How Chocolate is Made

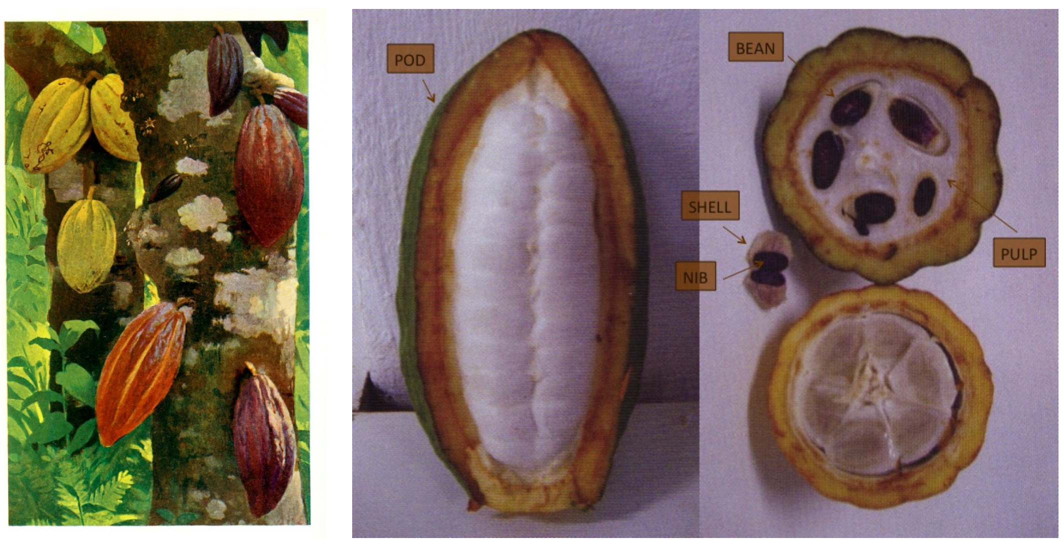
Gregory Owen

January 5, 2013

If you're reading this, I assume that you already have some vague idea that chocolate starts out as a bean before it takes the shape of the tasty bars with which we are familiar. I assume, also, that you'd like to know more about the journey from bean to bar and, specifically, how you can make that journey happen. Here's what we know so far.[1]

1 On the Plantation

Before diving right in to the part of the processes that we actually do, it is important to understand that a lot of stuff happens to the chocolate before it gets to us. The processes that occur on the plantation can have a significant effect on the quality and flavor of the chocolate, so it's good to have some idea of what happens upstream.



(a) On a *Theobroma cacao* tree [2] (b) An opened cacao pod with pulp, beans, and nib labeled [1]

Figure 1: Cacao pods

Every chocolate bar you've ever eaten began its life as a pod [fig 1(a)] on the cacao tree, *Theobroma cacao*. Each pod contains 30-45 cacao beans encased in a sticky white pulp. The beans are made up of two parts: a dark nut, known as the nib, and a papery shell [fig 1(b)].

The chocolate process begins with the pods being cut down from the trees and split open. The beans are then scooped out of the pod and are left to ferment with the pulp [fig 2(a)] for about a week. Fermentation kills the beans, preventing them from germinating later, and also develops flavor precursors that are essential to tasty chocolate.

[1] Unless otherwise specified, all information comes from Emmanuel Ohene Afoakwa's book *Chocolate Science and Technology* [1]

(a) Fermenting in a box

(b) Drying in the sun after fermentation

Figure 2: Cacao beans [1]

After fermenting, the beans are dried in the sun [fig 2(b)]. This reduces the weight of the beans and makes them less susceptible to molds.

2 Roasting

Once they have dried, the beans leave the plantation and are shipped to the factory (us). The first step we take is to roast the beans (fig 3).

Roasting accomplishes the following goals:

- **Develops the flavor of the chocolate** Remember those flavor precursors that were created during the fermentation step? By roasting the beans, we develop those precursors into actual flavors. Heating the beans produces a series of chemical reactions known as the Maillard reactions, in which amino acids and sugars react to form all sorts of tasty chemicals. [3] Roasting also drives off the more volatile acids that are naturally present in cacao beans.
- **Kills bacteria** For those keeping track at home, the beans have just spent more than a week outside of the pod at the plantation, either fermenting or drying in the open air. Anything left out for that long in a tropical atmosphere is practically guaranteed to have some sort of microbes hanging around on it, and we don't want those in our chocolate.
- **Puffs up the shells** This will be important for the next step. Roasting causes the water within the bean to boil (not all of it dried out in the drying step), puffing out the shell in much the same way as a popcorn kernel expands. The puffed-out shell is then easier to remove from the nib.

