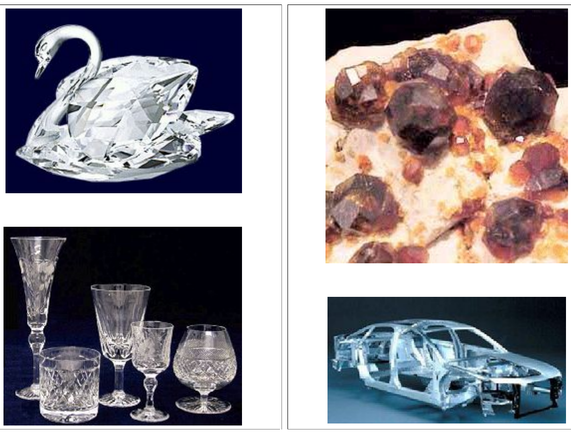
4.1.2 Metals are Crystals

What are Crystals?

- Now we have the first key to some of our "why" questions. Many of the properties of metals come straight from the fact that *all metals are* ***crystals***.
    - In particular, ductility, i.e. the ability to deform *plastically*, is tied to metals being crystals. The big question then is:

What, exactly, is a crystal?

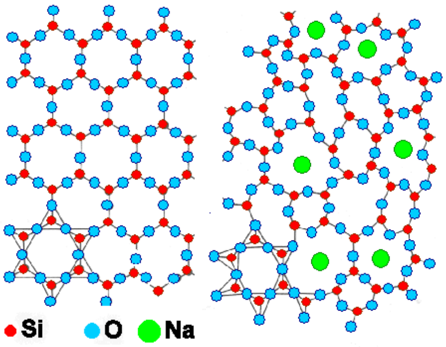
- The first thing you must learn is that a *real* crystal has nothing to do with the fancy glasses, known as "**crystal**", that you put on your festive dinner table. These so-called "crystals" are in fact the *exact opposite* of real crystals. They are made from **amorphous** glass.
  Exactly the same thing holds for all those cute "crystal" things at airport shops all over the world.



Not crystals | Crystals

Crystals and Non-crystals

    - What I mean by *real* crystals are *all* solid materials with an *orderly arrangement* of most of their atoms as shown schematically below.



Schematic drawing of a crystalline and amorphous solid.

On the left we have *crystalline* **quartz** (SiO_2), known as **rock crystal**, with an orderly and repetitive arrangement of the silicon (Si) and oxygen (O) atoms. On the right is *amorphous* **glass** with no apparent order, consisting once more essentially of SiO_2 plus some incorporated "dirt" like sodium (Na).

- On occasion you find obvious crystals in nature. Things like rock crystals (= quartz), diamonds, rubies, and so on. More often, however, you find these kind of crystals in jeweler's shops or in mineral exhibits in museums.
    - These **gemstones** and minerals are commonly addressed as "crystals" because they have some *peculiar geometric shape*; they come as cubes, pyramids, octagons, and so on.
      You might believe that crystals are rare since most of us find crystals rather

[Misc. Link](#)

Gem-stones

- These **gemstones** and minerals are commonly addressed as "crystals" because they have some *peculiar geometric shape*; they come as cubes, pyramids, octagons, and so on.

  You might believe that crystals are rare since most of us find crystals rather infrequently outside jewelry stores. When did you find your last diamond or ruby on the beach or in the mountains?

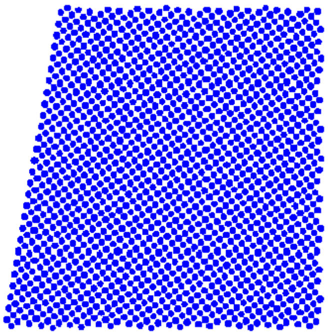
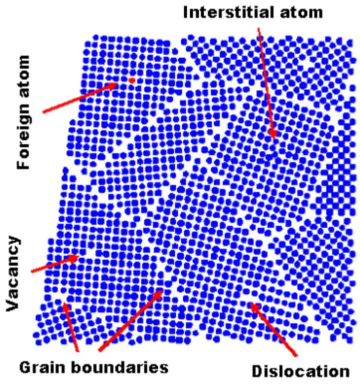
  Your believe is wrong. The exact opposite is true.

