36. Stellar Evolution
Main Sequence Evolution

As the hydrogen in the core is slowly used up, a star’s ‘thermostat’ gradually raises the core’s temperature.

With a higher temperature, more energy flows out, and luminosity increases.

For example, the Sun had only \(\sim 70\%\) of its present luminosity when it formed.
Broken Thermostat

A Main-Sequence Star...

H begins fusing to He in a *shell* around the contracting He core — but this can’t stop the contraction, so the core gets *hotter* and the star gets even more luminous.
After the Main Sequence

Once hydrogen starts burning in a shell, a star becomes larger, redder, and much more luminous — at least for a while...
Triple-Alpha Process

When the core temperature hits $10^8$ K, helium nuclei can overcome their repulsion and fuse to make carbon.

Compared to hydrogen fusion, this is not very efficient.
Helium ‘Burning’ Star

The central thermostat once again stabilizes the star’s energy production, and the total luminosity decreases.
Models predict that stars get smaller, bluer, and less luminous after He ignition.

HR diagrams of old star clusters reveal stars with the predicted properties.
High core temperatures enable helium to fuse with other nuclei, producing $^{16}\text{O}$, $^{20}\text{Ne}$, $^{24}\text{Mg}$, ...
Asymptotic Giant Branch

Double-shell Supergiant

After the helium in the core is gone, burning continues in two shells.

This situation is unstable. Thermal pulses eject mass (up to $10^4 \, M_\odot/\text{yr}$).
Fate of the Sun

A diagram illustrating the lifecycle of the Sun, including stages such as the main sequence, red giant, double shell-burning red giant, and planetary nebula. The diagram also shows the evolution of luminosity and surface temperature.
Evolution of High-Mass Star ($M \geq 8 \, M_{\odot}$)

Main-Sequence Star
- Core: $4H \rightarrow \text{He}$
- Photosphere

Red Supergiant
- Core: inert He
- Shell: $4H \rightarrow \text{He}$
- Photosphere

Helium-burning Star
- Shell: $4H \rightarrow \text{He}$
- Core: $3\text{He} \rightarrow \text{C}$

Initial evolution follows same sequence as a low-mass star.
After the helium in the core is gone, burning continues in two shells. Until the core contracts enough to ignite carbon.
Late Stages of Evolution

By the end of its life, a high-mass star has multiple shells of nuclear burning, making a wide range of elements.

<table>
<thead>
<tr>
<th>Reactants</th>
<th>Temperature</th>
<th>Products</th>
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</thead>
<tbody>
<tr>
<td>$^{12}\text{C} + ^{12}\text{C}$</td>
<td>$6 \times 10^8 \text{ K}$</td>
<td>$^{24}\text{Mg}, ^{23}\text{Mg} + \text{n}, ^{23}\text{Na} + \text{p}, ^{20}\text{Ne} + ^4\text{He}, ^{16}\text{O} + 2 ^4\text{He}$</td>
</tr>
<tr>
<td>$^{20}\text{Ne} + ^4\text{He}$</td>
<td>$1.2 \times 10^9 \text{ K}$</td>
<td>$^{24}\text{Mg}$</td>
</tr>
<tr>
<td>$^{16}\text{O} + ^{16}\text{O}$</td>
<td>$1.5 \times 10^9 \text{ K}$</td>
<td>$^{32}\text{S}, ^{31}\text{S} + \text{n}, ^{31}\text{P} + \text{p}, ^{28}\text{Si} + ^4\text{He}, ^{24}\text{Mg} + 2 ^4\text{He}$</td>
</tr>
<tr>
<td>$^{32}\text{S}, ^{28}\text{Si}, \text{He}$</td>
<td>$\sim 3 \times 10^9 \text{ K}$</td>
<td>$^{56}\text{Fe}, ^{56}\text{Co}, ^{56}\text{Ni}$</td>
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However, the iron-group elements represent the end of this process.