4.2 A Powerful Threesome

4.2.1 Be Dense!

Most atoms, like most people, like to bond. The only party poopers among atoms are the **noble gases**. They will never ever associate with anybody else, not even their own kind, except when it is really, really cold.
Noble metals like Gold (Au) and Platinum (Pt) are a bit more social; at least they hang together with their own kind, forming solid gold and platinum. If needs be and you really force them, they also might get together with some of the lesser breeds like chlorine (Cl), but they don't like that very much. They like even less to associate with the proletarian oxygen (O). That's why they are typically found as **pure metal** and not as *oxides* like pretty much everybody else.
Gold, by the way, has not much practical uses. All it can do is to be decorative, just like certain heiresses, duchesses, princesses, models and so on.

- It appears that hanging out *only* with members of your own class, and looking down at the vast majority of other elements (antisocial behavior in other words), was conceived to be a "noble" thing when the "noble" elements got their group name.
  But let's not be too tough with our noble elements. Yes, they do loath association with the lower classes, just like human nobility—but they didn't rob and kill like real noblemen.

Most of our regular, hard-working metal atoms enjoy very much to consort with oxygen (O) atoms; take aluminum (Al), magnesium (Mg), titanium (Ti) and iron (Fe) as examples. When those metals bond with oxygen, lots of bonding energy is released. You have seen this. Whenever you watch fireworks, you watch magnesium (and other metals) being burnt (= combined with oxygen). The release of plenty of bonding energy provides the spectacular effects.

- Some other metals also like oxygen but aren't too hot about it. Examples are copper (Cu) and silver (Ag). What that means is that their union with oxygen is still favorable but does not release all that much energy. That's why you do find them as oxides (or other compounds) but also as pure metals.

Most atoms aren't fundamentalists. They do not insist that there is just one way to eternal bliss but keep their options open. If no sexy and very desirable oxygen atoms can be had as partners, they take whatever they can get. Sulfur (S) or phosphorus (P), for example. Or something a bit more complex like carbonates (C + O; e.g. $FeCO_3$), hydroxides (H + O; e.g. $Fe(OH)_2$) or silicate (Si + O; e.g. $FeSiO_3$).

- What's more, they are not even fixed on being heteros, on getting close *only* with partners of some other sex. You got to realize that hetero atoms have far more fun than humans. There are 90 different other sexes out there to play around with instead of just one for humans! And all of them also like their own kind as a partner just fine, even if most would prefer oxygen or sulfur. That's why pure metals can exist, too.

Since at this point we are not yet much interested in the various iron oxides (known as iron ores), hydroxides (known as rust), or the more perverse associations, we now look *exclusively* at the homo-erotic side of iron or all the metals. This makes life easier because we can deduce a few things.

- Consider yourself to be a lonely atom, ready to bond to something. You look around but all you find are other atoms of your own kind. In this case a general rule of thumb applies to many (but not all!) atoms, in particular a lot of metal atoms. This rule is simple:
  - You want as many partners as possible.
  - You want your partners as close as possible.

  I just ask you to believe me here. Those rules are reasonable anyway, and easy to substantiate with just a tiny bit of quantum theory. Even without quantum theory, you can see that the two rules result if an atoms attracts some other atom with a force that is the same in all directions. It will then attach other atoms as closely as possible. As long as there is still a free space in its surroundings, it can attract more atoms until it is completely surrounded by others and that implies close-packing as many partners as possible.
- If you consider an atom to be a little sphere, applying these rules will now tell you *why* and *how* they form a *crystal*. You even know *what* kind of crystal. **Think!**

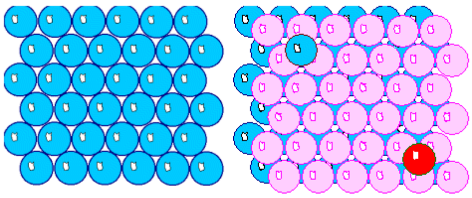
Those atoms are just doing what you would be doing when you stack a bunch of oranges (or canon balls).

