The LIFE & WORK of NEWTON

The enormous impact of the Newtonian revolution on world history has led many to assert that Newton is the single most important person in world history (that his ideas changed the world, and that without him and his theory, things would be quite different). Claims like this are impossible to discuss precisely since we do not know what would have happened 'if things had been different'. Moreover, neither Newton nor anyone else can emerge from nothing- what Newton did was built upon and partly created by the work of others, and sprang from general trends and beliefs in the world at that time. Nevertheless this sort of question has been a topic of debate amongst historians (and writers like Tolstoy) for centuries. One way to think of it is by an analogy with turbulent flow- great whirlpools and eddies of history control large movements and masses of people over long periods, and little can be done to change them- but on occasion, at a critical point of the flow, small perturbations can grow into large consequences, and a small group of people can influence the larger course of history. In the case of Newton it is clear that the time was ripe for a scientific revolution, and as Newton himself clearly acknowledged, he was building on previous work, and to some extent performing a synthesis. As he put it in a famous remark(made, curiously enough, to Robert Hooke): "*if I have seen further than others, it is because I have been standing on the shoulders of giants.*".

However, much depends on the details of execution- the *way* in which he formulated his dynamics was crucial. Newton understood well enough the importance of what he was doing, and the huge break it was going to make with the past. Thus, despite the forbidding character of the *Principia*, his master work, it was framed in a way such as to give not only a definitive formulation of what came to be called classical dynamics, but also a new and very important philosophical viewpoint. This is characteristic of any new fundamental theory in physics- it reinterprets the world.

In this section we survey Newton's life and work. In another section we discuss the basic structure of Newtonian mechanics; and in another section we discuss his work on optics (along with that of Huyghens and other Dutch workers).

(1) EARLY LIFE of NEWTON

Isaac Newton was born in the manor house of the tiny village of Woolsthorpe, near Grantham in Lincolnshire, on December 25, 1642. Apparently very small and fragile (small enough to put in a quart pot, so the story told by Newton goes), his life hung in the balance for a week after birth. His father, who had died 3 months before Newton was born, was a yeoman farmer, who if not wealthy had sufficient means, and left a sizeable will. When Newton was 3 years old, his mother remarried the rector Barnabas Smith, from the next village 2 km away, leaving Newton to be raised by his grandparents- much ink has been expended by biographers on the effect this must have had on Newton, who was in adult life a very prickly and insecure character. We know little about Newton's pre-teen years, except that he attended day schools in the neighbouring villages of Skillington and Stoke. In August 1653, when Newton was 10, the Reverend Smith died at the age of and Isaac's mother Hannah returned to Woolsthorpe, having borne 3 children by Barnabas Smith.

At the age of 12, Newton was sent to grammar school in Grantham. Here he received the standard education of the time, which included Latin and Greek, and Biblical studies - at that time this meant absorbing the canons of the Anglican Protestant faith. He was placed in the lowest class at Grantham, but as time went on he rose academically to the top of the school. Apart from a playground fight that he won due to sheer spirit began a rise to the top of the school, Newton apparently kept little company with the other boys of the school- he was a solitary boy, a 'sober, silent, thinking lad', and apparently preferred the company of girls. There was apparently an adolescent romance with a Miss Storer, the stepdaughter of the apothecary Mr. Clark with whom Newton lodged all the time he was at school in Grantham. This was the only recorded romantic attachment of his life. Most of the stories about Newton recorded at this time in Grantham concern 'his strange inventions and extraordinary inclination for mechanical works'. Amongst these were a windmill powered by a treadmill run by a mouse (the mouse stimulated by pulling a string tied to its tail), various working designs and models for kites, dolls' furniture, and a little four-wheeled vehicle which ran by crank, which he could turn while sitting in it. He also devised a very large number of sundials, which could be found all over Clark's house, along with many drawings by Newton (mostly of people- he learned to be a proficient draftsman).

In late 1659, when he turned 17, Newton's mother called him home to Woolsthorpe, and appointed a servant to teach him about running the farm- this was the vocation intended for him. This did not go well. Sent out to look after the sheep, he spent his time building model waterwheels, dams, and sluices, leaving the sheep to run wild; and when sent to market he would bribe the servant to go in his place, while he spent the day reading or designing various devices. This went on for 9 months, until both his uncle William Ayscough (his mother's brother) and his former schoolmaster Mr Stokes stepped in, and put pressure on Newton's mother to send him back to school to prepare for university. Stokes even agreed to drop the fee for school attendance, and to lodge Newton at his own home. Hannah Newton eventually conceded, and he returned to Grantham. Finally in June 1661 Newton set out for Cambridge- by all accounts both the servants at Woolsthorpe and the boys at Grantham were glad to see the back of him.

These were turbulent years in England. Years of strife had culminated in the execution of Charles I in 1649, and the establishment of Puritanical rule under Oliver Cromwell, when Newton was 7 years old. Cromwell's rule was not popular, and after his death Charles II returned from exile on the continent to take the throne in 1659 (the 'Restoration'). The long reign of Charles II, from 1659-1685, was relatively peaceful, and encouraged by the tolerant attitude of Charles, who was a well-known *bon vivant.* However this did not resolve the constitutional problems of the country - Charles himself had Catholic sympathies, and allowed Louis XIV (the 'Sun King' of France) to persuade him into a naval war with the Protestant Dutch (secretly subsidized by the French, according to the 'treaty of Dover'). This war lasted from 1672-1678 and was not resolved in favour of either power. Nor was it particularly popular in a largely Protestant country. Charles's power was restricted by Parliament- who held the financial strings- and by the antipathy of most of the country towards France and Catholicism. In 1678 the revelation of the treaty of Dover, and of the entirely fictitious 'Popish plot' to overthrow the Protestant church and state, led to the exclusion of Catholics from Parliament, and the exclusion of Catholics from many important positions. By the last years of his reign Charles had succeeded in reversing some of these changes, and begun to engineer a system in which royal prerogative was increased- however his efforts were ultimately unsuccessful (see below). We will see that the lack of strife in England during the Newton's early years was probably crucial in allowing him to fully develop his ideas.

On arrival in Cambridge, Newton entered Trinity College. Then as now, Trinity was the most famous of the Cambridge colleges; and then as now, life at Trinity reflected rather clearly the *mores* and class structure of the upper end of English society (by the end of the 20th century, most Oxford and Cambridge colleges were admitting women- but in 2004 the students are still overwhelmingly from the higher strata of British society- over 50% of students from the top 7% of income earners). In Newton's day Cambridge was almost entirely reserved for the sons of the aristocracy and landed gentry. Newton himself entered Trinity as a subsizar, ie., as a pauper student who earned his keep by performing menial tasks for the fellows, fellow commoners (very rich students), and pensioners (the merely affluent). Apparently his mother was not prepared to pay for any more of his education (although she did not lack the means to do so). In those days the syllabus reflected 4 centuries of Aristotelianism, and Cambridge University was not an intellectual centre- it seems that the best one say is that it allowed Newton the time and opportunity to start reading and thinking about a wide variety of subjects. Our best record of these is provided by a diary or notebook he kept, in which his reading was recorded, and his thoughts on it. Part of this notebook was entitled "*Quaestiones quaedam Philosophicae*", and we can follow therein his reading of parts of Galileo, Thomas Hobbes, Henry More, Robert Boyle, and many others including Plato and Aristotle. Most of all he studied Descartes, who was naturally not on any syllabus but whose ideas had already created considerable interest. Newton organised his notes into 45 categories, ranging over questions about matter, time and place, colours and other sensory qualities, and even occult qualities. What is interesting here is that his philosophical interests had quickly gravitated towards questions of physics (a subject yet to be clearly defined), and that he very quickly found almost any previous philosophy lacking. This is most clear in his extensive notes on Descartes- in particular on Descartes's theory of light and how it accorded with his vortex theory of matter and dynamics in the universe. Newton was fascinated by light and vision at this time, subjecting himself to experiments that could have cost him his sight (these included staring at the sun as long as possible, and inserting objects behind his eye as far as he could- in both cases to see the effect on his vision).

