CHAPTER VI
AN HISTORICAL CASE STUDY -- GALILEO AND THE COPERNICAN THEORY

[Science] is written in this grand book - I mean the universe - which stands open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometrical figures, without which it is humanly impossible to understand a single word of it; without these, one is wandering about in a dark labyrinth.

--Galileo

Let us now turn to an example of scientific reasoning in situ. I have chosen certain episodes in Galileo's life for two reasons: First, this story is one of the most famous and fascinating in the history of science. Secondly, it provides excellent material with which to illustrate the ways in which real life scientific practice does and does not conform to the Popperian model.

The controversy over the acceptability of the Copernican theory involved at least four separable debates. As you study this case it will be helpful to keep the following four topics in mind:

1. The Astronomical Dispute: What were the competing models of the universe? What was the evidence for and against each?

2. The Dispute in Physics: What were the competing theories of motion? What was the evidence for and against each?

3. The Religious Dispute: What were the competing theories about the proper relationship between the Bible and science? What were the arguments on each side?
4. The Methodological Issues: To what extent was Galileo introducing new scientific methods as well as new scientific theories? Was Galileo a Popperian? (That is to say, does his methodological practice conform to Popper's theory of scientific method?)

Although the story I tell below is intended to be roughly correct and certainly not seriously misleading, at times I have oversimplified things slightly. And since there is an evergrowing body of historical information about this period, my story (and the secondary sources on which I relied) may very well be out-of-date at some points.

I. Life Begins at Forty-Five

Prior to his famous telescopic observations, Galileo's scientific career had not been anything extraordinary. After brief studies at a monastery, Galileo studied medicine and then mathematics at the University of Pisa. In 1589, he gained the chair of mathematics there. In 1591 he moved to the University of Padua.

At that time mathematics included not only Euclidean geometry but also quantitative sciences such as astronomy. Most discussions of subjects which we would include under physics took place within philosophy departments. One concern of Galileo (and other anti-Aristotelians) was to introduce mathematical methods into the study of motion. When Galileo later moved to court at Florence in 1610 he insisted that his title be "mathematician and philosopher to the grand duke of Tuscany."

During this period Galileo gave lectures on Ptolemaic astronomy. He also knew about the Copernican system and wrote a letter to Kepler in 1597 in which he expressed his sympathy towards it. However, he did not make his sentiments public, although Kepler urged him to.

At this time Galileo was much more interested in mechanics than in astronomy. While at Pisa he wrote, but did not publish, a treatise on motion (called De Motu) in which he criticized the Aristotelian account of the motions of

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1Based on Stillman Drake's article on Galileo in The Dictionary of Scientific Biography.
falling bodies and projectiles. Galileo's own positive account of motion in
this early work was a variant of the Medieval impetus theory. It was only
later that he arrived at a theory which resembles the modern account.

Galileo also invented several useful practical instruments - a pro-
portional compass for surveyors, a pendulum device for timing pulses in
hospitals, and a clever little balance to be used for assaying metals accord-
ing to their density. In 1606 someone stole his idea for the proportional
compass and so Galileo pressed charges. Following the custom of the times
Galileo also wrote a pamphlet denouncing the plagiarist: "Difesa . . . contro
alle calunnie & imposture di Baldessar Capra." At the time when Galileo
heard about the telescope (subsequently he sold the idea to the Venetian
government) this pamphlet was his only published work.

II. Aristotelian\textsuperscript{1} Cosmology and Physics

Although the Aristotelian world-view had been criticized and revised
in important ways during the Middle Ages,\textsuperscript{2} it was the traditional Aristotelian
cosmology and physics which Galileo always set up as the chief opponent. And
to a large extent, people in the Church and University establishments were
Aristotelians.

According to Aristotle, the universe if finite. It is convenient to
divide phenomena into two classes: sub-lunar (or terrestrial) and celestial.
Below the moon everything is composed of four elements - earth, air, fire,
and water. Each element has associated with it a natural propensity for
motion. Fire and air have levity and tend to go up (away from the center of
the earth). Earth and water are heavy and tend to go down. Thus the upward
motion of smoke (composed largely of the element air) and the downward
motion of a cannon ball (largely earth) are natural motions requiring no
further explanation. Cannon balls fall faster than cork balls because they
are heavier (they have a larger percentage of the element earth in them).
All objects move faster as they get closer to their natural place. Thus
smoke goes faster and faster as it flees away from the earth and cannon
balls go faster as they near the center of the earth.

\textsuperscript{1}Aristotle died in 322 B.C.

\textsuperscript{2}This section is written with apologies to historians of Medieval
Science.
In addition to these natural motions, there are also so-called "violent" motions. All horizontal motions, such as the flight of an arrow, are violent. Vertical motions are also violent if they are in an unnatural direction (e.g., when we throw a ball straight up). Whereas natural motions happen spontaneously, violent motions have to be forced to occur. They always require a source of motive power, such as the hand and arm of the person throwing the ball or the "animal soul" of a wiggling worm.

The speed of violent motions increases with the strength of the motive force and decreases with resistance. For example, a sledge will go faster if it is pulled by two horses instead of one and slower if it is pulled through mud instead of on beaten ground.

One problem for the Aristotelian was to explain why projectiles, such as an arrow or ball, continued to move once they ceased to be in contact with the source of motive power. One proposal was that air was set in motion by the original action of the bowstring or arm and somehow continued to propel the projectile. Another more ingenious solution went roughly as follows. As the projectile moved forward, there was a tendency for a vacuum to form in its wake. However, since nature abhors a vacuum, air would swarm in to fill the empty space, thus hitting the rear of the projectile and propelling it onward.

According to Aristotle, things in the celestial domain behaved quite differently. Heavenly bodies were made out of a fifth element (called the "quintessence") and in this sphere there was no generation or corruption or change of any kind. The natural motion for bodies made of the fifth element was circular. The planets, stars, sun and moon were embedded in transparent crystalline spheres all of which were internested like a graduated series of embroidery hoops. The outermost sphere (called the primum mobile) provided the dominant 24 hour circular motion shared by all bodies in the celestial system, although each planet, etc., also had its own proper motion, too.

A popular analogical model which was used for pedagogical purposes in the Middle Ages was the following: Imagine a round solid wheel rotating on its axis. Suppose that there are also circular grooves on the wheel populated by marching ants. Here the wheel corresponds to the primum mobile
which carries the stars around every 24 hours and the ants correspond to the sun, moon and planets. An ant's total motion is compounded of two parts - the basic motion of the wheel (shared by all ants) and its own proper motion as it walks along the wheel.

