Why do stars get into trouble which leads to catastrophies?

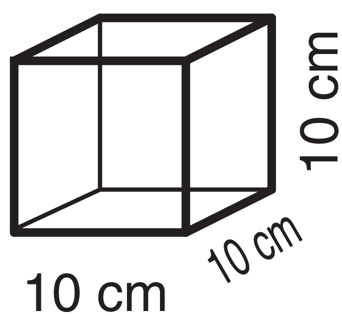
- Stars are large amounts of matter which originally collected out of a very large volume of space.
- Stars are held together by gravity.
- Stars lose energy into space.
- Stars make up the lost energy by internal sources:
  - Gravity
  - Nuclear
  - Thermal
- Pressure resists gravity.
- When nuclear energy runs out, pressure can no longer resist gravity for some stars.
- Rotation of matter around some central gravity point can modify the collapse.

The end point of star's lives is governed by the interplay between the above factors and can lead to catastropies of various type. For other stars, the end point is a quiet transition to a more or less inert configuration (white dwarf or neutron star). If more matter is added to one of these more or less inert stars, they become reactivated and may undergo a catastrophy.

How do stars hold together without collapsing?

- There are two parts to this question – holding together and not collapsing.
- At the simplest level:
  - holding together means gravitational attraction
  - not collapsing means pressure support.

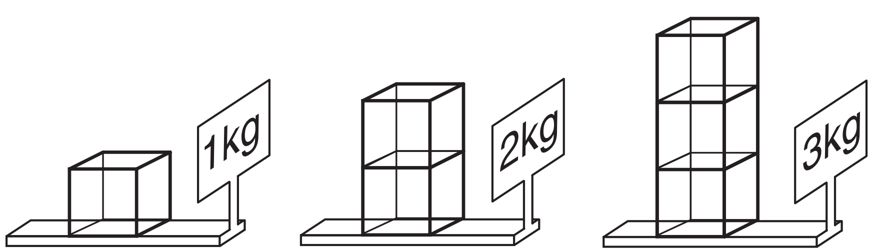
We can start by examining how pressure builds up:



This figure shows a cube of water which is 10 cm on a side. The volume of this cube is $10 \times 10 \times 10 = 1000\,\text{cm}^3$ or one liter. We know that the weight of this liter on earth is 1 kilogram because water has a density of 1 gram per cubic centimeter. The area supporting the base of the cube is 100 square centimeters. Two identical cubes can be placed next to each other and produce a weight which would register 2 kg and their bases would cover 200 cm^2. The pressure which is the force divided by the area remains constant since both doubled when we went from one cube to two.

If this water is unsupported on its sides the cube will spread out into a pool and no longer have the shape of a cube. We can prevent this by putting the water inside some sort of container or by freezing it to ice (neglect the fact that ice expands when it freezes).

Now suppose we stack cubes on top of each other. With two cubes we get a weight of 2 kg and with three we get a weight of 3 kg:



How does pressure build up as fluids deepen?

The stack of two or more cubes leaves the area at the base the same but increases the total force of the stack on the base. Consequently the pressure now increases as the height of the stack increases. When we go to construct the walls of the container, as long as we are using liquid water, we will find that it is harder to keep the walls from bursting and we will have to use a stronger plastic bag. If we put adjacent double of triple height stacks onto the scale, the weight or force will double or triple as before. We see that increasing the height of the stack increases the pressure but increasing the number of adjacent stacks does not.

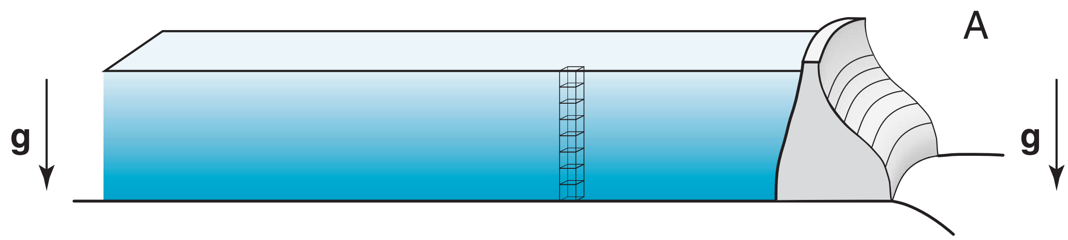
What is the difference between ice and water?

In a solid the atoms or molecules are bound by electrical forces between neighboring atoms or molecules to retain a fixed relative orientation. A large block of atoms or molecules must then retain its shape and cannot flow or deform. The interatomic or intermolecular forces then provide the support to prevent the spreading out of the block into a puddle. In a fluid the atoms or molecules have a fixed distance from one another but are not confined to have a fixed geometry. They are a bit like the beans in a beanbag — the volume of the bag stays the same but the shape can be anything. The change from ice to water takes energy and frees up the confined atoms. In a fluid the pressure is the same in all directions since the particles cannot exert any force to resist twisting or bending. Eventually even the solid becomes fluid as in the formation of a glacier. Under conditions of high pressure, it is generally true that the pressure is essentially the same in all directions.

