Remarkable Physicists

From Galileo to Yukawa

Ioan James

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The 250 years from the second half of the seventeenth century saw the birth of modern physics and its growth into one of the most successful of the sciences. The reader will find here the lives of fifty of the most remarkable physicists from that era described in brief biographies. All the characters profiled have made important contributions to physics, through their ideas, through their teaching, or in other ways. The emphasis is on their varied life-stories, not on the details of their achievements, but, when read in sequence, the biographies, which are organized chronologically, convey in human terms something of the way in which physics was created. Scientific and mathematical detail is kept to a minimum, so the reader who is interested in physics, but perhaps lacks the background to follow technical accounts, will find this collection an inviting and easy path through the subject's modern development.

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From Galileo to Yukawa

Ioan James

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Preface

This book is intended for those who would like to read something, but not too much, about the life-stories of some of the most remarkable physicists born between the middle of the sixteenth century and the first decade of the twentieth, a period of just over 350 years. There are five subjects in each of the ten chapters, making fifty profiles altogether. The subjects have all made an important contribution to physics, through their ideas, through their teaching, or in other ways. The emphasis is mainly on their varied life-stories, not on the details of their achievements. By minimizing technical detail, I have been able to concentrate on a representative selection of physicists whose lives seem to me of special interest. The reader who wishes for more detail about the technicalities can so easily find it elsewhere that only the briefest of indications are given here.

In writing this book I have had in mind the reader who is interested in physics but is not necessarily familiar with the history of the subject. The biographies are arranged chronologically by date of birth, so that when read in sequence they convey in human terms something of the way in which physics developed. Each of the profiles is illustrated by a portrait of the subject, except for one case where none is known. As we shall see, the remarkable physicists of our period were a surprisingly diverse collection of people. One thing that emerges clearly is that there is no such thing as a typical physicist. Any student of physics who might be looking for a role model will find some interesting possibilities. At the end I have tried to draw some general conclusions. I have also provided some suggestions for further reading.

My thanks are due to the many people who have helped me either by reading parts of the text in draft and commenting or by dealing with particular questions. Among them are Blemis Bleaney, David Brink, Sir Roger Elliott, Dominic Flament, Robert Fox, John Roche, Paolo Salvatore, Rosemary Stewart, David Thomson, David Tranah, and John Tyrer. As far as possible the sources of the illustrations and longer quotations are given at the end of the book.

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Prologue

All of us, as children, have a strong desire to learn about the natural world. What we are taught about it, at home and at school, is the result of centuries of enquiry and thought. To make it easy for us we are not taken through all the stages of the historical process of discovery, and may not realize the epic struggle which went on in order to establish the basic facts of physics. What we are taught about heat, light and sound may seem rather obvious, but it was not always so. We may be knowledgeable about the universe but much of what we know was discovered within living memory. If we are at all scientifically inclined we will be fascinated by electricity and magnetism and by many other mysterious phenomena that were poorly understood until recently and perhaps are not fully understood even now.

I have chosen to begin with Galileo and Kepler, key figures in the Renaissance of science. The scientific revolution which followed fifty years later is associated primarily with the ideas of Newton but of course others were involved, notably Huygens. In the eighteenth and nineteenth centuries there were enormous advances in the understanding of heat, light, sound, electricity and magnetism, to name just a few of the fundamental concepts. At the end of the nineteenth century it was possible to find scientists who believed that there were no more major discoveries in physics to be made. However, the twentieth century saw the birth of quantum theory and the theory of relativity. Although modern physics arose out of classical physics, there was such a profound and far-reaching discontinuity that use of the term revolution is again justified. Although its implications are still being worked out, a natural place to finish my story seems to be with the period sometimes referred to as the golden age. I begin, therefore, with physicists born in the middle of the eighteenth century, and end with some of those born in the early twentieth. To have included subjects born later in the twentieth century, when the invisible college of physics was growing so rapidly in size, would have unduly extended a book that is already long enough.

Although the subjects of these profiles are of many different nationalities, I would have preferred to have achieved a wider geographical spread. Including Russia, ten different European countries are represented; Britain, France and Germany are particularly strongly represented, with justification, I believe. However, only four countries outside Europe are represented, the USA, New Zealand, India and Japan. To a large extent this is a reflection of the way physics has developed. In many countries it is only relatively recently that remarkable physicists have begun to appear. I would also have liked to include more women, but until quite recently it was so difficult for a woman to become a physicist that it is surprising that so many succeeded, rather than so few. Even today it is quite normal for a woman to abandon a promising career on marriage, in order to concentrate on raising a family.

Biographies of the men and women who contributed something important to physics in this period do not all make interesting reading; careful selection is necessary. With an eye to variety I have chosen those which seemed to me the most remarkable. There were many other subjects I should like to have included, but not enough is on record to allow a satisfactory profile to be written. It is not sufficient just to rely on an obituary notice or eulogistic memorial address. All too often personal papers have been lost and no biography has been written because not much survives for a biographer to work on. For example, take the case of Rudolf Clausius, one of the greatest German physicists of the nineteenth century. We know that he was severely wounded during service as a non-combatant in the Franco-Prussian war. We know that he was married and had six children, that his wife died in childbirth and that he married again. However, the only aspect of his personality that can be inferred from comments of his contemporaries is his contentious nature. We read in letters of 'that grouch Clausius'; in portraits we see a strong, unforgiving face. That is about all there is on record about his life, apart from listing the successive stages in his career.

The period from the birth of Galileo Galilei in 1564 to the death of Louis de Broglie in 1987 spans over four centuries, during which there were substantial changes in scientific terminology. The term physics, in anything like the sense we use it today, had not come into use at the start of our period; the term natural philosophy was often used instead, and physicists were referred to as philosophers. Of course men like Descartes, Leibniz and Kant were philosophers in the modern sense, but they were deeply interested in physics as well and so the former usage is not inappropriate. In the eighteenth century the Paris Academy distinguished between the mathematical sciences, which included physics, and the physical sciences, which did not. In fact experimental physics was in its infancy, and it was natural to group theoretical physics with mathematics. University students who later became physicists normally started out as mathematicians. Nowadays mathematical physics is usually regarded as part of mathematics and theoretical physics as part of physics but in many respects the distinction is an artificial one and serves no purpose in what follows.

Mediaeval universities had much in common, with curricula based on the *quadrivium* and *trivium*. After the Reformation, however, they developed in different ways in different parts of Europe, although Latin remained the academic language. Throughout the eighteenth century and even later, they were almost exclusively concerned with education, especially preparation for entry into the professions. Divinity, law and medicine were taught, but the physical sciences were largely ignored. Until relatively recently universities did not regard research as part of their mission. That was left to academies, especially those of Berlin, Paris and St Petersburg. Such academies were in the nature of research institutes, under control of the state.

British scientists, above all Newton, played a leading role in the scientific revolution of the seventeenth century, but the ascendancy of Britain did not last. Towards the end of the eighteenth century Britain was being left far behind in the field of scientific research after more than a century of steady progress on the continent, particularly in France. 'It is a source of wonder and regret to many that this island, having astonished Europe by the most glorious display of talents in mathematics and the sciences dependent upon them, should have suddenly suffered its ardour to cool and almost entirely to neglect those studies in which it infinitely excelled other nations', wrote one of the few British scientists who tried to do something about it. In France science was becoming increasingly professionalized; in other countries this process occurred much later. As a result France came to dominate most aspects of early-nineteenth-century science. The foundations of theoretical physics were laid in Paris and transmitted in various ways to other countries. Laplace's physical astronomy was followed by Poisson's theory of electricity, Ampère's theory of electromagnetism, Fresnel's theory of light and Fourier's theory of heat.

