a velocity greater than the velocity of light; it merely becomes heavier and heavier, the added energy being converted into mass.

From his 1905 theory, Einstein deduced his famous formula equating the energy of a system to its mass multiplied by the square of the velocity of light. As we shall see, his formula was soon used to explain the source of the energy produced by decaying uranium and radium; and eventually it led to the construction of the atomic bomb. Thus Einstein, a lifelong pacifist, who renounced his German citizenship as a protest against militarism, became instrumental in the construction of the most destructive weapon ever invented - a weapon which casts an ominous shadow over the future of humankind.

Just as Einstein was one of the first to take Planck's quantum hypothesis seriously, so Planck was one of the first physicists to take Einstein's relativity seriously. Another early enthusiast for relativity was Hermann Minkowski, Einstein's former professor of mathematics. Although he once had characterized Einstein as a "lazy dog", Minkowski now contributed importantly to the mathematical formalism of Einstein's theory; and in 1907, he published the first book on relativity. In honor of Minkowski's contributions to relativity, the 4-dimensional space-time continuum in which we live is sometimes called "Minkowski space".

In 1908, Minkowski began a lecture to the Eightieth Congress of German Scientists and Physicians with the following words:

" From now on, space by itself, and time by itself, are destined to sink completely into the shadows; and only a kind of union of both will retain an independent existence."

Gradually, the importance of Einstein's work began to be realized, and he was much sought after. He was first made Assistant Professor at the University of Zürich, then full Professor in Prague, then Professor at the Zürich Polytechnic Institute; and finally, in 1913, Planck and Nernst persuaded Einstein to become Director of Scientific Research at the Kaiser Wilhelm Institute in Berlin. He was at this post when the First World War broke out

While many other German intellectuals produced manifestos justifying Germany's invasion of Belgium, Einstein dared to write and sign an anti-war manifesto. Einstein's manifesto appealed for cooperation and understanding among the scholars of Europe for the sake of the future; and it proposed the eventual establishment of a League of Europeans. During the war, Einstein remained in Berlin, doing whatever he could for the cause of peace, burying himself unhappily in his work, and trying to forget the agony of Europe, whose civilization was dying in a rain of shells, machine-gun bullets, and poison gas.

7.3 General relativity

The work into which Einstein threw himself during this period was an extension of his theory of relativity. He already had modified Newton's equations of motion so that they exhibited the space-time symmetry required by his Principle of Special Relativity. However, Newton's law of gravitation. remained a problem.

Obviously it had to be modified, since it disagreed with his Special Theory of Relativity; but how should it be changed? What principles could Einstein use in his search for a more correct law of gravitation? Certainly whatever new law he found would have to give results very close to Newton's law, since Newton's theory could predict the motions of the planets with almost perfect accuracy. This was the deep problem with which he struggled.

In 1907, Einstein had found one of the principles which was to guide him, the Principle of Equivalence of inertial and gravitational mass. After turning Newton's theory over and over in his mind, Einstein realized that Newton had used mass in two distinct ways: His laws of motion stated that the force acting on a body is equal to the mass of the body multiplied by its acceleration; but according to Newton, the gravitational force on a body is also proportional to its mass. In Newton's theory, gravitational mass, by a coincidence, is equal to inertial mass; and this holds for all bodies. Einstein decided to construct a theory in which gravitational and inertial mass necessarily have to be the same.

He then imagined an experimenter inside a box, unable to see anything outside it. If the box is on the surface of the earth, the person inside it will feel the pull of the earth's gravitational field. If the experimenter drops an object, it will fall to the floor with an acceleration of 32 feet per second per second. Now suppose that the box is taken out into empty space, far away from strong gravitational fields, and accelerated by exactly 32 feet per second per second. Will the enclosed experimenter be able to tell the difference between these two situations? Certainly no difference can be detected by dropping an object, since in the accelerated box, the object will fall to the floor in exactly the same way as before.

With this "thought experiment" in mind, Einstein formulated a general Principle of Equivalence: He asserted that no experiment whatever can tell an observer enclosed in a small box whether the box is being accelerated, or whether it is in a gravitational field. According to this principle, gravitation and acceleration are locally equivalent, or, to say the same thing in different words, gravitational mass and inertial mass are equivalent.

Einstein soon realized that his Principle of Equivalence implied that a ray of light must be bent by a gravitational field. This conclusion followed because, to an observer in an accelerated frame, a light beam which would appear straight to a stationary observer, must necessarily appear very slightly curved. If the Principle of Equivalence held, then the same slight bending of the light ray would be observed by an experimenter in a stationary frame in a gravitational field.

Another consequence of the Principle of Equivalence was that a light wave propagating upwards in a gravitational field should be very slightly shifted to the red. This followed because in an accelerated frame, the wave crests would be slightly farther apart than they normally would be, and the same must then be true for a stationary frame in a gravitational field. It seemed to Einstein that it ought to be possible to test experimentally both the gravitational bending of a light ray and the gravitational red shift.

This seemed promising; but how was Einstein to proceed from the Principle of Equivalence to a formulation of the law of gravitation? Perhaps the theory ought to be modeled after Maxwell's electromagnetic theory, which was a field theory, rather than an "action at a distance" theory. Part of the trouble with Newton's law of gravitation was that it allowed a signal to be propagated instantaneously, contrary to the Principle of Special Relativity. A field theory of gravitation might cure this defect, but how was Einstein to find such a theory? There seemed to be no way.

From these troubles Albert Einstein was rescued (a third time!) by his staunch friend Marcel Grossman. By this time, Grossman had become a professor of mathematics in Zürich, after having written a doctoral dissertation on tensor analysis and non-Euclidean geometry, the very things that Einstein needed. The year was then 1912, and Einstein had just returned to Zürich as Professor of Physics at the Polytechnic Institute. For two years, Einstein and Grossman worked together; and by the time Einstein left for Berlin in 1914, the way was clear. With Grossman's help, Einstein saw that the gravitational field could be expressed as a curvature of the 4-dimensional space-time continuum.

In 1919, a British expedition, headed by Sir Arthur Eddington, sailed to a small island off the coast of West Africa. Their purpose was to test Einstein's prediction of the bending of light in a gravitational field by observing stars close to the sun during a total eclipse. The observed bending agreed exactly with Einstein's predictions; and as a result he became world-famous. The general public was fascinated by relativity, in spite of the abstruseness of the theory (or perhaps because of it). Einstein, the absent-minded professor, with long, uncombed hair, became a symbol of science. The world was tired of war, and wanted something else to think about.

Einstein met President Harding, Winston Churchill and Charlie Chaplin; and he was invited to lunch by the Archbishop of Canterbury. Although adulated elsewhere, he was soon attacked in Germany. Many Germans, looking for an excuse for the defeat of their nation, blamed it on the pacifists and Jews; and Einstein was both these things.

7.4 Einstein's letter to Freud: Why war?

Because of his fame, Einstein was asked to make several speeches at the Reichstag. and in all these speeches he condemned violence and nationalism, urging that these be replaced by and international cooperation and law under an effective international authority. He also wrote many letters and articles pleading for peace and for the renunciation of militarism and violence.

Einstein believed that the production of armaments is damaging, not only economically, but also spiritually. In 1930 he signed a manifesto for world disarmament sponsored by the Womens International League for Peace and Freedom. In December of the same year, he made his famous statement in New York that if two percent of those called for military service were to refuse to fight, governments would become powerless, since they could not imprison that many people. He also argued strongly against compulsory military

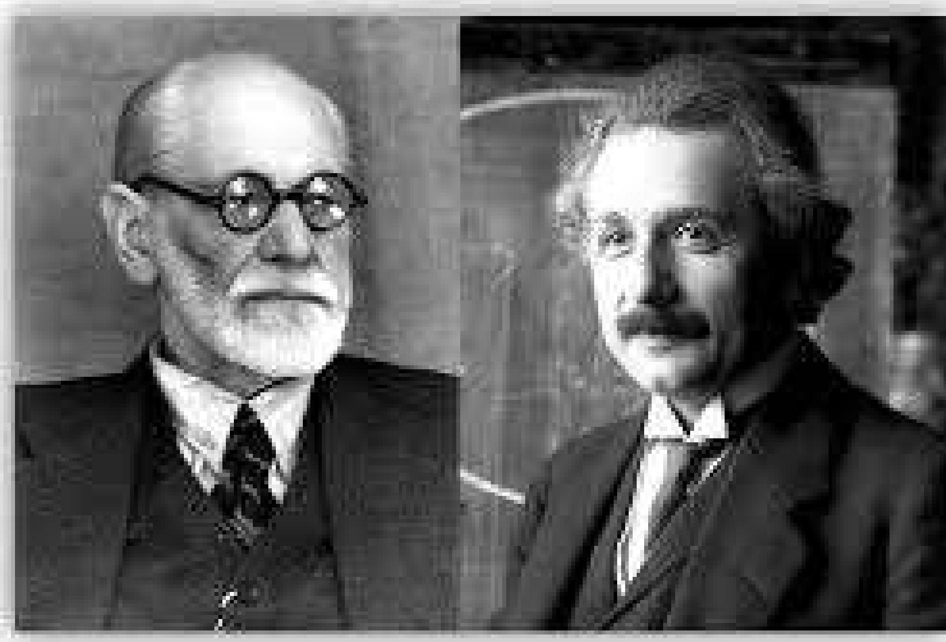

Figure 7.1: **Sigmund Freud and Albert Einstein (public domain). Their exchange of letters entitled "Why War?" deserves to be read by everyone concerned with the human future.**

service and urged that conscientious objectors should be protected by the international community. He argued that peace, freedom of individuals, and security of societies could only be achieved through disarmament, the alternative being "slavery of the individual and annihilation of civilization".

In letters, and articles, Einstein wrote that the welfare of humanity as a whole must take precedence over the goals of individual nations, and that we cannot wait until leaders give up their preparations for war. Civil society, and especially public figures, must take the lead. He asked how decent and self-respecting people can wage war, knowing how many innocent people will be killed.

In 1931, the International Institute for Intellectual Cooperation invited Albert Einstein to enter correspondence with a prominent person of his own choosing on a subject of importance to society. The Institute planned to publish a collection of such dialogues. Einstein accepted at once, and decided to write to Sigmund Freud to ask his opinion about how humanity could free itself from the curse of war. A translation from German of part of the long letter that he wrote to Freud is as follows:

"Dear Professor Freud, The proposal of the League of Nations and its International Institute of Intellectual Cooperation at Paris that I should invite a person to be chosen by myself to a frank exchange of views on any problem that I might select affords me a very welcome opportunity of conferring with you upon a question which, as things are now, seems the most important and insistent of all problems civilization has to face. This is the problem: Is there any way of delivering mankind from the menace of war? It is common knowledge that, with the advance of modern science, this issue has come to mean a matter of life or death to civilization as we know it; nevertheless, for all the zeal displayed, every attempt at its solution has ended in a lamentable breakdown."

"I believe, moreover, that those whose duty it is to tackle the problem professionally and practically are growing only too aware of their impotence to deal with it, and have now a very lively desire to learn the views of men who, absorbed in the pursuit of science, can see world-problems in the perspective distance lends. As for me, the normal objective of my thoughts affords no insight into the dark places of human will and feeling. Thus in the enquiry now proposed, I can do little more than seek to clarify the question at issue and, clearing the ground of the more obvious solutions, enable you to bring the light of your far-reaching knowledge of man's instinctive life upon the problem.."

"As one immune from nationalist bias, I personally see a simple way of dealing with the superficial (i.e. administrative) aspect of the problem: the setting up, by international consent, of a legislative and judicial body to settle every conflict arising between nations... But here, at the outset, I come up against a difficulty; a tribunal is a human institution which, in proportion as the power at its disposal is... prone to suffer these to be deflected by extrajudicial pressure..."

Freud replied with a long and thoughtful letter in which he said that a tendency towards conflict is an intrinsic part of human emotional nature, but that emotions can be overridden by rationality, and that rational behavior is the only hope for humankind.

7.5 The fateful letter to Roosevelt

Albert Einstein's famous relativistic formula, relating energy to mass, soon yielded an understanding of the enormous amounts of energy released in radioactive decay. Marie and Pierre Curie had noticed that radium maintains itself at a temperature higher than its surroundings. Their measurements and calculations showed that a gram of radium produces roughly 100 gram-calories of heat per hour. This did not seem like much energy until Rutherford found that radium has a half-life of about 1,000 years. In other words, after a thousand years, a gram of radium will still be producing heat, its radioactivity only reduced to one-half its original value. During a thousand years, a gram of radium produces about a million kilocalories, an enormous amount of energy in relation to the tiny size of its source! Where did this huge amount of energy come from? Conservation of energy was one of the most basic principles of physics. Would it have to be abandoned?

The source of the almost-unbelievable amounts of energy released in radioactive decay could be understood through Einstein's formula equating the energy of a system to its mass multiplied by the square of the velocity of light, and through accurate measurements of atomic weights. Einstein's formula asserted that mass and energy are equivalent. It was realized that in radioactive decay, neither mass nor energy is conserved, but only a quantity more general than both, of which mass and energy are particular forms. Scientists in several parts of the world realized that Einstein's discovery of the relationship between mass and energy, together with the discovery of fission of the heavy element uranium meant that it might be possible to construct a uranium-fission bomb of immense power.

Meanwhile night was falling on Europe. In 1929, an economic depression had begun in the United States and had spread to Europe. Without the influx of American capital, the postwar reconstruction of the German economy collapsed. The German middle class, which had been dealt a severe blow by the great inflation of 1923, now received a second heavy blow. The desperate economic chaos drove German voters into the hands of political extremists.

On January 30, 1933, Adolf Hitler was appointed Chancellor and leader of a coalition cabinet by President Hindenburg. Although Hitler was appointed legally to this post, he quickly consolidated his power by unconstitutional means: On May 2, Hitler's police seized the headquarters of all trade unions, and arrested labor leaders. The Communist and Socialist parties were also banned, their assets seized and their leaders arrested. Other political parties were also smashed. Acts were passed eliminating Jews from public service; and innocent Jewish citizens were boycotted, beaten and arrested. On March 11, 1938, Nazi troops entered Austria.

On March 16, 1939, the Italian physicist Enrico Fermi (who by then was a refugee in America) went to Washington to inform the Office of Naval Operations that it might be possible to construct an atomic bomb; and on the same day, German troops poured into Czechoslovakia.

A few days later, a meeting of six German atomic physicists was held in Berlin to discuss the applications of uranium fission. Otto Hahn, the discoverer of fission, was not present, since it was known that he was opposed to the Nazi regime. He was even said to have exclaimed: "I only hope that you physicists will never construct a uranium bomb! If Hitler ever gets a weapon like that, I'll commit suicide."

The meeting of German atomic physicists was supposed to be secret; but one of the participants reported what had been said to Dr. S. Flügge, who wrote an article about uranium fission and about the possibility of a chain reaction. Flügge's article appeared in the July issue of Naturwissenschaften, and a popular version in the Deutsche Allgemeine Zeitung. These articles greatly increased the alarm of American atomic scientists, who reasoned that if the Nazis permitted so much to be printed, they must be far advanced on the road to building an atomic bomb.

In the summer of 1939, while Hitler was preparing to invade Poland, alarming news reached the physicists in the United States: A second meeting of German atomic scientists had been held in Berlin, this time under the auspices of the Research Division of the German Army Weapons Department. Furthermore, Germany had stopped the sale of uranium from mines in Czechoslovakia.

The world's most abundant supply of uranium, however, was not in Czechoslovakia, but in Belgian Congo. Leo Szilard, a refugee Hungarian physicist who had worked with Fermi to measure the number of neutrons produced in uranium fission, was deeply worried that the Nazis were about to construct atomic bombs; and it occurred to him that uranium from Belgian Congo should not be allowed to fall into their hands.

Szilard knew that his former teacher, Albert Einstein, was a personal friend of Elizabeth, the Belgian Queen Mother. Einstein had met Queen Elizabeth and King Albert of Belgium at the Solvay Conferences, and mutual love of music had cemented a friendship between them. When Hitler came to power in 1933, Einstein had moved to the Institute of Advanced Studies at Princeton; and Szilard decided to visit him there. Szilard reasoned that because of Einstein's great prestige, and because of his long-standing friendship with the Belgian Royal Family, he would be the proper person to warn the Belgians not to let their uranium fall into the hands of the Nazis. Einstein agreed to write to the Belgian king and queen.

On August 2, 1939, Szilard again visited Einstein, accompanied by Edward Teller and Eugene Wigner, who (like Szilard) were refugee Hungarian physicists. By this time, Szilard's plans had grown more ambitious; and he carried with him the draft of another letter, this time to the American President, Franklin D. Roosevelt. Einstein made a few corrections, and then signed the fateful letter, which reads (in part) as follows:

"Some recent work of E. Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into an important source of energy in the immediate future. Certain aspects of the situation seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe, therefore, that it is my duty to bring to your attention the following.."

"It is conceivable that extremely powerful bombs of a new type may be constructed. A single bomb of this type, carried by boat and exploded a port, might very well destroy the whole port, together with some of the surrounding territory.."

The letter also called Roosevelt's attention to the fact that Germany had already stopped the export of uranium from the Czech mines under German control. After making a few corrections, Einstein signed it. On October 11, 1939, three weeks after the defeat of Poland, Roosevelt's economic adviser, Alexander Sachs, personally delivered the letter to the President. After discussing it with Sachs, the President commented,"This calls for action." Later, when atomic bombs were dropped on civilian populations in an already virtually-defeated Japan, Einstein bitterly regretted having signed Szilard's letter to Roosevelt. He said repeatedly that signing the letter was the greatest mistake of his life, and his remorse was extreme.

Throughout the remainder of his life, in addition to his scientific work, Einstein worked tirelessly for peace, international understanding and nuclear disarmament. His last public act, only a few days before his death in 1955, was to sign the Russell-Einstein Manifesto, warning humankind of the catastrophic consequences that would follow from a war with nuclear weapons.

A few more things that Einstein said about peace:

We cannot solve our problems with the same thinking that we used when we created them.

It has become appallingly obvious that our technology has exceeded our humanity.

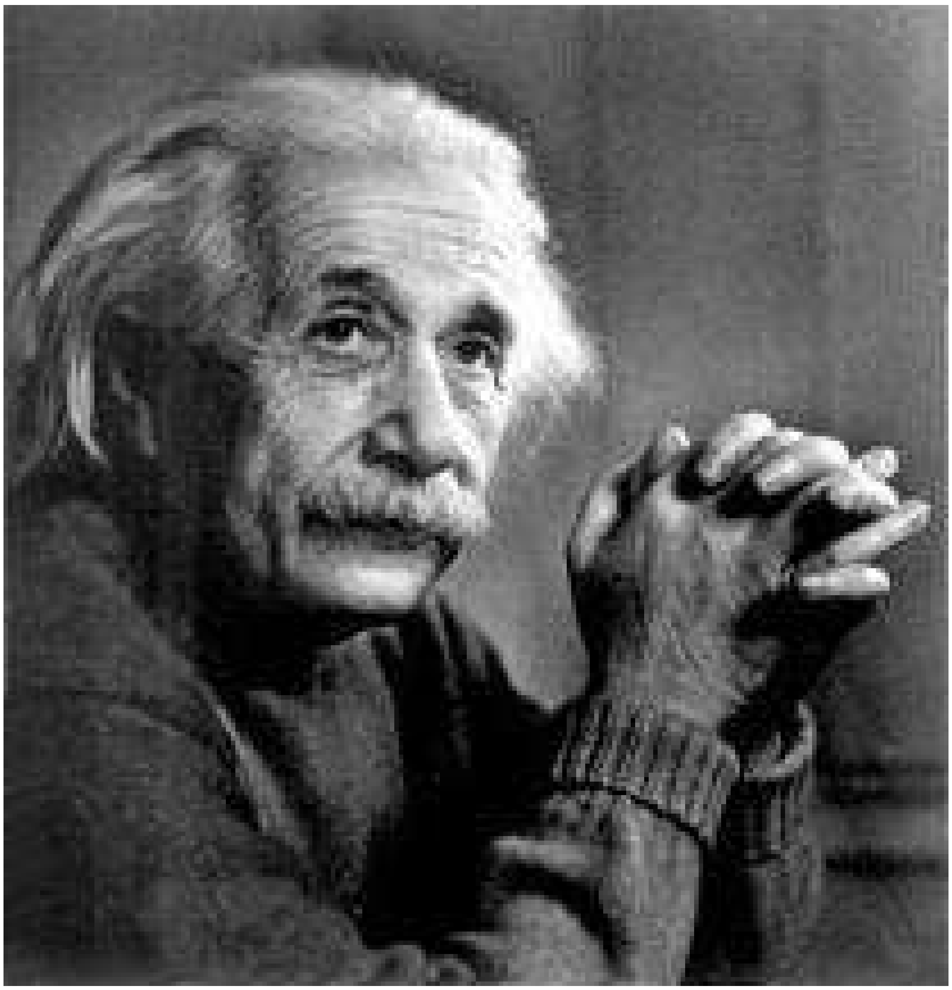

Figure 7.2: **Signing the Russell-Einstein declaration was the last public act of Einstein's life.**

Peace cannot be kept by force; it can only be achieved by understanding.

The world is a dangerous place to live; not because of the people who are evil, but because of the people who don't do anything about it.

Insanity: doing the same thing over and over again and expecting to get different results.

Nothing will end war unless the people themselves refuse to go to war.

Past thinking and methods did not prevent world wars. Future thinking must prevent war.

You cannot simultaneously prevent and prepare for war.

Never do anything against conscience, even if the state demands it.

Taken as a whole, I would believe that Gandhi's views were the most enlightened of all political men of our time.

Without ethical culture, there is no salvation for humanity.

War seems to me to be a mean, contemptible thing: I would rather be hacked in pieces than take part in such an abominable business. And yet so high, in spite of everything, is my opinion of the human race that I believe this bogey would have disappeared long ago, had the sound sense of the nations not been systematically corrupted by commercial and political interests acting through the schools and the Press.

7.6 The Russell-Einstein Manifesto

In March, 1954, the US tested a hydrogen bomb at the Bikini Atoll in the Pacific Ocean. It was 1000 times more powerful than the Hiroshima bomb. The Japanese fishing boat, Lucky Dragon, was 130 kilometers from the Bikini explosion, but radioactive fallout from the test killed one crew member and made all the others seriously ill.

In England, Prof. Joseph Rotblat, a Polish scientist who had resigned from the Manhattan Project for for moral reasons when it became clear that Germany would not develop nuclear weapons, was asked to appear on a BBC program to discuss the Bikini test. He was asked to discuss the technical aspects of H-bombs, while the Archbishop of Canterbury and the philosopher Lord Bertrand Russell were asked to discuss the moral aspects.

Figure 7.3: **Joseph Rotblat believed that the Bikini bomb was of a fission-fusion-fission type. Besides producing large amounts of fallout, such a bomb can be made enormously powerful at very little expense.**

Figure 7.4: **Lord Russell devoted much of the remainder of his life to working for the abolition of nuclear weapons. Here he is seen in 1962 in Trafalgar Square, London, addressing a meeting of the Campaign for Nuclear Disarmament.**

Rotblat had became convinced that the Bikini bomb must have involved a third stage, where fast neutrons from the hydrogen thermonuclear reaction produced fission in a casing of ordinary uranium. Such a bomb would produce enormous amounts of highly dangerous radioactive fallout, and Rotblat became extremely worried about the possibly fatal effect on all living things if large numbers of such bombs were ever used in a war. He confided his worries to Bertrand Russell, whom he had met on the BBC program.

After discussing the Bikini test and its radioactive fallout with Joseph Rotblat, Lord Russell became concerned for the future of the human gene pool if large numbers of such bombs should ever be used in a war. After consultations with Albert Einstein and others, he drafted a document warning of the grave dangers presented by fission-fusion-fission bombs. On July 9, 1955, with Rotblat in the chair, Russell read the Manifesto to a packed press conference.

The document contains the words: **"Here then is the problem that we present to you, stark and dreadful and inescapable: Shall we put an end to the human race, or shall mankind renounce war?... There lies before us, if we choose, continual progress in happiness, knowledge and wisdom. Shall we, instead, choose death because we cannot forget our quarrels? We appeal as human beings to human beings: Remember your humanity, and forget the rest. If you**

can do so, the way lies open to a new Paradise; if you cannot, there lies before you the risk of universal death.”

In 1945, with the horrors of World War II fresh in everyone’s minds, the United Nations had been established with the purpose of eliminating war. A decade later, the Russell-Einstein Manifesto reminded the world that war *must* be abolished as an institution because of the constantly increasing and potentially catastrophic power of modern weapons.

Suggestions for further reading

1. Paul Arthur Schlipp (editor), *Albert Einstein: Philosopher-Scientist*, Open Court Publishing Co., Lasalle Illinois (1970).
2. Banesh Hoffmann, *Albert Einstein, Creator and Rebel*, The Viking Press, New York (1972).
3. Albert Einstein and Leopold Infeld, *The Evolution of Physics*, Cambridge University Press (1971).

Chapter 8

THE CURIES

8.1 X-rays

In 1895, while the work leading to the discovery of the electron was still going on, a second revolutionary discovery was made. In the autumn of that year, Wilhelm Konrad Roentgen (1845-1923), the head of the department of physics at the University of Würtzburg in Bavaria, was working with a discharge tube, repeating some of the experiments of Crookes.

Roentgen was especially interested in the luminescence of certain materials when they were struck by cathode rays. He darkened the room, and turned on the high voltage. As the current surged across the tube, a flash of light came from an entirely different part of the room! To Roentgen's astonishment, he found that a piece of paper which he had coated with barium platinocyanide was glowing brightly, even though it was so far away from the discharge tube that the cathode rays could not possibly reach it!

Roentgen turned off the tube, and the light from the coated paper disappeared. He turned on the tube again, and the bright glow on the screen reappeared. He carried the coated screen into the next room. Still it glowed! Again he turned off the tube, and again the screen stopped glowing. Roentgen realized that he had discovered something completely strange and new. Radiation of some kind was coming from his discharge tube, but the new kind of radiation could penetrate opaque matter!

Years later, when someone asked Roentgen what he thought when he discovered X-rays, he replied: "I didn't think. I experimented!" During the next seven weeks he experimented like a madman; and when he finally announced his discovery in December, 1895, he was able to report all of the most important properties of X-rays, including their ability to ionize gases and the fact that they cannot be deflected by electric or magnetic fields. Roentgen correctly believed X-rays to be electromagnetic waves, just like light waves, but with very much shorter wavelength.

It turned out that X-rays were produced by electrons from the cathode of the discharge tube. These electrons were accelerated by the strong electric field as they passed across the tube from the cathode (the negative terminal) to the anode (the positive terminal).

Figure 8.1: **Wilhelm Konrad Roentgen (1845-1923). Wellcome Images.**

Figure 8.2: **X-ray photograph by W.K. Roentgen. Wellcome Images.**

They struck the platinum anode with very high velocity, knocking electrons out of the inner parts of the platinum atoms. As the outer electrons fell inward to replace these lost inner electrons, electromagnetic waves of very high frequency were emitted.

On January 23, 1896, Roentgen gave the first public lecture on X-rays; and in this lecture he demonstrated to his audience that X-ray photographs could be used for medical diagnosis. When Roentgen called for a volunteer from the audience, the 79 year old physiologist, Rudolf von Kölliker stepped up to the platform, and an X-ray photograph was taken of the old man's hand. The photograph, still in existence, shows the bones beautifully.

Wild enthusiasm for Roentgen's discovery swept across Europe and America, and soon many laboratories were experimenting with X-rays. The excitement about X-rays led indirectly to a third revolutionary discovery - radioactivity.

8.2 Radioctivity

On the 20th of January, 1896, only a month after Roentgen announced his discovery, an excited crowd of scientists gathered in Paris to hear the mathematical physicist Henri Poincaré lecture on Roentgen's X-rays. Among them was Henri Becquerel (1852-1908), a professor of physics working at the Paris Museum of Natural History and the École Polytechnique. Becquerel, with his neatly clipped beard, looked the very picture of a 19th century French professor; and indeed, he came from a family of scientists. His grandfather had been a pioneer of electrochemistry, and his father had done research on fluorescence and phosphorescence.