It seems that sometime in late 1663 Newton also discovered mathematics- a subject not taught in any way at school, and barely at university. By 1664 he was buying various advanced books, which by Christmas 1664 included the works of Franz van Schootens, Descartes, and Wallis, on geometry, algebra, and infinite series. During this time period Newton seems to have absorbed much of the mathematics of his day, purely by solitary study, and become extremely interested in both pure mathematics and how it might be applied to the world. However at this point a rather important problem had to be resolved. If Newton wishes to further continue his studies, he needed to secure a position at Cambridge for a longer time- he had not distinguished himself in his first 3 years of conventional studies. In practise this meant obtaining a college scholarship, which would give him 4 years more time- but these were fairly competitive (and worse still, more than half of them went to students from the exclusive Westminster school- a concession towards the upper echelons of society which still continues today in some Oxbridge colleges).

Luckily for Newton, he did get the scholarship, in April 1664- apparently either his patron Humphrey Babington helped here, or perhaps the newly arrived Lucasian Professor of Mathematics, Isaac Barrow. The scholarship gave him some financial independence, and he settled in to indulge in further pursuit of his investigations- apparently these were fairly intense, since he often went nights without sleep and days without eating. Within a year, however, he was forced to quit Cambridge- the Plague arrived in England in 1665, and it was extremely dangerous to stay in cities. Newton left in the early summer, and for 8 months the university was almost deserted. He returned in March 1666 but left again in June- the plague had returned. It was not until April 1667 that he was able to return definitively.

STUDIES in WOOLSTHORPE

During these two years of university closure, Newton returned to Woolsthorpe, to his mother's house. 50 years later, Newton recalled these days- after a description of what he had worked on, he added by way of explanation:

"*All of this was in the two plague years of 1665-66. For in those days I was in the prime of my age for invention, and minded Mathematicks and Philosophy more than at any time since*"

From these remarks, and similar ones made during the dispute over priority in the invention of calculus, came the legend of Newton's *annus mirabilis.* In fact it is probably better seen as a natural result of his existing endeavours, which he was able to pursue more easily because of the leisure afforded by Woolsthorpe. In any case, it is clear that during this time Newton laid many of the foundations for his later work, and in some cases came to conclusions that would not be published until 30 years later.

Working on mathematics, Newton began by listing a set of 'problems' which he wanted to investigate- he ended up with 22 of these, grouped in 5 categories. He began by investigating tangents to curves (differentiation) and the 'quadratures' of curves (ie., the areas under them- now known as 'integration'). With these 'new analyses' he calculated the area under a hyperbola, and eventually devised methods to find the area under almost all algebraic curves then known. In the autumn of 1665 he then extended these ideas to treat the areas swept out by curves kinetically, as areas swept out by a moving point. He used the term 'fluxionals', to describe increments of area in this method- this marks the beginning of the modern version of calculus, and in it he already saw 'velocity' as a fluxional, defined with respect to infinitesimal time intervals- with time defined as an absolute quantity. He also then found the relation between integration and differentiation, and in the course of summing varios series expansions, found the 'binomial theorem'. In 1666 he returned on 2 occasions to these mathematical questions, and summarised his results in 3 papers- one written on 13 November 1665, entitled "to find ye velocities of bodys by ye lines they describe"; and two more written in 1666, entitled "To resolve problems by motion these following propositions are sufficient". The last of these was written in October 1666, and contains a full description of his theory of calculus.

Mathematics was not the only subject occupying him at that time- in fact much of his time was spent looking at problem in mechanics and optics. In the science of mechanics, Descartes had analysed impact in terms of an internal force possessed by a moving body, which he called the "force of a body's motion'. Newton instead argues for a cause and effect relation between external forces acting upon a body, and changes in its motion. At the same time he realised that the momentum of 2 bodies, isolated from each other, would remain constant, even after collisions between them- this would later become the principle of momentum conservation. It might seem from this that Newton had already found his 2nd law of motion. However at this point he was confused by the more complex problem of the mechanics of circular motion, and Newton ended up agreeing with Descartes that a body in circular motion strives to constantly recede from the centre- which apparently conformed with the Cartesian idea that bodies in motion had their own innate 'centrifugal' force (a name due to Huyghens). Newton calculated the centrifugal force for a circular motion of velocity v at radius r as $F = mv^2/r$, and then, recalling his studies of Galileo's "Dialogue Concerning the Two Chief World Systems" he used his result to show that the earth's rotation does not fling bodies into the air because the force of gravity, measured by the rate of fall of falling bodies, is greater than the centrifugal force arising from the earth's rotation. He then went on to show that if he supposed Kepler's 3rd law to be true (that the mean radii R of a planet's orbit is related to its orbital period T by $R \propto T^{2/3}$), then this implied that the centrifugal force (and hence the force of gravity) must vary like $F \propto 1/R^2$. Again, this seems like he had was very close to finding the universal law of gravitation- but this is to underestimate the leap required to go from a single result to a total system of dynamics, which would not come until 30 years later. In fact, as we shall see below, Newton had to make several huge steps in the intervening period before he would be able to formulate his universal principles of mechanics.

During the same enforced stay at Woolsthorpe, Newton continued experimenting with what he called the 'celebrated phaenomena of colours' stimulated partly by ideas appearing the '*Micrographia* published in 1665 by Robert Hooke. Hooke advocated a theory in which colours were a mixture of light and darkness, as well as the idea that light came in 'pulses'; he argued for a scale ranging from brilliant red, which was held to be pure white light with the least amount of darkness added, to dull blue, the last step before black, which was seen as the complete extinction of light by darkness. Newton realised that this was could not be the case - a white page with black writing did not appear coloured when viewed from a distance and the black and white blended- it appeared grey.

At that time a number of investigators were using prisms to experiment with colour, and the main view was that somehow the prism coloured white light from, eg., the sun. In their experiments, Descartes, Hooke, and Boyle had put a screen close to the prism and seen that a light ray passing through the prism came out as a mixture of colour. In the study upstairs at Woolsthorpe, Newton set up an experiment in which the light beam travelled 22 feet from the window, through his prism, to project a spectrum on the far wall. The white light split into different colours and each colour had been bent a different amount by the prism. He then carried out many experiments on this system. The most crucial of these- what he called his '*Experimentum Crucis*'- consisted in putting a screen with a small slit in the way of his spectrum, so that only light of one colour, eg., blue, passed through to the wall. He then placed a second prism in the path of this blue light. The pure blue light remained unchanged, proving that the prism did not change the colours, and thereby making the crucial discovery that white light was simply made from colours mixed together, which the prism was able to separate. He confirmed this by recombining different colours from 3 different prisms, to get white light again.

None of this was able to explain the colours of solid bodies. Newton's efforts in this direction were less successful because he incorrectly believed that these colours were all produced by reflection- that if a body appeared blue, it was because it preferentially reflected blue light. He also investigated a peculiar phenomenon found by Hooke, which was that if a piece of curved glass were put into contact with a flat piece, then one could see very fine rings around the point of contact. this was one of the reasons that Hooke had advocated pulses. Newton was able to give a quantitative treatment of the size of these rings (now known as 'Newton's rings'), knowing the curvature of the curved glass, thereby extracting the length of the pulses. However he regarded these 'pulses' as being some kind of vibrational disturbance in the medium of corpuscles which made up the light- rather than supposing that the pulse really *was* light, as Hooke did. From this time on we see Newton's undeviating belief that light was made from particles.