- Here is the proof:

Stacking of canon balls

Source: Photographed somewhere in Copenhagen

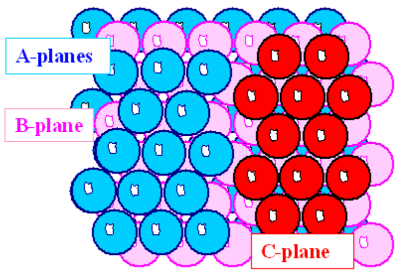
- When stacking oranges, without ever thinking about it, you sure like hell form a *close-packed* arrangement. In other words, you arrange spheres in such a way that each sphere has as many neighbors as possible as close as possible. You follow the rules from above.
  - So let's do it now - to the extent it can be done on a screen. Take a bunch of cannon balls, oranges, marbles, ping-pong balls, atoms, or whatever spherical objects with identical sizes you can find and, as a first step, arrange them as close as possible in a plane. In other words, generate a layer of spheres with the highest **packing density** possible.



Evolving the two types of close-packed crystals

Closest possible packing of (blue) spheres or atoms in one layer.	Adding a second layer (pink) and starting a third one (blue or red)

- How to arrange the first (blue) layer is absolutely clear. The same is true for the second (pink) layer) You just put a first (pink) sphere on the natural place - the indent - on top of the first layer and keep going.
  - The problem starts with the third layer - and you may not even notice it. What you and I would do is to put some sphere on the natural place - the indent - on top of the second, just as before. Then we go on and add the others laterally.
  - You will not encounter any problem doing that. However, you are now generating just *one* out of the *two* possible arrangements that are *completely different*, except for being close packed.
    Let's just look and see what happens if we continue stacking next to the blue and red balls in the right hand part of the figure above:



Two types of close packed crystals
The third layers with blue / red spheres do not match at the "seam".

- Both variants are fine. You are packing as closely as possible. But they are different. Very different, indeed.

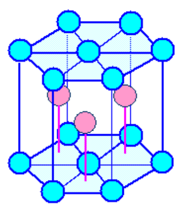
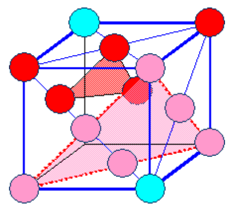
- I did not color the third layer blue and red because I was running out of colors. The blue layer is blue because those spheres sit exactly *on top* of the first blue layer which I now call an **A**-plane. The stacking sequence of layers, if we would go on with this, is ABABAB...
  The red spheres are red because the do *not* sit right on top of the A-plane spheres, and of course they cannot sit on top of the B-plane spheres either. They are thus something new: the C-plane. Only the 4th plane can be an A-plane once more so the stacking sequence is ABCABCABC...
- Both versions have exactly the same packing density but are otherwise quite different. And please note that in both cases you get a *crystal*, and orderly arrangement of spheres = atoms. There is just no way *not* to get a crystal following the rules. Here is the answer to one of our bigger why questions:

Why do many atoms form crystals? Because they want to be close packed!

- Why do they want to be close packed? See above.
- Both versions, we are sure, have the *highest* possible packing density. You can't get more balls into a given space than arranging them in one of the two ways.
  Think about that a bit. Is that really true? If you can *disprove* that statement by finding some arrangement with an even higher packing density, you would be an instant super star in the world of math and science. But don't try. Trust me. You cannot disprove this. Unfortunately you (and I) cannot prove it either (see below).

So stacking atoms in a neat ordered way on top of each other will unavoidably produce not only a crystal, it actually can produce *two* types of crystals - and thus gave a first answer to another big why question. "Is the *arrangement* of the atoms in a crystal the same for all metals?" No, it isn't!
The question we have now is: *what* kinds of crystals do we get by stacking in the two possible ways?

- While it is rather obvious how the blue - pink - blue ABABA... stacking sequence produces the *hexagonal* crystal *lattice* shown in the figure below, it's not so obvious what we get by stacking the blue - pink - red - blue ABCABC... sequence.