Deep layers

How to use adjacent cube stacks

As we pile more cubes onto our scale, it becomes harder to find a way to hold the sides in due to the increasing pressure and consequent increasing force on the walls. One way to make the problem easier is to put the cube stacks next to each other so that the face on the left supports the face on the right and vice versa. Eventually we form a reservoir and can build a dam at the front to hold everything back:



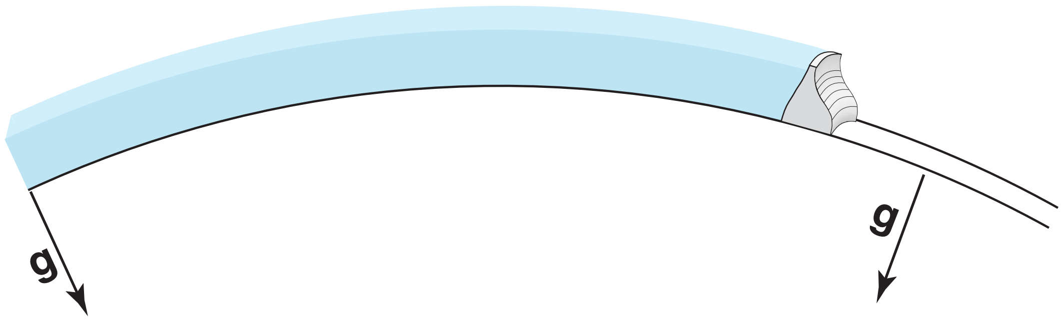
The cube stack in the middle of the reservoir is held on all sides by the adjacent cube stacks. The force on the bottom is the same as if the cube stack were isolated. Only the dam has to support the sideways pressure force due to the cube stack which has three sides supported by adjacent cube stacks but one face against the dam. Presumeably the back of the reservoir becomes shallow and one could cast a fishing line in to see what lurks below the surface.

Force and mass

We have been a bit imprecise in discussing the amount of mass which is given in kilograms or grams and the force the mass applies to the scale. The amount of mass is independent of where we put the cube as long as the density is kept fixed. The force comes from the Earth for conditions with which we are familiar. If we put the cube near a star, we would have to calculate the gravitational force the star creates from the distance to the star and the amount of matter contained in the star. The force also points from the center of the cube toward the center of the star.

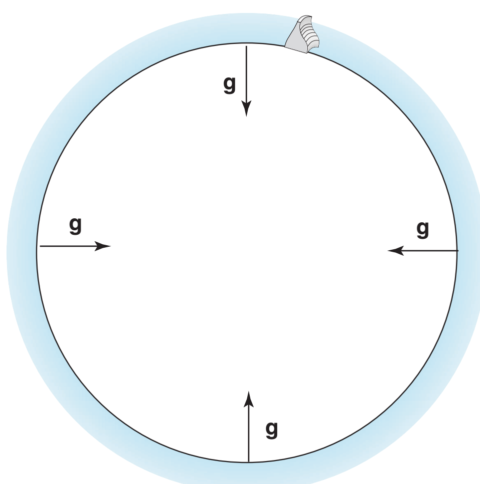
The Earth is not flat

The curved surface Returing to the reservoir, as we make it larger, we have to take into account the fact that the surface of the spherical Earth is curved:



The force of gravity always points toward the center of the Earth and if you travel over the surface on a boat, you find the direction changes so that the reservoir is not a rectangle but rather a piece out of a shell of a sphere.

Really deep reservoirs ⟶ **Waterworld** As we add cube stacks to the reservoir, eventually we will have a large enough body of water that we can cover the whole surface:



In the case where the whole surface is covered with the fluid, the dam is no longer needed. The back side of the reservoir will loop clear around the sphere and support the front side of the dam. If we pull this dam out of the configuration, nothing will happen except that the water will flow into the void left by the departed dam.

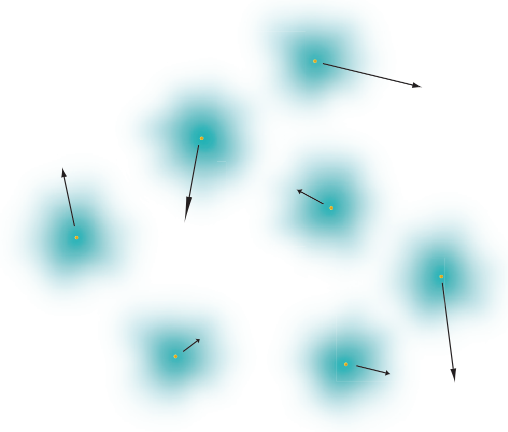
How does the matter resist compression?

The weight (gravity force) of the cube stack above the bottom cube must be resisted by this cube. The force on its top face is the same as the force on the bottom of the reservoir except for the weight of the bottom cube itself. The bottom of the reservoir pushes up on the lower face of the bottom cube while the stack above pushes down on the top face. Thus the bottom cube is caught in a vise grip which tends to make the cube collapse. It doesn't collapse because the fluid or gas inside the cube is required to provide a balancing pressure which resists each of these compressing forces. This is a requirement for stability and the fluid will adjust itself on a relatively rapid time scale until this condition is satisfied.