Roasting is the step in the process at which we can most directly affect the flavor of our final chocolate, and is the step in which we can most perfect our craft. It's kind of a big deal, is what I'm saying. Roasting is also one of the most fun parts of the chocolate process. The smell that starts coming off of the beans as they roast is absolutely *fantastic*.

We will generally roast the chocolate for about 20-25 minutes at temperatures between 250° and 350° F. I have found that hitting the beans with 5 minutes of high heat (350° F) before lowering to a cooler roasting temperature (250° F) for 15 more minutes generally works pretty well. Since the oven in the Bake Shop can't change temperature very quickly, we may need to settle for a constant-temperature roast

Some things to look for to determine if the beans are done are the color of the bean (it should be dark, chocolatey brown all the way through), bendiness (the bean should give a little when bent between thumbs

Figure 3: Roasting beans in oven

and forefingers), puffiness of the shell (it should come off easily), and taste (it should be crunchy, not chewy and should not taste raw or nutlike). Another good indicator that the beans are getting close to done is when they start popping.

3 Winnowing

Once the beans have been roasted, we need to remove the shell from the nib. The shell is papery, crunchy, and doesn't contribute any flavor to the final product, so we want to discard it.

Back in the day, we used to do this step by hand, with a rolling pin, hairdryer, and bowls. That sucked, took forever, and was really inefficient, so in fall 2012 we made an Automatic Winnower [fig 4] as part of the HackPrinceton hackathon. We won third place (out of 3) and got $1,000 for it.

To separate the shell from the nibs, we feed the roasted beans into the winnower via the feed chute of the Champion Juicer. They then fall past the juicer's rotating blades, which crack the beans into pieces of nib and shell. You can see an example of cracked beans in figure 5(a).

These pieces fall down the PVC entry pipe until they hit a barrier where the entry pipe connects to the rest of the piping. Once they hit the barrier, the pieces of nib and shell feel the pull of the vaccuum generated by our Shopvac. Here we exploit the different densities of the shell and nib to help separate the two: the lighter shell is sucked up by this vaccuum and deposited in a recepticle, while the denser nib keeps falling into a removable container below.

4 Grinding and Melanging

After the winnowing is completed, we should ideally be left with a pile of pure nib [fig 5(b)]. We can now grind this into chocolate.

We pour the nib pieces into a Champion Juicer [fig 6(a)], which grinds the beans into a liquid known as cocoa liquor [fig 6(b)]. Part of the liquor will pass through the filter on the bottom of the juicer, while the

Figure 4: The Timothy Anderson Automatic Winnower (“Timmy”)

(a) The cracked beans before winnowing

(b) The winnowed nib, (mostly) free from shell

Figure 5: The results of the winnowing process

rest will flow out the front of the juicer. This unfiltered cocoa liquor must be passed through the Champion again to purify it. Eventually, almost all of the cocoa liquor will have passed through the filter (the liquor that has not passed through the filter contains the pieces of shell that we were unable to winnow away; we discard this part of the liquor since it tastes bad).

At this point, the cocoa liquor looks just like melted chocolate. Unfortunately, it is nowhere near as delicious. In fact, it tastes like Baker’s Chocolate (which, incidentally, it is). To combat the bitterness, we now add sugar. The chocolate (cocoa liquor + sugar) now tastes delicious. We have only a few steps left.

First, we must grind down the chocolate to an even finer consistency. The human tongue can distinguish individual particles down to 30 microns in diameter. The Champion can’t get our chocolate below this threshold, especially after we’ve added sugar, so our chocolate will taste grainy at this point.

