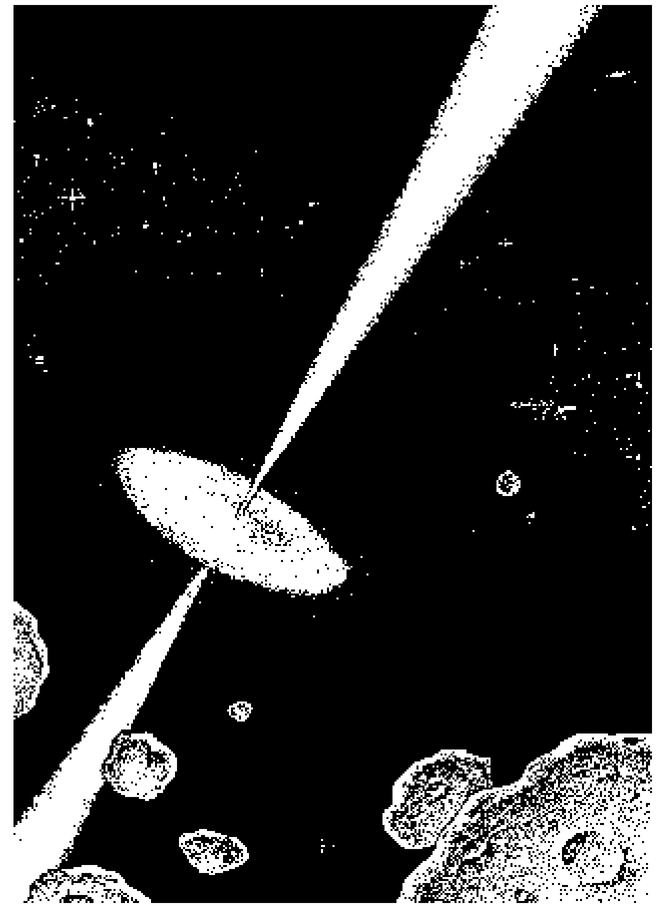
Astronomy 102: Black Holes, Time Warps, and the Large-Scale Structure of the Universe

What do black holes, wormholes, time warps, spacetime curvature, hyperspace and the Big Bang have in common?

- Explanations with their origins in Einstein's theories: the **special theory of relativity** (1905) and the **general theory of relativity** (1915).

This semester we will discuss all of these exotic phenomena, mostly qualititatively, in the context of Einstein's theories.

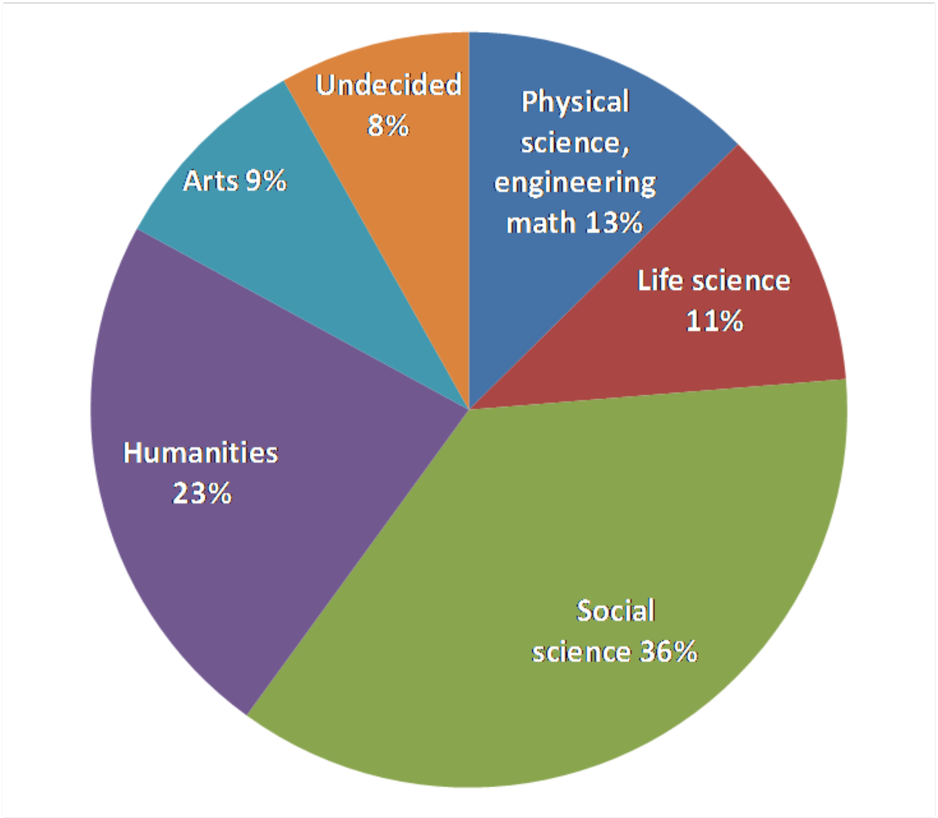


Artist's conception of the quasar 3C273, from Thorne, *Black holes and time warps*.

