GALILEO's SCIENTIFIC RESULTS

The dramatic quality of Galileo's life tends to obscure his most important scientific achievements. What consistently attracts most attention is his astronomical work, and his conflict with the Church over the Copernican theory. The latter was important in the sense that it had an enormous effect on the future relationship between science and religion- the church won the battle but lost the war. But from a purely scientific point of view the most important work of Galileo was only published at the end of his life, and as a direct result of his confinement under house arrest. This was his 'Dialogue concerning 2 New Sciences', published in 1638. In it he outlined in full detail all his results in physics, their explanation, and the combination of experimental and theoretical methods which had led him to these. These results and the methodology were pivotal in the whole development of modern science.

(1) GALILEO's ASTRONOMICAL OBSERVATIONS

The story of Galileo's early telescopic observations has already been given above- and more details appear below on the observations of the moon, Jupiter's moons, and sunspots. In passing let us note that Galileo also made extensive observations of the stars, and of Saturn and Venus. His stellar observations revealed a seemingly infinite array of stars beyond what can be seen by the naked eye- the pictures of the region below Orion's belt and of the Pleiades star cluster are particularly famous. Note that a pair of modern binoculars is capable of revealing everything that Galileo saw- however, one has to escape from the light of modern cities to do do this.

Galileo first turned his telescope towards Saturn on 25 July 1610 and it appeared as three bodies (his telescope was not good enough to show the rings but made them appear as lobes on either side of the planet). Continued observations were puzzling indeed to Galileo as the bodies on either side of Saturn vanished when the ring system was edge on. Also in 1610 he discovered that, when seen in the telescope, the planet Venus showed phases like those of the Moon, and therefore must orbit the Sun not the Earth. This did not enable one to decide between the Copernican system, in which everything goes round the Sun, and that proposed by Tycho Brahe in which everything but the Earth (and Moon) goes round the Sun which itself goes round the Earth. Most astronomers of the time actually favoured Brahe's system- in fact it was beyond the capabilities of the instruments of Galileo's day to decide between the two. Nevertheless Galileo was well aware that these discoveries provided circumstancial evidence for Copernicanism, even in the absence of a cast-iron proof. In fact his theory of falling bodies was more significant in this respect (see below).

We now proceed to a more detailed discussion of his most important observations, setting them in a historical context.

The Moon

Ignoring the occasional pre-telescopic appearance of exceptionally large sunspots, the Moon is the only heavenly body which shows features to the naked eye. These features are permanent, and it has thus always been obvious that the Moon keeps the same face turned towards us (although there are minor fluctuations that were not studied until the invention of the telescope). These features were of course known to the ancients, without knowing what they were. We recall that in the work of Aristotle the Moon marked the frontier of the changeable realm of the 4 elements- this 'sublunary realm' was the one of change and corruption. Beyond this realm was the perfect and unchanging realm of the celestial spheres. Aristotle's ideas were not without critics at that time. Thus, eg., Plutarch (46-120 AD) in "*On the Face in the Moon's Orb*", suggested that the Moon had deep crevasses which always remained in shadow, and that the Moon might be inhabited.

In mediaeval times the followers of Aristotle were faced with a problem in trying to understand the lunar 'spots' (in reality these are the *maria*, dark regions where lava covered parts of the surface in the early part of the moon's life). Various ideas were discussed. The most commonly accepted explanation was that variations in the density of the Moon caused an otherwise perfectly spherical body to show an inhomogeneous face to us. Interestingly, even though many images of the Moon appear in medieval and Renaissance works of art (usually as a crescent), it was almost never shown with its blemishes. Only have a few sketches of Leonardo da Vinci, and a drawing by William Gilbert, make any attempt to depict the moon as it really appears- and neither of these was published until after the invention of the telescope.