III. Ptolemaic Astronomy

The simple concentric sphere model of the universe described above gave a rough, qualitative account of what we can observe in the sky, but it didn't get the details right. In particular, it failed to explain the retrograde motion of the planets - the fact that at certain times the planets appear to move backwards.

In order to obtain a more accurate theoretical modelling of what we actually observe in the sky, Ptolemy introduced various geometrical devices, the most famous being the epicycle. If we were to develop our ants-on-the-wheel analogy, we would have to imagine the ants moving along the groove on a little Tilt-a-whirl!

The proper motion of a planet moving on an epicycle can be diagrammed as follows:

By a judicious adjustment of the sizes and velocities of the big circle (called the deferent) and the little circle (the epicycle) one could hope to reproduce both the velocity and duration of the retrograde motion. Note that on this model, the planet is closer to the earth when it is in retrograde motion and hence we should expect it to appear biggest and brightest.

1Ptolemy flourished in 127-51 A.D. His book on astronomy was called the Almagest.

2For more details, see T. S. Kuhn, The Copernican Revolution.
at this time. This effect is in fact observed, and is especially dramatic in the case of Mars.

Although the epicycle was a useful geometrical device for "saving the phenomena" it was difficult to make a realistic physical model of it. (Some made the deferent into a hollow tube and had a solid epicycle rolling around in it like a marble.

Ptolemy himself sometimes treated his theory simply as a useful calculating device or instrument and did not claim that it was a true physical description.

IV. The Medieval Impetus Theory

During the Middle Ages, there was much piece-meal criticism of Aristotle's natural philosophy. We will mention only a few of the revisions in his theory of motion. In order to handle the problem of projectile motion, it was suggested that as they were hurled a certain degree of motive force was impressed on them. This impressed force or impetus kept them moving until it was used up in combatting the resistance of the medium.

Impetus was analogous to heat - it takes effort to raise the temperature of a body, but once it is heated up it will stay hot until the heat dissipates into a cooler environment.

The impetus theory explained natural motion as the result of a constant tendency (or conatus) of a body to move towards its natural place. Falling bodies speed up because the conatus continues to act as it falls thus giving the body more and more impetus.

When we throw a body upward it moves more and more slowly until its remaining impetus upward just balances the conatus downward. At that moment it is stationary; then the conatus takes over and it falls faster and faster to the ground.

Medieval philosophers also proposed a quantitative account of the motion of falling bodies, using the following geometrical figure:

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1One important contributor was Nicole Oresme, 1323-82.
Let \( y \) be the velocity of a falling body and \( x \) be the time elapsed, then the area is related to the distance covered! Since triangle \( ABC \) is equal in area to the rectangle \( \frac{1}{2} AB \cdot AC \), we see that the distance traversed by a uniformly accelerated body is the same as that covered by a body moving at a constant velocity equal to the mean of the initial and final velocities.

In modern algebraic notation we would write:

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\text{distance} = \frac{(\text{final velocity} - \text{initial velocity}) \cdot x}{2}
\]

The "Mean Speed Theorem," as it was called, provided a method for integrating under a very simple curve and as such was a quite legitimate piece of mathematics. However, the medieval philosophers had no way of knowing whether their diagram described any important motions in nature such as the motion of bodies in free fall because they had not checked in detail the behavior of falling bodies.

Actually it is rather difficult to do a direct experimental test of the Mean Speed Theorem because bodies fall so rapidly. (A ball dropped from the top of a ten-story building takes about three seconds to hit the ground.) Galileo later measured distances and times for balls rolling down inclined planes and this provided an indirect test of the Mean Speed Theorem.

V. Copernican Theory

In *De revolutionibus orbium caelestium*, published just after his death in 1543, Copernicus put forward a detailed heliocentric system of the universe. Like Ptolemy's system it was constructed out of circles (Kepler introduced elliptical orbits in 1609-1619). It was superior to Ptolemy's account in two major respects. First, it gave more accurate predictions as to

\[1\] For a charming account of the personalities as well as the scientific achievements of the characters in this story, see Arthur Koestler's *The Sleepwalkers*. Koestler calls Copernicus (1473-1543) "the timid canon".
exactly where the heavenly bodies would be seen at any given time. This improved accuracy was not due to any intrinsic superiority of the Copernican system, but arose simply because he had used more up-to-date observations in fixing the various orbital parameters. The second advantage of the new system was the fact that it was supposedly simpler. Although Copernicus used at least as many circles as Ptolemy did (hence the overall simplicity of the new system was hardly greater), his theory did have one impressive feature: It was not necessary to introduce epicycles to explain the existence of retrograde motion. The qualitative aspects of the retrograde motions of both the superior and inferior planets were a natural result of the basic geometry of the situation. Since the earth was moving around the sun with all the other planets, it was relatively easy to see that sometimes they might appear to be moving backwards - for example, when the earth passed the outer planets which were moving more slowly.

There were some other technical qualitative advantages to Copernicus' system which appealed to astronomers. However, it presented real problems for the physicists.

In his introductory chapter, Copernicus tried to suggest a modification of the Aristotelian doctrine of natural motions. But his system required that the earth have two "natural" motions. One, the yearly revolution around the sun, wasn't so bad - at least the other planets also moved this way. But the daily rotation around its axis caused all sorts of problems. None of the other heavenly bodies were observed to spin. And if the earth was whirling around like a great top, why didn't things fly off like mud from the rim of a spinning wheel? Why weren't there terrible winds?

Copernicus hinted at a couple of possible answers but he didn't work out the details. Neither did he offer any arguments for either of them: "Perhaps the contiguous air contains an admixture of earthy or watery matter and so follows the same natural law as the Earth, or perhaps the air acquires motion from the perpetually rotating Earth by propinquity and absence of resistance . . ." [De revolutionibus, Section 8]

Even though the Copernican system desperately needed the foundations which only a new physics could provide, it might still have been taken as a serious new cosmological conjecture had it not been for its cautious preface.
The story of the publication of De revolutionibus is a very complicated one, full of unknowns and ironies. A few of the facts are these. It is almost certain that Copernicus would never have gotten around to publishing anything had not Rheticus, a young enthusiastic Lutheran astronomer and mathematician, heard about his heliocentric ideas and literally seduced Copernicus into writing them up.