In Britain, the Royal Society of London did not function like the continental academies but nevertheless served as a focus for research activity. 'Men of science', to use the phrase in vogue, might well become fellows of the Royal Society but were not usually attached to any other institution. Apart from a few wealthy amateurs, scientific training was still largely an apprenticeship entered into for love of the subject. Only a few scientists made a living through teaching or other scholarly professions; a few scattered practitioners found posts at the Royal Institution, the British Museum or similar establishments, but no-one embraced science as he might the church or law or medicine to support himself and a family. In the informal apprenticeship that produced a scientific practitioner, a master guided the novice into full participation in his speciality through advice or example. Discussion of scientific principles and findings, observation of scientific activities and criticism of scientific efforts were the chief tools of instruction. The master directed the reading of his apprentice, showed him how to use apparatus and how to design experiments and instruments, and introduced him to the scientific community.

Although Britain had no precise equivalent of the continental academies, the combination of the Royal Society and the Royal Institution served just as well, if not better. Moreover, there was hardly a town of any consequence that could not boast a Philosophical Society, where the progress of science could be reported upon, and the annual meetings of the British Association for the Advancement of Science performed a similar function at a national level. In nineteenth-century Britain, as we shall see, it was the north, rather than the south, which took the lead in scientific education and research, partly because the Scottish universities had always been strong in science. In the second half of the century reform of the ancient universities of Oxford and Cambridge, and the foundation of a number of new institutions of higher education, began to transform the situation in England.

Thus a distinctive school of physics developed in Britain, and the same was true in other countries, although at all times the subject tended to transcend national boundaries. While the international character of the subject was maintained, a particularly strong rivalry developed between the French school and the German school of physics. From about 1830 science in Germany became increasingly strong; towards the end of the nineteenth century Germany's reputation in chemistry, physics, biology and medicine was rivalled only by Britain. In the twentieth century, if scientific success can be measured by the award of Nobel prizes, Germany's record far outshone that of any other country. Of all the 100 Nobel prizes in science awarded between 1901, when the awards were founded, and 1932, the year before Hitler came to power, no less than 33 were awarded to Germans or scientists working in Germany. Britain had 18 laureates; the USA had six. Of the German laureates about a quarter of the scientists were of Jewish extraction, although the Jewish population made up no more than one per cent of the German people at the time. It might be added that Austria-Hungary supplied a considerable proportion of the physicists who contributed most to German leadership in scientific research.

Until the nineteenth century scientific research was usually published in book form. This was the age of the treatise, of which Newton's

Principia is a prime example. However, correspondence between the leading researchers also played an important role, as we shall see. At the same time individuals moved around a surprising amount, considering how difficult travelling was until quite recently, and they disseminated new ideas in the process. The earliest scientific journals were *Le journal des sçavans* and the *Philosophical Transactions* of the Royal Society of London. Both first appeared in 1665, the French journal a few months before the British. The former was clearly intended to serve the interests of the European educated public generally; after the French Revolution it was renamed the *Journal des savants*, and became more of a literary and less of a scientific journal. The latter was always more focused on science but even so was originally designed to 'give some accompt of the present undertakings, studies and labours of the ingenious in many considerable parts of the world'. Similar publications soon began to appear in other countries. It has been estimated that, out of 755 titles of serials of some scientific interest that had appeared up to the end of the eighteenth century, 401 were published in Germany, 96 in France, 50 in Great Britain, 43 in the Netherlands and 37 in Switzerland. The first specialized journal in physics is generally considered to have been the *Journal der Physik*, issued at Halle and Leipzig from 1790. The *Philosophical Magazine* in England, which is still extant, began to appear in 1798.

In what follows, expressions in foreign languages will usually be translated into English, with or without the original as seems appropriate. Literal translation is sometimes unsatisfactory, for example solar system seems preferable to world system for the French *système du monde* and counsellor or excellency to privy councillor for the German title *Geheimrat*. Expressions such as *Lycée* and *Grande Ecole* in French and *Gymnasium* and *Technische Hochschule* in German seem better left untranslated. It is important to remember that the meaning of a term may vary a good deal according to time and place. The term professor might often be interpreted as lecturer, otherwise it might seem strange that almost all university posts were professorships and that they could be held in plurality: they were often ill-paid. It seems best to elucidate any other points that might cause difficulty, such as the special features of the educational systems in different countries, when they first arise. Regarding place-names, I prefer the old name Breslau rather than the new name Wrocław, for example, but Dubrovnik rather than Ragusa and Regensburg rather than Ratisbon, as being more likely to be familiar to the reader: at first I write Leyden, later Leiden – consistency in such matters seems unnecessary.

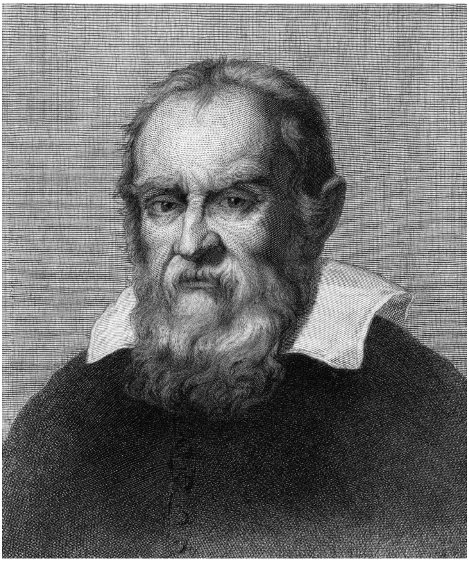
1 From Galileo to Daniel Bernoulli

Our first five remarkable physicists were born in the 137 years from 1564 to 1700. They came from Italy, Germany, the Netherlands, England and Switzerland.

Galileo Galilei (1564–1642)

The great scientist we know as Galileo was born in Pisa on February 15, 1564. He was the eldest son of the notable composer, lutenist and musical theorist Vincenzio Galilei, of a long-established Florentine family, and his wife Giulia (née Ammananti), a native of Pisa who considered herself socially superior to her husband. They had five or six other children. Like Dante, Leonardo, Michelangelo and other great Italians of that period he is universally known by his first name rather than by his family name. In 1574 the family moved to Florence. After four years of education in the Camaldolese abbey of Vallombrosa on the upper Arno, Galileo was expecting to make his career in the church. However, his father decided otherwise and arranged for his son to live in Pisa with a cousin, who would train him as a wool merchant. Before long it became clear that the young man was unusually able and so, at the age of seventeen, he entered the University of Pisa, training to become a doctor in accordance with his father's wishes. However, he was dissatisfied with the lectures provided, left after four years without taking a degree, and when he returned home it was to work on mathematics. Apparently he was introduced to the subject by Ostilio Ricci, said to have been a student of Tartaglia's, who was mathematician at the court of the Grand Duke of Tuscany. Galileo took pupils and gave some public lectures on mathematics in Siena and Florence. In 1587 he visited the leading Jesuit astronomer and mathematician Father Christopher Clavius at the Gregorian University in Rome, who was interested in his first research papers, one on the determination of centres of gravity of parabolic conoids and another on an ingenious balance (*La bilancetta*) he had designed for determining specific weights with precision.