Like his father, Henri Becquerel was studying fluorescence and phosphorescence; and for this reason he was especially excited by the news of Roentgen's discovery. He wondered whether there might be X-rays among the rays emitted by fluorescent substances. Hurrying to his laboratory, Becquerel prepared an experiment to answer this question.

He wrapped a large number of photographic plates in black paper, so that ordinary light could not reach them. Then he carried the plates outdoors into the sunlight, and on each plate he placed a sample of a fluorescent compound from his collection. After several hours of exposure, he developed the plates. If X-rays were present in the fluorescent radiation, then the photographic plates should be darkened, even though they were wrapped in black paper.

When he developed the plates, he found, to his excitement, that although most of them were unaffected, one of the plates was darkened! This was the plate on which he had placed the compound, potassium uranium sulfate. Experimenting further, Becquerel found other compounds which would darken the photographic plates - sodium uranium sulfate, ammonium uranium sulfate and uranium nitrate. All were compounds of uranium!

At the end of February, Becquerel made his first report to the French Academy of Sciences; and until the end of March, he brought a new report every week, describing new properties of the remarkable radiation from uranium compounds. Then the weather turned against him, and for many weeks, Paris was covered with thick clouds. Too impatient to wait for sunshine, Becquerel continued his experiments in cloudy weather, hoping that even without direct sunlight there would be some slight effect.

To his astonishment, the plates were blackened as much as before, although without direct sunlight the fluorescence of the uranium compounds was much diminished! Could it be that the mysterious penetrating radiation from the uranium compounds was independent of fluorescence? To answer this question, Becquerel next tried placing the uranium-containing compounds on photographic plates in a completely darkened room. Still the plates were blackened! The effect was completely independent of exposure to sunlight!

This was indeed something completely new and strange: The radiation seemed to come from the uranium atoms themselves, rather than from chemical changes in the compounds to which the atoms belonged. If the energy of Becquerel's rays did not come from sunlight, what was its source? Two of the most basic assumptions of classical science seemed to be challenged - the indivisibility of the atom and the conservation of energy.

8.3 Marie and Pierre Curie

Among Henri Becquerel's colleagues in Paris were two dedicated and talented scientists, Marie and Pierre Curie. As a boy, Pierre Curie (1859-1906), the son of an intellectual Parisian doctor, had never been to school. His father had educated him privately, recognizing that his son's original and unworldly mind was unsuited for an ordinary education.

At the age of 16, Pierre Curie had become a Bachelor of Science, and at 18, he had a Master's degree in physics. Together with his brother, Jacques, Pierre Curie had discovered the phenomenon of piezoelectricity - the electrical potential produced when certain crystals, such as quartz, are compressed. He had also discovered a law governing the temperature-dependence of magnetism, "Curie's Law".

Although Pierre Curie had an international reputation as a physicist, his position as chief of the laboratory at the School of Physics and Chemistry of the City of Paris was miserably paid; and his modest, unworldly character prevented him from seeking a better position. He only wanted to be allowed to continue his research.

In 1896, when Becquerel announced his revolutionary discovery of radioactivity, Pierre Curie was newly married to a Polish girl, much younger than himself, but equally exceptional in character and ability. Marie Sklodowska Curie (1867-1934) had been born in Warsaw, in a Poland which did not officially exist, since it had been partitioned between Germany, Austria and Russia. Her father was a teacher of mathematics and physics and her mother was the principal of a girl's school.

Marie Sklodowska's family was a gifted one, with strong intellectual traditions; but it was difficult for her to obtain a higher education in Poland. Her mother died, and her father's job was withdrawn by the government. Marie Sklodowska was forced to work in a humiliating position as a governess in a uncultured family, meanwhile struggling to educate herself by reading books of physics and mathematics. She had a romance with the son of a Polish landowning family; but in the end, he rejected her because of her inferior social position.

Marie Sklodowska transmuted her unhappiness and humiliation into a fanatical devotion to science. She once wrote to her brother: "You must believe yourself to be born with a gift for some particular thing; and you must achieve that thing, no matter what the cost." Although she could not know it at the time, she was destined to become the greatest woman scientist in history.

Marie Sklodowska's chance for a higher education came at last when her married sister, who was studying medicine in Paris, invited Marie to live with her there and to enroll in the Sorbonne. After living in Paris with her sister for a year while studying physics, Marie found her sister's household too distracting for total concentration. She moved to a tiny, comfortless garret room, where she could be alone with her work.

Rejecting all social life, enduring freezing temperatures in winter, and sometimes fainting from hunger because she was too poor to afford proper food, Marie Sklodowska was nevertheless completely happy because at last she had the chance to study and to develop her potentialities. She graduated from the Sorbonne at the top of her class.

Pierre Curie had decided never to marry. He intended to devote himself totally to science; but when he met Marie, he recognized in her a person with whom he could share his ideals and his devotion to his work. After some hesitation by Marie, to whom the idea of leaving Poland forever seemed like treason, they were married. They spent a happy honeymoon touring the countryside of France on a pair of bicycles.

The next step for the young Polish student, who had now become Madame Curie, was to begin research for a doctor's degree; and she had to decide on a topic of research.

Figure 8.3: **Marie Sklodowska and her sister Bronislawa, ca. 1896. Marie lived with her married sister while studying physics at the Sorbonne in Paris. Rejecting all social engagements, she devoted herself to her studies, and graduated at the top of her class.**

The year was 1896, and news of Becquerel's remarkable discovery had just burst upon the scientific world. Marie Curie decided to make Becquerel's rays the topic of her thesis.

Using a sensitive electrometer invented by Pierre and Jacques Curie, she systematically examined all the elements to see whether any others besides uranium produced the strange penetrating rays. Almost at once, she made an important discovery: Thorium was also radioactive; but besides uranium and thorium, none of the other elements made the air of her ionization chamber' conduct electricity, discharging the electrometer. Among the known elements, only uranium and thorium were radioactive.

Next, Marie Curie tested all the compounds and minerals in the collection at the School of Physics. One of the minerals in the collection was pitchblend, an ore from which uranium can be extracted. She of course expected this uranium-containing ore to be radioactive; but to her astonishment, her measurements showed that the pitchblende was much *more* radioactive than could be accounted for by its content of uranium and thorium!

Since both Marie Curie's own work, and that of Becquerel, had shown radioactivity to be an atomic property, and since, among the known elements, the only two radioactive ones were uranium and thorium, she and her husband were forced to the inescapable conclusion that the pitchblende must contain small traces of a new, undiscovered, highly radioactive element, which had escaped notice in the chemical analysis of the ore.

At this point, Pierre Curie abandoned his own research and joined Marie in an attempt to find the unknown element which they believed must exist in pitchblende. By July, 1898, they had isolated a tiny amount of a new element, a hundred times more radioactive than uranium. They named it "polonium" after Marie's native country.

By this time, however, they had discovered that the extra radioactivity of pitchblende came from not one, but at least two new elements. The second undiscovered element, however, was enormously radioactive, and present only in infinitesimal concentrations. They realized that, in order to isolate a weighable amount of it, they would have to begin with huge amounts of raw pitchblende ore.

The Curies wrote to the directors of the mines at St. Joachimsthal in Bohemia, where silver was extracted from pitchblende, and begged for a few tons of the residue left after the extraction process. When they received a positive reply, they spent their small savings to pay the transportation costs.

The only place the Curies could find to work with the pitchblende ore was an old shed with a leaky roof - a chillingly cold place in the winter. Remembering the four years which she and her husband spent in this shed, Marie Curie wrote:

"This period was, for my husband and myself, the heroic period of our common existence... It was in this miserable old shed that the best and happiest years of our lives were spent, entirely consecrated to work. I sometimes passed the whole day stirring a boiling mass of material with an iron rod nearly as big as myself. In the evening, I was broken with fatigue... I came to treat as many as twenty kilograms of matter at a time, which had the effect of filling the shed with great jars full of precipitates and liquids. It was killing work to carry the receivers, to pour off the liquids and to stir for hours at a stretch the boiling matter in a smelting basin."

Marie and Pierre Curie began by separating the ore into fractions by various chemical

Figure 8.4: **Pierre Curie, (1859-1906). He shared the 1903 Nobel Prize in Physics with his wife Marie.**

treatments. After each treatment, they tested the fractions by measuring their radioactivity. They could easily see which fraction contained the highly radioactive unknown element. The new element, which they named "radium", had chemical properties almost identical to those of barium; and the Curies found that it was almost impossible to separate radium from barium by ordinary chemical means.

In the end, they resorted to fractional crystallization, repeated several thousand times. At each step, the radium concentration of the active fraction was slightly enriched, and the radioactivity became progressively stronger. Finally it was two million times as great as the radioactivity of uranium. One evening, when Marie and Pierre Curie entered their laboratory without lighting the lamps, they saw that all their concentrated samples were glowing in the dark.

After four years of backbreaking labor, the Curies isolated a small amount of pure radium and measured its atomic weight. This achievement, together with their other work on radioactivity, brought them the 1903 Nobel Prize in Physics (shared with Becquerel), as well as worldwide fame. Madame Curie, the first great woman scientist in history, became a symbol of what women could do. The surge of public enthusiasm, which had started with Roentgen's discovery of X-rays, reached a climax with Madame Curie's isolation of radium.

It had been discovered that radium was helpful in treating cancer; and Madame Curie was portrayed by newspapers of the period as a great humanitarian. Indeed, the motives which inspired Marie and Pierre Curie to their heroic labors were both humanitarian and idealistic. They believed that only good could come from any increase in human knowledge. They did not know that radium is also a dangerous element, capable of causing cancer as well as curing it; and they could not foresee that research on radioactivity would eventually

Figure 8.5: **Marie Curie. Nobel Prize in Physics photo (1903). Later, she also won the Nobel Prize in Chemistry.**

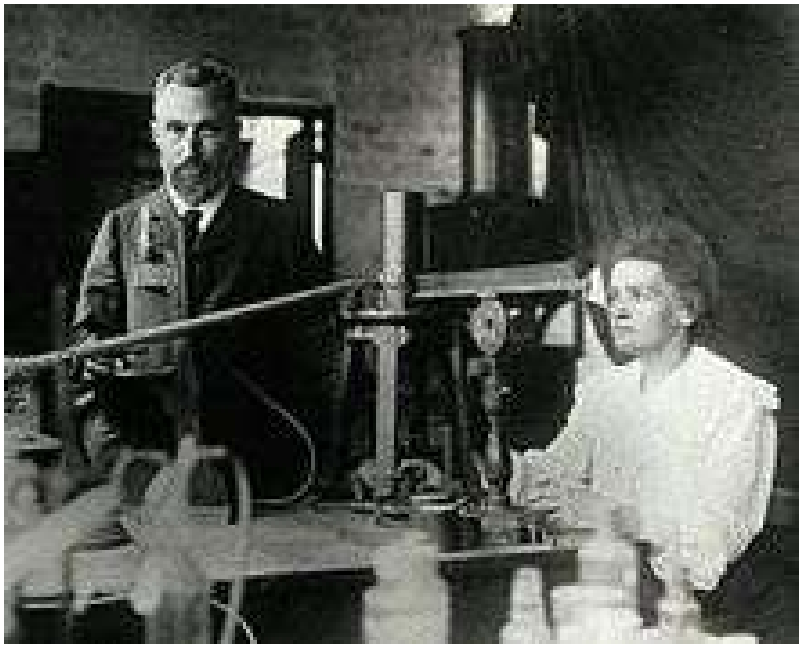

Figure 8.6: **Marie and Pierre Curie in their laboratory.**

lead to nuclear weapons.

Suggestions for further reading

1. Nitske, Robert W., *The Life of W. C. Röntgen, Discoverer of the X-Ray*, University of Arizona Press, 1971.
2. Glasser, Otto (1933). *Wilhelm Conrad Röntgen and the Early History of the Roentgen Rays.* London: John Bale, Sons and Danielsson, Ltd
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Chapter 9

THOMS0N

9.1 Sir William Crookes

In the late 1880's and early a 1890's, a feeling of satisfaction, perhaps even smugness, prevailed in the international community of physicists. It seemed to many that Maxwell's electromagnetic equations, together with Newton's equations of motion and gravitation, were the fundamental equations which could explain all the phenomena of nature. Nothing remained for physicists to do (it was thought) except to apply these equations to particular problems and to deduce the consequences. The inductive side of physics was thought to be complete.

However, in the late 1890's, a series of revolutionary discoveries shocked the physicists out of their feeling of complacency and showed them how little they really knew. The first of these shocks was the discovery of a subatomic particle, the electron. In Germany, Julius Plücker (1801-1868), and his friend, Heinrich Geisler (1814-1879), had discovered that an electric current could be passed through the gas remaining in an almost completely evacuated glass tube, if the pressure were low enough and the voltage high enough. When this happened, the gas glowed, and sometimes the glass sides of the tube near the cathode (the negative terminal) also glowed. Plücker found that the position of the glowing spots on the glass near the cathode could be changed by applying a magnetic field.

In England, Sir William Crookes (1832-1919) repeated and improved the experiments of Plücker and Geisler: He showed that the glow on the glass was produced by rays of some kind, streaming from the cathode; and he demonstrated that these "cathode rays" could cast shadows, that they could turn a small wheel placed in their path, and that they heated the glass where they struck it.

Figure 9.1: **Heinrich Geissler (1814-1879) was a German physicist and skilled glassblower who pioneered the development of the low pressure gas-discharge tube.**

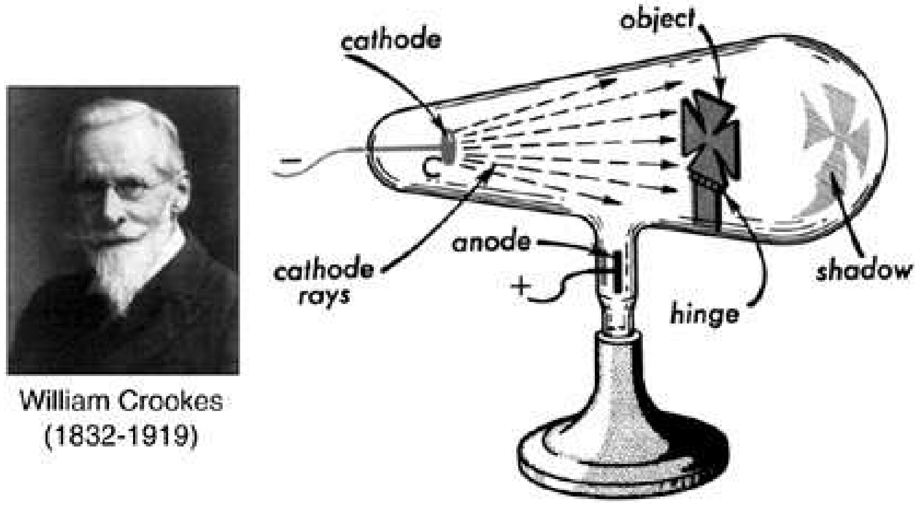

Figure 9.2: **Sir William Crookes showed that cathode rays could cast shadows.**

9.2 Thomson's discovery of electrons

Sir William Crookes believed that the cathode rays were electrically charged particles of a new kind - perhaps even a "fourth state of matter". His contemporaries laughed at these speculations; but a few years later a brilliant young physicist named J.J.Thomson (1856-1940), working at Cambridge University, entirely confirmed Crookes' belief that the cathode rays were charged particles of a new kind.

Thomson, an extraordinarily talented young scientist, had been appointed full professor and head of the Cavendish Laboratory at Cambridge at the age of 27. His predecessors in this position had been James Clerk Maxwell and the distinguished physicist, Lord Rayleigh, so the post was quite an honor for a man as young as Thomson. However, his brilliant performance fully justified the expectations of the committee which elected him. Under Thomson's direction, and later under the direction of his student, Ernest Rutherford, the Cavendish Laboratory became the world's greatest center for atomic and subatomic research; and it maintained this position during the first part of the twentieth century.

J.J. Thomson's first achievement was to demonstrate conclusively that the "cathode rays" observed by Plücker, Geisler and Crookes were negatively charged particles. He and his students also measured their ratio of charge to mass. If the charge was the same as that on an ordinary negative ion, then the mass of the particles was astonishingly small - almost two thousand times smaller than the mass of a hydrogen atom! Since the hydrogen atom is the lightest of all atoms, this indicated that the cathode rays were *subatomic* particles.

The charge which the cathode rays particles carried was recognized to be the fundamental unit of electrical charge, and they were given the name "electrons". All charges observed in nature were found to be integral multiples of the charge on an electron. The discovery of the electron was the first clue that the atom, thought for so long to be eternal and indivisible, could actually be torn to pieces.

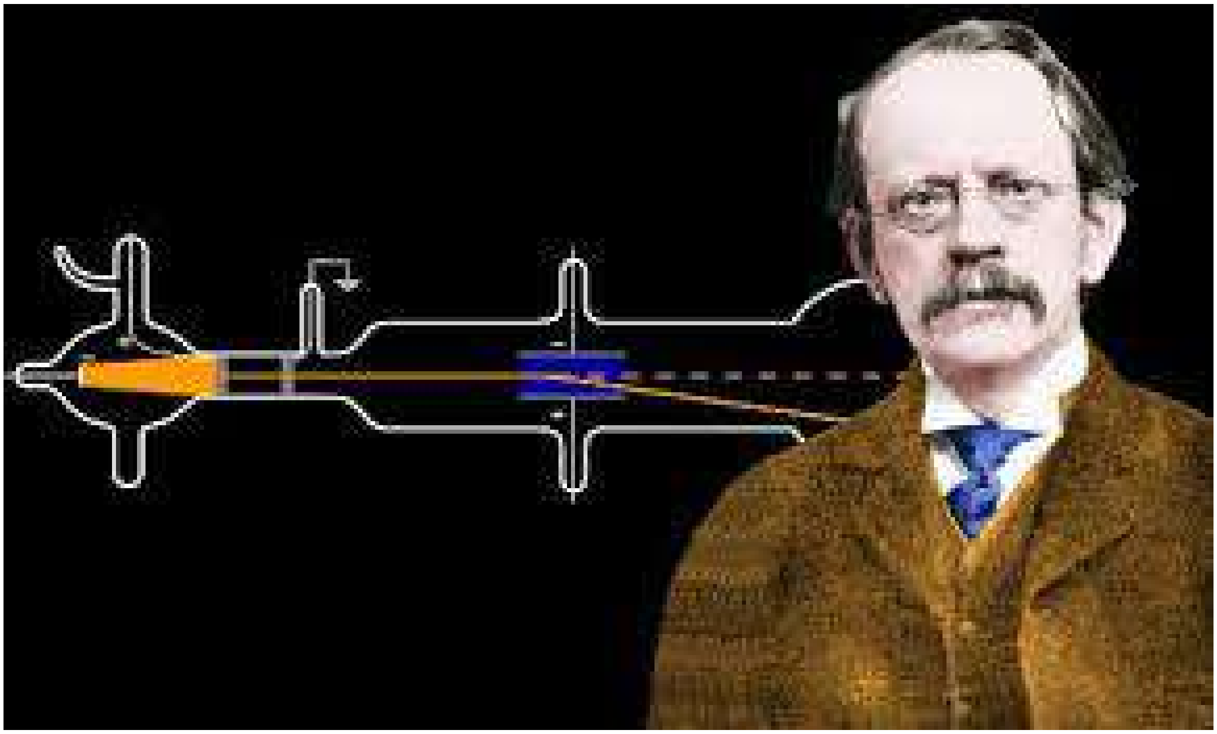

Figure 9.3: **Sir Joseph John Thomson (1856-1940). Thomson's informality, enthusiasm and speed made him an inspiring teacher. It is remarkable that 9 of his students and research associates, including his own son, were awarded either the Nobel Prize in Physics or the Nobel Prize in Chemistry.**

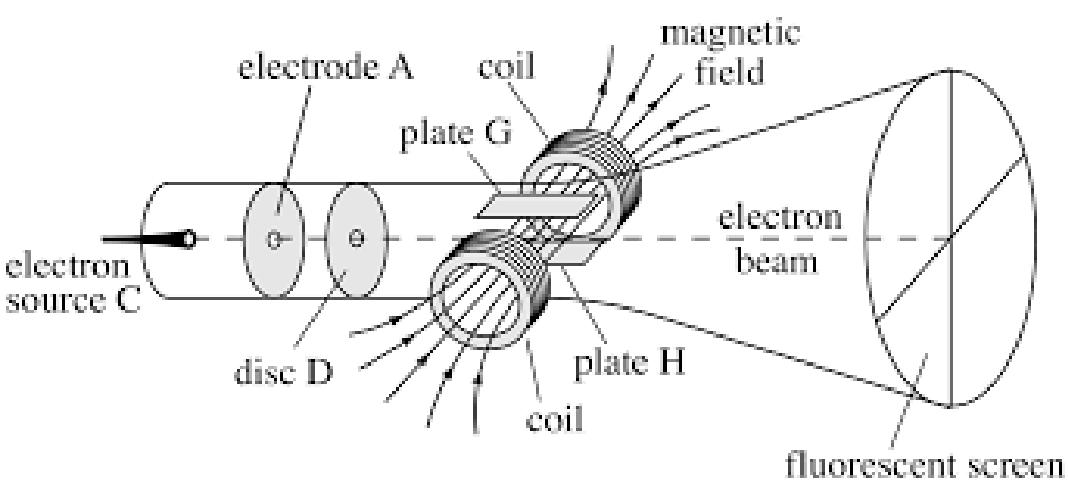

Figure 9.4: **This figure shows how Thomson determined the ratio of the electron's charge to its mass. A beam of electrons passes through a region of the vacuum tube in which there is both a vertical electric field and a horizontal magnetic field. The trajectory of the electron then depends on the charge to mass ratio.**

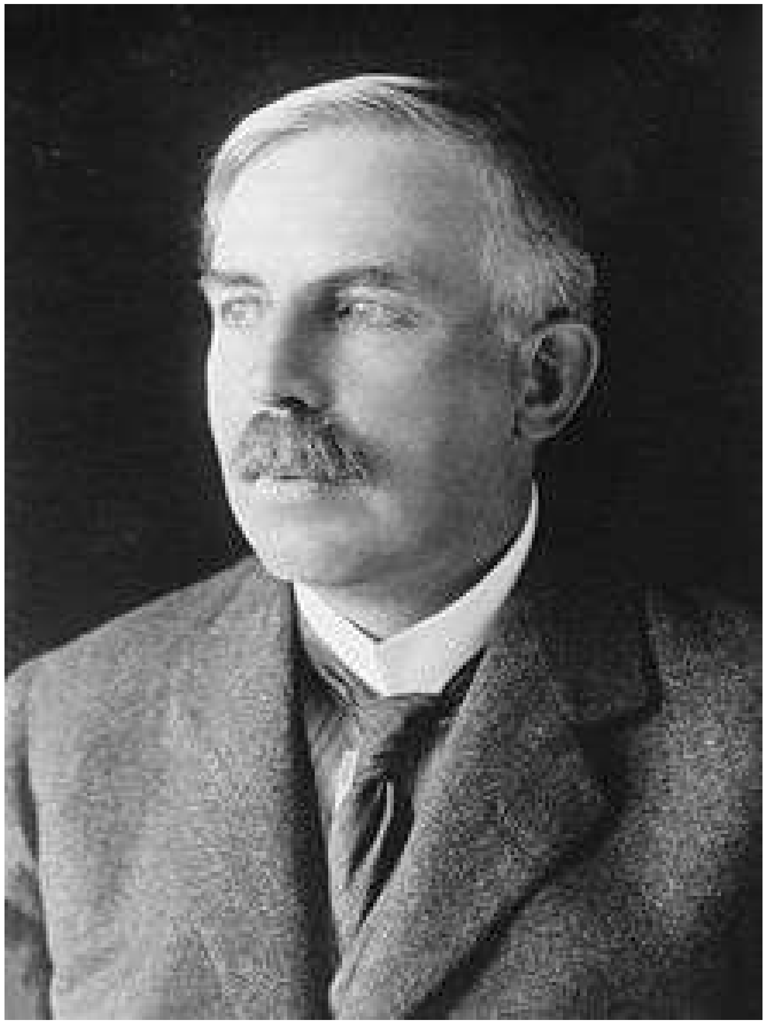

Figure 9.5: **Lord Rutherford of Nelson (1871-1937). As a young physics graduate in New Zealand, Rutherford was awarded a fellowship for postgraduate study under Thomson at Cambridge University's Cavendish Laboratory. At the end of his time at the Cavendish, Thomson was able to obtain a position for Rutherford at McGill University in Canada. It was in Canada that Rutherford did the pioneering studies of radioactive decay of elements for which he was awarded the Nobel Prize in Chemistry in 1908. Returning to England, Rutherford established a research group at what is now the University of Manchester. It was here that he and his coworkers performed the scattering experiment which led to Rutherford's model of the atom. In 1919 he became the Director of the Cavendish Laboratory, and in 1925, President of the Royal Society. Rutherford has been called the "father of nuclear physics", and is considered to be the greatest experimental physicist since Michael Faraday.**

Figure 9.6: **Charles Glover Barkla (1877-1944), who studied under Thomson at the Cavendish. He was awarded the Nobel Prize in Physics in 1917. The motivation for the award, cited by the Nobel Committee, was as follows: "Following the discovery of X-rays, it was soon established that an irradiated compound emitted secondary X-rays. In secondary spectra, lines appeared corresponding to different wavelengths. Around 1906, Charles Barkla showed that each element's secondary spectrum was unique, irrespective of temperature, structure, and chemical composition. Its spectrum was therefore a characteristic property of an atom and thus became an important tool in atomic research."**

Figure 9.7: **Niels Bohr (1885-1962). When he went to England in 1911 to meet J.J. Thomson, Bohr brought with him a detailed list of errors in Thomson's papers, which he presented to the older scientist, mistakenly expecting Thomson to be pleased. Thomson gave Bohr some experimental work to do which Bohr considered to be too trivial to be interesting. However, while at the Cavendish, Bohr met Ernst Rutherford, who invited him to work at his laboratory in Manchester. Bohr was destined to propose a quantum explation of the mysterious stability of Rutherford's model of the atom. In 1922, Bohr received a Nobel Prize in Physics for his work on the quantum theory of atomic structure.**

Figure 9.8: **Max Born (1882-1970). In 1907, he studied for six months under J.J. Thomson at the Cavendish Laboratory. In 1954, Max Born was awarded a Nobel Prize in Physics for his numerous contributions to quantum theory. In fact, Born made important contributions to many branches of physics, including solid state physics, optics, and the theory of elasticity.**

