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Galileo Agonistes

My topic this evening is one that 50 years ago I had aspirations of delving into, then got lured away from, and now once more seek to come to terms with. Galileo in life was a combative controversialist, and ever since he has been a subject of controversy. My talk will be an interpretation. I shall first review what I think can be said about Galileo's discovery of the law of free fall, taking care not to inject post-Galillean physics into the Galilean moment - a source of frequent errors. Then I shall speak of Galileo's struggle to keep the Church from condemning heliocentric astronomy, the failure of that struggle, and his trial before the Inquisition. My subject, I must warn you, requires attention to details. God, or the devil, is in the details..

I start with the old story in old textbooks about how the whole fabric of Aristotle's cosmology and physics came tumbling down one day in 1589, when Galileo, aged 25, newly appointed mathematics instructor at the University of Pisa, before professors and students assembled, dropped two cannonballs of different sizes from the Leaning Tower of Pisa. A simultaneous thud, we're told, heralded the birth of a new, experimental physics.

Alas, this account omits crucial details. The original story was told by Viviani, Galileo's last pupil, who likely had it from his old teacher. The experiment, says Viviani, was designed, to show **[Exhibit A:]**[1]

that the speeds of mobile bodies *of the same material* [my emphasis] but of unequal weight, moving through the same medium, are not in the ratio of their absolute weights, as Aristotle claimed, but they move with equal speed...; and neither do the

speeds of a given mobile body, moving through diverse mediums, have the inverse ratio of the resistances, or densities of these mediums...

The import of these details emerges from a treatise on motion Galileo was writing in 1589.[2] Consider first the second point. According to Aristotle's *Physics*, a given body falls in different mediums with speeds that are inversely as the resistances of those mediums.[3] If the resistance were absent, Aristotle says, the speed of the falling body would be infinite.

Exhibit B: Aristotle's Rule of Speeds in Different Mediums

Let V_A, V_B be the body's speeds in mediums A and B; and let R_A, R_B be the resistances in those mediums. Then according to Aristotle

$$V_A : V_B :: R_B : R_A.$$

Suppose $R_A \to 0$. Then the ratio $R_B : R_A$ becomes infinite, and so must $V_A : V_B$. Therefore $V_A \to \infty$, which is impossible.

Aristotle concludes that a medium must be present; the void can't exist.

Galileo in his early treatise rejects Aristotle's proportion. A piece of wood falls in air with a certain speed, call it unit speed. Galileo identifies the resistance in Aristotle's proportion with density. Let the density of air be unit density, and let the density of water be 4 (800 would be more like it, but I use Galileo's numbers). Then by Aristotle's rule, the piece of wood should fall in water with a speed of one-fourth. But it doesn't fall; it rises and floats. Galileo thinks the speed of fall or rise varies as the difference between the density of the body and the density of the medium.

Whence this idea? It smacks of Archimedes. In fact, Galileo has written a little book on the famous crown problem. He knows the principle of buoyancy:

a body immersed in a fluid is buoyed up by a force equal to the weight of the displaced fluid. That principle is irreconcilable with Aristotle's doctrine of heaviness and lightness. According to Aristotle, heavy bodies, by their heaviness, fall toward the center of the universe; light bodies, by their lightness, recede from that center. Heaviness and lightness are the fundamental qualities of the sublunary elements in Aristotle's world. Galileo in 1589 still assumed, with Aristotle, that the center of heavy things is the center of the world. But as an Archimedean, he has had to conclude that there is no such thing as lightness; all bodies are heavy, but some are more dense than others. A body goes up or down depending on whether its density is less or greater than the density of the medium.

Galileo, however, is an Archimedean with an Aristotelian question. Archimedes did not deal with motion; force for him was static force, force balanced by another force. Galileo, like Aristotle, wants to know the cause of the speed of falling bodies. Aristotle had stated that the downward motion of a mass of gold or lead is quicker in proportion to its size, its weight.[4] If greater heaviness is greater downward tendency; mustn't the heavier body fall faster? Well, Galileo has learned it can't be so.

Of two pieces of the same material, suppose the heavier fell faster. Tie them together. The combination must fall more slowly than its heavier part, since it is held back by the lighter part.[5] But this combination constitutes a heavier body, so it ought to fall faster. Aristotle's idea contradicts itself.

Galileo concludes that every body of a given material, in a given medium, has a speed of fall or rise determined by the difference in density between the body and the medium. The greater the difference in density, the greater the body's speed. What Galileo at this time called the body's natural speed of fall could be determined if the medium were entirely removed, but this, he believed, was not physically possible.

Is all this right? No. For one thing, Galileo is speaking of a natural speed, not an acceleration of fall. The adjective natural here expresses an Aristotelian notion: a body moves naturally if the arché of its motion is internal to it, not imposed from without. Galileo at the end of his life will still be using this term "natural" as though in the Aristotelian sense, but it will have become for him a question.[6]

What about the acceleration? Galileo in 1589 considers it to be not natural but adventitious. It occurs, of course, whenever a body starts falling from rest; to reach the speed determined by its density and that of the medium, it must pass through all lesser degrees of speed. To explain this, Galileo supposes that an impetus was originally impressed on the body to raise it up; when it is let fall, this impetus diminishes at its own rate, the way the heat impressed on a piece of iron diminishes when the iron is separated from the fire that was the heat's source. As the impetus diminishes, the body picks up speed; and when all the impetus is gone, it moves uniformly.

This theory is scarcely testable. It looks like an intellectual trap. Where did Galileo get it? - for it is unlikely he invented the whole thing.

He had entered the University of Pisa in 1581, aiming at a medical career. In 1585 he dropped out without a degree, disgusted by his professors' standpat Aristotelianism. Mathematics had caught his fancy - Euclid and

Archimedes. Natural philosophers, he said, should do as mathematicians do, deducing consequences from definitions and axioms.[7] He was out to become a university mathematician. How gain the requisite reputation?

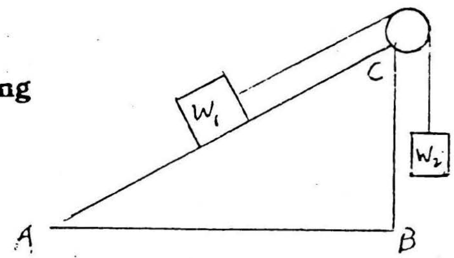
He published the book about Archimedes' buoyancy principle I mentioned earlier. He devised mathematical derivations, and sent them about for critique. In 1587 he visited Christopher Clavius, mathematics professor at the Collegio Romano, the Jesuit college in Rome. The Jesuits were then a new and innovative force in education. They had recently debated among themselves whether mathematics was precisely applicable to the world, and Clavius had taken the affirmative, arguing that astronomy, music, optics, mechanics - *scientiae mediae*, "middle sciences," the schoolmen had called them - applied exactly. Many of Galileo's early MSS, we now know, echo lectures given at the Collegio Romano.[8] Galileo was specializing in mechanics, astronomy, and the critique of Aristotle's physics.

The exact route whereby Galileo acquired his early doctrines on motion remains unclear. A Venetian named Benedetti had held similar doctrines, but Galileo apparently didn't know his work at first hand.[9]

In 1589 Galileo obtained his first post, at Pisa; it paid pitifully little. When his father died in 1591, he became the family breadwinner. With support from Clavius and others he obtained a better-paying professorship at the University of Padua. There he remained from 1592 to 1610.