Rheticus took the finished manuscript from Copernicus' house in Frauenburg up on the Baltic Sea down to Nuremberg and was intending to see it through publication but had to leave town unexpectedly. (It seems that he got into trouble because of his liking for what the Germans call "the Italian perversion").

In any case, another Lutheran, this one a theologian called Osiander, took over responsibility for the printing. Although Osiander was sympathetic to the Copernican system he knew that Luther opposed it and so he added a preface to the reader in which he proposed that the heliocentric system not be construed as a realistic description of the universe but merely as a useful device for making astronomical calculations: "For these hypotheses need not be true or even probable . . . as far as hypotheses are concerned, but no one expect anything certain from astronomy, which cannot furnish it, lest he accept as the truth ideas conceived for another purpose [i.e., as mere calculating aids], and depart from this study a greater fool than when he entered it. Farewell."

Osiander's Preface accomplished what he intended it to. Copernicus' system became popular as a basis for making calendars and star charts. But it had little impact on pure science.

VI. Galileo's Telescopic Observations

In 1609 Galileo heard about the newly invented telescope and designed one which was good enough for astronomical observations. By March, 1610, he had already made a series of discoveries which refuted or at least seriously undermined several features of Aristotle's cosmology.

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1For Galileo's own account (including diagrams), see his 1610 "Siderius Nuncius," translated in S. Drake, Discoveries and Opinions of Galileo.
First of all, he "observed" (we will return later to the question of the reliability of Galileo's interpretations of what he saw) that the moon had mountains. This was inconsistent with Aristotle's claim that the heavenly bodies were perfect and suggested that some of them might be made of stuff similar to the earth.

Secondly, he "observed" (again there are some problems about interpretation) that Jupiter had four moons (he called them "Medicean stars" in order to gain points with the Venetian Duke). This discovery argued against the claim that Jupiter was carried along by an invisible crystalline sphere. (Tycho Brahe had reached a similar conclusion in 1577 when he observed a comet move freely through several places where spheres were supposed to be.)

The moons revolving around Jupiter also showed conclusively that there was more than one center of motion in the universe. This was important because Copernicus had the moon moving around the earth as the earth in turn moved around the sun. The Jupiter-four moons system showed that such a motion was possible. It did not of course prove that the earth-moon system actually worked in a similar manner.

Galileo also determined the composition of the Milky Way. This discovery had no direct relevance to the debate over the Copernican system. However, it did indicate that Aristotle didn't get everything right and also that the Universe was bigger than had been previously suspected.

In 1543 Copernicus had pointed out two important areas in which his system and Ptolemy's made different predictions. One concerned the phases of Venus. On Copernicus' account, if Venus shone by reflected light, it should appear to wax and wane. According to the Ptolemaic system it should always appear crescent shaped. Since Venus always appears round, some Ptolemaic enthusiasts concluded that it must generate its own light as do the stars and the sun.

In 1610 (but not in time to be reported in The Starry Messenger), Galileo observed that Venus did indeed have phases, the timing and apparent magnitudes of which were just as predicted by the Copernican system.

This discovery provided a decisive refutation of the Ptolemaic system. Unfortunately, the other major new prediction of the Copernican system, stellar parallax, told against it and for a geocentric system. If the earth
is in motion, a line between an observer on earth and a fixed star does not quite stay parallel the year around. Therefore, each star should seem to shift its position slightly with respect to the pole of the stellar sphere.

However, stellar parallax could not be detected - even with the new telescope. (It was eventually observed in 1838.) Defenders of Copernicus could explain this away by postulating that the stars were much farther away than had been thought, but this seemed like a rather ad-hoc move since there was no reason to believe it except that it would save the Copernican theory from refutation.

The observations of the sunspots around 1612 by Galileo and others showed that Aristotle was wrong in claiming that the heavenly bodies were immutable. It was not clear exactly what or where the sunspots were but they surely came and went in a most imperfect fashion!

VII. Galileo's Dialogue

In 1632 Galileo published his Dialogo sopra i due Massimi Sistemi del Mondo; Tolemaico, e Copernico. His strategy had two parts. First, he wished to show that it was possible that the earth moved. To do so he had to answer all the physical arguments against Copernicus, e.g., that birds would get left behind, etc. Essentially what was required was a new physics of inertial motion.

Secondly, he wanted to show that the earth actually moved. His major argument here was his theory of the tides (which, as we will see, many historians of science find embarrassingly mistaken).

Before looking at these arguments in any detail, the significance of the title must be pointed out. Galileo speaks of two world systems, but in so doing he omits a third possibility, the very one which was most popular in the early 17th century. Tycho Brahe, a very good Danish astronomer, who invented many new instruments and had by far the most accurate astronomical data available at that time, had proposed a third alternative which seemed to many to be the ideal compromise. It was geocentric - so there were no problems about birds getting blown away and furthermore it explained the absence of stellar parallax. But all the planets revolved around the
sun - so, unlike the Ptolemaic system, it made the right predictions about the phases of Venus.

Galileo, unlike his contemporaries, never took Tycho's system seriously. For one thing, he considered it to be very inelegant - it seems rather clumsy to have all the planets carried around the earth by the sun. But more importantly, he recognized that if his theory of the tides was correct, it would refute all geostatic systems, Ptolemaic, Tychonic, or what have you. It all hinged on his theory of the tides.

Galileo's Dialogo is a masterpiece of both polemics and popular scientific writing. There are three protagonists: Simplicio is a very likable but fundamentally stupid Aristotelian. Salviati is the slick expert who often refers in reverential tones to a learned Academician (obviously Galileo). The moderator is Sagredo, a kind of Dick Cavett character - personable, alert and determined to keep both sides honest. (Unfortunately, Sagredo does not know about the Tychonic system.) Almost all of the discussion is non-technical. Galileo's quantitative theory of motion came later in the Discorsi.

From the beginning Galileo attacks a naive reliance on observation and common sense reasoning. He points out that as we walk along the street at night the moon appears to run along behind us like a cat on the rooftops. Likewise as a ship floats along a canal, the shore sometimes appears to be moving instead. A tower in the distance appears to be a continuous translucent streak.

But all of these appearances are deceiving. The observations suitable for science have to be based on correct theories and good instruments. For example, observations of size (such as in the case of the tower) have to be corrected by the laws of perspective. Many observations with the naked-eye can be improved by using the telescope. And observations of relative motion alone can never tell us which object is actually at rest.