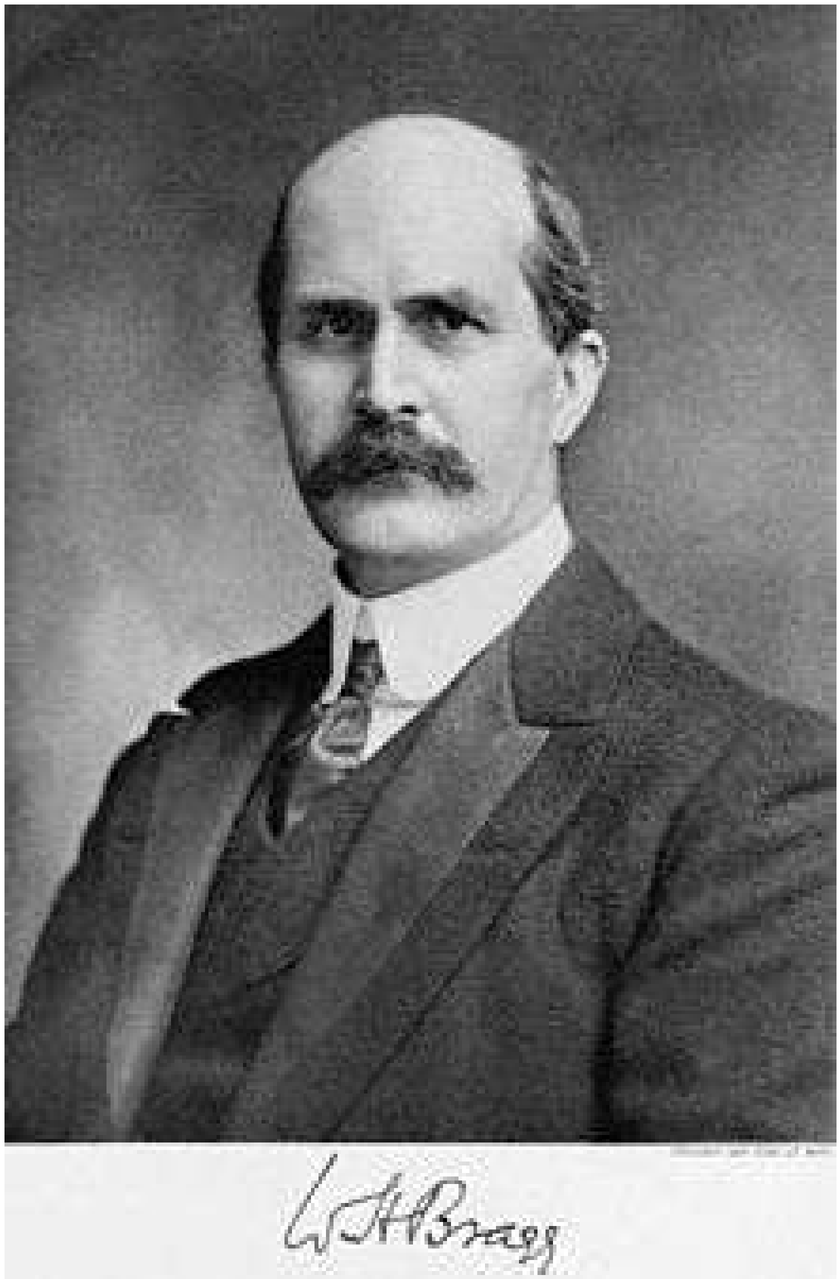

Figure 9.9: **Sir William Henry Bragg (1862-1942). He and his son, Lawrence Bragg shared the 1915 Nobel Prize in Physics "for their services to the analysis of crystal structure by means of X-rays". He studied with J.J. Thomson at Cambridge University after having won a scholarship to Trinity College in 1885. X-ray crystallography, pioneered by Bragg and his son, has proved to be enormously important both in chemistry and in biology. It has allowed us to understand the structure of both organic and inorganic molecules, and initiated the science of molecular biology.**

Figure 9.10: **Sir Owan Willans Richardson (1879-1959) is shown here together with Niels Bohr. He began research at the Cavendish in 1900, studying the emission of electrons from a hot wire. This led to his discovery of what came to be known as Richardson's Law: $s = AT^{1/2}e^{-b/T}$. Here s is the current, T is the temperature, and A and b are constants. Richardson's work on thermionic emission was honored with a Nobel Prize in Physics in 1928.**

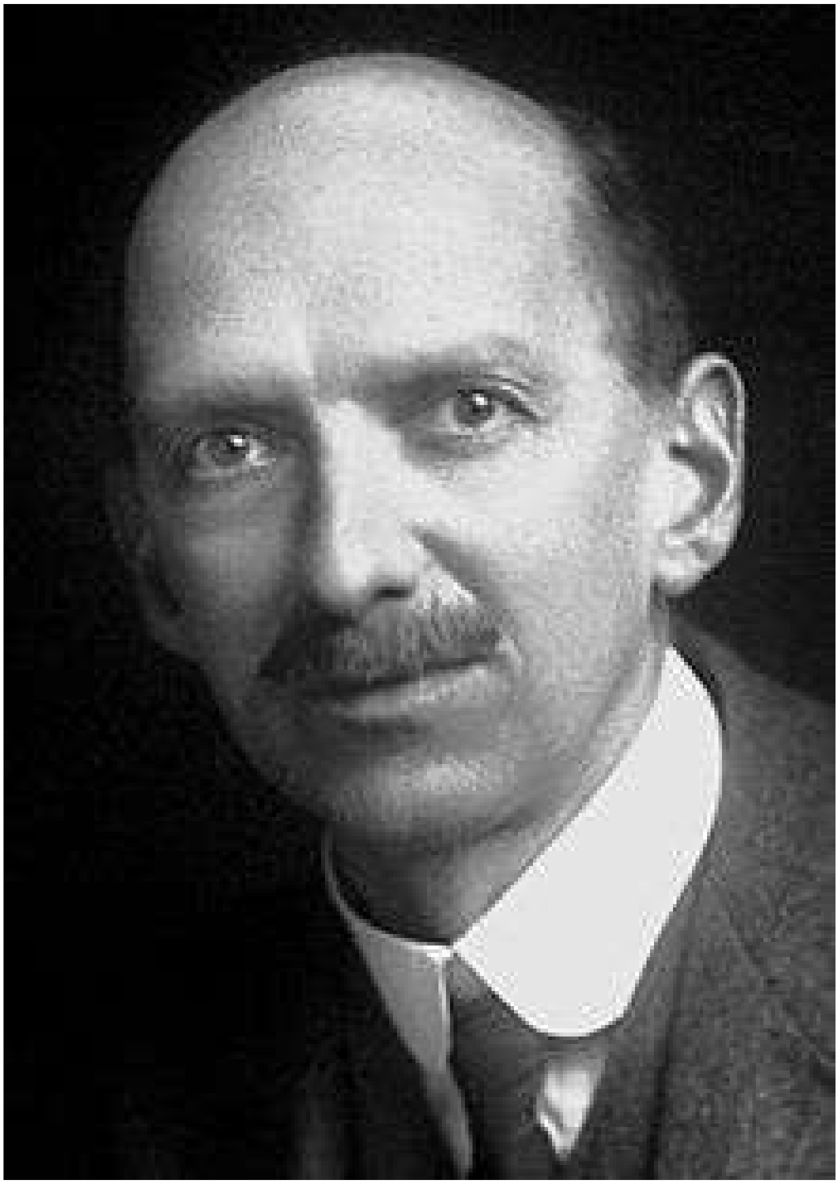

Figure 9.11: **Charles Thomson Rees Wilson (1869-1959). He won a Nobel Prize in Physics in 1927 for his invention of the cloud chamber. This invention, which paved the way for advances in modern particle physics, was the outcome of work which Wilson did at the Cavendish Laboratory under J.J. Thomson, starting in 1895. In Wilson's cloud chambers humid air is rapidly expanded. Condensation can then be observed along the paths of fast-moving charged particles, which leave trails of ions on which water condenses.**

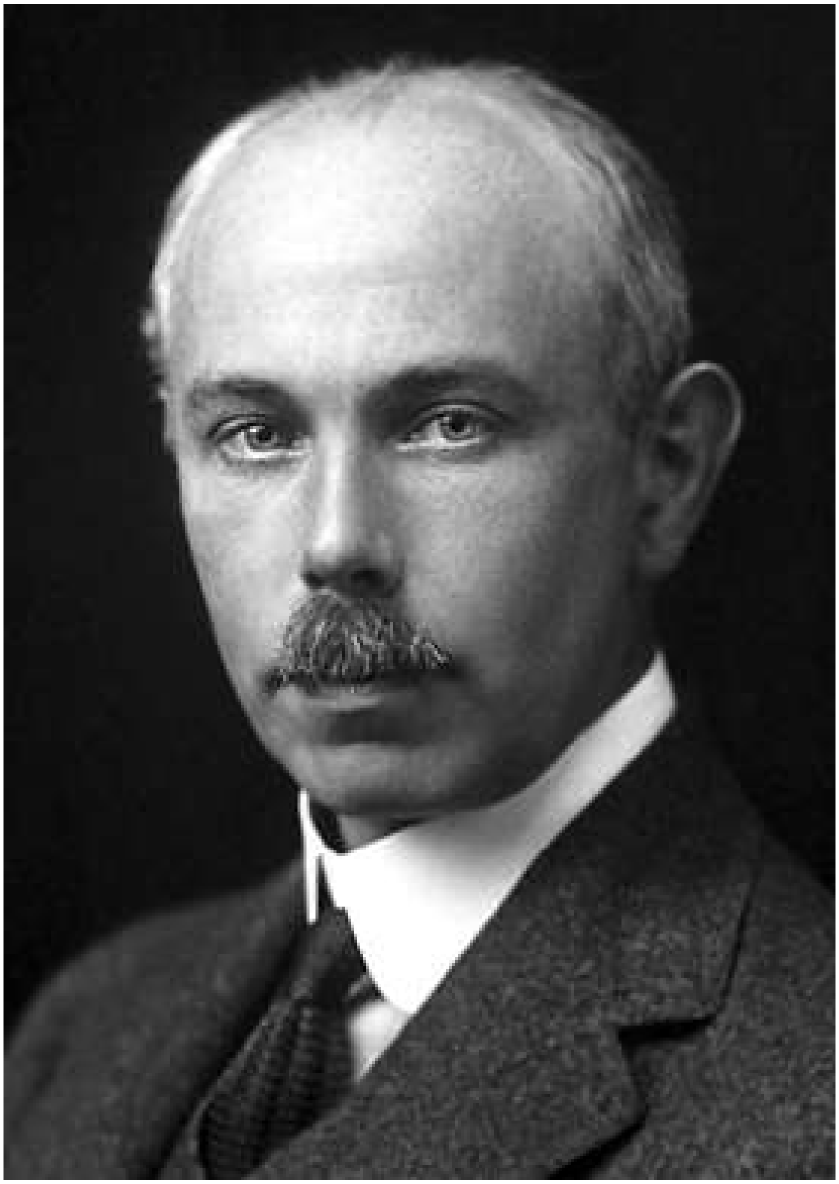

Figure 9.12: **Francis William Aston (1877-1945). In 1911 he began research at the Cavendish Laboratory at the invitation of J.J. Thomson. Using crossed eclectic and magnetic fields, just as Thomson had done in determining the charge to mass ratio of the electron, Aston determed this ratio for ionized atoms. He was able to determine the mass of many atoms with great accuracy. Using his mass spectrometer, Aston found that the masses of atoms are approximately (but not exactly) integral multiples of the mass of the hydrogen atom. He also discovered the isotopes of many non-radioactive elements. His work was honored with a Nobel Prize in Chemistry in 1922.**

Figure 9.13: **Sir George Paget Thomson (1892-1975), J.J. Thomson's son. While his father regarded the electron as a particle, G.P. Thomson demonstrated experimentally that it also had wavelike properties. He passed a beam of electrons through a thin metal foil and observed a diffraction pattern, as had been predicted by the French aristocrat and physicist Louis de Broglie in 1924. G.P. Thomson shared the 1937 Nobel Prize in Physics with C.J. Davidson and L.H. Germer, who had independently performed a similar experiment at the same time.**

Figure 9.14: **J.J. Thomson deserves credit for making Cambridge University's Cavendish Laboratory the world's most important center for physics for a long period. In the 1930's the center of interest shifted to Niels Bohr's Institute for Theoretical Physics in Copenhagen, but the Cavendish Laboratory continued to make important contributions. For example, it was at the Cavendish that Crick and Watson constructed their famous model of DNA.**

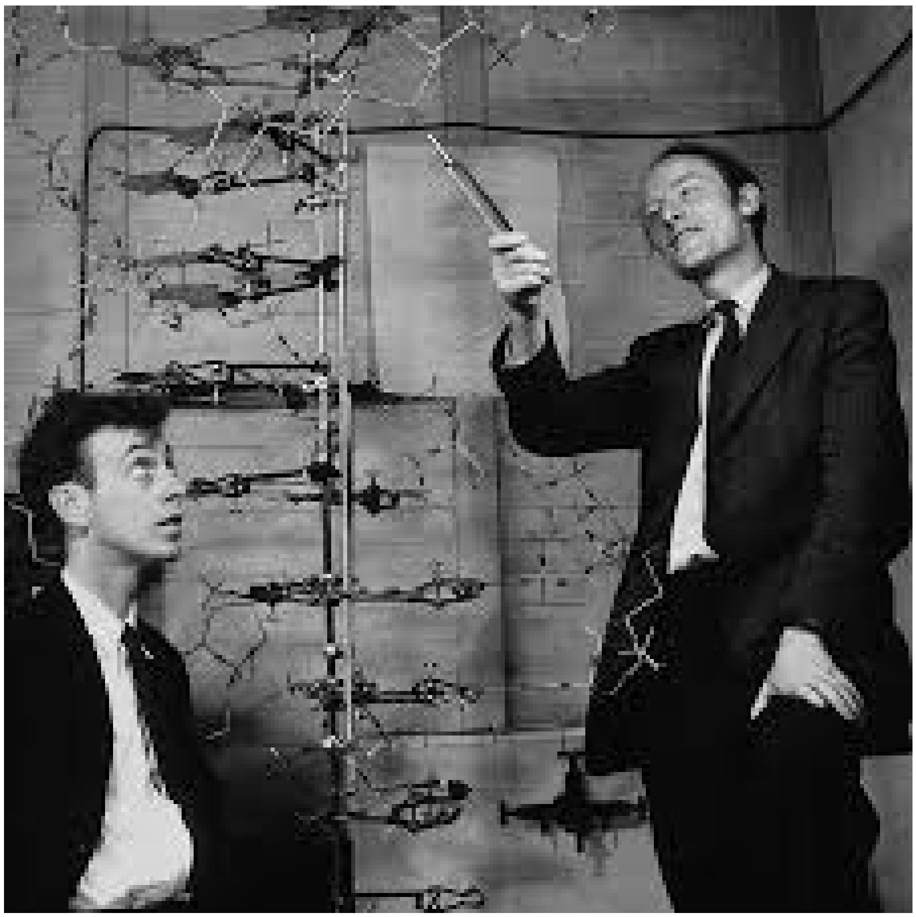

Figure 9.15: **Francis Crick (1916-2004) and James Dewey Watson (born 1928) at the Cavendish Laboratory with their model of DNA. After their discovery of the structure of DNA, it became clear that it was this molecule that carried genetic information between generations. Crick was originally a physicist, but his interest shifted to biology after he read Erwin Schrödinger's book, *What is Life?*.**

Suggestions for further reading

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Chapter 10

RUTHERFORD

10.1 Rutherford's model of the atom

In 1895, the year during which Roentgen made his revolutionary discovery of X-rays, a young New Zealander named Ernest Rutherford was digging potatoes on his father's farm, when news reached him that he had won a scholarship for advanced study in England. Throwing down his spade, Rutherford said, "That's the last potato I'll dig!" He postponed his marriage plans and sailed for England, where he enrolled as a research student at Cambridge University. He began work at the Cavendish Laboratory, under the leadership of J.J. Thomson, the discoverer of the electron.

In New Zealand, Rutherford had done pioneering work on the detection of radio waves, and he probably would have continued this work at Cambridge, if it had not been for the excitement caused by the discoveries of Roentgen and Becquerel. Remembering this period of his life, Rutherford wrote:

"Few of you can realize the enormous sensation caused by the discovery of X-rays by Roentgen in 1895. It interested not only the scientific man, but also the man in the street, who was excited by the idea of seeing his own insides and his bones. Every laboratory in the world took out its old Crookes' tubes to produce X-rays, and the Cavendish was no exception."

J.J. Thomson, who was interested in studying ions (charged atoms or molecules) in gases, soon found that gaseous ions could be produced very conveniently by means of X-rays. Rutherford abandoned his research on radio waves, and joined Thomson in this work.

"When I entered the Cavendish Laboratory", Rutherford remembered later, "I began to work on the ionization of gases by means of X-rays. After reading the paper of Becquerel, I was curious to know whether the ions produced by the radiation from uranium were of the same nature as those produced by X-rays; and in particular, I was interested because Becquerel thought that his radiation was somehow intermediate between light and X-rays."

"I therefore proceeded to make a systematic examination of the radiation, and I found

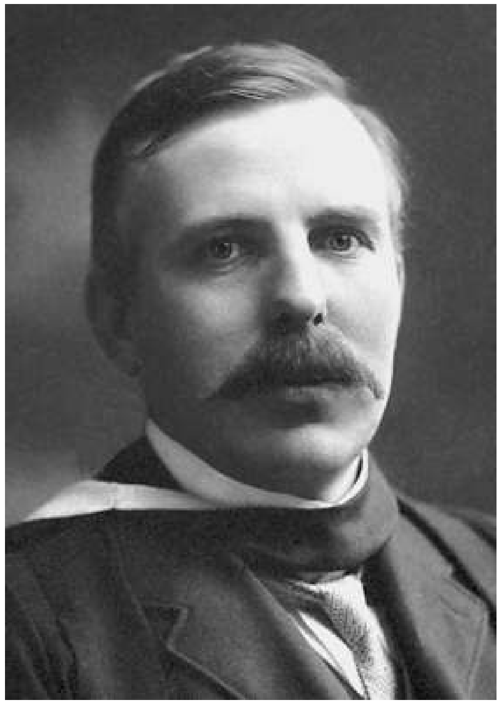

Figure 10.1: **Rutherford receiving the 1908 Nobel Prize in Chemistry.**

that it was of two types - one which produced intense ionization, and which was absorbed by a few centimeters of air, and the other, which produced less intense ionization, but was more penetrating. I called these alpha rays and beta rays respectively; and when, in 1898, Villard discovered a still more penetrating type of radiation, he called it gamma-radiation."

Rutherford later showed that the alpha-rays were actually ionized helium atoms thrown out at enormous velocities by the decaying uranium, and that beta-rays were high-speed electrons. The gamma-rays turned out to be electromagnetic waves, just like light waves, but of extremely short wavelength.

Rutherford returned briefly to New Zealand to marry his sweetheart, Mary Newton; and then he went to Canada, where he had been offered a post as Professor of Physics at McGill University. In Canada, with the collaboration of the chemist, Frederick Soddy (1877-1956), Rutherford continued his experiments on radioactivity, and worked out a revolutionary theory of transmutation of the elements through radioactive decay.

During the middle ages, alchemists had tried to change lead and mercury into gold. Later, chemists had convinced themselves that it was impossible to change one element into another. Rutherford and Soddy now claimed that radioactive decay involves a whole series of transmutations, in which one element changes into another!

Returning to England as head of the physics department at Manchester University, Rutherford continued to experiment with alpha-particles. He was especially interested in the way they were deflected by thin metal foils. Rutherford and his assistant, Hans Geiger (1886-1945), found that most of the alpha-particles passed through a metal foil with only a very slight deflection, of the order of one degree.

10.2 The Geiger-Marsden scattering experiment

In 1911, a young research student named Ernest Marsden joined the group, and Rutherford had to find a project for him. What happened next, in Rutherford's own words, was as follows:

"One day, Geiger came to me and said, 'Don't you think that young Marsden, whom I'm training in radioactive methods, ought to begin a small research?' Now I had thought that too, so I said, 'Why not let him see if any alpha-particles can be scattered through a large angle?' I may tell you in confidence that I did not believe that they would be, since we knew that the alpha-particle was a very fast, massive particle, with a great deal of energy; and you could show that if the scattering was due to the accumulated effect of a number of small scatterings, the chance of an alpha-particle's being scattered backward was very small."

"Then I remember two or three days later, Geiger coming to me in great excitement and saying, 'We have been able to get some of the alpha-particles coming backwards'. It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

"On consideration, I realized that this scattering backwards must be the result of a single collision, and when I made calculations, I found that it was impossible to get anything of that order of magnitude unless you took a system in which the greater part of the mass of the atom was concentrated in a minute nucleus."

"It was then that I had the idea of an atom with a minute massive center carrying a charge. I worked out mathematically what laws the scattering should obey, and found that the number of particles scattered through a given angle should be proportional to the thickness of the scattering foil, the square of the nuclear charge, and inversely proportional to the fourth power of the velocity. These deductions were later verified by Geiger and Marsden in a series of beautiful experiments."

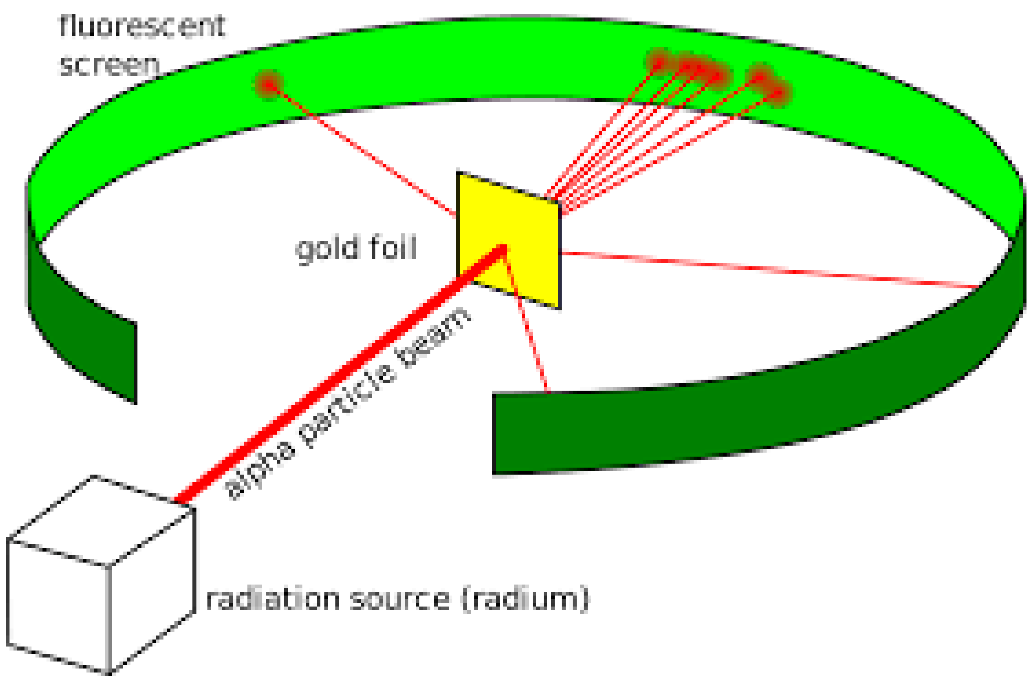

Figure 10.2: **The Geiger-Marsden scattering experiment. To Rutherford's great surprise, the experiment showed that some of the alpha particles were scattered backwards. After treating the problem mathematically, Rutherford concluded that most of the mass of an atom must be concentrated in a very small, positively-charged nucleus, around which the much lighter electrons circulate in orbits.**

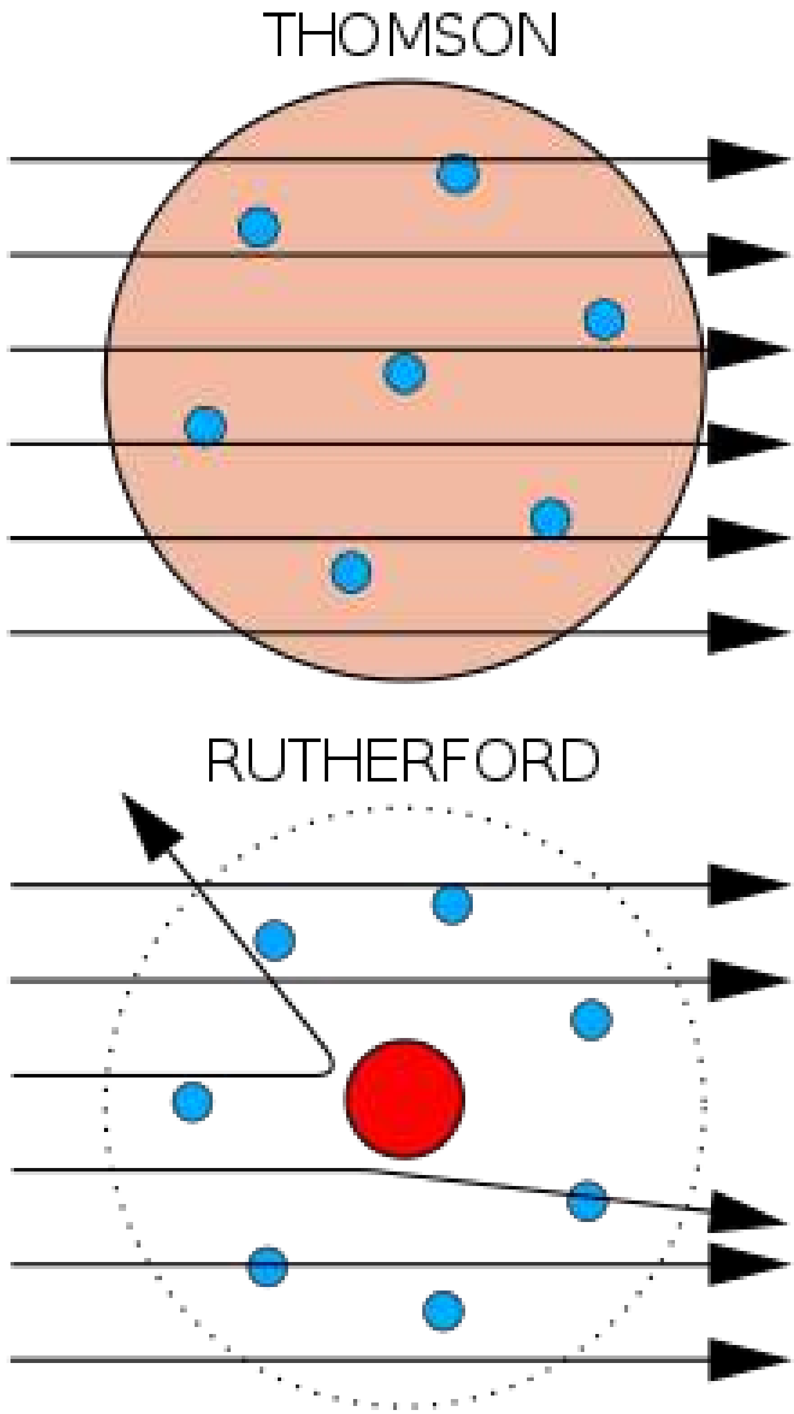

Figure 10.3: **In Thomson's model of the atom, the electrons were embedded, like raisins in a pudding, in a diffuse background of positive charge. The Geiger-Marsden experiment forced Rutherford to propose a new model to account for the observed back-scattering of alpha particles.**

10.3 Rutherford's model of the atom

According to the model proposed by Rutherford in 1911, every atom has an extremely tiny nucleus, which contains almost all of the mass of the atom. Around this tiny but massive nucleus, Rutherford visualized light, negatively-charged electrons circulating in orbits, like planets moving around the sun. Rutherford calculated that the diameter of the whole atom had to be several thousand times as large as the diameter of the nucleus.

10.4 Informality, enthusiasm and speed

Rutherford's model of the atom explained beautifully the scattering experiments of Geiger and Marsden, but at the same time it presented a serious difficulty: According to Maxwell's equations, the electrons circulating in their orbits around the nucleus ought to produce electromagnetic waves. It could easily be calculated that the electrons in Rutherford's atom ought to lose all their energy of motion to this radiation, and spiral in towards the nucleus. Thus, according to classical physics, Rutherford's atom could not be stable. It had to collapse.

Rutherford's laboratory was like no other in the world, except J.J. Thomson's. In fact, Rutherford had learned much about how to run a laboratory from his old teacher, Thomson. Rutherford continued Thomson's tradition of democratic informality and cheerfulness. Like Thomson, he had a gift for infecting his students with his own powerful scientific curiosity, and his enthusiastic enjoyment of research.

Thomson had also initiated a tradition for speed and ingenuity in the improvisation of experimental apparatus - the so-called "sealing-wax and string" tradition - and Rutherford continued it. Niels Bohr, after working with Rutherford, was later to continue the tradition of informality and enthusiasm at the Institute for Theoretical Physics which Bohr founded in Copenhagen in 1920.

Most scientific laboratories of the time offered a great contrast to the informality, enthusiasm, teamwork and speed of the Thomson-Rutherford-Bohr tradition. E.E. da C. Andrade, who first worked in Lenard's laboratory at Heidelberg, and later with Rutherford at Manchester, has given the following description of the contrast between the two groups:

"At the Heidelberg colloquium, Lenard took the chair, very much like a master with his class. He had the habit, if any aspect of his work was being treated by the speaker, of interrupting with, 'And who did that first?' The speaker would reply with a slight bow, 'Herr Geheimrat, you did that first', to which Lenard answered, 'Yes, I did that first'."