The invention of the telescope made it clear what the surface of the moon was really like. Even with his earlier telescopes, Galileo saw not only the "ancient" spots, but many smaller ones, in which the width of the dark lines defining them varied with the angle of solar illumination. These dark lines changed with the solar illumination, and he saw light spots in the dark part of the Moon near the 'terminator' (the line marking the edge of the dark unilluminated part of the moon), which gradually merged with the illuminated part as this part advanced. Galileo realised that the changing dark lines were shadows and that the lunar surface is covered with mountains, craters, and valleys, particularly in the lighter regions. Very high mountains appear as points of light on the dark side of the 'terminator' (the line between daytime and night-time regions on the surface of the moon); this is of course because the mountain tops are still illuminated well after sunset in the lower regions. In the same way valley bottoms and crater floors remain dark well after sunrise or before sunset. We now know that some lunar mountains reach up to 10 km above the surrounding surface, and crater walls up to 7 km above the crater floors. With his telescope Galileo was not able to see enough detail to give an unambiguous interpretation of what he saw. Nor could he at the time have seen that the dark maria are relatively smooth regions, where vast lava flows have covered most of the relief.

Galileo originally intended to make a series of drawings of the Moon showing its changing phases. This was apparently never done, and in fact Galileo never returned to detailed observations of the Moon. (although in the 1630s he did observe the lunar librations mentioned above). Curiously, it was a long time before any kind of map of the moon was produced (apart from an unpublished one of Thomas Harriot). Simple diagrams were produced by Christoph Scheiner (one of Galileo's competitors), Giuseppe Biancani, and Charles Malapert. In the dry air of the Alpes-Maritimes of southern France, Nicholas Claude Fabri de Peiresc and the astronomer Pierre Gassendi, together with the artist Claude Mellan, and using Gassendi's sketches and guidance, produced 3 engravings of the Moon, showing the first quarter, the full Moon, and the last quarter.

The first real map, showing the relief across the whole face of the moon (and not the view at a given time) was made in 1645 by the Belgian astronomer Michel Florent van Langren. In 1647 Hevelius, a wealthy brewer in Danzig (now Gdansk), published his *Selenographia*, which presented engravings at all different phases of the Moon along with 3 large plates of the full Moon. The first of these shows the full Moon as it appears through the telescope, the second in the way terrestrial maps are presented, and the third is a composite map of all lunar features. The *Selenographia* was a model for all subsequent maps, although his nomenclature for lunar features was eventually superceded by the system of the Jesuit astronomer Giovanni Battista Riccioli, who in 1651 gave the large dark regions the names of '*maria*' (eg., the Sea of Tranquillity, Sea of Storms, Sea of Clouds, etc.) and the craters the name of philosophers and astronomers (eg., Copernicus, Tycho, Plato, Aristarchus, Ptolemy, Kepler, etc).

Satellites of Jupiter

The 4 largest satellites of Jupiter are all larger than the moon, and would just be visible to the naked eye without the brilliant light of Jupiter. Thus the telescope used by Galileo in 1610 made these four "Galilean" satellites easy to see. On 7 January 1610 he observed Jupiter and saw 3 fixed stars near it, strung out on a line through the planet. This caught his attention, and he returned to it the following evening. By trial and error Galileo learned to stop down the aperture of his instrument (reducing the glare of Jupiter) so as to make useful observations. Over the next week he found that there were 4 stars, which appeared to be carried along with the planet, changing their position with respect to each other and Jupiter. By 15th January he understood he was dealing with bodies that revolved around Jupiter- it had four moons. This discovery was described in the middle of March 1610, in the *Siderius Nuncius* (Starry Messenger), and it immediately made Galileo famous. The challenge to traditional Aristotelian cosmology was immediately clear. In the orthodox view, by now a central feature of Catholic dogma, there was only one center of motion, the center of the universe, which was the Earth. On the other hand according to the Copernican theory, the Earth went around the Sun while the Moon went around the Earth. There were thus two centers of motion, which seemed an absurdity. Galileo's discovery showed there were now at least two centers of motion in the universe, the Earth or Sun, and Jupiter. Thus, although the Galilean satellites (a term first used by Kepler) did not prove the Copernican system to be correct, they did fatal damage to the Aristotelian one.

In the purely astronomical realm, the satellites of Jupiter posed a new problem for astronomers. It had taken centuries in Antiquity to arrive at adequate geometrical modes for the motions of the known planets. Now there was a new system of planetary bodies in miniature, and astronomers had to develop models that could predict their motions. There was a great incentive to come up with good mathematical models, for the satellites offered some hope for the solution of the problem of longitude at sea. While in Rome, and after his return to Florence, Galileo continued to make observations with his telescope. Already in the Starry Messenger he had given rough periods of the four moons of Jupiter, but more precise calculations were certainly not easy since it was difficult to identify from an observation which moon was I, which was II, which III, and which IV. He made a long series of observations and was able to give accurate periods by 1612. At one stage in the calculations he became very puzzled since the data he had recorded seemed inconsistent, but he had forgotten to take into account the motion of the Earth round the sun.

