The Chemistry of Baking

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THE CHEMISTRY OF BAKING

By

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Graduation with Honors from the
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Abstract

The processes of cooking and baking can be described by molecular-level chemical reactions. By identifying the key variables of flour-based baked goods, it is possible to manipulate recipes and create an improved overall final product. This thesis explores the effects of manipulating proteins, water, lipids, air, and the biochemical reactions of yeast in baked goods.
Cooking is one of the milestones in human evolution. In trying to understand how we became what we are, researchers have traced the controlled use of fire back to approximately 1 million years ago (Berna, 2012). Richard Wrangham (2009), a biological anthropologist at Harvard University, has gone a step further. Because cooking makes extraction of nutrients from food easier, Wrangham argues cooking provided a tremendous boost to our immediate evolutionary ancestors. An advantage that still holds to this day since every culture we know of incorporates cooking.

After harnessing fire it took some time before we find recorded thoughts on what made food the way it is. The Greek philosophers Democritus, Leucippus, and Epicurus (of the Epicureans) pondered the nature of matter and hypothesized that matter was made of up atoms and that these atoms had shapes which reflected the material’s properties. In the case of salt, the atoms were thought to be sharp and pointed because of the taste (Pfeffer and Nir, 2001). This was later expanded to “Bitter taste is caused by small, smooth, rounded atoms, whose circumference is actually sinuous therefore it is both sticky and viscous. Salt taste is caused by large, not rounded atoms, but in some cases jagged ones.” (Kirk et al, 1999)

But philosophy isn’t where we normally turn when learning about food. Cooking started as an act, even if it was an accidental one. Once the utility of cooking was established it could only have been learned by watching, imitating, and talking. Writing had not been invented yet so cookbooks were out of the question and too much trial and error meant wasting valuable food (at best) or poisoning those you were cooking for (at
Even today cooking is often learned at home while practicing with a patient parent, grandparent, relatives, or friends who don’t mind falling back on delivered pizza if things don’t work out right. Professional chefs work their way through the ranks and routinely apprentice in the kitchens of more established chefs.

Has television changed this? Though cooking shows first appeared in the 1940s (James Beard, Joseph Milani, Ernie Kovacs, and Dione Lucas), many think back to Julia Child on PBS, or for those too young for that, their favorite celebrity chef on Food Network, The Cooking Channel, or any of a host of shows on a variety of channels. In fact, 80% of adults over the age of eighteen watch some type of cooking show each week (Harris Poll May 10-17, 2010). But this is not necessarily helpful. Back in 1996 a poll conducted by the American Meat Institute found that 53% of respondents said they knew less about cooking than their mothers or grandmothers (16% said they knew more). It could be argued this is reinforced by the Harris Poll which revealed that 30% of adults prepare less than two meals at home a week. The silver lining in all of this is 70% of American adults prepare three or more meals per week at home.

As instructive as the data are on how often adults cook, the question of what they cook also reveals something important. Familiar recipes are used 81% of the time, and % of respondents said they would use pre-prepared or pre-packaged convenience foods to help cut corners in the kitchen. Less than half (46%) often use written recipes/techniques and only 41% used television shows and/or Internet resources as inspiration for new additions to their cooking repertoire. This is perhaps a blessing in disguise because a study published in 2012 in the *British Medical Journal* assessed 100 different celebrity chef meals and 100 ready to eat meals from supermarkets and found that none fully
complied with the nutritional standards of either the World Health Organization or the United Kingdom’s Food Standards Agency.

People may feel crunched for time and families may be fragmented more than they used to be. To the extent that this is true it is reasonable that cooking is perceived as more of a chore than in other times. For those looking for information about cooking and who wish to understand what they are doing in the kitchen it would seem that television and other media are a poor substitute for the personal interaction that used to occur more frequently in the kitchen. As noted above, “celebrity chef” cookbooks may not be the best resource from a health perspective, and in fact, many cookbooks have little more than recipes organized by some hierarchy. Yet as slow food and local/seasonal eating habits combine with awareness of health issues from overeating, there are many who want to understand what is happening when they cook. What is a critical step or ingredient and why? Can a desire to make a dish healthier inadvertently ruin it? What about alternatives that can save calories or fat? Why do some food labels sound like you should be wearing a HAZMAT suit when opening the package?

The above questions are just specific versions of “What is going on when I cook?” and this is, for the most part, ignored in cookbooks. This thesis, however, is very much concerned with understanding what is happening and explaining it on an atomic/molecular scale. Please, don’t stop reading now! Most people study no more chemistry than is absolutely required and that is precisely why this thesis has been written: to show how chemistry does not have to be relegated to labs where individuals in white coats use glassware and hazardous chemicals. Instead, chemistry is about understanding how the world around us behaves. Eating is something we all engage in.
Cooking is an act that turns into a monotonous chore for the vast majority of us. So why not understand food and cooking a little better? Why not use a knowledge of chemistry to see what can and can’t be done with a recipe? Maybe even spot a recipe that is doomed from the start and not worth the effort in the first place? Few of us go to culinary school but almost everyone takes at least one chemistry class in high school. It is possible to enjoy food and cooking without either, but for those that want an advantage in the kitchen, prior formal instruction in chemistry (even if it was a long time ago) makes you closer to a chemist than a trained chef. With this in mind, it is time to delve into atoms and molecules. Then recipes and explanations come. Or for those that remember their chemistry or are just impatient, jump to the recipes but be prepared to flip back in order to understand the full explanation. Either approach will provide you with the chance to see what happens with food and cooking at a molecular level. Or more importantly, how relevant chemistry can be to explaining things that are important to you in everyday life.

By Jack G. Goldsmith, PhD.

University of South Carolina
Chapter 1: Variables in Baking

When you consider baking at the molecular level, the key players are the same as in any living system: proteins, lipids, and carbohydrates all interacting in an environment dominated by water. The raw ingredients of baking are all derived from a living source, after all, so it makes sense that the most important molecules in our bodies or in the cells of a plant or the milk of a cow are also the most important molecules when we bake. Complex molecules like proteins and lipids and carbohydrates do the heavy lifting, but in baking and in life, none of the chemistry would be possible without water.

Water is one of the simplest yet most important substances in chemistry. A small, polar molecule, it’s often called the “universal solvent”. It’s the only substance known to occur naturally in all three phases of matter: gas, liquid, and solid. As we will eventually learn, all three phases of water play important roles in the chemistry of baking. Water is needed for so much more than boiling pasta or making coffee, although these are probably its most important uses for college students, and in this thesis we will learn of its importance in everything from gluten formation to mechanical leavening (more on this later).

First let’s look at the structure that makes water unique. The chemical formula of water, as most people know, is H$_2$O. Each hydrogen atom is bonded to the central oxygen atom. The oxygen atom also has two lone pairs of electrons, that is two pairs of electrons that are not shared with any other atom. These lone pairs give water its bent shape and its polarity, an extremely important property.
Water is a polar molecule, which means it has strong intermolecular forces like dipole-dipole interactions. It is also capable of hydrogen bonding, the strongest intermolecular force. Hydrogen bonding occurs only when hydrogen atoms are bonded to oxygen, nitrogen, or fluorine atoms. The molecules then form a strong network of interactions. Hydrogen bonding causes water to have a very high boiling point. Most substances of similar molecular weight to water boil at very low temperatures, but water boils at the relatively high temperature of 100°C. We would never be able to cook with water if it boiled at, say, room temperature.

Dashed lines show hydrogen bonds between water molecules:
Water’s polarity also helps it act as an excellent solvent for most substances. Small water molecules can completely surround molecules or ions of other substances, pulling them apart and creating solutions.

Water molecules solvate ions of sodium and chloride:

In baking, we rely on water to do a lot of heavy lifting, so to speak. Most types of dough and batter start out as essentially a suspension of ingredients in water. The water allows the important structural molecules, like proteins, and other components like sugars and lipids to interact and produce their chemistry (Potter, 2010). Consider what would happen if we tried to make a batch of chocolate chip cookies without any wet ingredients. We’d mix the sugar, then sift in flour, salt, and baking soda. Then we’d add in plenty of chocolate chips and end up with a bowl of chocolate chips covered in an unappetizing
white powder. I shudder to think about the wasted chocolate if we tried to put them in the oven. Now if we had properly introduced water through the addition of butter and eggs, the sugar would dissolve and the proteins in the flour would interact to give the dough its proper consistency. Then, once the dough enters the oven, the water vaporizes, drying out the dough and allowing the solid structure to form. The water vapor also expands to provide mechanical leavening to our cookies.

As a biochemist, I have a particular appreciation for the importance of proteins. They are responsible not only for the metabolic functions within our cells, but the structure of those cells, communication between cells, and much more. Despite their importance, their true structure and function can easily be forgotten when we think of proteins in the kitchen.

In cooking, “protein” is typically used as a general term to refer to the animal-derived portion of the meal, or as the essential nutritional component that we all know is necessary for building muscle and staving off anemia. Proteins are quite literally the building blocks of life, and as such are present in nutritionally significant quantities in most vegetables and grains, not just in the tissues of other animals. (As a longtime vegetarian, you’ll forgive me for being passionate about this fact.)

Now you may be wondering, since we’re talking about baking in this thesis, why is the protein content of vegetables important? Cupcakes and pastries are not known for their high protein content. However, manipulating proteins will be one of the most important things we do in order to create the many different baked goods in this book.
The most important protein we will talk about is gluten. This is the large protein network formed from proteins found in wheat (gliadins and glutenins). It is responsible for creating the structure of dough and the consistency of the final product (Coultate, 2009). For more about how to manipulate gluten, see page 10.