(2) CAMBRIDGE- EARLY YEARS

From 1666-1689, Newton was at Cambridge almost continuously. The first problem he faced was the election for a fellowship, which if successful would give him a permanent place in the college, and the freedom to continue his work. On 2nd October 1667, Newton was elected a fellow of the College of the 'Holy and Undivided Trinity', swearing to 'embrace the true religion of Christ with all my soul', and to 'take holy orders when the time prescribed by these statutes arrives, or resign from the college.' Apart from this, a fellow in those days had little duties- the main thing was to avoid 'the 3 sins of crime, heresy, and marriage'. It seems that Newton continued to use the time- continuing his work on optics, and now also turning his attention to alchemy, which would remain an interest of his for at least 30 years. He also withdrew even further into his solitary life. However during this time he was drawn into one significant interaction with the outside world. The first Lucasian professor of mathematics at Cambridge, Isaac Barrow, passed on to Newton in early 1669 a new book by Nicholas Mercator, which he had been sent by the mathematician Collins; in this book Mercator had succeeded in summing a series for the expression $log(1+x)$. Newton immediately recognised that although other mathematicians had not yet uncovered the very general results for series that he had derived in Woolsthorpe, they soon would. He then sent back, via Barrow, a manuscript entitled "*De Analysi per aequationes numero infinitorum infinitas*" ('On the analysis of infinite series'), detailing his general results. In fact Barrow had had to put considerable pressure on Newton to send this- Newton's reticence and neurotic desire to avoid public exposure were by this time highly developed. In spite of a request to keep the manuscript private, Collins actually distributed copies of it, and for the first time mathematicians outside Cambridge began to hear of the young Newton.

Shortly thereafter, in October 1669, Newton became the second ever Lucasian professor of mathematics. This rather astonishing elevation of Newton to one of only eight such endowed professorships in the university was engineered by Barrow- who stood down from the position in order to move on to a position as chaplain to the king. After this it was hard for Newton to avoid more contact with the outside world. Collins persisted in asking Newton for contributions, and even at one time had in his hands an early draft of the theory of fluxions- but Newton asked for it back and Collins never saw it again.

WORK in OPTICS

It was Newton's reflecting telescope, the first example of which he had made in 1668, that finally attracted the full attention of the scientific community. He made this first telescope entirely on his own, including the casting of the mirror, and with tools that he had devised specifically for the purpose. The first reflecting telescope was only six inches long, and one inch in diameter, yet it magnified 40 times. He then made a second more powerful one which could magnify up to 150 times. Newton was sufficiently proud of his telescope that he couldn't resist showing it to others, and eventually the Royal Society heard of it, and asked to see it. When finally Barrow brought it at the end of 1671, it caused a sensation. Within a month Henry Oldenberg, the secretary of the Royal Society, had communicated the news to Huyghens in Leiden (who was enormously impressed with 'the marvellous telescope of Mr Newton'), and the Society had elected Newton as a member. Newton was flattered, despite his pretence of indifference, and in return he communicated details of the operation and construction to Huyghens in several letters- and then finally, after hesitation, sent to the Royal Society his 'endeavour to testify my gratitude by communicating what my poore and solitary endeavours can effect towards ye promoting your Philosophicall designes'. This was his theory of colours, finally sent on 6th February 1672, and which Oldenberg then published in 19 February 1672 in the *Philosophical*

Transactions of the Royal Society. Newton's description of his telescope appeared in the following issue.

The letter Newton sent contained the results of his investigations and experiments from the Woolsthorpe years, plus an account of how these had helped him to the design of the reflector. It was the first time that his work had been made available for open discussion by other scientists. Most initial reactions were very favourable, and queries from the French Jesuit Pardies, professor at the Collège Louis le Grand (then and now one of the most exclusive prep schools in France), about whether or not the recent discovery by Grimaldi of diffraction should be included in his theory of light, led Newton to articulate his approach to scientific questions in a very interesting passage:

"*in answer to this, it is to be observed that the doctrine which I explained concerning refraction and colours consists only in certain properties of light, without regarding any hypotheses by which these properties might be explained. For the best and safest method of philosophizing seems to be, first to inquire diligently into the properties of things, and to establish those properties by experiment, and then to proceed more slowly to hypotheses for the explanation of them. For hypotheses should only be employed in explaining the properties of things, but not assumed in determining them, unless so far as they may furnish experiments. For if the possibility of hypotheses is to be the test of truth and reality of things, I do not see how certainty can be attained in any science; since numerous hypotheses can be devised, which shall seem to overcome new difficulties. Hence it has been here thought necessary to lay aside all hypotheses, as foreign to this purpose...*"

Although Pardies replied that he was satisfied, it is rather hard to believe he could have been reconciled to a methodology so utterly opposed to that of Descartes.

Unfortunately not all readers did not respond so sympathetically. Robert Hooke, a leading power at the Royal Society, considered optics to be his domain, and in a letter sent only 1 week after Newton's submission, on the 15 Feb 1672, he disdainfully rejected most of Newton's conclusions. The reply from Newton was 4 months in coming- in the interim he composed a very full exposition of his ideas on light, which he then decided not to publish, and contented himself with a vehement attack on Hooke in June. After this it became more and more difficult to get Newton to respond to letters, although he did for a time respond to letters from Huyghens. At one point he even threatened to withdraw from the Royal Society- in any case, for some years thereafter he refused to communicate to anyone directly except for Oldenberg and Collins. This policy he maintained apart from a few departures- most notably to send in to the Royal Society in 7th December 1678 2 manuscripts on optics, one entitled "*Discourse of Observations*", and the other "*An hypothesis explaining the properties of light discoursed of in my several papers*". The latter was an attempt by Newton, under the stimulus of by then 6 years of letters received from abroad, to give some sort of explanation for the properties of light that he had found. In it he expressed again his idea that light was a particle, which was guided in its flight by an aether, exerting a pressure on the light corpuscles. Inhomogeneities in the aether explained refraction and reflection, and vibrations in the aether explained the phenomena of 'Newton's rings'. He went further- collisions and surface tension were explained by aethereal pressure, and the circular motion of planets in their orbits, and gravitational force in general, came from the pressure of a constant stream of aether which poured into massive bodies. We see that in spite of already knowing of the inverse square law of gravitation, Newton was still under the spell of an almost Cartesian idea of the origin of gravity, and also of light, and rather far from his later theory. His reasons for this point of view were not to be found in his published work, but in his unpublished alchemical work (see below).

ALCHEMY and RELIGION

After this Newton took no real interest in either optics or mechanics for a long time. This was in spite of seeing, in Sept 1677, two communications sent to Oldenberg from the then young Leibniz, describing Leibniz's mathematical researches- from which it would have been obvious to Newton that Leibniz already was well on the way to inventing the calculus independently from Newton. The reason for his neglect is simple- his interests had shifted. During the period 1672-1684, most of Newton's time was consecrated to work on what for him were quite fundamental questions- in theology and alchemy.

