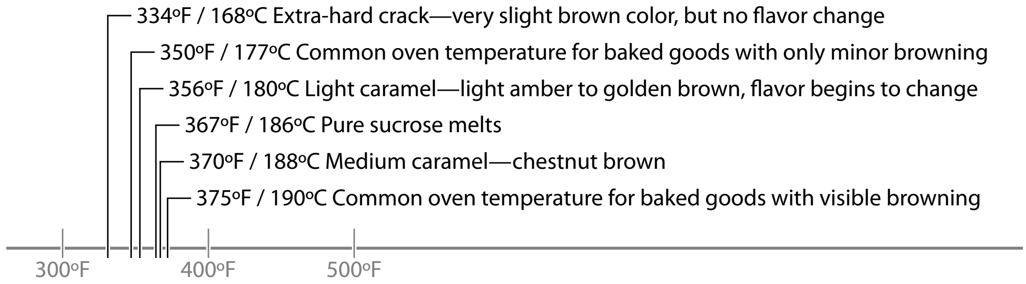
356°F / 180°C: Sugar Quickly Caramelizes



Temperatures related to sucrose and baking.

Caramel sauce: delicious, calorie-laden, and made by the simple act of heating sugar. Unlike the Maillard reaction, which is named for the chemist who first described the reaction, caramelization is named for the end result. The word *caramelization* comes from the 17th-century French for "burnt sugar," originally Late Latin for "cane" (*canna* or *calamus*) and "honey" (*mel*)—a good visual description of melted, browned sugar!

There are a couple of different ways to burn sugar (besides getting distracted while cooking). The simplest is with dry heat: sugar in a dry pan will *thermally decompose*—literally, breaking down under heat. In the case of sucrose, the molecular structure will break apart and go through a series of reactions that create over 4,000 different compounds. Some of those compounds are brown (the best-looking tasteless polymerization reactions you've ever seen!), while others smell wonderful (you can thank fragmentation reactions for these, as well as blaming them for some of the bitter tastes).

Heating sugar with water, as is done in wet-method caramel recipes, changes things slightly. When wet, sucrose will *hydrolyze*—a reaction that involves taking in water (hence "hydro"). In the case of sucrose, it hydrolyzes into glucose and fructose, called *sucrose inversion*. With heat, those molecules then rearrange their structure into another form that kicks off a water molecule and begins a chemical reaction journey. The hydrolysis of sucrose is a simple reaction. Even if you're not up on your high school chemistry, you can see that the count of atoms on one side of the equation lines up with the count on the other side:

$$C_{12}H_{22}O_{11} + H_2O = C_6H_{12}O_6 + C_6H_{12}O_6$$

Sucrose + Water = Glucose + Fructose

This is how pastry chefs make invert sugar syrup! The concentration of sugar, temperature, and pH all speed up the reaction, so if you've ever seen a caramel recipe call for cream of tartar, that speeds up the conversion to glucose and fructose. And, because fructose has a lower caramelization temperature (more on that in a minute), a wet caramel sauce should, in theory, caramelize at lower temperatures and have a different chemical makeup than a dry one. The full chemistry of caramelization is still poorly understood—while researchers have been able to describe some of the reactions, the full pathway taken on the chemical reaction journey still has its mysteries.

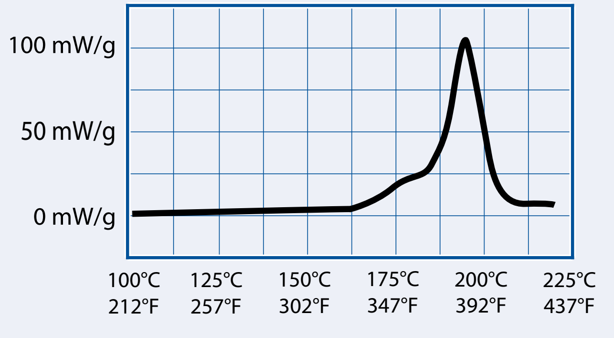
Describing the temperatures for caramelization is also tricky because of the closeness between melting points and decomposition temperature ranges. Melting, a physical change, is not the same thing as decomposition, a chemical change. By definition, sucrose is a pure substance: it has a specific molecular structure. Pure sucrose melts at 367°F / 186°C, a state change where it goes from solid to liquid. Glucose, likewise, has a melting point of 294°F / 146°C; fructose comes in at a relatively cool 217°F / 103°C.