Unfortunately this did not resolve all problems to do with the orbital motion of the Galilean satellites. It took almost two centuries after Galileo before models for their motion, and tables based on these models, reached satisfactory accuracy. The main problem was that the interactions between these satellites cannot be neglected, and tidal forces from Jupiter are also important- proper calculation of these had to wait until new mathematical methods had been developed, and applied to solve Newton's equations for the motion of several interacting bodies in motion.

The names of the satellites were not established immediately. Galileo wanted to name them the "Medicean Stars", after his patrons, and through most of the seventeenth century they were known by that name. In his notebooks, Galileo referred to them individually by number; Peiresc tried to differentiate between them using the names of individual members of the Medici family, but this system was not published. Simon Marius, in his '*Mundus Iovialis*' (1614), suggested 2 other systems of his own, followed by a suggestion of Kepler's, viz., that one use the names of 3 maidens courted by Jupiter in the Greek legends (Io, daughter of the River god Inachus; Callisto of Lycaon; and Europa of Agenor), plus Ganymede, the son of King Tros, whom Jupiter transported to heaven on his back, whilst in the form of an eagle. Kepler's suggestion eventually, in the 18th century, became the standard practise.

We now have extensive knowledge of each individual Galilean satellite, mainly because of visits by NASA spacecraft- each is a whole world with unique and very interesting properties, about which whole books have been written. It is speculated that perhaps life exists in oceans that exist many km below the icy crust of Europa (note that the surface temperature at this distance from the sun is usually below -150 C, except on Io, which is heated by tidal interactions with Jupiter, and in a state of constant volcanic eruption).

The Sun, and Sunspots

In mediaeval Aristotelian cosmology, the existence of spots that comes and go on the Sun would mean that there is change in the realm of the perfect heavens. Given this, plus the difficulty of observing the Sun, it is hardly surprising that records of sunspots are almost non-existent in Europe before the seventeenth century. Records of naked-eye sunspot observations in China go back to at least 28 BC. It is also possible that the Greek philosopher Anaxagoras observed a spot in 467 BC, and there are a few other remarks in the ancient Greek literature. Although there is still some controversy about priority, Galileo and Thomas Harriot were the first to observe sunspots with a telescope, near the end of 1610; Johannes and David Fabricius and Christoph Scheiner then observed them in March 1611, and Johannes Fabricius was the first to publish his results in "*De Maculis in Sole Observatis*" ("On the Spots Observed in the Sun") which appeared in the autumn of 1611.

By this time Galileo had shown sunspots to a number of people in Rome in spring 1611. However he did not begin a systematic study until a year later. Scheiner began his serious study of spots in October 1611, and his first published work, "*Tres Epistolae de Maculis Solaribus Scriptae ad Marcum Welserum*" ("Three Letters on Solar Spots written to Marc Welser") appeared in January 1612. Scheiner was a Jesuit mathematician at the University of Ingolstadt; desiring to preserve the perfection of the Sun, he argued that sunspots were satellites of the Sun. Finally, in April 1612, Galileo turned his full attention to sunspots, along with his student Benedetto Castelli, who invented the method of projecting the Sun's image through the telescope onto paper- a far more effective and less dangerous method than using coloured filters. This led to an exchange of letters between the two (via the intermediary of Welser), which were eventually published in Rome by the Lyncean Academy in the summer of 1613. Galileo argued that spots were, in fact, on the surface of the Sun or in its atmosphere- they appeared to him most likely to be clouds, whereas Scheiner, wishing to maintain the perfection of the sun, argued they were solar satellites. Galileo followed this up with a large number of sunspot observations, so that the motion of the spots across the Sun's disc could be easily followed. Galileo also criticized Scheiner's *a priori* method of argument, in which the premise that the Sun is perfect led to the conclusion that it cannot have spots on its surface. He reported his results in the "Discourse on floating bodies", published in 1612- and as noted above, in the letters on the sunspots, which appeared in 1613.