Proteins are very large molecules that are essentially long strings of amino acids. There are 20 amino acids typically found in nature. They differ from each other in subtle ways, as we will see on page 13. The bonds in protein molecules can be broken quite easily at the temperatures we use for baking, allowing amino acids to move around and combine with other molecules, like sugars. When this happens we observe the Maillard Reactions. This is the browning that we see on the crust of bread or the bottom of cookies. (For more about this reaction, see page 45.) It is quickly apparent how important proteins are, since they provide both the structure and color of baked goods.
Chapter 2: Proteins- a Closer Look

Gluten is a major buzzword in the food world these days, but there are probably more misconceptions about it floating around than actual fact. Every food blogger on the internet seems to be on some sort of gluten-free, soy-free, raw vegan diet and they all swear that going gluten-free is the magical key to weight loss, clear skin, better health, etc. (I just wonder what is the point of being a food blogger if all you can eat is lettuce?) Unfortunately most of their claims about the evils of gluten are inaccurate. For people with celiac disease, an autoimmune disorder of the small intestine that is caused by a reaction to gliadin, one of the two component proteins of gluten, a gluten-free diet is truly the only treatment and eliminating gluten will improve their condition. The same goes for individuals with a more vague “gluten sensitivity”, often caused by an underlying wheat allergy. (When I studied in France my friend Hanna developed gluten sensitivity from consuming mostly bread and beer and cheese and not much else while we were there. A casualty of the lifestyle of poor French students, which has been greatly mourned.)

So what is gluten anyway? Gluten is the protein component of bread; it is what gives bread it’s lovely, airy, chewy texture and allows the bread to rise by trapping carbon dioxide released by yeast, and retains this texture by trapping the steam released during baking. Gluten is actually a composite of the two major proteins found mainly in wheat, glutenin and gliadin (Coultate, 2009). The structures of these proteins are not well characterized, but some of the functionally important elements of each protein have been described.
There are three types of gliadins, which are primarily monomeric proteins. All three types of gliadins, including α-, γ- and ω-gliadin are responsible for the “gluten allergy” known as celiac disease. Gliadins are soluble in alcohols and their only intramolecular structure is disulfide linkages (discussed in just a bit). Glutenins are, in general, much larger proteins. They are insoluble and made up of aggregates protein polymers of both high and low molecular weight. These polymers contain intermolecular disulfide bonds for stability. It makes up about 47% of the total protein in wheat flour and is responsible for the elasticity and strength of dough. You can think about glutenins as long strings that become stuck together in an elastic web through their interaction with gliadins. This elastic web is part of the essential process of gluten formation. As we work dough, this web of proteins becomes stronger and more durable, essential to proper break consistency. Glutenins and gliadins contain a high proportion of particular amino acids that allow them to form the gluten network, specifically glutamine and cysteine. Several types of bonding occur when glutenin chains link. Hydrogen bonding occurs between glutamines, and sulfide bonds form between cysteine residues. Certain other amino acids may also be able to form bonding interactions (Coultate, 2009).

It’s actually possible to physically separate out glutenins and gliadins from flour using nothing but water and rubbing alcohol. As you’ll see below, the differences in these proteins provide clues as to how they interact to form the matrix of gluten in dough.

**Separate your own gluten!**

Begin with approximately 1 cup of flour in a bowl. Add just enough water to form a very firm ball of flour. Set the ball of dough in the bottom of the bowl, and carefully
cover with water. Let sit for at least an hour. This allows the gluten to form and hydrates the starch.

After the ball of flour has soaked for an hour, remove it from the bowl of water. Turn your kitchen faucet on to a gentle stream and carefully run the ball of dough under the water while gently kneading and turning. This step rinses out all of the starch from the flour and leaves you with pure(ish) gluten. Continue rinsing until the water runs clear. You will have a very squishy, very stretchy blob of pure gluten that I’m sure would come in very handy if you ever wanted to play a practical joke on a gluten-intolerant friend.

Once you have completely rinsed out all of the starch, place the ball of gluten into a glass or bowl so that it is covered in rubbing alcohol. The glutenins and gliadins should separate out into visible strands. Experiment from Cooking for Geeks. (Potter, 2010).

When you mix wheat flour into an aqueous solution, (dough is an aqueous suspension after all- just a very viscous one) glutenins and gliadins are able to come together and form intermolecular disulfide bonds, crosslinking the molecules (Corriher, 1997). Disulfide bonds are formed when sulfur atoms of two thiol groups interact. In the
case of gluten formation, the source of the sulfur is cysteine residues on the surface of wheat proteins. Cysteine is an amino acid, which are the building blocks of proteins. As stated before, there are 20 amino acids in total, and they form long chains to create large proteins. Amino acids are a very important building block in chemistry and biochemistry, including the chemistry of food, which is, after all, a biological system. Therefore, it is important to deviate from the discussion about bread for a moment to fully understand the role of amino acids.

### Amino Acids and Their Role in Food Chemistry

Amino acids get their name from the common structure that they all share, which includes an amine (-NH$_2$) group at one end and a carboxylic acid (-COOH) group at the other end. In addition, all amino acids have a side chain (designated –R) in the figure below that can range from simply a hydrogen atom to long chains or ring structures containing atoms such as oxygen, sulfur, or nitrogen in addition to the carbon and hydrogen that make up all organic compounds. There are hundreds of synthetic and naturally occurring amino acids, but only 20 are used to build proteins within cells. These 20 are the only ones that will be important for our discussion. The standard structure of an amino acid is shown below. The R group stands for any side chain, which is the distinguishing feature of amino acids, and can range from a simple hydrogen atom to aromatic ring structures to chains containing functional groups like alcohols or another amino group.
This structure becomes very important when we discuss the Maillard reaction (see page 45). At different pH levels, that is to say different levels of hydrogen ion concentration present in any solution, either the carboxylic acid, the amine group, the side chain, all, or neither can be protonated or deprotonated. This greatly impacts the reactivity of the amino acid and its ability to perform useful chemistry. At high pH, or basic conditions, which produce the most desirable Maillard reaction results, the carboxylic acid end is deprotonated while the amine group exists as NH$_3^+$. This is because the carboxylic acid is an acid, so it donates protons (also known as H$^+$ ions, while amine groups are generally bases and will accept protons. The carboxylic acid of most amino acids will lose its proton at a pH of around 2, and the amine group will tend to accept an additional proton at or below a pH of 9, so in a slightly basic dough we can expect that the amine group will be a better target for the reducing sugars that will help form flavor compounds (Coultate, 2009). The structures below illustrate the three differently protonated forms of glycine, the simplest amino acid.

Amino acids form the building blocks of proteins, which are essential for almost all functions of any cell (and that includes your body!). They form long chains by
creating peptide bonds between two amino acids, linking nitrogen to carbon. The formation of a peptide bond is shown below.

![Peptide bond structure](image)

Proteins are extremely important in food for many reasons, which I will elaborate later on in this thesis. For the discussion of bread and gluten in this chapter, the individual amino acids and their side chains are much more important to understand. This knowledge will of course come in useful when we exploring other cooking processes as well, because manipulating proteins is often the primary goal when cooking a food item. There are many different types of amino acids, but I will just show the structure of a few that will serve important functions later on.

Cysteine is probably one of the most important, because it is the only amino acid that contains a thiol (-SH) group and so can perform unique chemistry. Cysteine residues are often critical in holding the shapes of proteins and even stabilizing complexes of proteins. It is particularly important in the development of gluten, as will be discussed shortly. Observe the structure of the thiol side chain:
Other important amino acids are those with side chains that can perform meaningful chemistry, which usually means they have an alcohol (-OH), amino (-NH2), or carboxylic acid (-COOH) side chain. Here are a few examples:

Glutamic Acid  Serine  Lysine

Cysteine is the only amino acid that is capable of forming disulfide bonds, and as such is very important in creating the tertiary structure of proteins. What we refer to as the primary structure of a protein is simply the sequence of amino acids linked together, and the second structure is α-helices or β-sheets formed as these amino acids form peptide bonds. Tertiary structure is the larger, 3D structure that is created by amino acids
that are distant in the overall amino acid sequence interacting via their side chains. Below there is an image showing how two cysteine residues form the disulfide bridge that provides the crosslinking of proteins. As the rough diagram below shows, glutenins and gliadins come together and form several disulfide bonds with each other, linking them into one molecule, gluten.

Formation of a disulfide bond between cysteine residues of two proteins:
Glutenin strands (grey) link to gliadin (green) through disulfide bonds:

However, simply letting the gluten form on its own is extremely inefficient (Potter, 2010). Though sticky, dough is not terribly wet, so the protein molecules don’t have a lot of room to float around and bump into each other. This is where kneading comes in. Kneading the dough physically pushes the protein molecules together, allowing the disulfide bonds to form. It also stretches these bonds, aligning the gluten into long parallel sheets that allow it to trap air efficiently. In addition, kneading the dough hydrates the gluten, as shown in the figure below. Hydration introduces small pockets of water in between the layers of gluten. During baking, these water pockets turn to steam and create the final rise of the dough, known as ovenspring (Corriher, 1997).

Water hydrates gluten as it is stretched through kneading (Reuben and Coulitate, 2009):
Recently, recipes for bread that requires no kneading at all have become very popular. I was skeptical that these recipes would produce desirable bread, but when I tried a recipe for myself I found the results to be quite pleasing. These recipes accomplish substantial gluten formation because the dough contains more water than most bread dough, allowing the protein molecules to interact on their own easier. The dough also has to sit out at room temperature for a full 24 hours. As I explained previously, normally we must knead dough for several minutes in order to overcome the slow rate of gluten formation, which is known as the rate of reaction in chemistry (Potter, 2010). There are several ways chemists can speed up the rate of reaction during an experiment, chiefly agitation (stirring or, in the case of making bread, kneading) and heating.

