b. And in a letter of 1625 he indicates that Jupiter, Saturn, and Mars are subject to an inequality that will require centuries of observation before it will become amenable to analysis -- a point he alludes to in the Preface to the Tables (Wilson, ibid. p. 240) -- see XVIII, p. 237, (letter to Bernegger) and X, p. 44, ln 21-25, which cites observations by Regiomantanus and Walther

c. His view seems to be one of using the Tables to expose and then characterize these discrepancies in order to refine the theory to handle them, as he had begun to do with the moon; and he recognized that his values for the elements depended on Tycho's parallax corrections for the sun

d. Nevertheless, he had clearly become concerned that astronomy might not be "perfectible"

7. Note that Kepler raised the question, is planetary astronomy perfectible? -- i.e. can the (undisturbed) motion of the planets be predicted into the indefinite future to within observable accuracy?
   a. A question receiving its first reasonably conclusive answer only in the last decade of the twentieth century
   b. For Kepler, not a question about whether e.g. ellipse and area rule exact, but about whether any variation over time in the orbital elements can be specified in a way that makes physical sense
   c. If some alternative to Keplerian trajectories can do this better, then for Kepler it would have had claim to being superior to his
   d. The possibility that no account of the motion could do this he found threatening
8. In addition to such effects that Kepler found beyond his reach, the Tables have shortcomings in orbital elements that they need not have had (see table in Appendix)
   a. Primarily from Tycho's theory of the sun, which had a far too large correction for parallax, because of a far too large horizontal parallax of the Sun -- i.e. Tycho had the sun much too near the earth; this error affects everything else because observing from the earth
   b. This resulted in an excess eccentricity of the earth-sun orbit; this in turn contributed to Kepler's eccentricity for Mars being a little too small (0.09253 versus 0.09304, or 430 parts ingress vs. 433.8) and the aphelion being a little advanced (148° 59′ 54″ versus 148° 41′ 58″)
   c. Kepler reduces Tycho's 3′ to 1′ after concluding parallax of Mars is less than 1¼′, but still does not change earth-sun eccentricity
   d. Nevertheless, as Gauss was to remark in 1809, the problem for post-Keplerian astronomers "was no longer to deduce elements wholly unknown, but only slightly to correct those already known, and to define them within narrower limits." (Wilson, "Derivation", p. 25)

II. Some Philosophic Issues Concerning Kepler's "Laws"

A. Kepler's Substantive Legacy: the Generalizations

1. His most obvious legacy was a comparatively simple, yet extraordinarily accurate version of the Copernican system -- the sort of simplicity and accuracy that Copernicus had yearned for
   a. The Copernican system with Keplerian orbital motion

b. The system as we have known it almost ever since -- at least ever since Newton

2. Wilson says that progress in astronomy over the next century "depended in large measure on the adoption ... of six Keplerian innovations" (p. 161)

    a. The five from *Astronomia Nova* listed in the table

    b. Joined by the 3/2 power rule, relating the different orbits about a single central body

3. The area rule, the ellipse on an inclined plane, and the 3/2 power rule, together characterize what has since become known as “Keplerian motion” (with planar orbit through true sun implicit)

    a. Three (plus one) generalizations about the motions of six planets, extended (with qualifications) to include the moon and the Galilean satellites of Jupiter

    b. Those generalizations the part of the legacy that we will be focusing on for the rest of this class and in subsequent weeks

    c. Came to be called "laws," but only after 1687

4. Kepler also left a large body of mathematical procedures for working with Keplerian orbits that still remain the basis for many astronomical calculations

    a. Seven orbital elements: eccentricity, semi-major axis length, angular position of the line of apsides, angular position of the line of nodes, inclination, the location of the planet at some epochal reference time, and sidereal period or mean (daily) motion

    b. Given these, procedures allow determination of all other "positional" aspects of the Copernican (or, of course, the Tychonic) system

    c. (Subject to second-order effects, causing slow variations in these elements -- see current values from Danby, derived from gravitation theory, not purely from observation)

    d. (Kepler included allowance only for slow precession of equinoxes, aphelia, and line of nodes)

5. Finally, he left not just a large body of largely discarded conjectures about the physics underlying all of this, but also an indication of how the astronomical features listed above could serve as an initial evidential basis for delving into the physics

    a. Not just a legacy of insisting on physics as part of astronomy

    b. But an indication of how astronomical findings might begin yielding conclusions about celestial physics

B. Some Advances in Turning Data into Evidence

1. Even from our limited review of orbital astronomy so far, it should be clear what the basic problem is of turning data into evidence in any new area of scientific research

    a. Need theoretical apparatus to extract evidence from data

    b. In absence of well-substantiated theory, must use working hypotheses of some sort -- hypotheses that cannot really be separately tested because they are needed to draw conclusions from data in the first place

    c. Problem: how to avoid garden-paths ("castles in the sky") owing to "bad" working hypotheses