Luckily, there is a tool especially designed to grind chocolate particles down below the detectable limit:

(a) Our grinding setup

(b) Cocoa liquor flowing out of the Champion Juicer

Figure 6: Grinding

Figure 7: Chocolate being melanged [4]

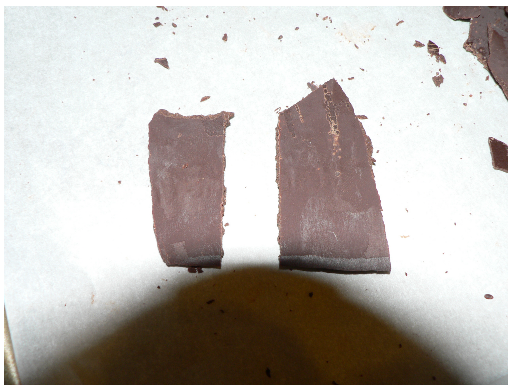
the melanger [fig 7]. After grinding, we pour our liquid chocolate into the melanger, add sugar, and let it run for 8-12 hours. If the chocolate solidifies at any point during melanging, it can be remelted by putting it into a low-temperature oven for about 10 minutes.

5 Tempering

At this point, we only need to solidify our chocolate and then sell it. Unfortunately, this is rather more easily said than done. We still need to pass through the most technically demanding step of the chocolate process: tempering.

A full understanding of tempering requires a significant knowledge of the chemistry of chocolate, which I have decided to include in the Appendix. Instead of giving the whole background here, I'll just gloss over almost all of the details and skip directly towards the process.

On the most basic level, tempering is necessary because the particles that make up a chocolate bar can arrange themselves in many different ways. The different arrangements of the chocolate particles on a molecular level create different physical properties of the final chocolate on a much larger scale. Chocolate with the correct molecular arrangement (referred to as Form V chocolate) is dark brown, glossy, and makes a satisfying snap when broken [fig 8(a)]. Chocolate with an incorrect molecular arrangement (Form IV chocolate) is lighter in color, matte, and will crumble when broken instead of snapping [fig 8(b)]. Mistempered chocolate will also exhibit an unsightly white coating called fat bloom [fig 8(c)].



(a) Properly tempered chocolate is dark brown and snaps cleanly

(b) Poorly tempered chocolate is lighter and crumbles

(c) Poorly tempered chocolate also exhibits ugly white impurities known as fat bloom

Figure 8: The effects of tempering

To ensure that our chocolate is properly tempered, we perform the following steps:

5.1 Melt the chocolate

By raising the chocolate above 110° F, we erase all existing crystalline structures within the chocolate. We can now cause the the chocolate to crystallize into the form we want. It is generally safe to use a microwave at this step, melting the chocolate for 15-20 seconds, mixing it up, and then repeating until it is of uniform consistency and above 110° F.

5.2 Create seed crystals

In order to encourage our chocolate to crystallize into the correct molecular arrangement (Form V), we will cause a small portion of the chocolate to crystallize into that form and then use that portion of the chocolate as "seed crystals": when recombined with the rest of the chocolate, the seed crystals encourage the rest of the chocolate to crystallize into Form V as well.

To create these seed crystals, we remove $\frac{1}{4}$th to $\frac{1}{3}$rd of the melted chocolate from the bowl and pour it onto a flat surface (either a plate or a marble slab). Once the chocolate is on this surface, we work it with a spatula, pushing and turning it around until it begins to solidify. This encourages the formation of Form V crystals for some unknown reason.

5.3 Add the seed crystals back into the main mass of chocolate

Once the chocolate we used to create seed crystals has solidified into a paste, we recombine it with the rest of the chocolate. Note that our goal is for the final equilibrium temperature of the seed crystal + main chocolate mixture to be between 87 and 90 degrees Fahrenheit (see Appendix). Because the seed crystal chocolate will have cooled significantly, the rest of the chocolate should be above 90° F when the seed crystals are added back in (the exact temperature is something we'll have to look into).

After adding the solidified seed crystal chocolate into the rest of the chocolate, we use the spatula to try and break up the seed crystal chocolate into chunks a little smaller than a golf ball. This ensures that the non-seed chocolate is sufficiently exposed to the seed crystals. Ideally, we will now wait until the chocolate mixture comes to thermal equilibrium and is a thick pudding-like liquid of even consistency. If the mixture seems too cold (below 87° F), we will either start over and retemper or move directly to the next step. If the mixture is too hot, we will probably have to start over.

5.4 Pour the chocolate, cover it, and let it solidify

At this point, the chocolate should be on its way to solidifying into Form V crystals. We can now pour it onto a sheet of parchment paper (or into a mold), cover it with parchment paper, and leave it to solidify. Note that the covering step is absolutely critical to producing well-tempered chocolate. Uncovered chocolate is practically guaranteed to bloom because it will cool too quickly (see Appendix).