It is common amongst interpreters of Newton to neglect or even ignore completely Newton's work in alchemy and theology- pretending that it was either an abberation, or at best irrelevant to his most important work. This view (which is particularly common amongst scientists) makes no sense- and even a mild familiarity with Newton's writings shows that his research into both subjects is related in crucial ways to his work in mechanics and optics. Indeed, in his alchemical research he was partly looking for underlying explanations and/or principles which might bear on his discoveries in optics and mechanics; and his theological work was part and parcel of his search for general philosophical principles. To believe that the theory of mechanics embodied in the *Principia*) sprung by magic from bare philosophical ground, is analogous to belief in a virgin birth- and neither belief is terribly reliant on historical fact.

Chemistry and Alchemy: Newton's work in chemistry and alchemy (and the line between the 2 was not even defined in those days) began very early- from his notes it is known that already in 1669 he was deeply interested in the subject, and by 1672 it already occupied most of his time. In 1669 he purchased 2 ovens, glass equipment, and chemicals, in order to begin an experimental programme of research, that continued almost unbroken (except for the late 1680's) for over 30 years! At the same time he had already begun to assemble a set of manuscripts and notebooks, which now constitute most of Newton's surviving papers.

The first sign in any of Newton's infrequent published work of this new interest is to be found in his 1678 works on optics. In his "Hypothesis explaining the properties of light" he postulated a universal aether, whose behaviour was governed by a number of principles- these were divided into active principles like a tendency to condense into massive bodies (the mechanism of gravity) or into fermenting or burning objects- or to be 'exhaled' in the formation of vapours (ie., vapourisation or boiling). The following passage gives a taste of the ideas- this is a discussion of what are now called phase transitions (eg.,, gas/liquid transitions):

"*For Nature is a perpetuall circulatory worker, generating fluids out of solids, and solids out of fluids, fixed things out of volatile, and volatile out of fixed, subtile out of gross, and gross out of subtile. Some things to ascend and make the upper terrestrial juices, rivers, and the atmosphere; and by consequence others to descend for a Requitall to the former*"

Remember that this quote is taken from a paper published in the transactions of the Royal Society, whose subject was optics. In some ways it is not much of an advance over Aristotle- it seems ironic that one of the major themes of debate at this time was over the existence of non-existence of 'occult' qualities in matter, and perhaps the main proponent of the use of mechanical principles to replace occult ideas was none other than Descartes- eg., in his theories of vortices to explain magnetic forces and gravitation. Newton was wrestling with precisely the same set of questions, and they were as old as the Greeks- whether to explain dynamics by active or innate principles, whether a void existed and was needed to understand motion, what was the fundamental substance or substances, and in what way were they manifested in the ever-changing properties of visible matter. It is absolutely crucial to understand that Newton and Descartes were working in an intellectual framework no different from their forbears. For both of them, as for many others, it was then natural to look upon the phenomena of magnetism and gravity as unusually interesting, along with the properties of light- in all 3 cases one was apparently dealing with invisible influences acting at a distance. The temptation to find something common between these phenomena, and to look for some hidden substance to explain the transmission of these influences, would have been very hard to resist.

In Newton's case it is quite clear from his unpublished alchemical work what was going on. Having come to what was for him simply a preliminary and very partial understanding of some mechanical phenomena, and of some features of light, he was after some deeper and *non-mechanical* explanation of these properties. Such a search made sense- how could mechanical models explain phenomena like magnetism and gravity, which were clearly non-mechanical?

It is interesting to contrast the views of both Newton and his contemporary Robert Boyle (sometimes called the father of modern chemistry) with the standard alchemical views of that time. The standard alchemical system treated Nature as a living principle, not as mechanical- this was of course Aristotelian- with an activating spirit, such that all things were generated by the fusion of 'male and female principles'. In 17th century Europe this was mixed up with Christian philosophical ideas dating back to the 4th century, concerning the Holy Trinity- thus Effararius the Monk identified 3 basic activating principles, which were body, soul, and spirit (with body being feminine Venus, spirit being masculine Mars, and soul being identified with sun and moon). These activating principles existed in matter- they were causative agents, responsible for change- and there was a widespread belief in one pure or fundamental agent manifested in what was known as the 'philosopher's stone'. Because this agent was capable of causing change in matter, it was eagerly sought after by alchemists (by some, for the purpose of transmuting base metals into gold). In terms of such ideas, phenomena such as the solubility of some materials in others, or vaporisation, were explained by the sympathy or antipathy of some principles for others. Thus the dissolving of a substance in a solvent was explained as the 'sympathy between the substance and its menstruum'.

Boyle, on the other hand, sought underlying mechanical explanations for chemical phenomena- in the size and shapes of particles and pores. Newton was having none of this- he postulated a secret alchemical principle, the 'sociability' of some materials for others. Thus the insolubility of water in oil (and vice-versa) but its solubility in wine was to be explained. Thus also was gravity to be explained, by the sociability of aether for massive bodies. In correspondence with Boyle over several years, Newton discussed these ideas, to cover a very broad range of physical phenomena. In a manuscript begun in 1679, he elaborated his ideas in much more detail. This work, "*De Aere et Aethere*", attempted to understand physical phenomena such as capillary action, vapourisation, and the expansion of gases, by appeal to the repulsion between most bodies. This repulsion was for Newton was a fundamental part of his system- it came from the existence of a hard nucleus in material bodies, surrounded by sphere of more tenuous matter, which did not admit other matter. He also attempted to treat 'electric and magnetic effluvia' with these ideas.

In all of this theoretical speculation Newton was both driven and harnessed by his experimental work. This was extraordinarily extensive, but little of it appeared in his published work. Much of it is very hard to read now- in the absence of any understanding of the elements, how atoms from ions and bond in various ways to form molecules, etc., chemical phenomena were analysed in terms of 'combination of liquors', which were infused with various spirits, which were more or less sociable with others, etc. Often certain compounds or solutions of compounds were identified as being somehow basic or elemental, when in fact they were complex transient forms of what are now known to be the basic elements. All this led to enormous confusion and a proliferation of names and technical terms describing things that either do not exist at all, or are in reality composites of more basic things. This shows what happens when the basic taxonomy of a subject is flawed.

Nevertheless, some of this work is fascinating. One of these experiments may have played a crucial role in subsequent developments (although the historical record is insufficiently complete to decide). In order to understand the interaction between aether and matter, Newton set out to measure the resistance that aether caused to the motion of the pendulum. The experiment was simple in conception, but hard to do accurately. A long (11 ft. long) pendulum was made with a large wooden box as the weight. This box could be filled with extra weights, thereby giving it extra mass, and lessening the effect of air resistance on its motion. Newton then used the theoretical result of Galileo, that without interaction with the aether, the period of motion would be unaffected by the extra weight. By measuring heavier and heavier masses, he sought to find the contribution of the aether to the frictional relaxation of the pendulum motion (assuming it would affect heavier masses less). The difficulty in doing the experiment was of course to eliminate all other sources of friction, so that only resistance from the aether was left. The interest of this experiment is that he found no discernable contribution from the aether- the decay of the pendulum oscillations was almost independent of the weight of the box, within very small errors. Thus in spite of his theoretical prejudice, Newton decided there was no measurable interaction between matter and aether. It is not clear how much of a *direct* role this played in Newton's later thinking, but it certainly must have influenced his later rejection of the aether (in the *Principia* a lengthy discussion of dissipative pendulum motion appears in book II, section 6).

Theology: Newton kept his theological ideas very much to himself- much of what we know has only been uncovered in the last 30 years. It seems as though his interest was awakened in the early 1670's, and by 1674 he was very heavily involved. Again, his interest in theological matters was not the aberration of an eccentric, but followed naturally from his desire to get to the bottom of things, and discover fundamental truths about the world. It is also argued by some historians that his interest in these questions was precipitated by the necessity for a fellow of Trinity college to be ordained into the Anglican Church, and to affirm his orthodox religious beliefs- in Newton's case this had to be done by 1675, or he would lose his livelihood as a fellow of the college.

