a. The physics in Kepler was immature science, but the efforts on trajectories were far from it; indeed, even Ptolemy was well past the point of immaturity at which Galileo was starting

b. So, here able to see more clearly the process of getting a science off the ground, of the struggle to turn observations into evidence

6. Yet notice that Kepler's orbital astronomy and Galileo's mathematical theory of motion were endeavoring to achieve formally the same sort of thing -- a mathematical specification of motions, trajectories and locations along them versus time

a. I.e. a mathematical specification of position in space and speed versus time

b. {Though Galileo imitating in style of presentation not mathematical astronomy, but Archimedes (d. 212 B.C.), whose works (re-published in 1543) he had studied under Ricci at Pisa

c. Galileo's "paradigm" not just Archimedes legendary *On Floating Bodies*, but also works in "mechanics" as *On the Equilibrium of Planes*, which announces the principle of the lever}

7. And also the same thing evidentially, namely to establish some (presumably lawlike) generalizations concerning certain sorts of motions

a. Kepler through numerical agreement within observational accuracy-- or, with Horrocks, through progressively closer agreement -- along with plausible underlying physics

b. Our question now: how was Galileo's approach different from that?

B. The Fundamental Empirical Problems Contrasted

1. Although the formal goals were the same, Galileo faced profoundly different evidential problems in trying to formulate an empirical theory of motion

a. I.e. problems of bringing observations to bear in order to answer questions

b. Will spell these problems out and examine Galileo's general approach to them before turning to his substantive theory

2. The fundamental difference: no problem in orbital astronomy observing position versus time -- e.g. geocentric longitude and latitude versus time

a. Relevant unit of time so long -- e.g. a day, or even 0.001 days (more than 86 sec) -- that no problem making observations

b. Basic evidential problem was need to infer the missing dimension -- e.g. geocentric distance r -- and also to find preferred reference point for motion (relative to fixed stars) -- e.g. Sun -- in order to distinguish apparent motions from ones observable from fixed stars

3. By contrast, objects fall to Earth in too short a time for us simply to observe the sequence of locations versus time and thus to generate data akin to Tycho's

a. Questions of distance of object from us and preferred reference for motion no problem at all in local motion

b. But the relevant unit of time much too short to make useful naked eye observations, or even to recognize qualitatively any general pattern in distance versus time

c. Galileo needed Doc Edgerton's camera technology for his work on local motion (in contrast to e.g. a telescope)

d. Adding to this problem was that of determining velocities, especially when not uniform; observed planetary motions slow enough that could readily determine deg/day variations -- i.e. averaged angular motions across a few days -- as well as mean daily motion

4. So, from the outset the problem of theory construction and adducing supporting evidence was of an entirely different form

   a. In mathematical astronomy, had various observed locations versus time, and question was how well theory reproduced these observations; discrepancies could be used as a basis for further refinement

   b. In the case of local motion, had only some qualitative phenomena, comparable to Greek astronomy before 200 B.C., and nothing like a set of observations theory was to reproduce

5. Equally, however, those theorizing about local motion had one enormous advantage: they could intervene in the natural process in order to observe what happens under different circumstances

   a. Use Ian Hacking's word 'intervene' here, rather than 'experiment' because want to preserve latter for the special, narrower forms of intervention in which observation is yielding an answer to a specific question

   b. Astronomy was not just unable to conduct experiments, but was unable to intervene in the processes about which it was theorizing in any way at all

6. So, *Two New Sciences* our first encounter with anything remotely resembling experimental science, though Galileo was performing experiments from 1590's on

   a. In keeping with this, our central concern in this class will be with experimentation as a source of evidence -- experimentation as used by Galileo and some others

   b. For several reasons -- some of them novel with Galileo -- a far more complicated matter than is often thought

C. A Further Complication: Pertinent Variables

1. A further complication facing Galileo arose because he was trying to construct a mathematical account of local motion generally, and not just the motion of a handful -- e.g. 6 or 7 -- bodies

   a. A general account requires decisions about which variables are relevant -- i.e. make a difference -- like *eccentricity* and *longitude of aphelion* in astronomy

   b. Kepler did not have to give an account of the orbital elements a further new planet would have -- nor even of an account of such things as the different values of actual eccentricity -- in his account of the orbits

   c. Apollonius had identified key variables in terms of which to parameterize the non-uniform apparent motions, in the process reducing those motions to mathematically manageable uniform motions

   d. Much of *Two New Sciences* devoted to questions of how to "conceptualize" -- i.e. which distinctions to mark -- and parameterize motion near the surface of the Earth