In 1589 Galileo was appointed to a teaching post in mathematics at the priest-dominated University of Pisa, at that time something of an intellectual backwater. During his time there he wrote, but did not publish, a



paper called *De motu*, about the flight of projectiles and other dynamical problems. Three years later he moved to a professorship in Padua, one of the leading universities of Europe, where Copernicus had taught and Dante had studied. Padua, in the Venetian Republic, offered a far more congenial atmosphere than Pisa. Professors were not well-paid; they were expected to supplement their modest salaries by private tuition. Galileo was an excellent teacher, whose students were devoted to him. He presided over a lively household of young men to whom he taught practical subjects such as military architecture, elementary astronomy and perspective. He also ran a small workshop to manufacture scientific instruments, and, as a result of his entrepreneurship, he became a man of means. Even so, after the death of his father in 1591, he found it difficult to meet his responsibilities towards his improvident brother, who frequently came to him for money, also his sisters needed dowries if they were to marry, so that at times he ran the risk of being arrested for debt.

In the nearby city of Venice Galileo found friends in the nobility. The most important of these was Gianfrancesco Sagredo, a confirmed bachelor, who seemed to have been exhausted by dissipation in his youth. However, as he grew older he turned to tamer pursuits, including wild parties at his country estate on the River Brenta. Sagredo was interested in science and he formed a lasting friendship with Galileo, which they continued by correspondence when the Doge sent Sagredo to Aleppo for three years in a diplomatic capacity in 1608. Galileo never married but he formed a lasting relationship with a twenty-one-year-old Venetian serving-woman named Marina Gamba, said to be beautiful, hot-tempered, lusty and probably illiterate. Galileo's shrewish mother thoroughly disapproved of her and caused trouble. Marina had three children by Galileo: Vincenzo, Virginia and Livia. Galileo took an interest in their son's education; once they were old enough he placed their daughters in the convent of San Matteo in Arcetri, on the outskirts of Florence.

Galileo was already coming round to the view that the heliocentric system of Copernicus was much more plausible than the geocentric system of Aristotle and Ptolemy. In this he was influenced by the German astronomer Johannes Kepler, whose profile comes next. Among other things, Galileo invented a machine for raising large amounts of water from aquifers, an air thermoscope and a computing device for geometrical and ballistic purposes described in his first printed work *Le operazioni del compasso geometrico e militare* (Padua, 1606), which described the operation of a lightweight military compass he had designed in collaboration with a Venetian toolmaker. In pure science his research led him about 1602 to the discovery of the isochronicity of the pendulum and to the preliminary but wrong discussion of the law of falling bodies. In 1609 he was the first to apply the newly invented telescope to astronomical observations, revealing the mountains on the moon, numerous stars invisible to the naked eye, the nature of the Milky Way and four of Jupiter's satellites (named the Medicean stars). These sensational discoveries were described in his *Sidereus nuncius* (*The Sidereal Messenger*) (Venice, 1610), one of the most important scientific books of the seventeenth century, which at once made Galileo famous all over Europe. The popular excitement was overwhelming.

The Pope had declared the first year of the new century to be a Jubilee year. It was to be a year of celebration but also of renewed determination to stem the tide of reform. The greatest intellectual of the church of Rome, Cardinal Robert Bellamine, led the drive to stamp out heresy. One of the first victims was the Dominican friar Giordano Bruno, who was imprisoned, tortured and burnt at the stake for his beliefs. He conjectured that 'There are countless constellations, suns and planets; we see only the suns because they give light; the planets remain invisible, for they are small and dark. There are also numberless earths, circling round their suns.'

Students came from many parts of Europe to sit at Galileo's feet, including French, English, German and Polish nobility, also the Swedish King Gustavus Adolphus. The new Grand Duke of Tuscany, young Cosimo de Medici, was one of his former pupils. In 1610, feeling he was not sufficiently appreciated in the Venetian Republic, Galileo relinquished his chair at the University of Padua after eighteen years of great creative activity and accepted an appointment as chief mathematician and philosopher at the court of the Medicis. Back in Florence, he devoted his entire energy to scientific research under the benevolent protection of the Grand Duke. In his social circle, the place of Sagredo was taken by a wealthy and accomplished young patrician named Filippo Salviati. His country retreat Le Selve in the hills above the lower Arno became a centre for philosophical discussions, in which Galileo was surrounded by young disciples.

Galileo decided it was time for another visit to Rome, this time as a kind of scientific ambassador, sponsored by the Grand Duke. Galileo was received by Pope Paul V, the successor of Clement VIII, and generally lionized. He set about promoting the new cosmology by demonstrating the latest discoveries. These included the phases of the planet Venus, the composite structure of Saturn and the existence of sun-spots, all described in his *Istoria e dimostrazioni intorno alle macchie solari* (Treatise on Sunspots) (Rome, 1613). However, the Jesuits at the Gregorian University continued to cling to the old cosmology. One of them was Father Clavius, on whom he had called twenty-four years earlier; the German mathematician took note of Galileo's discoveries, but refused to embrace Copernicanism.

Galileo found an important new patron in Federico Cesi, an influential young nobleman who possessed an enormous curiosity and the courage to break the confines of his aristocratic upbringing. When he was only eighteen Cesi had established the Accademia dei Lincei, arguably the first successful scientific society to be founded in the seventeenth century. The stated aim of the Lincei was to bring together 'philosophers who are eager for real knowledge, and who will give themselves to the study of nature, and especially to mathematics. At the same time, it will not neglect the ornaments of elegant literature and philology, which like graceful garments, adorn the whole body of science.' Initially the society had only four members, all non-scientists and all under thirty years of age; there hung about the Lincei a certain air of the occult and of pseudo-science, even the taint of scandal. The society held its meetings in Cesi's palace, which contained a splendid library, including many proscribed books, and a collection of scientific instruments, specimens and curiosities. Its early fame rested mainly on Galileo's participation; later it gave him much-needed support, stimulus and encouragement. Cesi was too powerful to have to worry about what the Jesuits at the Gregorian University thought.

Galileo was becoming more and more audacious in pointing to the incompatibility of the new celestial phenomena with traditional astronomy. He openly confessed his Copernican conviction, already stated in a letter to Kepler, at the same time as he successfully attacked current views on hydrostatics in his *Discorso intorno alle cose che stanno in su l'acqua* (*Bodies in Water*). Increasingly Galileo had to defend his discoveries and opinions against numerous attacks from scientific opponents and jealous academic enemies. A conspiracy among the latter aiming at Galileo's downfall led first to an abusive sermon against him in Florence in 1614. There were signs of paranoia in his reaction, although the enemies were real enough. The most powerful of these was Cardinal Bellarmine, the persecutor of Giordano Bruno, who warned him not to defend the Copernican system in public. As a result, he wrote a letter to Christina, the mother of the Grand Duke, giving his carefully considered opinions about the proper relation between science and religion; this *Letter to the Grand Duchess Christina* was not published until 1636.

Galileo was already fifty years of age. He was suffering from arthritis, a condition of long standing, and from pains in the chest and kidneys. On his return from Rome he first took advantage of Salviati's villa Le Selve to recuperate before settling down in a modest villa of his own, at Bellosguardo, overlooking Florence and not too far from Arcetri where his daughters lived inside their convent. However, it is hardly surprising that the following years saw some decline in his scientific activity. He mainly occupied himself with computing tables of the motion and eclipses of the moons of Jupiter, which could be used to determine longitude at sea. He tried in vain to sell this idea to the Spanish and Dutch governments. In 1618 he was involved in a bitter argument over the nature of comets, which lost him the sympathy of his former supporters among the Roman Jesuits. A result of this controversy was the polemical work *Il saggiatore* (*The Assayer*) (Rome, 1623) in which Galileo expressed his thoughts on epistemological and methodological questions, stressing the necessity of quantitative experiments and observations and the strength of hypothetical–deductive reasoning.

