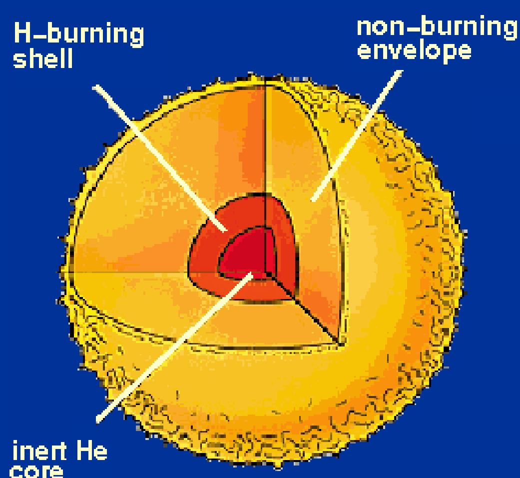
the evolution of high-mass stars

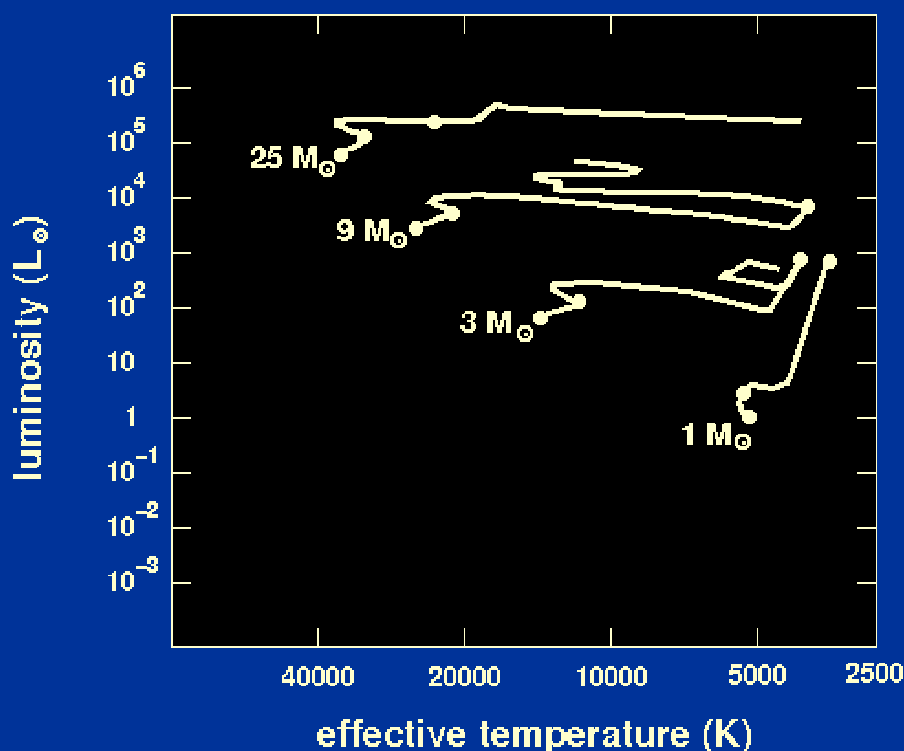
In stars with masses greater than about 1.1 $M_\odot$, the central temperature is high enough for the CNO cycle to become dominant. The strong temperature dependence of the CNO cycle means that the energy generation is much more concentrated at the centre of the star. The resulting steep temperature gradient is unstable to convection and hence such stars have convective cores. Convection has the effect of mixing the material in the core, bringing fresh hydrogen into the centre and spreading the newly-produced helium throughout the core. This keeps the chemical composition of the core uniform, which means that when the nuclear reactions have used up all of the hydrogen at the centre, there is no hydrogen left anywhere in the convectively mixed region and energy production ceases throughout the core. Just outside the core, hydrogen is still available for burning, but the temperature is too low for fusion to occur and hydrogen burning ceases altogether when the core burns out.

Figure 19: The structure of a high-mass star ($M > 1.1\ M_\odot$) on the sub-giant and red-giant branches of the HR diagram.