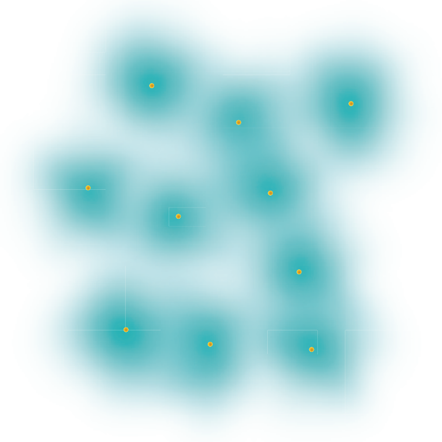
By applying statistical laws to the behavior of the atoms and their electrons, it is possible to calculate the pressure that any gas or fluid can provide as a function of the temperature and density of the material.

Most of the matter inside stars is gaseous. This means that each atom of the gas moves independently of all others except for brief periods when pairs of atoms come together in a collision. Usually at some inter atom distance, there is a strong force of repulsion which causes the atoms to bounce off each other and recoil in a new direction with a new velocity. When the atoms hit a wall such as the dam, they also bounce off in a new direction and exert a force on the wall as they reverse direction. This bouncing off walls is normally what we refer to as pressure. The pressure also applies to other parts of the gas since the atoms tend to reverse direction in each collision so that a force is exerted by one part of the gas on the adjacent parts of the gas.

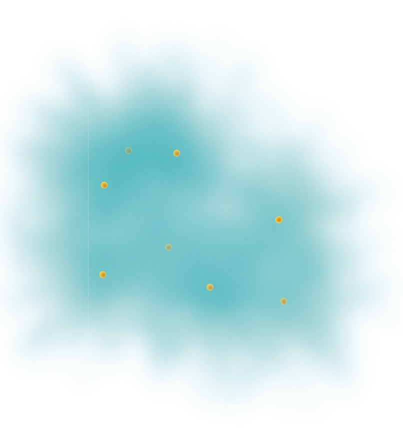
How do atoms (nuclei plus electrons) change when compressed?



Sketched are atoms each with its nucleus and surrounding cloud of electrons. They are all moving as indicated by the arrows.



These atoms are now so close that they begin to overlap. The overlap is not great enough to cause the electrons of the atoms to compete for the space available but the densities are altered by the overlap. The atoms can move as above although the arrows are not indicated.



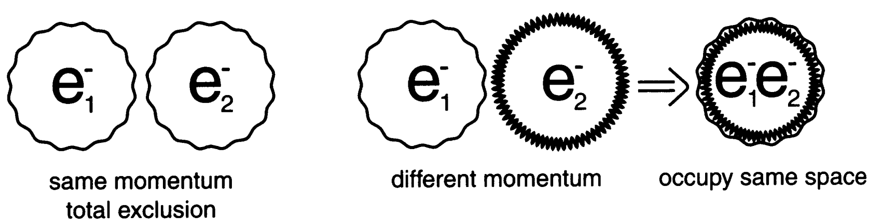
These atoms have more or less merged. The electrons are not really bound to an individual nucleus and can move from one nucleus to another. The overlap is so great here that the electrons compete for the space available and the electron energies are altered by the overlap. The nuclei can move in the same way as above while the electrons do not have as much freedom.

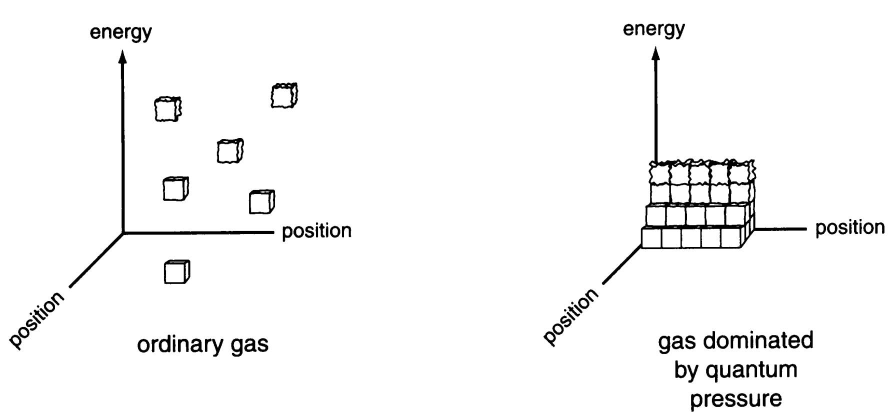
Quantum mechanics and the pressure due to electrons.

Quantum mechanics requires:

- The positions of all types of matter cannot be specified precisely. That is why on the previous slide, all electrons are represented as fuzzy clouds.
- The precision of position specification is inversely related to the energy of the particle and also inversely related to the energy of the particle.
- Electrons and other fundamental particles (neutron, proton, electron, positron, etc.) cannot be distinguished from each other as long as they are the same type of particle.
- No two identical particles can have the same position and energy.

The last point can visualized as follows:





Note that when otherwise identical electrons have different momenta they can occupy the same position it space.