Almost everything that is not somehow related to biology is a crystal.

- Wood, jellyfish, coconuts, fingernails and you are not crystals. Outside of biology, things like obsidian aren't crystals either. But amorphous minerals are the big exception. Crystals are the rule.

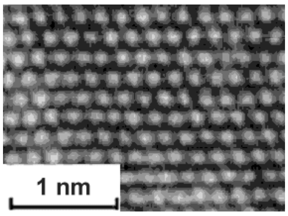
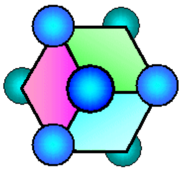
- Most of the rocks around us and *every metal* is a crystal. So how come nobody noticed this?
  - Because the overwhelming majority of natural crystals are *not* showy **single crystals** with an easily recognizable "crystal" shape, but **poly crystals**, an agglomeration of small crystals stuck together haphazardly. On top of that, these crystals are as full of defects as a politician of BS.

    The figure below illustrates that much better than many words:

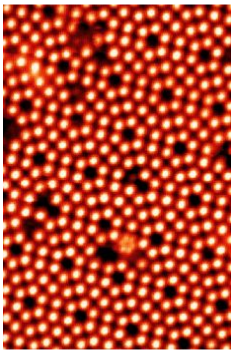
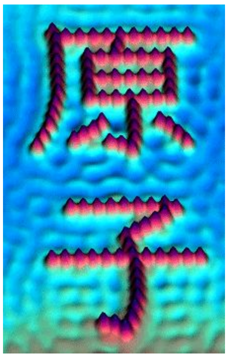
	**Schematic and two-dimensional drawing of an ideal perfect *single* crystal**
	**Schematic and two-dimensional drawing of a normal *poly* crystal full of *defects*.**

- It's hard to draw a *three*-dimensional version of the crystals above. If I would attempt that, the picture would be utterly confusing.
  - It's easy, however, to *imagine* what a three-dimensional perfect single crystal could look like. Just stack many layers of atoms as seen in the figure above on top of each other and your three-dimensional crystal looks in this projection *exactly* like the two-dimensional case.

    The only difference is that instead of just *one* atom you now have a whole stack. And that's what we are going to see in a suitable microscope. We must take care to orient the crystal in such a way that we look down a row of atoms. What we then will see for *iron* is shown below.

	
High Resolution Transmission Electron Microscope picture of an iron crystal. **Each white spot is a column of atoms.**	**How the (cubic) iron crystal is oriented in this case.**

- Just to demonstrate the point a bit more, I will also show you some pictures of my other favored material: silicon (Si).
  - The figures below shows images taken with a **scanning tunneling microscope** or STM. We see only the atoms of the *surface* here.
    You do not just see the atoms on the surface with an STM, you can even use it to move atoms. In this way you can make the smallest possible drawings, e.g. the Japanese sign for "atom"

	
Scanning Tunneling Microscope (STEM) picture of a silicon surface.	**Drawing with the STM**
The surface of a Si crystal as seen with an STM (in ultra-high vacuum). The red-white circles are single silicon atoms. Note that there are *vacancies*, too.	Si atoms (the red cones) on some "featureless" blue substrate. They have been individually placed to form the Japanese sign for "atom"
Source: Omnicron Corp.	Source: IBM STM image galery

- In some of the pictures the scale is given in nanometers (nm). **Nano** is Greek for midget and means really, really small. We don't need a scale, however, since we know that atoms, roughly, are about 0.3 nm large.
  - As promised I will not insult your intelligence by always going on about a "thousandth part of a millionth part of a meter", and so on. I presume that you know that "nano" means "billionth part" of whatever, or "whatever multiplied by 10^{-9}".
    A nanometer is the billionth part of a meter or the millionth part of a millimeter, and yes, it is really small but not "*unimaginably*" small. Use the link to refresh your memory if needs be.
    Note that right now you do not need to *unimagine* what a nanometer is. You actually *see* it. Just keep in mind:

A nanometer is the natural scale for atoms

- An atom is roughly 1 nm large (it's more like 1/3 of a nanometer actually), and a nm is therefore also the natural scale for *crystal lattice dimensions*.