A hopeful thing in Galileo's early work on natural motion was his attempt to verify his theory on inclined planes, where the motion is slower, more easily measurable. From the principle of the lever he had derived the rule for equilibrium of weights on diversely inclined planes.

Exhibit C: Equilibration of Weights on Inclined Planes



W_1, lying on CA, and connected with the vertically hanging weight W_2, is in equilibrium with W_2 if, and only if, $W_1 : W_2 :: CA : CB$.[10]

The larger weight W_1 is sustained on the incline by the smaller weight W_2 hanging vertically, because the downward tendency of W_1 is reduced by the constraint on its direction. To the downward tendency as reduced by the constraint in direction, Galileo gave the name *momento*.

In going from statics to kinetics, Galileo makes an Aristotelian mistake: he assumes that, not the acceleration, but the speed produced is proportional to the static force or *momento*. There should follow a certain ratio of the times down diversely inclined planes, but experiment disconfirms it. For a while at least, Galileo explained the disconfirmation as due to accidental causes.

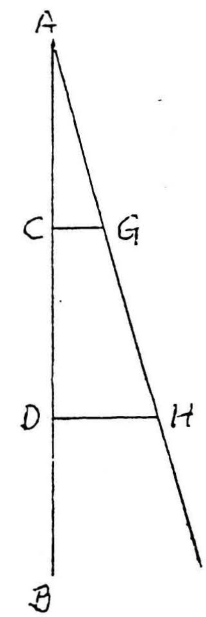
To get out of this trap, Galileo needed to focus on acceleration, and then by experiment to discover the rule - famous as Galileo's discovery - that the distances traversed are as the squares of the times. Galileo had made this discovery, it appears, by October, 1604. On that date, in a letter to his friend Paolo Sarpi in Venice, he wrote as follows:

Exhibit D: Galileo's Letter to Sarpi, October 1604

Thinking over the questions about motion, in which, to demonstrate the accidents observed by me, I have been lacking a totally indubitable principle that I could take as axiom, I am reduced to a proposition which has much that is natural and evident about it; and this being supposed, I demonstrate the rest, that is, that the spaces traversed in natural motion [are as the squares of the times], and consequently the spaces traversed

in equal times are as the odd numbers starting with unity... And the principle is this: that the mobile body goes increasing its speed in proportion to its distance from its starting point... Please consider it and tell me your opinion.[11]

For his demonstration, Galileo has only an outline of the steps, as we learn from a separate manuscript:[12] Exhibit E: Galileo's fol. 128.



I suppose (and perhaps I shall be able to demonstrate it) that the heavy body falling naturally goes continually increasing its speed in proportion to its distance from its starting-point....The speed with which the moving body has come from A to D is compounded of all the degrees of velocity it has had at all the points of the line AD, and the speed with which it has passed over AC is compounded of all the degrees of velocity it has had at all the points of the line AC. Therefore, the speed with which [the body] has passed the line AD has to the speed with which it has passed the line AC the ratio [of the square on DA to the square on CA].

The line AB represents distances traversed in falling. Lines at right angles to AB represent degrees of speed, increasing in proportion to the distance fallen through. A "degree of velocity" (*grado di velocità*) is a punctual speed, a speed at a point; it doesn't endure. Galileo speaks of compounding these punctual *gradi di velocità* to find the ratio of the speeds with which different distances are traversed. The degrees of speed thus compounded, he is saying, are measured by triangles; so the speeds with which AD and AC are traversed are as the triangles ADH and ACG. These are similar, and hence to one another as the squares on the corresponding sides.

From this result, Galileo needs to get to what he knows experimentally, that the distances from the beginning of motion are as the squares of the times. The steps he proposes for this derivation are wrong - careless blunders. No mathematically legitimate steps lead from the composition of punctual degrees of speed varying as distance, to the variation of distance with the squares of the times.

Galileo himself, 4 or 5 years later, in 1608 or 1609, proved that the supposition of Exhibit E won't do. His argument goes as follows. Suppose AC is half AD. AD contains an infinity of points, and so does AC. At each point of AD, and at each point of AC, there is a punctual speed. The punctual speeds in the one distance can be put in one-to-one correspondence with the punctual speeds in the other, in such a way that each punctual speed in AD is twice the corresponding punctual speed in AC. Galileo infers that AD, the double distance, would be traversed in the same time as AC, its first half. But then the rest of AD would have to be traversed instantaneously, which is impossible.

The argument, I believe, is valid. A motion starting from rest, with its speed varying as distance traversed, is impossible.

Suppose, however, that the line AB in Exhibit E represented time. Then the two compounded sums of degrees of velocity would be given by the two triangles ACG and ADH, and these triangles are as the squares of AC and AD, that is, as the squares of the times. If the areas of the triangles were proportional to distance traversed, we would have the result that Galileo has found experimentally.

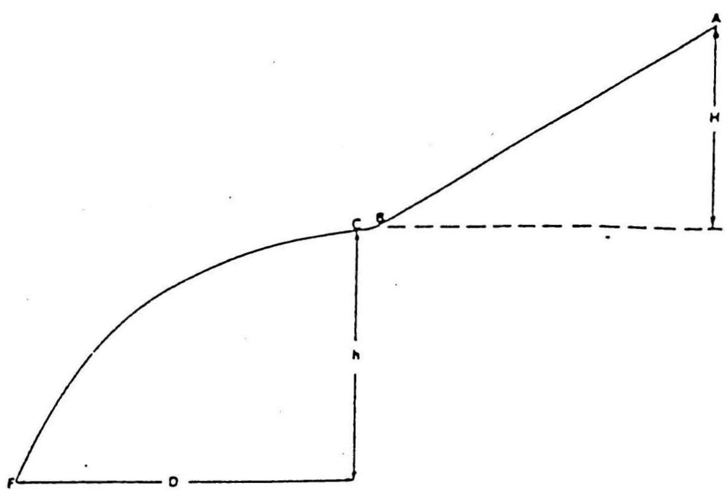
Eventually, in his *Dialogue on the Two Principal World Systems*, of 1632, Galileo will carry through just this derivation, in which an infinity of instantaneous speeds are compounded over time, and represented in a diagram as areas, and it is stated that for these areas to be as the distances traversed is *ben ragionevole e probabile*, very reasonable and probable.[13] A plausible proof but, Galileo recognizes, peculiar. It involves the very strange notion of instantaneous speed - a speed that doesn't have any duration, and so no distance is traversed by it - and it involves the adding up an actual infinity of such speeds. The serious application to the world of this questionable concept and procedure was unprecedented.

To return to 1604: Galileo at that time was unwilling to let AB represent time. Empirical evidence, he thought, showed that the speed of fall increases as distance. In the MS from which I've been quoting, he says that this principle appears to him *molto naturale*, and agrees with our experience with instruments that operate by percussion: the magnitude of the effect is as the distance from which the body falls. He is thinking, for instance, of pile drivers. He has tested the principle, dropping weights on a stretched bowstring. The impact pulls the bowstring downward into a V-shape. If the weight is let fall from the double height, the V is deeper. These two V-shapes can be reproduced statically by hanging weights on the bowstring; the two weights that produce the two V's are as 1:2. Galileo assumes that the effect is proportional to speed, and so concludes that speed is proportional to distance of fall.