The abrupt cessation of hydrogen burning means that the star now has no nuclear energy source and it is forced into a slow overall contraction. Part of the gravitational potential energy released is used to balance the radiation from its surface, but about half of it goes into heating up the core as the central density and pressure are increased by the contraction. Eventually, the core is hot enough that hydrogen can start burning in a thin shell just outside the core boundary. The star is now similar in structure to a hydrogen-shell-burning star of lower mass, as shown in figure 19, but it has a much thinner shell (because the dependence of energy production on temperature is more severe). Overall contraction stops, and the energy from the contraction of the core is now fed into an expansion of the envelope, just as for lower-mass stars. The main difference in the evolutionary tracks of higher-mass stars in the HR diagram is that the phase of overall contraction causes a hook to the left before progress to the giant region is resumed once the shell has ignited, as shown in figure 20.

Figure 20: The evolution of high-mass stars depicted schematically on an HR diagram. The track for a solar mass star is also shown for comparison. The three dots on each track represent, from left to right, the main-sequence, the onset of core contraction following hydrogen exhaustion, and the beginning of helium burning, respectively.



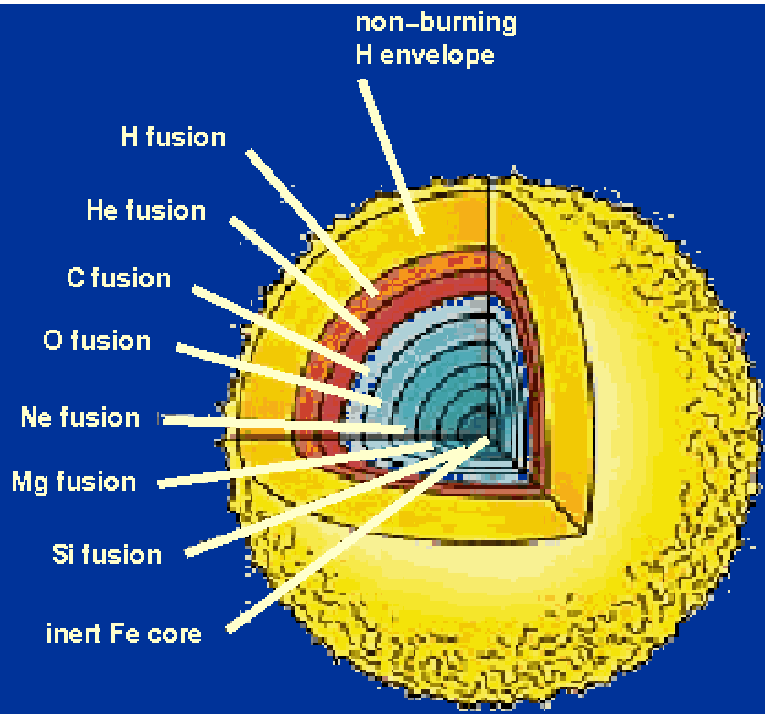
The exhausted core now consists of almost pure helium. Although there is no nuclear energy source, the centre of the star is initially hotter than the edge of the core and heat flows down this temperature gradient, cooling the centre and heating up the outside. This continues until the core becomes isothermal. The isothermal core grows slowly in mass as the shell gradually burns its way outwards into fresh fuel, leaving helium 'ash' behind. This continues until the core reaches the *Schönberg-Chandrasekhar limit* of about 10% of the mass of the star, at which point an isothermal core cannot support itself against gravity. This instability only occurs in stars with masses between about 2 $M_\odot$ and 6 $M_\odot$. For lower mass stars, the core becomes degenerate before the Schönberg-Chandrasekhar limit is reached; for higher mass stars, the central temperature becomes hot enough for helium fusion to occur before the Schönberg-Chandrasekhar limit is reached.

In stars in which the Schönberg-Chandrasekhar limit is reached, the core begins to contract rapidly. The energy released goes into a rapid expansion of the whole star, and hence a rapid transition to the giant branch. Because of this rapid transition, very few stars are observed during this phase, which accounts for the *Hertsprung gap* seen in HR diagrams of galactic clusters. As lower-mass stars become red giants less rapidly, this agrees with the absence of a Hertzsprung gap in the HR diagrams of globular clusters.

The collapse of the helium core, whether rapid or not, raises the central temperature to the point where helium ignites via the triple-alpha process. If the core is not degenerate (i.e. $M > 2\ M_\odot$), helium ignites gently and there is no helium flash. The effect of helium ignition, whether violent or quiet, is to move a star off the giant branch towards higher surface temperatures (i.e. to the left of the HR diagram). There are now two nuclear energy sources, helium-burning in the core and hydrogen-burning in a shell, and the evolution is much more complicated than in the core-hydrogen-burning phase.