But these sugars begin to thermally decompose at temperatures lower than their melting points. The decomposition happens at a very, very slow rate at modest temperatures and begins to pick up to a noticeable rate as temperatures increase. For sucrose, that inflection point is somewhere around 338°F / 170°C—a good 30°F / 16°C below its melting point. If enough thermal decomposition happens before sucrose is heated to its melting point, granules of sugar will "apparently melt," to use the phrase coined by the researchers. Heating a granule of table sugar—a bunch of sucrose molecules (with some impurities!) packed into a crystalline structure—to just below its melting point will cause some of the

How Do Scientists Tell When Something Is Melting?

One common technique used is *differential scanning calorimetry* (DSC). In DSC, scientists closely monitor the temperature of a sample in a closed environment while heating it, either recording the precise amount of energy needed to raise the temperature at a constant rate, or recording the precise change in temperature while adding energy at a constant rate. DSC picks up phase changes (e.g., solid to liquid) and chemical changes (like protein denaturation or thermal decomposition) because these changes require heat energy but don't raise the temperature.

Take a look at the DSC graph. This graph shows how much energy was needed to heat a room-temperature sample to its melting point, raising the temperature at a constant rate over the course of about a minute. The graph noticeably ramps up around 338°F / 170°C and again around 356°F / 180°C, which is why caramelization is so often described as occurring at either of those temperatures. But notice that the line does slope up well before these temperatures! Heating sucrose at a slower rate will shift these two inflection points to lower temperatures; if it's heated slowly enough, decomposition and melting will show up in two distinct peaks. Cooking sugar "low and slow" will still thermally decompose it; it'll just take longer.



DSC graph for sucrose.

sucrose molecules to convert to other compounds via thermal decomposition. The granule of sugar is no longer a pure substance! This is why a granule of sugar "apparently" melts below its true melting point when heated slowly. Sugar, like everything else that makes up our food, is fascinating and complicated stuff.

As for flavor, caramelization is like the Maillard reaction in that it generates thousands of compounds, and these new compounds result in both browning and enjoyable aromas. For some foods, these aromas, as wonderful as they might be, can overpower or interfere with the flavors brought by the ingredients. For this reason, some baked goods are cooked at 350°F / 177°C or even 325°F / 163°C so that they don't see much caramelization, while other foods are cooked at 375°F / 191°C or higher to facilitate it. When cooking, ask yourself if what you are cooking is something that you want to have caramelized aromas, and if so, set your oven to at least 375°F / 191°C or extend the baking times out long enough for the reaction to occur. If you're finding that your food isn't coming out browned, it's possible that your oven is running too cold, so adjust the temperature upward.

Does starch caramelize?

Not directly. Starch is a complex carbohydrate; caramelization is the decomposition of simple carbohydrates, a.k.a. sugars. Given time under heat, starch will break down into dextrin, which is a bunch of glucose molecules linked together. Dextrins are commonly used as adhesives—the stuff you lick on the back of an envelope—and are made by heating starch for many hours. Additional processing converts them to things like maltodextrin (see page 416), but almost all of the browning you see in cooked food comes from sugars (caramelization) and reducing sugars with amino acids (Maillard reactions). Starch can be broken down into glucose, which will caramelize, either via enzymatic reactions or hydrolysis, so there are exceptions. To see the difference, try baking a pinch of dry cornstarch, sugar, and flour alongside slightly wetted versions of each (to see how water changes things) on a lined cookie sheet at 375°F / 190°C for 10 minutes and investigating the results.

Temperatures of common baked goods, divided into those below and above the temperature at which sucrose begins to visibly brown.

Foods baked at 325–350°F / 163–177°C	Foods baked at 375°F / 191°C and higher
Brownies	Breads Sugar cookies
Chocolate chip cookies *(chewy 12–15 minute cookies)*	Peanut butter cookies
Sugary breads: banana bread, pumpkin bread, zucchini bread	Chocolate chip cookies *(crispy 12–15 minute cookies; higher temperature means more evaporated water)*
Cakes: carrot cake, chocolate cake	Flour and corn breads Muffins

Sugar Cookies, Butter Cookies, and Cinnamon Snickerdoodles

What's the difference between a sugar cookie, butter cookie, and snickerdoodle? By weight, they're all ~25% sugar, ~25% butter, ~44% flour, ~5% egg, and 1% other. It's that "1% other" that makes all the difference. Butter cookies don't have any rising agent, while both sugar cookies and snickerdoodles do. Snickerdoodles also have cream of tartar, giving them a tangy flavor and chewier texture.