Galileo also extols the use of what are sometimes misleadingly called "thought experiments." For example, in criticizing the Aristotelian claim that heavier bodies fall faster, he not only reports on experiments done by dropping balls from towers, but also argues as follows: Suppose Aristotle
were right. Now imagine two identical cannon balls with strings attached falling side by side. Now suppose the strings become knotted. We now have a composite body which weighs twice as much as the separate parts. It follows on Aristotle's account that they should immediately start falling faster. But that is absurd. Therefore, Aristotle is wrong.

(Because Galileo criticized naive observation and relied on thought experiments, some historical commentators have concluded that he was not an empiricist. However, this may only show that he was a sophisticated empiricist. It hinges in part on what is meant by "absurd" in the above argument. Do we conclude that the cannon balls would not speed up when tied together because of some a priori metaphysical principle such as "no effect without a cause"? Or is it because we have lots of experience which indicates that a change in velocity requires some force to be applied?)

Galileo argues in a variety of ways that the birds would not get left behind if the earth were moving. He points out that flies in the cabin of a ship share the ship's motion and do not have to fly all the way from Venice to Constantinople. Likewise, if a ball is dropped from the mast of a moving ship it lands at the foot of the mast, not behind it.

In the fourth and final section of the book Galileo switches from merely arguing that it is possible that the Copernican system is true and tries to prove that it is true. Here he claims that the ebbing and flowing of the tides is caused by a combination of the daily rotation and yearly revolution of the earth. Roughly, the theory goes like this: Consider a given point on the earth's surface. During the night the two motions add up so that water accelerates. During the day the daily and yearly motions partly cancel out, so the water slows down.

This theory, which Santillana calls "Galileo's folly" and Koestler labels as an idée fixe, is unsatisfactory for two reasons. First of all it violates Galileo's own ideas about motion. Relative to the earth, the water does not speed up or get left behind. It travels along with the earth just as the air does. Galileo's theory of the tides is inconsistent with his own physics.
Secondly, it predicts that there should be a high tide once a day. However, tides are generally observed to occur about every twelve hours. Galileo explained this discrepancy away by vague talk about the major tide bouncing back and forth in the sea bed. It was not a good concluding section for an otherwise brilliant book.

VIII. Galileo and the Church

Galileo's new discoveries challenged the traditional scientific view of his time and Galileo was not particularly gentle in dealing with either stupidity or dogmatism. Not surprisingly, he made many enemies, especially amongst those scholars who were also priests.

As the controversy about Copernicanism (and the shortcomings of Aristotelianism) became more and more heated, his opponents introduced a new argument against him--the Copernican theory is inconsistent with the Bible which is God's word. Therefore, the theory must be false and to defend it is to show a loss of Christian faith.

Galileo (who was a sincere Catholic, by no means an atheist) produced lengthy arguments against this move. In 1615 he wrote a public letter to the Grandduchess Christina in which he said the Bible's task is to tell us how to go to heaven not how the heavens go.

But to no avail. In February 1616 the theological consultors of the Pope gave a formal decision concerning the Copernican system.

They considered two propositions:

"I. The sun is the center of the world and completely immovable by local motion.

II. The earth is not the center of the world, nor immovable, but moves according to the whole of itself, and also with a diurnal motion."

Their official decision was as follows:

"The first proposition was declared unanimously to be foolish and absurd in philosophy and formally heretical inasmuch as it expressly
contradicts the doctrine of Holy Scripture in many passages, both in their literal meaning and according to the general interpretation of the Fathers and Doctors. All were agreed that [the second] proposition merits the same censure in philosophy, and that, from a theological standpoint, it is at least erroneous in faith."

In addition, Galileo was personally told to:
"relinquish altogether the said opinion, namely, that the sun is in the center of the universe and immobile, and that the earth moves; nor henceforth to hold, teach, or defend it in any way, either verbally or in writing."

(All translations taken from J.J. Langford, Galileo, Science and the Church.)

Given that it was now "formally heretical" to place the earth in the center and "erroneous in the faith" to say the earth moved, how is it that Galileo ever had the nerve to publish the Dialogue? Even more surprising is that at first it received an official stamp of approval from the officials in charge of the Index of Forbidden Books!

There were various factors at work. First, the Committee which declared the Copernican theory heretical had not a single scientist on it. So when Cardinal Barberini, a mathematician and astronomer, became Pope, Galileo believed that a different verdict might be forthcoming, especially since he now had what he considered to be a very strong argument for Copernicanism, namely his theory of the tides.

Secondly, Galileo used a rather sneaky device to protect himself. In the Preface he says he will deal with the Copernican theory as a purely mathematical device. And he also says that his only reason for writing about it is to show people from Protestant countries who resent the Church's edict against Copernicus that the folks in Rome (such as Galileo) really understood the theory before they banned it--the action was not taken because of deficiency of knowledge but because of superiority of faith!
Here is an excerpt.

"Judicious Reader,

There was published some years since in Rome a salutiferous edict, which, for obviating the dangerous scandals of the present age, imposed a seasonable silence upon the Pythagorean opinion of the mobility of the Earth. There want not such as unadvisedly affirm that that decree was not the production of a sober scrutiny but of an ill-informed passion: and one may hear some mutter that consultors altogether ignorant of astronomical observations ought not to clip the wings of speculative wits with rash prohibitions. My zeal cannot keep silence when I hear these inconsiderate complaints. I thought fit, as being thoroughly acquainted with that prudent determination, to appear openly upon the theatre of the World as a witness of the naked truth. I was at that time in Rome, and had not only the audiences but applauds of the most eminent prelates of that court; nor was that decree published without previous information given me thereof. Therefore, it is my resolution in the present case to give foreign nations to see that of this matter as much is understood in Italy, and particularly in Rome, as transalpine diligence could imagine. And, collecting together all the speculations of mine that concern the Copernican system, to let them know that the knowledge of all preceded the censure of the Roman Court; and that there proceed from this climate not only doctrines for the health of the soul but also ingenious discoveries for the delight of the mind.

To this end I have personated the Copernican in this discourse, proceeding upon an hypothesis purely mathematical."

(From the Salusbury (1661) translation of Galileo's Dialogue Concerning the Two Chief World Systems)

Of course Galileo doesn't believe a word of this—in the body of the book he defends Copernicanism as a true description of the Universe.