This is a mistake. How did Galileo correct himself? The scholars of this century have argued over whether Galileo was basically an experimentalist, or a desk mathematician.[14] He was both. In the case of the motion of natural fall it was by experiment that he emerged from error. The key experiment is a highly sophisticated, indeed a masterly experiment.[15]

Galileo arrived at the correct variation of speed in free fall only in 1608 or 1609, 20 years after the Leaning Tower demonstration. This discovery presupposed the prior discovery of the parabolic trajectory of projectiles. He clinched both discoveries using the apparatus diagrammed in Exhibit F.

Exhibit F: Apparatus for testing parabolic trajectory and law of free fall



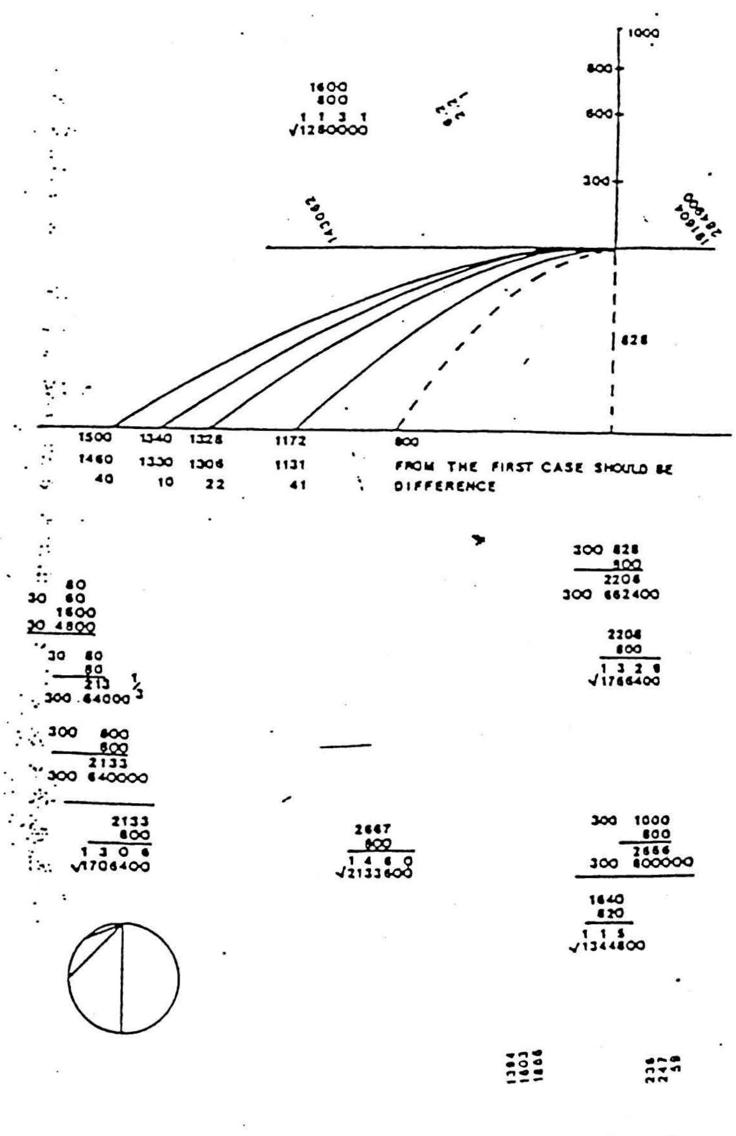
AB = grooved inclined plane of height H;

BC = grooved curve leading to horizontal projection at C;

CF = path of projectile when falling through height h and advancing through distance D.

Suppose, first, that the inclination of the inclined plane is fixed, and that the ball in repeated rolls is started each time from the same point A at height H, measured from the table-top on which the inclined plane rests. Then on reaching C it will be projected horizontally, always with the same horizontal speed so long as the initial conditions are unchanged. It will fall in a curve. What curve? Suppose that the height h can be adjusted, by raising or lowering the horizontal board onto which the ball falls. Then it becomes possible to accumulate a series of paired values of D and h, all of them pertaining to the same curve. Galileo suspected it was a semi-parabola with vertex at C. In that case h must vary as D^2. There is evidence that Galileo carried out this test. The semi-parabolic result is exactly what we would expect if h increases as the square of the time, while D increases linearly with the time.

Having confirmed the parabolic shape, Galileo turns the experiment around, and uses the parabolic shape to examine the speeds achieved in fall through different heights H along the inclined plane. The distances D turn out to vary as the square root of H. The relevant calculations are given in some detail in **Exhibit G: Essential details of folio 116v** *



* For explanation of calculations, see addendum to p. 11 at end.

The genius of this experiment is that it avoids measuring time, so much more difficult for Galileo than for us, and it gives a direct measure of instantaneous speed in descent along an inclined plane; the final speed in the descent is turned by the curved groove BC into a uniform horizontal speed proportional to the distance D; and then D proves to be as the square root of H.

In summary, Galileo's twenty-year struggle was brought to a successful conclusion by a combination of mathematical reasoning and sophisticated experimentation. A few years later, in a letter to his former student Benedetto Castelli, Galileo wrote:

> Nature is inexorable and immutable, and she does not care at all whether or not her recondite reasons and modes of operation are revealed to human understanding...[16]

I take that to express his sense of how formidable an opponent Nature is, in the contest that consists in trying to understand her.

The remainder of this lecture is about the middle phase of Galileo's life, beginning in July 1609 with his getting news of a spyglass constructed in Flanders, and ending with the publication of his *Dialogue on the Two Chief World Systems* in 1632, then his trial by the Inquisition the following year, and his condemnation for heresy in June 1633.

In July 1609 Galileo built his own first telescope. In August he built a better one, and by December he had a 20-power instrument, which he turned on the Moon. He saw mountains that cast shadows. From the lengths of the shadows he reckoned the approximate heights of the mountains in units of terrestrial distance. The Moon reflected sunlight, not as a polished mirror does, but as do sand, dirt, and rock; it looked rather Earth-like. Maybe plants could grow on it. Better dirt, Galileo thought, than jasper or diamond.

His report was met with incredulity. The lunar mountains, Christopher Clavius opined, were illusions of Galileo's telescope. On getting a better telescope, Clavius had to admit the appearances were as Galileo stated, but he wanted the Moon to be smooth, spherical and crystalline. Couldn't Galileo's mountains, he asked, be differences in density? To such suggestions Galileo had this reply:

> ...if we still want to let anyone imagine whatever he pleases, and if someone says that the Moon is spherically surrounded by transparent invisible crystal, then I shall willingly grant this - provided that with equal courtesy it is permitted me to say that this crystal has on its outer surface a great number of enormous mountains, thirty times as high as terrestrial ones, which, being of diaphanous substance, cannot be seen by us...The only fault here is that it is neither demonstrated nor demonstrable.[17]

In January 1610 Galileo discovered four small stars accompanying Jupiter. They appeared as if situated on a straight line passing through the planet and at right angles to the line of sight. In successive hours and on successive nights they individually changed their distances from Jupiter, passing from the east to the west of it and back again. By early 1611 Galileo was able to assign fairly accurate orbital periods about Jupiter to all four, assuming uniform circular motion. Thus, contrary to Aristotle, the Earth was not the only body about which celestial bodies move in circular motion.

Galileo called these stars Medicean after the ruling family of Tuscany, and so wangled for himself a position as "mathematician and philosopher to the Grand Duke of Tuscany". He could return to his native Florence.