Our primary goals in teaching Astronomy 102

- to **demystify** black holes, the Big Bang, and relativity, so you can evaluate critically the things you find about them in the media;
- to show you how scientific theories are conceived and advanced in general.

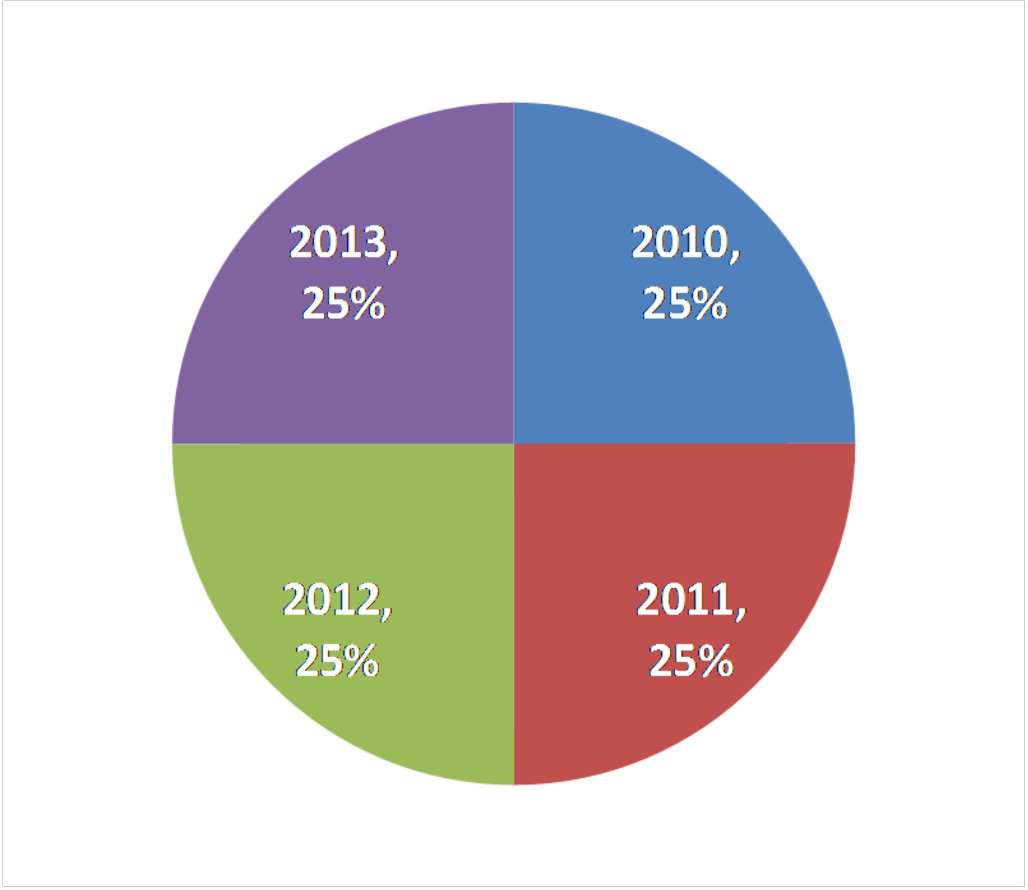
In doing so we aim primarily at **non-science majors.**



This semester's AST 102 class, plotted by concentration.

Our primary goals in teaching Astronomy 102 (continued)

We hope that by the end of the course you will understand and retain enough to be able to offer correct explanations of black holes and such to your friends and family, and that you will retain a permanent, basic understanding of how science works.

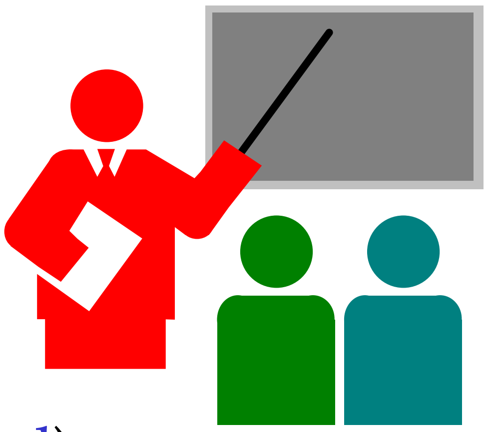


This semester's AST 102 class, plotted by cohort.