The Preface got the book past the censor, but one year later Galileo was tried for heresy. As a result, his book was placed on the Index, he
was put under house arrest and forced to kneel and recite a formal abjuration:

"I, Galileo, son of the late Vincenzio Galilei, Florentine, aged seventy years, arraigned personally before this tribunal and kneeling before you, Most Eminent and Lord Cardinals Inquisitors-General against heretical pravity throughout the entire Christian Commonwealth, having before my eyes and touching with my hands the Holy Gospels, swear that I have always believed, do believe, and with God's help will in the future believe all that is held, preached and taught by the Holy Catholic and Apostolic Church. But, whereas, after an injunction had been lawfully intimated to me by this Holy Office to the effect that I must altogether abandon the false opinion that the sun is the center of the world and immobile, and that the earth is not the center of the world and moves, and that I must not hold, defend, or teach, in any way, verbally or in writing, the said false doctrine, and after it had been notified to me that the said doctrine was contrary to Holy Scripture, I wrote and printed a book in which I treated this new doctrine already condemned and brought forth arguments in its favor without presenting any solution for them, I have been judged to be vehemently suspected of heresy, that is, of having held and believed that the sun is the center of the world and immobile and that the earth is not the center and moves.

Therefore, desiring to remove from the minds of Your Eminences, and of all faithful Christians, this vehement suspicion rightly conceived against me, with sincere heart and unpretended faith I abjure, curse, and detest the aforesaid errors and heresies and also every other error, and sect whatever, contrary to the Holy Church, and I swear that in the future I will never again say or assert verbally or in writing, anything that might cause a similar suspicion toward me; further, should I know any heretic or person suspected of heresy, I will denounce him to this Holy Office or to the Inquisitor or Ordinary of the place where I may be.

Further, I swear and promise to carry out and observe in their integrity, all penances that have been or shall be imposed upon me by this Holy Office. And if I should violate, which God forbid, any of these my promises and oaths, I submit by myself to all the castigations and penalties imposed and promulgated in the sacred canons and other constitutions, general and particular, against such delinquents. So help me God and these Holy Gospels which I touch with my hands."

(From J. J. Langford, Galileo, Science and the Church.)

There is no factual basis for the story that Galileo whispered "Eppur si muove" ("And yet it moves") as he got up. But he did continue to work on the new physics which was so desperately needed to go along with the new astronomy.

IX. Galileo's Discourse

In the Dialogue Galileo was able to answer many of the objections to the idea that the earth moved—for example, he argued that birds might "share" the motion of the earth just as a fly in the cabin shared the motion of a moving ship. But his systematic theory of motion only came after his condemnation and house imprisonment.
His manuscript, *Discourse on Two New Sciences*, was smuggled out to Holland and published at Leyden in 1638. In it he made an important beginning contribution to our modern theory of mechanics. He gave the correct law for falling bodies—namely, that the acceleration is constant (assuming no air resistance of course). And he gave a correct mathematical description of both projectile motion and bodies moving down inclined planes. To do so, he analyzed these motions into two components, vertical and horizontal. (Compare Aristotle's distinction between natural and violent motions.) The vertical motion was due to the acceleration experienced by any falling body. The horizontal motion was not caused by anything. Unlike Aristotle who believed that a steady input was necessary to keep an object moving horizontally, Galileo realized that in the absence of friction, a moving body would continue to move indefinitely.

Although Galileo probably had a concept of inertia similar to the one we learn in physics classes today, he did not state it as a law. (Descartes was the first to do so.) Neither did he have a concept of gravitational attraction. (That was one of Newton's contributions.)

X. The Denouement

As physics progressed after Galileo, the case for the heliocentric hypothesis became much stronger. Kepler introduced elliptical orbits for the planets, each of which had the sun at one focus. He also laid the foundations for the science of optics which explained in detail exactly how the telescope worked.

Newton discovered the law of gravity which explained not only why people stick on the earth as it turns (gravitational attraction pulls us in more than centrifugal force tends to make us fly off), but also why the earth revolves around the sun instead of moving in a straight line off into space.

And in the early 19th century more direct observational data became available. Stellar parallax was finally observed by a German astronomer and mathematician, Friederick Bessel, in 1838. (Some of you may encounter
Bessel functions in advanced mathematics.) At about the same time a Frenchman, Jean Bernard Leon Foucault, designed a clever but simple demonstration of the earth's motion, which many of you have seen in museums -- the Foucault pendulum. If a large pendulum is set in motion in a given direction one observes that during the course of a day the floor turns under it in a circle.

The punitive measures taken against Galileo did slow the progress of science for a time. Italian science went into a decline (although Galileo's pupil, Toricelli, discovered the barometer, a device hinted at by Galileo in the Discorsi). Descartes was so afraid of condemnation that he refused to publish his own work on cosmology, Le Monde. But perhaps it was the Church which lost most as a result of the controversy. For over a hundred years after the Copernican theory was accepted by all scientists, Copernicus' own book remained on the Index of forbidden books. As for Galileo's Dialogue, despite its being placed on the Index it became a best seller and was immediately translated into Latin (the official language of science in the 17th century) and English.
EXERCISES A:

1. One advantage of the Copernican system was that it gave a qualitative explanation of retrograde motion without postulating epicycles. How could one account for retrograde motion using the Tychonic system? Draw a diagram to accompany your answer.

2. According to the Tychonic system, should Venus have phases? Diagram, please.

3. Imagine a hockey puck in a vacuum on a perfectly smooth and flat piece of ice. It is now given a shove.
   
   (a) What happens, according to the Aristotelian theory of motion?
   
   (b) According to the impetus theory?
   
   (c) According to Galileo's theory?

4. Suppose Joshua wanted to give an astronomically precise command in order to get a few extra hours of daylight.

   (a) According to the Ptolemaic system, what should he have shouted?
   
   (b) According to the Copernican system?
   
   (c) According to the Tychonic?

5. (a) According to the Aristotelian cosmology, why doesn't the air fly away clear out to the stars?

   (b) According to Aristotle, should the core of the earth be more or less dense than the crust?

   (c) According to Aristotle should the air on top of a mountain be more or less dense than that in the valley?

   (d) Is Galileo's thought experiment (regarding tying together falling cannon balls) a cogent objection to Aristotle's theory? What could a sophisticated Aristotelian have replied?

6. According to the Mean Speed Theorem, if the velocity of a falling body increases uniformly with time, then the distance traversed is equal to the total time elapsed times the average velocity (mean speed). As it stands,
this is just a theorem in pure mathematics. It only becomes a statement in physics when we are prepared to assert that the antecedent is true. In order to see how one might test the truth of the antecedent experimentally, work out the following calculations. (They will also give you some idea of the magnitudes involved.)