References

[1] Afoakwa, Emmanuel Ohene. *Chocolate Science andTechnology.* Hoboken: Wiley-Blackwell. 2010.

[2] Head, Brandon. *The Food of the Gods.* `http://www.gutenberg.org/files/16035/16035-h/16035-h.htm`

[3] *Maillard Reaction.* Wikipedia. `http://en.wikipedia.org/wiki/Maillard_reaction`

[4] Nanci, John. *Chocolate Alchemy.* `www.chocolatealchemy.com`

[5] *Types of Chocolate.* Wikipedia. `http://en.wikipedia.org/wiki/Types_of_chocolate`

Appendix A: The Science of Tempering

To truly understand the tempering process, we begin with a discussion of what chocolate is. Dark chocolate (we'll ignore milk chocolate for now, but it's almost exactly the same) has two critical ingredients: cocoa liquor and sugar (fig 9).

Figure 9: The two crucial ingredients of dark chocolate, cocoa liquor and sugar, in the ratio used to make dark chocolate (75% cocoa liquor).

Cocoa liquor is what we get when we take nibs and grind them into a liquid. It has two very different components: the small, polar flavor particles that give chocolate its taste and the white, nonpolar lipid known as cocoa butter that gives chocolate its structure. Tempering is concerned with the structure of the crystals formed by cocoa butter as it cools.

Cocoa butter is a normal triglyceride fat: it consists of three long fatty acids hanging off of a triglyceride backbone (fig 10). You can imagine it as being shaped roughly like the profile of a chair, with two long legs on one side of the short triglyceride "seat" and a long back on the other. Because of their unusual shapes, cocoa butter molecules can be packed together into multiple different crystalline arrangements known as forms (fig 11).

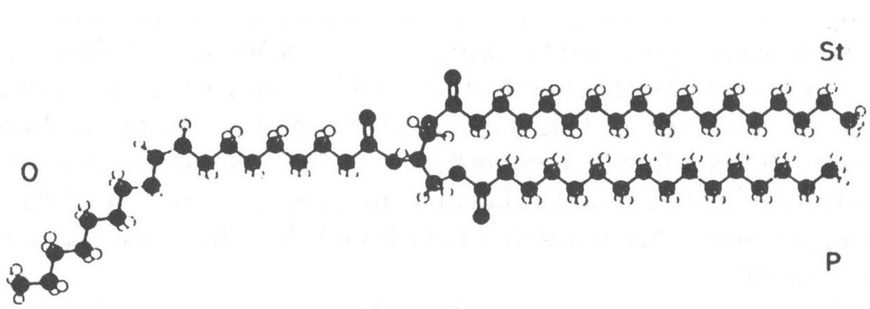
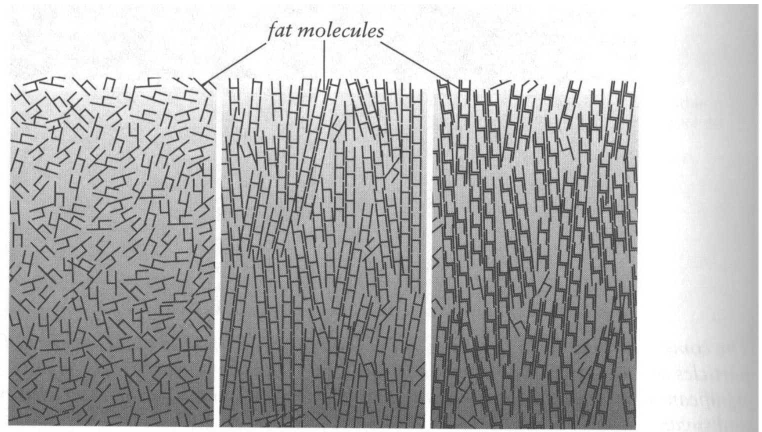


Figure 10: The cocoa butter molecule is a typical triglyceride fat



The crystallization of cocoa butter. Left: *In melted chocolate, the fat molecules (p. 798) of cocoa butter are in constant random motion.* Center: *When chocolate cools in an uncontrolled way, the fat molecules form loosely packed, unstable crystals, and the chocolate is soft and greasy.* Right: *When chocolate is carefully cooled, its fat molecules form tightly packed, stable crystals, and the chocolate is snappy and dry.*

Figure 11: Different arrangements of cocoa butter molecules

There are six known forms into which cocoa butter can solidify, referred to as Forms I-VI in order of their stability (fig 12). A higher form effectively corresponds to a tighter packing of the cocoa butter molecules: a denser packing has a lower potential energy and therefore requires more energy to undo, allowing the higher forms to remain stable at higher temperatures.

