The main sequence and the HR diagram

- color
- temperature
- brightness
- radius
Notice mass is not included on giant branches (density considerations)

Colors sometimes too faint for eye to discern. Divided by spectral class
An animated version

http://abyss.uoregon.edu/~js/ast122/lectures/lec15.html
Stellar evolution

- A medium mass protostar escapes becoming a long-lived red dwarf, or a dead brown one
  - Around same mass as Sun, or up to order of magnitude larger (numbers on the previous slide)
  - These are known as T Tauri protostars
- As a protostar becomes a star, entering the main sequence, the core heats up to millions of degrees (while the surface remains at a few thousand) and hydrogen is converted into helium
  - This is related to greater pressure with greater depth: think diving underwater. All about gravity, and fusion.
- Photons and neutrinos radiate away the energy from near center, latter quite easily
  - In external layers, convection takes over, like in your (classic) ovens: layers of gas turn over and mix, roiling
After $O(10)$ billion years (our Sun is thus about half-way spent) there is now lots of helium around.

Helium is heavier than hydrogen, and it is inert, so the core collapses under own mass.

Heat from collapse ignites leftover hydrogen, which becomes a rapidly expanding shell, bloating the star to $O(100)$ times its original radius.

Newly compressed core becomes hot enough to fuse helium to carbon ($3\rightarrow\alpha$ process) at $100+$ million degrees.

In few thousand years, this spreads into a helium flash.

- Before helium ignition and flash, all nuclear fusion ceases for $O(10)$ million years, so pressure eases up, and gravity leads to an extra squeeze at the center.
- Resulting heat reduces density of outer hydrogen dregs $\Rightarrow$ expansion.
- Hydrogen still converted into helium in outer shell. Surface cools, reddens.
1 million years to go: a carbon/oxygen core appears inside helium core that is even denser and hotter. Star re-stabilizes (but intense stellar winds are constantly tearing the cold, mostly inactive, hydrogen away from the outermost layers)

1 thousand years: neon/magnesium core (other elements persist as nested interior shells). In general, cycle is: fuel expended -> fusion pauses -> contraction occurs again -> at higher pressure and temperature and density, then new and different, higher-energy, reactions become possible that were not before. Progress gets faster & faster toward doom

~7 years: Oxygen/magnesium central nucleus. Starting to look like complex onion with concentric ‘skins’ of distinctive elements. Unique reactions happening across regions.

~1 year: Silicon/Sulfur. Temperature reaches the billions!!

~Days: Iron heart develops that is ~150% mass of our sun. End of the line because iron can not undergo nuclear fusion
~0.1 seconds to go: Fusion finally stops for good. The central sphere of elemental iron collapses in upon itself at \( \sim 0.25c \) (~50,000 mps). At 100+ BILLION degrees iron nuclei melt together (not technically fusion) and melt into fragments too.

**Maximum scrunch** occurs when the electromagnetic force, which is stronger than gravity, halts the contraction for good: the many, all positively-charged, protons floating around can’t stand closeness any longer. Collapse “springs” back. Neutrinos from iron nucleus overlap phase jiggling around.

Milliseconds into explosion: the iron recoil causes a massive shockwave to form. As it rips through the many skins of the star, it re-heats parts and generates nickel, and other, heavier elements, both radioactive and stable, sometimes even an entire periodic table worth. Explosion spreads them.

Seconds into explosion: Supernova neutrino burst takes away \( \sim 99.5\% \) of energy. Beats main shock wave, traveling at near-\( c \). Ironically, is the first sign of trouble externally. White dwarf, neutron star, or black hole is the result of the scrunch.
A diversity of fates

another branch: Red Dwarf

Life Cycle of a Star

By: Idrees Kahloon and Kevin Waterman

Stellar Nebula

After achieving equilibrium, the star begins burning up its supply of hydrogen and helium through nuclear fusion.

Massive Star

These fundamental stars produce heavy metals that help regulate the accretion rates of normal stars, their formation is still a great mystery.

Red Giant

Loss of fuel in the core results in expansion by up to 1000 times.

Planetary Nebula

The star has no energy left and begins losing layers and forms a complex structure.

Supernova

A stellar explosion that is triggered by the loss of any remaining fuel, enriches interstellar medium.

Supermassive

Gravity goes to infinity, as size -> 0

White Dwarf

Very dense star that is the end stage of average star life.

Neutron Star

Remnant of supernova that ejects particles.

Black Hole

Sources: http://www.cosmic.org/assets/images/starlife.jpg
http://en.wikipedia.org/wiki/Neutron_star
Midterm Essay Question (pick 1, 1 page)

- What are stars made out of, and how did we come about this information?
- We have recently observed new exoplanets: first form a hypothesis about their habitability, then explain how to test it.
- What are rogue planets and how did they form? Evaluate the different hypotheses of where they come from, and tie to the observations.
- Why are there no green stars, but only the other colors?
- Custom: pick a topic, on planets, asteroids, comets, or stars (units we’ve done)