Interestingly enough, some kneading actually does occur when the no-knead bread dough is sitting out overnight, it’s just not done by your hands. When the yeast
releases carbon dioxide, the gas forms bubbles that move upward through the dough to try to escape. The pressure that these bubbles exert on the newly forming gluten strands stretches and hydrates them on a very small level. The additive effect of many bubbles moving through the dough over many hours creates similar levels of gluten as does several minutes of kneading. However, there is a real trade-off when it comes to time. No-knead break takes 6 to 8 times as long to make as traditional bread, so you have to decide if you want to complete your bread in the course of an afternoon, or if you’re willing to wait 24 hours.

When you try the No-Knead Bread recipe on page 69, you will find that it’s basically the least laborious bread recipe out there. Simply mix, let sit for 20 to 24 hours, and bake. I decided to test the time parameters of this recipe by making three small batches of this bread and baking one after 12 hours, one after 24 hours, and one after 48 hours. The dough that sat for 24 hours before baking definitely held the most carbon dioxide and produced the largest of the three loaves. As the pictures below show, the center loaf, which sat for 24 hours had risen the most and had the largest pockets of air within the bread structure. The loaf that only sat for 12 hours did not have the time for gluten to properly form, so the carbon dioxide escaped from the dough. The dough that sat for 48 hours developed plenty of gluten, as it was extremely chewy. However it didn’t continue to rise and ended up much smaller than the 24 hour loaf, likely because the yeast used up the sugars readily available in the dough and ceased fermentation.
There are several large air pockets in the center loaf, the one that sat for 24 hours as the recipes recommend. The loaf on the left sat for only 12 hours, and the lack of air pockets shows that the dough did not develop adequate gluten to trap the carbon dioxide within the dough. Finally, the dough on the right, which sat for 48 hours, has air pockets but overall seems very dense.
Bread is the staple food of most cultures around the world and was one of the first food products ever created by early humans. Raising wheat for production of bread and beer was a major driving force for humans to abandon the nomadic lifestyle and develop a settled, agricultural lifestyle for the first time. There are thousands of different styles of bread from all around the world, from basic flatbreads to sourdoughs to complex pastries, all unique but based on the same basic principles.

The very simplest definition of bread is a dough of flour and water that has been baked. However there are a multitude of other ingredients added to bread to improve flavor, texture, and to make it rise. Throughout this chapter I will explain the role that these ingredients play in the bread making process and how we can manipulate them to create a more ideal bread.

First, let’s discuss the flour. As we will learn a little later on, the protein component of flour is the most important element to creating successful baked goods, but flour typically contains only between 8 and 13% protein (Corriher, 1997). The vast majority of flour is starch, the digestible carbohydrate component. The rest is fiber, water, and trace amounts of fat and minerals. Wheat is the most common grain used to make bread because most other grains aren’t capable of producing sufficient amounts of gluten, or they produce other compounds that inhibit gluten formation (Potter, 2010). Wheat was the first cereal crop to be domesticated by humans, and there are entire books about the domestication of wheat and how important the crop was to the development of agriculture and even human civilization itself. Anthropologists believe that the discovery
of how to produce bread and domesticate wheat to produce reliable crops is what lead Neolithic humans to settle down and form farming villages, eventually leading to large cities, structured civilization, and everything goes along with it. Although if you really want to impress your friends at the bar, you can break out this wonderful bit of knowledge: many researchers now believe that beer, rather than bread, was the first product intentionally produced by humans from wheat, and encouraged its domestication.

The type of flour that you choose to use when you bake is extremely important. For most everyday baking, all-purpose flour will work just fine. However, when making bread or pizza, a flour that has a higher protein content will produce a chewier final product. For fluffy cakes and flaky pastries, we want to minimize the gluten formation, so we may use a low-protein pastry flour. The following table compares the typical contents of various types of flour. When learning new recipes, it’s important to keep in mind that different brands of flour often have very different protein content, so for consistent results you should try to stick to one brand. Flour can also vary in the amount of carbohydrates, in the form of starch and sugars, and fiber. Whole-wheat flours will naturally have a much greater fiber content than others. However, carbohydrates and fiber don’t have as much of an effect on the final product as the protein content.

<table>
<thead>
<tr>
<th>Type of Flour</th>
<th>Protein Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-Purpose</td>
<td>9-12%</td>
</tr>
<tr>
<td>Bread</td>
<td>12-16%</td>
</tr>
<tr>
<td>Pastry</td>
<td>9-10%</td>
</tr>
<tr>
<td>Cake</td>
<td>8-10%</td>
</tr>
</tbody>
</table>
Water is the next critical ingredient in bread. It allows the gluten proteins to form, hydrates the dough, and creates steam during baking. The amount of water in the dough must be carefully controlled and varies depending on the type of bread being made. Most bread dough contains 25-40% water as compared to the amount of flour (Potter, 2010). Less water means denser bread, more water means lighter bread that rises more during baking. Technically, simply water and flour will create bread when baked, but it will be a flatbread and it probably won’t taste very good. My recipe for aloo paratha, an Indian potato-filled flatbread, uses very dense dough of just whole wheat flour and water, with salt and olive oil for taste. You can find this recipe later on page 72 and see for yourself how simple, unleavened dough turns out. I will warn you in advance, the recipe is an arm workout.

Yeast is the real champion in this story, the hero that saves the world from dense and tasteless bread, but it doesn’t always get the glory it deserves. I think this is because many people don’t fully understand what yeast does or even what it is. To clarify, yeast is a living single-celled microorganism. There are actually thousands of different species of yeast and are ubiquitous throughout the world. Most are completely harmless or even beneficial, and the first leavened breads were the result of natural yeasts in the air getting incorporating into the exposed dough left alone for several hours while the early baker was off gathering (Corriher, 1997). Just like animals, yeast releases carbon dioxide into the environment as a result of respiration. In bread, yeast cells consume sugars in the dough, break them down as food within their cells, and then release carbon dioxide as a by-product. This carbon dioxide gas forms bubbles within the matrix of the dough and causes the dough to rise when it is trapped by properly formed sheets of gluten. Many of
the flavors present in bread come from other metabolites of yeast, such as lactic acid. Yeast also has a very distinctive smell and creates the unmistakable aroma of baking bread. In my opinion, filling the house with that smell is worth the entire effort of making bread. Let’s look a little closer at the chemistry behind biological leavening.
Chapter 4- Microbiology at its Finest

Yeast are single-celled microorganisms that function as an essential leavening agent in most bread recipes. Yeasts are fungi that convert carbohydrates into carbon dioxide and alcohol through fermentation. While the term “yeast” is usually understood as *Saccharomyces cerevisiae*, the species used in bread making, winemaking, and brewing, there are actually over 1,500 known species of yeast (Coultate, 2009). Most are beneficial or ubiquitous, but some can even be pathogenic. Yeasts are eukaryotic organisms, meaning their cells have all the same organelles and most of the same molecular components as our cells. As such, yeasts provide a very important biochemical model system used in research. In fact, *S. cerevisiae* was the first eukaryotic genome to be completely sequenced. For simplicity, for the remainder of my conversation about yeast I will be referring to *S. cerevisiae*, baker’s yeast, unless otherwise specified. So yeast = *S. cerevisiae*.

*S. cerevisiae* cells:
Yeast is a living organism, and as such it has some very specific requirements for it to do its job. Yeast grow best at around 85 degrees Fahrenheit, but can be killed if temperatures get too high. Yeast also become dormant if temperatures get too low, which is why it’s so important that dough is left to rise in a warm area. Yeast must have an easily accessible food source, which is why we often add a small amount of sugar or honey to dough. However, bread flour contains maltose, a sugar that yeast can easily metabolize, so adding sugar isn’t strictly necessary (Coultate, 2009). Adding sugar simply helps “jump-start” the yeast’s action.

The yeast that I use in all of my recipes is active dry yeast, which is different from instant or rapid rise yeast in that the cells are coated in a thick protective layer that preserves the cells. The granules must be rehydrated prior to being mixed with the flour, which is why we let the yeast sit in a mixture of warm water and sugar or honey for about ten minutes before using them. Instant and rapid rise yeast have much smaller granules, so they can be sufficiently rehydrated with just the water added into all of the dry ingredients (Potter, 2010).

I performed an experiment to show the importance of the temperature of the water used to activate yeast. The water must be warm, but water that is too hot can kill the yeast. I set up five experimental conditions in which to test the activation of yeast: cold water, cold water with sugar added, warm water, warm water with sugar, and boiling water with sugar. I sprinkled ¼ teaspoon of active dry yeast granules over each container and waited ten minutes before observing the activation. Activated yeast forms a dense foam on top of the liquid as carbon dioxide starts to form. As the pictures below show, significant activation was only present in the glass that contained warm water with sugar.
added. Those conditions provided a food source for the yeast cells to use for fermentation and a temperature that promoted a fast metabolic rate.