Late in 1610 Venus was far enough from the Sun for telescopic observation, and Galileo found that it had phases like the Moon's. It had been considered self-luminous, but the phases were evidence that it shone by reflected sunlight. Galileo found Venus's diameter to vary over time by a factor of about 6; it was largest when Venus is a crescent, and smallest when it appears as a circular disk. Hence its orbit surrounded the Sun. By similar observations of Mars, he found this planet when 90° from the Sun to be gibbous, that is, not fully round; its diameter also varied by a factor of about 5, being largest when the planet was in opposition to the Sun. The Martian orbit therefore surrounded the Sun, and the Earth as well.

Continued improvement of his tables for the Jovian satellites led Galileo to a new discovery in July 1612. Comparing an observation with his tables, he realized that one of the satellites, the outermost of the four, had been eclipsed, passing into the shadow cast behind Jupiter by the Sun. He found that, if he took the mid-points of the satellite eclipses for epochs or starting-times, his tables became more accurate. The satellites were moving more uniformly with respect to the line from the Sun through Jupiter than with respect to the line from the Earth through Jupiter. The heliocentrist would expect this. It is also what would be expected under the semi-heliocentric arrangement, where the Earth remains at rest, the other planets go round the Sun, and the Sun circles the Earth: the so-called Tychonic system.[18]

Sunspots were observed from 1610 onwards. A German Jesuit, Christoph Scheiner, writing under the pseudonym Apelles, put forward the idea that they were planets, hence compatible with celestial immutability. Galileo, citing his own careful observations and measurements, destroyed this hypothesis with merciless sarcasm. The spots moved round the Sun with changes in shape and mutual distances which implied they were on or very close to the Sun's surface. The Sun must be rotating, with a period of about 25 days, about an axis through its center. The spots could be seen coming to be, coalescing, separating, ceasing to be. The Sun was a mutable body.

Following these telescopic discoveries, Galileo became for the first time a public proponent of Copernicanism. In his student days, he had opposed this doctrine, listing the standard dynamical objections against it: bodies let drop from a height would not fall vertically to the ground, and so on. His early *De Motu* shows that by 1590 he had studied Ptolemy's *Almagest* and Copernicus's *Revolutions* with care. In a late revision of the *De Motu*, he introduced the idea that a spherical body at the center of heavy things, if set rotating, would continue to rotate without the need for an internal or external mover.[19] Such a motion he called neutral, distinguishing it thus, both from the natural downward motion of a heavy body, where there is an internal arché, and from a forced motion where there is an external mover. A consequence, though Galileo does not mention it, is that the daily apparent westward rotation of the stellar sphere could be accounted for by supposing the Earth to be rotating eastward about its polar axis. Galileo also considered as neutral the motion of a ball rolling on a polished horizontal surface concentric with the Earth's center; the smallest force would set it moving, and it would then move forever unless impeded.[20] An extension of this was that a body dropped from a tower on a rotating Earth, since it shares the tower's motion, would fall to the tower's base. The standard dynamical objections to the Earth's diurnal rotaton, Galileo now realized, were without basis.

In 1597 Kepler sent Galileo a copy of his first book, *The Cosmographic Mystery*, which was outspokenly Copernican. Galileo in responding stated that he had held the Copernican view for some years, but had refrained from defending this position publicly,

> intimidated by the fortune of our teacher Copernicus, who though he will be of immortal fame to some, is yet by an infinite number (for such is the multitude of fools) laughed at and rejected.[21]

By 1613, Galileo's telescopic discoveries had shown Ptolemaic astronomy to be untenable. The semi-heliocentric arrangement, on the other hand, might still seem an option: it gave much of the economy of the Copernican system, without putting the Earth in motion. Galileo could refute arguments against the Earth's motion; what arguments did he have for its motion? He was averse to the wildly speculative theological symbolism that made Kepler a Copernican.[22] For the Earth's motion, he wanted terrestrial evidence. And already, in the 1590s, he thought he had found it: in the tides.

This is a vexed topic. Why, people ask, was Galileo so stupid as to propose a tidal theory that doesn't agree with Newton's? Galileo, of course, died 11 months before Newton was born, so couldn't learn from him. But what these people fail to realize is how much wrong guessing, by intelligent men, went on before a correct understanding of tides emerged. Galileo's theory, incidentally, was right in a respect in which Newton missed the mark.[23] First, however, what was Galileo's mistake? In his dialogue of 1632, he says,

> Of all great men who have philosophized on such a puzzling effect of nature [the tides], I am more surprised about Kepler than about anyone else; although he had a free and penetrating intellect and grasped the motions attributed to the Earth, he lent his ear to the dominion of the Moon over the water, to occult properties, and to similar childish ideas.[24]

In Galileo's view, attractions, sympathies, antipathies, were unscientific notions. He wanted mechanical explanations, preferably such as could be embodied in an actual model of brass, wood, water, and so on. Among 17th-century thinkers, he was not alone in thus restricting himself.

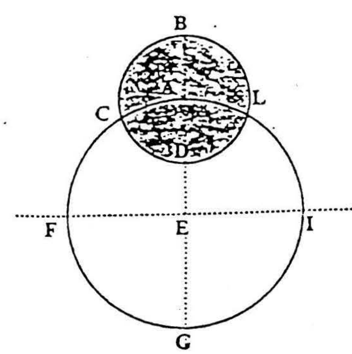
Among Galileo's contemporaries who attributed the tides to the Moon's attraction, none could account for there being two tides per day. The Moon crosses our meridian once every 25 hours, but, in Galileo's Venice as in our Chesapeake Bay, two high tides occur in that interval. So far as I know, the first to show why this should be so was Newton. What counts is differential attraction. When the Moon is on our meridian, it attracts the nearby waters more strongly than the Earth's center, and the Earth's center more strongly than the waters on the opposite side of the Earth. So when there is a high tide for us, there should be a high tide on the opposite side of the Earth as well.

Another difficulty is that high tide occurs, not when the Moon is overhead, but hours later; the delay varies from place to place. Why?

An observation that especially interested Galileo was this. In Venice, at the head of the Adriatic, the difference between high and low tide was about 6 feet, whereas at Dubrovnik, close to where the Adriatic opens into the Mediterranean, it was only a few inches. How explain that?

Galileo's theory had two main parts. The first of these is wrong, but not for the reasons usually given. Galileo supposes that, because the Earth has two motions, the diurnal rotation and the annual motion, the waters of the ocean are alternately accelerated and decelerated with a periodicity of one day. See Exhibit H, where the smaller circle is the Earth, the larger circle the Earth's annual orbit. At B, that is, at midnight, the diurnal and annual motions add together; at D, that is, at noon, the diurnal motion subtracts from the annual; at intermediate places the Earth's surface speed has intermediate values.

Exhibit H



This variation in surface speed, Galileo says, disturbs the waters; they slosh back and forth in their ocean basins, seeking to return to equilibrium. Does such a disturbance really occur? From a Newtonian point of view, Galileo's account is inadequate. Two accelerative fields are being combined. The combination would produce a disturbance, <u>if</u> the law of gravity were any other than an inverse-square law; a term from the inverse-square law cancels it out. This, to be sure, was not understood by Galileo or Newton or anybody till recently. Critics had better beware, but yes, Galileo was wrong.

But now, suppose the disturbance occurred. According to the second part of Galileo's theory, the resulting pendulum-like motion will have a characteristic period, determined by the size and shape of the basin. It will vary, Galileo says, as the length of the basin, and inversely as its depth. Actually, the period varies as the square-root of the length, but Galileo's second point, about the depth variation, is non-intuitive; presumably he discovered it by experiment. Apparently, by experiments with water in long basins, he observed that the water in the middle does not rise and fall, but moves back and forth, while the water at either end of the basin moves up and down. It was thus that he explained to himself the difference in the heights of the tides in Venice and Dubrovnik.