Cookies are a perfect example of both caramelization and Maillard browning reactions. Some people like their cookies barely browned; others like them nicely toasted up. Personally, I like sugar cookies tender and barely browned and butter cookies golden medium-brown.

In a small bowl, mix **2½ cups (350g) flour** and **1 teaspoon (6g) salt**. Optionally add **½ teaspoon (2.5g) baking powder**, skipping it if you're making butter cookies. If you're making snickerdoodles, also add **2 teaspoons (6g) cream of tartar**. Use a whisk or fork to thoroughly mix the ingredients together.

In a large bowl, cream together **1 cup (230g) unsalted butter** (room temperature) with **1 cup (200g) sugar**. Add **1 large (50g) egg** and **1 teaspoon (5 mL) vanilla extract** and mix together. Optionally add flavorings, such as **¼ teaspoon (1.25 mL) almond extract** or **1 teaspoon (2g) lemon zest**.

Stir half of the dry ingredients into the large bowl, mixing to combine. Repeat with the rest of the dry ingredients. If you have time, chill the dough for several hours at this point—traditionally these doughs are firmed up so that they can be rolled out and cut into shapes.

If you like, prepare sugar to roll the dough balls in by pouring **¼ cup (50g) sugar** onto a small plate. For snickerdoodles, add **1 tablespoon (8g) cinnamon** and mix it with the sugar. For flavored sugar cookies, try adding **2 tablespoons (12g) fennel seeds** to the sugar. For crinkle cookies, set out a second plate with **¼ cup (30g) powdered sugar**.

To bake, scoop the dough into ½ ounce / 15g portions, making small balls about 1" / 2.5 cm in diameter, and roll them in the sugar. (You can also roll the dough out and use cookie cutters—see page 340 for how to make your own.) Place the dough balls on a parchment-lined cookie sheet and flatten them, using either a fork for a lined surface or your palm for a flatter cookie. For tender, lighter cookies, bake at 325°F / 165°C for 10–12 minutes; for crispier, firmer cookies, bake at 375°F / 190°C for 10–12 minutes. If you like your cookies crispy brown throughout, try baking them at 325°F / 165°C for 25–30 minutes.

Notes

- *If sugar cookies or butter cookies aren't your thing, try adding flavoring to the mix, rolling the dough in sugar and chopped nuts, or dipping the baked cookies in chocolate. For chocolate-flavored cookies, replace ½ cup (70g) flour with ½ cup (40g) Dutched cocoa powder. For something festive, roll the dough balls in colored sugar. (To make your own colored sugar, mix a few drops of food coloring with ¼ cup (50g) sugar in a plastic bag, seal it, and shake well.) Or get fancy and make two batches of dough—one vanilla and one chocolate, or two batches dyed different colors—and then roll the two doughs together to form a sliceable log with one dough in the center and the other wrapping it.*
- *Modern-day snickerdoodles are essentially chewy sugar cookies dusted in cinnamon, but that wasn't always the case. The earliest recipe I know of skips the flour, which was presumably useful for the 19th-century cook who found herself (rarely himself) out of it yet wanting to cook a treat. If you like your snickerdoodles old-fashioned-style, see http://cookingforgeeks.com/book/snickerdoodles/ and use small eggs (modern-day eggs are larger).*
- *Crinkle cookies, often made with darker doughs that include cocoa powder or molasses, get their crackled appearance from being rolled in sugar. As the cookie expands, the sugar absorbs moisture, causing the surface to dry out and set before the cookie has fully expanded. For better results, roll your dough balls twice: first in granulated sugar, then in powdered sugar.*

325°F / 160°C **350°F / 180°C** **375°F / 190°C** **400°F / 200°C**

Cookies baked at 350°F / 180°C and lower remain a lighter color because sucrose won't caramelize at these temperatures much when baked at standard baking times. Try making two batches of cookies, one with fructose sugar instead of table sugar, to see what a difference caramelization makes!