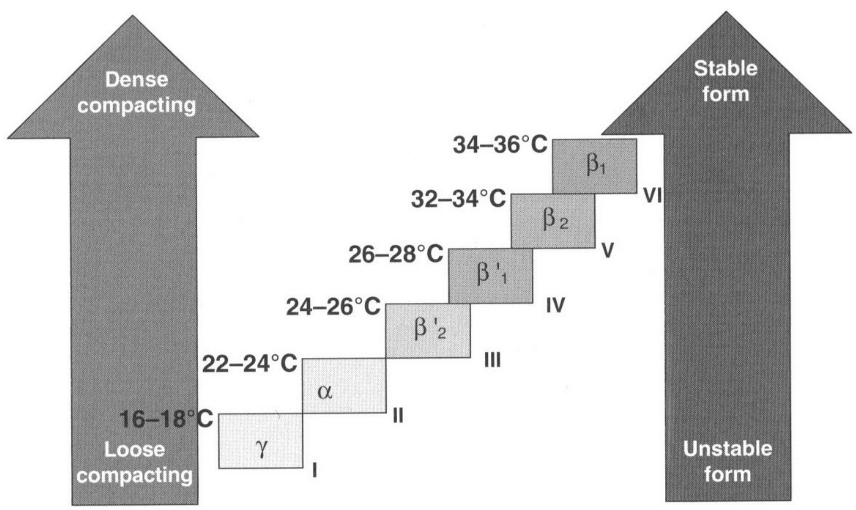


Figure 12: The 6 known forms of cocoa butter crystal and there respective melting points

The different crystalline forms also correspond to different macro-scale physical properties in the final chocolate. The denser packing of the higher forms produces glossier chocolate, since incoming light is more likely to reflect off of the dense, uniformly packed crystals of a higher form and more likely to scatter off of the looser, less even crystals of the lower forms. Chocolate that has crystals of the higher forms is also harder and more likely to snap when broken, as opposed to the lower-form chocolate that is pastier or crumbly.

Tempering seeks to maximize the desirable macro-scale qualities of the chocolate (dark brown color, glossy surface, and clean snap) by controlling the molecular-scale crystalline structure. Consider what would happen if did not temper our liquid chocolate after adding sugar and melanging it. If we simply leave out a bowl of our liquid chocolate, it will pass through the characteristic stability ranges of all six different forms of chocolate crystal as it cools to room temperature. Sections of the chocolate will solidify into each of the different forms, and the chocolate will look like a crystalline patchwork at the molecular level.

This isn't the whole story, however. Once the chocolate reaches room temperature, thermodynamic forces will start to kick in. Since Forms I-III are almost completely unstable at room temperature, they will very quickly devolve into Form IV, which is more stable (this process will be completed in about half an hour).

Form IV is more stable at room temperature, but not as stable as Form V. Over the course of the next day, the Form IV crystals in our chocolate will gradually turn into Form V. Conservation of energy dictates that, as the crystals pass from Form IV to the more stable (lower potential energy) Form V, they must release energy as heat. This heat then destabilizes the neighboring cocoa butter crystals, melting them.

The transition from Form IV to Form V is also accompanied by a physical contraction in the chocolate: Form V crystals are more tightly packed than Form IV crystals. As the crystals contract, the melted cocoa butter around them is forced out onto the surface of the chocolate, where its heat quickly radiates away into the air. This cocoa butter then resolidifies into crystals of solid fat on the surface of the chocolate, which we percieve as fat bloom.

Fat bloom is ugly but harmless. After all, it's just cocoa butter, which is already a major component of the chocolate itself. However, it looks unsightly and unprofessional, and we won't be able to sell our chocolate if it has bloomed. To prevent bloom, we want to get as much of our chocolate into Form V as possible during the first cooling phase, so that none of it has to pass through Form IV and possibly produce bloom.

To get only Form V crystals, we could just melt our chocolate, bring it down to just above the melting point of Form IV crystals, and hold it there until the chocolate solidified. Unfortunately, chocolate takes a long time to solidify at that temperature, and it would cost a lot of money to keep it hot for that long.