From left to right: cold water, warm water, cold + sugar, warm + sugar, boiling

A layer of foam is clearly visible on top of the fourth glass, the one with warm water and sugar. Under every other experimental condition, the granules of yeast simply sank to the bottom of the glass. The granules sink as they become hydrated, but if the conditions are favorable to fermentation carbon dioxide bubbles form and bring yeast cells back to the surface, forming the foam. As you can see in the picture, the glass with the foam is also much more turbid than the other glasses, an indication of this movement of the microorganisms.
Recipes call for activating yeast in warm water and sugar for a very good reason, but they don’t always call for using plain table sugar. Many use honey, and I often use agave nectar because it’s what I use to sweeten my coffee. I tested if sugar or honey produced more fermentation using a similar method to the temperature experiment. I mixed warm water with about a tablespoon of sugar or honey, and then added ½ teaspoon of yeast. I also used warm milk, to test if yeast could ferment the lactose in milk, and an artificial sweetener, to test if a sweet but sugar-free bread would be possible (although I’m not sure why anyone would want that). Honey produced the most fermentation, although sugar produced almost as much. Unsurprisingly, the artificial sweetener produced no fermentation. The milk did not produce any fermentation either, showing that baker’s yeast is not capable of fermenting the disaccharide lactose. Many microorganisms can ferment disaccharides, but fermentation of monosaccharides is
generally faster. This is why honey, which contains the monosaccharides glucose and fructose, is fermented faster than table sugar, which is a disaccharide molecule called sucrose.

Structures of common mono- and di- saccharides:

Glucose

Fructose

Sucrose (table sugar)

Maltose (found in wheat)

Lactose
Left to right, the glasses contain sugar, artificial sweetener, honey, and milk. The thick layers of foam are clearly visible on the glasses containing sugar and honey. The granules of yeast did not sink in the glass containing artificial sweetener, so there was a layer of bacteria on top of the liquid. However, it was apparent that no bubbles of carbon dioxide had formed. Side by side with the sugar glass, you can see that the honey produced a thicker layer of foam. Both layers of foam had large bubbles of carbon dioxide, showing that the yeast cells were very happy with their environments.
To further illustrate the real power that these tiny cells have, I tried a different method of activating the yeast. I dissolved 1 tsp of sugar and 2 tsp of yeast into ¼ cup of warm water and let it sit. At first the mixture looked just like the usual methods did, but after about 5 minutes, a thick foam had developed. Ten minutes later, the foamy mass had doubled in size. After ten more minutes, the yeast foam was ready to overflow the bowl.

Five Minutes

Fifteen Minutes

Twenty-five Minutes

After this yeast had activated so nicely, it was clear that I had some very happy microbes. I added the yeast foam to a mixture of 1 cup flour and 1 cup water to see what it could do. The mixture started at a volume of about 400 mL in my
beaker, and after an hour the volume had more than doubled to over 1 L. These are some truly hardworking (and hungry) microbes.

Finally, I decided to test the importance of activating yeast prior to using it in dough. I prepared two batches of dough using identical ingredients, activating the yeast for one in water and honey beforehand, and simply adding the yeast granules to the dry ingredients for the other. The dough with pre-activated yeast rose much faster and produced a larger, lighter loaf of bread. The dough that did not have activated yeast still rose and nearly doubled in size after two hours, but produced a smaller loaf of bread that baked faster and browned more. Both loaves of bread were perfectly good, but if you want a really light bread that is risen to its fullest potential, it is important to activate the yeast and let the bread rise for several hours.
After one hour of rising, the dough with activated yeast (on the left) is clearly larger.

At two hours of rising, the activated dough is still larger, but the dough without activated yeast has started to catch up as the water hydrates both the gluten and the yeast granules.

The dough was then punched down and shaped into boules to proof for an hour before baking. The dough with activated yeast is still on the left.
Before proofing:

After proofing:

And the finished products:
Yeast in its current form has only been used by bakers for a little under 150 years. Before the field of microbiology was developed, bakers and brewers really didn’t have any way to manipulate the microorganisms that they were using to make their products. Fortunately for them, yeast and other bacteria that are capable of fermentation are abundant and can easily catch a ride from the field into the kitchen on the grain, flour, grapes, or whatever else was used to make bread or alcoholic beverages. (Not to mention that even the kitchen of the most neurotic germophobe is still filled with billions of bacteria.) When introduced into a wet environment with plenty of carbohydrate food sources but a lack of gaseous oxygen (aka dough), yeast start breaking down the carbohydrates and undergoing glycolysis and anaerobic respiration to turn sugar into ATP, usable energy to drive cellular processes, with the by-products of ethanol and carbon dioxide. Ethanol is what makes drinking wine so much fun and carbon dioxide is the gas that makes our bread rise (Coultate, 2009).
The reactions that happen when you add yeast to flour and water are fascinating and are extremely important for understanding even how your own body’s cells function. From all of the different organic molecules that we take into our bodies in the form of food, the only one that our cells really care about is glucose. All of the proteins, lipids, and complex carbohydrates can be broken down and altered until their carbon atoms are used to make 6-carbon glucose molecules. Those glucose molecules then enter a ten-step process of reactions known as glycolysis, where the glucose molecule is eventually turned into two 3-carbon molecules called pyruvate. Under normal conditions in plant and animal cells, the cells use oxygen to create a huge amount of energy, recycling the by-products in the process. However, when oxygen isn’t available bacteria can get creative and undergo anaerobic respiration to produce either lactic acid or ethanol and carbon dioxide (Coultate, 2009).
Under glycolysis, glucose is metabolized to pyruvate without the production of CO$_2$. In an anaerobic environment, pyruvate will be converted to ethanol and CO$_2$ gas, which causes bread dough to rise.
Fats, provided by milk or butter, can aid the formation of bread structure, up to a point. Adding too much fat into the dough will cause too much lubrication, if you will, and prevent the proteins from crosslinking and cause the gluten strands to slide over each other rather than forming a strong matrix (Corriher, 1997). My recipe for Swirl Bread in the appendix includes both milk and butter, and the final product is wonderfully soft and light and moist. It’s not as chewy as traditional breads that are made without fat, but the dough still rose beautifully to an enormous, majestic loaf.

Fats featured prominently in one of the first recipes that I made, play dough. My mom used to make it all the time when I was little and I thought that she must be some sort of kitchen magician, but in reality it couldn’t be easier to make. For those who are new to the kitchen or nervous about making bread, play dough is the perfect place to start. No one’s going to eat it so you don’t have to worry about poisoning anyone, and making play dough will familiarize you with the process of hydrating dough, kneading, and forming gluten. All of the basic process of making dough come into play here. Flour and water create the gluten structure that allow the dough to hold its shape, but the addition of oil prevents the dough from becoming too stretchy so that it can be easily torn by tiny hands.
Lipids prevent a complete gluten web from forming:

However, the oil also performs another very important function, it prevents retrogradation of the starches in the dough. Retrogradation occurs when amylose and amylopectin chains realign to re-form a crystalline structure by forming hydrogen bridges while the chains are parallel. It is one of the processes that causes bread to go stale. When starches are dissolved in water, the crystalline structure is lost and they form a gel. This is one of the reasons why proper hydration is so important when making bread, so that the starch crystals don’t interfere with gluten formation. When you bake bread, water is removed but the starches remain gelatinized. After the bread is removed from the oven, starches solidify without returning to their crystalline structure, so it can take many days before any effects of retrogradation in baked bread are noticed. (In my experience, fresh-baked bread will be long gone before this has any danger of happening.) But play dough is intended to be used over and over again for several weeks or months, so this
retrogradation must be stopped. Fats prevent retrogradation by preventing the chains of starch from realigning in gel form during baking (Potter, 2010). The large, hydrophobic molecules of lipids get in between the starches and prevent the starches from coming in contact. The oil in this recipe keeps the play dough hydrated and malleable for weeks at a time, with proper storage.

A source of sugar is a very common ingredient in bread recipes, because it provides the yeast access to food. Yeast can break down the starches in flour, but it much prefers the simple sugars in honey, fruit juices, malt syrup, or even table sugar. Adding sugar creates a very desirable flavor, particularly in whole wheat breads. Many sourdough starters call for adding some sugar initially to jump-start the yeast’s metabolism. Traditionally, sourdough bread starters are supposed to consist only of flour and water and trap naturally occurring fermentative bacteria from the wilds of your kitchen (Corriher, 1997).

Sourdough starters that rely on catching wild yeasts are hard to accomplish. Days of feeding and waiting and feeding some more, only to realize that the yeast aren’t fermenting and dumping the whole smelly mess down the sink. So how do you get the sourdough flavor without all of the hassle? A yeast starter! This is essentially a wet sourdough starter with a small amount of active dry yeast added that sits overnight before being added to more ingredients to form the dough (Corriher, 1997). (The recipe can be found on page 75). The yeast multiply and ferment overnight, resulting in acid production that provides the sourdough flavor. This recipe is not a no-knead bread, after the starter sits overnight it is added to more flour and salt and the gluten is formed manually by kneading.
I compared the bread made with a starter after 12 hours to one made with a starter that sat for 24 hours. I experienced a similar result from my experiments with the no-knead recipe in that the longer the starter sat did not actually improve the results. The dough made with 12-hour starter rose much more than the dough made with 24-hour starter, likely because as time passed the yeast cells began to use up the sugars and ran out of nutrients, so by the time I made the dough there were not as many living yeast cells. The 12-hour loaf rose much more, even from ovenspring, as evidence by the large split in the loaf of bread. The 24-hour loaf was smaller and baked quicker.
Chapter 6 - Chemicals in the Kitchen

By now we’ve discussed plenty of methods of optimizing biological leavening in bread, but what about other baked goods? Bread is great, but every once in a while a girl needs a cupcake, and yeast is one thing that doesn’t really go with chocolate. When we bake cakes, cookies and other sweet things, we have to rely on other methods of leavening. Chemical leavening relies on the reaction of added chemicals to produce carbon dioxide gas, and mechanical leavening occurs when water vaporizes and gases expand inside the baking dough. Chemical leavening also works much faster than yeast, so you can have your biscuits in about 20 minutes rather than 4 hours.