(a) In one second a ball bearing dropped from Ballantine Hall, fell 4.9 meters. Approximately how many stories is this? If we assume that the ball started with zero velocity and that its velocity increased uniformly, what was its terminal velocity? Draw a Mean Speed Theorem diagram to scale to accompany your answer.

(b) If the Ballantine Ball continued to increase its velocity uniformly (i.e., if its acceleration is constant), how far will it fall in the next second? Expand your diagram.

(c) What total distance will it have travelled after 3 seconds? Expand your diagram.

(d) Draw a new scale diagram in which you plot distance traversed versus time elapsed.

(e) Suppose the highest tower in town is the Leaning Tower of Pisa which is about 55 meters high and your best method of measuring short time intervals is by counting pulse beats. Could one find out through direct experimentation whether falling bodies increase their velocity uniformly? Discuss possible experiments and their expected accuracy.

7. Use the data from problem #6 for this question. A certain boat has a mast which is 4.9 meters high. It is travelling forward at 20 kilometers an hour.

(a) If a ball is dropped from the mast, where, according to Aristotelian physics, should it land? (Is this effect observable?)

(b) Where, according to Galilean physics, should it land?
STUDY GUIDE FOR
Galileo's "Letter to the Grand Duchess Christina,"
pp. 173-216, of Drake, ed., Discoveries and Opinion's of Galileo

(Most of Drake's "introduction, pp. 145-71, is optional. However, do read at least pp. 165-71.)

This letter "concerning the use of Biblical quotations in matters of science" was intended to be circulated among influential people. Galileo hoped to persuade the authorities not to ban the Copernican theory.

As there was no word "scientist" at this time, Galileo often speaks of philosophers or mathematicians in contexts where we would tend to speak of scientists or mathematical physicists. It is a bit confusing, however, because his Aristotelian opponents who are not much interested in experiments are also called "philosophers".

There are a wide variety of different positions which one could take regarding the relationship between science and the Bible. Here are some of them:

If a statement in the Bible and a scientific statement conflict, then:

(a) One should always reject the scientific claim because the Bible is true.
(b) One should always reject the Biblical claim, because the Bible is not an authority on scientific matters.
(c) One should reinterpret the Biblical claim - Nature and the Bible must agree.
(d) One should reinterpret the Biblical claim only if the scientific claim is proved beyond doubt. The Bible takes priority - the onus is on the scientist who disagrees with the Bible to prove that he or she is right.
(e) One should reinterpret the Biblical claim even if the scientific statement is only an hypothesis. The Bible is no guide to scientific truth - the onus is on the theologian to not inhibit the scientist in any way.
1. a. Which of the above positions does Galileo defend in this essay? Or would you phrase his position differently?
   b. Does he slide back and forth between various positions in the course of the letter? If so, give quotations illustrating each position.
   c. What was Cardinal Bellarmine's position? Give quotes to illustrate your summary.

2. Does Galileo claim or hint that he has conclusive proof that the Copernican theory is correct? Is he cautious or bold on this matter? If so, what is his evidence for saying Copernicus is correct?

3. In contemporary philosophy of science there are two basic views concerning the nature of scientific claims, the so-called "realist" and "instrumentalist" positions. According to the realist position, good scientific theories are ones which correctly describe what the universe is really made of and how these constituents interact. Such theories explain the events which we observe around us. On the realist view, the aim of science is true, explanatory theories.

   According to the instrumentalist position, scientific theories should not be viewed as attempts to describe the world; it is incorrect to speak of them as being true or false. Rather they are formal instruments (or conceptual schemes) which enable us to organize our experience and make successful predictions. According to the instrumentalist, we should not ask (as the realist insists we must) whether Dalton's atomic theory (or the theory of quarks) is true or false -- that is, whether there really are Daltonian atoms (or quarks) and whether what the theory says about them is correct. What we should ask is whether Daltonian atoms (or quarks) are convenient fictions. Do they provide a useful conceptual tool for the classification and correlation of experimental results? On the instrumentalist view, the aim of science is economical formalisms which are useful prediction instruments.

   Which of the following people in our story acted as if they were realists (as defined above)? Which were instrumentalists? Or can you say? Ptolemy, Copernicus, Osiander, Galileo, Tycho, Bellarmine.
EXERCISES B:

1. When did Galileo make his first important telescopic discoveries?

2. About how old was he?

3. What was he doing professionally at the time?

4. Briefly describe his early education and previous scientific experience.

5. Should Galileo be given any credit at all for the invention of the telescope?

6. What exactly did Galileo see through his telescope that caused him to conclude that the moon had mountains?

7. What exactly did he see that caused him to conclude that Jupiter had moons revolving around it?

8. Galileo attacked the Aristotelian world-view on many fronts. If the moon had mountains, which Aristotelian teaching would this refute?

9. Which Aristotelian doctrine did Jupiter's moons disprove?

10. At first, Galileo argued that the earth could be moving. Later he argued that it did move. How could one use the moon's mountains to argue that it was possible that the earth moved?

11. How could Jupiter's moons be used to argue that it was possible that the earth moved?

12. Since the telescope turned images upside down and gave them colored fringes, some people concluded that it was not a reliable instrument for science. How could one show that it could be relied on in science?
13. Although the moon looked bigger through the telescope, the stars looked smaller. What did Galileo's opponents conclude from this?

14. How did Galileo explain this surprising phenomenon?

15. Did Galileo have any independent evidence for this explanation or was it ad hoc?

16. Galileo pointed out that when a ship begins its journey, sometimes one has the sensation that the shore is moving away from the ship. How is this fact relevant to the question of the earth's motion?

17. What good reason could the Aristotelians give for saying that in fact it is the ship that is moving, not the shore?

18. The Aristotelians argued that if the earth rotated, birds flying to the east would get left behind. Assuming the earth's circumference is 25,000 miles, how fast would the birds have to fly just to keep even, according to the Aristotelians?

19. Galileo replied that the birds would have no more problems than would a fly in the cabin of a fast moving ship. If you were an Aristotelian, how would you answer this point?

20. According to the Aristotelians, if the earth is moving, then the paths of cannonballs should be affected. Suppose a certain cannon projects balls with a total flight time of 2 seconds. If it were aimed straight north, where would the ball land, according to the Aristotelians? Is this predicted effect big enough to be experimentally detectable?

