G. Galileo's "Laws" at the End of "The Fourth Day"

1. Upshot: comparatively little public direct evidence for the theory of projectile motion at the time Galileo put it forward
    a. The maximum range at 45 deg result a plus for the theory
    b. To the extent that the Tables work in practical situations, some evidence, though limited
    c. Perhaps a little more evidence from symmetry around 45 deg, provided that it is observed
2. Much of the evidence for Galileo's projectile theory must therefore come from evidence for the individual underlying claims
    a. Uniform acceleration: the law of free fall
    b. A universal value of vertical acceleration
    c. Continuing horizontal motion over relevant distances
    d. No cross-talk between two components of motion when compounded
3. We have already found that the evidence for uniform vertical acceleration was limited and problematic at the time
    a. Inclined plane 1,3,5,... pattern, and Riccioli's observation of the same in free fall
    b. But experimental data highly suspect and not independently confirmed, forcing us to conclusion that at most the experiments had failed to falsify the claim
    c. Riccioli's efforts open the way to improved experiments, however, including much more careful inclined plane measurements
4. Little evidence had yet been developed on the universality of g, though it might be forthcoming once experiments improve
    a. Once rolling versus falling exposed, inclined plane may provide good results (for will appreciate need for one type of motion)
    b. Uniformity of measured value of g would be strong evidence for uniform acceleration
5. Thus little overall empirical evidence for Galileo's theory: it is not clearly false, but it is far from empirically established
    a. And issues about nomologicality, *ceteris paribus* conditions, range of laws, whether exact or only approximate, and character of approximation if the latter -- issues raised by Galileo himself in the "Fourth Day" -- have scarcely been empirically addressed at all
    b. The contrast with Kepler's laws here is quite sharp
6. Much more reason to continue with the theory at the time than to think it true, once and for all
    a. The rich mathematical development offers potential for experiments, especially as technology improves
    b. Also, it is the only game in town -- the only theory that offers even the beginning of a possibility for bringing empirical data systematically to bear
    c. And its mathematical form and extent set a standard that any alternative to it had to meet

V. Remarks on Galileo's Contribution to Modern Science

A. Observation, Theory, and Experiment

1. Galileo saw and expressed more clearly than anyone the limitations of simple observation of nature and hence the need for experiments
   a. Intrinsic limits on what we can observe -- e.g. from time and acuity -- and limits arising because events in nature are the combination of multiple processes, the observation of any one of which is then confounded by the others
   b. These limits can be pushed back through experimentation -- observation in specially contrived circumstances -- and through the use of special equipment -- e.g. the telescope
   c. Highly contrived experiments often needed to isolate one natural process from others, as in freedom from air resistance, and even then may have to extrapolate to what would happen in the limit
2. He also saw that experiments, to a much greater extent than mere observation, are closely tied to theories
   a. His experiments themselves were tied to specific theoretical predictions which the theory itself usually makes salient, typically because other theories not likely to make the same prediction
   b. The raw data -- e.g. distance covered -- will typically have to be interpreted using the theory -- e.g. as speed
   c. The theory to which the experiment is addressed is often an idealization, so that e.g. whether data falsify it can be a matter of interpretation, dictated in part by the theory itself
   d. Background theoretical assumptions about confounding effects will be required to justify the claim that the effects are being controlled for and the experiment is not being confounded
   e. And background theoretical assumptions may be needed to relate what is actually measured (e.g. amount of water escaping) to what it is being taken to measure (viz. time)
3. Any special equipment used will reflect background theories about what it does and does not provide
   a. Optics for the telescope, water flow and pendulum for time, percussion effects for impetus etc.
   b. Theories tie observations and measurements to quantities of interest, and license interpretations and claims of accuracy
4. Galileo saw experimentation as serving several roles
   a. Falsification of theories above all else -- a Popperian view
   b. Cross-roads experiments to justify initial assumptions in developing a theory
   c. Confirmation of theory via successful salient prediction, or more modestly by failure to falsify
      (1) Quantitative patterns such as the 1,3,5,... progression and double-height result, $a=2*\sqrt{(h*p)}$
      (2) Qualitative results such as simple incline not the fastest between two points and all chords to bottom traversed in same time, or even 1,3,5,… progression of high approximation

d. Though far less so than Mersenne and Riccioli, measurement of quantities of interest, which the theory makes salient and implies should have stable measurable values