Bakers generally have two options available to them for chemical leavening, baking soda and baking powder. These two leavening agents look identical, but they have very different properties. If you look through recipes, you will find that recipes for biscuits, cakes, and scones usually call for baking powder, while recipes for cookies typically call for baking soda. Let’s look a little closer at these two substances and examine why they are each ideal for different purposes.

Baking soda is actually sodium bicarbonate, or NaHCO₃. Bicarbonate ions are basic, and will react with an acid to produce carbon dioxide gas, which is the gas that gets introduced into the batter. Most people should have mixed baking soda and vinegar at some point in their childhood and observed the resulting explosion of foam. However, there must be an acid available for the bicarbonate to react with. Baking powder provides this acid. Baking powder usually consists of NaHCO₃ and acid salts like sodium aluminum sulfate and calcium phosphate. The bicarbonate ions can react with these acid
salts and release carbon dioxide right into the dough. Another benefit of using baking powder is that some formulas are double acting, meaning it will start to release carbon dioxide as soon as it is dissolved in a liquid, and will release even more carbon dioxide once it is heated during baking (Potter, 2010). We use baking powder to get fluffy biscuits and cakes, and you will see that my recipes for these call for baking powder.

Reaction of baking soda and vinegar, releasing CO$_2$:

$$\text{NaHCO}_3 + \text{CH}_3\text{COOH} \rightarrow \text{CH}_3\text{COONa} + \text{H}_2\text{O} + \text{CO}_2$$

Two-step mechanism that produces CO$_2$:

However, when I’m making cookies, I don’t want them to be light and soft and airy. I want them to be dense and crisp. Nearly all cookie recipes call for baking soda, but don’t include any acid for it to react with anyway. So what’s the point of including it? It turns out that baking soda actually greatly increases the amount of browning that occurs during baking. More browning equals more complex flavors, and that is never a bad thing. This is all due to the Maillard reactions, a very important set of reactions in
cooking that we have seen over and over in this thesis. The Maillard reactions occur between amino acids, the building blocks of proteins, and sugars. During baking or cooking, proteins from flour and eggs break down and combine with sugars in a variety of ways, producing hundreds of aromatic flavor compounds (Coultate, 2009). The Maillard reactions produce the crust on bread, and browning on meat, to name a few examples. The Maillard reactions actually work better in a basic environment, which explains why adding baking soda increases browning of the cookies.

A simple example of the type of molecules formed through the Maillard reactions:

When amino acids are in basic environments, they are deprotonated and have increased nucleophilicity, meaning that they will be more prone to attack sugar molecules and form new compounds. (See page 13 to refresh your memory about amino acids and their roles in cooking.) The baking soda makes dough or batter a more basic environment, thus speeding up the Maillard reaction (Potter, 2010). Nucleophilicity is a very important
concept in organic chemistry and biochemistry, but in the outside world it might not seem terribly relevant because it’s something that happens only at the smallest level of chemical processes. This is true, but nucleophilic reactions happen inside our bodies every day and are a pretty fascinating set of reactions to study. If you haven’t had organic chemistry in a while you’re probably thinking, “This makes no sense, why do I care about this word I can’t pronounce and how is it going to help me make better food?” Well, you do care about it and here is why.

A nucleophile is a chemical substance that donates an electron pair to form a bond. Chemists in the audience might recognize that this also makes it a Lewis base, but that’s not really relevant outside of an intro level chemistry class. Any molecule that has a free pair of electrons can be a nucleophile, but some are better than others. Ions or molecules with a negative charge will be much better nucleophiles than a molecule that simply has an extra pair of electrons. Since nucleophiles donate electrons, negative subatomic particles, they are naturally attracted to the nuclei of other atoms, because the nucleus contains the positively charged protons. Hence derives their name, nucleophile, meaning nucleus-loving. Nucleophilicity is a measure of how strong of a nucleophile a substance is. In regards to the Maillard reactions, amino acids become highly nucleophilic when in a basic environment because they lose the hydrogen atom off of their carboxylic acid, leaving a negatively charged oxygen atom that will easily donate its extra electrons to form a bond with another atom (Coultate, 2009).
Amino acids in an acidic, neutral, and basic environment, respectively:

\[
\begin{align*}
\text{Acidic:} & \quad \text{H}_3\text{N} - \text{CH} - \text{C} - \text{OH} \\
\text{Neutral:} & \quad \text{H}_3\text{N} - \text{CH} - \text{C} - \text{O}^- \\
\text{Basic:} & \quad \text{H}_2\text{N} - \text{CH} - \text{C} - \text{O}^-
\end{align*}
\]

Hopefully, you’re starting to pick up on the fact that if you can improve the nucleophilicity of your chosen chemical, be it in the kitchen or in the lab, it will react quicker and with a wider variety of substances. So the more basic the dough or broth or whatever else you want to be flavorful and brown, the quicker the Maillard reactions will happen and the more browned your product will become (and it will hopefully also be more flavorful). The simplest way to do this is to add baking soda, because the vast majority of food products are actually acidic (Potter, 2010). Baking powder will not increase the pH of your food, because as we discussed on page 43, baking powder is a mixture of basic bicarbonate ions and acidic ions such as tartaric acid, which is also known as cream of tartar. When mixed with water, the acids and bases in baking powder will simply neutralize each other and won’t change the overall pH.

Adding baking soda to promote the Maillard reactions is used most often in cookies and other baked goods. You’re not going to coat the outside of your steak with baking soda before you pan-fry it; that would be silly. However, many recipes that involve caramelizing onions suggest adding a small amount of baking soda in the pan. Another perfect example of raising the pH to increase crust formation is when you boil bagels or pretzels in water with baking soda dissolved in it before baking it. This creates
the thick crust that bagels are famous for, and also causes the crust to set very quickly so
the inside stays dense and chewy and the bagel doesn’t rise in the oven. In the case of
pretzels, the baking soda helps them to develop their characteristic dark color.

Another common way to encourage the Maillard reactions on the surface of baked
goods is to use an egg wash on top of the dough before baking. Primarily, the eggs raise
the pH of the surface of the dough, encouraging the Maillard reactions. Below are several
examples of the color that can be created when using an egg wash.

As I mentioned above, the baking soda is critical for creating brown and delicious
cookies through the Maillard reactions. I experimented with using baking powder in my
recipe instead of baking soda, using equal parts of both baking powder and baking soda,
and leaving out both chemicals altogether. Long story short: stick to the baking soda. The
original recipe is perfect. When made with baking powder, the cookies had a good cakey
texture but none of the great flavor produced by the Maillard reactions. I expected the
combination of baking soda and baking powder to produce a cakey and brown cookie,
but the result was flat and extremely crunchy. However the color was the same as the
original recipe, so the Maillard reactions did occur in that instance. When baking soda
and baking powder were both left out of the recipe, the result was incredibly similar to the baking powder recipe.

Left to right: baking soda (original), baking powder, both, neither

Original texture:
Baking powder texture:

Baking soda + Baking powder:

Neither added:
I’ve begun to sense a theme in my experiments… recipes are the way they are for a reason. If it’s not broken don’t fix it, and my chocolate chip cookies were certainly not broken.
Chapter 7- The Importance of Air in Baking

Chemical leaveners are an extremely important tool for every baker, but it is also essential to be able to manipulate the natural mechanical leavening that occurs every time you put dough or batter into the oven. Mechanical leavening uses the steam created when liquids in the dough or batter are vaporized during the cooking process (Potter, 2010). All baked goods undergo mechanical leavening to some extent (this is known as ovenspring), but it is the main leavening process in many pastries, while breads rely on biological leavening and biscuits and muffins rely on chemical leavening. One of the best ways to control mechanical leavening is through the addition of butter, which contains both fats and water, which can vaporize. If we control the temperature and size of butter incorporated into the dough, we can get some truly impressive results (Corriher, 1997).

The following image shows how gas expands to fill a balloon when heated. The same principle takes place when baking, the gas molecules are just water inside the dough and the “vessel” is whatever we are baking.
So how much airiness does this mechanical leavening provide? It’s simple enough to calculate. To chemists, vaporization is simply a phase change that can be defined and quantified by a set of equations and calculations. Most American grocery-store butters contain approximately 20% water and 80% fat. So let’s say we start with 10 grams of butter. That means we have 2 grams of water, which comes to approximately 0.1 moles of water. (A mole is a chemical unit that refers to the total number of molecules of material in a sample. One mole is exactly \( 6.022 \times 10^{23} \) molecules.) We can use the ideal gas equation, \( PV=nRT \), to roughly estimate how much volume of steam we will produce in our croissant. \( P \) is the pressure, which in the case of baking is atmospheric pressure, 1 atm. \( V \) is volume, which is what we’re looking for. The number of moles is \( n \), and \( R \) is a constant known as the gas constant. \( T \) is the temperature in Kelvin. A quick calculation later and we can expect that, if we bake our croissants at 400 degrees Fahrenheit, we will
produce almost 4 liters of steam! That much gas can create a lot of lift and separation within our croissant. If we were really motivated we could even calculate the amount of work that much gas could do on the croissant dough, but that’s a bit more suited for a physics textbook than a cookbook.