21. How would Galileo answer this point?

22. One can test whether a released object such as a cannonball or bird continues to share the motion of the "parent" body. Galileo claimed to have done the following experiment: a ball was released from the top of the mast of a moving ship. According to Galileo, where should the ball land?
23. According to Aristotle, where should the ball land? (Assume the time of fall is one second and that the ship is moving at 30 mph.) Is the effect big enough so that sailors throwing down ropes from the crow's nest, etc., would have noticed it?

24. Sophisticated Aristotelians would have invoked the impetus theory to explain this particular experimental result. How would such an explanation go?

25. A heavy ball rolled on a smooth floor goes a long way but eventually comes to a stop. How would the impetus theory explain this?

26. How would Galileo account for this?

27. According to the impetus theory, would birds and cannon balls behave differently than they do if the earth moved?

28. So far we have discussed Galileo's arguments that it was possible that the earth moved. Now let us turn to his attempts to show that it actually did. The first argument was based on his discovery of the phases of Venus. Explain why this discovery went against the Ptolemaic system.

29. Could the Copernican system account for this phenomenon?

30. How about the Tychonic system?

31. Galileo became interested in sunspots because they appeared to move across the face of the sun. How might this phenomenon be relevant to the question of whether the earth moved around the sun?

32. Galileo thought that the tides provided the best argument for the earth's diurnal motion. According to Galileo, what caused the tides?

33. On Galileo's account, how often should the tides ebb and flow? How did he explain the discrepancy between his account and observations?
34. Was Galileo's account of the tides consistent with his account of the motion of the ball dropped from the ship's mast?

35, 36. The clearest experimental arguments for Copernicus' theory came from 19th century discoveries - stellar parallax and Foucault's pendulum. Briefly describe each of these and show how they support the Copernican system. Does each provide evidence for diurnal rotation, annual revolution, or both?

REVIEW QUESTIONS

1. Order of Events.

In evaluating the arguments for and against a scientific theory, we have to be very sensitive to what was (and was not) known at the time. Give an approximate date for each of the following developments.

(a) The prediction that Venus should have phases.
(b) The discovery that Venus does have phases.
(c) The invention of the telescope.
(d) The experimental determination of the angle of stellar parallax.
(e) The observation that comets move through the places where the crystal spheres were thought to be.
(f) Publication of Galileo's technical systematic account of the motions of projectiles and falling bodies.
(g) Galileo's trial by the Inquisition.

2. Galileo's Attack on Aristotelian Physics and Cosmology and Ptolemaic Astronomy.

What evidence or arguments did Galileo provide against each of the following doctrines? Be precise but brief.

(a) Heavenly bodies are perfect and immutable.
(b) On earth heavier bodies fall faster than lighter ones.
(c) If a body is moving horizontally, something must be continually
pushing it.

(d) The Ptolemaic system.

3. **Comparision of the Tychonic and Copernican Systems.**

Although Galileo did not often discuss it, the major rival to the Copernican system at his time was the Tychonic system (not the Ptolemaic).

(a) Give a list of various reasons why Galileo's opponents preferred Tycho's system to that of Copernicus.

(b) Give a list of a variety of reasons why Galileo preferred the Copernican theory.

4. **Observation and the Reliability of the Telescope.**

Everyone agreed that science should be based on observation, but which observations can be trusted?

(a) List a variety of reasons why some of Galileo's opponents distrusted the telescope.

(b) How did Galileo answer each of these objections? (Could he answer all of them?)

(c) Did Galileo ever criticize his opponents' observation claims? If so, give examples. If not, explain why not.

5. **Instrumentalism - Realism.**

(a) Briefly state the two positions.

(b) Why might a very conservative religious person prefer the instrumentalist view of science?

(c) What would an instrumentalistic interpretation of the Bible be like?
APPENDIX I:

How Well Does the Galileo Case-Study Fit the Popperian Model of Scientific Method?

a. Explanatory Problems

According to the Popperian account of science, scientific investigations begin with explanatory problems -- "why-questions". This was certainly true in the Galileo case which dealt with a wide variety of explanatory problems such as the following:

- Why do the planets exhibit retrograde motion?
- Why does the sun (appear to) rise and set?
- Why does Venus have phases?
- What causes an arrow to fly when it is no longer in contact with the moving bow string?
- What causes the tides?
- Why do stars appear smaller through a telescope (while everything else looks larger)?
- Why do iron needles float although other iron objects sink?

In each of these questions one is either asking for a deep explanation of an observed regularity or else requesting an explanation for a violation of an assumed regularity.

Galileo and his contemporaries also worked on a few problems which involved the search for a systematic, unified description of a variety of phenomena -- what we might call "how-questions":

- How can one best describe the motion of terrestrial falling bodies?
- How can one best describe the motions of all the celestial bodies in the solar system?

However, Popper appears to be correct in his emphasis on the importance of explanatory problems, as opposed to descriptive problems, for the scientific enterprise.
b. **Testable Solutions**

According to Popper, the next step in scientific investigations is to propose a testable solution to the explanatory problem -- one proposes a refutable theory.

This certainly occurred in our case-study. For example, the theory that all moving objects have an external mover was refutable (and refuted, by the case of arrows). But frequently it was not easy to see how the theories involved could be tested. It was centuries before a good test for the Ptolemaic system was devised (viz., look for the phases of Venus) and then it was only practical because of the fortuitous invention of the telescope. The stellar parallax test of the Copernican theory had to await improved instrumentation and better estimates of stellar distances.

Galileo's idealized theory of falling bodies could not be tested directly. His explanation of why stars appeared smaller through the telescope appears to be completely untestable. As long as the impetus theory did not specify the rate at which impetus decayed, it would have been very difficult to test its vague claims.

I think one must conclude the following: Although it is desirable that scientists work with highly testable theories, in practice they deal much of the time with theories which are very difficult to test. Sometimes the theories are too vague; sometimes they are so idealized as to be only indirectly related to experience; sometimes the necessary equipment or auxiliary theories are not available; sometimes people are just not clever enough to figure out good tests for the theories.

By requiring that theories be highly testable Popper has stated an ideal for science. He has not described the practice of many scientists much of the time.

c. **Scientific Criticism**

According to Popper there are two major forms of scientific criticism: The first we will call the **problem check**: Does the theory provide a testable solution to the problem which motivated it? The second we will call
the observation check: Are the predictions of the theory consistent with experience?

We saw a couple of examples of the first sort of criticism in our case-study. When certain theologians argued that God could make the moon appear to be mountainous even though it was really crystalline, Galileo rightly objected that such a conjecture could not be tested. And I believe many felt that Galileo's own "irradiation" theory was totally ad-hoc and untestable.