In 1623 one of his former supporters, Cardinal Maffeo Barberini, became Pope Urban VII, and, after a fourth visit to Rome, Galileo felt himself encouraged to begin with the composition of a major work on astronomy, planned many years before and finally published under the title *Dialogo sopra i due massimi sistemi del mondo* (*Dialogue Concerning the Two Chief World Systems*). This was a technical account in the form of a dialogue among a supporter of the Aristotelian–Ptolemaic tradition named

Simplicio, a youthful enquiring mind named Sagredo and an advocate of the new astronomy named Salviato. Galileo had tried to safeguard himself by letting Simplicio prevail, and the book was published with the imprimatur of the ecclesiastical authorities. Nevertheless the strength of Salviato's arguments was evident.

The initial reception of the book was generally favourable, but it gave Galileo's enemies the opportunity they had been waiting for. The Pope thought the imprimatur should never have been granted and tried to have the book suppressed, but it was too late. He decided that Galileo must stand trial and summoned him to Rome. The Grand Duke was powerless to shield Galileo from the wrath of the Pope. For reasons of health Galileo asked for the proceedings to be held in Florence. This was refused but, as a concession, when he arrived in Rome, instead of being committed to prison while awaiting trial, he was allowed to live in the Tuscan embassy. Formally the charge against him was one of disobedience. His accusers maintained that Bellamine in 1616 had formally admonished Galileo not to promote Copernicanism in public; Galileo denied this, documentation was lacking and Bellamine was no longer alive to give evidence. During the trial the ailing Galileo was imprisoned in the Vatican, until eventually, more dead than alive and under threat of torture, he was forced solemnly to abjure his Copernican convictions before the Congregation of the Holy Office, before being sentenced to life imprisonment and punished in other ways.

Initially he was confined to the palace of the Archbishop Ascanio Piccolomini of Siena, a man of broad cultural interests, where he was treated as an honoured guest. Before long, however, the Pope's agents reported that the episcopal palace did not keep him sufficiently isolated and he was allowed to move to his villa in Bellosguardo. In 1631, finding the journey from there to see his daughters too much, Galileo proposed to move to a house in Arcetri itself. The Pope agreed that he could do so, although still effectively under house arrest, since he was not even allowed to go to nearby Florence without permission, which was sometimes withheld. His younger daughter Livia suffered from depression but Galileo was to find great comfort in the company of his elder daughter Virginia in his declining years. In the simple beauty of the weekly letters she sent him, as 'Suor Maria Celeste', we can follow her efforts to comfort him and lift his spirits; unfortunately his side of the correspondence has not survived. Sadly, she died from dysentery not long after he had arrived in Arcetri, at the age of thirty-three.

Galileo's own health was seriously threatened; there was a troublesome hernia and palpitations of the heart, and he also suffered from insomnia and melancholia. He continually heard his beloved daughter calling him. The Florentine Inquisitor was right to believe that the aged Galileo would never again attempt to promote Copernicanism. In fact, Galileo went further by stating that the falsity of Copernicanism must not on any account be called into doubt, especially by Catholics. All Copernican conjectures, he wrote, are removed by the most solid arguments from God's omnipotence. He had resigned himself to the fact that his own part in the campaign to establish Copernicanism was over, although his personal convictions remained the same and many were protesting against the injustice of his condemnation and sentence.

Galileo engaged in new research, although hampered both by cataracts and by glaucoma, ending in complete blindness, and by the constant supervision of the Inquisition. He succeeded in finishing his final and most important work, the *Discorsi e dimostrazioni matematiche intorno a due nuove scienze* (*Discourses on Two New Sciences*) (Leyden, 1638), which was, significantly, published beyond the reach of the Inquisition. This work, containing among other things the proof of the laws governing the fall of a body in a vacuum, the principle of the independence of forces and the complete theory of parabolic ballistics, was destined to become one of the cornerstones upon which Huygens and Newton one generation later built classical mechanics. The laws of fall made it possible to study accelerated motion. Simplicio, Sagredo and Salviati reappear to debate the arguments in another dialogue like the one he had used in 1632; Galileo's fondness for this manner of presentation may have come from his father, who in 1581 had published a *Dialogo della musica antica e moderna*. Galileo died at Arcetri during the night of January 8, 1642. He was buried privately in Santa Croce, the great church where so many famous Tuscans lie, but not in the Galilei family tomb, for fear of Papal disapproval. No monument to his memory was erected until 1737, when he was re-interred and the skeleton of a young woman was found beneath his in the original grave; it is thought that this could have been his beloved daughter.

Galileo had a versatile mind. He was an accomplished amateur musician and a master of the vernacular language; his polemical work *Il saggiatore* is one of the Italian classics. He occupied himself with almost every branch of physics, but is chiefly remembered for the example he gave of the efficacy of the hypotheco-deductive method combined with quantitative experiments. In general history too he occupies an important place because of his personal fate, which was an important factor in the widening fissure between natural science and the spirituality of the counter-Reformation. The last traces of official anti-Copernicanism were not removed until 1822. While geocentrism was the official doctrine, there was some latitude for teaching heliocentrism as a working hypothesis in schools and universities where Jesuits were in control.

Johannes Kepler (1571–1630)

Kepler was a near-contemporary of Galileo but his life-story was very different, as was his family background. He was born in the small Lutheran town of Weil der Stadt, near Stuttgart, on December 27, 1571. Judging by the account Kepler wrote of his early life, he seems to have had a most miserable childhood. He described his father Heinrich as 'criminally inclined, quarrelsome, liable to a bad end' and his mother Catharina (née Guldenmann), as 'small, thin, swarthy, gossiping and quarrelsome', adding that 'treated shabbily, she could not overcome the brutality of her husband'. When he was three years old, his father joined a group of mercenary soldiers to fight the Protestant uprising in Holland. His mother followed her husband to Flanders. The children were abandoned to the care of grandparents who treated them roughly. When their parents returned in 1576 the family, in disgrace because of Heinrich's part in the persecution of Protestants, had

to leave Weil for nearby Leonberg, in the Grand Duchy of Württemberg. Heinrich rejoined the infamous Duke of Alba's military service for a few more years; by 1588 he had abandoned his family forever.

The future astronomer was a sickly child, with thin limbs and a large pasty face surrounded by dark curly hair. He was born with defective eyesight – short-sighted in one eye, multiple vision in the other. His stomach and gall bladder gave constant trouble; and he nearly died from smallpox. He began his education at the German Schreibschule in Leonberg but soon moved to the Latin school, there laying the foundation for the complex Latin style displayed in his later writings. After a period of 'hard work in the country', during which he did not attend school at all, he entered the Adelberg monastery school at thirteen; and two years later enrolled at the more senior Maulbronn, one of the preparatory schools for the Protestant University of Tübingen. In October 1587 Kepler formally matriculated at the university; but because no room was available at the Stift, the seminary where, as a student supported by the enlightened Duke of Württemberg, he was expected to lodge, he continued at Maulbronn for another two years. In September 1588 he passed the baccalaureate examination at the university, although he did not actually take up residence there until the following year. He was unpopular with his fellow-students, who gave him a hard time.