One of the best, and certainly most délicieux examples, of manipulating mechanical leavening is croissants. When making croissants for example, you start with cold, solid butter. When the croissants begin to bake, the butter quickly melts and then the water in the butter vaporizes into steam, greatly increasing in volume and separating the layers of dough. This is why it is so important to keep the croissant dough cold. If at any point in the turning or shaping process the dough becomes too warm, the butter will melt into the dough and the layers will disappear. There will be nothing for the steam to separate once the dough goes into the oven. A similar process is used in most pastries, scones, and biscuits. However instead of turning the dough, these recipes usually call for cutting cold butter into the dry ingredients, creating tiny beads or flakes of cold butter within the dough. The steam then creates bubbles of air and gives the biscuits their typically crumbly texture (Corriher, 1997). We’ll discuss this process in biscuits shortly, but for now, we shall journey to La France.

When you walk into a proper French bakery you will instantly be overwhelmed by a hot, yeasty, buttery aroma that can only be what heaven itself smells like. If you are really lucky you will see behind the counter a fresh batch of croissants, still on their sheet pan. The only logical thing to do at that point is order several of those piping hot beauties and try not to put all of them in your mouth at once. If you take the time to appreciate the
masterpiece in your hand you can begin to tease out all the aspects of culinary science that make the croissant such a wonderful pastry.

The most distinctive feature of a croissant is its buttery, flaky texture that derives from the thousands of alternating layers of butter and dough created when the dough is prepared properly. There’s also the chewy, yeasty bread created by using high-gluten bread flour and allowing the dough many hours of rising. The shiny brown surface created by an egg wash prior to baking is a perfect example of how bakers can use the Maillard reactions to their advantage. Croissants are a complicated pastry, and not to be attempted by the novice baker. But after you read all I have to say about the science of making this pastry, I promise you will never be able to settle for crescent rolls in a can again. At the end of this section you’ll find my recipe for chocolatines, a variation on the traditional croissant popular in the south of France.

The French call the layers of a croissant *milles-feuilles*, which means thousands of sheets. When you perform the turns of a croissant recipe, which simply means folding and rolling out the dough, you physically create over a thousand tiny layers of butter within the dough. This is how, if you keep the dough cold enough throughout the process, the finished product has so many visibly separated layers when you bite into it. It is imperative that the dough be kept cold so that the butter can provide mechanical leavening to the croissant. With the play dough recipe I made on page 68, I performed a little experiment to show the importance of keeping the croissant dough cold throughout the folding process.
Creating Layers: An Experiment

I made two different colors of play dough and split each color in half. I let one half come to room temperature and put the other half in the refrigerator to chill for 24 hours. Then I rolled out the play dough to imitate the process of the turns in a croissant recipe. Each turn involves folding a rectangle of dough in thirds like a letter and then rolling it back out to its original size. For the chilled play dough, I let it rest in the refrigerator for 30 minutes between each turn to ensure that the dough did not warm up from handling it. As you can see in the images below, the room temperature dough mixed together instead of forming discrete layers, while the chilled dough stayed mostly separated.

<table>
<thead>
<tr>
<th>Turn #</th>
<th>Room Temperature</th>
<th>Chilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1" alt="Room Temperature Image" /></td>
<td><img src="image2" alt="Chilled Image" /></td>
</tr>
</tbody>
</table>
As you can see above, by only the 3\textsuperscript{rd} turn the room temperature dough had already turned into a uniform mess. However, the chilled dough remained stratified until even after the 5\textsuperscript{th} turn. The play dough is not a perfect model, so it did start to turn purple, but if you look closely there are still clear areas of blue and pink, which would represent butter and dough in the croissant recipe. This easy experiment illustrates how important it is to prevent the butter from melting into the dough prematurely when making croissants.
and how being patient and using proper technique can mean the difference between monumental success and downright failure. No one wants a dense croissant.

Making croissants can be quite the lengthy process, and in this case I wanted to experiment with dough that rested properly in the fridge between experiments and that was left at room temperature. I also tested a “quick” croissant recipe that cut the butter into the flour instead of folding it in.

As expected, the croissants that turned out the best were the ones that were made by the traditional method and kept cold. They were by far the lightest and had the most visible separation. The croissants that were kept at room temperature still rose and separated somewhat, but were much denser overall. The quick method croissants were delicious, the flavor was exactly what it needed to be, but they didn’t have any flakiness to them. The pictures below illustrate the difference between the quick method, the room temperature, and the chilled croissants.

Quick method  Room-temp  Chilled
Detail of the flakiness of each croissant:

Quick  Room-temp  Chilled

Detail of the inside layers:

Quick  Room-temp  Chilled
One source of tremendous debate in the South is whether or not to use butter or shortening in your biscuits. If you want them truly fluffy, I say use butter. Butter contains water, which can vaporize, while shortening does not. Also butter is delicious. But don’t take my word for it; take a look at the following experiments. We already know that temperature is extremely important whenever you’re making biscuits, scones, pies, or other pastries. The first step of any such recipe is to cut cold butter into flour, and you’re always warned to handle the dough as little as possible. Just as with the croissants, this is to keep the butter solid so that when it hits the oven the water component of the butter can turn to steam. This separates the layers of the croissants, makes biscuits fluffy, scones crumbly, and pie crusts flaky (Corriher, 1997).

I experimented with a classic buttermilk biscuit recipe, using different sources of fat at different temperatures. I used cold butter, room temperature butter, cold shortening, and room temperature shortening. As expected, both the cold butter and the cold shortening produced more air pockets than their room-temperature counterparts.
I also tested baking the biscuits made with cold butter in a round cake pan with all of the biscuits touching, as many recipes suggest, versus on a sheet pan “drop biscuit” style.
The biscuit baked on the sheet pan rose more in the oven, but became much crisper on the outside and even burned in places in the same amount of time that it took for the biscuit baked in the round pan became lightly golden-brown.

We’ve seen the importance of using cold butter if you want to maximize the effects of mechanical leavening, but this is not the only situation in which butter can be useful. It’s a rare cookie recipe that doesn’t start out with a cup of softened butter. Softened butter you say? But keeping the butter cold is so important! It turns out that soft butter can be equally important in determining the final texture of the product, by incorporating air prior to baking through the creaming process. When you cream butter and sugar, the sugar crystals create tiny pockets of air in the butter, which can expand
when the dough is baked (Corriher, 1997). Ideally the butter should sit at room
temperature for several hours before beginning to make the dough. It’s tempting to try to
conserve time by popping the butter in the microwave for a few seconds, but
microwaving butter can turn it from solid to liquid in a split second. Liquid butter is
impossible to cream, and your resulting cookie dough will be dense and the cookies will
be flat and probably all run together in the oven.

Butter is a wonderful thing, and it’s a perfect example of how molecular structure
can be manipulated to suit the chef’s needs. Keeping the butter cold can create crumbly
pockets of buttery goodness inside a biscuit or scone, and even create the miraculous
layers of a croissant. Warm butter can cream with sugars to create microscopic air
pockets that give light and tender cookies. These changes in temperature allow the
molecules to adopt different conformations, which give different properties to the same
substance.
Get Cooking!

Whenever someone asks why I love chemistry, I always say its simple- chemistry is all around us! Chemistry can explain what happens in our bodies, in the air, how to make every product imaginable, and especially how to make my favorite foods and drinks. Through this thesis, I’ve had the opportunity to explore the chemistry of one of my favorite activities- baking.

By far, the most important chemistry to manipulate in baking is gluten formation. The amount of gluten that we allow to form can lead to a chewy pizza crust or fluffy cupcakes, and we can control this through the type of flour we use and the techniques used to prepare it.

Every individual ingredient we add is important and must be controlled carefully. Adding fats can soften the gluten formation in breads, or provide significant leavening or layer formation if the butter or shortening is kept cold. Choosing the right chemical leavener produces the proper texture in your final product. Adding proteins like eggs holds the product together. Manipulating the pH can change the color and even deepen the flavor of your product.

Even if you think you don’t understand chemistry, every time you go into the kitchen, you’re a chemist. And even if you’re a lab rat who survives on pizza, any chemist can translate what they know from chemicals to food. My own knowledge of both chemistry and food have been deepened greatly throughout this process, and I hope I can spread this knowledge to anyone else interested in chemistry, food, or both. The
recipes to follow help to illustrate the basic principles explored in this thesis, and once you’ve mastered the basics, a whole world of flavor exploration is open for you.
Appendix I: Recipes
Traditional Bread

Recipe adapted from Cooking for Geeks.

Ingredients:

3 cups bread flour
1 tsp salt
1 package active dry yeast
1 cup warm water
1 tsp honey

1. Combine the warm water and honey, sprinkle yeast on top and wait ten minutes until it begins to bubble.

2. Whisk together flour and salt. Add the yeast mixture and stir just to combine. Let sit 20 minutes.

3. Knead dough for about 5 minutes, until it is very smooth and elastic. Cover and let rise until doubled, 2 to 4 hours.

4. Punch down risen dough and shape into a boule. Cover again, and let proof for up to an hour while the oven is preheating.

5. Preheat oven to 425 degrees with a baking stone inside. Let the oven and stone heat up for a minimum of 30 minutes to ensure complete preheating.

6. Place a cookie sheet filled with water on the rack below the baking stone. Slash the top of the dough and then transfer it to the baking stone with a pizza peel or piece of cardboard.

7. Bake 30-35 minutes until golden brown and the bottom of the bread sounds hollow when tapped.
Play Dough

There are two additional ingredients in play dough that we haven’t discussed yet: significant salt and cream of tartar. Salt will be a component of almost every single recipe I put in this book, but usually just for taste. However, in play dough, salt is an important preservative. Cream of tartar also acts as a preservative, as it prevents mold. Cream of tartar is actually the potassium salt of tartaric acid, a carboxylic acid. It’s a common ingredient in baked goods, particularly in combination with baking soda. The cream of tartar provides acid for baking soda, a base, to interact with and release carbon dioxide gas. In play dough, the cream of tartar provides a high acid content that prevents the growth of mold. You don’t want your kid’s favorite new plaything getting slimy and moldy, after all.