2. In the case of Ptolemy and Copernicus, we have seen some working hypotheses that paid off to an extent, but then became confining
   a. E.g. epicycles (more precisely, mean retrograde loops) yielded r/R, and hypothesis that five planets orbit the Sun yielded relative r's
   b. But troubles in using discrepancies or other data for refinements past a certain point
   c. Problems in the data themselves, and in determining their level of accuracy, an obstacle
3. One advance, from Tycho: having a body of data of a reasonably well-defined level of accuracy, already corrected for some systematic observational errors (though not independently corroborated)
   a. Could thus begin to separate discrepancies arising because of second-order effects or because of basic theory being wrong from observational errors -- always the key
   b. Extent and uniformity of precision of the body of data help in exposing bad data points and in estimating systematic corrections: play data off against one another, using minimal theory
   c. Thus, for example, Kepler came to realize that Tycho's correction for parallax was almost certainly too large -- i.e. Tycho had the Sun too close to the Earth
   d. Kepler called attention to this source of error, but postponed alterations until parallax better defined and his 0.018 eccentricity for earth could then come not from taking half of Tycho’s value, but more directly from observations
4. A second advance, from Kepler, in working with data: pursue converging evidence, or at least corroborative evidence
   a. E.g. triangulations in support of oval etc., corroboration of area rule using solar theory, etc.
   b. Use (tentative) theory wherever possible to obtain more than one inferential route from data to an evidential conclusion
   c. Also use (tentative) theory to determine when a discrepancy can be from very small errors in data versus when it is indicating an error -- sensitivity analysis
      (1) E.g. contrast between rejection of "vicarious" theory and willingness to proceed with bisected eccentricity
      (2) Assessment of latitude theory, and acceptance of discrepancies in table of 28 observations pending better data (i.e. with better corrections for atmospheric refraction)
   d. But, modulo this recognition of sensitivities, do not ignore discrepancies that may be informative
5. A third advance, from Kepler: in absence of physics, insist on regularities that promise to point to physics, thereby contrasting orbital theories that amount only to what we would call "curve-fits"
   a. E.g. regularities that can plausibly result from a single physical mechanism
   b. Superposed regularities from superposition of physical mechanisms
   c. This in contrast to conclusions that seem hopeless to explain physically
6. But even with these advances, still had serious problems in extracting evidence from Tycho's data
   a. Small residual discrepancies, such as in a^3/P^2 for Venus: what are they indicating?

b. Non-stable values of elements over time indicate either a "secular" or a long-term process: at best many years of data needed, and at worst astronomy ultimately not "perfectible" at all

c. And how to get evidence bearing on the question whether the theory is just describing the way things happen to be (by accident), or the way in which things in some sense have to be

C. Accidental Versus Nomological Generalizations: Projectability

1. Applying the term "laws" to Kepler's generalizations on planetary motion is more than a little anachronistic -- which is why I have been using shudder-quotes around the word throughout

   a. Kepler's three generalizations came to be known as his laws only following Newton's *Principia*, which offered justification for their having such a status

   b. Indeed, the term 'laws' was introduced into astronomy, so far as I can determine, only through the extension of the notion of laws of motion, as in Descartes

   c. First place Kepler's regularities called "laws" appears to be Leibniz's *Tentamen*, which offered a "Keplerian" alternative to Newton's *Principia*

2. Still, the important logical distinction concerning such generalizations -- the distinction that separates laws from other generalizations -- is ancient and universal

   a. Accidental generalizations -- e.g. 'all the coins in my pocket are silver' -- do not support counterfactual conditonals -- 'if that penny were in my pocket, it would be silver'

   b. Nomological (or lawlike, to use Nelson Goodman’s term) generalizations -- e.g. 'all mammals have lungs' -- do -- 'if sharks were mammals, they would have lungs'

3. A question about the range of counterfactuals supported still arises even with this distinction

   a. Just as with Ptolemaic theory for Venus through Saturn, Kepler’s planetary theory was taken to yield answers to comparative questions that required it to support counterfactuals like, “If the eccentricity of Jupiter were the same as that of Mars, then Jupiter’s retrograde loops would …”

   b. In both cases the theory connected the elements of the orbits to further observable features in ways that the evidence gave grounds for such comparative counterfactual claims

   c. But that still leaves open questions about whether the theory supports counterfactuals beyond those concerning the specific planets, like “If there were still another planet, it too would describe an ellipse, sweeping out equal areas in equal times with respect to Sun at its focus”