"At the Manchester colloquium, which met on Friday afternoons, Rutherford was, as in all his relations with the research workers, the boisterous, enthusiastic, inspiring friend, undoubtedly the leader but in close community with the led, stimulating rather than commanding, 'gingering up', to use a favorite expression of his, his team."

Although Rutherford occasionally swore at his "lads", his affection for them was very real. He had no son of his own, and he became a sort of father to the brilliant young men in

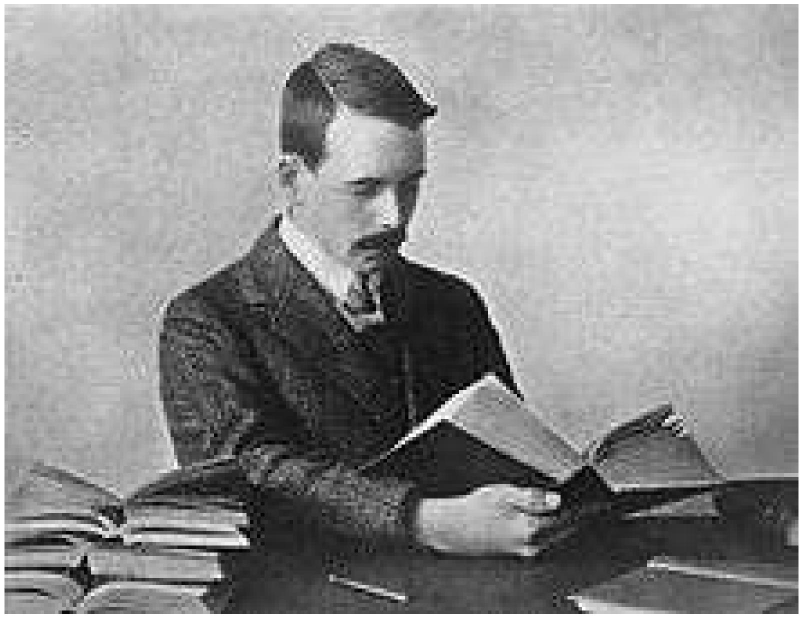

Figure 10.4: **Henry Moseley (1887-1915).**

his laboratory. Their nickname for him was "Papa". Such was the laboratory which Harry Moseley joined in 1910. At almost the same time, Moseley's childhood friend, Charles Darwin (the grandson of the "right" Charles Darwin), also joined Rutherford's team.

After working on a variety of problems in radioactivity which were given to him by Rutherford, Moseley asked whether he and Charles Darwin might be allowed to study the spectra of X-rays. At first, Rutherford said no, since no one at Manchester had any experience with X-rays; "and besides", Rutherford added with a certain amount of bias, "all science is either radioactivity or else stamp-collecting".

However, after looking more carefully at what was being discovered about X-rays, Rutherford gave his consent. In 1912, a revolutionary discovery had been made by the Munich physicist, Max von Laue (1879-1960): It had long been known that because of its wavelike nature, white light can be broken up into the colors of the spectrum by means of a "diffraction grating" - a series of parallel lines engraved very closely together on a glass plate.

For each wavelength of light, there are certain angles at which the new wavelets produced by the lines of the diffraction grating reinforce each other instead of cancelling. The angles of reinforcement are different for each wavelength, and thus the different colors are separated by the grating.

Max von Laue's great idea was to do the same thing with X-rays, using a crystal as a diffraction grating. The regular lines of atoms in the crystal, von Laue reasoned, would act be fine enough to fit the tiny wavelength of the X-rays, believed to be less than one ten-millionth of a centimeter.

Von Laue's experiment, performed in 1912, had succeeded beautifully, and his new

Figure 10.5: **Sir Charles Galton Darwin (1887-1962), grandson of the "right" Charles Darwin.**

technique had been taken up in England by a father and son team, William Henry Bragg (1862-1942) and William Lawrence Bragg (1890-1971). The Braggs had used X-ray diffraction not only to study the spectra of X-rays, but also to study the structure of crystals. Their techniques were later to become one of the most valuable research tools available for studying molecular structure.

Having finally obtained Rutherford's permission, Moseley and Darwin threw themselves into this exciting field of study. Remembering his work with Harry Moseley, Charles Darwin later wrote:

"Working with Moseley was one of the most strenuous exercises I have ever undertaken. He was, without exception, the hardest worker I have ever known... There were two rules for his work: First, when you started to set up the apparatus for an experiment, you must not stop until it was set up. Second, when the apparatus was set up, you must not stop work until the experiment was done. Obeying these rules implied a most irregular life, sometimes with all-night sessions; and indeed, one of Moseley's experteses was the knowledge of where in Manchester one could get a meal at three in the morning."

After about a year, Charles Darwin left the experiments to work on the theoretical aspects of X-ray diffraction. (He was later knighted for his distinguished contributions to theoretical physics.) Moseley continued the experiments alone, systematically studying the X-ray spectra of all the elements in the periodic system.

Niels Bohr had shown that the binding energies of the allowed orbits in a hydrogen atom are equal to Rydberg's constant , R (named after the distinguished Swedish spectroscopist, Johannes Robert Rydberg), divided by the square of an integral "quantum number", n. He had also shown that for heavier elements, the constant, R, is equal to the square of the nuclear charge, Z, multiplied by a factor which is the same for all elements. The constant, R, could be observed in Moseley's studies of X-ray spectra: Since X-rays are produced when electrons are knocked out of inner orbits and outer electrons fall in to replace them, Moseley could use the Planck-Einstein relationship between frequency and energy to find the energy difference between the orbits, and Bohr's theory to relate this to R.

Moseley found complete agreement with Bohr's theory. He also found that the nuclear charge, Z, increased regularly in integral steps as he went along the rows of the periodic table: Hydrogen had Z=1, helium Z=2, lithium Z=3, and so on up to uranium with Z=92. The 92 electrons of a uranium atom made it electrically neutral, exactly balancing the charge of the nucleus. The number of electrons of an element, and hence its chemical properties, Moseley found, were determined uniquely by its nuclear charge, which Moseley called the "atomic number".

Moseley's studies of the nuclear charges of the elements revealed that a few elements were missing. In 1922, Niels Bohr received the Nobel Prize for his quantum theory of the atom; and he was able to announce at the presentation ceremony that one of Moseley's missing elements had been found at his institute. Moseley, however, was dead. He was one of the ten million young men whose lives were needlessly thrown away in Europe's most tragic blunder - the First World War.

10.5 Artificial transmutations of elements

During the First World War, Rutherford's young men had joined the army, and he had been forced to spend most of his own time working on submarine detection. In spite of this, he had found some spare time for his scientific passion - bombarding matter with alpha particles. Helped by his laboratory steward, Kay, Rutherford had studied the effects produced when alpha particles from a radium source struck various elements. In a letter to Niels Bohr, dated December 9, 1917, Rutherford wrote:

"I have got, I think, results that will ultimately have great importance. I wish that you were here to talk matters over with me. I am detecting and counting the lighter atoms set in motion by alpha particles, and the results, I think, throw a good deal of light on the character and distribution of forces near the nucleus... I am trying to break up the atom by this method. In one case, the results look promising, but a great deal of work will be required to make sure. Kay helps me, and is now an expert counter. Best wishes for a happy Christmas."

In July, 1919, Bohr was at last able to visit Manchester, and he heard the news directly from his old teacher: Rutherford had indeed produced artificial nuclear transmutations! In one of his experiments, an alpha-particle (i.e. a helium nucleus with nuclear charge 2) was absorbed by a nitrogen nucleus. Later, the compound nucleus threw out a proton with charge 1; and thus the bombarded nucleus gained one unit of charge. It moved up one place in the periodic table and became an isotope of oxygen.

Bohr later wrote: "I learned in detail about his great new discovery of controlled, or so-called artificial, nuclear transmutations, by which he gave birth to what he liked to call 'modern Alchemy', and which in the course of time, was to give rise to such tremendous consequences as regards man's mastery of the forces of nature."

Other scientists rushed to repeat and extend Rutherford's experiments. Particle accelerators were built by E.O. Lawrence (1901-1958) in California, by J.H. van de Graff (1901-1967) at the Massachusetts Institute of Technology and by John Cockcroft (1897-1967), working with Rutherford at the Cavendish Laboratory. These accelerators could hurl protons at energies of a million electron-volts. Thus, protons became another type of projectile which could be used to produce nuclear transmutations.

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Chapter 11

BOHR

11.1 Christian Bohr's household

Christian Bohr (1855-1911) was appointed professor of physiology at the University of Copenhagen in 1886. In this position, he made a number of important discoveries connected with respiration in mammals, including what is now known as the "Bohr effect", i.e. the tendency of high concentrations of CO_2 and of H^+ ions to increase the efficiency of hemoglobin in releasing oxygen. Christian Bohr was also the teacher of August Krogh, who later won a Nobel Prize in Medicine and Physiology.

Christian Bohr's wife, Ellen Adler Bohr, belonged to a wealthy Jewish banking family, and Niels Bohr was born in the impressive multi-story Adler mansion that still stands today near one of Copenhagen's canals opposite the Danish Parliament. During the time that Niels and Harold Bohr were growing up, this house was the meeting place for many of Copenhagen's leading intellectuals, and the boys were allowed to attend meetings where scientific and philosophical questions were debated. This upbringing contributed to the fact that both Niels and Harold later became famous in their respective fields, physics and mathematics.

The Bohr family has produced outstanding scientists for four generations. Besides Christian, Niels and Harold Bohr, there is also Niels' son Aage, who shared a Nobel Prize in Physics for his work on the excited states of nuclei. Aage's sons, Vilhelm and Thomas, are also outstanding scientists.

Having been brought up in a highly intellectual household, Niels Bohr's scientific abilities developed early. In 1905, when Niels was 20, a gold medal competition was announced by the Royal Danish Society of Sciences and Letters. The challenge was to investigate a method for determining the surface tension of liquids. The method had been proposed earlier by Lord Raleigh, and it involved measuring the frequency of oscillations on the surface of a water jet. After working in his father's laboratory, making his own glassware to produce elliptical water jets, and presenting his results together with a mathematical analysis, Niels Bohr won the gold medal.

Figure 11.1: **Christian Bohr (1855-1911), the father of Niels and Harold Bohr. He was Professor of Physiology at the University of Copenhagen.**

Figure 11.2: **Niels Bohr (1885-1952) as a young man.**

Figure 11.3: **Niels Bohr and his wife, Margrethe.**

11.2 Planck, Einstein and Bohr

According to the model proposed by Rutherford in 1911, every atom has an extremely tiny nucleus, which contains almost all of the mass of the atom. Around this tiny but massive nucleus, Rutherford visualized light, negatively-charged electrons circulating in orbits, like planets moving around the sun. Rutherford calculated that the diameter of the whole atom had to be several thousand times as large as the diameter of the nucleus.

Rutherford's model of the atom explained beautifully the scattering experiments of Geiger and Marsden, but at the same time it presented a serious difficulty: According to Maxwell's equations, the electrons circulating in their orbits around the nucleus ought to produce electromagnetic waves. It could easily be calculated that the electrons in Rutherford's atom ought to lose all their energy of motion to this radiation, and spiral in towards the nucleus. Thus, according to classical physics, Rutherford's atom could not be stable. It had to collapse.

Niels Bohr became aware of this paradox when he worked at Rutherford's Manchester laboratory during the years 1911-1913. Bohr was not at all surprised by the failure of classical concepts when applied to Rutherford's nuclear atom. Since he had been educated in Denmark, he was more familiar with the work of German physicists than were his English colleagues at Manchester. In particular, Bohr had studied the work of Max Planck (1858-1947) and Albert Einstein (1879-1955).

Just before the turn of the century, the German physicist, Max Planck, had been studying theoretically the electromagnetic radiation coming from a small hole in an oven. The hole radiated as though it were an ideally black body. This "black body radiation" was very puzzling to the physicists of the time, since classical physics failed to explain the frequency distribution of the radiation and its dependence on the temperature of the oven.

In 1901, Max Planck had discovered a formula which fitted beautifully with the experimental measurements of the frequency distribution of black body radiation; but in order to derive his formula, he had been forced to make a radical assumption which broke away completely from the concepts of classical physics.

Planck had been forced to assume that light (or, more generally, electromagnetic radiation of any kind) can only be emitted or absorbed in amounts of energy which Planck called "quanta". The amount of energy in each of these "quanta" was equal to the frequency of the light multiplied by a constant, h, which came to be known as "Planck's constant".

This was indeed a strange assumption! It seemed to have been pulled out of thin air; and it had no relation whatever to anything that had been discovered previously in physics. The only possible justification for Planck's quantum hypothesis was the brilliant success of his formula in explaining the puzzling frequency distribution of the black body radiation. Planck himself was greatly worried by his own radical break with classical concepts, and he spent many years trying unsuccessfully to relate his quantum hypothesis to classical physics.

In 1905, Albert Einstein published a paper in the *Annalen der Physik* in which he applied Planck's quantum hypothesis to the photoelectric effect. (At that time, Einstein was 25 years old, completely unknown, and working as a clerk at the Swiss Patent Office.)

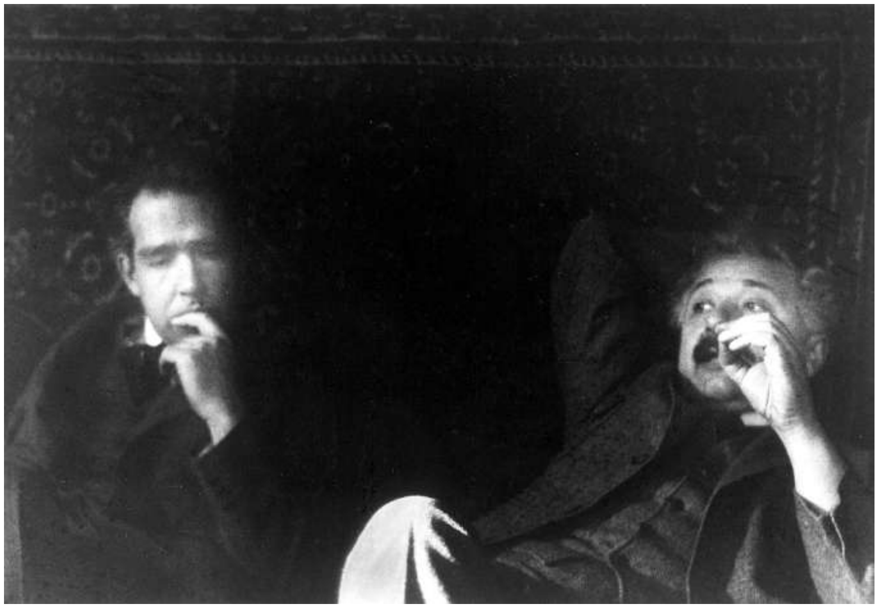

Figure 11.4: **Niels Bohr and Albert Einstein in a photo by Paul Ehrenfest. Public domain, Wikimedia Commons**

The photoelectric effect was another puzzling phenomenon which could not in any way be explained by classical physics. The German physicist Lenard had discovered in 1903 that light with a frequency above a certain threshold could knock electrons out of the surface of a metal; but below the threshold frequency, nothing at all happened, no matter how long the light was allowed to shine.

Using Planck's quantum hypothesis, Einstein offered the following explanation for the photoelectric effect: A certain minimum energy was needed to overcome the attractive forces which bound the electron to the metal surface. This energy was equal to the threshold frequency multiplied by Planck's constant. Light with a frequency equal to or higher than the threshold frequency could tear an electron out of the metal; but the quantum of energy supplied by light of a lower frequency was insufficient to overcome the attractive forces.

Einstein later used Planck's quantum formula to explain the low-temperature behavior of the specific heats of crystals, another puzzling phenomenon which defied explanation by classical physics. These contributions by Einstein were important, since without this supporting evidence it could be maintained that Planck's quantum hypothesis was an *ad hoc* assumption, introduced for the sole purpose of explaining black body radiation.

As a student, Niels Bohr had been profoundly impressed by the radical ideas of Planck and Einstein. In 1912, as he worked with Rutherford at Manchester, Bohr became convinced that the problem of saving Rutherford's atom from collapse could only be solved by means of Planck's quantum hypothesis.

Returning to Copenhagen, Bohr continued to struggle with the problem. In 1913, he found the solution: The electrons orbiting around the nucleus of an atom had "angular momentum". Assuming circular orbits, the angular momentum was given by the product of the mass and velocity of the electron, multiplied by the radius of the orbit. Bohr introduced a quantum hypothesis similar to that of Planck: He assumed that the angular momentum of an electron in an allowed orbit, (multiplied by 2 pi), had to be equal to an integral multiple of Planck's constant. The lowest value of the integer, n=1, corresponded to the lowest allowed orbit. Thus, in Bohr's model, the collapse of Rutherford's atom was avoided.

Bohr calculated that the binding energies of the various allowed electron orbits in a hydrogen atom should be a constant divided by the square of the integer n; and he calculated the value of the constant to be 13.5 electron-Volts. This value fit exactly the observed ionization energy of hydrogen. After talking with the Danish spectroscopist, H.M. Hansen, Bohr realized with joy that by combining his formula for the allowed orbital energies with the Planck-Einstein formula relating energy to frequency, he could explain the mysterious line spectrum of hydrogen.

When Niels Bohr published all this in 1913, his paper produced agonized cries of "foul!" from the older generation of physicists. When Lord Rayleigh's son asked him if he had seen Bohr's paper, Rayleigh replied: "Yes, I have looked at it; but I saw that it was of no use to me. I do not say that discoveries may not be made in that sort of way. I think very likely they may be. But it does not suit me." However, as more and more atomic spectra and properties were explained by extensions of Niels Bohr's theories, it became clear that Planck, Einstein and Bohr had uncovered a whole new stratum of phenomena, previously unsuspected, but of deep and fundamental importance.

Figure 11.5: **Another photo of Bohr and Einstein by Ehrenfest. Public domain, Wikimedia Commons**

11.3 Atomic numbers

Bohr's atomic theory soon received strong support from the experiments of one of the brightest of Rutherford's bright young men - Henry Moseley (1887-1915). Moseley came from a distinguished scientific family. Not only his father, but also both his grandfathers, had been elected to the Royal Society. After studying at Oxford, where his father had once been a professor, Moseley found it difficult to decide where to do his postgraduate work. Two laboratories attracted him: the great J.J. Thomson's Cavendish Laboratory at Cambridge, and Rutherford's laboratory at Manchester. Finally, he decided on Manchester, because of the revolutionary discoveries of Rutherford, who two years earlier had won the 1908 Nobel Prize for Chemistry.

Rutherford's laboratory was like no other in the world, except J.J. Thomson's. In fact, Rutherford had learned much about how to run a laboratory from his old teacher, Thomson. Rutherford continued Thomson's tradition of democratic informality and cheerfulness. Like Thomson, he had a gift for infecting his students with his own powerful scientific curiosity, and his enthusiastic enjoyment of research.

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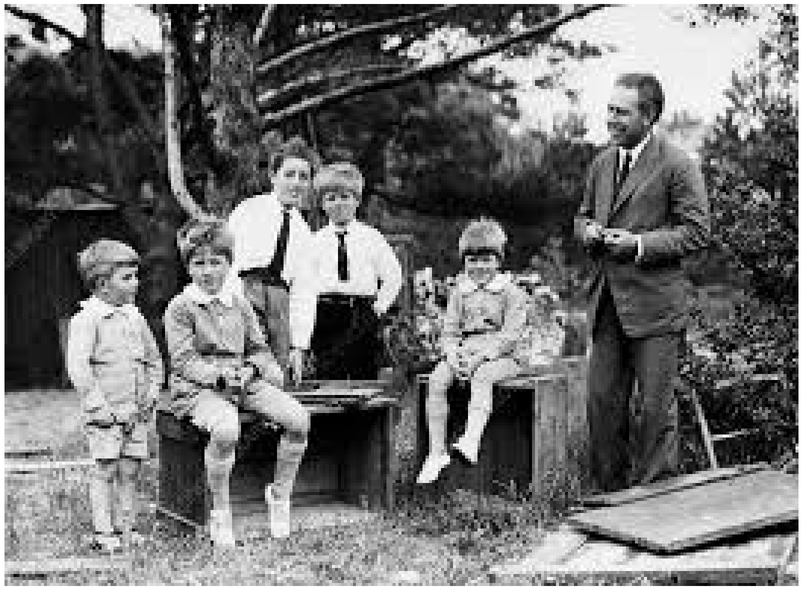

Figure 11.6: **Niels Bohr with his sons at their summer house in Tisvilde.**

11.4 Bohr's Institute of Theoretical Physics

In 1916, Niels Bohr was appointed professor of theoretical physics at the University of Copenhagen, a post that had been created especially for him. The following year, in 1917, he started to raise money for the construction of a new institute in which his new department could be housed. The project received large contributions from the Danish government and the Carlsberg Foundation, and from wealthy Danish businessmen. Bohr himself designed the building, which opened in 1920.

During the period when Hitler's Nazi party was coming to power in Germany, Bohr was able to offer a refuge at his Institute of Theoretical Physics to many important physicists who could no longer remain in Germany. Those to whom Bohr gave refuge included Guido Beck, Felix Bloch, James Franck, George de Hevesy, Otto Frisch, Hilde Levi, Lise Meitner, George Placzek, Eugene Rabinowitch, Stefan Rozental, Erich Ernst Schneider, Edward Teller, Arthur von Hippel and Victor Weisskopf. Because of this, because of Bohr's dynamic and inspiring presence, and because he was able to continue the tradition of informality, enthusiasm and speed which characterized J.J. Thomson's Cavendish and Rutherford's Manchester laboratories, Bohr's institute became the world's most important center for theoretucl physics, especially during the 1930's.

Bohr was tirelessly energetic. He liked to discuss his ideas in dialogue with one of the bright young men at his institute, putting forward an idea, and expecting a counter-argument to be thrown back. It was like a game of ping-pong. In this way, a new idea could be tested by exploring all of its consequences.

When a new scientist arrived at his institute, Bohr liked to invite the newcomer to accompany him on a two-day walking tour to his summer house in Tisvilde, about 50 kilometers north of Copenhagen. In his autobiographical book "Physics and Beyond", Werner Heisenberg describes such a two-man tour together with Bohr. This custom allowed Bohr to get to know both the personality and the potential scientific contributions of the new arrival. It also allowed Bohr to get some exercise and to keep himself in good physical condition.

The Nazi occupation of Denmark

On 9 April, 1940, Nazi Germany invaded and quickly occupied Denmark. The Germans explained that their purpose was "to protect Denmark from a British invasion". During the first three years of occupation the Germans allowed the Danish government, police force and army to exist. However, in 1943, after extensive sabotage actions by the Danish resistance movement, the German policy changed and became much harsher.

Shortly after this sudden change, the Danes became aware that their Jewish population was in danger of being arrested and sent to concentration camps. Luckily it was possible for Danish citizens to organize a secret rescue operation, in which almost all members of Denmark's Jewish community escaped to Sweden in small boats. Among them were Niels Bohr and his son Aage.

Niels and Aage Bohr fly to England

After some time in Sweden, where he helped to organize aid for Jewish refugees from Denmark, Niels Bohr and his son Aage flew to England in a small aircraft. It flew at a high altitude in order to avoid observation. Niels Bohr's oxygen mask did not fit properly because of his unusually large head, and he became unconscious. Luckily this was noticed before anything very serious happened.

Figure 11.7: **The Institute of Theoretical Physics, established by Niels Bohr at the University of Copenhagen. Today it is known as the Niels Bohr Institute**

Figure 11.8: **Another view of the Niels Bohr Institute.**

Figure 11.9: **Aage Bohr (1922-2008), one of Niels and Margrethe Bohr's sons. Together with Ben Mottelson, he was awarded the 1975 Nobel Prize in Physics for developing a successful theory of the excited states of nuclei.**

Figure 11.10: **Ben Roy Mottelson (born in 1926), who shared the 1975 Nobel Prize in Physics with Aage Bohr. Although now very old, he still comes in to work at the Niels Bohr Institute.**

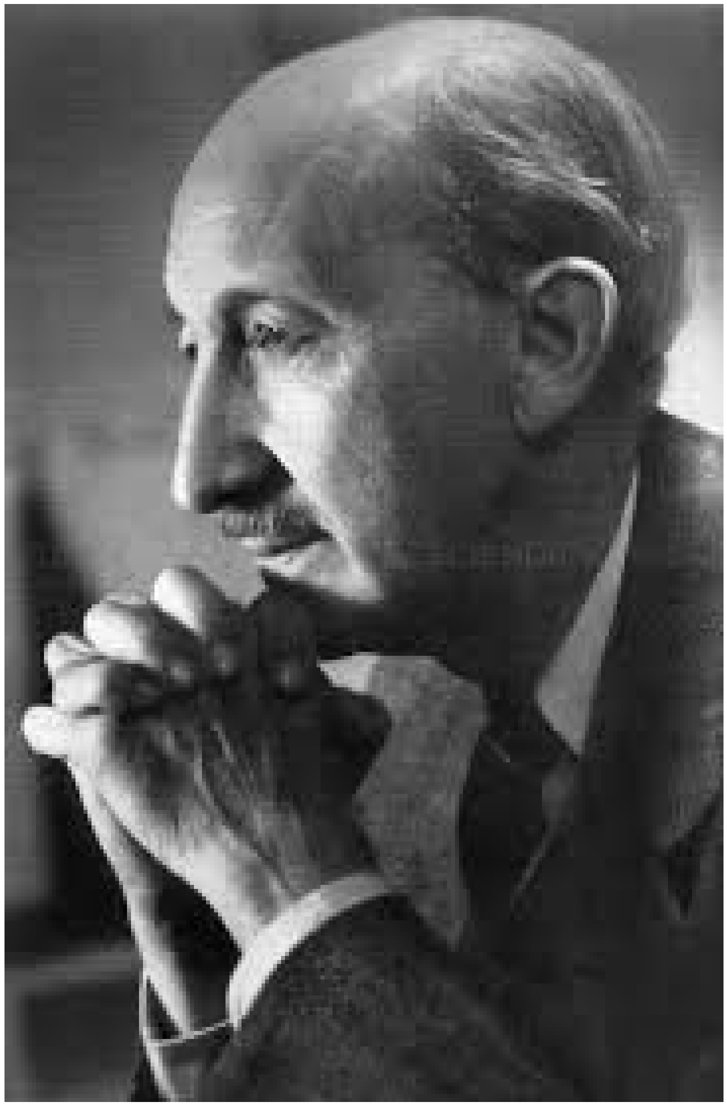

Figure 11.11: **George de Hevesy (1885-1966), co-discoverer of the element Haffnium, and pioneer of the use of radioactive tracer elements in biochemistry. He received the Nobel Prize in Chemistry in 1943 for work which he performed at the Niels Bohr Institute. The name "Haffnium" is derived from the Latin name for Copenhagen.**

11.5 Bohr anticipates the nuclear arms race

After escaping from Denmark to Sweden in a fishing boat in 1943, Niels Bohr and his son Aage flew to England, and then to Los Alamos in the United States, where work on a nuclear bomb was in progress. In 1943, a special intelligence unit called "Aslos" had been set up to determine how far German work on a nuclear bomb had progressed. Advanced units, entering mainland Europe after D-Day, intervied captured German scientists and found that the German program had never come near to producing a nuclear bomb.

The news that the Germans would not produce atomic bombs was classified as a secret. Nevertheless, it passed through the grapevine to the scientists working on the atomic bomb project in America; and it reversed their attitude to the project. Until then, they had been worried that Hitler would be the first to produce nuclear weapons. In 1944, they began to worry instead about what the American government might do if it came to possess such weapons.

At Los Alamos, Niels Bohr became the center of discussion and worry about the ethics of continued work on the bomb project. He was then 59 years old; and he was universally respected both for his pioneering work in atomic physics, and for his outstandingly good character.

Bohr was extremely worried because he foresaw a postwar nuclear arms race unless international control of atomic energy could be established. Consequently, as a spokesman for the younger atomic scientists, he approached both Roosevelt and Churchill to urge them to consider means by which international control might be established.

Roosevelt, too, was worried about the prospect of a postwar nuclear armaments race; and he was very sympathetic towards Bohr's proposals for international control. He suggested that Bohr travel to England and contact Churchill, to obtain his point of view.

