

Thank you Sara for the nice introduction. As a mathematician, I feel deeply honored to give a webinar for the American Chemical Society. Not that I'll be talking about my math research. I'll be talking about sous vide cooking.

[SLIDE 2] Before we begin, how often do you cook? Do you (a) cook almost everyday, (b) not daily, but quite a lot, (c) only for special occasions, or (d) almost never? [Comment on the results.]

[SLIDE 3] Sous vide is a method of cooking in vacuumized pouches at precisely controlled temperatures. While “sous vide” is French for “under vacuum,” it's the precise temperature control that's really important. It's why the world's top restaurants have been cooking sous vide since the 1970s. In the 1990s, food scientists began studying it — but mainly to extend shelf-life. And adventurous home cooks got into it in the mid-2000s.

Why is sous vide cooking becoming so popular? Because it solves a fundamental problem in traditional cooking. [SLIDE 4] Most food is best when heated to a small temperature range. Beef is medium-rare when it's heated to about 55 degrees Celsius. Fish becomes dry when it's heated above about 65 degrees Celsius. And bread's best at around 90 degrees Celsius. But most traditional cooking uses heat sources that are much hotter than this. [SLIDE 5] Boiling water at 1 atmosphere is 100 degrees Celsius; ovens are often heated to 175 degrees; and grills often exceed 300 degrees. This huge temperature difference has important consequences: mainly, cooking time becomes crucial and all but center gets overcooked.

[SLIDE 6] Sous vide cooking solves this problem by cooking at your food's ideal temperature. If you want a medium-rare steak, you vacuum-seal it and put it in a

55 degree Celsius water-bath until it's heated through. It can't get hotter than 55 degrees in a 55 degree water-bath. So cooking time is no longer crucial. And when you do take it out of the bath, it'll be the same doneness from edge-to-edge. Moreover, holding it at 55 degrees for hours or days will tenderize it. This lets you turn tough meat into tender meat.

[SLIDE 7] Vacuum-sealing's also important. For example, it keeps volatile flavor compounds from evaporating — so the food's more flavorful. But I won't talk much about vacuum-sealing today.

[SLIDE 8] I'll use three recipes to explain the science and chemistry of sous vide cooking: soft-cooked eggs, beef chuck roast , and chicken breasts.

For a soft-cooked egg, most people want a white that's set but tender and a chocolate-syrup-consistency yolk. What causes these texture changes? [SLIDE 9] Mostly globular proteins denaturation. The proteins go from a specific shape to a randomly looped chain. These randomly looped chains get tangled and cause the egg white and yolk to thicken and gel.

There are many things that'll cause proteins to unfold. [SLIDE 10] Sous vide cooking mostly uses heat. But most the methods of denaturing proteins are used in the kitchen: Whipping egg whites or heavy cream to soft-peaks is an example of mechanical agitation. Ceviche uses lemon or lime juice to denature raw fish proteins by changing the pH. Cured hams use inorganic salts to denature some of the ham's proteins. And marinades often include the polar-solvent alcohol — partly because it denatures proteins. Admittedly, detergents are rarely used as an ingredient — but

they're certainly used in the kitchen. Anyway, most denaturation is irreversible. So a hard-boiled egg doesn't revert back to a raw egg when it cools.

[SLIDE 11] Now we often hear that someone "can't even boil an egg." But soft-cooked eggs are surprisingly tricky. Say you boil an egg and get a pancake-syrup-consistency yolk. Then you boil an egg — for the same amount of time — and get a yogurt-consistency yolk. Why such a difference? Well, large eggs aren't all the same size. When I measured a dozen eggs, I got about a 5% difference between the largest and the smallest diameter. While 5% may not sound like much, it means there's about a 70 to 80 second difference in cooking time if you want the same yolk consistency.

[SLIDE 12] The big idea is to use a water-bath around the temperature that egg whites and yolks coagulate. A food chemistry reference book will tell you that egg whites begin to coagulate at 62 degrees Celsius and yolks at 65 degrees. So you try putting your eggs in a 63 to 64 degree Celsius water-bath for an hour. You'll find that the white's formed a soft gel. And you'll find that the yolk's a syrup- to honey-consistency. Now, being a scientist, you try several temperatures above and below this to see how the yolk's texture changes with temperature. Sure enough, the yolk's fairly fluid at 61 degrees Celsius and it's a thick gel at 66 degrees.

[SLIDE 13] You may wonder if the yolk's texture only depends on temperature or if temperature is just changing the reaction rate. To test this, you might set your water-bath to 60 degrees Celsius and try times separated by a factor 2. Perhaps surprisingly, you get similar changes in yolk texture by doubling the time as you do by increasing the temperature 1 degree Celsius — [SLIDE 14] I say surprisingly

because most reaction rates double with a 10 degree increase in temperature.

Nonetheless, it shows that both time and temperature are important. César Vega, who gave an ACS webinar last year, wrote a great paper on the relationship between time, temperature, and yolk texture.

[SLIDE 15] When you grill meat or poultry, do you (a) always use a thermometer to see when it's done, (b) sometimes use a thermometer, or (c) never use a thermometer? [Comment on the results.]

