b. Indeed, notice Galileo's whole approach here: put forward a hypothesis, develop a mathematical theory yielding striking predictions that are amenable to quasi-qualitative tests!

c. But the experiments were almost certainly too difficult to set up in a way that would yield meaningful results at the time

G. Mersenne's Efforts and the Lacuna: 1633-1647

1. Mersenne, perhaps provoked by a remark in Galileo's *Dialogue*, sees a different way of bridging any lacuna in the evidence for claims about free-fall: measure the distance of fall in the first second -- in effect g/2 -- the constant of proportionality in $s \propto t^2$

   a. Galileo's remark: objects fall 4 cubits in first sec, which Mersenne knew to be way too small

   b. Galileo himself calls attention to a lacuna in the argument for the Postulate in the original edition of *Two New Sciences* [207]

   c. If stable value regardless of height, and if it yields reasonable results for total elapsed times, then direct evidence for claim that free fall uniformly accelerated

2. Fr. Marin Mersenne (1588-1648) a professor of natural philosophy at the University of Paris, a close friend of Gassendi and Descartes, and a long time correspondent and admirer of Galileo's

   a. Deeply committed to experimentation, and hence naturally tried to reproduce Galileo's experiments, as well as to conduct many further ones on his own, in the process discovering such things as the non-isochronism of circular pendula

   b. Relevant publications: *Les Méchanique de Galilée* (1634), *Harmonie Universelle* (1636), *Les nouevelles pensées de Galilée* (1639), *Cogitata Physico-Mathematica*, *Phenomena Ballistica* (1644), and *Reflexiones Physico-Mathematica* (1647)

   c. Huge intellectual correspondence: 17 volumes already published

3. Mersenne made the advance of using a 3 and 1/2 ft pendulum, with period near 1 sec (1 sec at 60 deg arc), to measure the distance objects would fall in varying times

   a. Experiment performed 50 times, yielding 3 (Paris) ft in 1/2 sec, 12 in 1 sec, 48 in 2 sec, 108 in 3 sec, 147 in 3.5 sec (*Harmonie Universelle*, p. 138)

   b. Note that listed values were perfect; actual values were 110 ft in 3 sec and 146.5 ft in 3.5 sec

   c. Still, would appear to be fairly compelling evidence for the 1,3,5,... progression in free fall

   d. A few years later (in 1640s) dropped objects from 300 ft dome of St. Peter's Basilica in Rome, finding times not 5 sec, as implied by above, but between 5 and 6 seconds

   e. Ultimately concluded that Galileo's principle of free fall is only a rough approximation, even in absence of air resistance

4. Moreover, his earlier positive result is not all that good in retrospect, for implied acceleration is way too small -- around 788 cm/sec/sec, versus correct value of 981

   a. Indeed, value closer to that for rolling spherical ball (701 cm/sec/sec) than for falling object

b. Raising the possibility that he first made a measurement on an inclined plane, then let that value "prejudice" his observations in the free-fall experiment

c. Other possible sources of error: objects too light to minimize resistance; timing inaccuracies

5. Mersenne knew something was going on, for the 3 ft pendulum he switched to later was descending from 90 deg in roughly 1/2 sec, the time his object was falling 3 ft

   a. I.e. constrained pendulum just as fast as free fall, something he knew was wrong -- a paradox

   b. Concludes that experiments are of limited value, for impossible to obtain precise measurements under controlled conditions -- this in spite of repeating the experiments many times

H. Riccioli's Efforts and the Lacuna: 1640-1651

1. Somewhat independently of Mersenne, Riccioli, a Jesuit Priest at Bologna, conducted his own very careful free-fall measurements during the 1640's in response to Galileo's claims

   a. Giovanni Battista Riccioli, S.J., (1598-1671), the last major scientific supporter of Ptolemy and opponent of Copernicus: *The New Almagest* (1651)

   b. {His system an amalgam of Ptolemy and Tycho: Jupiter and Saturn around the Earth, others around Sun -- claiming that evidence not yet sufficient to justify abandoning *Almagest*}

   c. Hence, generally not treated with the respect he deserves in the historical literature