The study of the characteristic frequencies of ocean basins is a central feature of present-day tidal theory. The initial disturbance is caused, not as Galileo supposed, but by the gravitational attractions of the Moon and Sun. Newton knew that the shapes of ocean basins had something to do with the tides, but he lacked the mathematics for treating the problem. The first to give a correct mathematical formulation of the pendulum-like component of tidal motion was Laplace, a century after Newton.

Let these remarks suffice as to what is wrong and right about Galileo's theory of the tides.

Galileo's campaign for heliocentrism roused the biblical fundamentalists. In December of 1613, the Medicis invited Castelli, professor of mathematics in Pisa, to dinner. The Grand Duchess Christina pressed him to defend the compatibility of heliocentrism with the miracle reported in Chapter 10 of the

Book of Joshua, where Joshua says in the sight of Israel, "Sun, stand thou still." Castelli reported the evening's discussion to Galileo, who responded with a long letter on the same theme. The letter was copied and circulated widely.

On December 21, 1614, Tommaso Caccini, a young firebrand of a Dominican, preached a sermon in Florence's Santa Maria Novella, denouncing the Galileists and all mathematicians as practitioners of diabolical arts and enemies of true religion. On the following February 7 Niccolò Lorini, a pious elderly Dominican, sent to the Inquisition in Rome a copy of Galileo's letter to Castelli, here and there altered maliciously, to be examined for heretical content. Meanwhile Galileo had expanded the letter into a longer letter to the Grand Duchess Christina.

Scripture, Galileo quotes a churchman as saying, tells how to go to heaven, not how heaven goes. It has to do with faith and morals, not with the make-up of the natural world. It is addressed to uneducated folk, and must speak their language. For the sake of theological consistency, some of its statements must be interpreted metaphorically: God does not literally stretch forth a hand, or have a backside, or get angry. As for implicit or explicit assertions in Scripture about the natural world, Galileo took his cue from Augustine's treatise, *On the literal interpretation of Genesis*. If natural philosophers have established a fact by observation or strict demonstration, their conclusion must take precedence over the literal interpretation of Scripture. And, Galileo went on to insist, the Church should remain uncommitted on matters where the fact has not yet been, but might be thus established. Such a matter, he urged, was the Copernican hypothesis.

Two comments. Galileo here assumed that faith and natural philosophy do not and cannot conflict. This seemed to him obvious. For us today, it can be a more difficult question.

Secondly, Galileo identified strict science with truths established by observation or by demonstration.[25] By observation, for instance, he had established that the Moon is mountainous. The propositions of Euclid had been established by demonstration from premisses which he took to be indubitable. In the case of the Copernican hypothesis, he knew of no indubitable premisses from which it could be derived. Thus in arguing from the tides, Galileo argued *exsuppositione*, presupposing the Earth's motion. The explanation could become an established truth only if all possible alternatives were disproved. In his *Dialogue* of 1632 Galileo has Salviati say: "We have established the impossibility of explaining the motions observed in the tides while simultaneously maintaining the immobility of the containing vessel."[26] That is a claim to have excluded the alternatives. Evidently Galileo underestimated the difficulty of doing that. Exclusion of all alternatives, in any ultimate sense, is probably impossible. But the point I want to make is that Galileo did not articulate a practicable methodology for the new science.

In December 1615, against the advice of the Tuscan ambassador, Galileo went to Rome to try to clear his name of the suspicion of heresy and to campaign against the suppression of the Copernican theory. He was an ardent campaigner. One Roman witness reported in January 1616:

> He discourses often amid fifteen or twenty guests who make hot assaults upon him, now in one house, now in another.

Monday...he achieved wonderful feats; and what I like most was that, before answering the opposing reasons, he amplified them and fortified them himself with new grounds which appeared invincible, so that, in demolishing them subsequently, he made his opponents look all the more ridiculous.[27]

His efforts were to no avail. On 24 February 1616, theological consultants appointed by the Holy Office to assess Galileo's Copernicanism reported to the Pope as follows (**Exhibit J:**)

Propositions to be assessed:

(1) The Sun is the center of the world and completely devoid of local motion.

Assessment: All said that this proposition is foolish and absurd in philosophy, and formally heretical since it explicitly contradicts in many places the sense of Holy Scripture, according to the literal meaning of the words and according to the common interpretation and understanding of the Holy Fathers and the doctors of theology.

(2) The Earth is not the center of the world, nor motionless, but moves as a whole and also with diurnal motion.

Assessment: All said that this proposition receives the same judgment in philosophy and that in regard to theological truth it is at least erroneous in faith.[28]

On the following day, 25 February, (see **Exhibit K:**)

His Holiness [the Pope] ordered the most illustrious Lord Cardinal Bellarmine to call Galileo before himself and warn him to abandon these

opinions; and if he should refuse to obey, the Father Commissary, in the presence of a notary and witnesses, is to issue him an injunction to abstain completely from teaching or defending this doctrine and opinion or from discussing it; and further, if he should not acquiesce, he is to be imprisoned.[29]

On 26 February, (see **<u>Exhibit L:</u>**)

At the palace of...the said Most Illustrious Lord Cardinal Bellarmine,...and in the presence of the Reverend Father Michelangelo Segizzi,..., Commissary of the Holy Office, having summoned the above-mentioned Galileo before himself, the same Most Illustrious Lord Cardinal warned Galileo that the above-mentioned opinion was erroneous and that he should abandon it; and thereafter, indeed immediately,..., the aforesaid Father Commissary, in the name of His Holiness the Pope and the whole Congregation of the Holy Office, ordered and enjoined the said Galileo, who was himself still present, to abandon completely the above-mentioned opinion that the Sun stands still at the center of the world and the Earth moves, and henceforth not to hold, teach, or defend it in any way whatever, either orally or in writing, otherwise the Holy Office would start proceedings against him. The same Galileo acquiesced in this injunction and promised to obey.[30]

According to the Pope's command, please recall, an injunction was to be imposed <u>only</u> if Galileo refused to obey the initial order to abandon his erroneous opinions. There is no evidence that Galileo refused, so the injunction would appear to be illegal. Another suspicious circumstance is that it is not signed, as injunctions usually were. Is the document a forgery, as some scholars have supposed? Or does its remaining unsigned mean that Bellarmine and Segizzi were at loggerheads? Bellarmine was chief theological adviser to the Pope, and a Jesuit; Segizzi, head of the Inquisition, was a Dominican. The Dominicans had for centuries had charge, not only of the Inquisition, but of all questions relating to theological orthodoxy. Segizzi can have been jealous of Bellarmine, or suspected him of leniency in the Galileo matter. Bellarmine may have refused to sign the document, or told Galileo to ignore it as illegal. We do not know.

The rumor circulated that Galileo had been forced to abjure, that is, to renounce under oath his Copernicanism, and had been given salutary penances. In May Galileo asked, and received from Bellarmine, a certificate denying theis rumor. It asserted (**Exhibit M**) that

he has only been notified of the declaration made by the Holy Father and published by the Sacred Congregation of the Index, whose content is that the doctrine attributed to Copernicus...is contrary to Holy Scripture and therefore cannot be defended or held....

This certificate was signed by Bellarmine and given to Galileo. To say with Bellarmine that the Copernican doctrine could not be defended or held, was not to say with Segizzi that it could not be taught or discussed in any way whatever. In the schools, heretical doctrines were commonly discussed, even debated, in order that they might be understood.

