2.3 Some Definitions

2.3.1 Let's get to Work.

- Enough small talk, we need to do some work now. We have used everyday words like iron, cast-iron, wrought iron, steel, and so on, and we now need a few definitions in order to avoid confusion and to be sure that we really know what we are talking about.

Iron

- Iron is simply a chemical element; its symbol is ***Fe*** (from Latin "**ferrum**" = iron).
  - *Pure* iron, and that means iron containing only very small amounts of impurities, melts at **1536 ^{o}C** (**2732 ^{0}F**). We already know that this is a rather high temperature, not easily reached with "natural" means.
- What we don't know yet are the answers to some of the more *general* "why" questions. Why do things melt? And why at quite different temperatures?
  - We need to look into that a bit and for that we need to discuss first what "temperature" actually means. You may now feel a bit amused; thinking that you sure know what temperature means. Well, we'll see if you do.

Wrought Iron

- *Pure* iron (Fe), in a chemist's sense, is a rather recent thing. For a very long time the best approach to half-way pure iron is what we still call "*wrought iron*".
  - "Wrought" is just old-fashioned English for "worked", and the term "wrought iron" simply refers to the way it was made: the smith banged together the little lumps of relatively pure iron found in the "*bloom* " of ancient smelting furnaces after the smelting process. In German, by the way, wrought iron is called "Schmiedeeisen" ("forged iron") because it was forged together.
- Talking about impurities in iron, we first talk about *carbon*, another chemical element. Wrought iron does not contain more than about **0,1%** of carbon. There is no clear-cut definition, however, and a lot of times when people (or archaeologists) use the expression "wrought iron" they might refer to what is known as mild steel with up to 0.4 % carbon.
  - By the way, **concentrations** given in percent (%), if not otherwise stated, always refer to "*weight percent*". A concentration of 0.5 % carbon in iron, for example, means that you have 5 grams (g) of carbon in 1 kilogram (kg = 1000 g) of the stuff; leaving 995 g for the iron. This leads us to the next item:

Carbon

- Carbon (from Latin "carbo", meaning charcoal), is simply another chemical element (symbol **C**).
  - In its purest and most stable form carbon is found as **graphite** but there are many other modifications or *phases* of pure carbon like

    1. **Diamonds**; very exciting for females.
    2. **Carbon nanotubes** (***CNT***); very exciting for materials scientists.
    3. "**Bucky balls**" made from Carbon.
    4. "**Graphene**", a sheet of just one atomic layer of carbon atoms; extremely exciting for physicists and materials scientists.
    5. "Amorphous" diamond, very annoying for people trying to clean their ovens (it's part of that hard black stuff).

    Coal, by the way, is not even coming close to being pure carbon; it's full of all kinds of impurities. Only after it has been thoroughly cleaned could we call it carbon but for historical reasons we then call it **coke**. You can test your skills in working with this Hyperscript by finding the special modules dealing with much of the above; I did not make the links on purpose.
- Carbon is a great element not only for **carbon-based life forms** like slime mold, mosquitoes or you and me, but also for illustrating a supremely important concept:

One and the same element
(or compound)
might exist in modifications as different as diamond and graphite.

- We need a good name for that phenomena. From now on we will call those different modifications, structures, manifestations, different states of being, or whatever *you* like to call different forms of the same stuff by one word: different **phases** of the same material.
  This is something very important that you need to remember. So let me repeat:

One and the same material might exist in different phases.

Phases

- The concept of "phases" is supremely important for making iron, steel, and swords (and about anything else). So, what exactly is a *phase* ? We will get into that in great detail later, for now we just ascertain the following examples:
  - Graphite is a distinct phase of pure solid carbon; diamond is *another* phase of pure solid carbon.
    Ice is a distinct solid phase of aitch-two-o (**H_2O**). *Liquid* water and *steam* are other phases of the substance or chemical compound **H_2O**, consisting of one oxygen (O) atom and two hydrogen (H) atoms. Whatever phase you look at—it's still aitch-two-o. I *must* call it aitch-two-o or **H_2O** in chemical shorthand because—surprise!— there is *no common name* for this substance. There are *only* names for some of its phases.
- If one and the same material exists in different phases, logic dictates that we must be able to induce **phase changes** . That will be a decisive thing for sword making.
  - So let's look at phase changes in iron right away. Iron (Fe) crystallized in one way and then called "*ferrite*" is a different phase from iron crystallized in a different way called *austenite*. In contrast, *iron carbide* (called "cementite" (Fe_3C)) and *rust* (a mixture of iron oxides and hydroxides) are *not* different phases of iron. They are different *chemical compounds* and thus different materials

