"Food for Thought" explores the relationship between food/drink and chemical engineering processes/concepts.

SOLID LIQUID GAS PLASMA CAKE

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In presentations our colleague Milo Koretsky will speak of how students distinguish behaviors and solutions appropriate to "school world" — where all pertinent information is contained in the problem statement leading to One Right Answer that is known by The Teacher — and the "real world" — where things are a bit less clearly defined than all that.[1] Sometimes we can observe a similar phenomenon for our students' understanding of science: there's "school world" science, where everything is explained by what's in the book, and "real world" science, where those rules just don't seem to apply. One of our big tasks as educators is to help students make these two worlds match, and I think an appeal to *cake* can be an important step in doing so.

For example, if you ask chemical engineering students about the phases of matter, they will happily tell you that things are solids, liquids, gasses (or, sometimes, plasmas, apparently the letter "y" of matter) and go on to give you practical definitions of the same. And if you ask how substances tend to transform, students will add with absolute confidence that it's nearly all about temperature — at low temperature, materials are solids, and as you go upwards, they tend to become liquids then gasses, although at some pressures for some substances, sometimes you do not pass liquid (or collect $200) and go straight to gas. But a place where this all goes sideways is when you ask the same students what phase "cake" is.

Cake (and bread and cooked eggs) are clearly solids by all conventional definitions — they have a definite size and shape. But cake starts its existence as a liquid and, upon heating, rather than becoming a vapor, becomes a *solid*. If you really want to mess with students, ask them if this means the entire temperature-dependence runs backwards and if you can vaporize cake with low temperature. I know this seems beyond obvious, but this is a discussion I have had with actual 20-year-olds who are most of their way through an engineering education. It is only in Food Science class that it is dawning upon them that they have no conceptual framework for the phase behavior of cake, Jell-O®, eggs, or macaroni. It's kind of a big deal. So now that we're all laughing at the plain silliness of this, what's going on here?

First, it's worth stating that many of the foods that do follow the classic path of solid→liquid→vapor with increasing temperature do not do so homogeneously. Take butter, for example. A stick of butter seems to be a more or less solid and continuous phase at refrigerator temperatures. But it is actually both a suspension of proteins and an emulsion of a water-phase in a more-or-less solid continuous-fat-phase. And it's this fat whose phase behavior we observe when melting butter on a stovetop, which reveals that there was always liquid water there as well as solid-ish protein agglomerates. The foods that can melt at elevated temperatures generally have a similar chemical situation in which a continuous phase dominated by a particular chemical constituent is responsible for what we see as the entire food "melting" or "freezing" — be it butter, Maggi® cube, cheddar cheese, lollipop, or the fatty part of a pork belly.

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So how about all those things that don't melt when you heat them up? Like butter, they're also typically a mixture of many (often a great many) chemical compounds. But what's different is that whatever the most continuous phase is, it's usually full of something polymeric. This also tends to come as a surprise to students, who often view "polymer" and "plastic" as synonyms and tend to expect both to be human-made. Starch and fiber are both polymers of sugars (e.g., glucose) and proteins are polymers of amino acids. Just as with butter, some polymeric systems melt and freeze just fine — they're thermoplastics. But there's more than one way to turn a polymer solid. By cross-linking polymer chains — be they food or synthetic — we can make a *thermoset*, a polymer that stays solid even at a temperature that would tend to liquify a non-cross-linked version.

If you look through some polymer science textbooks, many introduce thermosets by saying they are *like* bread or cake. This is amusing because I couldn't find a Food Science text that described cake as being *like* silicone. If you ever want to cause a spirited debate in your department, ask at a faculty meeting if the materials folks would consider cake to be a thermoset or merely *like* a thermoset (as I did).

Cake is undeniably *like* a thermoset in that, as you heat it, it does not melt but becomes solid. But that's not the only thing going on. Imagine cake just freshly cooked. Is there steam in your mind's eye? Evaporation is indeed part of what is occurring, and as the water leaves the system, a very well mixed collection of high molecular weight solids is left behind. In this way, it seems that cake is a mixture whose individual components are moving from solid→liquid→vapor at different temperatures. So is cake just the *bottoms* fraction of a rather skewed batch distillation?

Yes – and…. there's another cool phenomenon at play here as well. While evaporation occurs during cooking, there is still water in cake. It just tends to be bound up in starch granules, which swell and become gel-like. That's a very good thing! If you've ever tried to eat uncooked grains – be they wheat, rice, corn, or others – you may have discovered they don't digest very well. While increasing the surface area of these grains through grinding to flour undeniably provides more access for digestive enzymes to act, the situation isn't that much better. That's because without cooking in a moist environment, the starch granules that make up most of the nutritional value of grains are semicrystalline.[2] It's difficult for enzymes to attack and split off the sugars from the starches when the starches are all crystals. Softening and swelling those crystals with warm water, however, opens them right up to enzymatic action when eaten. A fun consequence of this is a shift in the glass transition temperature (Tg) of the starch-water complex.[3] When baked goods or cooked eggs are removed from their high temperature cooking environment, they are quite soft and deformable – the cake can still fall, the cookie can bend. But as they cool, they become items you can cut or crumble or even snap. The Tg of swelled starch is somewhere in the 50-60 ºC range,[4] right there between the temperature of cake coming out of the oven and room temperature.

Another factor to consider is revealed when we look closely at a slice of cake. It's got little bubbles in it — it's actually a *foam*. It is a little like polyurethane foam, wherein the bubbles arise from the blowing agent being hit by the heat of reaction between the polymer precursors. Is the solidity of cake based on this structure? After all, you can "sculpt" whipped cream (foam) much more readily than the liquid from which it is made. While that is certainly helpful in giving cake its shape, the fact that you can slice cake at room temperature implies that the continuous phase surrounding the foam is solid rather than liquid. And while the bubbles in a cake expand during baking (due to steam generation as well as the volume increase that occurs with temperature increase), they tend to be generated in the mixing phase *before* baking and expanded with chemical agents like baking powder.

So is cake *distillation, gel, foam*, or *thermoset*? It is also possible for multiple physical phenomena to be occurring simultaneously, leaving us with multiple true reasons why cake doesn't melt at high temperature. If gelation were the only mechanism for cake's solidification, roux would be cake (it isn't). If dehydration were the only thing occurring, we'd be able to reverse the process by adding back liquid water (we can't). If you happen to leave a cake out in the rain, it will indeed be soggy and less solid-like, but will not revert to its ingredients. It will be a soup with macroscopic chunks of cake and icing flowing down. (I don't know about you, but I don't think that I could take it.) And this helps confirm that cake (and bread and scrambled eggs) are indeed also thermosets and not just *like* thermosets. Cross-linking of proteins at elevated temperature is part of what gives cakes, breads, and cooked eggs their solid forms.

The bottom line is that It. Is. Complicated. And this is perhaps one of the most important points that we Chemical Engineering educators can teach students. It's easy to learn a fact that covers 80% of cases and be right pretty often such as liquid + heat = gas. But there are almost always exceptions that only reveal themselves after additional data collection. Sometimes liquid + heat = cake!

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