Reading:

C&O: Ch. 2, [Skim p.34-53]
Croswell: Ch. 2

Homework due Thursday. Tips

#1. If you need to lookup a quantity, OK. List where you got it from
Challenge #2: Draw this scene 24 hours later.
The Moon had moved to the East 24 hours later.
Q: Was the Aldebaran in the same or different location 24 hours later
Sidereal & Solar Day

**Solar Day:** Average Time from sunrise to sunrise = 24 hours = 86,400s

**Sidereal Day:** Time from “star-rise” to “star-rise”. Rotation period of the Earth = 23 hours, 56 minutes, 4 sec.

**FIGURE 1.10** Earth must rotate nearly 361° per solar day and only 360° per sidereal day.
Celestial Coordinate Systems

We can specify where in the sky to find an object, without knowing its distance. Thus most **Celestial Coordinate Systems** use only two angular coordinates. They differ depending on the *axis* of the system.

- **Horizontal** (altitude, azimuth) = (A, h) [observer’s axis]
- **Equatorial** (right ascension, declination) = (α, δ) [Earth’s rotation axis]
- **Ecliptic** (longitude, latitude) = (λ, β) [Earth’s orbital axis]
- **Galactic** (longitude, latitude) = (l, b) [Galaxy’s rotation axis]

Coordinate systems also need a reference point, which is arbitrary.

Conventions include:
- Horizontal System: Due North = 0 degrees
- Equatorial & Ecliptic system: Vernal Equinox (or “First Point in Ares”) = 0 deg.
- Galactic System: Galactic center = 0 degrees.
Sun’s Apparent Annual “Motion”
The “Vernal Equinox” is also a point in space. It is the origin of the Equatorial & Ecliptic Coordinate systems. Its coordinates are: $\alpha=0$, $\delta=0$ (Eq.)
Tycho Brahe

- Tycho Brahe (1546-1601) was a Danish nobleman
- He made the most precise observations of the planets to date ...without using a telescope.
- He proposed a combined Helio and Geo-centric Theory.
- However he refused to share his precise data on planets positions with anyone until....
- he died.
After Tycho died, his assistant, Johannes Kepler, took his place.

Kepler tried to determine the planets’ orbital paths....

Starting with the orbit of the Earth

His first model for the planetary orbits (advanced earlier) involved geometric shapes
Early on, Kepler thought the orbits of the planets had the same proportions as the “5 Perfect Solids” of geometry.

(Astronomy was consider part of the field of geometry)

He worked on this idea for years, but realized it didn’t work...
Johannes Kepler

- However, Kepler did not give up.
- He tried to find a Copernican (i.e. circular) orbit for Mars which matched Tycho’s data.
- After years of laborious calculation, he found the best circular orbit, which matched Tycho’s data for 10 oppositions!!

- But...
- ...disagreed with two other data points by 8 arc minutes.
- This was unacceptable: Tycho’s errors were only 4 arc min.

For if I had thought I could ignore eight minutes of longitude..I would already have made enough of a correction. .. Now, because they could not have been ignored, these eight minutes alone will have led the way to the reformation of all of astronomy....

Johannes Kepler, Astronomia Nova

(“A New Astronomy, based on Causation, or A Physics of the Sky”)
Kepler deduced that Copernicus’ assumption of uniform circular motion must be wrong...

This led to the discovery of Kepler’s Laws of Planetary Motion

Kepler’s First Law:

1. The orbits of planets are **ellipses** with the Sun at one focus.

   An ellipse is defined as: all points, the sum of whose distances from **two focal points (foci)** is constant.
An ellipse has two “diameters”: Major axis & Minor axis
Ellipse Shapes

Circle
Spherical Coordinates:

- $r$: Planet’s Distance from Sun
- $\theta$: Planet’s angle

$F, F'$: Two foci of the ellipse

- $r'$: Planet’s Distance from $F'$

Semi-major axis $a$ and semi-minor axis $b$

Definition of an Ellipse:

$$r + r' = 2a$$

Eccentricity:

$$e = \frac{\text{dist. betw. foci}}{a}$$
Consider this point

\[ r = r' \]
\[ r + r' = 2r = 2a \]
So, \( r = a \)

Triangle: \( (ae)^2 + b^2 = r^2 \)

\( (ae)^2 + b^2 = a^2 \)
\( b^2 = a^2 (1 - e^2) \)

\( e^2 = 1 - (b/a)^2 \)

\[
 r = \frac{a (1 - e^2)}{1 + e \cos \theta} \quad (0 \leq e < 1).
\]

Try:
\( \theta = 0 \)
\( \theta = 90 \)
Table 4-1  Kepler’s Laws of Planetary Motion

I. The orbits of the planets are ellipses with the sun at one focus.
II. A line from a planet to the sun sweeps over equal areas in equal intervals of time.
Kepler’s 3rd Law: Harmonic Law

\[ P^2 = a^3 \]

- \( P \) = orbital period in years
- \( a \) = semi-major axis in A.U.
Kepler’s Laws

I. The orbits of the planets are ellipses with the sun at one focus.
II. A line from a planet to the sun sweeps over equal areas in equal intervals of time.
III. A planet’s orbital period squared is proportional to its average distance from the sun cubed:

\[ P_y^2 = a_{AU}^3 \]

Orbital periods are measured in years

Semi-major axes are measured in Astronomical Units (AU)

1 AU = (average) Earth-Sun distance (150,000,000 km)
Isaac Newton  
(1643 - 1727)

- Kepler’s laws explained **how** planets orbit.
- But a complete theory requires an explanation of **why**.

- Isaac Newton provided the answer 60 years later: **Gravity**.

- Starting with basic principles, Newton was able to prove Kepler’s Laws of Planetary Motion.
Newton’s Three Laws of Motion

- In his book *Principia* he found three basic principles for why and how things move.

1. Bodies in motion will *remain in motion*, (in a straight line) unless acted upon by an outside force.

2. If you apply a **Force**, an object with mass will **accelerate**.
   - $F_{\text{NET}} = m \ a$

3. “For every action, there is an equal and opposite reaction.”

- Since the Moon does not move in a straight line, there must be a force acting upon it. Newton proposed that **gravity** keeps the Moon in orbit.
Newton’s Orbital Cannon

- Newton imagined a powerful cannon on a very tall hill.
- If it is fired with more power, the shot will go farther.
- Since the Earth is curved, a very powerful shot could fly all the way around the Earth!

- This is what the Moon does!
Universal Law of Gravitation

\[ F = G \frac{Mm}{r^2}, \]

\[ G = 6.67 \times 10^{-11} \text{ N m}^2/\text{kg}^2 \]

Combining this Force with Newton’s 3 Laws of motion produces Kepler’s Laws of Planetary Motion.

The notion that the same force acting on an apple would cause planets to orbit was revolutionary.
Circular Motion

acceleration is directly toward the center of the circle!

\[ a_c = \frac{v^2}{r}. \]