2. Best known decision of this sort by Galileo is that weight of falling objects not a pertinent variable, in contrast to Aristotle's claim that speed is proportional to weight
   a. (And in contrast to Galileo's earlier view)
   b. Famous Galilean thought experiment to support his new claim, involving light and heavy objects falling together [107-109]
   c. Leaning Tower of Pisa experiment story probably a myth, for he never claims to have done it, though others may well have done it and he may well have done parallel experiments
   d. But does report what happens in such an experiment: heavy one lands first, but by small differences versus Aristotle's claim
3. Qualitative result of experiment thus licenses (1) the conclusion that Aristotle's claim is false! and (2) the conclusion that weight at most a minor or second-order variable
   a. Galileo initially contends that the statement that the heavy and light arrive at the same time describes the result to a very close approximation
   b. And that might license saying that they land at the same time, as a description of the phenomenon, even though the heavier always lands first
4. But Galileo does not stop there: the effect of weight is much greater in a medium in which resistance effects are large, like water, than in one where resistance effects are small, like air
   a. Argues that this trend a basis for concluding that no weight effect at all in absence of a resisting medium

      "Surely a gold ball at the end of a fall through a hundred braccia will not have outrun one of copper by four inches. This seen, I say, I came to the opinion that if one were to remove entirely the resistance of the medium, all materials would descend with equal speed." [116]

   b. Thus weight not only a minor or second-order variable, but more important it is associated with a second-order mechanism or process beyond that of fall itself, something induced by fall -- a profound distinction
5. Galileo clearly attempted to come up with an account of resistance, but ultimately concluded (Day Four) that too many variables were involved for it ever to be amenable to a scientific account
   a. Starts with an account in terms of buoyancy, but adds surface friction and velocity effects
   b. Concludes that velocity effects become strong enough at some point to result in terminal or maximum velocities [137]
   c. The question whether a science of resistance is possible at all will remain a concern right through to the end of the next semester
6. {Notice the transformation from Galileo's earlier view of motion
   a. Acceleration now natural and basic, while terminal speed from a second-order effect

b. Transformation from experiments in which recalcitrant results come to be viewed as fundamental

c. In other words, Galileo's own path to the theory in *Two New Sciences* largely hidden from view there, but does involve a substantial reconceptualization, a la Kuhn

d. Most important element of reconceptualization: motion in the absence of a resisting medium versus motion in its presence; further element: equal increments in time, not space}

D. Galileo's Approach: An "Idealized" Science

1. Galileo sees one notable weakness in the argument that weight is not a pertinent variable: effects of weight may be attributable to resistance over large distances, but what about over small ones

a. I.e. sees limitations of experiments used so far:

"The experiment made with two moveables, as different as possible in weight, made to fall from a height in order to observe whether they are of equal speed, labors under certain difficulties....In a small height it may be doubtful whether there is really no difference [in speeds], or whether there is a difference but it is unobservable." [128]

b. Note: same type of problem as with stellar parallax: distinguishing between no effect at all and an effect too small to measure adequately

c. Solution: devise an experiment which would reveal any such small differences through their cumulative effect

"...one might many times repeat descents from small heights, and accumulate many of those minimal differences of time that might intervene between the arrival of the heavy body at the terminus and that of the light one, so that added together in this way they would make up a time not only observable, but easily observable." [128]

2. Experiment uses two balls, one of cork and one of lead, at the end of 5 braccia pendulums

a. Resistance affects the height of the light pendulum more, but time of descent remains the same for both, for they stay perfectly in phase with one another (over 100 cycles) [p. 128]

b. Key point: lead and cork bobs pass equal arcs in equal times, and hence in equal speeds

c. Since period independent of initial height and of speed, have grounds for arguing that period, unlike velocity, not affected by resistance at all -- i.e. separate two mechanisms and then confirm that weight shows up only in the second one

3. {Claims made by Galileo about circular pendula in "The First Day" a peculiar mixture of right and wrong, with many of the wrong ones, including this one; Meresenne had denied the isochronism of circular pendulums in print in the mid-1630s, before *Two New Sciences* appeared

a. Small arc circular pendula are isochronous, and their periods are proportional to the square roots of their lengths, to high accuracy even with air resistance

b. But large arc circular pendula are decidedly not isochronous, as is evident in trivial experiments, insofar as, for small values of $k^2 = \sin^2(\theta_0/2)$

$$P = 2*pi*\sqrt{(\ell/g)}[1 + (1/2)\ k^2 + (1*3/2*4)\ k^4 + (1*3*5/2*4*6)\ k^6 + ...]$$