4. Rather than just ask whether the evidence justified taking Kepler’s generalizations as lawlike, better to ask about the range of counterfactual questions over which the evidence supported answers

   a. E.g. over the specific planets, versus over all (possible) bodies orbiting the Sun, versus all (possible) celestial bodies engaged in celestial motions

   b. I.e. over what range does the evidence support the *projection* of Kepler’s generalizations beyond the known planets (over the period of observations entering into the *Rudolphine Tables*)

   c. Goodman singled out the *projectability* of lawlike generalizations; all I am adding is an insistence on being attentive to the range of the projections beyond the given cases

5. Upshot, a special evidence problem: given a generalization that holds for certain things, determine whether it is properly construed as nomological, instead of as merely accidental, and then the range over which it should be taken to project beyond those certain things
    a. This the most serious evidence problem facing any scientist who happens upon a regularity -- wants empirical evidence that observed regularity not a mere artifact
    b. General issue: how to bring empirical evidence to bear to show that an observed regularity ought to be taken to be nomological and, if so, the range of its projectability

D. A Complication: Exact Versus Approximate "Laws"

1. Given an observed regularity, the question whether it should be taken to be nomological is confounded by a number of other questions, involving further logical distinctions
2. The most important of these is whether the regularity or generalization holds exactly or only approximately -- i.e to some appropriate standard of approximation
    a. Generalizations that hold only approximately are still of interest in science -- indeed, most "laws" of science are in this category -- for maybe the inexactitude is just from secondary effects of lesser interest
    b. E.g. Boyle's law: pressure ∗ volume = constant: does this hold exactly, or only to a very high approximation?
    c. Here too we need to distinguish between how the generalization is intended or taken, on the one hand, and how it ought to be
3. Thus a further evidence problem: given a generalization, determine whether it holds (or ought to be taken as holding) exactly or only approximately, including what I will below call essentially exactly
    a. This problem is confounded by the fact that measurements themselves are inherently inexact, not only because of observational errors, but also because of systematic errors (biases) intrinsic to the measurement process being employed that have nothing to do with the regularity itself
    b. Thus, for example, Tycho's incorrect value for the Sun-Earth distance introduced a systematic error in his parallax correction for the Sun and hence in the corrected observations Kepler used; this systematic error propagates throughout the *Rudolphine Tables*, producing subtle discrepancies of the order of a few minutes in calculated longitudes
    c. Often a major undertaking to parcel out variance in measurements to decide whether generalization should be taken to be exact, and if not, how inexact: 180 years required in the case of Boyle's law, more than 80 years in the case of Kepler's
4. Generalizations that hold only approximately admit of a further distinction between ones that hold in the mean and ones that do not
    a. Agreement in the mean versus skewed agreement: how are deviations from the generalization distributed with respect to it, via least square error, or in some other, systematically biased way

b. Agreement in the mean comparatively rare among the approximate laws of the physical sciences -- e.g. Boyle's law

5. One more distinction among generalizations that hold only approximately is between ones that are idealizations and ones that are not
   a. Idealization: a generalization that would hold exactly if certain (secondary) effects were not present ("essentially exact"), or that is in some other way idealized
   b. E.g. Boyle's law would hold exactly if molecules were point masses that did not exert forces on one another at a distance; and laws of linearized elasticity drop all higher order terms
   c. This distinction is orthogonal to the former one, yielding four (or six, if essentially exact is treated as separate) distinct categories: idealization in the mean, etc.
   d. Must also allow for idealizations of another sort: ones that serve only to simplify mathematics, like linear elasticity
6. Still a further evidence problem in the case of any generalization that holds only approximately: does it hold in the mean or not, and is it an idealization or not, and if so, what sort of idealization
   a. First part concerns the nature of the approximation, and therefore is closely related to the question of exact versus approximate (e.g variance from "hidden variables")
   b. But the second part raises important new evidential problems, for close examination of high quality data is not going to tell you much about whether an idealization

E. Further Complications: Range and Qualifications

1. Two further complications, over and above those above, arise, especially with nomological generalizations
   a. Both, because of imprecisions usually inherent in the statement of the generalization
   b. I.e. imprecision or vagueness in what the generalization is asserting
2. First, the range over which the generalization holds or is being taken to hold is not always clear -- universal, but over what class?
   a. E.g. 'all mammals have lungs' is presumably taken to hold over a natural kind, mammals, but which animals fall within this range is not immediately given, nor given a priori
   b. Similarly, Boyle's law is taken to hold (approximately) only over a range of pressure, and not at extreme high pressures
   c. And Boyle's law can be variously stated: pressure is proportional to 1/volume, to density, to mole density, reflecting the range of circumstances in which it is said to hold
3. Second, nomological generalizations almost invariably include a largely tacit "ceteris paribus" clause that, because it is tacit, is not always clear
   a. E.g. a mammal with surgically removed lungs is not taken to be a counterexample to 'all mammals have lungs'
   b. And Boyle's law has the explicit ceteris paribus condition, temperature remaining constant