At Tübingen, Kepler's thought was profoundly influenced by Michael Maestlin, the professor of mathematics and astronomy. Although Maestlin was at best a very cautious Copernican, the 1543 *De revolutionibus* he owned is probably the most thoroughly annotated copy extant; he edited the 1571 edition of the *Prutenicae tabulae* and used them to compute his own *Ephemerides.* Kepler was an exemplary student; and, when he applied for a renewal of his scholarship, the university senate noted that he had 'such a superior and magnificent mind that something special may be expected of him'. Nevertheless, although Kepler himself wrote concerning his university education that 'nothing indicated to me a particular bent for astronomy', in student disputations he often defended Copernicanism.

In August 1591 the twenty-year-old Kepler received his master's degree from Tübingen and thereupon entered the theological course. Halfway through his third and last year, however, there occurred an event that completely altered the direction of his life. The teacher of mathematics and astronomy at the Lutheran school in the Styrian capital of Graz had died, and Tübingen was asked to nominate a replacement. Kepler was chosen, and, although he was reluctant to abandon his intent of becoming a Lutheran pastor, at the age of twenty-two he embarked on the career destined to immortalize his name.

Kepler arrived in southern Austria in April 1594 to take up his duties as teacher and as provincial 'mathematicus'. In the first year he had few pupils in mathematical astronomy and in the second year none, so he was asked to teach Virgil and rhetoric as well as arithmetic. However, the young Kepler made his mark in another way; one of the duties of the mathematicus was to produce an annual calendar of astrological forecasts. His first calendar, for 1595, contained predictions of bitter cold, peasant uprisings and Turkish invasions. All were fulfilled, to the great enhancement of his local reputation. Five more calendars followed in annual succession, and later, when he had moved to Prague, he issued prognostications for the years 1602 to 1606. Later still Kepler produced a series of calendars from 1618 to 1624, excusing himself with the remark that, when his salary was in arrears, writing calendars was better than begging.

Kepler's attitude to astrology was mixed. He rejected most of the commonly accepted rules and repeatedly referred to astrology as the foolish stepdaughter of astronomy. However, casting horoscopes provided welcome supplementary income and later became a significant justification for his office as imperial mathematicus. Moreover, the profound feeling he developed for the harmony of the universe included a belief in a powerful accord between the cosmos and the individual. These views found their fullest development in the *Harmonicae mundi*, published towards the end of his life.

Meanwhile, just over a year after his arrival in Graz, Kepler's fertile imagination hit upon what he believed to be the secret key to the universe – the number, dimensions and motions of the planets. This theory, published in his decisively pro-Copernican treatise *Mysterium cosmographicum* of 1596, was based on the idea that the five regular solids space out the six known planets; each planetary orbit is circumscribed by a regular solid and has inscribed in it the solid of the next planet below. Although the principal idea was erroneous, Kepler established himself as the first (and, until Descartes, the only) scientist to demand physical explanations for celestial phenomena.

Kepler had submitted his manuscript to the scrutiny of the Tübingen senate because his publisher would not proceed without its approval. Although they raised no objection to the publication, he was requested to explain his discovery in a clearer and more popular style. When it appeared, the reasons for abandoning the Ptolemaic in favour of the Copernican system were set forth with remarkable lucidity. Kepler sent copies to various scholars, including Galileo and the great Danish astronomer Tycho Brahe. Its faults notwithstanding, *Mysterium cosmographicum* thrust Kepler into the front rank of astronomers. Seldom has so wrong a book been so seminal in directing the future course of science.

Meanwhile Kepler's friends arranged his marriage to Barbara Müehleck, the eldest daughter of a wealthy mill-owner. She was two years younger than Kepler and had been widowed twice. Early in 1596 Kepler sought her hand, but her family thought him beneath her and the negotiations were difficult and protracted. They insisted that the modest fortune she brought to their marriage be reserved for their children. The wedding took place the next spring, under ominous constellations, as Kepler noted in his diary. He soon realized that his wife would never understand anything of his work – 'simple of mind and fat of body' was Kepler's later description of her. Of their five children, one boy and one girl survived to adulthood.

The numerous Protestants in Graz remained unmolested by their Catholic rulers until 1598. Then, on a day in late September, all the teachers, including Kepler, were abruptly ordered to leave town before sunset. Although Kepler was allowed to return, unlike his colleagues, conditions remained tense. In the second half of the sixteenth century the Czech kingdom of Bohemia experienced great prosperity under the Habsburg emperor Rudolph II, who made Prague his capital and attracted to it a galaxy of artists, scholars, alchemists and magicians. In August 1599 Kepler learned that the wealthy, aristocratic Brahe had been appointed imperial mathematicus by Rudolph, with an exceptionally generous salary. Early in 1600, Kepler made an exploratory visit to the observatory Brahe had established at Benatky Castle, near Prague. It was equipped with scientific instruments of the highest quality, although telescopes had not yet come into use. Kepler respected the outstanding precision of Brahe's observational data and expected that he would be given access to them. However, Brahe treated him as a novice, rather than an independent investigator, and refused to share his results. The two astronomers soon quarrelled, but before Kepler returned to Graz they had achieved some degree of reconciliation.

In Graz, by this time, the counter-Reformation was taking effect, and in August 1600 Kepler and other Protestants were expelled from the predominantly Catholic city. Already deeply depressed by the death of his first two children, he decided to go back to Prague, with his family. When they arrived, Kepler found that Brahe's chief assistant, Longomontanus, had just died. Kepler was appointed in his place, but Brahe still refused to share his observational data, and there was further friction when payment of Kepler's salary was delayed. He returned to Graz in April 1601 on an extended visit occasioned by his father-in-law's death and the need to safeguard his wife's interests.

Eventually the differences between the two astronomers were patched up; then in the autumn Brahe was suddenly taken ill and towards the end of October he died. Almost at once Kepler was appointed to succeed him as imperial mathematicus, although five months passed before he received his first instalment of salary. One of his various duties was to complete Brahe's work on what became known as the *Tabulae Rudolphinae*, giving the positions of a great many stars and perpetual tables for calculating the positions of the planets on any date in the past or future. This task, involving enormous quantities of laborious calculations, was by no means congenial to Kepler, and, even when it had been completed, publication was delayed, as we shall see.

Kepler's main interest remained more in theoretical astronomy. He began to speculate that the solar system might be held together by magnetic attraction. Although this was not right, it represented an imaginative leap in the direction of universal gravitation. He also began to consider the possibility that the planetary orbits might be elliptic, with the sun at one focus, and here of course he was right. These ideas appeared in his next important book, the *Astronomia nova* of 1609. Unfortunately publication was held up, partly by the lack of imperial financial support but also by opposition from the heirs of Brahe. They took away Brahe's scientific instruments and allowed them to decay unused. They also tried to remove the vital records of his observations, but Kepler managed to prevent this.

Despite poor eyesight, Kepler was one of the pioneers of research into optics. He found a good approximation to the law of refraction; Descartes, the discoverer of the precise law, said that Kepler was his true teacher in optics, who knew more about this subject than did any of those that preceded him. This research was published in his *Dioptrice* of 1611, which also contains an account of a new astronomical telescope with two convex lenses. Towards the end of his life he wrote a small work on the gauging of wine casks, which is regarded as one of the significant works in the prehistory of the integral calculus. In lighter vein he also wrote a paper discussing why snowflakes are hexagonal.