5. Galileo was one of the first to realize that experimentation becomes much more potent in the context of theories with rich mathematical development
   a. Mathematics ties variables to one another, licensing multiple experiments and measurements bearing on a single claim
   b. When pushed hard enough, mathematics may yield special, even remarkable, predictions that allow more telling tests
   c. Question-answering theories help in the design and interpretation of special equipment
6. Finally, Galileo recognized not just the need for skill and ingenuity in the conceptual design of experiments, but also in their detailed implementation
   a. E.g. vellum in the grooves of the inclined plane -- such tricks needed for experiment not to be confounded by unwanted elements
   b. Making an experiment work at all -- or better, with more exacting results -- often takes exceptional skill of a special sort, and exceptional pertinacity

B. The Theory of Local Motion: Scope and Content

1. What Galileo has left us with is a *fragment* of a physical theory about natural motion near the surface of the earth in the absence of air resistance and various frictional effects
   a. Fragment covers free fall, motion constrained by an inclined plane, and motion of a projectile over limited distances once it is launched
   b. Offers answers to questions that had never been answered before, as advertised at the outset [190]
   c. Puts forward three laws still with us -- law of free fall, law of projectile motion, and a not quite right law of inclined planes -- as well as his initial form of pathwise independence
2. Theory built around eight fundamental claims about how natural mechanisms affect motion near the surface of the earth in the absence of resistance etc., the last of which is mere conjecture on his part
   a. The propensity to fall vertically to the earth is the only natural mechanism altering such motion
   b. This propensity becomes expressed in the form of uniform acceleration (in time)
   c. The speed acquired over a given height is independent of the path followed
   d. The speed acquired is the same for all bodies falling from the same height, and hence independent of weight (and shape, etc.)
   e. The speed acquired is just sufficient to raise the body back to its initial height
   f. Naturally acquired motion remains uniform and in a straight line along the horizontal (at least for distances small in comparison with the radius of the earth)
   g. A body projected horizontally describes to high approximation a semi-parabola (at least for distances small in comparison with the radius of the earth), with the dimensions of the semi-

parabola dictated by the height from which its initial horizontal speed would be acquired naturally; and, by symmetry, a body projected at an acute angle upwards describes a corresponding full parabola (with the same qualification)

h. The distance of fall in the first second (i.e. g) is the same everywhere around the earth

3. The theory Galileo has offered is only a fragment because it fails to cover all the processes governed by this propensity to fall

   a. In particular, fails to cover pendular motion -- motion under vertical acceleration with object constrained to remain a fixed distance from some point (versus constrained by plane to a particular direction)

   b. But just a fragment also because it wrongly conflates rolling with slipping and falling, and hence requires supplementation

   c. And because no answer to projectile trajectory when curvature of earth taken into account

   d. {I.e. lots of clean-up work to be done}

4. Comparatively little evidence was available at the time in support of the theory -- i.e. in support of the fundamental claims

   a. Sufficient agreement with 1,3,5,... pattern in inclined planes and (thanks to Riccioli) free fall, and successful explanation of maximum range at 45 deg give reasons not to reject

   b. But much too limited measurements of acceleration rates -- i.e. fall in first sec -- many independent measurements of which would have provided stronger evidence; and far too limited a range of experiments

   c. {Again, lots of clean-up work to be done}

5. Yet a rich mathematical development, yielding a large range of potential experiments for the future

   a. Sufficiently wide range of results from so few fundamental assumptions that theory promises to have high explanatory power

   b. Successes with three types of motion give reason for expecting it ultimately to cover pendular motion too

6. Therefore the community had good reasons to take the theory seriously and to continue work in developing and assessing it

   a. Find ways of bringing experimental results to bear -- e.g. as Mersenne and Riccioli did -- including results determining g and thus verifying its uniformity and ubiquity

   b. Extend the mathematical development to cover other types of motion governed by the propensity to fall and to answer such further questions as, what is the shortest time path?

C. Galileo's Research in its Historical Context

1. The research reported in Days 3 and 4 of *Two New Sciences*, which was almost entirely conducted in Padua and hence before 1610, was not so insular and unique as my presentation of it has suggested

   a. Have already emphasized the tradition in Italian mechanics leading up to it

b. Tartaglia, in particular, had worked on artillery, though not remotely with the mathematical success of Galileo

c. And others elsewhere both before and after worked on projectile motion in particular

2. Among the most notable of these, though he never published, was Galileo's contemporary, Thomas Harriott (ca. 1560-1621), sometimes called "the English Galileo"

a. His work on projectiles appears to have recognized from the outset that the observed trajectory is not symmetric in the manner of a parabola, but with descent more sharply vertical than ascent

b. He nevertheless pursued a mathematical theory akin to Galileo's, though the kind of trajectories he worked on were less mathematically tractable

c. (See Schemmel's two volumes, the second of which contains the manuscripts)