In 1623 Maffeo Barbarini, an educated Florentine and a friend and admirer of Galileo, became Pope Urban VIII. The event was hailed as the dawn of a new, liberal-minded regime. In the spring of 1624 Galileo went to Rome, and obtained the pope's permission to write a dialogue on the two systems of the world, Ptolemaic and Copernican, geostatic and geokinetic. Urban did not fear that Copernicanism would be proven true. Though we might be unable to account for the tides except on the geokinetic theory, God, being omnipotent, could bring them about in a different way. Galileo, Urban ordered, should feature this argument in his dialogue. In non-theological language, it says that our explanations are always hypothetical.

An ambiguity, let me say, lurks in this word "hypothesis." Its accepted meaning, in Galileo's day, was instrumentalist. A hypothesis was a likely story, useful for prediction, but without further claim to truth. It was <u>mere</u> hypothesis. Much astronomical theory in that day cannot be viewed otherwise. But a hypothesis can have a different meaning, which I shall call <u>fallibilist</u>. The fallibilist does not know the ultimate truth of his hypothesis, but he pursues it as possibly revealing a piece of the system of the world. In support of this hope, or faith, he looks to the logical economy of the hypothesis, its aesthetic aptness, the reach of its pragmatic success. I suspect that to Galileo the initial appeal of the Copernican arrangement was a fallibilist appeal. But in Galileo's basic, Aristotelian conception of science, science consisted of empirical facts together with necessary demonstrations. Such a conception was inadequate to the needs of the new science.

Well, Galileo set about writing his dialogue. He was now 60. For 20 years arthritic attacks had kept him in bed for days at a time; progress was slow. The MS was at last completed toward the end of 1629. It included a new argument accounted for except on a geokinetic theory. Argument *ex suppositione*, with the alternatives dismissed..

The third interlocutor, Sagredo, is the eager listener, intent on Salviati's argument, anticipating its conclusions, objecting in order to elicit clarification. A keen observer of natural effects, he is excited by the explanatory possibilities of the heliocentric hypothesis. Mustn't Galileo have shared this openness to learning that he describes so charmingly in Sagredo?

From the beginning, unfavorable comments about the *Dialogue* circulated in Rome. And now the injunction of 1616 was brought forth from the Inquisition archives, and the Pope was informed of its content. Just at this juncture, in the spring of 1632, Urban VIII was facing an international crisis of gigantic proportions. For 8 years he had pursued balance-of-power politics in alliance with Cardinal Richilieu in France, and in accommodation of the Protestants in Germany. Now Gustavus Adolphus, the Swedish Protestant general, had invaded Bavaria, the center of German Catholicism, and had sacked the Jesuit Colleges there. Urban had to realign the papacy with the Spanish Hapsburgs. Meanwhile, the Spanish cardinals were charging Urban with leniency in the fight against heresy; he was threatened with impeachment unless he took a more forceful stand.[31]

To the pope, thus pressured, Galileo's failure to inform him of the injunction was treachery in his own backyard. He was outraged.

In the summer of 1632, sales of Galileo's *Dialogue* were stopped in the papal states, and all copies were confiscated. A specially appointed commission examined the book and concluded that Galileo had violated the injunction.

The Tuscan government, of which Galileo was an employee, attempted to forestall a trial, without success. The first interrogation took place on 12 April 1633. Asked about the events in 1616, Galileo stated that he had been given an oral warning by Cardinal Bellarmine that the Earth's motion could neither be held nor defended, but only discussed hypothetically. He denied having received a special injunction prohibiting him from discussing this motion in any way whatsoever; as evidence for this, he produced Bellarmine's certificate. He denied that his *Dialogue* held or defended the Earth's motion; rather, it showed that the arguments for it were not conclusive.

Bellarmine and Segizzi were dead; Galileo was the sole surviving witness of the events of 26 February 1616. The strongest charge, of disobedience to a papally imposed injunction, was fatally weakened. But, Urban insisted, a sentence there must be. In a private conference, Maculano, now Commissary of the Holy Office and chief judge in the trial, persuaded Galileo to plead guilty to a lesser charge, promising in return a light sentence. Galileo re-read his *Dialogue*, and deposed as follows on 30 April (see **Exhibit N**):

> **I freely confess that [my book] appeared to me in several places to be written in such a way that a reader, not aware of my intention, would have had reason to form the opinion that the arguments for the false side, which I intended to confute, were so stated as to be capable of convincing because of their strength, rather than being easy to answer....**[32]

Galileo's excuse for having given this impression was that he was more desirous of glory than was suitable; he wanted to appear clever:

> **My error then was, and I freely confess it, one of vain ambition, pure ignorance, and inadvertence.**[33]

In confessing to ambition and a desire to appear clever, Galileo, I believe, was honest. He was a proud man, product of a Florentine tradition of gentility, culture, and independent thought that went back to the 15th century, before the age of despotism and excessive bowing and scraping. But had he really intended to make the arguments for Copernicanism appear weak, as he claimed? That claim was disingenuous.

What else could he have said? In his letter to the Grand Duchess Christina he had written (see **Exhibit O**):

> **...to command that the very professors of astronomy themselves see to the refutation of their own observations and proofs as mere fallacies and sophisms is to enjoin something that lies beyond any possibility of accomplishment....Before this could be done they would have to be taught how to make one mental faculty command another, and the inferior powers the superior, so that the imagination and the will might be forced to believe the opposite of what the intellect understands.**[34]

The Pope was not satisfied. He ordered that Galileo be interrogated under the formal threat of torture in order to determine his intention, a standard procedure. Whatever the outcome, he was to abjure publicly, to be held under arrest at the Inquisition's pleasure, and his book was to be banned. On 21 June the interrogation was carried out, Galileo maintaining the innocence of his intention. On the following day he was read the sentence, and he recited the formal abjuration.

So Galileo lost the battle. His writings were instrumental in winning the war. Not, to be sure, in the papal states, where natural science sputtered to a stop, but elsewhere in Europe, where Galileo's *Dialogue* appeared in Latin and in English, and his last work, *The Two New Sciences*, also appeared. The problems of inertial motion that Galileo had posed within a pre-inertial framework were solved within an inertial framework by Huygens, Newton, and others. Newton, who had read the *Dialogue*, says that Galileo discovered the law of free fall and the parabolic path of projectiles by applying Newton's first two laws of motion: an impossible feat of anachronism, but science was hastening on and leaving its history behind.

In articulating his Rules of Philosophizing, Newton quoted a line from the *Dialogue* that Galileo had given in Latin and attributed to Aristotle: *frustra fit per plura quod potest fieri per pauciora* ("in vain is that done with many that can be accomplished with fewer").[35] It was a slogan enjoining logical economy. To Galileo, logical economy was a hopeful clue to hidden system. By late 1684, Newton, applying the slogan, had reached the result that the solar system's center of gravity was not at the Sun's center but near it. He had, he claimed, "proved the Copernican system apriori." It was more than a determined sceptic would grant. But the hypothesis was showing its power, preparing for a pragmatic success that would leave its rivals in the shade. The science that Galileo initiated by showing that we can be in motion without knowing it has flourished. Generalized and formalized in successive steps by Newton, by

Lagrange, by Einstein, its fruitfulness has not yet been exhausted.

Notes

1. From Viviani's *Racconto istorico della vita di Galileo Galilei*, as quoted by E.A. Moody, "Galileo and Avempace," *Journal for the History of Ideas*, XII (1951), p.167 n.8.