Eventually Scheiner published his results in a massive volume, the *Rosa Ursina*, ("Rose of Orsini"), in which he abandoned the idea that spots were solar satellites.

Scheiner's studies were followed by those of Johannes Hevelius (1647), Pierre Gassendi (1658), and Giovanni Battista Riccioli (1651). After this time, however, sunspot activity decreased, so that the observation of a large sunspot in 1671 was treated as a rare event. After 1710 sunspot activity increased again- we now know that the sunspot frequency goes through cycles, and the period of low activity is known as the Maunder Minimum, after Edward Walter Maunder (1851-1928.

A proper understanding of sunspots has only come in the 20th century, with an understanding of the the constitution of stars and how they work. The surface regions of the sun are extraordinarily complex. Sunspots are somewhat unstable areas in which concentrated magnetic fields emerge from deeper regions, through which radiation and particles funnel from deeper regions of the sun. They are darker because they are considerably cooler than their surroundings. Large spotlike regions have now been observed on other stars using interferometric methods.

(2) GALILEO's WORK in PHYSICS

The inquisition actually did the world an enormous favour by imprisoning Galileo- it is unlikely that he would have assembled the results of his 35 years of experimentation and theoretical analysis in his final work, if this had not happened. This work was dictated to Viviani, then smuggled out of Italy to Leiden in Holland, and published there as "*Discorsi e Demostratione Matematiche intorno a due nuove Scienze*" (now translated as "Dialogues concerning 2 new sciences") in 1638. It is one of the most important books in human history.

GALILEO's METHODOLOGICAL APPROACH to PHYSICS

Galileo is, with good reason, regarded by many as the father of modern physics (indeed of modern science). It is worthwhile understanding why this is so, and what was so new and important- both in what he did, and how he did it. To properly appreciate his approach it is highly recommended that one look at the original texts of Galileo's published work.

We can begin with Galileo's book '*Il Saggiatore*' (The Assayer). This was just about to be published by the Accademia dei Lincei in 1623, when Maffeo Barberini was elected Pope; Galileo was quick to dedicate his work to the new Pope. This work, apart from vigourously criticising Aristotle, described Galileo's scientific method in some detail. It contains a famous quote regarding mathematics, which sums up one aspect of Galileo's approach to physics:

"*Philosophy is written in this grand book, the universe, which stands ever open to our gaze. But the book cannot be understood unless one first learns to comprehend the language, and to read the characters in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures without which it is humanly impossible to understand a single word; without mathematics one is simply wandering in a dark labyrinth.*"

This however was only part of Galileo's multifaceted approach to understanding the book of Nature. United with the mathematical and deductive approach in his mind was the necessity to probe Nature using experiments. Galileo was not of course the first to do experiments on natural phenomena, but he was the first to do it systematically, and to study such a comprehensive array of phenomena. His point of view on this was expressed in a number of aphorisms; for example

"*We must deal with the real world, and not one written on paper*" (from the dialogue on 2 world systems)

As part of this attitude Galileo was wont to emphasize that it was better to admit ignorance than to be wrong, or to argue on the wrong side- thus his exhortation to his pupils to confess 'I don't know' instead of trying to offer explanations, and to understand that no matter how deeply one might penetrate into a subject, an infinity remained to be understood. The point here was that in science, just as in philosophy, an admission of ignorance is the first step towards understanding- and in the case of physics, the next step was to perform an appropriately designed experiment. The importance of this step can hardly be overestimated. The influence of Galileo's point of view was quickly felt in certain circles; for example, in the motto adopted by the new 'Academia del Cimento', which was '*test and test again*". Its novelty is also worth stressing- although the idea that general statements or principles about the world should be tested, and should be capable of withstanding experimental test, now just seems to be obvious common sense, at the time many found it to be a strange and disturbing idea. No less a figure than Descartes strongly criticised Galileo's method, arguing that it was incorrect to explain physical effects or phenomena without a prior knowledge of their causes (NB: note that the term 'cause' is here being used in the somewhat more Aristotelian sense of denoting the fundamental laws or 'causative principles' of nature).