Unlike Kepler himself, Catharina did not like living in Prague. She never felt comfortable in court circles. Moreover, she was often homesick and became upset when they ran short of money. He began to search for suitable employment in a place she would find more congenial. The need became pressing in May 1611 when Rudolph was deposed and Prague became a scene of bloodshed in the struggle for the kingdom. Moreover, Kepler's wife became seriously ill and their three children were stricken with smallpox, from which his favourite son died. Throughout his life Kepler kept trying to obtain a position in Protestant Württemberg, but without success, and now any remaining hopes of this were finally dashed when the theologians of Württemberg raised objections to his Calvinistic sympathies. He declined the offer of a professorship at the University of Bologna. Instead he decided to move to Linz, the chief city of Upper Austria, where he had been offered the specially created post of provincial mathematicus. However, before the move could take place his wife died from the typhus brought to Prague by the troops. It was not until January 1612 that he was able to leave for Linz; by then his appointment as imperial mathematicus had been renewed, so he was able to hold this as well as his provincial post, which was virtually a sinecure.

Soon after he arrived in Linz Kepler began to look for a new wife. In a letter he listed in detail eleven possibilities, and explained how God led him to choose the fifth, a woman who had evidently been considered beneath him by his family and friends. She was Susanna Reuttinger, a twenty-four-year-old orphan; the marriage was far happier than the first, but, of their seven children, five died in infancy or childhood, as had three of the five children of his first marriage. Then his aged but meddlesome mother was accused of and tried for witchcraft, and Kepler had to travel to Württemberg to arrange for her defence, which occupied much of his time and energy over the following three years. She was imprisoned and threatened with torture but in the end set free; she died shortly afterwards.

Kepler, a peaceful and deeply religious man, suffered greatly for the sake of his conscience throughout his life, particularly in Linz. His long stay there had started badly, for the local Lutheran pastor, who knew the opinion of the Württemberg theologians, excluded him from holy communion because of his Calvinistic tendencies. Kepler did not accept the exclusion willingly and made repeated appeals to the Württemberg consistory, but always in vain. While his co-religionists considered him a renegade, the Catholics tried to win him to their side.

All these troubles notwithstanding, Kepler published two major works during his fourteen years in Linz. The more important was his *Harmonicae mundi*, a work that had occupied him on and off for many years; this was published in 1618, with a dedication to King James the First of England. This has been described as a great cosmic vision woven out of science, poetry, philosophy, theology and mysticism. Kepler believed that the archetypal principles of the universe were based on geometry rather than on number, and it is in this work that the regular polyhedra known as the stellated dodecahedra make their debut. His other major work of this period is his *Epitome astronomiae Copernicanae*, a textbook of the Keplerian system. In the dedication he wrote 'I like to be on the side of the majority', but in his Copernicanism and in his deep-felt religious convictions he rather learned the role of being a member of a staunch, lonely minority. However, it was Galileo, a far bolder polemicist, who became the persuasive purveyor of the new cosmology.

When the counter-Reformation swept into Linz in 1625 an exception was made so that he was not banished, but his library was temporarily sealed and his children forced to attend Catholic services. By the summer of 1626 Linz was blockaded and Kepler's house, alongside the city wall, was burnt down. As soon as the long siege had been lifted, Kepler petitioned the emperor for permission to move to Ulm, where he knew that there were printers who could undertake the composition of the *Tabulae Rudolphinae*. Although he had worked in Linz longer than he had in any other place, Kepler was not sorry to leave. He packed up his household effects, books, manuscripts and printing equipment and travelled by boat up the Danube to Regensburg. After settling his wife and children he continued by road to Ulm to see the *Tabulae Rudolphinae* through the press. Even before that task had been finished, Kepler began to search for a new base. England was one possibility; in 1620 the English Ambassador Sir Henry Wootton had called on him in Linz and invited him to England, but nothing came of this. In fact Kepler never moved out of the region consisting of southern Germany, Bohemia and adjacent Austria.

In the end, reluctant to lose the financial security provided by his salaries as provincial and imperial mathematicus, Kepler went back to Prague to apply to Rudolph's successor for these appointments to be continued. The newly crowned king received him graciously, promising a reward for the dedication of the *Tabulae Rudolphinae*, but making it clear that the astronomer needed to become a Catholic if he wanted to remain in the imperial service. The imperial commander-in-chief, Albraecht von Wallenstein, was more accommodating. Wallenstein, then at the height of his power, had just been granted the duchy of Sagan in Silesia as a personal fief. Anxious to raise its status, as well as to have close access to an astrologer, he appointed Kepler as his personal mathematicus. Kepler objected that he was unwilling to 'let himself be used as an entertainer' and would not compromise his own scientific convictions to satisfy his astrologically minded patron. However, Wallenstein, who had no real interest in science, compromised by employing Kepler to calculate the precise positions of the planets and then obtaining the predictions from less-inhibited astrologers.

Kepler collected his family at Regensburg, settled his affairs in Linz and finally reached Sagan in July 1628. He found the inhabitants unfriendly and the local dialect almost incomprehensible. Before long religious strife broke out when, for political reasons, Wallenstein started to press Catholicism on his subjects. Although Kepler was not personally affected, the persecutions made it difficult to attract printers to work on the *Tabulae Rudolphinae*. He secured an assistant by the name of Jacob Bartsch, a young scholar who had studied astronomy and medicine at Strasbourg, who later became his son-in-law. Kepler wrote another book, the *Somnium*, which described an imaginary journey to the moon and used this to present an ingenious polemic on behalf of the Copernican system. The idea of universal gravitation, which 'vexed and haunted his mind', seems implicit in his description of the journey.

In Sagan Kepler waited in vain for the payment of his claims for arrears of salary, the responsibility for which had been transferred to Wallenstein. When the latter lost his position as commander-in-chief Kepler returned to Regensburg, presumably intending to consult the emperor and friends at the imperial court about his future and to collect at least some of his arrears of salary. However, a few days after arriving there Kepler became sick with an acute fever; his condition steadily worsened, he became delirious and, on November 15, 1630, he died. The symptoms are those of typhus, which was prevalent during the Thirty Years War. He was buried in the Protestant cemetery, soon to be completely destroyed in the conflict. His wife and children were left almost destitute, but Jacob Bartsch helped them collect the money owed to Kepler's estate by the state treasury. A wealth of papers left by the great astronomer passed through various hands; much has been lost but the remainder is to be found in libraries in Austria, Germany and elsewhere. The thousands of manuscript sheets left at his death went to his son Ludwig, who promised publication but lacked both the time and the knowledge for such an undertaking. A monumental *Gesammelte Werke* in nineteen volumes has been published, as well as a great deal of secondary literature.

Kepler's scientific thought was characterized by his profound sense of order and harmony, which was intimately linked with his theological view of God the creator. He saw in the visible universe the symbolic image of the Trinity. Repeatedly he stated that geometry and quantity are co-eternal with God and that mankind shared in them because man is created in the image of God. From these principles flowed his ideas on the cosmic links between man's soul and the geometrical configurations of the planets. Today, when physicists are said to be searching for a 'theory of everything' that would allow them to 'read the mind of God', we may be reminded of Kepler's indefatigable search for the mathematical harmonies of the universe. Yet contrasting with this mysticism was his insistence on physical causes.