Nuclear evolution beyond core helium-burning depends on whether or not the carbon-oxygen core ever becomes hot enough for further fusion reactions to occur and whether the core becomes degenerate. For stars with initial masses of $M > 8\ M_\odot$, the core is non-degenerate and carbon can ignite quietly, burning first to oxygen and neon. At lower initial masses, a *carbon flash* occurs, as the core is degenerate. Further reactions are possible and a series of burning episodes builds up successive shells of more and more processed material. Elements produced in these shells include magnesium, silicon and sulphur. For stellar masses greater than about 11 $M_\odot$, burning can proceed as far as iron and other elements of comparable nuclear mass, principally chromium, manganese, cobalt and nickel (the so-called *iron-peak* elements). At this point, because iron is the most stable element, with the highest binding energy per nucleon, to produce elements heavier than iron it is necessary to *add* energy. The star has thus exhausted all its possible nuclear fuels and it has an *onion skin* structure, with successive shells containing the ashes of the various burning stages, as shown in figure 21.

Figure 21: The onion-ring structure of a red supergiant (a pre-supernova star). Note that this diagram is not to scale - the outer hydrogen burning shell has a radius of order $10^{-2}\ R_\odot$, whereas the star has a radius of order $10^{3}\ R_\odot$.



The evolution of a massive star undergoing these different phases of core and shell burning beyond helium is very complex. As the core and shell energy sources vary in relative strength, the star makes a number of excursions to and fro across the HR diagram. In high-mass stars, these rightward (core exhaustion) and leftward (core ignition) excursions, between the red and blue (supergiant) branches respectively, occur with only a slight systematic increase in luminosity and hence the evolutionary tracks of high-mass stars occur virtually horizontally in the HR diagram. In very high-mass stars, the nuclear evolution in the central regions of the star occurs so quickly that the outer layers have no time to respond to the successive rounds of core exhaustion and core ignition, and there is only a relatively steady drift to the right on the HR diagram before the star arrives at the pre-supernova state, as shown in figure 20. It should be noted that the details of this stage of stellar evolution remain uncertain. In addition, the time taken to make these latter excursions in the HR diagram are very small compared to the duration of the earlier phases. So we do not expect to observe all the complications of an individual evolutionary track to show up in a star cluster HR diagram.

With no nuclear energy generation, the iron core becomes degenerate. As lighter elements continue to burn in shells above it, the iron core grows in mass until it exceeds the *Chandrasekhar limit* of around 1.4 $M_{\odot}$ - the maximum possible mass of a white dwarf, above which electron degeneracy pressure is insufficient to prevent gravitational collapse. The core then begins to collapse. The core's iron nuclei decompose into those of helium, which then fragment into protons and neutrons, and the protons then combine with the electrons to form more neutrons, all at the expense of the star's gravitational potential energy. In this way, the collapsed core becomes a *neutron star*, where it is the degeneracy pressure exerted by neutrons which prevents continued gravitational collapse. Meanwhile, the outer layers of the star are still collapsing: they hit the hard surface of the newly formed neutron star and bounce off, creating a shockwave which blows off the outer layers of the star in a *Type II* supernova explosion, as depicted in the animation of figure 22.

Figure 22: An animation showing the final stages of a Type II supernova explosion.

What remains after a Type II supernova explosion? The expelled envelope of the star becomes visible as a *supernova remnant*, as shown in figure 23, at the centre of which lies the core of the star. If the core of the star has a mass below approximately 3 $M_\odot$, it is a neutron star, those that exhibit pulsed radiation being known as *pulsars*.

Figure 23: The crab nebula - the remnant of a supernova which exploded about 900 years ago.

But if the mass of the core exceeds approximately 3 $M_\odot$, there is nothing to prevent the core from collapsing to a state of zero radius and infinite density (within the laws of physics as they are presently understood). Such an object is known as a *black hole*. Isolated black holes cannot be directly observed, as the escape velocity from the surface exceeds the speed of light. Evidence that they exist has been confirmed via observations of binary stars, where the motion of the visible star is measured in order to determine the mass of the compact object lying at the heart of the accretion disc in figure 24. If the mass of the compact object is measured to be $M > 3\ M_{\odot}$, the existence of a black hole is inferred.

Figure 24: An artists impression of an X-ray binary star, some of which are believed to harbour black holes.