Nowadays it is much easier for us to appreciate that both features of Galileo's methodology were essential to his success. A blind attempt to probe Nature experimentally, without any attempt to have a theoretical dialogue with the results, leads one into Galileo's dark labyrinth; but as Galileo well knew, theorizing in the absence of experiment is equally likely to lead physics into blind alleys. The deliberate use of the dialogue form to present his arguments and even his experimental results is quite central to Galileo's approach, and in line with his feeling that experiments formed an integral part of the theoretical dialogue with nature. Galileo would, with good reason, have been very disappointed by the split between theory and experiment which exists in most scientific labs nowadays.

However, there is no question that Galileo himself was largely responsible for the split that began in the 17th century between physics and philosophy. It is unlikely that this is what he himself intended. Galileo was strongly opposed to some of the tenets of Aristotelian philosophy as interpreted by the Catholic Church- in particular, to Aristotle's ideas about falling bodies, about moving projectiles, about motion in the void, and about the structure of the heavens. But there is no reason to suppose that he was either anti-religious or anti-philosophical, or that he even held strong philosophical opinions. His relentless attacks on Aristotle were to some extent more polemical than a manifestation of a true philosophical (or anti-philosophical) position- they were essentially an attack on established authority. His point was to emphasize that the only true authority in questions on Nature was Nature herself. In fact Galileo frequently resorted to Aristotelian arguments when he felt them to be appropriate (for example in the 'Dialogue', to pin down essential points and establish the Copernican worldview); and his works were all deliberately written in the dialogue form introduced by the Platonic school. Thus Galileo did not himself see any real distinction between philosophical inquiry and science. However the opposition of Descartes and other rationalist philosophers to the empirical methods and ideas of Descartes essentially drew the battles lines for future debate. In the end the result was that (i) physics emerged as a distinct science, and (ii) that the importance of philosophy as a discipline was greatly diminished- and that the place of metaphysics in philosophy was eclipsed, particularly in the Anglo-Saxon countries, was eclipsed by epistemological questions. Philosophy also became much more sceptical, following the example of Galileo and in the wake of later scientific advances. Few in the 20th century were impressed by the kind of grand philosophical system favoured in Ancient and mediaeval times- the last attempt to create such a system in the West was Immanuel Kant, nearly 250 years ago (see later notes).

It almost goes without saying the power of dogmatic religion to influence or control people's beliefs has been drastically reduced since Galileo took on established authority nearly 400 years ago. It is of course interesting to speculate on how things would have happened had the church not attempted to suppress the advances in physics that Galileo started. This we cannot easily guess- however it is a reasonable bet that Galileo would have been quite pleased to see how things turned out.

ACHIEVEMENTS in PHYSICS

Galileo saw rightly that the orthodox framework for understanding nature was so far off the mark that one essential task was to give a correct explanation of a large number of physical phenomena. This not only allowed him to build a case against Aristotelian ideas, but also to give a more or less systematic exposition of his methodology. However his ideas developed gradually over a long period of time.

Early Work- "De Motu": During his time at the university of Pisa (1589-1592), Galileo began a book, "*De motu*" ("On motion"), which was never published. In it, we can trace the early development of his ideas on the dynamics of bodies.

One of the fundamental assertions of Aristotelian philosophy is that there is no effect without a cause, except in the celestial realm. Applied to moving bodies, this was taken to mean that there is no motion without a 'force'. For Aristotelians this meant that speed was proportional to force and inversely proportional to resistance (ie., friction). Consider what this meant for falling bodies. If their weight determines the speed of their fall, then when two different weights are dropped from a high place the heavier will fall faster and the lighter slower, in proportion to the two weights. A 100 kg weight dropped from a tower would reach the Earth 100 times faster than a 10 kg weight.

In fact, as Galileo argued, it is not even necessary to do an experiment to see that this idea cannot be correct. Suppose, for example, one connects the two weights. Then the Aristotelian view would have the lighter weight slowing down the heavier one, making the time of fall greater. But one can also argue that the two together form a heavier composite body, which should fall faster. This paradox shows the theory must be wrong.