Instead, we use the seed crystal method described in the main document. This works reasonably well, but we still need to keep the chocolate covered as it cools in order to insulate it and keep it above the Form IV melting point as long as possible. To demonstrate the power of covering the chocolate, I produced a graph (fig 13) of the temperature of chocolate as it cooled under different conditions.

Looking at the data points for the untempered chocolate (in red), we see an unusual trend. While the chocolate begins cooling exponentially (as predicted by Newton's Law of Cooling), it begins to heat up again at around the 60 minute mark. I did not add any heat to the chocolate; it was *spontaneously generating heat*, from what I assume were the changes in the crystalline structure.

We can see a similar bump in all of the trials. Note, however, that there are two different temperatures at which the bumps appear: for the untempered and tempered but uncovered trials, the bump occurs at a lower temperature than for the two covered trials. These temperatures are not necessarily the temperatures at which the crystals begin to form, but are rather the temperatures at which the heat given off by the crystallization begins to outweigh the loss of heat to the environment.

It is important to note, however, that the covered trials, both of which exhibited macro-scale properties consistent with Form V crystals, had a bump at a higher temperature than the uncovered trials, both of which exhibited macro-scale properties consistent with Form IV crystals. There is therefore some reason to believe that covering the chocolate is sufficient to cause it to favor Form V crystals over Form IV, most likely through the added insulation provided by the cover.

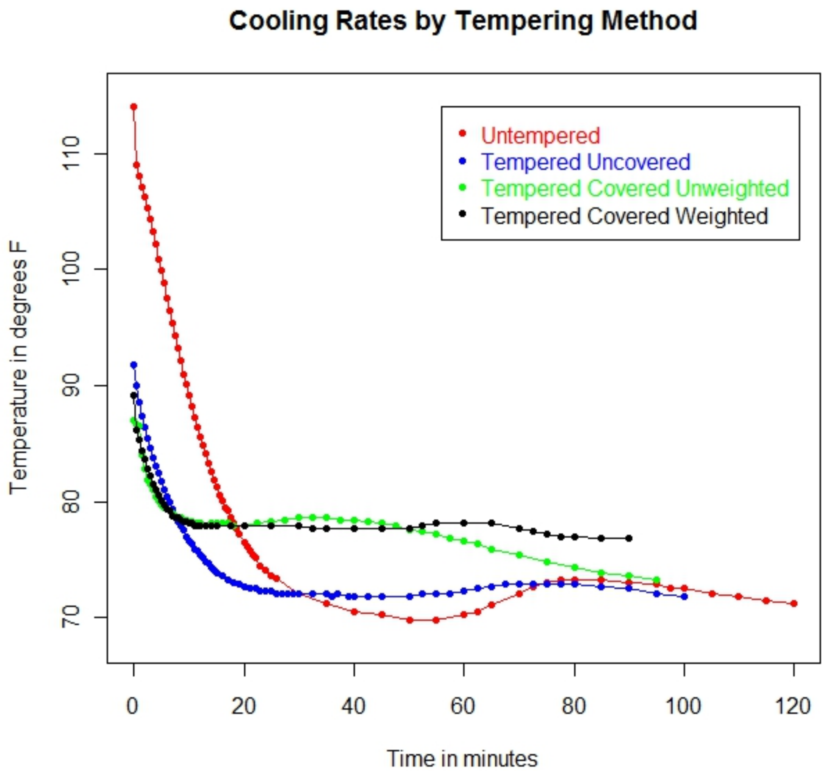


Figure 13: Temperature of chocolate over time. Note the different temperatures at which crystals form in the covered vs. uncovered trials.

Appendix B: Milk Chocolate, Percentages, and Lecithin

A lot of people have been asking about milk chocolate, so I thought I'd outline the things that make milk chocolate different from ordinary chocolate. As part of the discussion, I'll also cover the meaning of the percentages you may have seen on some upscale dark chocolates, as well as the use of lecithin in chocolate.

To begin with, milk chocolate has three critical ingredients: cocoa liquor, sugar, and powdered milk. Note that the milk has to be powdered (the water in liquid milk will cause the chocolate to seize and be ruined).

The powdered milk is what gives milk chocolate its defining physical characteristics: different taste (both from the added milk flavor and the decreased chocolate flavor), lighter color, and crumblier/pastier consistency. Alert readers will notice that the last two qualities are also defining characteristics of poorly tempered chocolate. There is a reason for this.