Single vs. Poly Crystals

- Single and rather *perfect* crystals are indeed quite rare. *Dirty* poly crystals, full of defects, are all over the place.
  - If we definitely need single crystals, for example in **silicon** micro technology or for titanium alloy turbine blades, we have to make them with great effort.
    Usually, however, we are much better off with poly crystals. Not only are they far easier to make and thus far cheaper than single crystals, they are actually *better* for many products, like car bodies or swords. Perfection is not always good; being disordered and messy like the poly crystal in the drawing above, does have advantages for making swords, as we will see.
- Just to make sure you remember: not everything is a crystal. You, just as about all other inwardly slimy *biological* objects, are not crystalline, neither is glass (typically silicon dioxide with some "dirt", see the figure above).
  - Man-made **polymers** like Teflon, nylon, vinyl, acrylic, or "PET" (polyethylenterephthalat, the stuff plastic bottles are made from), are not crystalline either but also amorphous.
    Nevertheless, crystalline materials are far more common than amorphous materials and, remember, *all metals are crystals*! Well, almost all. But we need not worry about the few and rather weird exceptions to the rule.
- A big "*why*" question comes up at this point.

Why does a bunch of metal atoms stick together in an orderly fashion?

  - Re-phrased and generalized, the question is:*Why* do most atoms form a crystal most of the time whenever they stick together?
- Going a bit beyond that questions, the next obvious questions is

Is the *arrangement* of the atoms in a crystal the same for all metals?

- In a first step to getting answers we simply note that most of our 90 or so different atoms like to **bond** to other atoms. Bonding between atoms is just another word for saying that the atoms like to share some electrons in some way.
  - Bonding with a suitable partner (or with more than one partner for the more promiscuous atoms) via exchanging or sharing electrons, simply makes a better *state of being*. Bonding with a suitable partner is just more comfy, as most of us know. Atoms, it appears, are human, too. Or was that the other way around?
    While the majority of atoms likes to bond with other ones, a few atoms prefer to be antisocial and stay in splendid isolation at all circumstances. Those snobs we call **"noble" elements**. Foremost in this group we have the **noble gases**, for example helium (He), argon (Ar), or xenon (Xe). Then we have the **noble metals**, in particular gold (Au) and platinum (Pt). It makes you wonder how the antisocial behavior of "noble" atoms relates to human nobility, the kind of people who typically induced other people to work for them in exchange for letting them live. The common denominator might be found in the word "antisocial".
  - How do we define a "better state of being" or being "comfy" in cold scientific terms? You know when you feel comfy but how can you put a number on it?
    In the world of atoms or other particles, being comfy simply means having as little (free) **energy** as possible. If you are a couch potato, why should your atoms be otherwise?
    The energy of bonded atoms is usually lower than that of atoms hanging around in isolation, and that's why atoms like to bond. If you know your atom, you can actually predict its bonding preferences and behavior.
- With some **quantum theory** we can calculate how much energy atoms will gain by pairing up, by forming threesomes, and so on. This means we have *chemistry* covered (in principle).
  - **Chemistry**, after all, is about getting atoms together to form something new. Take one silicon (Si) atom and two oxygen (O) atoms, get them close enough, and they will combine to form a Silicon dioxide (SiO_2) molecule. Get a bunch of those and they will produce solid **quartz**, one of our most important materials in electronics.
    One hydrogen (H) atom and two oxygen (O) atoms produce water (H_2O), quite important too. 2 atoms of carbon (C) plus 5 atoms of hydrogen (H) and 1 atom of oxygen (O) produce ethanol (C_2H_4OH). Mix ethanol with water and add a little bit of this and that and you have red wine, extremely important for making me comfy.