	
The two close-packed crystals Lattcie points = atoms here.	
ABABAB... sequence or **hexagonal close packed lattice**	ABCABC... sequence or **cubic close packed lattice**

It may take you a while to figure out that the ABCABC… stacking sequence generates a nice *cubic* kind of crystal as shown above. That's OK. It takes my student quite some time, too.

- Your two options are
  - Sit down and ponder this. Hint: the *planes* on which we stack the atoms in the blue - pink - red - blue - … or ABCABC... sequence are the pink diagonal planes bordered in red in the cube above.
  - Believe me.

We call the crystal units shown in the figure above the **elementary cell** or **unit cell** of the **crystal lattice** with the term "lattice" being self-explaining at this point, I hope.

- We have produced *two* different kinds of crystal lattices by just stacking atoms as tightly as possible. And, yes, to preempt your question: it matters *a lot* for the properties of a metal if it crystallizes in one way or the other.
  I hope you noticed that I have started to answer those questions that came up not long ago?

Thinking hard (very hard) about ways to stack atoms (no longer as close as possible), we will find several more lattice types. There are 14 altogether, and it is good practice to give those lattices a name.

- The ones in the figure above we call "**hexagonal close packed**", and "**face centered cubic**".
  The distance between the *lattice points* we call **lattice constant(s)**; 0.3 nm is a typical number for that. One number will do for a cube; two are needed for a hexagonal lattice.

- The terms "*cubic*", "*close-packed*", and "*hexagonal*" are self-explaining, and so is "*face-centered*" as soon as you realize that in that lattice we have an atom each at the corners of the cube *and* one atom in the *center* of every *face* of the cube.
  Scientists like to abbreviate things and henceforth these two types of lattices will be addressed as "***hcp***" for "*hexagonal close packed*" and "***fcc***" for "*face centered cubic*".
- By the way, any atom in both lattices has exactly 12 close neighbors if you start to count. Again, you either believe me or count yourself. More close neighbors you cannot have if you and your neighbors are perfect spheres.

By the way once more, our little exercise did not only produce a lot of new words and abbreviations, it also provided an interesting (or boring, as the case may be) little conundrum and an acute embarrassment to mathematicians.

- Let's say you are the doubting type and ask: are there, maybe, even better ways to pack spheres as closely as possible than the two ones we came up with, just by fooling around with circles on paper? You're not the first to ask this (obvious) question.

The question of how to pack as many spheres as possible (with identical diameters) in as little space as possible is quite old. If you have to pack canon balls into cramped ships, you actually like to know the answer.

- **Johannes Kepler** (1571 - 1630), of "earth around the sun" fame, gave the first decisive answer. *Kepler theorem*: you do it as shown above, there is no better way. Nobody since has come up with a better arrangement, so reasonable and practical people tend to believe that Kepler's theorem is true.
- There are, however, people who are not reasonable and practical; they are called **mathematicians**. This people want a cold, hard, logical and thus mathematical *prove* that there is no better arrangement.
  Kepler could not rigidly prove his theorem. The mathematicians weren't surprised. They thought of him as a physicist from which you couldn't expect even the simplest math, and set out to prove Kepler's theorem themselves. Piece of cake, it seemed—but they couldn't do it for more than 400 years. Kepler's theorem, the truth of which is obvious, proved to be a really tough nut to crack.
  In 1998 **Thomas Hales** announced that he has proved Kepler's theorem, but the mathematical community at large is still checking if he is really right.
  This is perhaps a bit embarrassing for the mathematicians but we, being reasonable and practical people, know for sure that there is no better arrangement. We are thus not surprised that the two kinds of close-packed crystals as shown above - fcc and hcp - are the preferred crystal lattices for roughly *two thirds* of our common metals.

Now you know *how* a lot of metals condense into a crystal. How about the remaining third?

- The rest, including *iron*, turns out to be a bit touchier about the number of close neighbors they like to have. They feel that having 12 close neighbors like the fcc and hcp metals is a bit vulgar. They prefer to be a bit less crowded and go with just 8 next neighbors.