Whatever the truth may be, well before 1675 Newton had come to conclusions about the doctrines of the church that were heterodox in the extreme. His essential conclusion was that in the 4th century battle between the beliefs of Arius (according to whom God was one, and Jesus only a prophet or mediator) and those of Athanasius (who argued for the Holy Trinity of God, Jesus, and the Holy Spirit), the entire Christian doctrine had been corrupted by the victory of Athanasius. For Newton this was extremely serious- the worship of Jesus as the the son of God, or as part of God, was a form of superstitious idolatry, which for him was sinful. It had, in his opinion, opened the way to a host of false saints and martyrs, as well as the concentration of power in a religious hierarchy, and to the perversion of monasticism. Newton was led by his historical research to the idea that the true religion was that of Noah, before the corruption of Athanasius and the council of Nicaea in 380 AD; that ancient people had all worshipped gods, but that these were basically the same god under different names. Many of his ideas on this were written down in a manuscript entitled "*Theologia gentilis origines philosophicae*" (the philosophical origins of gentile theology), around 1684.

To a modern reader much of this may seem to be rather obscure, and it is perhaps hard to understand why Newton was so exercised by such questions. This is merely a measure of how much the world has changed since the 17th century- Newton was living in the wake of a thousand years of dogmatic religion, which had entirely shaped the European society of his day- he could be no more free from the idealogy of his day than we are of ours. In Newton's case his ideas led him to what was a shattering conclusion for someone in his position- not only that the Christian doctrines of his day were corrupt, but that Christianity itself had nothing in particular to distinguish it from other religions. It seems from his writings that he became an Arian (ie., a follower of Arius) but that apart from a few discussions with very close acquaintances (amongst whom the philosopher John Locke occupied an almost unique place) he kept his beliefs utterly secret.

It is easy to imagine Newton under different circumstances becoming a religious figure himself, even a prophet of sorts. His fervent attempts to come to terms with religious doctrine were not distinct from his work on 'Natural Philosophy', but merely the inevitable result of a search for philosophic truth, wherever this might lead. In Newton's day such a search could hardly lead elsewhere but to an inquiry into religious truth.

The remarkable thing is that he was able to keep his ideas secret. The moment of truth came when he had to be ordained into the Anglican church. We have no first hand documentation of what happened, but it seems that Newton must have spoken with someone (probably Isaac Barrow, by now Master of Trinity college); we have no idea what was said. In any case on 27 April 1675, a Royal dispensation was granted *in perpetuity* to the Lucasian professor (not to Newton), allowing exemption from the taking of Holy Orders if so desired by the said Professor. Thus Newton avoided expulsion from the college, only a month before the deadline for ordination.

(3) The PRINCIPIA: DAWN of NEWTONIAN MECHANICS

It is possible to imagine Newton's researches into theology and alchemy continuing for many years after the time of his most intense interest in these subjects, in the late 1670's and early 1680's. As we have seen, he was animated by a desire in his alchemical work to get find a non-mechanical theory which would explain the known phenomena of mechanics, optics, and chemistry, and his attention was focussed on explanations in terms of an aether, having various 'occult' (ie., 'hidden') properties, of a 'pre-mechanical' kind. Since he showed no desire to publish any of this work, or even to share it informally, it is unlikely that Newton would have been more than a footnote in history had things continued in this way.

However fate intervened, and a sequence of events in the years 1680-84 would set him off on an entirely different course. This led him to completely revise his ideas, and culminated in a quite extraordinarily intense outburst of creativity, in which he constructed a philosophical and mathematical system of mechanics, devoid of any aether, and quite different from his previous ideas. This theory was embodied in the "*Philosophiae Naturalis Principia Mathematica*" ('The Mathematical Principles of Natural Philosophy'), which was written during the period 1686-87. None of this story is simple, and it also involves the intervention of other key personalities at certain stages. However the final result was quite astounding, and the '*Principia*" is rightly argued by many historians to have been one of the most crucial developments in the history of the world.

Early Developments (pre-1684): By the late 1670's Newton had more or less withdrawn from contact with the most of the world- his contact with Oldenberg (secretary of the Royal Society) ceased at the death of the latter in Sept. 1677; and in spring 1679 his mother died. Apart from occasional correspondence with Boyle, the affairs of Trinity college (by then in serious financial trouble) and dealing with the estate of his mother, Newton's time was completely taken up by his private research work.

The road that led to the *Principia* apparently began with a correspondence initiated by Robert Hooke (by this time secretary of the Royal Society) in late 1679. Hooke put a question to Newton concerning his ideas of orbital motion (which he had first sketched in 1674). In this question Hooke was apparently the first to make the correct assumption, that the motion of a body about, say, the earth, would be governed by its initial rotation, plus the influence of a centrally attractive force, varying like $1/r^2$, where r was the distance from the earth's centre. At no point did Hooke assume any outward centrifugal force (the name given by Huyghens), which had been supposed by everyone up to that time (including Newton, who had always assumed 2 matching inward and outward forces for circular motion). As noted by Newton, the question can be checked experimentally, by dropping a ball from a high tower. However, in a mistake that Newton would severely regret, he answered Halley that the motion would be a kind of spiral falling towards the Earth's centre- to which Hooke responded, in a subsequent exchange of letters, that he thought it would on the contrary be an ellipse, assuming the $1/r^2$ attraction (this is the correct answer).

Newton quickly realised his mistake- and a few months later worked out the correct theory (without sending it to Hooke). At the time he did not follow this up- but the issues would not go away- shortly thereafter, in Nov 1680, a spectacular comet appeared in the sky, exciting the interest of many including Newton; and it was followed by another in 1682 (what Halley later realised had to be periodic- it is now called Halley's comet, and returns every 76 years). It appears from Newton's notes and observations of these comets that he slowly came to the realisation that the cometary dynamics could be understood in the same way as planetary motion- this appears to be the first step on the road to the idea of universal gravitation.

In January 1684 an interesting discussion took place at the Royal Society in London, between Edmund Halley, Robert Hooke, and Christopher Wren. The topic was celestial mechanics, and Hooke asserted to the other two that he could demonstrate all celestial dynamics starting from an inverse square attraction- but that he would not yet reveal his proof. As a consequence of this, Halley asked Newton 8 months later, on a visit to Cambridge, what would be the motion of an object in such a force field. As Halley recounts, Newton immediately answered that it would be an ellipse- which he knew because he had calculated it. Halley asked for details, which Newton promised he would send. What he sent in Nov. 1684 was an elaboration of his notes from 1680- in a 9 page manuscript he demonstrated that a $1/r^2$ attraction would lead to motion along a conic section (ie., an ellipse, parabola, or hyperbola), proved Kepler's 2nd and 3rd laws, and treated the motion of a projectile through a resistive medium.

Halley immediately realised that he was dealing with merely a small part of what Newton must know, and immediately returned to Cambridge to ask Newton to elaborate on his short manuscript, which Newton had entitled "*De* *motu corporum in gyrum*" (On the motion of bodies in an orbit). As reported by Halley to the Royal Society on 10 Dec 1684, Newton agreed to do this. It is unlikely that either Halley or Newton realised at that time what this would lead to.