As mentioned in the previous Appendix, the structure of solid chocolate is defined by the crystalline matrix formed by the cocoa butter molecules. The remaining particles of the chocolate, the flavor particles and the sugar, are essentially coated by the cocoa butter and suspended within the matrix (since the flavor and sugar particles are polar, they do not mix easily with the nonpolar lipid tails of the cocoa butter).

Adding in additional particles (namely, the powdered milk) means that the cocoa butter matrix now contains even more impurities than in dark chocolate. These impurities destabilize the crystalline matrix, making even well-tempered milk chocolate behave like poorly tempered dark chocolate.

One of the ways to solve this instability is to add more cocoa butter. With more cocoa butter molecules relative to non-cocoa butter particles, the matrix can be shored up and made more stable. By adding more cocoa butter, however, the relative concentration of chocolate flavor particles is decreased, which results in the lighter color and weaker chocolate flavor of most milk chocolates.

Another way to increase the stability of the chocolate without adding additional cocoa butter (which is expensive and can reduce the flavor of the chocolate bar) is to use lecithin. Lecithin, which usually appears as "soy lecithin" on ingredients lists, is an emulsifier (literally, a chemical that helps to stabilize an emulsion like that of the particles in the cocoa butter). More precisely, it is a phospholipid that can mix with polar particles at one end and nonpolar particles at the other. Because it can create a highly miscible interface between the flavor particles and the cocoa butter matrix, lecithin is a far more effective tool for increasing the stability of chocolate than merely adding cocoa butter.

Besides the different physical characteristics of milk chocolate, there are also additional challenges in its manufacture. Because powdered milk is more delicate than the other chocolate particles, milk chocolate has to be kept at lower temperatures throughout the tempering process. The interference of the extra particles with the cocoa butter matrix also changes the melting temperatures of the different forms of chocolate. Because of these difficulties, we will have to have a secure hold on the dark chocolate process before venturing into milk chocolate.

Finally, the meaning of the percentages on chocolate bars. If a dark chocolate bar advertises itself as "85% dark" or "85% cocoa content", this means that chocolate flavor particles and cocoa butter combined make up no less than 85% of the mass of the chocolate bar. The percentage allows us a (somewhat) mathematical way to rate the intensity of a chocolate bar.

Note that this measure by no means directly corresponds to the actual intensity of the bar. Because the mass of the cocoa butter is included in the calculation, you could theoretically call a hunk of cocoa butter "100% chocolate", though it would taste nothing like Baker's chocolate, which is the typical example of 100% chocolate.

For reference, dark chocolates tend to be greater than 35%, with nicer ones greater than 60%. Milk chocolates must be greater than 10% in the US. [5] Our dark chocolate will have to be 70% or greater, since we are not adding any additonal cocoa butter to our bars (below 70%, there are too many additional particles that extra cocoa butter or lecithin becomes necessary to stabilize the bar).

Appendix C: Water and Chocolate

Water is very bad for chocolate. If you've read Appendix B, you'll know that solid chocolate is made up of flavor particles (and sugar) suspended in a crystalline fat matrix. The flavor particles are, for the most part, polar (hydrophylic). The fat matrix, being made of fat, is largely nonpolar (hydrophobic). For those of you who haven't already forgotten high school chemistry, this means that the flavor particles don't mix very well into the fat matrix.

On the other hand, those polar particles love to mix with water. If you put even a little bit of water into liquid chocolate, the nearby flavor particles will preferentially dissolve into the water. They can dissolve in a much higher concentration in the water than the fat matrix, so they form dense clumps, depleting the surrounding areas of the chocolate. This process is known as "seizing".

Because these clumps are large compared to the individual particles that compose them, the fat matrix has a much harder time coating them. The crystalline structure can't readily form around these impurities, so it is weakened. You end up with pasty, crumbly chocolate. As if that weren't bad enough, the clumping of the flavor molecules drastically changes the taste of the chocolate. I don't know the exact mechanism, only that it tastes really bad and is unmarketable.

If your chocolate has seized, you're pretty much screwed. There's no known way to fully resuscitate seized chocolate. If you're careful, you can maybe get the seized chocolate to solidify, but it still won't taste good. Your best bet is to start over with a new batch of chocolate and be very careful to avoid getting any water in it.