[SLIDE 16] Cooking eggs is simple compared with cooking meat. But denaturing proteins is the key to both. Meat is about 75% water, 20% protein, and 5% fat and other substances. We often divide the proteins into muscle fibers, soluble proteins, and connective tissue. Generally, muscle fibers and connective tissue shrinks when heated, and soluble proteins expand when heated. On further heating, the connective-tissue protein collagen denatures into water-soluble gelatin. This can significantly increase tenderness; it's why tough cuts have been braised since ancient times.

[SLIDE 17] In traditional cooking, the following things happen when you heat meat: First, muscle fibers begin to shrink around 35 to 40 degrees Celsius and this shrinking increases up to about 80 degrees. The soluble proteins begin to aggregate and gel around 40 degrees and finish around 60 degrees. (The soluble proteins include the enzymes and also the myoglobin, which give meat its color.) This gelling actually increases tenderness because it makes it easier for our teeth to cut through the muscle fibers. The connective tissue begins to shrink around 60 degrees Celsius but shrink more intensely over about 65 degrees. Most of this connective tissue is

collagen and further heating can convert it into gelatin. Also above about 60 to 65 degrees, the muscle fibers shrink in a way that squeezes out a lot of water.

[SLIDE 18] The denaturing of these proteins lines up nicely with the cook's concept of doneness: cooks say meat is rare at around 50 degrees Celsius, medium-rare around 55 degrees, medium around 60 degrees, and well done at 70 degrees and above. The muscle fibers have started to shrink for rare meat and some of the soluble proteins have denatured. Between medium-rare and medium, more of the soluble proteins denature but the connective tissue has started shrinking. By well-done, the soluble proteins have denatured — turning the meat gray — and the muscle fibers have squeezed out some of the water.

[SLIDE 19] If you eat beef, do you prefer it (a) rare, (b) medium-rare, (c) medium, or (d) well done? [[Comment on the results.](#)]

[SLIDE 20] Recall that the big idea in sous vide cooking is to cook your food at its ideal temperature. So if you like your beef medium-rare, you'd put it in a 55 degree Celsius water-bath. When we cooked our eggs between 60 and 70 degrees Celsius, both time and temperature were important. And both are also important when cooking meat.

[SLIDE 21] A few additional things happen when we hold meat at 55 degrees Celsius. I'll mention two. First, there are many enzymes that haven't been denatured and can catalyze chemical reactions, like protein hydrolysis. Protein hydrolysis is basically the digestion of proteins. And digesting connective-tissue increases tenderness. Another is that collagen can unfold into gelatin starting around 51 to 53 degrees Celsius — if it's held there long enough. Neither of these is easy to do in

traditional cooking; but both are easy in cooking sous vide. And both increase tenderness.

Since these changes are easy to do with sous vide cooking, we can use them to transform tough cuts into tender cuts. [SLIDE 22] For example, we can make a beef chuck roast both tender and medium-rare. You just vacuum-seal the chuck roast and put it into a 55 degree Celsius water-bath for about 24 hours. When you take it out, the meat's interior will be pink and be as tender as prime-rib.

But we can't quite serve the chuck roast right out of the bag. [SLIDE 23] The flavor of meat mostly comes from two things. The browning or Maillard reaction gives the savory and roast flavors. And the species characteristics come from the fat. So you can make beef taste like lamb by basting it with lamb-fat. It's also why people joke that any lean cuts, regardless of species, taste like chicken. Our chuck roast has lots of flavorful fat, but the Maillard reaction doesn't start noticeably until around 130 degrees Celsius. And good browning and roasted flavors around 150 degrees. The trick is to use a very high temperature to brown the outside without overcooking our perfectly cooked roast.

[SLIDE 24] The Maillard reaction is a very complex reaction between amino acids and reducing sugars, like glucose, fructose, and lactose. After the initial reaction, an unstable intermediate structure is formed; it undergoes further changes and produces hundreds of reaction by-products. The Maillard reaction rate can be increased by increasing the temperature, adding a reducing sugar, or increasing the pH. Increasing the pH, say with a pinch of baking soda, works great when browning onions but doesn't help much when browning meat. [SLIDE 25] With beef, I like to

use a butane blowtorch — which can burn at over 1900 degrees Celsius — to brown the outside to a beautiful mahogany brown. With chicken and pork, I often use a pan with smoking hot oil. But sometimes I apply a 4% glucose-wash to increase the reaction rate so I can use a pan with shimmering oil instead. A really hot grill works great, too.

[SLIDE 26] To summarize, we start with a tough-cut of meat like beef chuck roast — something most people braise. We vacuum-seal it and put it in a 55 degree Celsius water-bath for 24 hours. As the meat comes up to temperature, the muscle fibers start to shrink and some of the soluble proteins denature. After 24 hours, the meat has become tender because enzymes have allowed some proteins to hydrolyze and a lot of the collagen has unfolded into gelatin. Finally, we brown the outside of the chuck roast with a blowtorch to produce roast and savory flavors.