The Writing of the PRINCIPIA: During the periood from Aug 1684-spring 1686, Newton almost ceased all communication with the outside world. There were key exchanges with Flamsteed, by means of which one can measure his progress in the rewriting of our understanding of Nature; and there were repeated discussions and exchanges with Halley, who was detemined by any means to get Newton to publish the full extent of his work. For the result of Halley's prodding was to push Newton gradually into a deeper and deeper refinement of the results in his original 9-page manuscript. This began with a series of attempts to revise the manuscript, as Newton tried to refine his ideas, make them more rigorous, and, most importantly, give them some kind of philosophical underpinning.

It was this last philosophical endeavour that motivated Newton to find a framework in terms of which all dynamics could be derived- without such a framework, it was clear that physics could be no more than a piecemeal collection of results having no sure foundation. He began with the existence of what he called 'centripetal' forces (in contrast to the centrifugal force discussed by Huyghens), and a preliminary version of what later became the first law. Dissatisfied, he produced a 2nd version in which 5 laws of dynamics appeared, including the relation between applied force nand change of motion- what we now call the 2nd law. In a 3rd version he introduced the idea of absolute space (which is no longer used in physics- more on this below). By this time it was quite clear what the two most difficult steps were for Newton. He had dropped the whole idea of an aether- this was a huge step, and forced him inevitably to the idea of forces acting at a distance through the vacuum- there was no other way to explain planetary motion once the aether had been dropped. The assumption of such an idea must have been extraordinarily difficult, and yet he had been driven to it by all his investigations over the previous years. Having made it, he was then faced with another huge problem- how to deal with the idea of '*inherent force*', which was viewed as the internal force a body possesses, which keeps it moving in the same direction and speed in the absence of an external force. To us this seems completely misguided- but at the time Newton was working in a framework, which had begun with Aristotle, in which the dynamical properties of a body were inherent in the body- a framework which, up to this point, Newton had accepted along with everyone else.

Newton's struggles with inherent force can be observed by looking at his various attempts to formulate what eventually became his first law. His first attempt formulates it as follows:

'*The inherent, innate, and essential force of a body is the power by which it perseveres in its state of resting or moving uniformly in a right line, and is proportional to the quantity of the body. It sis actually exerted proportionally to the change of state, and in so far as it is exerted, it can be called the exerted force of a body...*'

and we see the way in which already the connection to the future 2nd law is being made. In a second attempt he wrote:

'*a body, by its* "vis inertiae" *(force of inertia) alone., perseveres in its state of resting or uniform motion*'

where the force of inertia is just another name for 'inherent force'. Eventually, in his final formulation in the 1st law of the *Principia*, all reference to an inertial force would be dropped. However, even in the Principia, Newton was not able to relinquish the idea that there was something unique about a state of rest, even in the vacuum- the concepts of Absolute space and Absolute Time appear still. Thus 'absolute motion' would be defined with respect to Absolute space. Newton was never able to accept what was in fact the inevitable consequence of his formulation- that motion was relative, that no frame of reference was preferred, and that the 1st law was merely a special case of the 2nd, in the absence of any external force. In fact Newton was never happy with the idea of forces transmitted through the vacuum, and he apparently regarded the idea that motion was purely relative as being both atheistic and Cartesian!

For Newton the formulation of the 2nd law was easy- indeed he had done it already many years before. What was less trivial was to give a proper definition of *mass*. This he inevitably did in terms of inertia:

'*The 'inherent force of matter' is the power of resisting by which any body, as much as in it lies, perseveres in its state of resting or moving uniformly in a right line,; and it is proportional to its body and does not differ at all from the inactivity of the mass except in our mode of conceiving it. In fact a body exerts this force only in a change of state effected by another force impressed upon it, and its exercise is 'resistance' and 'impetus' which are distinct only in relation to each other.*'

Later Newton would attempt to clarify by explaining that the total mass of a body was the volume times the density (which of course merely displaced the problem to one of defining the density). For a more modern understanding of how one should understand 'mass' in the 2nd law, go to the section on Newtonian mechanics.

Finally, the initial formulation of the 3rd law was essentially completed in these initial attempts to rewrite his original manuscript for Halley. He formulated it thus:

'*As much as any body acts on another so it experiences in reaction...the force of the body exerted to conserve its* *state is the same as the the force impressed on the other body to change its state, and the change of state of the first body is proportional to the first force, and the second body to the second force.*'

This concludes the dynamical part of Newton's theory. At the same time he was coming slowly to the idea of universal gravitation. This seems to have begun both with his knowledge of planetary motions, and his understanding of his pendulum experiments- Newton was inevitably led to understand that if masses were attracted to the earth by a force proportional to their mass (as demonstrated by the equal period of pendula with different masses, or the equal rate of fall of different masses), then the same could be true of celestial bodies, including not only the planets but their moons. Using the $1/r^2$ law he could then verify that this was indeed the case, provided the 2nd law was assumed- the periods of the planetary orbits could be calculated accurately without knowing their masses. It was then quite inevitable, once the 3rd law was accepted, that if the sun attracted the Earth or Jupiter, then they must also attract the sun, and affect its motion (although by a very small amount). In this way the hypothesis of universal gravitation emerged- that *all* massive bodies exerted a gravitational force proportional to their mass, and falling off as the square of the distance away from them. As Newton put it:

'*The forces proportional to the quantity of matter arise from the universal nature of matter*'

Thus was a new structure for the world slowly born in early 1685- by gradual attempts to free the mind from the constraints of an older structure.

By early summer 1685 it seems that Newton was sufficiently happy with his basic formulation that he was ready to work out some of its consequences. In fact this was quite crucial- his formulation of the laws had emerged from his studies of various specific but limited problems such as planetary or pendulum motion, and for his own satisfaction he had to see that it really worked for all dynamic systems. All of Newton's previous investigations, over the 20 year period since his work in Woolsthorpe, now came to the fore- we see how essential this gestation period was for the production of the *Principia*. In the next 6 months the original revisions for Halley expanded to to 2 books, which Newton entitled "*De motu corporum*" (The motion of Bodies); no longer was he just dealing with planetary motion. In these books he dealt with the following crucial problems (amongst others):

– *The gravitational attraction exerted by a sphere of uniform density*: The essential point was to show that the force towards the centre of the sphere, on any body outside the sphere, would be proportional to $1/r^2$. More generally one can show this if the density is inhomogeneous, provided it only depends on the distance from the centre of the sphere. In this way Newton could justify all calculations which treated the gravitational force of the earth as though it came from the centre- a quite crucial result. He was then later able to look at small deviations from sphericity of the earth- in a result which turned out to be important he calculated from the measured results for falling bodies that the earth was an oblate spheroid, with an equatorial diameter roughly 30 km greater than the polar one (see *Principia* vol III, propositions XIX, XX). The polar flattening is thus very small, only 1 part in 400; the earth's diameter is roughly 12,000 km. For a time afterwards, French astronomers claimed the opposite (an equatorial flattening) but this was eventually understood to be incorrect.

– *The mutually perturbing effects of the planets*: This is caused by the gravitational interactions between the planets, during their motion around the sun. Even though these perturbations are small compared to the huge gravitational force of the sun, they are easily seen by watching planetary motions over a long time. This was a very hard problem- eventually Newton settled for an approximate treatment of the 3-body problem (ie., the motion of 2 planets around the sun, with interactions between them included), and was able top show how, eg., Saturn would be alternately slowed and then speeded up as Jupiter caught up with it and passed ahead of it. We now know that an exact treatment of even this problem is impossible- that the 3-body Newtonian system can be chaotic. This understanding only came in the 20th century- before this the problem of the long-time dynamics of planetary orbits, and their stability, was a central problem in astronomy and mathematics.