Recipe from *Family Education*.

Ingredients:

- 3 cups flour
- 3 cups water
- 1 ½ cups salt
- 6 tsp cream of tartar
- 3 tbsp oil
- Food coloring

1. Combine everything in a large pot. Heat over medium heat, stirring constantly, until the dough pulls away from the sides and starts to form a ball.
2. Turn the dough out onto the counter. Carefully- it will be hot- start to knead the dough until it smooths out and takes on the consistency of play dough. This will take a few minutes.
3. Have fun creating with your play dough! You can see what I did with mine on page 56.
No-Knead Bread

All of the delicious reward of homemade bread, none of the tedious kneading or shaping. If you’re patient enough to wait 24 hours, or don’t have 6 hours at one stretch to devote to making traditional bread, this is the recipe for you.

Recipe adapted from Cooking for Geeks.

Ingredients

3 cups bread flour
1 ¼ cups water
1 tsp salt
1 tsp instant yeast (NOT active dry)

1. Mix just until the flour is completely moistened.
2. Cover with plastic wrap and let rest at room temp for 20 to 24 hours. The dough will have approximately doubled in size, and it will look very wet and bubbly.
3. Place a cast-iron pot in the oven and preheat the oven to 450 degrees.
4. Transfer dough to a floured surface and fold a few times. The dough will be extremely sticky. Roughly shape into a boule, although this dough does not hold shape well. Let proof while oven is preheating.
5. After dough has roughly doubled in size, the oven and pot will be sufficiently preheated. Dump the dough into the pot and cover with the lid. Bake 30 minutes.
6. Remove lid and bake another 15 minutes until the crust is dark gold. Enjoy!
**Swirl Bread**

This bread will change your life. It’s the perfect consistency for sandwiches, but it’s so delicious on its own that the likelihood of it lasting long enough to be made into sandwiches before everyone within smelling distance finishes it off chunk by chunk is slim to none. At least in my apartment a loaf of this stuff has never lasted more than 24 hours. No regrets.

As I mentioned before, this recipe contains both milk and butter, which introduce fat into the dough. Fat molecules inhibit the gluten formation so the resulting bread is much softer. The proteins and sugars in the milk also help create a lovely brown crust on this bread. The flavor possibilities with this bread are endless. My favorite filling to create the swirl that gives this recipe its name is sriracha and cheddar cheese, but making a swirl with garlic butter and parmesan cheese after mixing fresh rosemary into the dough was a very close second. But you could also make a sweet loaf of bread that would be perfect for breakfast by filling the inside with cinnamon sugar. Or Nutella. This is a great opportunity to get creative in the kitchen, fill this bread with whatever you think would be delicious and never look back.

Recipe adapted from *Parsley Sage and Sweet*.

Ingredients:

1 ¾ cup milk  
2 tbsp unsalted butter  
2 tbsp sugar  
1 package active dry yeast, or ¼ ounce  
2 cups bread flour  
2 cups all purpose flour  
2 tsp salt  
Fillings of choice, about 1 cup total

1. Put milk, butter, and sugar in a saucepan over low heat. Stir to dissolve sugar and heat just until butter has melted. The mixture should not be much warmer than
100°F or you will risk killing the yeast. You can be fancy and use a thermometer or just stick your finger in it and make sure it’s only lukewarm.

2. Sprinkle yeast on top of the warm milk mixture and let it sit for at least ten minutes to activate. When the yeast is activated there should be a good layer of foamy stuff on top of the milk, and you should smell yeast. If there’s no foam, you either killed your yeast by adding it to liquid that was too hot, or your yeast was expired. Start over.

3. Combine both flours and salt in a bowl, plus any herbs or other dry seasonings you wanted to add. Pour in milk mixture and mix until combined.

4. Transfer to a floured surface and need for about a minute, until the dough all comes together. Form dough into a ball and let rest in an oiled bowl for 20 to 30 minutes.

5. Transfer dough back to the floured surface and knead for up to five minutes, until the dough becomes very soft, elastic and smooth. Let dough rise in the oiled bowl until doubled, about 2 hours.

6. Shape dough into an approximately 9-by-12 inch rectangle. This is where you spread your delicious fillings over the dough, being careful to leave a 1-inch margin on the ends so that the filling doesn’t leak out. Roll up the dough so that it will fit in the pan.

7. Lightly oil the pan and then transfer your log of dough into the pan to proof. Let rise until the dough is puffing up over the sides of the pan, about another 2 hours. This is a good time to begin preheating your oven to 400 degrees.

8. Once dough is proofed in the pan and ready for baking, slit the surface of the dough lengthwise. Put your pan in the oven, and then place a cookie sheet filled with water on the rack below your bread. Bake for 30 minutes.

9. Remove loaf from pan and return to oven. Bake for another 10 minutes, or until the bottom of the bread sounds hollow when tapped.

10. Enjoy one of the most delicious creations you have ever experienced!!!
Aloo Paratha

As a vegetarian, I’ve developed a deep appreciation for Indian cuisine. An obsession, almost. With the help of an Indian neighbor, I started exploring cooking using Indian flavor profiles and traditional recipes. I’m including this recipe for aloo paratha, potato-filled flatbreads, as an example of a traditional bread using unleavened dough. When you make this dough, you will find that it is much more dense than the bread dough I’ve discussed previously, and that is of course because there is no yeast to introduce air into the dough. These delicious flatbreads are somewhat laborious to make, but absolutely worth it. Anyone you serve them to will undoubtedly think you are a culinary genius, which, after all, is the point of learning the chemistry of cooking.

Recipe adapted from *My Diverse Kitchen*.

First, prepare the filling:

Ingredients:

1 onion, diced

About 4 potatoes, enough to make 2 cups mashed

1 tsp ginger paste

½ tsp garlic paste

2 jalapeños, finely chopped

¼ tsp chili powder

¼ tsp turmeric

½ tsp ground coriander

1 tsp cumin

1 tsp garam masala
salt to taste

1. Peel and boil the potatoes. Mash until smooth.
2. Heat 1 tbsp olive oil in a large pan. Add the ginger and garlic pastes and onion, sauté until onions are translucent.
3. Add chili powder, turmeric, coriander, cumin, and garam masala. Saute for about a minute.
4. Add the potatoes and jalapeños, mix well over the heat until everything is evenly distributed. Finish with sea salt. Allow filling to cool while preparing the dough.

Now the dough:

Ingredients:

2 ¼ cup whole wheat flour
1 tbsp olive oil
1 tsp salt
Approx. 1 ¼ cup water

1. Mix together flour, salt, and olive oil in a large bowl.
2. Add water a little bit at a time until you have dough that is elastic but not sticky. The dough should be firm but smooth.

Assembling the flatbreads:

1. Take a ball of dough slightly larger than a golf ball and roll it out into a circle, using a light dusting of flour.
2. Place a ball of the potato filling in the center of the circle of dough. Bring up the sides of the dough to enclose the potato, pinching the dough together at the top.
3. Flatten the dough slightly and carefully roll out into a circle. Use the rolling pin very lightly to ensure that the potato filling doesn’t come out.

4. Heat a skillet to medium heat. Cook the paratha on one side until brown spots appear on one side, this should take 3 to 4 minutes. Then cook on the other side. You don’t need any oil in the skillet, as long as the dough is intact it shouldn’t stick to the skillet.
Yeast Sourdough Starter

As I mentioned on page 41, a starter that catches wild yeast is extremely difficult to perfect. I’ve found that the best way to get that wonderful sourdough taste in the fraction of the time is with a yeast starter that only has to sit overnight.

Recipe adapted from CookWise.

Ingredients:

2 ½ cups bread flour
½ cup wheat flour
½ tsp active dry yeast
2 cups warm water

1. Dissolve the yeast into the water and let stand for a few minutes.
2. Combine the flours in a large bowl.
3. Add the water and yeast mixture to the flour and stir until combined. It should be approximately the consistency of pancake batter.
4. Cover the starter with plastic wrap so that the plastic is touching the surface of the starter.
5. Let stand in a warm area for 12 hours.

The day after making your sourdough starter, you can make wonderful sourdough bread.

Ingredients:

3 cups bread flour
1 ½ tsp salt
1 tsp sugar/honey/agave

Yeast starter

1. Combine the flour, salt, and sugar if using table sugar.
2. Add the honey or agave to the starter if using that.
3. Add the starter to the flour, and mix until combined.
4. Turn the dough out onto a floured surface and knead for ten minutes until very smooth.
5. Allow the dough to rise until doubled, approximately 1 ½ hours.
6. Punch down the dough and cut in half.
7. Form each half into a boule and let proof for another 2 hours.
8. Preheat the oven with your baking stone to 450°.
9. When ready to bake, turn down the oven to 375°.
10. Slash the tops of the loaves, and bake for 45 minutes.
**Chocolate chip cookies**

For a treat as ubiquitous at the chocolate chip cookie there are about as many ways to make them as there are bakers who make them. There are chewy, soft cookies with big chunks of chocolate, thin, crispy cookies, even light and caky versions. Most people have a preference for one variety over another, but after years of experimentation I think I’ve come up with a recipe that can please even the most discriminating cookie aficionado.

My mom first taught me how to make her famous chocolate chip cookies when I was 8 years old. It was really just the recipe on the back of the package of chocolate chips, but something about her technique made them better than anyone else’s. I was a quick learner and no more than a year later I had taken over as preferred cookie-maker in the household. I eventually began to incorporate elements of new recipes until I came upon the perfect combination of elements to create a cookie that is crispy on the edges, chewy and caky in the middle, full of complex flavor and with no lack for chocolate.