Kepler never rid himself of a feeling of dependence; neither could he exhibit the imperious self-assurance of a Brahe or a Galileo. Nevertheless, his ready wit, modest demeanour and scrupulous honesty, as well as his wealth of knowledge, won him many friends. Although Newton seemed reluctant to acknowledge his influence in the *Principia*, that great work was presented to the Royal Society of London as 'a mathematical demonstration of the Copernican hypothesis as proposed by Kepler', and Halley, in reviewing the *Principia*, wrote that Newton's 'first eleven propositions were found to agree with the phenomena of the celestial motions as discovered by the great sagacity and diligence of Kepler'. In one of Galileo's letters to Kepler he states 'I thank you because you were the first one, and practically the only one, to have complete faith in my assertions.'

Although Kepler today is remembered chiefly for his three laws of planetary motion, these were but the elements in his much broader search for cosmic harmonies and a celestial physics. With the exception of Rheticus, he became the first enthusiastic Copernican after Copernicus himself. Kepler has been described as an astronomer's astronomer; he found an astronomy whose clumsy geocentric or heliostatic planetary mechanisms typically erred by several degrees and he left it with a unified and physically motivated heliocentric system nearly a hundred times more accurate. The writer Coleridge, in his *Table Talk*, gave it as his opinion that Galileo was a great genius and so was Newton, but it would take two or three Galileos and Newtons to make one Kepler. Few would agree with this sweeping statement but nevertheless Kepler's enquiring mind helped to break the mould of mediaeval cosmology.

Christiaan Huygens (1629–1695)

Unlike his English counterpart Isaac Newton, Christiaan Huygens came of a distinguished family. His paternal grandfather had been secretary to William the Silent during the eventful years after 1578, when he had accomplished

his mission of establishing a free commonwealth in defiance of the most powerful empire then existing. The last quarter of the sixteenth century saw the independence of the seven northern provinces of the Netherlands completed after an eighty-year struggle with Spain. The father of the scientist, Constantin Huygens, showed ability in mathematics but his education was directed towards a career as a courtier and diplomat. As secretary to the Prince of Orange he did much to guide his country through difficult times. A man of outstanding ability and brilliance, he became a close friend of René Descartes; after their first meeting Descartes wrote of him 'I could not believe that a single mind could occupy itself with so many things and acquit itself so well with all of them.' Constantin Huygens was a poet, student of natural philosophy and classical scholar, as well as courtier and diplomat.

Constantin Huygens married his cousin, Susanna van Baerke, daughter of a wealthy merchant of Amsterdam and by all accounts an intelligent and cultivated woman. Christiaan, their second child, was born on April 14, 1629, only a few months before the death of Kepler. There were four other children, of whom Constantin the younger, born the previous year, is the only one that concerns us here. When their mother died in 1637, after only ten years of married life, another cousin took care of the family, which moved to a house near The Hague. The two eldest sons, who early showed brilliance, were taught at home by a private tutor until 1645. Their education included singing, playing the lute and the composition of Latin verse. Like Newton as a boy Christiaan loved drawing and the making of mechanical models, on which he spent much labour and ingenuity. From the beginning, however, he showed special promise of ability in geometry, whereas his brother Constantin excelled in literary compositions. Christiaan was rather delicate and by nature gentle, and his sensitivity seemed almost feminine to his father. Descartes was much impressed by some early exercises of Christiaan and saw that great things might be expected from this rather serious boy with the pale face and the large dark eyes.

In 1645, when Christiaan was sixteen, both brothers entered the University of Leyden, where they studied jurisprudence and mathematics. The mathematics professor, a protégé of Descartes, regarded Christiaan as his best pupil. In 1644 Descartes had published his *Principia philosophiae*, an attempt to reduce all the changes of nature to mechanical processes. Later Christiaan recalled that 'it seemed to me when I first read this book that everything in the world became clearer and I was sure that when I found some difficulty it was my fault that I did not understand this thought. I was then only fifteen or sixteen years old.'

In 1647, after almost two years at Leyden, Christiaan Huygens joined his brother in studying law at the College of Orange at Breda. This college, of which his father was curator and in which Descartes seems to have taken a personal interest, achieved a temporary fame but did not survive into the next century. After his studies there were over, Christiaan Huygens began to visit some of the neighbouring countries, notably Denmark. He made plans for a visit to Paris in the company of his father but France, following the death of Louis XIII, was in a state of disorder and it was not until 1655 that he first went to the French capital. Before that he was able to establish contact with some of the French scientists through correspondence with Père Mersenne, another friend of his father's. Although Mersenne died in 1648, his influence on the young Huygens was important.

Any ambition Huygens might have retained for a diplomatic career was abandoned when William II died in 1650. Instead he found his metier in scientific research. In the next sixteen years he proved himself to be as good at it as anyone else at this time, with the possible exception of Newton. He studied telescopes and microscopes and introduced improvements in their design. His studies in mechanics touched on statics, hydrostatics, elastic collisions, projectile motion, pendulum theory, gravitational theory and an implicit concept of force, including centrifugal force. He pictured light as a train of wave fronts, transmitted through a medium consisting of elastic particles. Fundamental research in pure and applied mathematics, optical studies and the discovery of the large satellite Titan of Uranus all belong to this period. Thanks to his success in designing a more powerful telescope than anyone else had managed, he was able in 1655 to detect the rings of Saturn for the first time.

From 1655, when he settled in Paris, Huygens moved in an elegant and leisured society, occasionally visiting the salons. Thanks, no doubt, to his father's influence, he became a protégé of the powerful Jean-Baptiste Colbert. He toured the chateaux of the Ile de France and of the Loire Valley and accompanied his father on a brief visit to London. Constantin was well known in England; he had studied at Oxford, played the lute at the court of James the First and received an English knighthood. When he returned to England later, Christiaan was able to build on these contacts. His long stay in Paris was interrupted in 1664, when he went back to The Hague for two years.

On his return to Paris in 1666, Huygens was elected to membership of the Paris Academy, which had just been established officially, and for the next seventeen years he made the French capital his home. At the same time, however, he was developing his contacts in London, where the informal society of men of science which had been meeting in Gresham College had become recognized as the Royal Society. On his second visit to London Huygens was very impressed by this lively new body and thought that what it was doing surpassed anything happening in Paris. He arranged to be kept informed about scientific work in England, especially the discoveries of Newton, whose investigations in many respects ran parallel to his own.

Having dealt with the Fronde and established himself in power the young Louis XIV declared war on the new Dutch Republic. Rather surprisingly, Huygens remained in Paris while his homeland was in danger. Accepted as the most distinguished of the academicians, he presided over the Paris Academy until 1675, using his diplomatic skills to see the new institution through its formative years. In research he became interested in the problem of determining longitude at sea, so important for navigation. He invented the pendulum clock, intended for use on board ship, but this was not a success. He then developed the use of springs as regulators in clocks. His research in this area was published in his celebrated *Horologium oscillatorium* of 1673.

I digress at this point to say a few words about the mathematical work of the polymath Gottfried Leibniz, since it was Huygens who was his mentor during the period when Leibniz invented the differential and integral calculus. Leibniz started work on this about 1673, some years after Newton but independently. Both worked out complete algorithms that, except in their foundation, are substantially those in use today. Although he is not usually regarded as a physicist, Leibniz made some notable contributions to natural philosophy, but to go into these here would be too much of a digression.