– *Stability of orbits*: even though he was not able to deal with the 3-body problem, Newton could show that for the 2-body problem (eg., the sun and a single planet) there were only two possible laws of gravitational attraction that would lead to elliptic orbits- one being the usual $F \sim 1/r^2$ law, in which attraction falls off as the inverse square of distance, and the other being the harmonic attraction, in which attractive force *increases* in proportion to the distance, ie., $F \sim r$. He also found that for these laws the orbits were stable, ie., that the orientation of the ellipses in place, their size, etc., would not change in time.

– *The Tides, and precession*: This is also a very complex problem, which Newton could not solve fully. Interestingly he dealt with tides in terms of a belt of fluid around the earth, which was deformable- and then by making this belt or ring solid, he was able to deal with the precessional motion of the earth (ie., the slow motion of the orientation of the earth's axis of rotation- which takes 25 years to complete a single cycle). Knowledge of the shape of the earth is of course necessary to determine the precessional motion, and fine oscillatory corrections to it (known as 'nutation'); this is now completely understood using Newtonian dynamics .

– *The moon's orbit*: This is a very complex 3-body problem, since it involves the sun perturbing the motion of the moon in its orbit around the earth. Newton probably spent more time on this than any other problem- and indeed he found a result for the progression of the apsides, caused by the sun, which was half of the correct observed value, and which caused him great frustration (he was never able to resolve this problem). In the centuries that followed more and more sophisticated attacks were made on the orbital and rotational dynamics of the moon, including its tidal interactions with the sun and the earth- we now have a complete understanding of this.

– *Frictional motion through a medium*: Newton concentrated particularly here on the motion of projectiles through air and fluids, and on the damping of pendulum motion by air. By assuming various dependences on velocity for the dissipation of the motion he was able to give an accurate treatment of the decay of pendulum motion and the slowing down of projectiles.

– *Motion of fluids*: Newton began an attack on what became a crucial part of physics- the propagation of disturbances on fluids and elastic media like solids (including air). His treatment dealt with the velocity of waves and their dependence on the fluid density, their direction of propagation, the oscillation of fluid in pipes, and so on. His treatment was correct, and the formulation of the physics of a fluid as a collection of particles was similar to that of Descartes and others. However he was not willing to go as far as Huyghens, and treat light in this manner (this is discussed in the section on Optics).

– *Vortices, and motion in a fluid vortex*: This last problem was a key problem, since Descartes had argued for a theory in which celestial motions are controlled by a medium in which vortices are centred on massive bodies like the sun, and continental physicists like Huyghens followed Descartes in this. Newton showed first that the vortex motion of a fluid was unstable, and would decay; and then that the motion of an object in a vortex was such that its orbital period T would vary like the square of the distance from the vortex centre (ie., $T \sim r^2$), instead of Kepler's result that $T \sim r^{2/3}$ (which latter of course Newton could establish from the $1/r^2$ law of gravitation). This was a fatal blow to the Cartesian theory.

By Nov 1685 these 2 books were finished- after revisions and further expansions, they would become the first 2 volumes of the *Principia*; on 21 April 1686, Halley was able to inform the Royal Society that the manuscripts were nearly ready, and on 19 May 1686 the Society voted to print them. However at this point 2 problems arose. The first arose because the Royal Society was almost bankrupt- and so on 2 June they asked Halley to pay for the printing costs. The second arose because Hooke asked that he be properly referenced in the work. This caused a huge dispute between Newton and Hooke, and almost caused Newton to abandon the 3rd volume which he had already begun. By a mixture of flattery and persuasive common sense Halley managed to convince Newton to eventually finish the 3rd volume- however instead of being the expected interpretation of the work for the less mathematical reader, Newton turned it into a highly technical treatment of lunar dynamics, with a partial treatment of cometary motion- only in the opening passages do we find any relic of the original more philosophical discussion originally envisaged, along with the following admonition:

"*It remains that, from the same principles, I now demonstrate the frame of the System of the World. Upon this subject I had, indeed, composed the 3rd book in a popular method, that it might be read by many; but afterward, considering that such as had not sufficiently into the principles could not easily discern the strength of the consequences, nor lay aside the prejudices which for many years they had been accustomed, therefore to prevent the disputes which might be raised on such accounts, I I chose to reduce the substance of this book into the form of Propositions (in the mathematical way), which should be read by those only who had first made themselves masters of the principles established in the preceding books...*"

Rarely have the feelings of a scientist wishing to avoid the oversimplification or popularisation of his work been expressed more clearly. Newton largely succeeded in his goal- he was interpreted first by other scientists, so that when philosophers like Voltaire came to try and understand him, most of the questions of principle had already been debated by people that at least understood what Newton was saying. This prevented the sort of popular reaction that he feared, for many of the ideas in the *Principia* were strong stuff- universal gravitation and action at a distance through a vacuum in particular excited a violent reaction from the continent, and were not fully accepted in France for a century thereafter.

When one comes to look at the final published version of the *Principia* there is precious little of what we would now call philosophy. In the preface to the first book, Newton lists 8 definitions. For example-

"*Definition I: The quantity of matter is the measure of the same, arising conjointly from its density and its bulk*"

"*Definition V: A centripetal force is that by which bodies are drawn or impelled, or in any way tend, towards a point as to a centre*"

and so on. There is also an introductory Scholium, in which Absolute time and space, and by contrast relative motion, are discussed; and an introductory section in which he lists his 'Axioms', or laws of motion, along with lengthy explanations. Finally, in Book III there is a short discussion of rules of reasoning, and a Scholium at the very end whose purpose is to extol the virtues of the creator of the wonderful system of the world which is revealed to us in the dynamics of bodies. But this is all- for the most part, the *Principia* is what Newton called Philosophy and Mathematicks (and what we would now call classical physics).

What became of the unpublished popularisation? In fact Newton also wrote a document, intended to be part of the *Principia*, which he eventually suppressed, called the *Conclusio*. In that document there is a more extensive discussion of the nature of forces, in which Newton speculates about the variety of different forces that must exist in Nature, and the motions of objects that must exist at a microscopic scale and how these will play a role in heat, chemical processes, sensation, etc.

In another section on Newtonian dynamics I give a more detailed discussion of some of the underlying assumptions and philosophical ideas embodied in Newton's work.

NEWTON's LATER LIFE

During the writing and publication of the *Principia*, great political events began to shape the future of the British Isles. As the reign of Charles II drew to a close, his power over Parliament had increased to the extent that when Charles died in 1685, his avowedly Catholic brother James was able to ascend the throne (in spite of votes against such a succession by 3 earlier parliaments). By this time prominent Protestant intellectuals (such as John Locke) and politicians had already begun to take refuge, in anticipation of the coming storm. However James acted too quickly and foolishly, attempting within a year to overturn the 'Test Acts', and instal Catholics in many high offices, and ordering the proclamation in all churches of 'liberty of conscience to all dissenters' in 1687, and again in 1688. On May 18, 1688, James ordered the imprisonment of the Archbishop of Canterbury and 6 other bishops for refusing to do this- but they were acquitted by a jury. This set off riots in the streets, with the burning of the Pope in effigy. It also led to the secret invitation by the 'Immortal 7' (Admiral Edward Russell, the Bishop of London, and 5 peers), extended to Prince William III of Orange, Captain-General of the United Dutch republic, to come to England to preserve the country against the Papist forces. This move seems bizarre, but William was married to Mary, who was James's first daughter by his 1st marriage; and William was also a grandson of Charles I, executed in 1649.