Human and printed features of Astronomy 102

People:

- **Dan Watson**, professor
- **Brian DeCesare**, teaching assistant
- **Jae Song**, teaching assistant

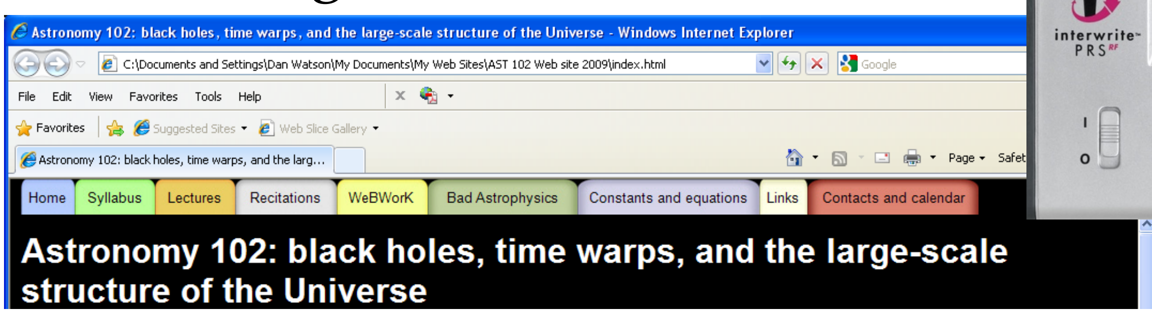


Textbooks (one required, three recommended):

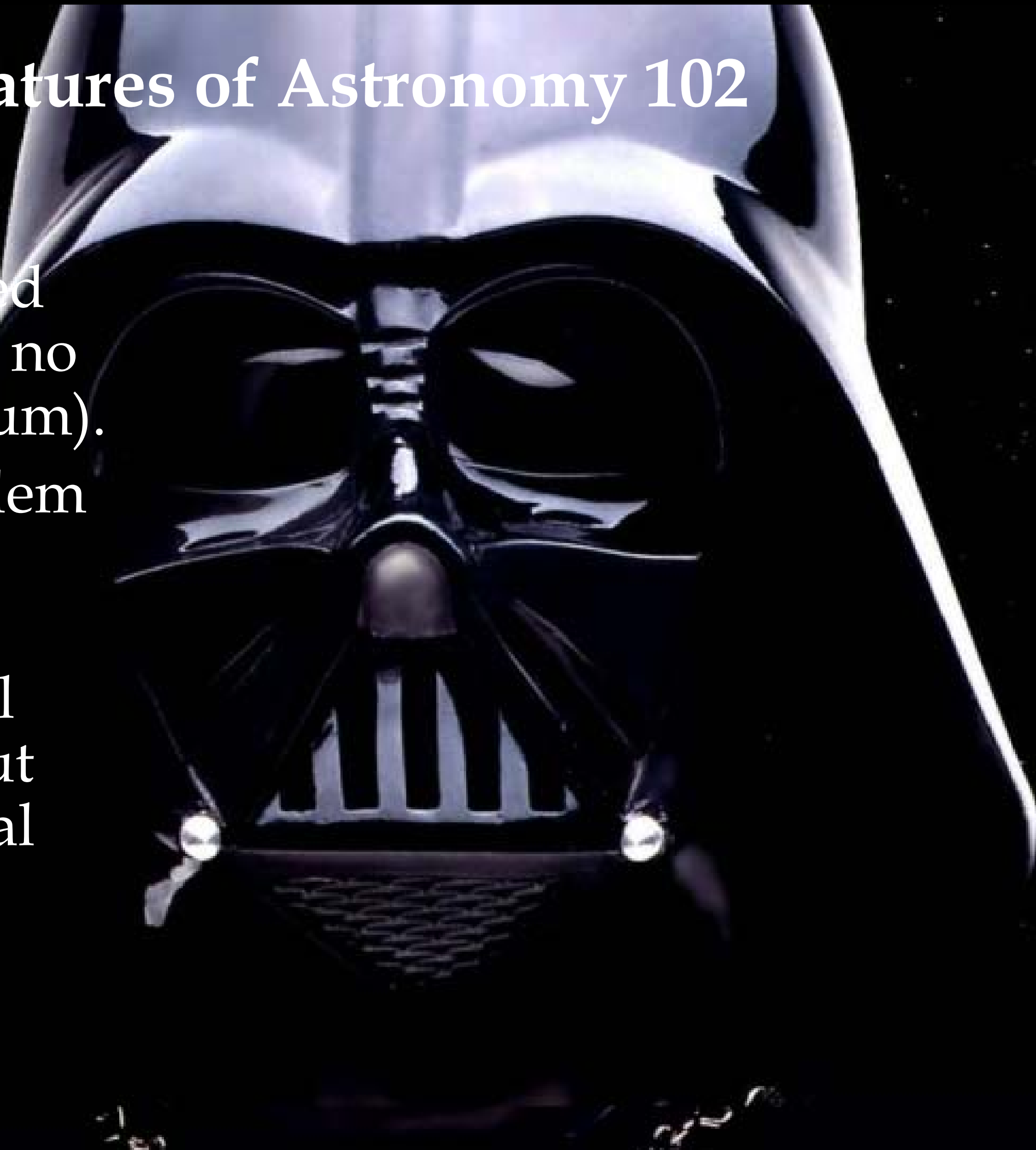
- Kip S. Thorne, *Black holes and time warps* (1994).
- Michael A. Seeds, *Foundations of astronomy* (2008). Also used in AST 104, 105, and 106.
- Stephen Hawking, *A brief history of time* (1988).
- Joseph Silk, *The Big Bang* (2005).