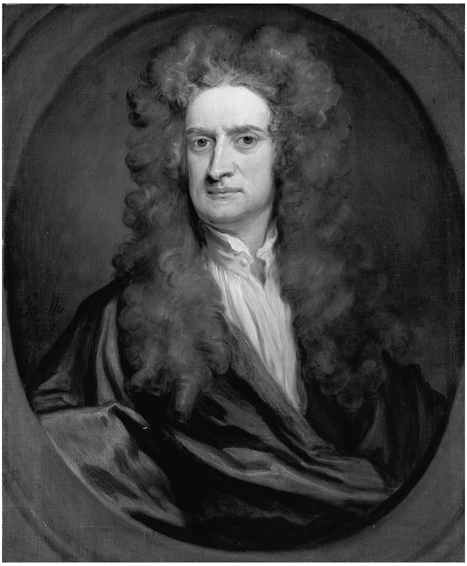
Huygens never enjoyed good health. From early youth he suffered from some kind of disability, perhaps migraine, accompanied by severe headaches. A serious illness in 1670 brought about complete prostration and he clearly believed himself to be close to death. Whatever it was, it lasted in acute form for several weeks and it was three months before he was able to return to work. Early in 1676 there was a recurrence, and this time he showed greater caution in meeting the danger. Life in Paris, he decided, seemed to be bad for his health, so he returned to The Hague for treatment. To his brother he confessed his doubts about whether he would ever return to the French capital and, even when he had recovered a year later, he procrastinated under the pretext of uncertain health, while continuing his scientific work in The Hague. It was not until the middle of 1678 that he returned to Paris; before long he was taken ill again.

Recurrent ill-health no doubt accounts for the reduction in his mathematical and scientific work after 1680. Early in 1681 he was taken ill again but not until September was he able to return to The Hague, where he slowly recovered. He had hopes of returning to Paris but, after his patron Colbert died in 1683, Catholic intolerance in France was undoing much that Colbert had been at pains to build. Huygens' position at the academy was undermined; his nationality and religion told against him. In 1687 his father died. His brother Constantin accompanied William of Orange to England the next year, leaving Christiaan feeling alone. He made a short visit to England himself in 1689, when he went to Cambridge to see Newton and to lend his support to Newton's bid to become Provost of King's College, but too little is known about this. The illness which had dogged him throughout his life again recurred in a severe form and, in March 1695, Huygens felt it necessary to summon his lawyer and make final corrections to his will. The following month he became worse and, from then until July, pain and sleeplessness spared him hardly at all; his days were filled with deep despair. He thought he was being poisoned, kept hearing voices and lived in fear of losing his reason. Weakened by suffering, he died on July 9.

The professional and serious interests of Huygens are the ones which are foremost in his correspondence. Nevertheless, it would be a mistake to consider him as always having been nothing but a patient researcher. He was a man of wide culture and acquaintance throughout Europe. Neither was he averse to feminine society. Marianne Petit, daughter of one of Louis XIV's engineers, seems to have had an attraction for Huygens; their separation was due to her withdrawal from society when she entered a religious order. There were also some distant cousins he visited in Paris and there is no doubt he felt considerable attraction for the eldest of these. The parallel between Newton and Huygens in natural philosophy is striking. No other natural philosopher of the seventeenth century even approached their level. In matters relating to physics, their intellectual menus are strikingly similar. Working within the same tradition, they dealt with the same problems in many cases and pursued them to similar conclusions. Beyond mechanics, there were also parallel investigations in optics. At nearly the same time and stimulated by the same book, Robert Hooke's *Micrographia*, they thought of identical methods for measuring the thicknesses of thin coloured films. In his own world of abstract thought he was incomparable, as Leibniz said, his loss inestimable. Yet Huygens' influence beyond his own century was slight, whereas Newton's was enormous. One of his limitations was that he worked alone, with few disciples. Also, like Newton, he often hesitated to publish, and, when the work finally saw print, others had covered the same ground. More important, however, was his philosophical bias. He followed Descartes in the belief that natural phenomena must have mechanistic explanations. He dismissed Newton's theory of universal gravitation as absurd, because it was no more than mathematics and proposed no mechanisms.

Isaac Newton (1642–1726)

Isaac Newton was born on Christmas Day 1642 in Woolsthorpe Manor, a farmhouse near the Lincolnshire village of Colsterworth, sixty miles north-west of Cambridge. The baby was premature and at first was not expected to survive. His yeoman father, who had only recently married, had died three months before the happy event, leaving his mother Hanna to run the family farm. In 1645 when the boy was three his mother married the elderly Reverend Barnabas Smith, with whom she went to live at his rectory in nearby North Witham, leaving her son in the charge of his maternal grandparents. As a boy Isaac Newton appears to have had little affection for



his stepfather, his grandparents and their children. He grew up lonely and loveless.

At the age of twelve, after early education at local schools, Newton was sent to King's School at Grantham. Since it was too far away for him to live at home during school terms, he lodged with an apothecary named Clark, who seems to have been very kind to him and, in particular, encouraged him to make things with his hands. On the death of her second husband in 1656, his mother returned to Woolsthorpe with the three children from her second marriage. Two years later she took the fourteen-year-old Isaac away from school to help her manage the farm. He proved a somewhat incompetent farmer, his mind too much on other things. On the advice of his mother's brother he was sent back to King's School to prepare for entry to the University of Cambridge.

Again he lodged with the Clarks; their stepdaughter Catherine Storey became an intimate friend. According to the antiquarian William Stukely, who had a long conversation with her in old age, Isaac was 'always a sober, silent thinking lad, and was never known scarce to play with the boys abroad, but would rather choose to be at home, even among the girls.' While he was preparing for Cambridge his childhood affection for Catherine deepened and it seems they became engaged to be married. Stukeley continues 'Sir Isaac and she being thus brought up together, 'tis said that he entertained a passion for her, nor does she deny it; but her portion being not considerable, and he being a fellow of a college, it was incompatible with his fortunes to marry; perhaps his studies too. 'Tis certain he always had a great kindness for her. He visited her whenever in the country, in both her husbands' days, and gave at a time when it was useful to her, a sum of money.'

Newton was admitted to Trinity College in 1661 at the age of nineteen. He began as a subsizar and then sizar, which meant that he had to perform menial duties for his seniors in return for free board and tuition, although his mother, who had been left comfortably off as the heir of her second husband, could have paid for her son's expenses as a commoner. Although he was studying hard, he was not following the syllabus. As a result, when he tried for a scholarship in his second year, he failed the examination in geometry.

Owing to an outbreak of the bubonic plague the Cambridge colleges were suspended for the years 1665/6 and so the young man went home. It was at Woolsthorpe that he conceived the theories which were to revolutionize science. When he returned to the university in 1667 Newton's abilities were starting to be recognized. Trinity elected him to a minor fellowship, against strong competition, and, after this had been converted into a major fellowship the following year, he was entitled to reside in the college indefinitely. He acquired a patron in Isaac Barrow, the Lucasian professor of mathematics, who was later to become Master of Trinity, a Crown appointment. To become known in Court circles, Barrow secured the position of Royal Chaplain and vacated the Lucasian chair in Newton's favour.

Newton's first lecture as Lucasian professor took place at Trinity College in January 1670. It was about his research on optics, material which would find its way into his book *Opticks* of 1704, a much more accessible work than the *Principia* of 1686. The audience was small, no-one came to the second lecture, and he continued talking to an empty room throughout almost every lecture he gave for the next seventeen years. After that he gave up all pretence of teaching, which he never enjoyed. Only three students ever came to him for tuition; they were intellectually undistinguished and nothing is known about how they found him.

Newton's early enthusiasm for making mechanical models had developed into a passion for making scientific instruments, especially optical instruments. The celebrated reflecting telescope was a notable example of his extraordinary skill. It was this that first brought him to the attention of the Royal Society. When they heard about the instrument the fellows of the Royal Society asked to see it. Newton sent them an improved model,