Phase Changes

- Phase changes actually are rather common. When the ice in your whisky melts, the material **H_2O** undergoes a *phase change* from a solid phase called *ice* into the liquid phase called *water*. We also call that a **phase transformation** or a *phase transition*.
  - When iron melts, or if anything else melts, there is also a phase transformation from solid to liquid, for that matter. Phase changes from solid to liquid are a bit trivial, you might think, so let's look at phase changes from one solid phase to another one.
    The phase change from carbon in its diamond phase to carbon in its graphite phase, for example, is easy to do: heat up a diamond without admitting air (otherwise it just burns) and you get graphite. It is easy to do because carbon prefers to be in the graphite phase at room temperature, and the diamond phase just needs a little incentive to change to graphite. You can try an experiment in your kitchen when your wife is not around. Women tend to oppose experiments that turn their diamonds into coal. That's probably while few experiments along that line have been performed. Reversing the process, making diamonds from graphite, is not quite that easy, by the way.
    Different phases of the same material may have very different properties. Tell your betrothed-to-be that the lump of graphite in that engagement ring you gave her is practically the same as a diamond, and she will tell you far more about the relative merits of different phases of the same element than you ever wanted to know.
- Pure solid iron (Fe), as it happens, comes in different phases, too, just like carbon. Phase changes occur whenever you heat it up beyond a certain temperature *and* when it cools down again.
  - Some of the different phases of pure iron have names like some of the different phases of **H_2O** or carbon. The *pure* iron phase prevalent at room temperature is called "**ferrite**". If we heat the ferrite phase to 912 ^{o}C (1674 ^{o}F) it changes to a phase called "**austenite**". Ferrite and austenite are just as different as diamond and graphite.
- Some really big "*why*" questions come up now. The answers will come up later:

Why would something consisting of a bunch of identical atoms manifest itself in different phases?
Why can different phases sometimes coexist ?
Why do phase changes happen at some specific temperature?

Steel and Cast-Iron

If we add a bit of carbon to (otherwise pure) iron, we obtain a range of materials that we call:

- (Carbon) *steel* if the carbon concentration is around 0.3 % to 2 %.
- *Cast-iron* if we have carbon concentrations in the range of 2 % to 4 %.

Note that "cast-iron" is a *name* for an iron-carbon *alloy*. That's why I'm going to write it with a hyphen. Cast-iron is *not* pure iron that has been *cast* into some mold; it is an iron *alloy* that got its name because it is easy to cast, in contrast to pure iron or steel.

There are a lot of iron alloys (mixtures of iron and other elements) around since there are a lot of other elements you can mix iron with. Some of those alloys we call *steel* and some others we call *cast-iron*. These names are thus just generic or collective names for a whole bunch of quite different iron alloys with different compositions.
The only common denominator is that all steel and all cast-iron varieties contain iron.

There are qualifiers for special steels and a plethora (= a hell of a lot) of names for it.

Steel names might be historical ("Wootz" steel, Sheffield steel, Tamahagane), scientific (hypoeutectoid vs. hypereutectoid steel), relating to people (Bainite, Martensite, Ledeburite) or describing appearances, processes or properties (pearlite, maraging steel, spring steel, mild steel, stainless steel, TRIP steel).
I'm just showing off here. We need to go into some of that later, however.

What we note right here is the essential "why" question concerning (carbon) steel

Why does a little bit of carbon inside iron change its properties so dramatically?

A carbon concentration somewhere between 0 % and 4 % determines if we have:

- Relatively soft pure iron with a high melting point of 1538 ^{o}C (2800 ^{o}F).
- Hard but tough or ductile steel with a still rather high melting point around 1500 ^{o}C (2730 ^{o}F).
- Very hard and rather brittle steel.
- Completely brittle cast-iron with a low melting point around 1150 ^{o}C (2102 ^{o}F).

Why? And *how* does the carbon work this miracle?

Melting Point of Alloys

What we should note right here is a simple truth: The melting point of (almost) *all* alloys, e.g. the alloy of iron and 4 % carbon that we count among "cast-iron", is always substantially *lower* than the melting point of the major pure element.

The same is true if we don't have a technical "**alloy**", implying that we mixed the constituents for the alloy intentionally, but just "**dirty**" or **impure** iron, implying that whatever is in there is not of our doing, and likely not what we want.
This makes clear why copper (Cu) alloys like *bronze* and *brass* were easier to deal with than the pure metals at the advent of metal technology.
Now *why* does the melting point go down if you add a bit of this or that? That's a really tough question that we nonetheless need to answer.