Of course one can also do experiments. As early as 1544, the historian Benedetto Varchi refers to actual tests showing that the Aristotelian picture was incorrect. In 1576, Giuseppe Moletti, Galileo's predecessor at the university of Padua, reported that bodies of the same material but different weight, as well as bodies of the same volume but different material, fell at the same speed from a tower. In *De motu* Galileo proposed that in free fall bodies dropped with a uniform speed determined by their density. However, when he put this theory to the test by dropping bodies from heights, he found that the theory was incorrect. There were two reasons for this- one was that the experiments were inaccurate, and the other was that Galileo had not yet understood that forces lead to accelerations rather than uniform motion.

"Dialogues concerning 2 new sciences": Over the next 30 years Galileo refined his experiments, and in the end he arrived at the correct law of falling bodies which states that in a vacuum all bodies, regardless of their weight, shape, or specific gravity, are uniformly accelerated in exactly the same way, and that the distance fallen is proportional to the square of the elapsed time. This was finally published in full detail in "Dialogues concerning 2 new sciences" in 1638. It was a crucial first step towards Newton's 2nd law of motion.

However this book contained much more than this. It was his most rigorous mathematical work, which treated a wide variety of problems. A partial list includes:

(i) The fracture of materials, including a discussion of the strength of different materials. The strength and resistance to fracture of different load-bearing beams, and how this depends on their cross-section and its shape, on their length (including beams with a cross-section varying down their length), and on where the load is placed. The strength and resistance to fracture of tubes, and how this depends on the length, and the internal and external diameter, and where the loads are placed. The resistance to slip of ropes wrapped around various objects, such as capstans, between cylinders, with and without grooves, etc. The strength of various load-bearing shapes under tension, including prisms, solids with triangular, parabolic, etc., cross-sections. How the strength of arbitrarily-shaped solids scales with their size. The force between objects with an evacuated space between them. The properties of levers, and solid equilibrium. Centres of gravity for solid bodies of many different shapes.

(ii) Extensive discussion of geometrical questions, relating to various complex forms (polygons, circles and other curves, etc) particularly where they are related to the shape of objects, which may or may not be in contact; the way to define lines in terms of points, etc.; the relationship of geometry to numbers and series of numbers (Cartesian geometry did not yet exist); the divisibility of matter into ever smaller parts, and the assertion that different materials must be made of constituents having different shapes, sizes etc. Calculation of areas, volumes densities, etc.

(iii) the phenomenon of light, its unmeasurably high speed of propagation, and the energy it carries which can be focussed using mirrors.

(iv) The motion of bodies through fluids, discussion of Aristotle's ideas on this, and why they must be wrong. The same thing for the fall of bodies through fluids, including air, and the the paradoxes that Aristotle's ideas give. The theory that the rate of fall (or rise, for bodies of density less than the surrounding fluid) depends on the relative densities of the body and the fluid, and not on the mass of the body. Dependence of the velocity on shape (streamlining). The argument that all bodies fall at the same rate in a vacuum. Experiments and experimental methods for determining densities, of both fluids and solid bodies. The frictional effect of the fluid on the motion of bodies through it, and how this depends on the velocity, and shape; the terminal velocity of objects moving under forces, and deceleration of objects like cannon balls in water.

(iv) Vibrations of strings, oscillations and resonance causing sounds in wine glasses, musical instruments, brass plates, etc, and in air, causing vibrations in the ear; the dependence of pitch on string tension, musical theory, etc.

(v) The dynamics of the pendulum: geometry of pendulum arcs, the period as a function of the length, resonant excitation of pendulum oscillations. Pendulum dynamics when string contacts intermediate bar- rise to height of initial release point, regardless of path, apart from frictional losses.

(vi) Uniform and accelerated motion: Time and distance intervals, definition and properties of velocity in terms of time and space increments (NB: pre-calculus). Definition of acceleration, uniform acceleration. Experiments on falling bodies (uniformly accelerated by gravity). Uniformly accelerated motion down inclined planes. Dependence of motion on slope of plane, and relation to geometric properties of chords cutting circles. General result for uniform acceleration- the distance goes like the square of the elapsed time ($s = \frac{1}{2}gt^2$, where g is acceleration); the dependence of g on slope of plane. Rise of bodies to same height as release point on any shaped slope, time of descent on various arcs. Results of some experiments.