4. Thus, given any observed regularity, still further evidence problems: to determine the range over which and the ceteris paribus conditions under which the generalization continues to hold
   a. Evidence problems here concern how the generalization ought to be stated -- in contrast to how it is intended
   b. Questions here obviously interrelated with questions about exactness and types of approximation, and hence so too are the evidence problems
   c. And questions here just another way of formulating those about range of projection raised in section before last, though here focused on proper way of formulating the generalization
5. Much of the history of science is concerned with developing empirical answers to questions about the range over which and the ceteris paribus conditions under which observed regularities hold
   a. I.e. to figuring out the precise, "correct"-- i.e. "preferred" -- statement of the generalizations
   b. A mark of the advanced sciences that they can bring empirical evidence to bear on these and the other questions concerning the status of generalizations

F. Questions to Ask About Kepler's Generalizations

1. In discussing Kepler's rules up to this point, have been primarily concerned with whether they ought to have been "accepted"; now see that a whole host of other questions need to be considered in tandem with this one
   a. Questions not only about how Kepler intended his generalizations
   b. But even more so, questions about how they ought to have been taken by him and by others in, say, 1630, at the time of his death, or the decades thereafter
2. Should the three (or if you prefer, the four or even five) generalizations at the heart of the Keplerian system be taken to be nomological, or mere observational artifacts
   a. E.g. artifacts from considering only the six planets -- a rather small data base, to say the least
   b. Or epochal artifacts -- generalizations that are holding to a reasonable approximation now, but will not hold in the future and perhaps did not hold in the past
   c. That the moon does not conform with Keplerian motion lends weight to these questions
3. Do the generalizations hold exactly, or at least essentially exactly, or only approximately, and if the latter, how do they hold -- i.e. in the mean or not, and as idealizations or not
   b. Kepler's suggestion: would be exact were it not for various secondary interactions among the planets
   c. Kepler says that the moon as well would conform were it not for its being physically governed by both the earth and the sun
4. Over what range of objects and values do the generalizations hold, and under what ceteris paribus conditions
   a. Do the generalizations extend to "secondary" planets like the moon and the satellites of Jupiter, not to mention comets, and do they continue to hold regardless of the range of, say, r?

b. Would a comet knocking a planet out of its orbit constitute a counterexample to them?

5. As we have already seen to some extent, Kepler was perfectly aware of questions like these (though not in our jargon for them) and he devoted a great deal of effort toward addressing them
   a. He, and others following him, wanted these questions to be resolved empirically, and not "philosophically" or through "final causes"
   b. And he, and those following him, became acutely aware of the methodological problems in bringing empirical evidence to bear on them
   c. How can such questions be addressed empirically? -- perhaps the most basic issue of this course

III. An Examination of the Evidence for Kepler's "Laws"

A. The Precise Statement of Kepler's Generalizations

1. Goal, then, is to assess the evidence bearing on Kepler's "laws" at the time of his death in the light of these distinctions and complications
   a. With particular emphasis on how he chose to attack the methodological problems arising with the further questions
   b. Best start with concerns about the precise statement of the three generalizations
2. Kepler took the generalizations to apply to the six planets, with some vagueness about their application to "secondary" planets
   a. He expressly remarks that the 3/2 power rule extends to the satellites (his word) of Jupiter, and he applies the other two generalizations to the moon to obtain first approximations
   b. But he is clearly aware that the moon violates his first two generalizations, and therefore knows some sort of qualification is needed in stating them for it
   c. Also, his physical account is geared fundamentally to the sun, so that not entirely clear whether appropriate to include, without further qualifications, bodies not orbiting the sun
3. Kepler does not as such address "ceteris paribus" conditions, but it is clear that he intends that the "laws" be taken to hold, at least to a very high level of approximation, so long as the planets remain undisturbed by physical processes not now at work!
   a. Whatever the physical processes now at work might be, so long as nothing extrinsic to them enters, then generalizations apply
   b. Generalizations viewed as sustained by distinct physical processes, not by the active hand of God, spirits, or minds of any sort!
4. In the *Epitome* he expressly views the first two generalizations as "real world" replacements for an ideal
   a. If the planets themselves were not magnetically sensitive and had started in the plane of the ecliptic, then perfect concentric, uniform circular motion in the plane of the ecliptic
   b. The first two generalizations thus capturing a "second-order" departure from this ideal
5. At the same time he intimates in both the *Epitome* and the *Rudolphine Tables* that the first two laws