Galileo's *Two New Sciences*: Projectile Motion

I. Issues Raised by Galileo's *Two New Sciences*

A. The Issues and Controversies Reviewed

1. Galileo was supposedly the "father" of modern experimental science by virtue of (1) his emphasis on the contrast between experiment and mere observation of nature and (2) his commitment to resolving issues empirically
    a. Have seen his ingenuity in designing experiments displayed in the *Dialogue* and *Two New Sciences* -- especially experiments putting the lie to Aristotelian doctrines
    b. But Galilean scholarship has suggested that many of the experiments he mentions he probably did not do
2. Worse, highly meaningful experiments on local motion, with careful measurements, were scarcely possible during his lifetime because of limited means for measuring time (and speed)
    a. Ideally would like to measure height or distance versus time, just as in astronomy, but total elapsed times are of the order of 5 sec or less, and need small fractions of these
    b. Thus the theory of local motion, in direct contrast to orbital astronomy, had few constraining data to build a theory around
3. Worse still, we can now see that Galileo, and presumably others, were laboring under a systematic conceptual error, conflating rolling on an inclined plane with falling
    a. Galileo's main way around the time problem was to "slow" time down by turning to inclined planes
    b. But there is a systematic error in his theory here, for a sphere rollling on its bottom has only 5/7 of the acceleration of a falling sphere, so any simple inference from inclined planes to vertical fall involves a fallacy
    c. Empirical results needed to force this distinction, but problems in getting good enough results -- e.g. good enough measures of distance in the first second -- to recognize the need
    d. Poorly behaved data whenever a mix of rolling and falling, as will happen except at low inclinations, and with good equipment
4. A further complication arises because Galileo is putting forward an idealized science -- i.e. a science about what would happen in the absence of air (and other medium) resistance effects
    a. Can try to minimize the effects of resistance, but no way to eliminate entirely, so that end up with need for special experimental domains in order to pursue meaningful evidence: experiments that require design, in contrast to mere interventions in natural processes
    b. For example, since resistance increases with velocity, all the more reason to use an inclined plane to keep velocities low
    c. In absence of suitable experiments, run the risk of developing an unfalsifiable theory, not really grounded empirically

d. And even with suitable experiments, discrepancies between theory and observation remain seriously ambiguous

5. All of this raises a host of issues about the contribution made by *Two New Sciences* in the development of 17th century science -- e.g.
   a. In what sense did Galileo discover and establish "laws" -- did he do more than guess (as Newton said of Kepler), and are they really our laws
   b. In what sense was he engaged in empirical science at all -- did he ultimately really differ in approach from, say, Descartes
6. Variety of interesting issues can be raised about Galileo, but from our point of view ultimately only two issues of concern
   a. How much was known (ca. 1650) about naturally accelerated local motion as consequence of *Two New Sciences*
   b. How did those involved think this knowledge was being secured -- i.e. what was their conception of empirical science, and what evidential reasoning were they following

B. Evidential Status of the "Law" of Free Fall
1. Galileo offered an impressive array of experiments falsifying Aristotle and legitimating his splitting of local motion into two distinct processes -- a basic process and induced resistance
   a. Simple vertical fall experiments enough to falsify Aristotle's claim that speed proportional to weight
   b. Variations of resistance with medium density and experiments with pendula justify parceling out variables, so that basic process depends only on such things as height and direction
   c. Thus an empirical basis for his idealization, which should then be thought of as a working hypothesis
   d. Shift away from naturally occurring process to one that occurs only in hypothetical or contrived circumstances a profound step
2. His fundamental claim -- the basic process involves uniform (vertical) acceleration in time -- is put forward as the simplest alternative to consider, a hypothesis
   a. Can give empirical grounds that motion is not uniform, and hence need some rule governing how speed changes
   b. Can show that proposed rule is at least physically plausible, and it is mathematically tractable
3. The principle of uniform acceleration entails a distinctive phenomenon -- incremental distances in a 1,3,5,... progression -- that had not been observed or reported before Galileo (in *Dialogue*)
   a. Distinctive both in the sense that a striking pattern (even if only to high approximation) and in the sense that not entailed by e.g. uniform acceleration in space or other salient alternatives
   b. Postulate relating speeds acquired in free fall to speeds acquired along an inclined plane provides an experimental framework in which 1,3,5,.... should be reasonably detectable

4. Inclined plane experiments yield results that are at least compatible with, and hence do not falsify, the theory
    a. Galileo claims much more in *Two New Sciences*: systematic experiments in which time measured for different lengths along plane across different inclinations, with agreement within e.g. 1/10 sec
    b. But Mersenne could not replicate even with a pendulum, Galileo presents no data for us to assess, and such precise results are unlikely without very good ways of measuring time
    c. Nevertheless real experimental results, done with care, should have shown enough agreement with predicted 1,3,5,... pattern to provide adequate grounds for not abandoning the theory!
    d. I.e. real experimental results, however obtained, should have come close enough to showing a 1,3,5,... pattern at low inclinations to give reason for preferring the theory to any other that had been proposed
    e. Failure to obtain the distinctive pattern at higher inclinations, however, raises worries
5. Moreover, the evidence presented for "the" law of free-fall in *Two New Sciences* has a clear lacuna, called attention to by Galileo, in the step from inclined plane results to claims about free fall
    a. Galileo's "postulate": speed acquired in fall through a given height is same regardless of inclination of path
    b. Lacuna that could be bridged by measuring and comparing accelerations -- i.e. distances in first second -- to determine whether one uniform underlying value, as theory claimed
    c. (Lacuna not just a matter of incomplete logic, as the difference in acceleration between rolling and falling shows)
6. By 1651 Riccioli bridges lacuna by measuring distance of fall in first second -- i.e. our g/2 -- to within 5 (or at least 10) percent and by observing 1,3,5,... progession in free fall
    a. Obtains more or less as good evidence for vertical fall as anyone had for inclined plane -- published results much too good to be true, but this just shows that actual results were surely good enough not to abandon theory
    b. Two step experiment -- first measure 1,3,5,... and with it what we call g/2, then predict and test times of fall from variety of heights -- also gives evidence that g reasonably uniform in vertical fall
    c. Nevertheless, his measured fall in the first second nearly 5 (if not 10) percent in error; so in fact the experiment was not so successful as it appeared to be at the time
    d. Precise measure in vertical fall difficult: a tenth of a second error in timing from a 145 ft height, perhaps from speed of sound delay, might account for this error, with any remaining from resistance effects; but why is the error uniform across all the results?
7. So, by 1650 the most that can be said is that the uniform (vertical) acceleration hypothesis had at least managed to survive some substantive empirical tests -- something no other theory had done