Churchill was desperately busy, and basically unsympathetic towards Bohr's proposals; but on May 16, 1944, he agreed to a half-hour interview with the scientist. The meeting was a complete failure. Churchill and his scientific advisor, Lord Cherwell, spent most of the time talking with each other, so that Bohr had almost no time to present his ideas.

Although he could be very persuasive in long conversations, Bohr was unable to present his thoughts briefly. He wrote and spoke in a discursive style, similar to that of Henry James. Each of his long, convoluted sentences was heavily weighted with qualifications and dependent clauses. At one point in the conversation, Churchill turned to Lord Cherwell and asked: "What's he talking about, physics or politics?"

Bohr's low, almost whispering, way of speaking irritated Churchill. Furthermore, the two men were completely opposed in their views: Bohr was urging openness in approaching the Russians, with a view to establishing international control of nuclear weapons. Churchill, a defender of the old imperial order, was concerned mainly with maintaining British and American military supremacy.

After the interview, Churchill became worried that Bohr would give away "atomic secrets" to the Russians; and he even suggested that Bohr be arrested. However, Lord Cherwell explained to the Prime Minister that the possibility of making atomic bombs, as well as the basic means of doing so, had been common knowledge in the international scientific community ever since 1939.

After his disastrous interview with Churchill, Niels Bohr carefully prepared a memorandum to be presented to President Roosevelt. Realizing how much depended on its success or failure, Bohr wrote and rewrote the memorandum, sweating in the heat of Washington's summer weather. Aage Bohr, who acted as his father's secretary, typed the memorandum over and over, following his father's many changes of mind.

Finally, in July, 1944, Bohr's memorandum was presented to Roosevelt. It contains the following passages:

"...Quite apart from the question of how soon the weapon will be ready for use, and what role it will play in the present war, this situation raises a number of problems which call for urgent attention. Unless, indeed, some agreement about the control of the new and active materials can be obtained in due time, any temporary advantage, however great, may be outweighed by a perpetual menace to human society."

"Ever since the possibilities of releasing atomic energy on a vast scale came into sight, much thought has naturally been given to the question of control; but the further the exploration of the scientific problems is proceeding, the clearer it becomes that no kind of customary measures will suffice for this purpose, and that the terrifying prospect of a future competition between nations about a weapon of such formidable character can only be avoided by a universal agreement in true confidence..."

Roosevelt was sympathetic with the ideas expressed in this memorandum. In an interview with Bohr, he expressed his broad agreement with the idea of international control of atomic energy. Unfortunately, the President had only a few months left to live.

Roosevelt's successor, Harry Truman, had not known about the existence of nuclear weapons before taking office, and he was cautiously feeling his way. Meanwhile, General Leslie Groves, the military commander of the Los Alamos project, was very anxious to get credit for ending World War II, rather than being blamed for wasting billions of dollars of the taxpayers' money. It was easy for Groves to convince Truman to give the order to drop bombs on Hiroshima and Nagasaki. Thus Bohr's efforts to prevent this tragedy failed, and the postwar nuclear arms race which he anticipated still casts a dark shadow over the future of human civilization and the biosphere.

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Chapter 12

QUANTUM THEORY

12.1 A wave equation for matter

In 1926, the difficulties surrounding the "old quantum theory" of Max Planck, Albert Einstein and Niels Bohr were suddenly solved, and its true meaning was understood. Two years earlier, a French aristocrat, Louis de Broglie, writing his doctoral dissertation at the Sorbonne in Paris, had proposed that very small particles, such as electrons, might exhibit wavelike properties. The ground state and higher excited states of the electron in Bohr's model of the hydrogen atom would then be closely analogous to the fundamental tone and higher overtones of a violin string.

Almost the only person to take de Broglie's proposal seriously was Albert Einstein, who mentioned it in one of his papers. Because of Einstein's interest, de Broglie's matter-waves came to the attention of other physicists. The Austrian theoretician, Erwin Schrödinger, working at Zürich, searched for the underlying wave equation which de Broglie's matter-waves obeyed.

Schrödinger's gifts as a mathematician were so great that it did not take him long to solve the problem. The Schrödinger wave equation for matter is now considered to be more basic than Newton's equations of motion. The wavelike properties of matter are not apparent to us in our daily lives because the wave-lengths are extremely small in comparison with the sizes of objects which we can perceive. However, for very small and light particles, such as electrons moving in their orbits around the nucleus of an atom, the wavelike behavior becomes important.

Schrödinger was able to show that Niels Bohr's atomic theory, including Bohr's seemingly arbitrary quantization of angular momentum, can be derived by solving the wave equation for the electrons moving in the attractive field of the nucleus. The allowed orbits of Bohr's theory correspond in Schrödinger's theory to harmonics, similar to the fundamental harmonic and higher overtones of an organ pipe or a violin string. (If Pythagoras had been living in 1926, he would have rejoiced to see the deepest mysteries of matter explained in terms of harmonics!)

Bohr himself believed that a complete atomic theory ought to be able to explain the

Figure 12.1: **Bust of Erwin Schrödinger in the courtyard arcade of the main building, University of Vienna.**

chemical properties of the elements in Mendeléev's periodic system. Bohr's 1913 theory failed to pass this test, but the new de Broglie-Schrödinger theory succeeded! Through the work of Pauli, Heitler, London, Slater, Pauling, Hund, Mulliken, Hückel and others, who applied Schrödinger's wave equation to the solution of chemical problems, it became apparent that the wave equation could indeed (in principle) explain all the chemical properties of matter.

Strangely, the problem of developing the fundamental quantum theory of matter was solved not once, but three times in 1926! At the University of Göttingen in Germany, Max Born (1882-1970) and his brilliant young students Werner Heisenberg and Pascal Jordan solved the problem in a completely different way, using matrix methods. At the same time, a theory similar to the "matrix mechanics" of Heisenberg, Born and Jordan was developed independently at Cambridge University by a 24 year old mathematical genius named Paul Adrian Maurice Dirac. At first, the Heisenberg-Born-Jordan-Dirac quantum theory seemed to be completely different from the Schrödinger theory; but soon the Göttingen mathematician David Hilbert (1862-1943) was able to show that the theories were really identical, although very differently expressed.

12.2 Felix Bloch's story about Schrödinger

There is an interesting story about Erwin Schrödinger's derivation of his famous wave equation. According to the solid state physicist Felix Bloch, Peter Debye was chairing a symposium in Zürich, Switzerland, at which de Broglie's waves were being discussed. At one point during the symposium, Debye said: "Well, if there are waves associated with every particle, there must be a wave equation." Then, turning to Schrödinger, he said: "You, Erwin. You're not doing anything important at the moment. Why don't you find the wave equation obeyed by de Broglie's waves?"

During the following weekend, the whole group started off for a skiing trip. "Come with us, Erwin!", they said, but Schrödinger replied: "No, forgive me, I think I will stay here and work." By the end of the weekend he had derived his famous non-relativistic wave equation. He had first tried a relativistic equation (now known as the Klein-Gordon equation), but had rejected it because he believed that the equation had to be first-order in time.

Later, Felix Bloch asked Peter Debye, "Aren't you sorry that you didn't derive the wave equation yourself, instead of giving the job to Schrödinger?" Debye replied wistfully, "At least I was right about the need for a wave equation, wasn't I?"

12.3 Dirac's relativistic wave equation

In 1928, P.A.M. Dirac derived a relativistic wave equation that was first-order in time. To do this, he made use of a set of four anticommuting matrices. Solutions to the Dirac equation in the absence of external fields also obey the Klein-Gordon equation, which

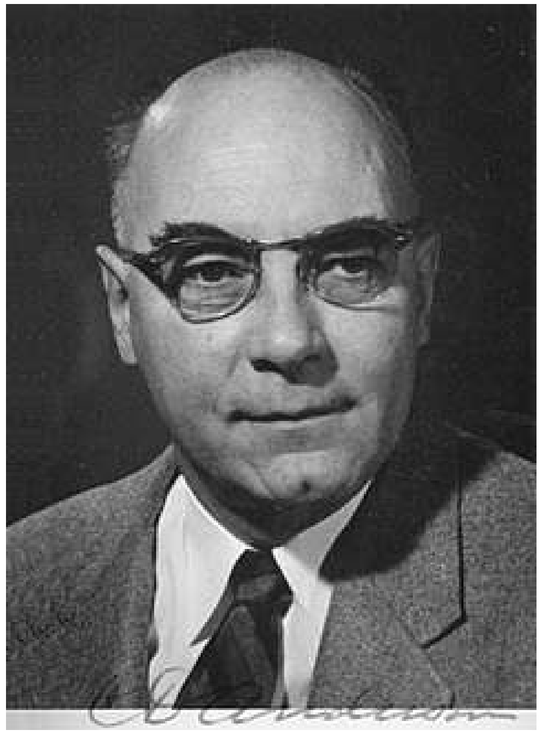

Figure 12.2: **Carl David Anderson in 1936.**

is second-order in time, the equation that Schrödinger first tried and then abandoned. Dirac's relativistic equation explained for the first time many details of the spectrum of hydrogen, but critics complained that it predicted the existence of negative energy states, and they asked, "Why don't the positive energy electrons fall down into these states?" Dirac replied "Because the negative energy states are all occupied." 'But then", the critics said, "an extremely energetic photon could create an electron-hole pair!" "Keep looking", Dirac answered, "and you will find that it sometimes happens." Thus, an astonishing consequence of Dirac's relativistic wave equation was the prediction of the existence of antimatter!

Years passed. Then, in 1932, the physicist Carl David Anderson observed in a cosmic ray photographic plate an event that confirmed Dirac's prediction of the existence of antimatter. A highly-energetic photon was annihilated, and converted into an electron-antielectron pair. The antielectron was given the name "positron". Since that time, the antiparticles of other particles have been discovered, created in high-energy events where a photon is annihilated and a particle-antiparticle pair created.

Figure 12.3: **Louis Victor Pierre Raymond, duc de Broglie, (1892-1987).**

Figure 12.4: **Heisenberg in 1933**

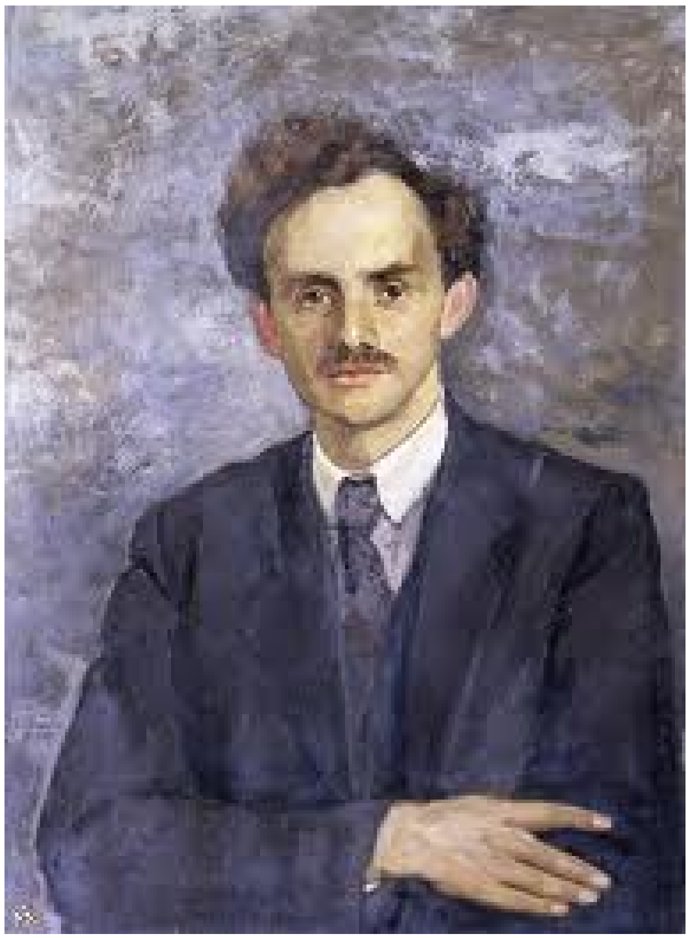

Figure 12.5: **P.A.M. Dirac, the greatest British physicist of the 20th century. A memorial inscribed with his relativistic wave equation stands in Westminister Cathedral, near to the statue of Newton.**

Figure 12.6: **Niels Bohr, Werner Heisenberg and Wolfgang Pauli, c. 1935.**

Figure 12.7: **Peter Debye, (1884-1966).**

12.4 Some equations

For readers with some mathematematical background, a few equations are included here.

The relativistic relationship between energy and momentum

$$E^2 - p^2c^2 = m^2c^4 \tag{12.1}$$

Here E stands for energy, p for momentum, m for mass, and c for the velocity of light.

The Klein-Gordon equation

$$\left(-\frac{\hbar^2}{c^2}\frac{\partial^2}{\partial^2 t} + \hbar^2\nabla^2\right)\psi = m^2c^2\psi \tag{12.2}$$

The Klein-Gordon equation can be derived from equation 12.1 by making the substitutions

$$\begin{aligned} E &\rightarrow \frac{\hbar}{i}\frac{\partial}{\partial x_4} \qquad x_4 \equiv ict \\ p_j &\rightarrow \frac{\hbar}{i}\frac{\partial}{\partial x_j} \qquad j = 1, 2, 3 \end{aligned} \tag{12.3}$$

where $\hbar$ is Planck's constant.

Schrödinger's non-relativistic wave equation

The non-relativistic relationship between energy and momentum is given by

$$E = c\sqrt{p^2 + m^2c^2} + V \approx \frac{p^2}{2m} + V \qquad m^2c^2 >> p^2 \tag{12.4}$$

Schrödinger's non-relativistic wave equation,

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V\right)\psi = E\psi \tag{12.5}$$

can be derived by making the substitutions

$$p_j \rightarrow \frac{\hbar}{i}\frac{\partial}{\partial x_j} \qquad j = 1, 2, 3 \tag{12.6}$$

If the wave function ψ has time-dependence of the form

$$\psi(\mathbf{x}, t) = \psi(\mathbf{x})e^{iEt/\hbar} \tag{12.7}$$

then we can write

$$i\hbar\frac{\partial\psi}{\partial t} = H\psi \tag{12.8}$$

where

$$H \equiv \left(-\frac{\hbar^2}{2m}\nabla^2 + V\right) \tag{12.9}$$

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Chapter 13

FERMI

13.1 Artificial transmutations

During the First World War, Rutherford's young men had joined the army, and he had been forced to spend most of his own time working on submarine detection. In spite of this, he had found some spare time for his scientific passion - bombarding matter with alpha particles. Helped by his laboratory steward, Kay, Rutherford had studied the effects produced when alpha particles from a radium source struck various elements. In a letter to Niels Bohr, dated December 9, 1917, Rutherford wrote:

"I have got, I think, results that will ultimately have great importance. I wish that you were here to talk matters over with me. I am detecting and counting the lighter atoms set in motion by alpha particles, and the results, I think, throw a good deal of light on the character and distribution of forces near the nucleus... I am trying to break up the atom by this method. In one case, the results look promising, but a great deal of work will be required to make sure. Kay helps me, and is now an expert counter. Best wishes for a happy Christmas."

In July, 1919, Bohr was at last able to visit Manchester, and he heard the news directly from his old teacher: Rutherford had indeed produced artificial nuclear transmutations! In one of his experiments, an alpha-particle (i.e. a helium nucleus with nuclear charge 2) was absorbed by a nitrogen nucleus. Later, the compound nucleus threw out a proton with charge 1; and thus the bombarded nucleus gained one unit of charge. It moved up one place in the periodic table and became an isotope of oxygen.

Bohr later wrote: "I learned in detail about his great new discovery of controlled, or so-called artificial, nuclear transmutations, by which he gave birth to what he liked to call 'modern Alchemy', and which in the course of time, was to give rise to such tremendous consequences as regards man's mastery of the forces of nature."

Other scientists rushed to repeat and extend Rutherford's experiments. Particle accelerators were built by E.O. Lawrence (1901-1958) in California, by J.H. van de Graff (1901-1967) at the Massachusetts Institute of Technology and by John Cockcroft (1897-1967), working with Rutherford at the Cavendish Laboratory. These accelerators could hurl protons at energies of a million electron-volts. Thus, protons became another type of projectile which could be used to produce nuclear transmutations.

13.2 Neutrons

During the 1920's, nuclear transmutations could be achieved only with light elements. The charges on the nuclei of heavy elements were so large that, with the energies available, alpha particles and protons could not react with them. The positively charged projectiles were kept at a distance by the electrostatic repulsion of the heavy nuclei: They could not come close enough for the powerful but short-range nuclear attractive forces to become effective. However, in 1932, a new projectile was discovered - a projectile which was destined to unlock, with grave consequences, the colossal energies of the heavy nuclei. This new projectile was the neutron.

Rutherford and Bohr had for some time suspected that an electrically neutral particle with roughly the same mass as a proton might exist. The evidence for such a particle was as follows: Each isotope was characterized by a nuclear charge and by a nuclear weight. The nuclear charge was an integral multiple of the proton charge, while the nuclear weight was approximately an integral multiple of the proton weight. For example, the isotope carbon-12 had charge 6 and weight 12. This might be explained by supposing the carbon-12 nucleus to be composed of twelve protons and six electrons. However, there were theoretical objections to a model in which many electrons were concentrated within the tiny volume of a nucleus. Therefore, in 1920, Rutherford postulated the existence of neutrons - elementary particles with almost the same mass as protons, but no electrical charge. Then (for example) the carbon-12 nucleus could be thought of as being composed of six protons and six neutrons.

In 1930, the German physicist, Walter Bothe (1891-1957), discovered a strange, penetrating type of radiation coming from beryllium which had been bombarded with alpha particles. In 1931 and 1932, Bothe's experiments were repeated in Paris by Irène Joliot-Curie (1897-1956) and her husband Frédéric (1900-1958). The Joliot-Curies noticed that the mysterious rays emanating from the bombarded beryllium could easily penetrate lead. They also noticed that when the rays hit a piece of paraffin, hydrogen nuclei were knocked out.

The strange rays were, in fact, neutrons, as the Joliot-Curies would have realized immediately if they had been familiar with Rutherford's prediction of the neutron's existence. The Joliot-Curies might have made the correct identification of the rays given time; but Rutherford's assistant, James Chadwick (1891-1974), was faster. On February 17, 1932, he published a paper in *Nature* reporting a series of experiments:

Chadwick had studied not only the velocities of the hydrogen nuclei knocked out of paraffin by Bothe's rays but also the velocities of nuclei knocked out of many other materials. In every case, he found that the velocities were consistent with the identification of the rays as neutrons. Chadwick completed his proof by showing that the rays moved with one-tenth the velocity of light, so that they had to be material particles rather than

Figure 13.1: **Irène Joliot-Curie as a child, with her parents, Pierre and Marie Curie. Although she and her husband Frèdèric narrowly missed discovering the neutron, they soon made another discovery of major importance - artificial radioactivity. Public domain, Wikimedia Commons**

radiation; and he showed that the rays could not be deflected by a magnet. Therefore they carried no charge.

13.3 Fermi studies artificial radioactivity

Although Irène and Frédéric Joliot-Curie narrowly missed discovering the neutron, they soon made another discovery of major importance - artificial radioactivity. The Joliot-Curies had been bombarding an aluminum target with alpha-particles and studying the resulting radiation. One day in 1934, they noticed to their astonishment that the aluminum target continued to radiate even after they had stopped the alpha-particle bombardment. They discovered that some of the aluminum atoms in the target had been converted to a radioactive isotope of phosphorus!

In 1934, news of the startling discoveries of Bothe, Chadwick and the Joliot-Curies reached a brilliant young professor of theoretical physics in Rome. Although he was only 33 years old, Enrico Fermi (1901-1954) already had a worldwide reputation for his work in quantum theory. He also had attracted a school of extremely talented young students, the first physicists in Italy to enter the new fields of quantum mechanics and relativity: Persico, Amaldi, Rasetti, Segrè, Pontecorvo, Majorana, Racah and Wick. It was a happy, informal group of young men.

Because of his reputation for scientific infallibility, Enrico Fermi was nicknamed "the

Pope", while Franco Rasetti was "the Cardinal" and Emilio Segrè was "the Basilisk". A medical colleague, Professor Trabacci, who generously supplied the group with equipment and chemicals, was known as "the Divine Providence".

In 1934, Fermi was feeling somewhat discouraged with theoretical work, and in the mood to try something new. His paper on the theory of beta-decay (later regarded as one of his major achievements) had just been rejected by *Nature*. At that moment, he heard of Chadwick's neutrons and the Joliot-Curie's artificial radioactivity. Putting the two things together, Fermi decided to try to produce artificial radioactivity by bombarding elements with neutrons.

There were good theoretical reasons why Fermi's plan should work, as well as practical reasons why it should fail. The argument in favor of neutrons was that they had no charge. Therefore they should be able to approach the nuclei of even heavy elements without being repelled by the electrostatic potential. The practical argument against neutrons was that it was difficult to produce them in worthwhile numbers. The yield of neutrons was only one for every hundred thousand alpha-particles.

Although he had no experience in working with radioactivity, Fermi managed to make his own Geiger counter. He also made a neutron source for himself by condensing radon gas (donated by "the Divine Providence") into a small glass tube of powdered beryllium held at liquid air temperature.

Being a methodical person, Fermi began at the bottom of the periodic table and worked systematically upwards. The first eight elements which he bombarded with neutrons showed no artificial radioactivity, and Fermi almost became discouraged. Finally, he came to fluorine, and to his delight, he succeeded in making it strongly radioactive by neutron bombardment. He succeeded also with several other elements beyond fluorine; and realizing that the line of research was going to be very fruitful, he enlisted help from Segrè, Amaldi, and the chemist, d'Agostino. Fermi also sent a cable to Franco Rasetti, who was on vacation in Morocco.

In order that the source should not disturb the measurements, the room where the elements were irradiated was far from the room where their radioactivity was measured - at the other end of a long corridor. The half-life of the induced radioactivity was very short in some elements, which meant that Fermi and Amaldi had to run full tilt with their samples, from one end of the hallway to the other.

One day a visitor arrived from Spain and asked to see *"Sua Eccellenza Fermi"*. (Fermi was a member of the Royal Academy of Italy, and therefore had the title "Excellency", which much embarrassed him). "The Pope is upstairs", said Segrè, and then, realizing that the visitor did not know this nickname, he added: "I mean Fermi, of course." The Spanish visitor arrived on the second floor of the institute just in time to see *"Sua Eccellenza Fermi"* dash wildly down the length of the corridor.

After this fashion, Fermi and his group finally reached the top of the periodic table. They carefully purified uranium from its disintegration products and bombarded it with neutrons. A new radioactivity was induced, quite different from the ordinary activity of uranium. The question was: to what element or elements had the uranium been converted?

With the help of the chemist, d'Agostino, they analyzed the uranium target, and proved

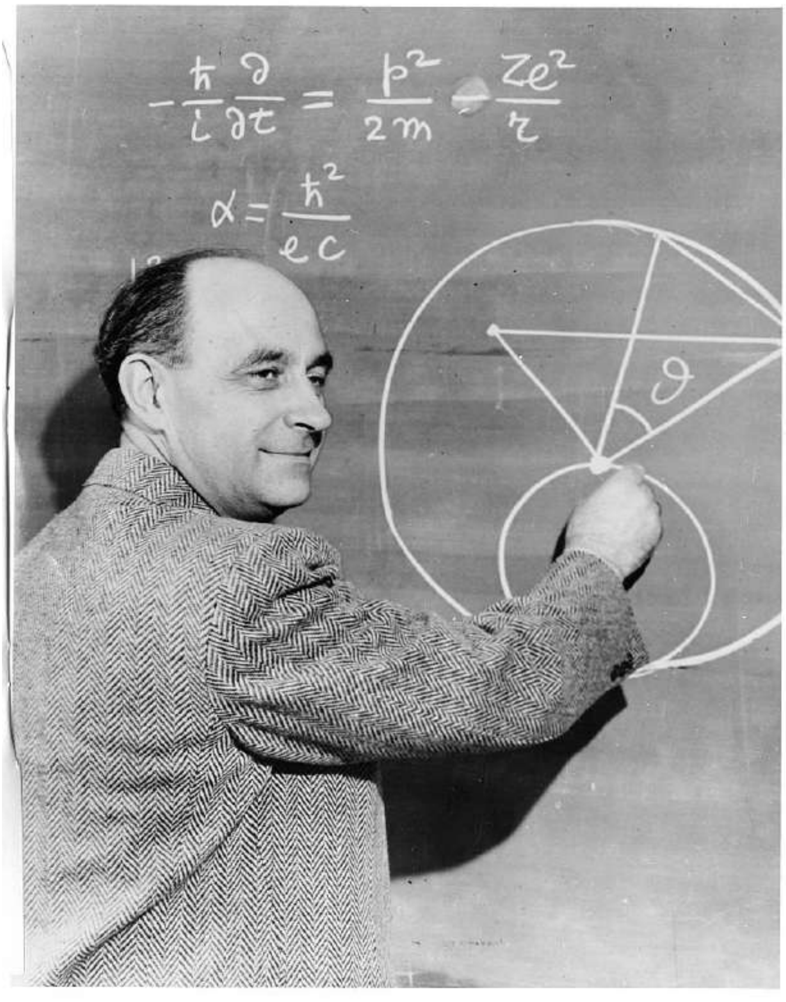

Figure 13.2: **Enrico Fermi at the blackboard. Public domain, Wikimedia Commons**

definitely that neutron bombardment had not converted uranium to any of the nearby heavy elements at the top of the periodic table. It seemed most likely that what they had produced by bombarding uranium was a new, unstable element, which had never before existed - element number 93! However, they lacked definite proof; and Fermi, always cautious, refused to jump to such a sensational conclusion.

By this time, the summer of 1934 had begun. The university year ended, as was traditional, with a meeting of the Academia dei Lincei, attended by the King of Italy. In 1934, the speaker at this meeting was Senator Corbino, who had been a talented physicist before he became a politician. Corbino had been responsible for raising money to support Fermi's group of young physicists; and he was justly proud of what they had achieved. In his 1934 speech before the king, Senator Corbino glowingly described their production of neutron-induced radioactivity; and he ended the speech with the words:

"The case of uranium, atomic number 92, is particularly interesting. It seems that, having absorbed the neutron, it converts rapidly by emission of an electron, into the element one place higher in the periodic system, that is, into a new element having atomic number 93... However, the investigation is so delicate that it justifies Fermi's prudent reserve and a continuation of the experiments before an announcement of the discovery. For what my own opinion on this matter is worth, and I have followed the investigations daily, I believe that production of this new element is certain."

Corbino had not cleared this announcement with Fermi. It was immediately picked up by both the Italian and international press and given great publicity. A new element had been made by man! The official newspapers of fascist Italy, in particular, made much of this "great discovery" which, they claimed, showed that Italy was regaining the glorious position which it had held in the days of the Roman Empire.

Fermi was thrown into a mood of deep despair by this premature publicity. He could not sleep, and woke his wife in the middle of the night to tell her that his reputation as a scientist was in jeopardy. Next morning, Fermi and Corbino prepared a statement attempting to halt the publicity: "The public is giving an incorrect interpretation to Senator Corbino's speech... Numerous and delicate tests must still be performed before the production of element 93 is actually proved."

Before the question of element 93 could be cleared up, the attention of Fermi's group was distracted by an accidental discovery of extreme importance. They had been obtaining inconsistent and inexplicable results. The radioactivity induced in a sample depended in what seemed to be a completely illogical way on the conditions under which the experiment was performed. For example, if the target was bombarded with neutrons while standing on a wooden table, the induced activity was much stronger than when the target was on a marble table.

Fermi suspected that these strange results were due to scattering of neutrons by surrounding objects. He prepared a lead wedge to insert between neutron source and the counter to measure the scattering. However, he did not use the lead wedge which he had so carefully prepared.

"I was clearly dissatisfied with something", Fermi remembered later, "I tried every excuse to postpone putting the piece of lead in its place. I said to myself, 'No, I do not want this piece of lead here; what I want is a piece of paraffin.' It was just like that, with no advance warning, no prior reasoning. I immediately took some odd piece of paraffin and placed it where the piece of lead was to have been."