(vii) Motion of projectiles: proof of Parabolic motion of projectiles. The dynamics of falling weights, independence of motion on mass of weights, role of friction. Dynamics of cannon balls. Vector addition of velocities. What is now called Galilean invariance- dependence of velocities on velocities of frame of reference. Momentum of projectiles. Form of parabola as function of initial projectile velocity- proof that 45^o trajectories have maximum range (without friction), various mathematical properties of trajectories and parabolae. Extensive data from experiments on projectile motion.

This is clearly a lot of material- but much of it is not germane to the development of physics later on. We single out here just a couple of themes from this work, to illustrate how Galileo worked, and some of his most important results.

Galileo's Inclined Plane Experiments: These were amongst his most important experiments. Galileo's inclined plane was a simple board with a groove down which he rolled a small metal ball. The crucial feature which he concentrated on in these experiments was the acceleration of the ball as it moved down the plane, and which had been ignored by Aristotle and indeed almost everyone before Galileo. Here is the description of one set-up, taken from his book:

"*A piece of wooden moulding, about 12 cubits [roughly 7 m] long, half a cubit [30 cm] wide and three finger-breadths [roughly 5 cm] thick, was taken; on its edge was cut a channel a little more than one finger in breadth; having made this groove very straight, smooth, and polished, and having lined it with parchment, also as smooth and polished as possible, we rolled along it a hard, smooth, and very round bronze ball.....we repeated this experiment more than once in order to measure the time with an accuracy such that the deviation between any two observations never exceeded one tenth of a pulse-beat...*"

In order to measure time intervals Galileo needed some kind of clock- since he had not yet devised the pendulum clock he used a simpler but less accurate method:

"*For the measurement of time, we used a large water vessel placed in an elevated position; to the bottom of this vessel was attached a pipe of small diameter giving a thin jet of water, which emptied into a small glass during the time of descent of each ball. The water thus collected was then weighed, after each descent, on a very accurate balance; the difference and ratios of these weights gave us the differences and ratios of the times.*"

Using a slight modification of this apparatus Galileo was also able to measure the dynamics of projectile motion. In Aristotle's theory of motion, projectiles were pushed along by an external force which was transmitted through the air. His mediaeval successors internalized this force in the projectile itself and called it "impetus." This impetus caused the object to move in a straight line until the impetus was used up, at which point the object fell to the ground. During the Renaissance, this view became untenable, for 2 reasons. First, the emphasis in the arts was on accurate representation of objects, using perspective- and this forced a better representation of motion. Second, the use of cannon in warfare forced a careful study of projectile motion. Thus came the gradual acceptance that projectiles did not move the way Aristotle and his followers had said, but rather in a smooth curve. However what this curve was had to be determined.

Galileo adapted his inclined plane apparatus by adding a curved piece at the bottom which deflected an inked bronze ball into a horizontal direction. The ball thus accelerated rolled along a flat table with uniform motion, and then fell off the edge. Where it hit the floor, it left a small mark. The mark allowed both the horizontal and vertical distances travelled by the ball, whilst in the air, to be measured. By varying the ball's horizontal velocity and vertical drop, Galileo was able to determine that the path of a projectile is parabolic.

Galileo's Pendulum Experiments: Galileo used pendula extensively in his experiments. We recall that in Aristotelian physics, a heavy body (that is, one in which the element earth predominates) seeks its natural place, the center of the earth. The back and forth/up and down motion of a heavy body suspended from a string was then very puzzling in the Aristotelian system. According to Vincenzo Viviani, Galileo began his study of pendula after watching a lamp swing back and forth in the cathedral of Pisa whilst a student there. His first notes on the pendulum date from 1588, but he only began serious study in 1602.

The importance of the work on the pendulum for Galileo was not limited to the understanding of the dynamics of falling or oscillating objects. It also provided him with a crucial tool- the means to measure time. This is because of the "isochronism" of the pendulum- its period of swing is independent of its amplitude (NB: this is actually only approximately true, but it is a very good approximation of the amplitude of swing is not too large). Galileo showed that the period of swing only depended on the length of the string- thus it can be used to keep time. His main discoveries can be summarized as follows:

(i) In the absence of friction, a pendulum will rise again to the same height as its point of release (this is actually a consequence of energy conservation, although Galileo was not able to put it in these terms- the concept of energy had not been properly understood in his day).