Electronic features of Astronomy 102

- ❑ **Computer-projected lectures**, for greater ease in presentation of diagrams, astronomical images and computer simulations, and for on-line accessibility on our…
- ❑ **Web site**, including all lecture presentations, schedule, practice exams, much more.
  - **Primary reference for course.**
- ❑ **Personal response system**, for in-lecture problem-solving. (**Required**; available at the UR Bookstore.)
- ❑ **WeBWorK** , a computer-assisted personalized homework and exam generator.



Onerous features of Astronomy 102

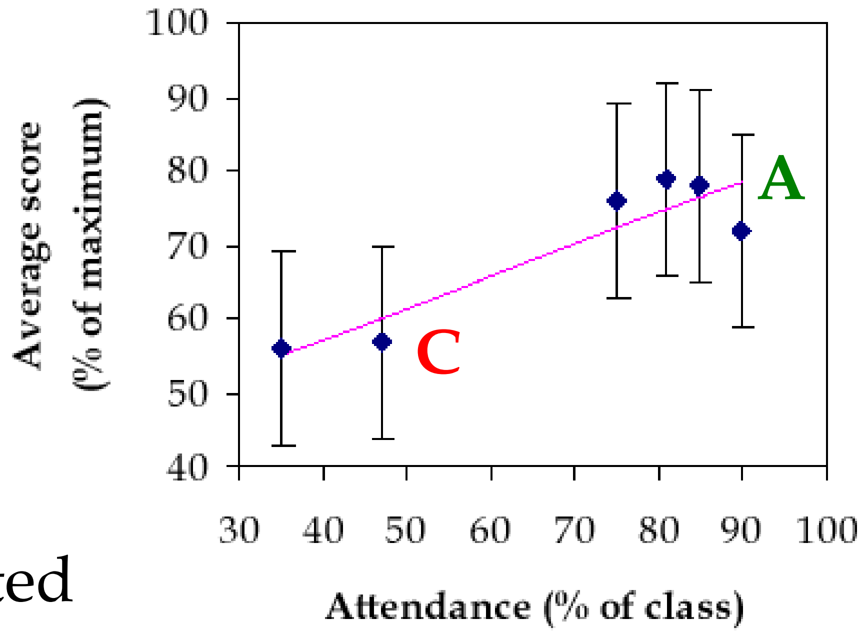


- The minimum of mathematics required to tell our story (but no less than the minimum).
- Six homework problem sets, all using WeBWorK.
- Three exams, also all using WeBWorK (but no *comprehensive* final exam).
- Grades (but on a straight scale, not a curve).

90% of success is showing up.

All members of the class are expected to attend all of the lectures, and encouraged to attend one recitation per week.

- This is for your own good. **You will very probably get a better grade if you go to class**, as is demonstrated by these average test score and average attendance data from past AST 102 classes.



- You may attend any recitation you like, whether you're registered for it or not.

Mid-Lecture Break

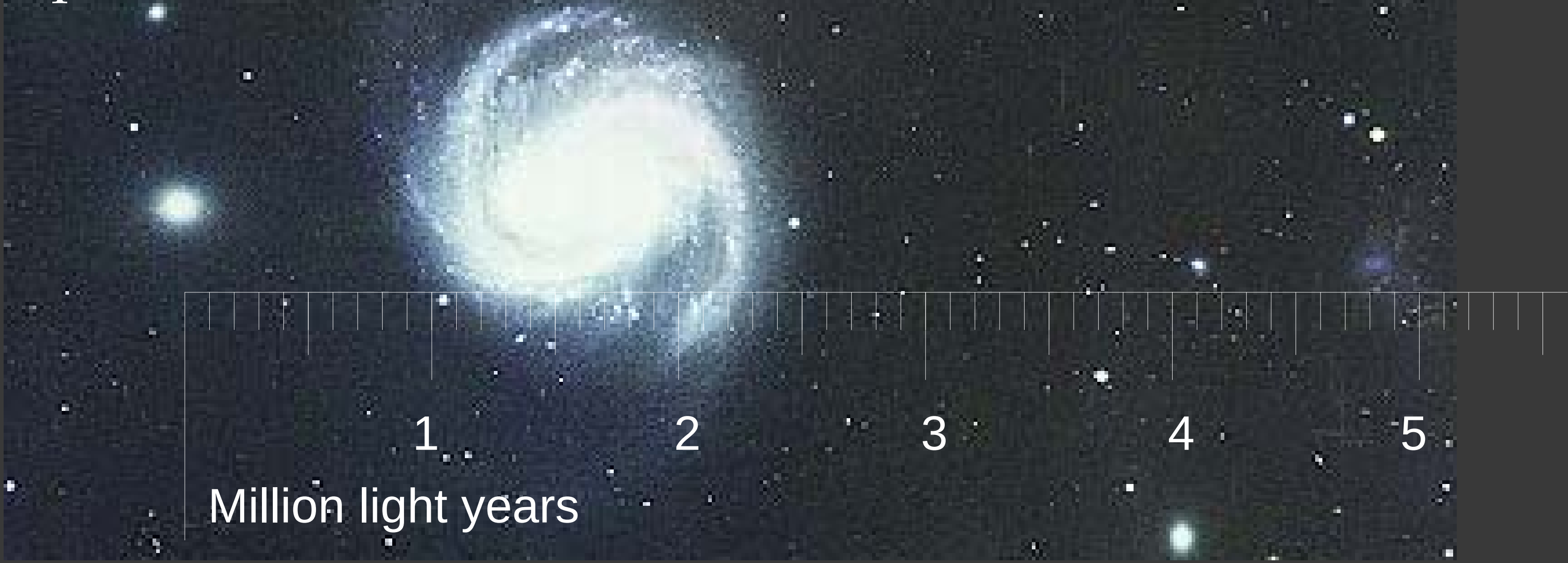
This will be a regular feature of Astronomy 102 lectures.