3. In virtually the immediate wake of *Two New Sciences*, Torricelli published his *De Motu Gravium Naturaliter Descendentium et Projectorum* of 1644, rederiving and extending Galileo's results

a. Have already mentioned both his independent derivation of pathwise independence from the principle named after him and his proof of upward projection at an angle completes the parabola

b. Openly acknowledged the idealized character of the theory of projectile motion

c. Subsequent work generally proceeded more from his book than from *Two New Sciences*

4. Several figures engaged in further development of Galileo's theory of motion between 1642 and 1684, especially Huygens, while others, whether proceeding from Galileo or striking out in new directions, tackled the artillery problem

a. Have already mentioned John Collins in England, but also Robert Anderson

b. Apparently with little success in providing military with a mathematical approach of any use to them, for they kept relying on trial-and-error

c. See the published version of Rupert Hall's dissertation (1952) for details on ballistics

d. And while he didn't work on the projectile problem, Gassendi did much in the early 1640s to support controversial Galilean claims

5. A more useful mathematical theory of projectile motion was not the only problem Galileo bequeathed to those following him:

a. The problem of the truly isochronous trajectory in fall, and with it a theory of isochronous pendular motion

b. The problem of the true trajectory of fastest descent, the brachistochrone problem

c. The problem of the trajectory of a projectile in the absence of a resisting medium, but with the curvature of the earth taken into account, and related problem of descent to the center of earth

d. A question about how far vertically the claim of uniform acceleration remains valid

D. Galilean Conceptions of Empirical Science

1. Whatever else is to be said, Galileo thought that empirical science could reach conclusions much stronger than mere conjecture

   a. See quote from (1605) letter on supernova of 1604 in Appendix
   b. ***Beyond conjecture*** through marshalling many detailed observations
   c. Question: what exactly, on Galileo's view, is the epistemic status of the conclusions that reach beyond mere conjecture?
2. At the outset of the discussion of naturally accelerated motion Galileo recommends his theory on the grounds that it is simple and in agreement with experimental observations
   a. I.e. a conception of empirical science under which it is aiming for the simplest theory that saves *experimental* phenomena -- i.e. phenomena in specially contrived circumstances
   b. But then he proceeds to offer very few experimental phenomena with which the theory is known to be in agreement
   c. And when he does offer them, his discussions of the agreement sought between theory and experiment end up suggesting three different conceptions of empirical science -- i.e. three different conceptions of how to marshal empirical evidence
3. A common thread to all three conceptions is that the theory of local motion is not to be regarded as "perfectible" in Kepler's sense -- not to be asked ultimately to make predictions exactly in accord with phenomena of motion observed in nature
   a. At the beginning the theory is presented as an idealization -- what would happen exactly if no resistance or friction effects were present
   b. And in the case of projectile motion, the theory is presented as holding only approximately over limited ranges, even in the absence of resistance
4. One conception of science: seeking detailed agreement, within observational accuracy, between predictions and experimental observations in which confounding effects suitably controlled
   a. Suggested in description of inclined plane [212f], where he describes a detailed experimental program of measurements of location versus time, and asserts that predictions always within "the tenth part of a pulse-beat"
   b. A conception of evidence like Kepler's to a point, but without imposing any requirements on underlying physics
   c. (No problem of selecting among competing alternatives)
5. Second conception: seeking sufficient agreement between predictions and experimental observations -- especially predictions of distinctive phenomenal patterns and salient qualitative contrasts -- to show that theory not empirically false
   a. Suggested in Galileo's descriptions of other experiments, such as the ones for free-fall, and perhaps what he actually did with the inclined plane, and what Mersenne and Riccioli unquestionably did throughout
   b. A Popperian conception of evidence (bold conjectures followed by efforts to refute), but equally a conception more accepting of the limits of experiment

6. Third conception: seeking sufficient agreement between predictions and empirical phenomena of interest to allow theory to serve practical purposes, both in prediction and explanation
    a. Suggested in Galileo's descriptions of the sort of accord to be expected in the case of projectiles and in his discussions (as well as the format) of his tables for projectile motion
    b. An "engineering" conception of evidence in which the crucial issue is whether the theory enhances the ability to understand (i.e. explain) and predict
7. These three conceptions involve fundamentally different evidential logics -- something that Galileo seems to show no cognizance of
    a. On the first conception, systematic discrepancies are a source of concern until they are shown to result from confounding effects in the experiment, after which attention turns to trying to find still better experiments or experiments that allow corrections to be introduced to compensate for the systematic errors produced by the confounding effects
    b. On the second conception, systematic discrepancies can be dismissed (without detailed arguments) so long as they are small enough that experimental results are not out-and-out incompatible with the theory
    c. On the third conception, systematic discrepancies are something to be adjusted for outside the theory -- e.g. through calibration -- and are of no evidential concern except when faced with competing theories that have a promise of being superior from a practical standpoint
8. {In general the best way to get at evidential logic is to consider what the response would have been to discrepancies between observation and theory!}