The effect of the paraffin was amazing. The radioactivity increased a hundredfold! Puzzled, the group adjourned for lunch and siesta. When they reassembled a few hours later, Fermi had developed a theory to explain what was happening: The neutrons had almost the same mass as the hydrogen atoms in the paraffin. When they collided with the hydrogen atoms, the neutrons lost almost all their energy of motion, just as a billiard ball loses almost all its speed when it collides with another ball of equal mass. What Fermi and the others had discovered by accident was that slow neutrons are much more effective than fast ones in producing nuclear reactions.

"What we need", said Fermi, "is a large amount of water." The group excitedly took the neutron source and targets to Senator Corbino's nearby garden, where there was a goldfish pond. The hydrogen-containing water of the pond produced the same result: It slowed the neutrons, and greatly enhanced their effect.

That evening, at Edouardo Amaldi's house, they prepared a paper reporting their discovery. Fermi dictated, while Segrè wrote. Meanwhile, Rasetti, Amaldi and Pontecorvo walked up and down, all offering suggestions simultaneously. They made so much noise that when they left, the maid asked Mrs. Amaldi whether her guests had been drunk.

The happy and carefree days of the little group of physicists in Rome were coming to an end. They had thought that they could isolate themselves from politics; but in 1935, it became clear that this was impossible.

One day, in 1935, Segrè said to Fermi: "You are the Pope, and full of wisdom. Can you tell me why we are now accomplishing less than a year ago?"

Fermi answered without hesitation: "Go to the physics library. Pull out the big atlas that is there. Open it. You shall find your explanation." When Segrè did this, the atlas opened automatically to a much-thumbed map of Ethiopia.

In 1935, Mussolini's government had attacked Ethiopia, and Italy had been condemned by the League of Nations. For thinking Italians, this shock revealed the true nature of Mussolini's government. They could no longer ignore politics. Within a few years, Enrico Fermi and most of his group had decided that they could no longer live under the fascist government of Italy. By 1939, most of them were refugees in the United States.

13.4 Hahn, Meitner and Frisch

Without knowing it, Enrico Fermi and his group had split the uranium atom; but four years were to pass before this became apparent. All the experts agreed that Fermi's group had undoubtedly produced transuranic elements. There was only one dissenting voice - that of the German chemist, Ida Noddack, who was an expert in the chemistry of rare elements. Knowing no nuclear physics, but a great deal of chemistry, Ida Noddack saw the problem from a different angle; and in 1934 she wrote:

"It would be possible to assume that when a nucleus is demolished in this novel way by neutrons, nuclear reactions occur which may differ considerably from those hitherto observed in the effects produced on atomic nuclei by protons and alpha rays. It would be conceivable that when heavy nuclei are bombarded with neutrons, the nuclei in question might break into a number of larger pieces, which would, no doubt, be isotopes of known elements, but not neighbors of the elements subjected to radiation."

No one took Ida Noddack's suggestion seriously. The energy required to smash a heavy nucleus into fragments was believed to be so enormous that it seemed ridiculous to suggest that this could be accomplished by a slow neutron.

Many other laboratories began to bombard uranium and thorium with slow neutrons to produce "transuranic elements". In Paris, Irène Joliot-Curie and Paul Savitch worked on this problem, while at the Kaiser Wilhelm Institute in Berlin, Otto Hahn (1879-1968), Lise Meitner (1878-1968) and Fritz Strassmann (1902-) did the same.

Meanwhile, night was falling on Europe. In 1929, an economic depression, caused in part by the shocks of the First World War, began in the United States; and it soon spread to Europe. Without the influx of American capital, the postwar reconstruction of the German economy collapsed. The German middle class, which had been dealt a severe blow by the great inflation of 1923, now received a second heavy blow. The desperation produced by economic chaos drove the German voters into the hands of political extremists.

On January 30, 1933, Adolf Hitler was appointed Chancellor and leader of a coalition cabinet by President Hindenburg. Although Hitler was appointed legally to this post, he quickly consolidated his power by unconstitutional means: On May 2, Hitler's police seized the headquarters of all trade unions, and arrested labor leaders. The Communist and Socialist parties were also banned, their assets seized and their leaders arrested. Other political parties were also smashed. Acts were passed eliminating Jews from public service; and innocent Jewish citizens were boycotted, beaten and arrested.

On March 11, 1938, Nazi troops entered Austria. Lise Meitner, who was working with Otto Hahn in Berlin, was a Jew, but until Hitler's invasion of Austria, she had been protected by her Austrian citizenship. Now, she was forced to escape from Germany. Saying goodbye only to Otto Hahn and to a few other close friends, she went to Holland for a vacation, from which she did not plan to return. From there, she went to Stockholm, where she had been offered a post by the Nobel Institute.

Meanwhile, Hahn and Strassmann continued to work on what they believed to be production of transuranic elements. They had been getting results which differed from those of the Paris group, but they believed that Irène Joliot-Curie must be mistaken. When Strassmann tried to show Hahn one of the new papers from Paris, he continued to puff calmly on his cigar and replied: "I am not interested in our lady-friend's latest writings". However, Strassmann would not be deterred, and he quickly summarized the most recent result from Paris.

"It struck Hahn like a thunderbolt", Strassmann said later, "He never finished that cigar. He laid it down, still glowing, on his desk, and ran downstairs with me to the laboratory."

Hahn and Strassmann quickly repeated the experiments which Irène Joliot-Curie had reported. They now suspected that one of the products which she had produced was actually an isotope of radium. Since radium has almost the same chemical properties as barium, they tried precipitating it together with a barium carrier. This procedure worked: The new substance came down with the barium.

Otto Hahn was the most experienced radiochemist in the world, and many years previously he had developed a method for separating radium from barium. He and Strassmann now tried to apply this method. It did not work. No matter how they tried, they could not separate the active substance from barium.

Could it be that an isotope of barium had been produced by bombarding uranium with neutrons? Impossible! It would mean that the uranium nucleus had split roughly in half, against all the well-established rules of nuclear physics. It could not happen - and yet their chemical tests told them again and again that the product really was barium. Finally, they sat down and wrote a paper:

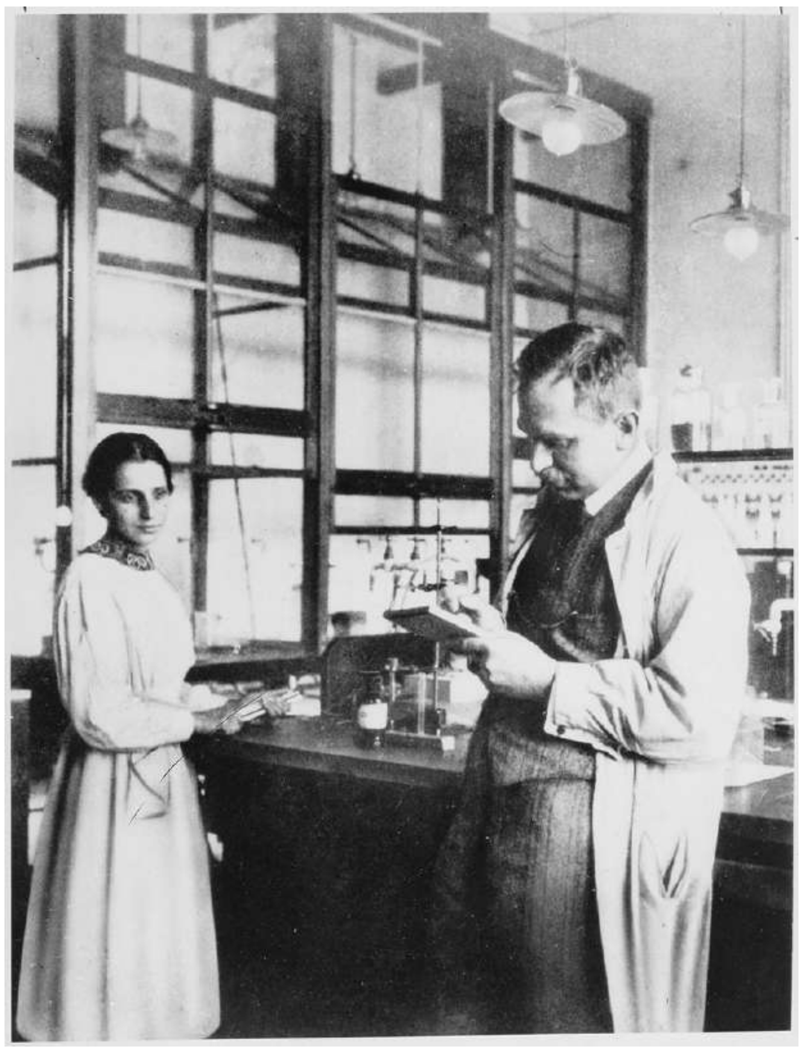

Figure 13.3: **Otto Hahn and Lise Meitner. Public domain, Wikimedia Commons**

"We come to this conclusion", Hahn and Strassmann wrote, "Our 'radium' isotopes have the properties of barium. As chemists, we are in fact bound to affirm that the new bodies are not radium but barium; for there is no question of elements other than radium and barium being present... As nuclear chemists, we cannot decide to take this step, in contradiction to all previous experience in nuclear physics."

On December 22, 1938, Otto Hahn mailed the this paper to the journal, *Naturwissenschaften*. "After the manuscript was mailed", he said later, "the whole thing seemed so improbable to me that I wished I could get the document back out of the mail box."

After making this strange discovery, Otto Hahn's first act had been to write to Lise Meitner, who had worked by his side for so many years. She received his letter just as she was starting for her Christmas vacation, which was to be spent at the small Swedish town of Kungälv, near Göteborg.

It was even more clear to Lise Meitner than it had been to Hahn that something of tremendous importance had unexpectedly come to light. As it happened, Lise Meitner's nephew, O.R. Frisch, had come to Kungälv to spend Christmas with his aunt, hoping to keep her from being lonely during her first Christmas as a refugee. Frisch was a physicist, working at Niels Bohr's institute in Copenhagen. He was one of the many scientists whom Bohr saved from the terror and persecution of Hitler's Germany by offering them refuge in Copenhagen.

When Frisch arrived, Lise Meitner immediately showed him Otto Hahn's letter. "I wanted to discuss with her a new experiment I was planning", Frisch said later, "but she wouldn't listen. I had to read the letter. Its content was indeed so startling that I was at first inclined to be sceptical."

Frisch put on his skis, and went out to get some air; but his aunt followed him over the snow, insisting that he think about the problem of uranium and barium. Lise Meitner knew the precision and thoroughness of Otto Hahn's methods so well that she could not imagine him making a mistake of that kind. If Hahn said that bombarding uranium with neutrons produced barium, then it *did* produce barium. She insisted that her nephew should try to explain this impossible result, rather than shrugging it off as an error.

Finally, aunt and nephew sat down on a log in the middle of the snow-filled Swedish forest and tried to make some calculations on the back of an envelope. They continued their calculations back at their hotel, consulting some tables of isotopic masses which Frisch had brought with him. Gradually, they formed a picture of what had happened:

The uranium nucleus was like a liquid drop. Although the powerfully attractive short-range nuclear forces produced a surface tension which tended to keep the drop together, there were also powerful electrostatic repulsive forces which tended to make it divide. Under certain conditions, the nucleus could become non-spherical in shape, with a narrow waist. If this happened, the electrostatic repulsion would split the nucleus into two fragments, and would drive the fragments apart with tremendous energy of motion.

Frisch and Meitner calculated that for a single uranium nucleus, the energy of motion would be roughly two hundred million electron volts. What was the source of this gigantic energy? By consulting tables of isotopic masses, the two scientists were able to show that in the splitting of uranium, a large amount of the mass is converted to energy. If one of the fragments was an isotope of barium, the other had to be an isotope of krypton. Using Einstein's formula relating energy to mass, they found that the lost mass was exactly equivalent to two hundred million electron volts. Everything checked. This had to be the explanation.

Meitner and Frisch were struck by the colossal size of the energy released in the fission of uranium. Ordinary combustion releases one or two electron volts per atom. They realized with awe that in the fission of uranium, a hundred million times as much energy is released!

When O.R. Frisch returned to Copenhagen, Niels Bohr was preparing to leave for a lecture tour in America. Frisch had only a few minutes to tell him what had happened, but Bohr was quick to understand. "I had hardly begun to tell him", Frisch said later, "when he struck his forehead and exclaimed, 'Oh what idiots we all have been! But this is wonderful! This is just as it must be!'"

There was no time to talk, but as Niels Bohr entered the taxi which would take him to the liner, *Drottningholm*, he asked Frisch whether he had written a paper. Frisch handed some rough notes to Bohr, and said that he would write a paper immediately. Bohr promised that he would not talk about the new discovery until the paper was ready.

Bohr's assistant, Rosenfeld, had accompanied him on the trip, and the long sea voyage to New York gave the two physicists a good opportunity to think about the revolutionary new discovery of nuclear fission. A blackboard was installed in Bohr's stateroom on the *Drottningholm*. Bohr and Rosenfeld covered this blackboard with calculations, and by the end of the voyage, they were convinced that Otto Frisch and Lise Meitner had correctly analyzed the problem of nuclear fission.

At the harbor in New York, they were met by Professor John Wheeler of Princeton, together with Enrico Fermi and his wife, Laura, who had become refugees in America. Laura Fermi remembered later the tense and worried expression with which Bohr described the rapidly-deteriorating political situation in Europe. With her imperfect knowledge of English and the noise of the pier, she could only make out a few of the words - "Europe - war - Hitler - danger".

Rosenfeld accompanied Wheeler to Princeton, while Bohr and his 19 year old son, Erik, remained a few days in New York. At Princeton, Rosenfeld was invited to address the "Journal Club", a small, informal group of physicists. Bohr had neglected to tell Rosenfeld that he had promised not to talk about nuclear fission until the Hahn-Strassmann and Meitner-Frisch papers were out; and Rosenfeld spoke about the revolutionary new discovery to the physicists at Princeton.

The news spread with explosive speed. Telephone calls and letters went out to other parts of America. The physicist, I.I. Rabi, who happened to be at Princeton, returned to Colombia University, where Fermi was working, and told him the news. Fermi acted with characteristic speed and decisiveness. He devised an experiment to detect the high-energy fragments produced by uranium fission; and he suggested to his co-worker, Dunning, that the experiment should be performed as fast as possible. Fermi himself had to leave for a theoretical physics meeting in Washington, where Bohr would be present.

When Bohr heard that Rosenfeld had talked about fission, he was very upset, because he had promised Frisch to remain silent until the papers were out. He sent a telegram to

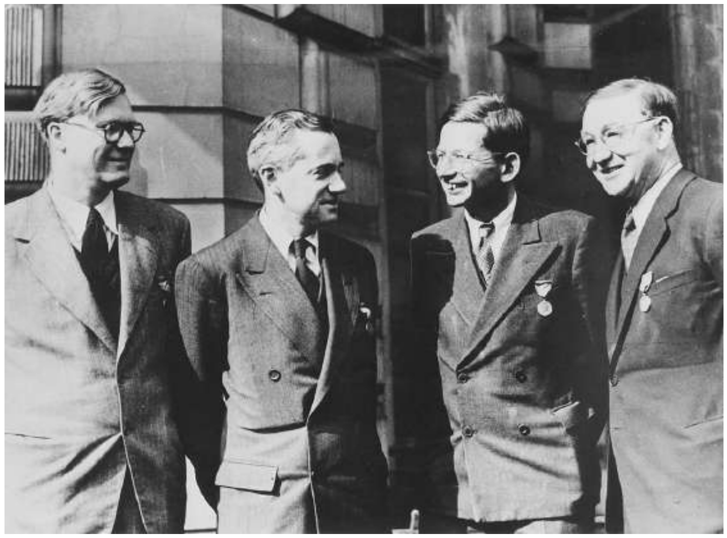

Figure 13.4: **Left to right: William Penney, Otto Frisch, Rudolf Peierls and John Douglas Cockcroft. Public domain, Wikimedia Commons**

Copenhagen urging Frisch to hurry with his manuscript, and urging him to perform an experiment to detect the fission fragments.

In fact, Otto Frisch had already performed this experiment, using a radium-lined ionization chamber containing a radium-beryllium neutron source. An amplifier connected with the chamber had shown giant bursts of ionization, which could only be due to the immensely energetic fission fragments.

On January 16, 1939, the same day that Rosenfeld had revealed the news about fission to the physicists at Princeton, Otto Frisch had mailed two papers to *Nature*. The first of these papers presented the theory of nuclear fission which he and Lise Meitner had developed, while the second described his experimental detection of the high-energy fragments.

On January 26, Bohr and Fermi arrived at the American capital to attend the Fifth Washington Conference on Theoretical Physics. The same day, Erik Bohr received a letter from his brother, Hans. The letter contained the news that Frisch had completed his experiment and had sent the paper to London. Simultaneously, Bohr learned from a reporter who was covering the conference that the Hahn-Strassmann paper had just been published in *Naturwissenschaften*. At last, Bohr felt free to speak. He asked the chairman whether he might make an announcement of the utmost importance; and he told the astonished physicists the whole story.

While Bohr was speaking, Dr. Tuve of the Carnegie Institution whispered to his colleague, Halfstead, that he should quickly put a new filament in the Carnegie accelerator. Several physicists rushed for the door to make long-distance telephone calls. Fermi decided to leave the conference immediately, and to return to New York. On the way out, Fermi met Robert B. Potter, a reporter from *Science Service*, who asked: "What does it all mean?" Fermi explained as well as he could, and Potter wrote the following story, which was released to newspapers and magazines:

"New hope for releasing the enormous energy within the atom has arisen from German experiments that are now creating a sensation among eminent physicists gathered here for the Conference on Theoretical Physics. It is calculated that only five million electron volts of energy can release two hundred million electron volts of energy, forty times the amount shot into it by a neutron (neutral atomic particle). World famous Niels Bohr of Copenhagen and Enrico Fermi of Rome, both Nobel Prize winners, are among those who acclaim this experiment as one of the most important in recent years. American scientists join them in this acclaim."

13.5 Chain reactions

Within hours of Bohr's announcement, scientists in various parts of America had begun to set up experiments to look for high-energy fission fragments. On the evening of January 26, Bohr watched, while giant pulses of ionization produced by the fission fragments were recorded on an oscilloscope at the Carnegie Institution's accelerator in Washington. Similar experiments were simultaneously being performed in New York and California.

At Columbia University, following Fermi's suggestion, Dunning had performed the experiment a day earlier, on January 25. The news spread rapidly. On the 9th of February, the Austrian physicists, Jentschke and Prankl, reported to the Vienna Academy that they too had observed fission fragments. By March 8, which was Otto Hahn's 60th birthday, an avalanche of papers on uranium fission had developed in the international scientific literature.

In the spring of 1939, Bohr and Wheeler published an important theoretical paper in which they showed that in nuclei with an even atomic mass numbers, the ground state energy is especially low because of pairing of the nuclear particles. For this reason, Bohr and Wheeler believed that it is the rare isotope, uranium-235, which undergoes fission. They reasoned that when a slow neutron is absorbed by uranium-235, it becomes a highly-excited state of uranium-236. The extra energy of this excited state can deform the nucleus into a non-spherical shape, and the powerful electrostatic repulsive forces between the protons can then cause the nucleus to split.

During the early spring of 1939, a number of scientists, including Fermi, Szilard and the Joliot-Curies, were becoming acutely aware of another question: Are neutrons produced in uranium fission? This was a question of critical importance, because if more than one neutron was produced, a chain reaction might be possible.

At Columbia University, Enrico Fermi and Leo Szilard began experiments to determine whether neutrons are produced; and similar experiments were performed by the Joliot-Curies in Paris. Both groups found that roughly two neutrons are released. This meant that a nuclear chain reaction might indeed be possible: It might be possible to arrange the uranium in such a way that each neutron released by the fission of a nucleus would have a good chance of causing a new fission.

The possibility of nuclear power became clear to the physicists, as well as the possibility of a nuclear bomb many millions of times more powerful than any ordinary bomb. Leo Szilard (who had seen the atrocities of Hitler's Germany at close range) became intensely worried that the Nazis would develop nuclear weapons. Therefore he proposed that the international community of physicists should begin a self-imposed silence concerning uranium fission, and especially concerning the neutrons produced in fission.

In Fermi's words, Szilard "..proceeded to startle physicists by proposing to them that, given the circumstances of the period - you see it was early 1939, and war was very much in the air - given the circumstances of the period, given the danger that atomic energy, and possibly atomic weapons, could become the chief tool of the Nazis to enslave the world, it was the duty of the physicists to depart from what had been the tradition of publishing significant results as soon as the *Physical Review* or other scientific journals might turn them out, and that instead one had to go easy, keep back some of the results until it was clear whether these results were potentially dangerous..."

"He sent in this vein a number of cables to Joliot in France, but he did not get a favorable response from him; and Joliot published his results more or less like results in physics had been published until that day. So the fact that neutrons are emitted in fission in some abundance - the order of magnitude one or two or three - became a matter of general knowledge; and of course that made the possibility of a chain reaction appear to most physicists as a vastly more real possibility than it had until that time."

On March 16, 1939, exactly two months after Bohr had arrived in America, he and Wheeler mailed their paper on uranium fission to a journal. On the same day, Enrico Fermi went to Washington to inform the Office of Naval Operations that it might be possible to construct an atomic bomb; and on the same day, German troops poured into Czechoslovakia.

A few days later, a meeting of six German atomic physicists was held in Berlin to discuss the applications of uranium fission. Otto Hahn, the discoverer of fission, was not present, since it was known that he was opposed to the Nazi regime. He was even said to have exclaimed: "I only hope that you physicists will never construct a uranium bomb! If Hitler ever gets a weapon like that, I'll commit suicide."

The meeting of German atomic physicists was supposed to be secret; but one of the participants reported what had been said to Dr. S. Flügge, who wrote an article about uranium fission and about the possibility of a chain reaction. Flügge's article appeared in the July issue of *Naturwissenschaften*, and a popular version of it was printed in the *Deutsche Allgemeine Zeitung*. These articles greatly increased the alarm of American atomic scientists, who reasoned that if the Nazis permitted so much to be printed, they must be far advanced on the road to building an atomic bomb.

13.6 Einstein writes to Roosevelt

In the summer of 1939, while Hitler was preparing to invade Poland, alarming news reached the physicists in the United States: A second meeting of German atomic scientists had been held in Berlin, this time under the auspices of the Research Division of the German

Army Weapons Department. Furthermore, Germany had stopped the sale of uranium from mines in Czechoslovakia.

The world's most abundant supply of uranium, however, was not in Czechoslovakia, but in Belgian Congo. Leo Szilard was deeply worried that the Nazis were about to construct atomic bombs; and it occurred to him that uranium from Belgian Congo should not be allowed to fall into their hands.

Szilard knew that his former teacher, Albert Einstein, was a personal friend of Elizabeth, the Belgian Queen Mother. Einstein had met Queen Elizabeth and King Albert of Belgium at the Solvay Conferences, and mutual love of music had cemented a friendship between them. When Hitler came to power in 1933, Einstein had moved to the Institute of Advanced Studies at Princeton; and Szilard decided to visit him there. Szilard reasoned that because of Einstein's great prestige, and because of his long-standing friendship with the Belgian Royal Family, he would be the proper person to warn the Belgians not to let their uranium fall into the hands of the Nazis.

It turned out that Einstein was vacationing at Peconic, Long Island, where he had rented a small house from a friend named Dr. Moore. Leo Szilard set out for Peconic, accompanied by the theoretical physicist, Eugene Wigner, who, like Szilard, was a Hungarian and a refugee from Hitler's Europe.

For some time, the men drove around Peconic, unable to find Dr. Moore's house. Finally Szilard, with his gift for foreseeing the future, exclaimed: "Let's give it up and go home. Perhaps fate never intended it. We should probably be making a frightful mistake in applying to any public authorities in a matter like this. Once a government gets hold of something, it never lets go." However, Wigner insisted that it was their duty to contact Einstein and to warn the Belgians, since they might thus prevent a world catastrophe. Finally they found the house by asking a small boy in the street if he knew where Einstein lived.

Einstein agreed to write a letter to the Belgians warning them not to let uranium from the Congo fall into the hands of the Nazis. Wigner suggested that the American State Department ought to be notified that such a letter was being written.

On August 2, 1939, Szilard again visited Einstein, this time accompanied by Edward Teller, who (like Szilard and Wigner) was a refugee Hungarian physicist. By this time, Szilard's plans had grown more ambitious; and he carried with him the draft of a letter to the American President, Franklin D. Roosevelt. Einstein made a few corrections, and then signed the fateful letter, which reads (in part) as follows:

"Some recent work of E. Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into an important source of energy in the immediate future. Certain aspects of the situation seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe, therefore, that it is my duty to bring to your attention the following.."

"It is conceivable that extremely powerful bombs of a new type may be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port, together with some of the surrounding territory.."

"I understand that Germany has actually stopped the sale of uranium from Czechoslo-

Figure 13.5: **Albert Einstein and Leo Szilard with the fateful letter to Roosevelt. Einstein later bitterly regretted signing the letter. Source: priceeconomics.com**

vakian mines which she has taken over. That she should have taken such an early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizäcker, is attached to the Kaiser Wilhelm Institute in Berlin, where some of the American work is being repeated."

On October 11, 1939, three weeks after the defeat of Poland, Roosevelt's economic advisor, Alexander Sachs, personally delivered the letter to the President. After discussing it with Sachs, the President commented,"This calls for action." Later, when atomic bombs were dropped on civilian populations in an already virtually-defeated Japan, Einstein bitterly regretted having signed the letter to Roosevelt.

13.7 The first nuclear reactor

As a result of Einstein's letter, President Roosevelt set up an Advisory Committee on Uranium. On December 6, 1941, the day before the Japanese attack on Pearl Harbor, the Committee decided to make an all-out effort to develop atomic energy and atomic bombs. This decision was based in part on intelligence reports indicating that the Germans had set aside a large section of the Kaiser Wilhelm Institute for Research on uranium; and it was based in part on promising results obtained by Enrico Fermi's group at Columbia University.

Enrico Fermi and his group at Columbia University had been exploring the possibility of building a chain-reacting pile using natural uranium, together with a moderator to slow the neutrons. Fermi's own description of the research is as follows:

"...We soon reached the conclusion that in order to have any chance of success with natural uranium, we had to use slow neutrons. So there had to be a moderator. And this moderator could be water, or other substances. Water was soon discarded. It is very effective in slowing down the neutrons, but it absorbs a little bit too many of them, and we couldn't afford that. Then it was thought that graphite might be a better bet..."

"This brings us to the fall of 1939, when Einstein wrote his now famous letter to Roosevelt, advising him of what was the situation in physics - what was brewing, and that he thought that the government had the duty to take an interest and to help along the development. And in fact, help came along to the tune of six thousand dollars a few months later; and the six thousand dollars were used to buy huge amounts - or what seemed at the time, when the eyes of physicists had not yet been distorted - what seemed at the time a huge amount of graphite."

"So the physicists on the seventh floor of Pupin Laboratories started looking like coal miners, and the wives to whom these physicists came home tired at night were wondering what was happening. We know that there is smoke in the air, but after all..."

"We started to construct this structure that at that time looked again an order of magnitude larger than anything we had seen before. Actually, if anybody would look at this structure now, he would probably extract his magnifying glass and go close to see it. But for the ideas of the time, it looked really big. It was a structure of graphite bricks, and spread through these graphite bricks in some sort of pattern, were big cans, cubic cans, containing uranium oxide."

Fermi's results indicated that it would be possible to make a chain-reacting pile using graphite as a moderator, provided that enough very pure graphite and very pure uranium oxide could be obtained. Leo Szilard undertook the task of procuring the many tons of these substances which would be required.

Work on the pile was moved to the University of Chicago, and the number of physicists employed on the project was greatly enlarged. Work preceded with feverish speed, because it was feared that the Nazis would win the race. Leona Woods, one of the few women employed on the project, recalled later: "We were told, day and night, that it was our duty to catch up with the Germans."

During the summer of 1942, Fermi succeeded in constructing a uranium-graphite lattice with a neutron reproduction factor greater than unity. In other words, when he put a radium-beryllium neutron source into the lattice, more neutrons came out than were produced by the source. This meant that a chain-reacting pile could definitely be built. It was only a matter of obtaining sufficient amounts of very pure graphite and uranium.