Image: wide-field view of the Orion Nebula, by David Malin (Anglo-Australian Observatory).

Today in Astronomy 102: How big is that?

Before discussing black holes, the Big Bang, and other celestial objects and phenomena, we need to become

- ❑ familiar with distances, time scales, masses, luminosities and speeds of astronomical importance, and
- ❑ proficient at **unit conversion**.



Sizes and distances in astronomy

	centimeters	kilometers	miles	light years
Diameter of a hydrogen atom	1.1×10^{-9}			
Diameter of a human hair	8.0×10^{-3}			
Diameter of a penny	1.9			
Diameter of Rochester	2.0×10^{6}	20	12	
Diameter of the Earth	1.3×10^{9}	1.3×10^{4}	7.9×10^{3}	
Diameter of the Moon	3.5×10^{8}	3.5×10^{3}	2.1×10^{3}	
Diameter of Jupiter	1.4×10^{10}	1.4×10^{5}	8.8×10^{4}	
Diameter of the Sun	1.4×10^{11}	1.4×10^{6}	8.6×10^{5}	
Diameter of the Milky Way galaxy	1.6×10^{23}			1.7×10^{5}
Distance to Buffalo	1.0×10^{7}	100	62	
Distance to the Moon	3.8×10^{10}	3.8×10^{5}	2.4×10^{5}	
Distance to the Sun	1.5×10^{13}	1.5×10^{8}	9.2×10^{7}	
Distance to the next nearest star, α Centauri	3.8×10^{18}			4
Distance to the center of the Milky Way	2.6×10^{22}			2.7×10^{4}
Distance to the nearest galaxy	1.6×10^{23}			1.7×10^{5}

Typical lengths and important conversions

- Diameter of normal stars: millions of *kilometers* (km)
- Distance between stars in a galaxy: a few *light-years* (ly)
- Diameter of normal galaxies: tens of *kilo-light-years* (kLy)
- Distances between galaxies: a *million light-years* (Mly)
- 1 ly = $9.46052961 \times 10^{17}$ cm = $9.46052961 \times 10^{12}$ km
- 1 km = 10^5 cm; 1 kly = 10^3 ly; 1 Mly = 10^3 kly = 10^6 ly.

Example: The Andromeda nebula (a galaxy a lot like our Milky Way) lies at a distance D = 2.5 Mly. How many centimeters is that?

$$D = 2.5\ \text{Mly} \times \frac{10^6\ \text{ly}}{1\ \text{Mly}} \times \frac{9.46 \times 10^{17}\ \text{cm}}{1\ \text{ly}} = 2.4 \times 10^{24}\ \text{cm}$$

More detail on numerical answers

Note that the last answer was written as 2.4×10^{24} cm.

- Not just 2.4×10^{24}. Numerical answers in the physical sciences and engineering are incomplete without units.
- And not 2.36513240×10^{24} cm, even though that's how your calculator would put it. Numerical answers should be rounded off: **display no more than one more significant figure than the least precise input number**.
  - If we had been told that the distance to the Andromeda galaxy is 2.5000000 Mly, then the conversion factor would have to have been put in with more significant figures, and the right answer would have been 2.36513240×10^{24} cm.

More detail on Unit Conversion

Previous example: repeated multiplication by 1. One may *always* multiply anything by 1 without changing its real value.