2. I.E. Drabkin and Stillman Drake, *Gallileo Galilei On Motion and On Mechanics* (University of Wisconsin Press, 1960), 3-131.

3. Aristotle, *Physics* IV, ch.8, 215a24-216a20.

4. *De Caelo*, 309b14-16.

5. "Aristotle," says Galileo, "makes this same assumption in his solution of the 24th Mechanical Problem." See Pseudo-Aristotle, *Mechanical Problems*, 855b34-36.

6. Galileo Galilei, *Two New Sciences* (tr. Stillman Drake; Univ. of Wisconsin Press, 1974), pp.158-59 (Ed. Naz., VIII, p.202).

7. In his early treatise on motion (see *Galileo Galilei On Motion and On Mechanics*, University of Wisconsin Press, 1960, p.50), Galileo says:

The method that we shall follow in this treatise will be always to make what is said depend on what was said before, and, if possible, never to assume as true that which requires proof. My teachers of mathematics taught me this method. But it is not adhered to sufficiently by certain philosophers who frequently, when they expound the elements of physics, make assumptions that are the same as those handed down in [Aristotle's] books *On the Soul* or those *On the Heaven*, and even in the *Metaphysics*. And not only this, but even in expounding logic itself they continually repeat things that were set forth in the last books of Aristotle. That is, in teaching their pupils the very first subjects they assume that the pupils know everything, and they pass on to them their teaching, not on the basis of things that the pupils know, but on the basis of what is completely unknown and unheard of. The result is that those who learn in this way never know anything by its causes, but merely have opinions based on belief, that is, because this is what Aristotle said. And few of them inquire whether what Aristotle said is true.

8. William A. Wallace, *Galileo and his Sources: the Heritage of the Collegio Romano in Galileo's Science* (Princeton, N.J.: Princeton University Press, 1984)

9. See Stillman Drake & I.E. Drabkin, *Mechanics in Sixteenth-Century Italy* (University of Wisconsin Press, 1969), pp.204-206.

10. See *Galileo Galilei On Motion and On Mechanics*, 173-75.

11. *Le Opere di Galileo Galilei*, X, 115.

12. *Ibid.*, VIII, 373-4.

13. Galileo, *Dialogue Concerning the Two Chief World Systems* (tr. Stillman Drake; University of California Press, 1962), p.229; Ed. Naz., VII, pp.255-56.

14. Alexandre Koyré was a prominent proponent of the platonist Galileo; see his *Études Galiléennes* (Paris: Hermann, 1939); *Metaphysics and Measurement* (Harvard, 1968), Chapters I-IV. Thomas Settle showed in 1961 that Galileo's inclined plane experiment could be performed with remarkable precision, using only means that would have been available to Galileo: see Thomas B. Settle, "An Experiment in the History of Science," *Science*, Vol.133 (1961), 19-23. Next, Stillman Drake took up the empiricist theme, and in 1973 published an article in *Scientific American* (May, 1973, pp.85-92) on "Galileo's Discovery of the Law of Free Fall." Unfortunately his enthusiasm and imagination got out of hand, and his reconstruction here (as in some other cases) cannot be sustained.

15. I am chiefly dependent here on R.H. Naylor, "Galileo's Theory of Projectile Motion," *Isis 71* (1980), 550-70, and David K. Hill, "Dissecting Trajectories," *Isis 79* (1988), 646-68.

16. Quoted from Maurice A. Finocchiaro, *The Galileo Affair: a Documentary History* (University of California Press, 1989), p.50.

17. Stillman Drake, *Galileo at Work* (Chicago: University of Chicago Press, 1978), pp.168-69.

18. Stillman Drake, *Galileo: Pioneer Scientist* (University of Toronto Press, 1990), pp.145-55, mistakenly characterizes this as compelling evidence for the Earth's annual motion about the Sun.

19. See *Galileo Galilei On Motion and On Mechanics*, pp.72-74; Stillman Drake, "The Evolution of *De Motu*," *Isis 67* (1976), 245

20. *Galileo Galilei On Motion and On Mechanics*, 171.

21. Galileo, *Opere* (Ed.Naz.), Vol.10, p.68.

22. Like Kepler, however, Galileo entertained the idea, "as not entirely unphilosophical," that the motion of the planets had its cause in the rotating Sun; see his "Letter to the Grand Duchess Christina" in Stillman Drake (tr.), *Discoveries and Opinions of Galileo* (Doubleday Anchor Books, 1957), pp.212-13.

23. I am indebted here to a recent study by Paolo Palmieri, "Re-examining

Galileo's Theory of Tides," *Archive for History of Exact Sciences*, Vol.53 (1998), 223-375.

24. Maurice A. Finocchiaro, *Galileo on the World Systems* (University of California Press, 1997), 304; Galileo, *Dialogue Concerning the Two Chief World Systems* (tr. Stillman Drake), 462.

25. See Ernan McMullin, "The Conception of Science in Galileo's Work," in Robert E. Butts and Joseph C. Pitt (eds.), *New Perspectives on Galileo* (D. Reidel Publishing Co., 1978), pp.209-57.

26. Finocchiaro, tr., *Galileo on the World Systems*, 288.

27. See Giorgio Di Santillana, *The Crime of Galileo*, pp.112-13.

28. Maurice A. Finocchiaro, *The Galileo Affair: A Documentary History*, 146.

29. *Ibid.*, 147.

30. *Ibid.*, 147-48.

31. See Pietro Redondi, *Galileo Heretic* (tr. Raymond Rosenthal; Princeton University Press, 1987), pp.228-33. Redondi's larger thesis that there was a hidden agenda in the Galileo trial, pertaining to Galileo's atomism and its

relation to the Eucharist, has not been accepted by other scholars.

32. Finocchiaro, *op.cit.*, p.278.

33. *Ibid.*

34. *Stillman Drake, Discoveries and Opinions of Galileo*, 193.

35. Galileo, *Dialogue Concerning the Two Chief World Systems* (tr. Stillman Drake, University of California Press, 1962), 123.

Addendum to p.11: the calculations of folio 116v.

In general: $D^2 \propto H$, or $D_1^2 : D_2^2 :: H_1 : H_2$; therefore $D_1^2 = D_2^2 (H_1/H_2)$.

Upper Middle: $H_1 = 600$, $H_2 = 300$, $D_2^2 = 800 \times 800$.

$$D_1 = \sqrt{\frac{800 \cdot 800 \cdot 600}{300}} = \sqrt{1280000} = 1131$$

Lower Left: $H_1 = 800$, $H_2 = 300$, $D_2^2 = 800 \times 800$.

$$D_1 = \sqrt{\frac{800 \cdot 800 \cdot 800}{300}} = \sqrt{1706666} = 1306$$

Upper Right: $H_1 = 828$, $H_2 = 300$, $D_2^2 = 800 \times 800$.

$$D_1 = \sqrt{\frac{800 \cdot 800 \cdot 828}{300}} = \sqrt{1766400} = 1329$$

Lower Middle with numbers to Right: $H_1 = 1000$, $H_2 = 300$, $D_2^2 = 800 \times 800$.

$$D_1 = \sqrt{\frac{800 \cdot 800 \cdot 1000}{300}} = \sqrt{2133333} = 1460$$

Handout for "Galileo Agonistes"