2. Goes to great trouble during the early 1640s to try to construct a pendulum that would yield exactly 1 sec in astronomical (i.e. sidereal) time (see Appendix, and also Koyré)

   a. Repeated tries, with friends counting cycles and comparing to the number of sec from one noon to the next -- e.g. unwilling to accept 86,998 vs. 86,640 seconds (mean solar day, tied to 86,164 seconds of sidereal day)

   b. Finally accepts a pendulum with a carefully measured period of 59.6 thd, the results from which he can then ratio -- 0.63 percent discrepancy

   c. Uses this to define a 1 sec pendulum and then construct some very fast precise pendula -- e.g. 1/2 sec and 1/6 sec periods checked against his 1 sec pendulum

3. Next conducts free-fall experiments from various heights, using chalk covered spheres of the same size, but differing weights

   a. Finds heavier ball lands sooner -- e.g. lighter lags from 12 to 40 ft in fall of 312 ft -- but not proportional to weight

   b. Thus confirms Galileo's claim that Aristotle wrong and weight secondary, though notice that not so secondary as Galileo said (inches)

4. Then finally turns to question of 1,3,5,... progression, first measuring times from different heights of one building using suitably heavy spheres, and then verifying result by dropping balls from precalculated heights off different buildings and comparing times

   a. Announced values: 15 (Roman) ft in 1 sec, 60 ft in 2, 135 in 3, and 240 in 4 -- perfect agreement with 1,3,5,....; from mean speed theorem, v = 120 (Roman) ft/sec after 4 sec

b. Obviously, we have to conclude that the results were adjusted to meet expectations; but even so, Galileo's theory at least survived the test: not incompatible with the results

5. So, with Riccioli have evidence for 1,3,5,... progression in free-fall comparable to Galileo's evidence for inclined plane, and evidential lacuna somewhat filled
   a. How good was Riccioli's value for fall in the first sec, 15 (Roman) ft?
   b. If the Roman foot is taken to be 29.57 cm (Koyré, Klein), then Riccioli's implied value for the acceleration of gravity amounts 887 cm/sec/sec, wrong by around 9.5 percent
   c. If instead (as Steven Weinberg proposed to me) his Roman foot is taken to correspond to his claim that the Tower of Asinelli is 312 Roman feet high -- now said to be 97.20 meters high -- it is 935 cm/sec/sec, wrong by a less than 5 percent; this seems far more plausible, given that a uniform error across all the distances must be an error in the distance measure
   d. Either way, it is close enough to reveal a clear difference between rolling and falling if any-one had done the experiment, for the value for rolling would have been less than 12 (Roman) ft whichever the measure, a clear discrepancy from the value expected from Riccioli's value
   e. Interesting question, given their concerns about the accuracy of their experiments, whether they would have taken the result seriously if they had done the experiment, or whether they would have instead attributed it to some sort of experimental vagary along the lines Mersenne did when confronted by a paradoxical result
6. At any rate by 1651 have not only some empirical evidence for Galileo's law of free-fall, but were also at least in a position to run an experiment showing the need to distinguish rolling from falling
   a. Through substantially improved means of measuring time
   b. Through measurement of a then comparatively easy and stable value to obtain, the distance traversed in the first second
   c. And through quite elaborate experimental programs in Riccioli's case, over a 10 year period

I. The Evidential Difficulties as of 1651: A Recap
   1. Because the experimental evidence for Galileo's "law" of free fall will be important later, let me summarize the difficulties in adducing evidence for it as of the early 1650s
   2. The "law" makes a claim about what happens in the absence of resistance, yet no resistance-free experiments could be carried out at the time
      a. The most that could be done was to take measures that seem to minimize the effects of resistance
      b. But then no experiment could be expected to yield precise agreement, and discrepancies were open to differing interpretations
   3. The best hope for carrying out precise, repeatable tests, the inclined plane, had the lacuna of assuming that inclined plane motion amounts to the same thing as vertical fall