E. A Conjecture About How Galileo Proceeded

1. My own sense of what Galileo did is that he took one basic insight -- the 1,3,5,... pattern -- and ran with it as far as it would carry him
    a. I don't care whether he first happened upon the insight theoretically or experimentally
    b. He saw both the theoretical and the evidential potential suggested by the pattern
    c. Then systematically explored by means of cross-roads experiments which variables make a difference to this phenomenon
2. To his credit, he developed the most elaborate and extensive mathematical theory that he could off of this basic insight
    a. Saw the empirical advantages of doing so -- the potential for developing evidence in the future -- as well as the aesthetic and conceptual advantages
    b. As such, ended up teaching the scientific world a basic lesson: in areas of basic physics the evidential criterion must ultimately be a combination of simplicity, completeness, and exactness
3. Equally to his credit, he saw how easy it was to mount empirical evidence against the theory, especially because of its idealization away from real-world factors and therefore did all he could to shield it from being too readily rejected

a. His putting forward the theory as an idealization, in contrast to Kepler's doing so, is clearly an attempt to protect the theory from falsification

b. A sound tenet of scientific practice, especially in the early stages of theory construction: don't abandon a theory because of discrepancies with observation unless in a position to use these discrepancies to advantage in forming a new theory

c. For theory is an indispensable lens to learning from experiment, so that better to have some theory that permits continued inquiry than no theory at all

d. (This is an alternative construal of what Koyré calls Galileo's "Platonism")

4. In this effort to shield the theory from being prematurely rejected Galileo commits his worst mistake: in not making clear the extent of agreement between theory and experiment, he saddles the world with a seriously distorted picture of scientific evidence

a. Basic picture: once you have a reasonably correct theory, the evidence for it will simply fall into line straightforwardly

b. Thus no real difference in the evidence problem faced in the early stages of theory construction and in an advanced science; the only problem is happening upon the truth

5. And as a corollary to this mistake, he imposes on the world an element of confusion about the logic of evidential reasoning in science that we are still laboring under

a. Confusion from conflating three quite different conceptions of science and evidential reasoning, as if they all had the same underlying logic, when they don't at all

b. A confusion that surfaces repeatedly when scientists begin debating the relative merits of different theories

c. The world outside science might have been better off if Galileo had been as difficult to read as Kepler was

6. Perhaps the best way to summarize my view of Galileo's new theory of motion is that it was far more local in two respects than is usually recognized when viewed retrospectively

a. His science of motion was truly local, confined not only to motions near the surface of the earth, but ones that were often of limited extent

(1) That was perfectly consistent with the tradition of the "mechanics" of machines like the lever which formed its context

(2) This in contrast to the view that Galileo was formulating a "kinematics" of motion of universal scope

b. The experiments Galileo presents as evidence, most of which are single, isolated experiments, deliver only limited evidence to the claims he takes them to be establishing

(1) Specifically because they were not supported by numerous complementary and follow-on experiments of the sort the "ski-jump" experiment would have been had it succeeded

(2) As such, his claims were backed-up by only highly localized evidence

c. These two together make the legend of Galileo's achievements somewhat bloated versus what he truly achieved

7. That said, the legend began in the 1650s when the eight fundamental Galilean claims listed above became widely accepted largely on the basis of Galileo's authority and the experiments he cited plus those of Mersenne and Riccioli, plus Gassendi's from the late 1630s (to be discussed next time)
   a. That doubtlessly helped promote the idea that individual experiments can be more definitive than they almost ever are
   b. The idea that limited experiments can be decisive is what Shapin and Schaffer decry in their well-known book on pneumatic experiments in the 1660s, *Leviathan and the Air-Pump*
   c. That Galileo's experimental results seemingly established the claims he proposed they did was no less far from being self-evident or self-explanatory, then and now, than those they criticize
   d. However much I disagree with the bottom-line of their book – *scientific truth is a social construct* – I wholeheartedly agree with the theme singled out from it: *the inadequacy of the* [*historiographical*] *method which regards experimentally produced matters of fact as self-evident and self-explanatory*
   e. Hopefully our short study of Galileo's efforts in mechanics has provided convincing evidence for it

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