Now we turn to the last recipe: chicken breasts. [SLIDE 27] When do you stop cooking your chicken breasts? When (a) it's juices run clear, (b) it's white when you cut into it, (c) it reaches 75 degrees Celsius or 165 degrees Fahrenheit, (d) it's dry and stringy, or (e) some other criteria? [Comment on the results.]

[SLIDE 28] We've talked a lot about proteins, but we haven't talked about microorganisms. Raw food often has millions of microorganisms on or in it. Most of these microorganisms are spoilage or beneficial bacteria that won't make you sick. But some microorganisms are pathogens; and they can make you sick if you eat too many of them. There are many ways to pasteurize your food; that is, reduce the number of pathogens to a safe level. [SLIDE 29] The most common is heat. And, like with egg yolks, there are many time and temperature combinations that'll lead to

pasteurization. You can also kill microorganisms with acids, salts, and spices among others. Really, anything that'll denature the enzymes in the microorganism will kill it.

[SLIDE 30] Because traditional cooking can't easily hold food at below 100 degrees Celsius, the so-called danger zone was popularized. People were taught that pathogens grow between 5 and 60 degrees Celsius. This isn't quite right. Food scientists agree that foodborne pathogens don't multiply below -1.3 degrees Celsius or above 52.3 degrees Celsius. Why the difference? At 5 degrees Celsius, it can take days for pathogens to grow to dangerous levels. And above 52.3 degrees but below 60 degrees Celsius it can take hours to pasteurize — at higher temperatures it only takes minutes or seconds to pasteurize. But holding food for hours at a particular temperature is easy with sous vide cooking.

So we can use sous vide cooking to pasteurize food at lower temperature than we can with traditional methods. For example, we can pasteurize chicken breasts at 60 degrees Celsius — so a medium doneness — instead of at 75 degrees — which is well done.

[SLIDE 31] When we pasteurize, we don't try to kill every single pathogen. We try to reduce the number of active pathogens to a level that's unlikely to make someone sick. A healthy person may need to consume millions of active pathogens per gram to get sick. But about 15 to 20% of the population is immunocompromised; and they can become ill with as few as 1 to 10 active pathogens per gram. If your food starts with say 100 active pathogens per gram and a serving is about 100 grams, then a million to one reduction will give a good safety-margin.

[SLIDE 32] While there are a lot of different pathogens, food scientists just focus on the toughest and the most dangerous. These usually include the Salmonella species, the pathogenic strains of E. coli, and Listeria monocytogenes.

Spore-forming pathogens — especially those that form neurotoxins — also make the list. Since this is more microbiology than chemistry, I'll encourage you to read the food-safety sections of my webpage or cookbook.

[SLIDE 33] If you want to pasteurize a chicken breast at 60 degrees Celsius — so it's a moist and juicy medium doneness — vacuum-seal it and put it in a 60 degree water-bath for 2 hours. For a slightly more well-done chicken breast, try 63 degrees Celsius for one and a half hours. These times and temperatures will reduce Listeria — a particularly heat-resistant bacteria — by at least a million to one. And these breasts will be moist and juicy because the muscle fibers and connective tissues won't have squeezed out much water.

[SLIDE 34] To conclude: Sous vide cooking is about balancing time and temperature. We usually pick the temperature that'll give us the doneness we want. Then we pick the time that'll give us the texture we want. But then we balance our desired texture and doneness with what's safe.

[SLIDE 35] Sometimes this balance is easy. For a pork chop, you might pick a medium doneness. This gives a temperature of 60 degrees Celsius. If the pork chop's tender, then you won't need to hold it at that temperature to tenderize it. But you probably want to pasteurize it, so you measure that it's 20 mm thick and lookup up in one of my tables that it'll take an hour and a half to pasteurize it. This pasteurization time isn't so long that it'll make the chop mushy or pappy, so you're

all done. You vacuum-seal your chop and put it into a 60 degree Celsius water-bath for one and a half hours. Then brown it for 15 to 20 seconds on each side in a very hot skillet for flavor.

[SLIDE 36] Sometimes the balance isn't easy. Take the famed filet mignon. If you want it rare, you can't pasteurize it because a common food pathogen grows at 50 degrees Celsius. Even if you want it medium-rare, it'll become mushy or pappy if you hold it at 55 degrees long enough to pasteurize it. So you might decide not to pasteurize it. Searing the outside with a blowtorch will reduce surface pathogens. But you shouldn't serve it to anyone who's immunocompromised. And even healthy people should know that it's a little risky — though no more risky than if it was prepared traditionally.

[SLIDE 37] That's it. I hope you've learned a few things. Please check out my website at www.douglasbaldwin.com. It has my free web guide on sous vide cooking and a review article I published last year. If you decide to buy a sous vide water-bath, I encourage you to buy my cookbook; it has over two hundred recipes while my free guide only has a dozen.

For more on the science of cooking, you might check out Harold McGee's *On Food and Cooking* and Nathan Myhrvold et al.'s *Modernist Cuisine* and — as every academic says — the references in my book and on my webpage.

Now I believe it's time for questions.