The birth of a son to James II on June 10, 1688 precipitated the ensuing events. On Nov 1st, 1688, William ordered a Dutch armada to sea. This apparently suicidal mission succeeded- extraordinarily, with no bloodshed. William, aided by fog, succeeded in landing in Exeter- and in the ensuing weeks many of the English forces, and much of the British Navy, went over to William's side. James, not a courageous man, finally fled to France- and William arrived just before Christmas in London to take over the throne- this was the 'Glorious Revolution'. Thereby began a long-lived alliance of the Netherlands and England against France (which manifested itself in the following years in the 'War of the Spanish Succession', in which the 'Grand Alliance' of England, Austria, the Netherlands, and most German states ranged itself against Louis XIV). The ensuing changes in the British Isles were fundamental. Refugees such as Locke returned from refuge in the Netherlands (Locke in 1689 on the same ship that carried Queen Mary), and from this time on strife shifted irreversibly to the European continent- to continue on and off until the present day. In 1707 England and Scotland united in the 'Act of Union', and Parliamentary government has prevailed, without civil war, since that time. This allowed the UK to turn its attention to developing what became the 'British Empire'; and it left scientists and other intellectuals free to pursue their research, largely free from religious interference.

Newton himself actually lived on for another 41 years after finishing the *Principia*, and had an interesting career, which involved him quite prominently in public life, most notably as Master of the Royal Mint. In the 6 years after *Principia*, he actually was involved in fairly strenuous intellectual work, but most of this consisted in putting into a coherent form work in alchemy, optics, and mathematics which he had previously done. At the same time he emerged from his shell and began to cultivate relationships with a variety of people, including John Locke and Christiaan Huyghens (who visited him several times in London). In 1693-4 he suffered some sort of a nervous breakdown, the details of which are still not completely known or understood. After this his really creative new work ceased, although he did later publish quite a lot of older work (including finally, in 1704, the results of his research in optics, much of which had been done 30 years before). The work on optics, published as "*Opticks*", was written in English rather than Latin, and in a way which made it much more accessible. As a result it became very well-known, and many in the London intelligentsia were led to try and repeat some of the more amusing experiments recounted in it. A detailed description of Newton's optical work, along with that of Huyghens, is given in another section (on optics).

In 1696 he left Cambridge for London, to take up a bureaucratic position, apparently with no regrets- Cambridge had done no more than provide him with a hiding place and the leisure to work uninterrupted, but little intellectual stimulus. In 1703 he was elected President of the Royal Society, and in 1705 he was knighted by Queen Anne. Until his death in 1727, Newton was lionized both by society and by the international scientific community, even in spite of the various disputes he got himself into (particularly with Leibniz, over the invention of the calculus), and his often dictatorial character. At his death, he was buried in a state funeral in Westminster Abbey- a rare honour for a mere scientist! It was this recognition, accorded to the author of perhaps the most important contribution made by a single person to the history of human thought, that so impressed the young Voltaire during his 3-year visit to England- and Voltaire later became one of Newton's champions for the Enlightenment, fighting against the 'Establishment' of churchmen and 'philosophes', in 18th century France.

In spite of the arrogance and occasionally rather mean behaviour he showed in his later life, Newton never lost the basic attitude towards Nature and 'Philosophy' that he had shown in his earlier years, and in his published work. Only a short time before his death he made a remark that has since become an epitaph to this remarkable man, and a testimonial to the spirit still animating theoretical physics today:

"*I do not know what I may seem to the world, but as 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 prettier shell than ordinary, whilst the great ocean of truth lay undiscovered all before me*"

Not much has changed since Newton's day in this regard- even though physics has advanced to a stage that Newton could have hardly imagined, it is even clearer now than it was then how little we really understand.

NEWTON and 'EXPERIMENTAL PHILOSOPHY'

Newton had interesting ideas about how 'philosophy' (by which he usually meant what would now be called physics) should be done. They were interesting mainly because although he was quite dogmatic about them, yet his strongly empiricist views on method were clearly at constant war with his more mystical views on what was the goal of philosophy. To get a good look at the empiricist side of his views one need look no further than the *Principia*, where he lays out rules for the correct pursuit of physics:

Rule I

We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances. To this purpose the philosophers say that Nature does nothing in vain, and more is in vain when less will serve; for Nature is pleased with simplicity, and affects not the pomp of superfluous causes.

Rule II

Therefore to the same natural effects we must, as far as possible, assign the same causes. As to respiration in a man and in a beast; the descent of stones in Europe and in America; the light of our culinary fire and of the sun; the reflection of light in the earth, and in the planets.

Rule III

The qualities of bodies, which admit neither intensification nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever. For since the qualities of bodies are only known to us by experiments, we are to hold for universal all such as universally agree with experiments; and such as are not liable to diminution can never be quite taken away…The extension, hardness, impenetrability, mobility, and inertia of the whole, result from the extension, hardness, impenetrability, mobility, and inertia of the parts; and hence we conclude the least particles of all bodies to be also extended, and hard and impenetrable, and movable, and endowed with their proper inertia. And this is the foundation of all philosophy.

Rule IV

In experimental philosophy we are to look upon propositions inferred by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions. This rule we must follow, that the argument of induction may not be evaded by hypotheses.

These remarks are very much in tune with the whole austere spirit of the *Principia* and its mechanical approach. Newton never abandoned them, even when trying to push some his much less secure views on light and the aether, for which he had in some cases very little experimental justification (let alone proof!). For example in his *Opticks*, published in 1704, he has a list of 'Queries' (which were nothing but the speculations in chapter 4 of his old manuscript, disguised in a form which made them less controversial). One of the last of these, Query 31, added to the final edition, goes as follows:

'*As in Mathematicks, so in Natural Philosophy, the Investigation of difficult Things by the Method of Analysis, ought ever to precede the Method of Composition. This Analysis consists in making Experiments and Observations, and in drawing general Conclusions from them by Induction, and admitting of no Objections against the Conclusions, but such as are taken from Experiments, or other certain Truths. For hypotheses are not to be regarded in Experimental Philosophy. And although the arguing from Experiments and Observations by Induction be no Demonstration of general Conclusions; yet it is the best way of arguing which the Nature of Things admits of, and may be looked upon as so much the stronger, by how much the Induction is more general. And if no Exception occur from Phenomena, the Conclusion may be pronounced generally. But if at any time afterwards any Exception shall occur from Experiments, it may then begin to be pronounced with such Exceptions as occur. By this way of Analysis we may proceed from Compounds to Ingredients, and from Motions to the Forces producing them; and in general, from Effects to their Causes, and from particular Causes to more general ones, till the Argument ends in the most general. This is the Method of Analysis: And the Synthesis consists in assuming the Causes discover'd, and establish'd as Principles, and by them explaining the Phenomena proceeding from them, and proving the Explanations*'

This passage is very interesting to see alongside the speculations about what substance filled empty space, and his answer that there must be some incorporeal but living and intelligent being of which space is the 'sensorium' (see Query 28).

There is no reason to believe that Newton was being either irrational or inconsistent here- he genuinely felt that one had to go to a non-mechanical explanation of the universe, in order to understand what lay beneath the mere mechanical facts and rules about the motion of bodies. It seems rather that he saw the 'Experimental Philosophy' as a way of harnessing and controlling the speculative or 'hypothetical' approach to which he was so prone, in order to keep speculation from running wild. In this he was surely adopting the correct strategy- given how little the purely speculative approach had yielded in 2000 years of 'philosophizing'. However one also feels that his Baconian view of how one proceeded, by inferring hypotheses from experiment, was hardly a good description of how he really arrived at his conclusions (although he seemed to think it was). For more on this topic see the section on Light and Optics.