There were also many examples of the second kind of criticism in the case-study. But what must be emphasized is how prevalent and troublesome the Duhemian problem is. Time after time in this scientific episode, one debated whether to blame the theory proper or some rather innocuous-looking auxiliary hypothesis.

Flying arrows refute the naive Aristotelian theory of motion if we can assume there are no air currents operating.

The absence of stellar parallax refutes the Copernican theory if we can assume the stars are not too far away.

The "full moon" phase of Venus refutes the Ptolemaic system if we assume that Venus glows from the reflected light of the sun (and not from some variable internal light!).

In some of the above examples the auxiliary hypothesis was readily acceptable. (As far as I know, no one tried very hard to rescue the Ptolemaic system in the way suggested). In other cases the auxiliary assumption was highly debatable, e.g., the stellar parallax example. Until there is clear agreement on the status of the auxiliary hypothesis, the refutation is inconclusive and one must continue to test both the auxiliary hypothesis and the main conjecture.

We have seen that in real-life scientific situations it is often not clear exactly which hypothesis a bit of observational evidence refutes. This case also illustrates how difficult it sometimes is to decide what counts as observational evidence.
Aristotelians observed that the earth was not moving -- they couldn't feel it move and they saw that the sun, etc. moved around it. Galileo did not consider these observations to be acceptable evidence, pointing out that our perceptions of relative motion were notoriously unreliable. Who can tell whether the shore is moving or the ship, just by looking? The Aristotelians, on the other hand, did not accept Galileo's telescopic observations as legitimate scientific evidence.

Everyone agrees that observations are the basis of science, but everyone also realizes that observations can be misleading. Young children and animals look for the baby behind the mirror. Many a beginning canoer coming into the shore has found out that the bottom is farther down that it looks. (The effect is due to refraction -- the same reason that a stick in water appears bent.) Who has not seen the moon follow you as you drive along past trees or walk past houses with chimneys? And who can deny that the sun and moon look bigger when they are close to the horizon?

Many illusions can be corrected and most observations can be refined by means of measuring devices. But instruments introduce new problems too. Generally the instrument requires the observer to have some skilled training. Even a simple car speedometer is misleading if you read it from the passenger's seat! And how many people know what happens to the odometer as you drive the car in reverse? Beginning microscopists focus on their own eyelashes. Beginning titrators make errors of parallax and forget to let the sides of the buret drain down before reading. Few physics students get reproducible results with a Wheatstone bridge the first time they use it. One has to learn to administer psychological tests -- even those scored by a computer. And even an automatic single-pan balance is not completely idiot proof -- it will give an inaccurate weight for a hot crucible.

d. The Replacement of Hypotheses

According to the Popperian account, scientists propose testable hypotheses as solutions to their explanatory problems, subject these hypotheses to severe empirical test, and then discard them if experimental results refute the theory.
As we have seen, however, due to the Duhemian problem, refutation of the central hypothesis is rarely a clear-cut affair. What happens more often historically is that a hypothesis gradually loses credibility and is eventually replaced by a more attractive one.

Tycho's system was never refuted -- it just gradually lost appeal as objections to the Copernican system were answered. There was no single crucial experiment which killed off the impetus theory. Rather people gradually became convinced that the inertia approach was more productive.

Scientists consider empirical criticism to be of crucial importance, but in real-life situations assessing the evidence for and against a theory can be a very complicated task and at a given time there may be no unambiguous answer to the question of whether a theory is refuted or not.

The situation is further complicated because scientists also consider non-empirical factors when they evaluate theories. Some of these extra considerations, such as concern over the theological implications of a theory, probably have no legitimate place in science; but others have more of a borderline status.

Take, for example, the issue of simplicity. Galileo preferred to work with ideal laws because they were more manageable or simpler than attempts to account for friction, etc. He also rejected Tycho's system because it didn't have the symmetry and coherence which he felt a correct description of the universe would exhibit.

There are probably two different sorts of appeals to simplicity being made here: In the first case a simple theory is preferred because it's easier to work with; in the second case, one believes that the simpler theory is more likely to be true!

The second sort of appeal to simplicity sounds very suspicious to the hard-headed, empirically-minded philosopher; yet scientists throughout the centuries have preferred conceptually simple, aesthetically elegant theories. A recent example: Watson reports that when the double-helix model of DNA occurred to him, he was filled with elation even before he checked it against x-ray data. As he puts it, "It was too simple not to be true!"
Of course, one must quickly add that had the model not fit the available data, Watson would have been ready to conclude that it wasn't true, despite its simplicity!

Simplicity appraisals don't override evidential considerations; but when the empirical situation is ambiguous (as it often is), simplicity may be the crucial factor in a scientific debate.

There are two pressing problems connected with simplicity for historians and philosophers of science:

(1) Can one give a clear account of exactly what features of a theory make it "simple"? Are a variety of different notions of simplicity involved?

(2) Can one justify the scientist's placing high value on simplicity? Is it just a sign of human laziness? Is it an artistic whim? Do we ever have any reason to believe "simple" theories are more likely to be true?

**EXERCISES C:**

1. Suppose all one knew about science was Popper's account of the Hypothetico-Deductive method as summarized in Chapter IV above. Which features of the Galileo case-study would such a person find surprising?

2. To what extent should a good theory of scientific method fit scientific practice? (If possible, give arguments both ways. You might want to compare the case of science with the following situations: Should a good theory of logic fit the way people argue? Should a good theory of ethics describe the lives of saints? Should a good theory of basketball fit the way people actually play?)

**APPENDIX II:**

What Ethical Problems Did Galileo Face? and How Did He Resolve Them?

Let us now review Galileo's scientific behavior from an ethical point of view. Since I do not want to judge him, I will only ask leading questions:

a. **Choice of Problems.** What criteria did Galileo use to choose his research problems? (Was he looking for pure understanding, beneficial
b. **Safe Design of Experiments.** Were any of the experiments or observations which Galileo carried out potentially harmful to the people who participated in them? Did Galileo behave responsibly towards them? (Include two fictional characters from the Brecht play—Andreas and the Little Monk.)

c. **Responsible Dissemination of Results.** Were any of Galileo's results likely to be used in a harmful way? Did Galileo communicate his findings in an honest, responsible manner? What might he have done differently?

d. **Behavior at the Trial.** Should Galileo have abjured? (Give pros and cons.)