The unit conversions always give a couple of useful forms of 1. Take, for example, the conversion 1 ly = 9.46x10^{17} cm:

$$\frac{9.46\times10^{17}\ \text{cm}}{1\ \text{ly}} = 1 = \frac{1\ \text{ly}}{9.46\times10^{17}\ \text{cm}}$$

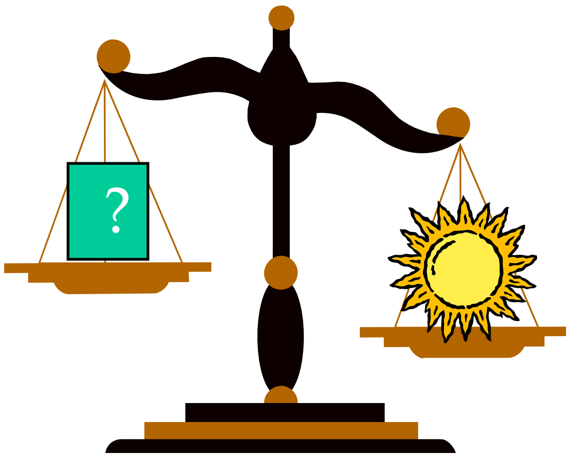
Choose forms of 1 that cancel out the units you want to get rid of, and that insert the units to which you wish to convert. This sometimes takes *repeated* multiplication by 1, as in the previous example:

$$D = 2.5\ \text{Mly}\times\frac{10^{6}\ \text{ly}}{1\ \text{Mly}}\times\frac{9.46\times10^{17}\ \text{cm}}{1\ \text{ly}} = 2.4\times10^{24}\ \text{cm}$$

There is nothing sacred about centimeters, grams and seconds.

Units are generally chosen to be **convenient amounts** of whatever is being measured. Examples:

- The **light-year (ly)** is far more convenient than the centimeter for expression of length in astronomy; on large scales we even use millions of ly (Mly).
- The convenient unit of **mass** in astronomy is the **solar mass:** the mass of the Sun.



Values of physical quantities are **ratios** to the values of the unit quantities.

Masses in astronomy

	Grams	Pounds	Solar masses ($M_\odot$)
Hydrogen atom	1.67×10^{-24}		
Penny (uncirculated)	3.2	0.0071	
Ton	1.02×10^{6}	2240	
Earth	6.0×10^{27}	1.3×10^{25}	3.0×10^{-6}
Moon	7.4×10^{25}		3.7×10^{-8}
Jupiter	1.9×10^{30}		1.0×10^{-3}
Sun	2.0×10^{33}		1
Milky Way galaxy	6×10^{45}		3×10^{12}

Typical masses and important conversions

- Smallest stars: 0.08 solar masses ($M_\odot$)
- Normal stars: around one $M_\odot$
- Giant stars: tens of $M_\odot$
- Normal galaxies: 10^{11} - 10^{12} $M_\odot$
- Clusters of galaxies: 10^{14} - 10^{15} $M_\odot$
- 1 $M_\odot$ = 2.0×10^{33} grams = solar mass = mass of the Sun
- 1 pound = 454 grams

Example: Vega, the brightest star in the Northern sky, has a mass of about 2.5 $M_\odot$. What is its mass in grams?

$$M = 2.5\ M_\odot \times \frac{2\times10^{33}\ \text{gm}}{1\ M_\odot} = 5.0\times10^{33}\ \text{gm}$$

How many Earths in the Sun?

That is, by what factor is the Sun more massive than the Earth?

Find the masses a couple of pages back, work it out and send the answer on your clicker.

Times and ages in astronomy

	seconds	hours	days	years
Earth's rotation period	8.64×10^{4}	24	1	
Moon's revolution period	2.3606×10^{6}	655.73	27.322	
Earth's revolution period	3.1558×10^{7}	8.7661×10^{3}	365.25	1
Century	3.16×10^{9}			100
Recorded human history	1.6×10^{11}			5000
Milky Way Galaxy's rotation period (at Sun's orbit)	7.5×10^{15}			2.4×10^{8}
Age of the Sun and Earth	1.44×10^{17}			4.56×10^{9}
Total lifetime of the Sun	4.7×10^{17}			1.5×10^{10}
Age of the Universe	4.4×10^{17}			1.4×10^{10}

Typical timespans and important conversions

- Planetary revolution period: around 1 year
- Life expectancy, normal stars: around 10^{10} years
- Life expectancy, giant stars: 10^6 - 10^8 years
- Rotation period of normal galaxies: 10^7 - 10^9 years
- 1 year = $3.16\text{x}10^7$ seconds
- 1 hour = 3600 seconds

Example: How many seconds is a normal human lifespan (US)?

$$t = 75 \text{ years} \times \frac{3.16 \times 10^7 \text{ seconds}}{1 \text{ year}} = 2.37 \times 10^9 \text{ seconds}$$

How many lifespans in the Solar system's age?

That is, by what factor is the age of the Sun and Earth longer than an average human lifespan?

Find the numbers in the last couple of pages, work it out, and send the answer using your clicker.

The fundamental dimensions

Distance, time and mass are fundamental dimensions.