Fermi calculated that a spherical pile, 26 feet in diameter, would be sufficiently large to produce a self-sustained chain reaction. At first, it was planned that the pile should be built at Argonne Laboratory, just outside Chicago. However, the buildings were not yet ready, and therefore Fermi suggested that the pile should instead be built in a squash court under the abandoned football stadium at the University of Chicago. (Football had been banned by the university's president, Robert Hutchins, who felt that it distracted students from their academic work.)

The squash court was not quite as high as Fermi would have liked it to be, and in case of a miscalculation of the critical size of the pile, it would be impossible to add extra layers. Therefore, Fermi and his young co-worker, Herbert Anderson, ordered an enormous

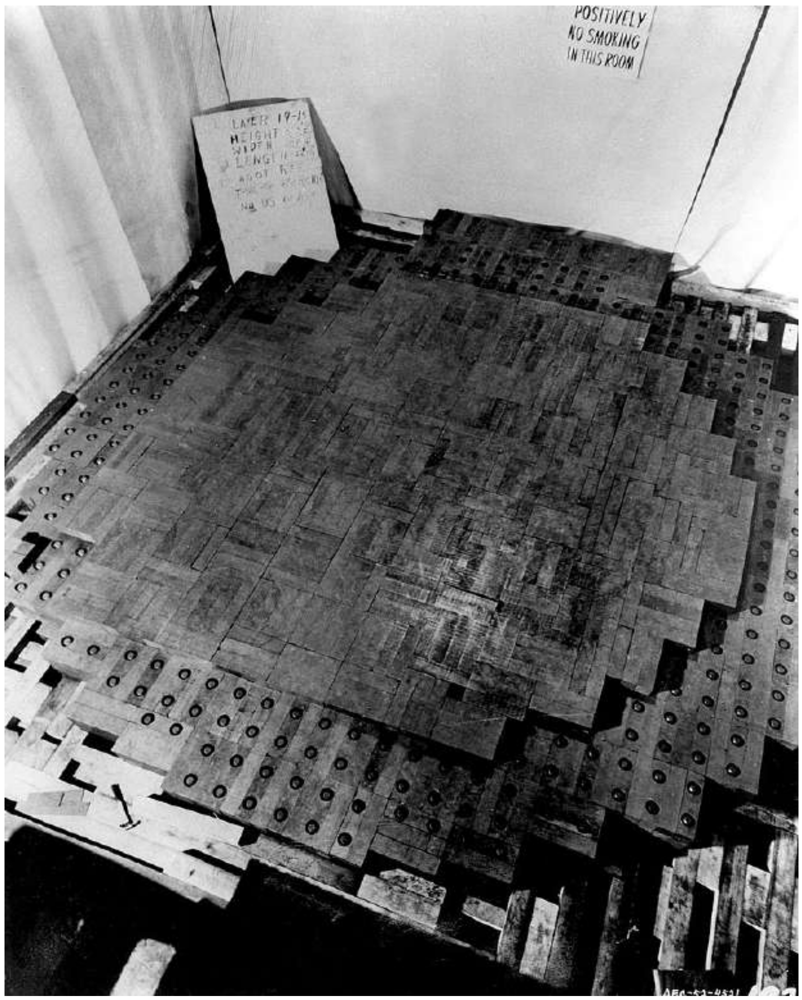

Figure 13.6: **This is the only photograph made during the construction of the first nuclear reactor. Public domain, Wikimedia Commons**

cubical rubber balloon from the Goodyear Tyre Company, and the pile was built inside the balloon. The idea was that, if necessary, the air inside the pile could be pumped out to reduce the absorption of neutrons by nitrogen. This turned out not to be necessary; and the door of the balloon was never sealed.

The graphite-uranium lattice was spherical in shape, and it rested on blocks of wood. The physicists labored furiously, putting the tons of uranium and graphite into place, measuring and cutting the blocks of wood needed to support the pile, and swearing to ease the tension. Leona Woods, wearing goggles and overalls, was indistinguishable from the men as she worked on the pile. Everyone was covered from head to foot with black graphite dust, and graphite also made the floor treacherously slippery.

On December 1, 1942, Herbert Anderson stayed up all night putting the finishing touches on the pile. If he had pulled out the neutron absorbing cadmium control rods, Anderson would have been the first man in history to achieve a self-sustaining nuclear chain reaction. However, he had promised Fermi not to do so.

Enrico Fermi got a good night's sleep; and on the next morning, December 2, he was ready to conduct the historic experiment. About forty people were present. Most of them were scientists who had worked on the pile; but there were a few visitors, including a representative of the giant DuPont chemical company, which was undertaking a contract to build more chain-reacting piles.

Fermi, and all the spectators, stood on the balcony of the squash court. On the floor of the court stood a single physicist, George Weil, who was ready to pull out the final control rod. On the top of the pile, crouched in the cramped space under the top of the balloon, was a "suicide squad" - three young physicists who had volunteered to sit there during the experiment with containers of cadmium salt solution, which they would pour into the pile if anything went wrong.

Fermi was confident that nothing would go wrong. He had calculated that even if the last control rod were removed completely, the neutron flux within the pile would not jump rapidly to a high level. Instead, it would begin to increase slowly and steadily. The slow response of the pile was due to the fact that much time was required for the fast neutrons released by fission to be slowed by collisions with carbon atoms in the graphite moderator.

Although, according to theory, there was no danger, Fermi approached the chain reaction with great caution. He explained to the spectators that George Weil would pull out the final control rod by very slow stages; and at each stage, measurements would be made to make sure that the behavior of the pile checked with calculations. The neutron flux was measured by Geiger counters, and recorded by a pen on a roll of paper.

"Pull it out a foot, George", Fermi said; and he explained to the spectators: "Now the pen will move up to this point and then level off." The response was exactly as predicted.

Throughout the morning, this procedure was repeated. However, by lunchtime, much of the control rod still remained within the pile. Fermi was a man of fixed habits, and although no one else showed any signs of being hungry, he said: "Let's go to lunch."

After lunch, the experiment was continued; and by 2:30 in the afternoon, the critical point was reached. "Pull it out another foot, George", Fermi said, and then he added: "This will do it. Now the pile will chain-react." The Geiger counters began to click faster

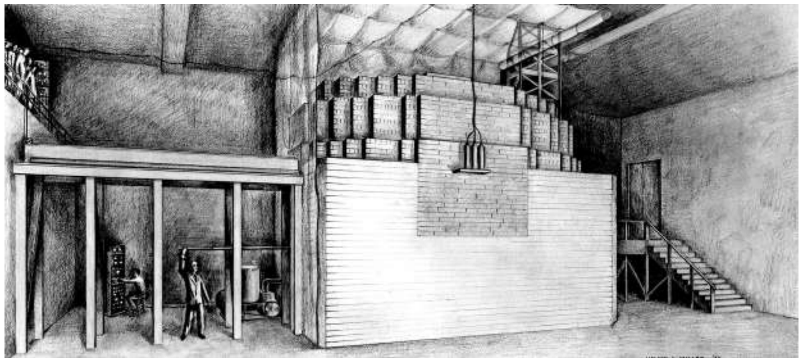

Figure 13.7: **Sketch of the world's first nuclear reactor, Chicago Pile 1 or CP-1, which was constructed under the football grandstands at the University of Chicago. Public domain, Wikimedia Commons**

and faster, and the recording pen moved upward with no sign of leveling off. On top of the pile, the suicide squad waited tensely with their containers of cadmium solution.

Leona Woods whispered to Fermi: "When do we get scared?" However, the pile behaved exactly as predicted, and after 28 minutes, the control rod was reinserted. Eugene Wigner then produced a bottle of Chianti wine which he had kept concealed until that moment, and everyone drank a little, in silence, from paper cups.

13.8 The atomic bomb

The chain-reacting pile had a double significance: Its first meaning was a hopeful one - It represented a new source of energy for mankind. The second meaning was more sinister - It was a step on the road to the construction of atomic bombs.

According to the Bohr-Wheeler theory, it was predicted that plutonium-239 should be just as fissionable as uranium-235. Instead of trying to separate the rare isotope, uranium-235, from the common isotope, uranium-238, the physicists could just operate the pile until a sufficient amount of plutonium accumulated, and then separate it out by ordinary chemical means.

This was done on a very large scale by the Dupont chemical company. Four large chain-reacting piles were built beside the Colombia River at Hanford, Washington. Cold water from the river was allowed to flow through the piles to carry away the heat.

An alternative method for producing atomic bombs was to separate the rare fissionable isotope of uranium from the common isotope. Three different methods for isotope separation seemed possible: One could make a gaseous compound of uranium and allow it to diffuse through a porous barrier. (The lighter isotope would diffuse slightly faster.) Alternatively, one could use a high-speed gas centrifuge; or one could separate the isotopes in a mass spectrograph.

All three methods of isotope separation were tried, and all proved successful. Under Harold Urey's direction, a huge plant to carry out the gaseous separation methods was constructed at Oak Ridge Tennessee; and at the University of California in Berkeley, Ernest O. Lawrence and his group converted the new giant cyclotron into a mass spectrograph. Ultimately, 150,000 people were working at Hanford, Oak Ridge and Berkeley, producing material for atomic bombs. Of these, only a few knew the true purpose of the work in which they were engaged.

Calculations performed in England by Otto Frisch and Rudolf Peierels showed that the critical mass of fissionable material needed for a bomb was about two kilograms. If this mass of material were suddenly assembled, a chain-reaction would start spontaneously. An avalanche of neutrons would develop with almost-instantaneous speed, because no time would be needed for the neutrons to be slowed by a moderator. The lower efficiency of the fast neutrons would be offset by the high concentration of fissionable nuclei, and the result would be a nuclear explosion.

Following a joint decision by Roosevelt and Churchill, English work on atomic bombs was moved to the United States and Canada, where it was combined with the research already being conducted there by American and refugee European scientists. Work on the bomb project was driven forward by an overpowering fear that the Nazis would be the first to construct nuclear weapons.

In July, 1943, Robert Oppenheimer of the University of California was appointed director of a secret laboratory where atomic bombs would be built as soon as material for them became available. At the time of his appointment, Oppenheimer was 39 years old. He was a tall, thin man, with refined manners, and a somewhat ascetic appearance.

Oppenheimer was the son of a wealthy and cultured New York financier. He had graduated from Harvard with record grades, and had done postgraduate work in theoretical physics under Max Born at the University of Göttingen in Germany.

Robert Oppenheimer had then worked with E.O. Lawrence, who was separating the isotopes of uranium, using the Berkeley cyclotron, which had been converted to a mass spectrograph. After making a technical innovation which greatly reduced the cost of separation, Oppenheimer had been appointed the head of the theoretical group of the atomic bomb project. He proved to be a gifted leader. His charm was hypnotic; and under his leadership, “something got done, and done at astonishing speed”, as Arthur Compton said later.

Oppenheimer proposed that all work on building atomic bombs should be assembled in a secret laboratory. This proposal was adopted; and because Oppenheimer had shown such gifts as a leader, he was made head of the secret laboratory.

At first, it was planned that this laboratory should be located near to the huge isotope separation plant at Oak Ridge, Tennessee. However, spies often were set on shore on the Atlantic coast of the United States by German submarines; and a number of spies were captured near to Oak Ridge. Therefore, Oppenheimer and General Leslie Groves (the military director of the project) looked for a more isolated site in the western part of the country.

Oppenheimer had boyhood memories of New Mexico, where he and his brother, Frank, had spent their vacations. He took General Groves to a boy’s school, which he remembered, on a high plateau near the Los Alamos canyon. The mesa where the boy’s school was

Figure 13.8: **Oppenheimer with General Leslie Groves, military head of the Manhattan Project. Public domain, Wikimedia Commons**

located was the flat top of a mountain, 7,000 feet above sea level, overlooking the valley of the Rio Grande River.

It was a completely isolated place. Apart from the few buildings of the school, one saw only scattered aspens and fragrant pines, the red rock of the mesa, and the Jemez mountains on the horizon, standing out sharply in the dry, transparent air. Sixty miles separated Los Alamos from the nearest railway station, at Santa Fe, New Mexico.

Oppenheimer and Groves decided that this would be an excellent place for the secret laboratory which they were planning; and they told the headmaster that the school would have to be closed. It would be bought for government war work. The buildings of the school would accommodate the first scientists arriving at Los Alamos while other buildings were being constructed.

Within a year of the first visit to the lonely mesa by Oppenheimer and Groves, 3,500 people were working there; and in another year, the population of scientists and their families had grown to 6,000. More and more scientists received visits from the persuasive young director, Robert Oppenheimer; and more and more of them disappeared to the mysterious "Site Y", a place so secret that its location and name could not be mentioned, and knowledge of its mere existence was limited to very few people.

Many of the scientists who had fled from Hitler's Europe found themselves reunited with their friends at "Site Y". Fermi, Segrè, Rossi, Bethe, Peierls, Chadwick, Frisch, Szilard and Teller all were there. Even Niels Bohr arrived at Los Alamos, together with his son, Aage, who was also a physicist.

Bohr had remained in Denmark as long as possible, in order to protect his laboratory and his co-workers. However, in 1943, he heard that he had been marked by the Germans for arrest and deportation; and he escaped to Sweden in a small boat. In Sweden, he helped to rescue the Jewish population of Denmark from the Nazis; and finally he arrived at Los Alamos.

As time passed, many of the scientists at Los Alamos, including Niels Bohr, became deeply worried about the ethical aspects of work on the atomic bomb. When the project had first begun, everyone was sure that the Germans had a great lead in the development of nuclear weapons. They were convinced that the only way to save civilization from the threat of Nazi atomic bombs would be to have a counter-threat. In 1944, however, as the Allied invasion of Europe began, and no German atomic bombs appeared, this dogma seemed less certain.

In 1943, a special intelligence unit of the American Army had been established. Its purpose was to land with the first Allied troops invading Europe, and to obtain information about the German atomic bomb project. The code-name of the unit was *Aslos*, a literal Greek translation of the name of General Groves. The Dutch refugee physicist, Samuel Goudschmidt, was the scientific director of the *Aslos* mission.

When Strasbourg fell to the Allies, Goudschmidt found documents which made it clear that the Germans had not even come close to building atomic bombs. While walking with one of his military colleagues, Goudschmidt exclaimed with relief, "Isn't it wonderful? The Germans don't have atomic bombs! Now we won't have to use ours!"

He was shocked by the reply of his military colleague: "Of course you understand, Sam, that if we have such a weapon, we are going to use it." Goudschmidt's colleague unfortunately proved to have an accurate understanding of the psychology of military and political leaders.

At the University of Chicago, worry and discussion were even more acute than at Los Alamos. The scientists at Chicago had better access to the news, and more time to think. A committee of seven was elected by the Chicago scientists to draft their views into a report on the social and political consequences of atomic energy. The chairman of the committee was the Nobel-laureate physicist James Franck, a man greatly respected for his integrity.

The Franck Report was submitted to the American Secretary of War in June, 1945; and it contains the following passages:

"In the past, science has been able to provide new methods of protection against new methods of aggression it made possible; but it cannot promise such effective protection against the destructive use of nuclear energy. This protection can only come from the political organization of the world. Among all the arguments calling for an efficient international organization for peace, the existence of nuclear weapons is the most compelling one..."

"If no efficient international agreement is achieved, the race for nuclear armaments will be on in earnest not later than the morning after our first demonstration of the existence of nuclear weapons. After this, it might take other nations three or four years to overcome our present head start..."

"It is not at all certain that American public opinion, if it could be enlightened as to the effect of atomic explosives, would approve of our own country being the first to introduce such an indiscriminate method for the wholesale destruction of civilian life... The military advantages, and the saving of American lives, achieved by a sudden use of atomic bombs against Japan, may be outweighed by a wave of horror and revulsion sweeping over the rest of the world, and perhaps even dividing public opinion at home..."

"From this point of view, a demonstration of the new weapon might best be made, before the eyes of representatives of all the United Nations, on the desert, or on a barren island. The best possible atmosphere for.. an international agreement could be achieved if America could say to the world: 'You see what sort of weapon we had but did not use. We are ready to renounce its use in the future, if other nations join us in this renunciation, and join us in the establishment of an efficient control'."

"One thing is clear: Any international agreement on the prevention of nuclear armaments must be backed by actual and effective controls. No paper agreement can be sufficient, since neither this nor any other nation can stake its whole existence on trust in other nations' signatures."

The Franck report then goes on to outline the steps which would have to be taken in order to establish efficient international control of atomic energy. The report states that the most effective method would be for an international control board to restrict the mining of uranium ore. This would also prevent the use of atomic energy for generating electrical power; but the price would not be too high to pay in order to save humankind from the grave dangers of nuclear war.

Unfortunately, it was too late for the scientists to stop the machine which they themselves had set in motion. President Franklin Roosevelt might have stopped the use of the bomb; but in August, 1945, he was dead. On his desk, unread, lay letters from Albert Einstein and Leo Szilard - the same men who had written to Roosevelt six years previously, thus initiating the American atomic bomb project. In 1945, both Einstein and Szilard wrote again to Roosevelt, this time desperately urging him not to use nuclear weapons against Japan; but their letters arrived too late.

In Roosevelt's place was a new President, Harry Truman, who had been in office only a few weeks. He came from a small town in Missouri; and he was shocked to find himself suddenly thrust into a position of enormous power. He was overwhelmed with new responsibilities, and was cautiously feeling his way. Until Roosevelt's death he had known nothing whatever about the atomic bomb project; and he therefore had little chance to absorb its full meaning.

By contrast, General Leslie Groves, the military commander of the bomb project, was very sure of himself; and he was determined to use atomic bombs against Japan. General Groves had supervised the spending of two billion dollars of the American taxpayers' money. He was anxious to gain credit for winning the war, rather than to be blamed for the money's misuse.

Under these circumstances, it is understandable that Truman did nothing to stop the use of the atomic bomb. In General Groves' words, "Truman did not so much say 'yes', as not say 'no'. It would, indeed, have taken a lot of nerve to say 'no' at that time."

13.9 August 6

On August 6, 1945, at 8:15 in the morning, an atomic bomb was exploded in the air over Hiroshima. The force of the explosion was equivalent to twenty thousand tons of T.N.T.. Out of a city of two hundred and fifty thousand people, almost one hundred thousand were killed by the bomb; and another hundred thousand were hurt.

In some places, near the center of the city, people were completely vaporized, so that only their shadows on the pavement marked the places where they had been. Many people who were not killed by the blast or by burns from the explosion, were trapped under the wreckage of their houses. Unable to move, they were burned to death in the fire which followed.

Some accounts of the destruction of Hiroshima, written by children who survived it, have been collected by Professor Arata Osada. Among them is the following account, written by a boy named Hisato Ito. He was 11 years old when the atomic bomb was exploded over the city:

"On the morning of August 5th (we went) to Hiroshima to see my brother, who was at college there. My brother spent the night with us in a hotel... On the morning of the 6th, my mother was standing near the entrance, talking with the hotel proprietor before paying the bill, while I played with the cat. It was then that a violent flash of blue-white light swept in through the doorway."

"I regained consciousness after a little while, but everything was dark. I had been flung to the far end of the hall, and was lying under a pile of debris caused by the collapse of two floors of the hotel. Although I tried to crawl out of this, I could not move. The fine central pillar, of which the proprietor was so proud, lay flat in front of me. "

"I closed my eyes and was quite overcome, thinking that I was going to die, when I heard my mother calling my name. At the sound of her voice, I opened my eyes; and then I saw the flames creeping close to me. I called frantically to my mother, for I knew that I should be burnt alive if I did not escape at once. My mother pulled away some burning boards and saved me. I shall never forget how happy I felt at that moment - like a bird let out of a cage."

"Everything was so altered that I felt bewildered. As far as my eyes could see, almost all the houses were destroyed and on fire. People passed by, their bodies red, as if they had

Figure 13.9: **It was like a scene from hell. Source: SGI International.**

been peeled. Their cries were pitiful. Others were dead. It was impossible to go farther along the street on account of the bodies, the ruined houses, and the badly wounded who lay about moaning. I did not know what to do; and as I turned to the west, I saw that the flames were drawing nearer..”

“At the water’s edge, opposite the old Sentai gardens, I suddenly realized that I had become separated from my mother. The people who had been burned were plunging into the river Kobashi, and then were crying our: ‘It’s hot! It’s hot!’ They were too weak to swim, and they drowned while crying for help.”

In 1951, shortly after writing this account, Hisato Ito died of radiation sickness. His mother died soon afterward from the same cause.

When the news of the atomic bombing of Hiroshima and Nagasaki reached Albert Einstein, his sorrow and remorse were extreme. During the remainder of his life, he did his utmost to promote the cause of peace and to warn humanity against the dangers of nuclear warfare.

When Otto Hahn, the discoverer of fission, heard the news of the destruction of Hiroshima, he and nine other German atomic scientists were being held prisoner at an English country house near Cambridge. Hahn became so depressed that his colleagues feared that he would take his own life.

Among the scientists who had worked at Chicago and Los Alamos, there was relief that the war was over; but as descriptions of Hiroshima and Nagasaki became available, there were also sharp feelings of guilt. Many scientists who had worked on the bomb project made great efforts to persuade the governments of the United States, England and Russia to agree to international control of atomic energy; but these efforts met with failure; and the nuclear arms race feared by Bohr developed with increasing momentum.

Figure 13.10: **Burned beyond recognition. Source: SGI International.**

Figure 13.11: **Memories of August 6. Source: SGI International.**

Figure 13.12: **The effects lasted a lifetime. Source: SGI International.**

Figure 13.13: **After the bombing. Source: SGI International.**

Suggestions for further reading

1. Robert Jungk, *Brighter Than a Thousand Suns*, Pennguin Books Ltd. (1964).
2. Werner Braunbeck, *The Drama of the Atom*, Oliver and Boyd, Edinburgh (1958).
3. Werner Heisenberg, *Physics and Beyond; Memories of a Life in Science*, George Allen and Unwin (1971).
4. Emilio Segrè, *Enrico Fermi, Physicist*, The University of Chicago Press (1970).
5. Laura Fermi, *Atoms in the Family*, The University of Chicago Press (1954).
6. O.R. Frisch, *What Little I Remember*, Cambridge University Press (1979).
7. James L. Henderson, *Hiroshima*, Longmans (1974).
8. Arata Osada, *Children of the A-Bomb, The Testiment of Boys and Girls of Hiroshima*, Putnam, New York (1963).
9. Michehiko Hachiya, M.D., *Hiroshima Diary*, The University of North Carolina Press, Chapel Hill, N.C. (1955).
10. Marion Yass, *Hiroshima*, G.P. Putnam's Sons, New York (1972).
11. Robert Jungk, *Children of the Ashes*, Harcourt, Brace and World (1961).
12. Burt Hirschfield, *A Cloud Over Hiroshima*, Baily Brothers and Swinfin Ltd. (1974).
13. John Hersey, *Hiroshima*, Penguin Books Ltd. (1975).

Chapter 14

BARDEEN

John Bardeen (1908-1991) was the only person ever to be awarded the Nobel Prize in Physics twice. He was first awarded the the prize in 1956, together with William Shockley and Walter Brattain, for the invention of the transistor. His second Nobel Prize in Physics was shared with Leon N Cooper and John Robert Schrieffer, for their theory of superconductivity (BCS Theory)

Bardeen's father was the Dean of Medicine at the University of Wisconsin. Not wishing to follow in his father's academic footsteps, John Bardeen first studied engineering, and worked as an engineer. However, work as an engineer failed to keep his interest, and in 1933 he became a graduate student in mathematics at Princeton University. At Princeton he worked under the Nobel Laureate physicist, Eugene Wigner (Dirac's brother-in-law), and wrote a thesis in solid state physics.

Bell Laboratories

The invention of the transistor, for which Bardeen was awarded his first Nobel Prize in Physics, was the result of work done at the Bell Telephone Laboratories, and something must be said about the conditions experienced by scientists and engineers working there. For many years the Bell Telephone Company was a monopoly, and under US laws they were not allowed to make more than a limited amount of profit. What should be done with the extra money? They decided to invest it in fundamental research. This meant that scientists working at the Bell Laboratories were free to work on whatever problem was most interesting and promising. The result of this policy is that nine Nobel prizes have been awarded as the result of work completed at the Bell Laboratories:

- 1937: Clinton J. Davisson shared the Nobel Prize in Physics for demonstrating the wave nature of matter.
- 1956: John Bardeen, Walter H. Brattain, and William Shockley received the Nobel Prize in Physics for inventing the first transistors.
- 1977: Philip W. Anderson shared the Nobel Prize in Physics for developing an improved understanding of the electronic structure of glass and magnetic materials.

Figure 14.1: **John Bardeen (1908-1991).**

- 1978: Arno A. Penzias and Robert W. Wilson shared the Nobel Prize in Physics. Penzias and Wilson were cited for their discovering cosmic microwave background radiation, a nearly uniform glow that fills the Universe in the microwave band of the radio spectrum.
- 1997: Steven Chu shared the Nobel Prize in Physics for developing methods to cool and trap atoms with laser light.
- 1998: Horst Störmer, Robert Laughlin, and Daniel Tsui, were awarded the Nobel Prize in Physics for discovering and explaining the fractional quantum Hall effect.
- 2009: Willard S. Boyle, George E. Smith shared the Nobel Prize in Physics with Charles K. Kao. Boyle and Smith were cited for inventing charge-coupled device (CCD) semiconductor imaging sensors.
- 2014: Eric Betzig shared the Nobel Prize in Chemistry for his work in super-resolved fluorescence microscopy which he began pursuing while at Bell Labs.
- 2018: Arthur Ashkin shared the Nobel Prize in Physics for his work on "the optical tweezers and their application to biological systems"[35] which was developed at Bell Labs.

14.1 The invention of transistors

Microelectronics

The problem of unreliable vacuum tubes was solved in 1948 by John Bardeen, William Shockley and Walter Brattain of the Bell Telephone Laboratories. Application of quantum theory to solids had lead to an understanding of the electrical properties of crystals. Like atoms, crystals were found to have allowed and forbidden energy levels.

The allowed energy levels for an electron in a crystal were known to form bands, i.e., some energy ranges with many allowed states (allowed bands), and other energy ranges with none (forbidden bands). The lowest allowed bands were occupied by electrons, while higher bands were empty. The highest filled band was called the "valence band", and the lowest empty band was called the "conduction band".

According to quantum theory, whenever the valence band of a crystal is only partly filled, the crystal is a conductor of electricity; but if the valence band is completely filled with electrons, the crystal is an electrical insulator. (A completely filled band is analogous to a room so packed with people that none of them can move.)

In addition to conductors and insulators, quantum theory predicted the existence of "semiconductors" - crystals where the valence band is completely filled with electrons, but where the energy gap between the conduction band and the valence band is very small. For example, crystals of the elements silicon and germanium are semiconductors. For such a crystal, thermal energy is sometimes enough to lift an electron from the valence band to the conduction band.

Bardeen, Shockley and Brattain found ways to control the conductivity of germanium crystals by injecting electrons into the conduction band, or alternatively by removing electrons from the valence band. They could do this by "doping" the crystals with appropriate impurities, or by injecting electrons with a special electrode. The semiconducting crystals whose conductivity was controlled in this way could be used as electronic valves, in place of vacuum tubes.

By the 1960's, replacement of vacuum tubes by transistors in electronic computers had led not only to an enormous increase in reliability and a great reduction in cost, but also to an enormous increase in speed. It was found that the limiting factor in computer speed was the time needed for an electrical signal to propagate from one part of the central processing unit to another. Since electrical impulses propagate with the speed of light, this time is extremely small; but nevertheless, it is the limiting factor in the speed of electronic computers.

14.2 The Traitorous Eight

According to the Wikipedia article on Shockley,

"In 1956 Shockley moved from New Jersey to Mountain View, California to start Shockley Semiconductor Laboratory to live closer to his ailing mother in Palo Alto, California. The company, a division of Beckman Instruments, Inc., was the first establishment working on silicon semiconductor devices in what came to be known as Silicon Valley.