(ii) The period of swing is independent of the amplitude of the swing (for small amplitude swings), and of the mass of the pendulum bob.

(iii) The period of oscillation of the pendulum is proportional to the square root of the length of the pendulum.

(iv) All of these results are valid in the limit that friction is very small- Galileo found that in reality the pendulum swing decays, and that lighter ones decay faster (the reason for this is that friction takes energy from the pendulum oscillations, and a heavier pendulum has more energy for a given amplitude of swing).

The motion of pendula suggested many interesting problems to Galileo. For example, what was the fastest motion from a higher to a lower point, along a circular arc like a pendulum bob, or along a straight line like on an inclined plane? By what mechanism does the friction affect the pendulum motion? How is the motion of one pendulum transferred to another to which it is weakly coupled (eg., by swinging from the same bar)? And so on. However, apart from questions of detail, the most important result of studying the pendulum was that it was a model system which exemplified both simple harmonic oscillation, and the fall of an object which was constrained to move along a certain path. Oscillatory motion is extremely widespread in Nature, and so many of the results obtained for the pendulum have more general value (eg., in the oscillations of strings, or springs, or fluids).

Very late in life, after he had been put under house arrest, Galileo put his mind to the question of how to improve the clocks that existed at that time. The mechanical clock, using a heavy weight to provide the motive power, had begun to replace the older water clock in late mediaeval times. But even the best mechanical clocks were almost useless for astronomical purposes. Galileo's student and assistant Vincenzo Viviani described the genesis of Galileo's clock design as follows:

"*One day in 1641, while I was living with him at his villa in Arcetri, I remember that it occurred to him that the pendulum could be adapted to clocks with weights or springs, serving in place of the usual tempo; he hoped that the very even and natural motions of the pendulum would correct all the defects in the art of clocks. However his blindness prevented him from making drawings and models to the desired effect, and so when his son Vincenzio came one day from Florence to Arcetri, Galileo told him his idea and several discussions followed. Finally they decided on a design to be put in practice , so as to learn the fact of those difficulties in machines which are usually not foreseen in simple theorizing.*"

Viviani wrote this in 1659, seventeen years after Galileo's death and two years after the publication of Christiaan Huygens's *Horologium* , in which Huygens described his own pendulum clock. Subsequent pendulum clocks were all based on Huygens's construction, and remained the best method of measuring time for 200 years thereafter. Far superior methods became available once the electromagnetic field was understood in the 19th century.

The Thermometer: At the beginning of the 17th century heat was hardly understood, and there was certainly no way to quantify it. In Aristotelian theory, heat and cold were fundamental qualities- they were qualities combined with "*prima materia*" to make up the elements, earth, water, air, and fire. Thus earth was dry and cold, fire dry and hot, etc. However Galileo and other contemporaries of his were interested in trying to quantify heat. In 1638 Benedetto Castelli recalled a device he had seen in Galileo's hands around 1603:

He took a small glass flask, about as large as a small hen's egg, with a neck about two spans long and as fine as a wheat straw. He warmed the flask well in his hands, then turned its mouth upside down into the a vessel placed underneath, in which there was a little water. When he took away the heat of his hands from the flask, the water at once began to rise in the neck, and mounted to more than a span above the level of the water in the vessel. Galileo had then made use of this effect in order to construct an instrument for examining the degrees of heat and cold.

Over the next few years this thermoscope was developed by Galileo and his friends Santorio Santorio and Gianfrancesco Sagredo, to include a numerical scale. The essence of the device depended on the expansion of air as it heats up. The first quantitative meteorological observations date from this time. Almost simultaneously Cornelis Drebbel and Robert Fludd developed similar instruments. Soon after thermometers were developed using liquids in glass, but there was little basic understanding of what was being measured- Each design used different scale divisions, often based on different reference points. It was thus impossible to compare temperatures in different places. In the early 18th century, universal temperature scales were developed by Daniel Gabriel Fahrenheit (1686-1736), Anders Celsius (1701-1744), and Ren-Antoine Ferchault de Raumur (1683-1757). Of these, the first two are still in use, and the Celsius system (adapted by Lord Kelvin to measure temperatures from absolute zero) has become the standard scientific temperature scale.