Exhibit A: **[Galileo's demonstration at the Leaning Tower of Pisa was designed to show] that the speeds of mobile bodies *of the same material* [emphasis added] but of unequal weight, moving through the same medium, are not in the ratio of their absolute weights, as Aristotle claimed, but they move with equal speed...; and neither do the speeds of a given mobile body, moving through diverse mediums, have the inverse ratio of the resistances, or densities of these mediums...**[From Viviani's *Racconto istorico della vita di Galileo Galilei*, as translated by E.A.Moody, "Galileo and Avempace," *Journal for the History of Ideas*, XII (1951), p.167n.8]

Exhibit B: Aristotle's Rule of Speeds in Different Mediums

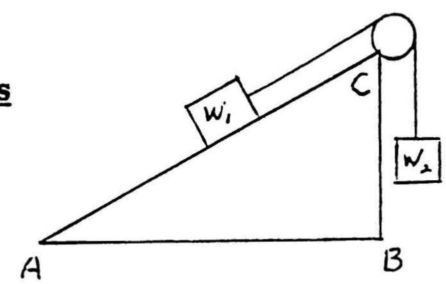
Let V_A, V_B be the body's speeds in mediums A and B; and let R_A, R_B be the resistances in those mediums. Then according to Aristotle

$$V_A : V_B :: R_B : R_A.$$

Suppose $R_A \rightarrow 0$. Then the ratio $R_B:R_A$ becomes infinite, and so must $V_A:V_B$.

Therefore $V_A \rightarrow \infty$, which is impossible. [Cf. Aristotle, *Physics*, 215a29-216a8.]

Exhibit C: Equilibration of Weights on Inclined Planes



W_1, lying on CA, and connected with the vertically hanging weight W_2, is in equilibrium with W_2 if, and only if, $W_1 : W_2 :: CA : CB$. [See Galileo, *On Mechanics* (tr.Stillman Drake; University of Wisconsin Press, 1960), 173-75.]

Exhibit D: Galileo's Letter to Sarpi, October 1604

Thinking over the questions about motion, in which, to demonstrate the accidents observed by me, I have been lacking a totally indubitable principle that I could take as axiom, I am reduced to a proposition which has much that is natural and evident about it; and this being supposed, I demonstrate the rest, that is, that the spaces traversed in natural motion are as the squares of the times, and consequently the spaces traversed in equal times are as the odd numbers starting with unity... And the principle is this: that the mobile body goes increasing its speed in proportion to its distance from its starting point... Please consider it and tell me your opinion.

Exhibit G: Essential details of folio 116v [From David K. Hill, "Dissecting Trajectories," *Isis 79*(1988), 646-68; p.663.]

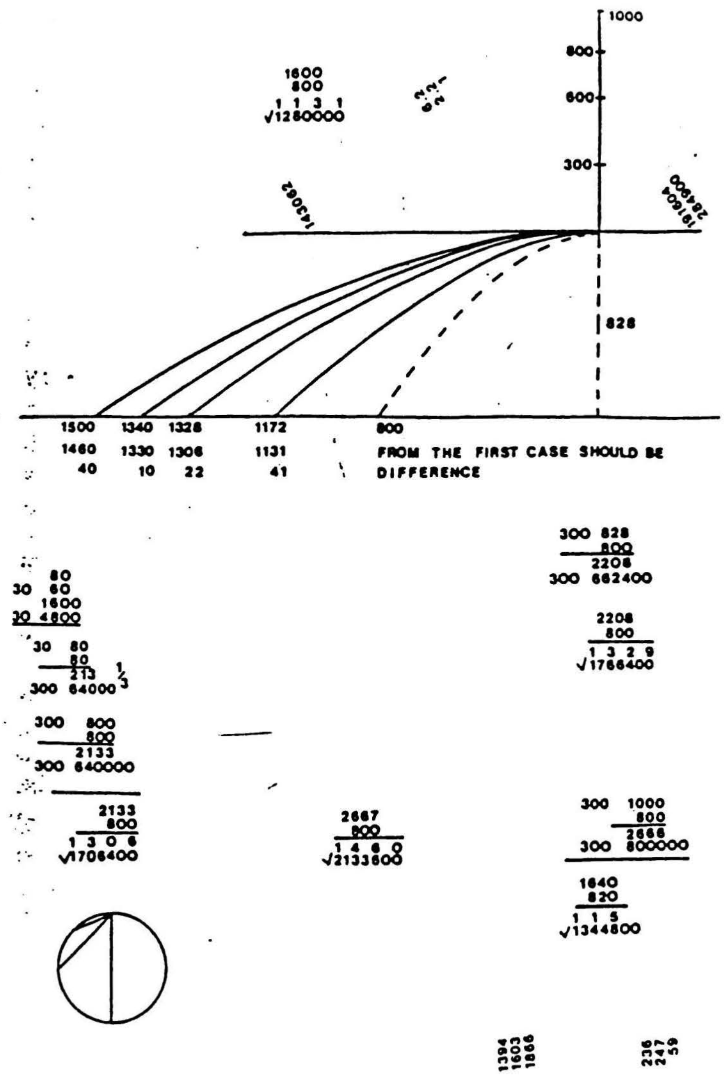


Exhibit H: "Acceleration" in Galileo's theory of the tides

AFGI = Earth's annual orbit

BCDL = the Earth

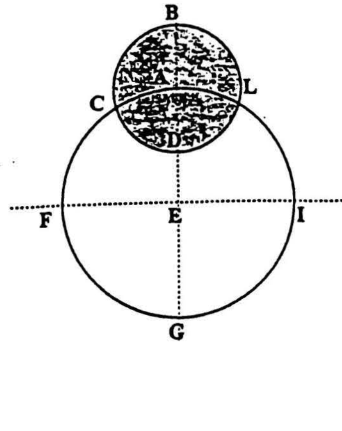


Exhibit M: Bellarmine's Certificate of 26 May 1616

We, Robert Cardinal Bellarmine, have heard that Sig. Galileo Galilei is being slandered or alleged to have abjured in our hands and also to have been given salutary penances for this. Having been sought about the truth of the matter, we say that the above-mentioned Galileo has not abjured in our hands, or in the hands of others here in Rome, or anywhere else that we know, any opinion or doctrine of his; nor has he received any penances, salutary or otherwise. On the contrary, he had only been notified of the declaration made by the Holy Father and published by the Sacred Congregation of the Index, whose content is that the doctrine attributed to Copericus (that the Earth moves around the Sun and the Sun stands at the center of the world without moving from east to west) is contrary to Holy Scripture and therefore cannot be defended or held. In witness whereof we have written and signed this with our own hands, on this 26th day os May 1616. [Finocchiaro, *op.cit.*, 153]

Exhibit N: Galileo's confession

I freely confess that [my book] appeared to me in several places to be written in such a way that a reader, not aware of my intention, would have had reason to form the opinion that the arguments for the false side, which I intended to confute, were so stated as to be capable of convincing because of their strength, rather than being easy to answer.... My error then was, and I freely confess it, one of vain ambition, pure ignorance, and inadvertence. [Finocchiaro, *op.cit.*, 278]

Exhibit O: From the letter to the Grand Duchess Christina:

...to command that the very professors of astronomy themselves see to the refutation of their own observations and proofs as mere fallacies and sophisms is to enjoin something that lies beyond any possibility of accomplishment.... Before this could be done they would have to be taught how to make one mental faculty command another, and the inferior powers the superior, so that the imagination and the will might be forced to believe the opposite of what the intellect understands. (Stillman Drake, *Discoveries and Opinions of Galileo*, p.278)