"His way [of leading the group] could generally be summed up as domineering and increasingly paranoid. In one well-known incident, he claimed that a secretary's cut thumb was the result of a malicious act and he demanded lie detector tests to find the culprit, when in reality, the secretary had simply grabbed at a door handle that happened to have an exposed tack on it for the purpose of hanging paper notes on. After he received the Nobel Prize in 1956 his demeanor changed, as evidenced in his increasingly autocratic, erratic and

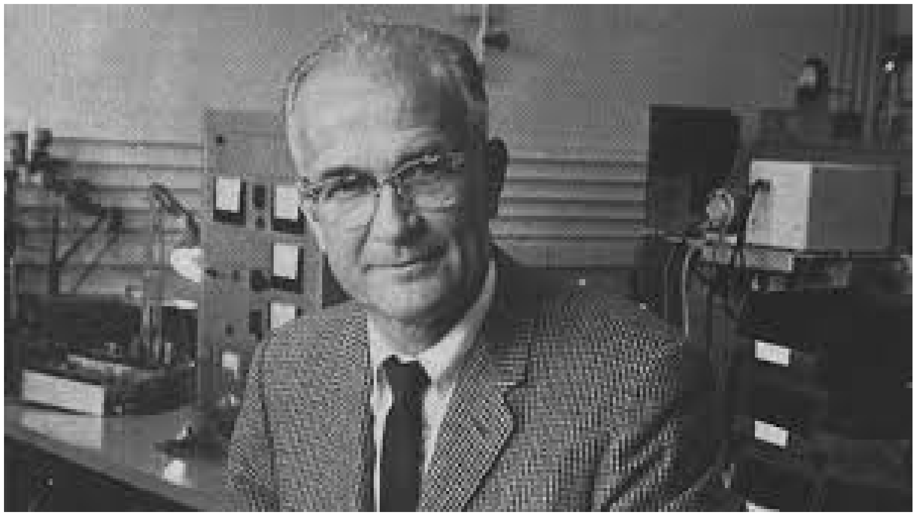

Figure 14.2: **William Shockley (1910-1989) shared the 1956 Nobel Prize in Physics with John Bardeen and Walter Brattain. He was so extremely difficult to work with that "the traitorous eight" resigned *en masse.***

hard-to-please management style. In late 1957, eight of Shockley's researchers, who would come to be known as the 'traitorous eight, resigned after Shockley decided not to continue research into silicon-based semiconductors. They went on to form Fairchild Semiconductor, a loss from which Shockley Semiconductor never recovered. Over the course of the next 20 years, more than 65 new enterprises would end up having employee connections back to Fairchild."

Figure 14.3: **The Traitorous Eight: From left to right, Gordon Moore, C. Sheldon Roberts, Eugene Kleiner, Robert Noyce, Victor Grinich, Julius Blank, Jean Hoerni and Jay Last.**

14.3 Integrated circuits

In order to reduce the propagation time, computer designers tried to make the central processing units very small; and the result was the development of integrated circuits and microelectronics. (Another motive for miniaturization of electronics came from the requirements of space exploration.)

Integrated circuits were developed in which single circuit elements were not manufactured separately. Instead, the whole circuit was made at one time. An integrated circuit is a sandwich-like structure, with conducting, resisting and insulating layers interspersed with layers of germanium or silicon, “doped ” with appropriate impurities. At the start of the manufacturing process, an engineer makes a large drawing of each layer. For example, the drawing of a conducting layer would contain pathways which fill the role played by wires in a conventional circuit, while the remainder of the layer would consist of areas destined to be etched away by acid.

The next step is to reduce the size of the drawing and to multiply it photographically. The pattern of the layer is thus repeated many times, like the design on a piece of wallpaper. The multiplied and reduced drawing is then focused through a reversed microscope onto the surface to be etched.

Successive layers are built up by evaporating or depositing thin films of the appropriate substances onto the surface of a silicon or germanium wafer. If the layer being made is to be conducting, the surface would consist of an extremely thin layer of copper, covered with a photosensitive layer called a “photoresist”. On those portions of the surface receiving light from the pattern, the photoresist becomes insoluble, while on those areas not receiving light, the photoresist can be washed away.

The surface is then etched with acid, which removes the copper from those areas not protected by photoresist. Each successive layer of a wafer is made in this way, and finally the wafer is cut into tiny “chips”, each of which corresponds to one unit of the wallpaper-like pattern.

Although the area of a chip may be much smaller than a square centimeter, the chip can contain an extremely complex circuit. A typical programmable minicomputer or “microprocessor”, manufactured during the 1970’s, could have 30,000 circuit elements, all of which were contained on a single chip. By 1986, more than a million transistors were being placed on a single chip.

As a result of miniaturization, the speed of computers rose steadily. In 1960, the fastest computers could perform a hundred thousand elementary operations in a second. By 1970, the fastest computers took less than a second to perform a million such operations. In 1987, a computer called GF11 was designed to perform 11 billion floating-point operations (flops) per second.

GF11 (Gigaflop 11) is a scientific parallel-processing machine constructed by IBM. Approximately ten floating-point operations are needed for each machine instruction. Thus GF11 runs at the rate of approximately a thousand million instructions per second (1,100 MIPS). The high speed achieved by parallel-processing machines results from dividing a job into many sub-jobs on which a large number of processing units can work simultaneously.

Computer memories have also undergone a remarkable development. In 1987, the magnetic disc memories being produced could store 20 million bits of information per square inch; and even higher densities could be achieved by optical storage devices. (A "bit" is the unit of information. For example, the number 25, written in the binary system, is 11001. To specify this 5-digit binary number requires 5 bits of information. To specify an n-digit binary number requires n bits of information. Eight bits make a "byte".)

In the 1970's and 1980's, computer networks were set up linking machines in various parts of the world. It became possible (for example) for a scientist in Europe to perform a calculation interactively on a computer in the United States just as though the distant machine were in the same room; and two or more computers could be linked for performing large calculations. It also became possible to exchange programs, data, letters and manuscripts very rapidly through the computer networks.

14.4 Moore's law

In 1965, only four years after the first integrated circuits had been produced, Dr. Gordon E. Moore, one of the founders of Intel, made a famous prediction which has come to be known as "Moore's Law". He predicted that the number of transistors per integrated circuit would double every two years, and that this trend would continue through 1975. In fact, the general trend predicted by Moore has continued for a much longer time. Although the number of transistors per unit area has not continued to double every two years, the logic density (bits per unit area) has done so, and thus a modified version of Moore's law still holds today. How much longer the trend can continue remains to be seen. Physical limits to miniaturization of transistors of the present type will soon be reached; but there is hope that further miniaturization can be achieved through "quantum dot" technology, molecular switches, and autoassembly.

A typical programmable minicomputer or "microprocessor", manufactured in the 1970's, could have 30,000 circuit elements, all of which were contained on a single chip. By 1989, more than a million transistors were being placed on a single chip; and by 2000, the number reached 42,000,000.

As a result of miniaturization and parallelization, the speed of computers rose exponentially. In 1960, the fastest computers could perform a hundred thousand elementary operations in a second. By 1970, the fastest computers took less than a second to perform a million such operations. In 1987, a massively parallel computer, with 566 parallel processors, called GFll was designed to perform 11 billion floating-point operations per second (flops). By 2002 the fastest computer performed 40 at teraflops, making use of 5120 parallel CPU's.

Computer disk storage has also undergone a remarkable development. In 1987, the magnetic disk storage being produced could store 20 million bits of information per square inch; and even higher densities could be achieved by optical storage devices. Storage density has until followed a law similar to Moore's law.

In the 1970's and 1980's, computer networks were set up linking machines in various

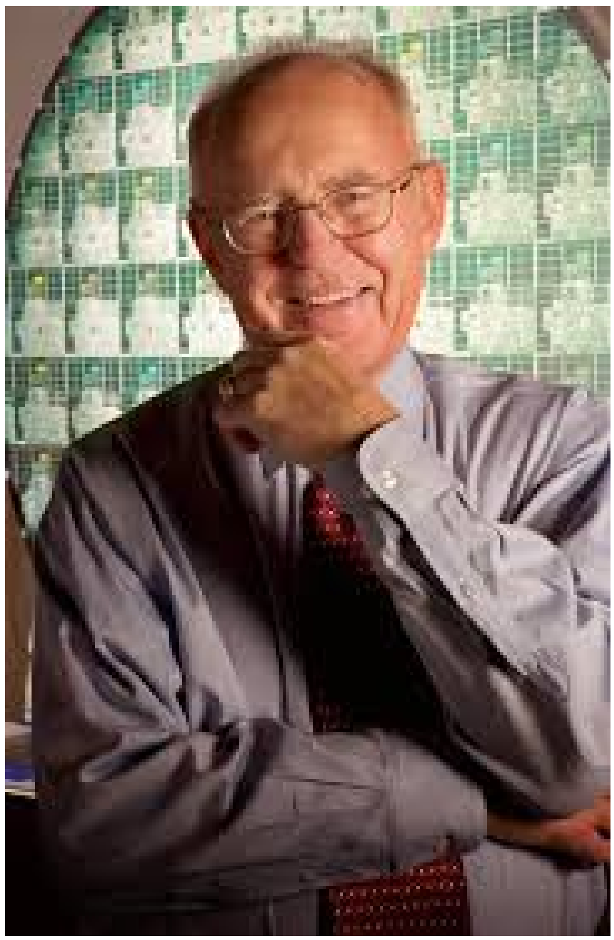

Figure 14.4: **Gordon E. Moore (born 1929), a founder of Intel and the author of Moore's Law. In 1965 he predicted that the number of components in integrated circuits would double every year for the next 10 years". In 1975 he predicted the this doubling would continue, but revised the doubling rate to "every two years. Astonishingly, Moore's Law has held much longer than he, or anyone else, anticipated.**

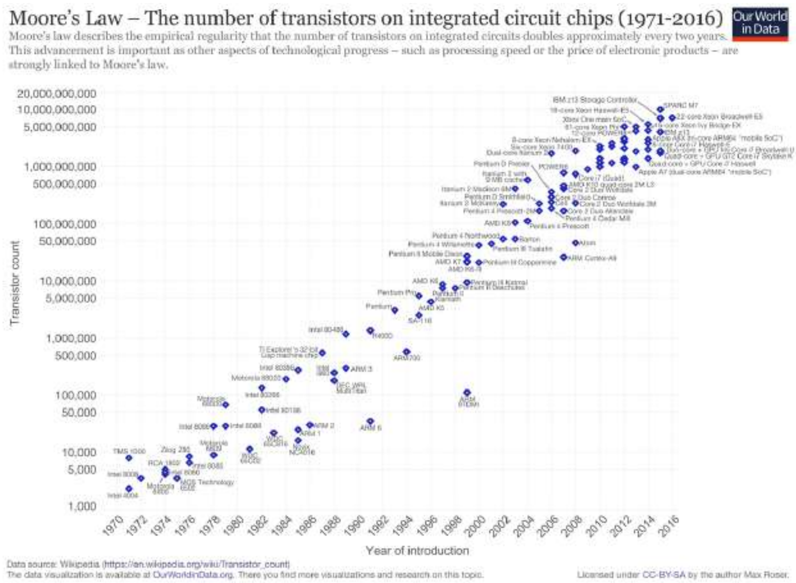

Figure 14.5: **Amazingly, Moore's Law has held much longer than he, or anyone else, anticipated. Perhaps quantum dot technologies can extend its validity even longer.**

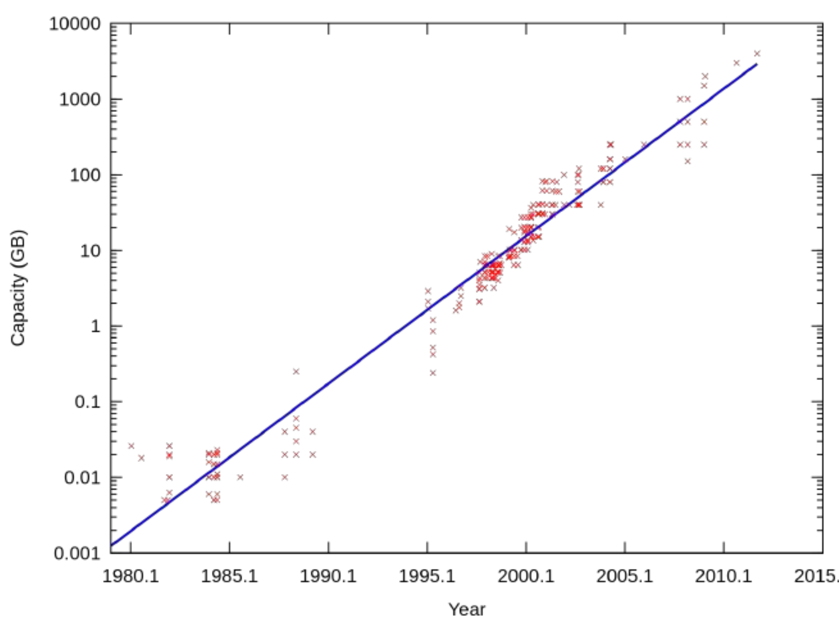

Figure 14.6: **A logarithmic plot of the increase in PC hard-drive capacity in gigabytes. An extrapolation of the rate of increase predicts that the individual capacity of a commercially available PC will reach 10,000 gigabytes by 2015, i.e. 10,000,000,000,000 bytes. (After Hankwang and Rentar, Wikimedia Commons)**

parts of the world. It became possible (for example) for a scientist in Europe to perform a calculation interactively on a computer in the United States just as though the distant machine were in the same room; and two or more computers could be linked for performing large calculations. It also became possible to exchange programs, data, letters and manuscripts very rapidly through the computer networks.

The exchange of large quantities of information through computer networks was made easier by the introduction of fiber optics cables. By 1986, 250,000 miles of such cables had been installed in the United States. If a ray of light, propagating in a medium with a large refractive index, strikes the surface of the medium at a grazing angle, then the ray undergoes total internal reflection. This phenomenon is utilized in fiber optics: A light signal can propagate through a long, hairlike glass fiber, following the bends of the fiber without losing intensity because of total internal reflection. However, before fiber optics could be used for information transmission over long distances, a technological breakthrough in glass manufacture was needed, since the clearest glass available in 1940 was opaque in lengths more than 10 m. Through studies of the microscopic properties of glasses, the problem of absorption was overcome. By 1987, devices were being manufactured commercially that were capable of transmitting information through fiber-optic cables at the rate of 1.7 billion bits per second.

14.5 Self-reinforcing information accumulation

Humans have been living on the earth for roughly two million years (more or less, depending on where one draws the line between our human and prehuman ancestors, Table 6.1). During almost all of this,time, our ancestors lived by hunting and food-gathering. They were not at all numerous, and did not stand out conspicuously from other animals. Then, suddenly, during the brief space of ten thousand years, our species exploded in numbers from a few million to seven billion, populating all parts of the earth, and even setting foot on the moon. This population explosion, which is still going on, has been the result of dramatic cultural changes. Genetically we are almost identical with our hunter-gatherer ancestors, who lived ten thousand years ago, but cultural evolution has changed our way of life beyond recognition.

Beginning with the development of speech, human cultural evolution began to accelerate. It started to move faster with the agricultural revolution, and faster still with the invention of writing and printing. Finally, modern science has accelerated the rate of social and cultural change to a completely unprecedented speed.

The growth of modern science is accelerating because knowledge feeds on itself. A new idea or a new development may lead to several other innovations, which can in turn start an avalanche of change. For example, the quantum theory of atomic structure led to the invention of transistors, which made high-speed digital computers possible. Computers have not only produced further developments in quantum theory; they have also revolutionized many other fields.

The self-reinforcing accumulation of knowledge - the information explosion - which characterizes modern human society is reflected not only in an explosively-growing global population, but also in the number of scientific articles published, which doubles roughly every ten years. Another example is Moore's law - the doubling of the information density of integrated circuits every two years. Yet another example is the explosive growth of Internet traffic shown in Table 17.1.

The Internet itself is the culmination of a trend towards increasing societal information exchange - the formation of a collective human consciousness. This collective consciousness preserves the observations of millions of eyes, the experiments of millions of hands, the thoughts of millions of brains; and it does not die when the individual dies.

14.6 Automation

During the last three decades, the cost of computing has decreased exponentially by between twenty and thirty percent per year. Meanwhile, the computer industry has grown exponentially by twenty percent per year (faster than any other industry). The astonishing speed of this development has been matched by the speed with which computers have become part of the fabric of science, engineering, industry, commerce, communications, transport, publishing, education and daily life in the industrialized parts of the world.

The speed, power and accuracy of computers has revolutionized many branches of science. For example, before the era of computers, the determination of a simple molecular structure by the analysis of X-ray diffraction data often took years of laborious calculation; and complicated structures were completely out of reach. In 1949, however, Dorothy Crowfoot Hodgkin used an electronic computer to work out the structure of penicillin from X-ray data. This was the first application of a computer to a biochemical problem; and it was followed by the analysis of progressively larger and more complex structures.

Proteins, DNA, and finally even the detailed structures of viruses were studied through the application of computers in crystallography. The enormous amount of data needed for such studies was gathered automatically by computer-controlled diffractometers; and the final results were stored in magnetic-tape data banks, available to users through computer networks.

The application of quantum theory to chemical problems is another field of science which owes its development to computers. When Erwin Schrödinger wrote down his wave equation in 1926, it became possible, in principle, to calculate most of the physical and chemical properties of matter. However, the solutions to the Schrödinger equation for many-particle systems can only be found approximately; and before the advent of computers, even approximate solutions could not be found, except for the simplest systems.

When high-speed electronic digital computers became widely available in the 1960's, it suddenly became possible to obtain solutions to the Schrödinger equation for systems of chemical and even biochemical interest. Quantum chemistry (pioneered by such men as J.C. Slater, R.S. Mullikin, D.R. Hartree, V. Fock, J.H. Van Vleck, L. Pauling, E.B. Wilson, P.O. Löwdin, E. Clementi, C.J. Ballhausen and others) developed into a rapidly-growing field, as did solid state physics. Through the use of computers, it became possible to design new materials with desired chemical, mechanical, electrical or magnetic properties. Applying computers to the analysis of reactive scattering experiments, D. Herschbach, J. Polanyi and Y. Lee were able to achieve an understanding of the dynamics of chemical reactions.

The successes of quantum chemistry led Albert Szent-Györgyi, A. and B. Pullman, H. Scheraga and others to pioneer the fields of quantum biochemistry and molecular dynamics. Computer programs for drug design were developed, as well as molecular-dynamics programs which allowed the conformations of proteins to be calculated from a knowledge of their amino acid sequences. Studies in quantum biochemistry have yielded insights into the mechanisms of enzyme action, photosynthesis, active transport of ions across membranes, and other biochemical processes.

In medicine, computers began to be used for monitoring the vital signs of critically ill patients, for organizing the information flow within hospitals, for storing patients' records, for literature searches, and even for differential diagnosis of diseases.

The University of Pennsylvania has developed a diagnostic program called INTERNIST-1, with a knowledge of 577 diseases and their interrelations, as well as 4,100 signs, symptoms and patient characteristics. This program was shown to perform almost as well as an academic physician in diagnosing difficult cases. QMR (Quick Medical Reference), a microcomputer adaptation of INTERNIST-1, incorporates the diagnostic functions of the earlier program, and also offers an electronic textbook mode.

Beginning in the 1960's, computers played an increasingly important role in engineering and industry. For example, in the 1960's, Rolls Royce Ltd. began to use computers not only to design the optimal shape of turbine blades for aircraft engines, but also to control the precision milling machines which made the blades. In this type of computer-assisted design and manufacture, no drawings were required. Furthermore, it became possible for an industry requiring a part from a subcontractor to send the machine-control instructions for its fabrication through the computer network to the subcontractor, instead of sending drawings of the part.

In addition to computer-controlled machine tools, robots were also introduced. They were often used for hazardous or monotonous jobs, such as spray-painting automobiles; and they could be programmed by going through the job once manually in the programming mode. By 1987, the population of robots in the United States was between 5,000 and 7,000, while in Japan, the Industrial Robot Association reported a robot population of 80,000.

Chemical industries began to use sophisticated computer programs to control and to optimize the operations of their plants. In such control systems, sensors reported current temperatures, pressures, flow rates, etc. to the computer, which then employed a mathematical model of the plant to calculate the adjustments needed to achieve optimum operating conditions.

Not only industry, but also commerce, felt the effects of computerization during the postwar period. Commerce is an information-intensive activity; and in fact some of the crucial steps in the development of information-handling technology developed because of the demands of commerce: The first writing evolved from records of commercial transactions kept on clay tablets in the Middle East; and automatic business machines, using punched cards, paved the way for the development of the first programmable computers.

Computerization has affected wholesaling, warehousing, retailing, banking, stockmarket transactions, transportation of goods - in fact, all aspects of commerce. In wholesaling, electronic data is exchanged between companies by means of computer networks, allowing order-processing to be handled automatically; and similarly, electronic data on prices is transmitted to buyers.

The key to automatic order-processing in wholesaling was standardization. In the United States, the Food Marketing Institute, the Grocery Manufacturers of America, and several other trade organizations, established the Uniform Communications System (UCS) for the grocery industry. This system specifies a standard format for data on products, prices and orders.

Automatic warehouse systems were designed as early as 1958. In such systems, the goods to be stored are placed on pallets (portable platforms), which are stacked automatically in aisles of storage cubicles. A computer records the position of each item for later automatic retrieval.

In retailing, just as in wholesaling, standardization proved to be the key requirement for automation. Items sold in supermarkets in most industrialized countries are now labeled with a standard system of machine-readable thick and thin bars known as the Universal Product Code (UPC). The left-hand digits of the code specify the manufacturer or packer of the item, while the right-hand set of digits specify the nature of the item. A final digit is included as a check, to make sure that the others were read correctly. This last digit (called a modulo check digit) is the smallest number which yields a multiple of ten when added to the sum of the previous digits.

When a customer goes through a check-out line, the clerk passes the purchased items over a laser beam and photocell, thus reading the UPC code into a small embedded computer or microprocessor at the checkout counter, which adds the items to the customer's bill. The microprocessor also sends the information to a central computer and inventory data base. When stocks of an item become low, the central computer generates a replacement order. The financial book-keeping for the retailing operation is also carried out automatically by the central computer.

In many places, a customer passing through the checkout counter of a supermarket is able to pay for his or her purchases by means of a plastic card with a magnetic, machine-readable identification number. The amount of the purchase is then transmitted through a computer network and deducted automatically from the customer's bank account. If the customer pays by check, the supermarket clerk may use a special terminal to determine whether a check written by the customer has ever "bounced".

Most checks are identified by a set of numbers written in the Magnetic-Ink Character Recognition (MICR) system. In 1958, standards for the MICR system were established, and by 1963, 85 percent of all checks written in the United States were identified by MICR numbers. By 1968, almost all banks had adopted this system; and thus the administration of checking accounts was automated, as well as the complicated process by which a check, deposited anywhere in the world, returns to the payers bank.

Container ships were introduced in the late 1950's, and since that time, container systems have increased cargo-handling speeds in ports by at least an order of magnitude. Computer networks contributed greatly to the growth of the container system of transportation by keeping track of the position, ownership and contents of the containers.

In transportation, just as in wholesaling and retailing, standardization proved to be a necessary requirement for automation. Containers of a standard size and shape could be loaded and unloaded at ports by specialized tractors and cranes which required only a very small staff of operators. Standard formats for computerized manifests, control documents, and documents for billing and payment, were instituted by the Transportation Data Coordinating Committee, a non-profit organization supported by dues from shipping firms.

In the industrialized parts of the world, almost every type of work has been made more efficient by computerization and automation. Even artists, musicians, architects and authors find themselves making increasing use of computers: Advanced computing systems, using specialized graphics chips, speed the work of architects and film animators. The author's traditional typewriter has been replaced by a word-processor, the composer's piano by a music synthesizer.

In the Industrial Revolution of the 18th and 19th centuries, muscles were replaced by machines. Computerization represents a Second Industrial Revolution: Machines have begun to perform not only tasks which once required human muscles, but also tasks which formerly required human intelligence.

In industrial societies, the mechanization of agriculture has very much reduced the fraction of the population living on farms. For example, in the United States, between 1820 and 1980, the fraction of workers engaged in agriculture fell from 72 percent to 3.1 percent. There are signs that computerization and automation will similarly reduce the number of workers needed in industry and commerce.

Computerization is so recent that, at present, we can only see the beginnings of its impact; but when the Second Industrial Revolution is complete, how will it affect society? When our children finish their education, will they face technological unemployment?

The initial stages of the First Industrial Revolution produced much suffering, because labor was regarded as a commodity to be bought and sold according to the laws of supply and demand, with almost no consideration for the needs of the workers. Will we repeat this mistake? Or will society learn from its earlier experience, and use the technology of automation to achieve widely-shared human happiness?

The Nobel-laureate economist, Wassily W. Leontief, has made the following comment on the problem of technological unemployment:

"Adam and Eve enjoyed, before they were expelled from Paradise, a high standard of living without working. After their expulsion, they and their successors were condemned to eke out a miserable existence, working from dawn to dusk. The history of technological progress over the last 200 years is essentially the story of the human species working its way slowly and steadily back into Paradise. What would happen, however, if we suddenly found ourselves in it? With all goods and services provided without work, no one would be gainfully employed. Being unemployed means receiving no wages. As a result, until appropriate new income policies were formulated to fit the changed technological conditions, everyone would starve in Paradise."

To say the same thing in a slightly different way: consider what will happen when a factory which now employs a thousand workers introduces microprocessor-controlled industrial robots and reduces its work force to only fifty. What will the nine hundred and fifty redundant workers do? They will not be able to find jobs elsewhere in industry, commerce or agriculture, because all over the economic landscape, the scene will be the same.

There will still be much socially useful work to be done - for example, taking care of elderly people, beautifying the cities, starting youth centers, planting forests, cleaning up pollution, building schools in developing countries, and so on. These socially beneficial goals are not commercially "profitable". They are rather the sort of projects which governments sometimes support if they have the funds for it. However, the money needed to usefully employ the nine hundred and fifty workers will not be in the hands of the government. It will be in the hands of the factory owner who has just automated his production line.

In order to make the economic system function again, either the factory owner will have to be persuaded to support socially beneficial but commercially unprofitable projects, or else an appreciable fraction of his profits will have to be transferred to the government, which will then be able to constructively re-employ the redundant workers.

The future problems of automation and technological unemployment may force us to rethink some of our economic ideas. It is possible that helping young people to make a smooth transition from education to secure jobs will become one of the important responsibilities of governments, even in countries whose economies are based on free enterprise. If such a change does take place in the future, while at the same time socialistic countries are adopting a few of the better features of free enterprise, then one can hope that the world will become less sharply divided by contrasting economic systems.

14.7 Neural networks

Physiologists have begun to make use of insights derived from computer design in their efforts to understand the mechanism of the brain; and computer designers are beginning to construct computers modeled after neural networks. We may soon see the development of computers capable of learning complex ideas, generalization, value judgements, artistic creativity, and much else that was once thought to be uniquely characteristic of the human mind. Efforts to design such computers will undoubtedly give us a better understanding of the way in which the brain performs its astonishing functions.

Much of our understanding of the nervous systems of higher animals is due to the Spanish microscopist, Ramón y Cajal, and to the English physiologists, Alan Hodgkin and Andrew Huxley. Cajal's work, which has been confirmed and elaborated by modern electron microscopy, showed that the central nervous system is a network of nerve cells (neurons) and threadlike fibers growing from them. Each neuron has many input fibers (dendrites), and one output fiber (the axon), which may have several branches.

It is possible the computers of the future will have pattern-recognition and learning abilities derived from architecture inspired by our understanding of the synapse, by Young's model, or by other biological models. However, pattern recognition and learning can also be achieved by programming, using computers of conventional architecture. Programs already exist which allow computers to understand both handwriting and human speech; and a recent chess-playing program was able to learn by studying a large number of championship games. Having optimized its parameters by means of this learning experience, the chess-playing program was able to win against grand masters!

Like nuclear physics and genesplicing, artificial intelligence presents a challenge: Will society use its new powers wisely and humanely? The computer technology of the future can liberate us from dull and repetitive work, and allow us to use our energies creatively; or it can produce unemployment and misery, depending on how we organize our society. Which will we choose?

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