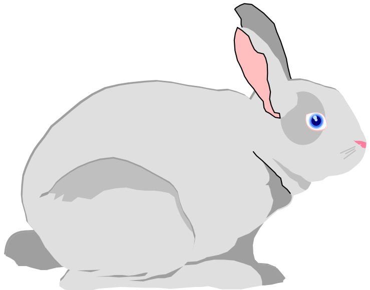
- Distances along each of the three different perpendicular directions of space determine the location of a given body with respect to others.
- Time determines the instant in the given body has that location.
- A given body's mass determines how strongly the force of **gravity** influences it.
- Each given body has an additional fundamental dimension like mass, corresponding to each of the forces of nature. Electric charge, for example, dictates how strongly the electrostatic force influences a given body.

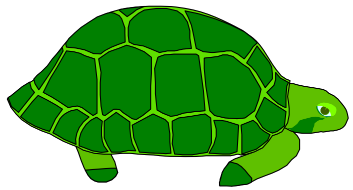
The fundamental dimensions (continued)

The dimensions of all other physical quantities are combinations of these fundamental dimensions.

- For instance: the dimension of **velocity**, and velocity's magnitude **speed**, is distance divided by time, as you know.
- The dimension of **energy** is mass times distance squared, divided by time squared.
  - i.e. mass times the square of the dimension of speed
- Units are the scales of the *quantities* that go with the *qualities* that are dimensions.

Thus: four fundamental dimensions for location (three space, one time), and in principle four for response to forces (gravity, electricity, and the strong and weak nuclear forces).





Speeds in astronomy

	cm per second	km per second	miles per hour
NYS Thruway speed limit	3.0×10^{3}	3.0×10^{-2}	65
Earth's rotational speed at the equator	4.7×10^{4}	0.47	1050
Speed of Earth in orbit	3×10^{6}	30	
Speed of Sun in orbit around center of Milky Way	2.5×10^{7}	250	
Speed of Milky Way with respect to local Universe	5.5×10^{7}	550	
Speed of light	2.9979×10^{10}	2.9979×10^{5}	

Typical speeds and important conversions

- Planetary orbits in a solar system: tens of km/s
- Stellar orbits in a normal galaxy: hundreds of km/s
- Speed between nearby galaxies: hundreds of km/s
- Speed of light: $2.99792458 \times 10^{10}$ cm per second
- Conversion factors: use those given for distance and time.

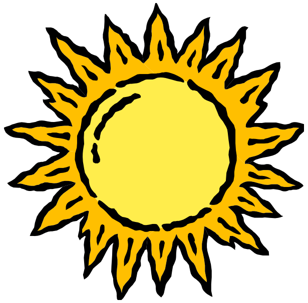
Example: One mile is equal to 1.61 kilometers. What is the speed of light in miles per hour?

$$c = 2.9979 \times 10^{10}\,\frac{\text{cm}}{\text{sec}} \times \frac{\text{km}}{10^5\ \text{cm}} \times \frac{\text{mile}}{1.61\ \text{km}} \times \frac{3600\ \text{sec}}{\text{hour}}$$

$$= 6.70 \times 10^8\,\frac{\text{mile}}{\text{hour}} \qquad \text{(670 \textit{million} miles per hour)}$$

Work, heat and energy in astronomy

Hydrogen atom binding energy	1.6×10^{-12} erg
Dietary calorie	4.2×10^{10} erg
Burn 1 kg anthracite coal	4.3×10^{14} erg
Detonate H bomb (1 megaton)	4.2×10^{19} erg
Earth-Sun binding energy	5.3×10^{40} erg
Sun's fuel supply at birth	2×10^{51} erg
Supernova (exploding star)	10^{53} erg



Units of energy

In AST 102 our usual unit of energy will be the **erg**:

$$1\ \text{erg} = \frac{1\ \text{gram} \times (1\ \text{cm})^2}{(1\ \text{second})^2} = \text{gm cm}^2\ \text{sec}^{-2}$$

which is the unit of energy in the CGS (centimeter-gram-second) system of units.

Possibly you are more familiar with the International System (SI, a.k.a. MKS for meter-kilogram-second) unit of energy, the **joule**:

$$1\ \text{joule} = \frac{1\ \text{kg} \times (1\ \text{m})^2}{(1\ \text{second})^2} = \text{kg m}^2\ \text{sec}^{-2} = 10^7\ \text{erg}$$

The others we have listed will find some uses too.

Luminosity (total power output) in astronomy

	ergs per second	watts (joules per second)	Solar luminosities $(L_\odot)$
100 W light bulb	1.0×10^{9}	100	
150 horsepower car engine	1.2×10^{12}	1.2×10^{5}	
Large city	10^{15}	10^{8}	
H bomb (1 megaton, 0.01 second)	4.2×10^{21}	4.2×10^{14}	1.1×10^{-12}
Sun	3.8×10^{33}	3.8×10^{26}	1
Largest stars	4×10^{38}	4×10^{31}	10^{5}
Milky Way galaxy	8×10^{43}		2×10^{10}
3C 273 (a typical quasar)	4×10^{45}		10^{12}

For the astronomical objects, the power is emitted mostly in the form of light; hence the name.