Recipe courtesy of Sue Claire

Ingredients:

1 stick unsalted butter and 1 stick salted butter, softened

¾ cup sugar

¾ cup brown sugar

2 eggs

2 tsp vanilla extract

2 ¼ cup all-purpose flour

2 tsp salt

2 tsp baking soda

3 cups chocolate chips
1. Cream the butter and sugars together until very well whipped. Add eggs, mix until well incorporated. Add vanilla extract.

2. Lightly mix 1 ¼ cup of the flour, baking soda, and salt before mixing into the wet ingredients. Once incorporated add in the remaining 1 cup of flour.

3. Generously add chocolate chips, mix until evenly distributed.

4. Drop tablespoons of batter onto cookie sheets approximately 1.5 inches apart. Bake in a 375 degree oven for 9 minutes, until the edges are browned and the centers are very lightly golden.

5. Let cookies rest on the cookie sheet for 2-3 minutes, then transfer to a cooling rack.

6. Enjoy straight out of the oven or store in an airtight container for up to a week, but they’re not going to last that long!
Chocolatines

Recipe adapted from CookWise.

Ingredients:

3 sticks unsalted butter, cut into cubes
½ cup and 2 cups bread flour
1 package active dry yeast
3 tablespoons sugar
1 cup warm whole milk
¼ cup all-purpose flour
1 tsp salt
1 tbsp brown sugar
2 tbsp heavy cream
1 tbsp oil for bowl
1 egg, beaten
1 cup chocolate chips, approximately

1. Toss butter cubes and ½ cup bread flour in a bowl, and then dump out onto the counter and shape into a square, cover with plastic wrap and place in the fridge until ready to use.

2. Add yeast and sugar to the warm milk. Let stand until the yeast is activated. Add 2 cups bread flour, all purpose flour, salt, brown sugar, and heavy cream. Mix thoroughly with a wooden spoon until the dough is soft and sticky. This is taking the place of kneading, so mix for at least 2 minutes. Get your arm workout in here!

3. Place dough in an oiled bowl, turn the dough to coat with oil. Cover and let rise in a warm place for 45 minutes.
4. Punch down the center of the dough, then pull up the bottom of the dough over to the center twice. Cover the dough again and let rest in the refrigerator for at a minimum of one hour, or overnight if possible.

5. On a floured counter, roll the dough out as large as possible. Place the square of butter and flour from the fridge on one half of the dough. Fold the other half of dough over and seal the edges. Carefully flatten with a rolling pin until the dough is back to the original size.

6. Complete the turns: Fold the dough in thirds like a letter, then let it rest in the refrigerator for an hour. Then roll it back out as large as possible, and fold in thirds again. Repeat this two more times. At any point, you can let the dough rest in the refrigerator overnight. For example, I completed two turns and then folded the dough in preparation for the third. I let the dough rest like this overnight, and the next morning I rolled the dough out one more time before preparing to shape the croissants.

7. Preheat the oven to 400 degrees.

8. Roll the dough out into a very large rectangle. Using a pizza cutter, cut the dough into even squares approximately 4 inches on each side. Work quickly to prevent the dough from rising on you, which will make uneven croissants. Cut the squares diagonally to create triangles.

9. Taking one triangle, place a few chocolate chips along one edge. Carefully roll up the dough into croissant shape, making sure the chocolate chips are secured inside. Place on a parchment-lined baking sheet. Once all of the croissants are rolled, let them proof for 15 minutes or so before baking.

10. Just prior to baking, place a pan with about an inch of water on the lowest rack of the oven. Brush the tops of the croissants with the beaten egg.

11. Bake at 400 degrees for 25 minutes, until very golden brown and smelling delicious!
**Buttermilk Biscuits**

Using the same temperature control techniques as we did to make croissants, we can make this southern classic. Buttermilk is an acidified milk, so in addition to providing delicious flavor, it also works with the baking powder to make the biscuits extra fluffy. The trick here is to handle the dough as little as possible, this keeps the butter cold and prevents the gluten from developing too much.

Recipe adapted from Ree Drummond.

Ingredients:

- 2 cups all-purpose flour
- 1 tbsp sugar
- 1 tsp salt
- 2 tsp baking powder
- ½ tsp baking soda
- ½ cup butter, cold and cut into pieces
- ¾ cup buttermilk
- 2 tbsp melted butter

1. Mix all of the dry ingredients together.
2. Using a pastry cutter or two knives, cut the butter into the dry mixture until it resembles small beads.
3. Add the buttermilk and stir until the dough just comes together.
4. Turn the dough out onto a floured surface and pat the dough out into a flat rectangle approximately ½ inch thick.
5. Cut out the biscuits using a biscuit cutter, a glass, or anything round with approximately the right diameter.
6. Place biscuits into a round cake pan so that they just touch.
7. Brush the top of the biscuits with melted butter.
8. Bake at 450° for 12-15 minutes until they are golden brown.
Pie Crust

Homemade pie crust also relies on the temperature control techniques to become flaky and tender. It may seem like a daunting task to make a pie entirely from scratch, but I promise it is deceptively simple. Just like with the biscuits, the key is to handle the dough as little as possible.

Recipe by Ina Garten.

Ingredients:

- 1 ½ sticks cold butter
- 1/3 cup cold shortening
- 3 cups all-purpose flour
- 1 tsp salt
- 1 tbsp sugar
- ½ cup cold water

1. Mix the dry ingredients.
2. Add the butter and shortening and cut them into the flour, until they resemble small beads.
3. Add the water slowly and combine until the dough forms a ball.
4. Wrap the dough in plastic wrap and let rest in the fridge for at least half an hour.
5. When you are ready to make your pie, cut the dough in half and roll each half into a large circle.
6. Transfer to a pie pan, fill with your favorite fillings, and bake until golden brown!
Scones

Continuing with recipes for cold-butter techniques, scones are essentially just a sweeter take on a biscuit. They should be tender and crumbly, and you can fill them with any flavor combination you choose. With this classic vanilla bean scone recipe, you won’t have to go to Starbucks to get your pastry fix.

Recipe adapted from *The Pioneer Woman*.

Ingredients:

3 cups all-purpose flour
2/3 cups sugar
5 tsp baking powder
¼ tsp salt
2 sticks unsalted butter, cold and cut into chunks
1 egg
¾ cups heavy cream
2 vanilla beans

Glaze:

5 cups powdered sugar
½ cup whole milk
1 whole vanilla bean
pinch of salt

1. Split the vanilla beans down the middle and scrape out the caviar. Mix the caviar into the heavy cream and set aside.
2. Mix together the dry ingredients.
3. Cut the butter into the dry ingredients until it is very crumbly.
4. Add the egg to the mixture of vanilla beans and cream, then add this to the dry ingredients and mix until combined.

5. Chill dough in the fridge for 30 minutes.

6. Turn the dough out onto a floured surface and press into a flat disk. Roll out the dough into approximately a rectangle about ¾ inch thick. Cut into triangles.

7. Bake at 350° for 18 minutes, until very lightly golden. Transfer to a wire rack.

8. Make the glaze by scraping the caviar from the vanilla beans and add to the milk.

9. Slowly add the milk to the powdered sugar and salt until very smooth.

10. Once the scones have cooled, cover them with the glaze. Let the glaze set for about an hour.
Snickerdoodle Cupcakes

These cupcakes have become an absolute necessity amongst my family and friends. In fact, my brother has expressly forbidden me from making any other kind of cupcake. In essence, this is just a vanilla cupcake recipe with some lovely spices mixed in. The important thing here is to beat the batter for just long enough to incorporate air, but not so long that gluten starts to form.

Ingredients:

3 cups all-purpose flour
1 tbsp baking powder
½ tsp salt
2 tsp cinnamon
1/4 tsp nutmeg
1/4 tsp ground cloves
1 cup softened butter
1 ¾ cup sugar
4 eggs
2 tsp vanilla extract
1 ¼ cup milk

1. Combine the flour, baking powder, salt, and spices in a large bowl.
2. In a separate bowl, cream together the butter and sugar. Then add in the eggs and vanilla extract.
3. To the butter mixture, alternately add part of the flour mixture and part of the milk, making sure that you start and end with flour.
4. After adding the final addition of flour, beat the batter on high for about 30 seconds to incorporate air.
5. Fill cupcake tins ¾ the way full, and bake at 350° for about 20 minutes, until lightly gold and a toothpick stuck into the center of the cupcake comes out clean.
6. Let cool, and then frost with cinnamon frosting.

**Cinnamon Buttercream Frosting**

This frosting is the perfect accompaniment to the snickerdoodle cupcakes. (It’s pretty good by itself too.) Just like with the cupcakes, it is a basic vanilla buttercream that I’ve added cinnamon to. I learned how to make buttercream from my Grandma with the “add till it looks right” method, so it can easily be altered to suit different tastes.

Recipe courtesy of Nina Browning.

Ingredients:

- ½ cup butter, very soft
- 4 or 5 cups powdered sugar
- ¼ cup cold milk, more or less as needed
- 1 tsp vanilla extract
- 1 ½ tsp cinnamon

1. Beat the butter and 4 cups powdered sugar together until crumbly.
2. Beat in the milk 1 tbsp at a time until the frosting is smooth with a thick, whipped consistency.
3. Beat in the vanilla extract, and then add the cinnamon.
4. Beat for another minute or so until the frosting is very light.
Appendix II: References


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