Lab: Tasty Rates of Reactions—Find Your Perfect Cookie

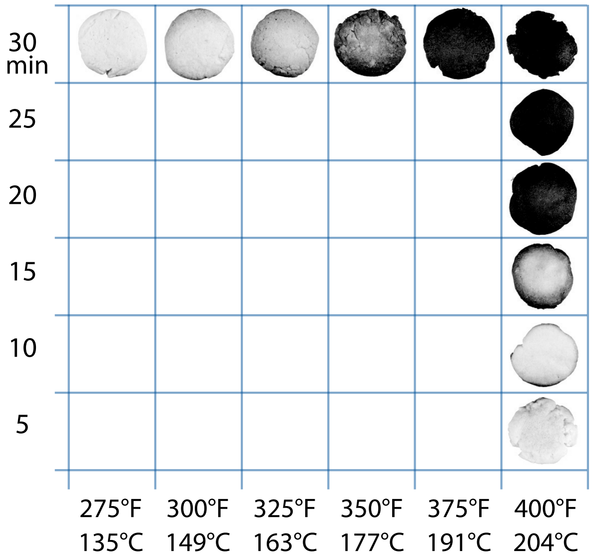
Here's an easy experiment to do, and the data is delicious! Everyone has their own idea of what makes a perfect cookie, and texture is a big part of perfection, at least for cookies. If you like your cookies gooey, they need to be baked so that some of the egg proteins remain unset. If you like your cookies crispy, they need to be baked so that most of the moisture in the dough evaporates away. But what if you want a cookie that's crispy around the edges and gooey in the middle? It's possible—with the right combination of time and temperature.

Almost all reactions in cooking are based on temperature. Different reactions occur at different temperatures, but it's not so simple as saying, "this reaction happens at *x* degrees." Reactions speed up with higher temperature, and many of the temperature ranges for different reactions overlap. For example, moisture in cookie dough will evaporate at the same time as the dough's egg proteins are setting.

Finding your perfect cookie requires playing around to figure out what exact time and temperature combination gives you the properties you like best. Try baking cookie dough at different times and temperatures to see how the different reactions change.

First, grab these supplies:

- One batch of light-colored cookie dough (see page 224 for sugar cookie dough, or use store-bought dough)
- Stuff to bake the cookies: spoon, spatula, parchment paper, a cookie sheet, a timer, and an oven
- Two sheets of letter or A4 paper and something to write with



Lab: Tasty Rates of Reactions—Find Your Perfect Cookie

Here's what to do:

1. Choose what time and temperature values and intervals you want to experiment with. For example, you could choose to do a range of temperatures from 300°F / 150°C to 375°F / 190°C in 25°F / 12.5°C intervals and a time range of 6 minutes to 21 minutes in 3-minute intervals.
2. Create a grid on your two sheets of paper, labeling the x-axis with each of your temperatures and the y-axis with each of your times. Leave about 2.5" / 6 cm between each label.
3. Bake!
   - a) Set your oven to the lowest temperature you choose.
   - b) Place small scoops of dough, about ½ ounce / 15g each, onto a lined baking sheet. If you're baking 6 different times for each temperature, then put 6 dough balls onto the sheet.
   - c) Set your timer to the beginning of the time range (e.g., 6 minutes) and begin baking the cookies.
   - d) When the timer goes off, remove one cookie and set it onto the grid at the correct spot.
   - e) Set the timer for the interval (e.g., 3 minutes), and remove another cookie when the time's up, repeating the process until all the cookies for the current temperature are baked.
   - f) When you're done with one temperature range, increase the oven to the next range and wait 10 minutes or so for the oven to adjust. (If you're doing this in a group, you can split up who does each temperature, but make sure to calibrate your ovens and use cookie sheets of the same material.)

Investigation time!

There are two different browning reactions that happen in baking: the Maillard reaction and caramelization. What do you notice about how long cookies take to bake to medium-brown at one temperature versus another temperature? Do you think you could estimate how much faster a cookie bakes with a 25°F / 12.5°C increase in temperature?

Take a look at the lowest-temperature, longest-cooked cookie and compare it to the highest-temperature, shortest-cooked cookie. What do you notice about the difference between the color of the edges and the centers? What would cause this?

What do you think would happen if you changed the ingredients in the dough, like decreasing the amount of sugar, or adding an acid like lemon juice?