Typical luminosities and important conversions

- Normal stars: around one solar luminosity ($L_\odot$)
- Giant stars: thousands to hundreds of thousands of $L_\odot$
- Normal galaxies: 10^9 - 10^{10} $L_\odot$
- Quasars: 10^{12} - 10^{13} $L_\odot$
- 1 $L_\odot$ = 3.8×10^{33} erg/s = luminosity of the Sun
- 1 watt = 10^7 erg/s

Example: Vega, the brightest star in the Northern summer sky, has a luminosity of about 1.9×10^{35} erg/s. What's that in solar luminosities?

$$L = 1.9\times10^{35}\ \text{erg/s}\times\frac{1\ L_\odot}{3.8\times10^{33}\ \text{erg/s}} = 50\ L_\odot$$

Rates

Speed and luminosity are examples of rates.

- Speed v is the rate of change of position x with time t:

$$v = \frac{\Delta x}{\Delta t} \quad \Rightarrow \quad \Delta x = v\Delta t \text{ if } v \text{ is constant.}$$

↑ (Δx): position *interval* (distance)

↑ (Δt): time *interval*

- Luminosity L is the rate of change of energy E with time t:

$$L = \frac{\Delta E}{\Delta t} \quad \Rightarrow \quad \Delta E = L\Delta t \text{ if } L \text{ is constant.}$$

Speed as a rate

Example: The radius of the Earth's orbit around the Sun is $1.5\text{x}10^{13}$ cm. What is its orbital speed (assumed constant)?

$$v = \frac{\Delta x}{\Delta t} = \frac{2\pi r}{\Delta t} = \frac{2 \times 3.14159 \times \left(1.5 \times 10^{13}\ \text{cm}\right)}{1\ \text{year}} \times \left(\frac{1\ \text{year}}{3.16 \times 10^{7}\ \text{seconds}}\right)$$

$$= 3.0 \times 10^{6}\ \frac{\text{cm}}{\text{sec}} \times \left(\frac{\text{km}}{10^{5}\ \text{cm}} \times \frac{1\ \text{mile}}{1.61\ \text{km}} \times \frac{3600\ \text{sec}}{\text{hour}}\right) = 66{,}800\ \text{mph.}$$

Example: How long should it take to get to Buffalo from here, at the Thruway speed limit?

$$\Delta t = \frac{\Delta x}{v} = \frac{60\ \text{miles}}{65\ \dfrac{\text{miles}}{\text{hour}}} = 0.92\ \text{hour} \times \left(\frac{60\ \text{minutes}}{\text{hour}}\right) = 55\ \text{minutes.}$$

Now you try, with PRSs

There are eight furlongs in a mile, and two weeks in a fortnight. Suppose we take the furlong to be our unit of length, and a fortnight to be our unit of time.

Then, what are the units of speed?

A. Furlong fortnights

B. Fortnights per furlong

C. Furlongs per fortnight

D. Furlongs per second.

And again.

There are eight furlongs in a mile, and two weeks in a fortnight. Suppose we take the furlong to be our unit of length, and a fortnight to be our unit of time.

What is the NYS Thruway speed limit in this new system of units?

A. 1.5 furlongs per fortnight

B. 1.5×10^5 furlongs per fortnight

C. 8×10^{-4} furlong fortnights

D. 42 fortnights per furlong

Luminosity as a rate

Example: How long could the Sun live at its current luminosity, considering the fuel supply with which it was born?

$$\Delta t = \frac{\Delta E}{L} = \frac{2\times 10^{51}\ \text{erg}}{3.8\times 10^{33}\ \dfrac{\text{erg}}{\text{sec}}} = 5.3\times 10^{17}\ \text{sec}\times\left(\frac{\text{year}}{3.16\times 10^{7}\ \text{sec}}\right)$$

$$= 1.7\times 10^{10}\ \text{years}\quad \text{(17 billion years).}$$

It has already lived 4.56 billion years.

Example: What is *your* "luminosity" in erg/sec, if you eat 3000 calories a day and don't gain or lose weight?

$$L = \frac{\Delta E}{\Delta t} = \frac{3000\ \text{Cal}}{1\ \text{day}}\times\left(\frac{1\ \text{day}}{86400\ \text{sec}}\times\frac{4.2\times 10^{10}\ \text{erg}}{\text{Cal}}\right) = 1.5\times 10^{9}\ \frac{\text{erg}}{\text{sec}}.$$

Remember the How Big Is That sheet

Many important physical quantities that we will use frequently are collected on the The How Big Is That sheet, found under the “Constants and Equations” tab on the AST 102 Web site.

- You will always have access to this page while you’re doing homework or exams. Thus you don’t have to memorize all the numbers.
- However, to use the sheet effectively, and to understand our astronomical discussions, you must become familiar enough with them to know about how big most of them are.
  - It would do you good to memorize at least the “typical” values of things, on the previous pages.