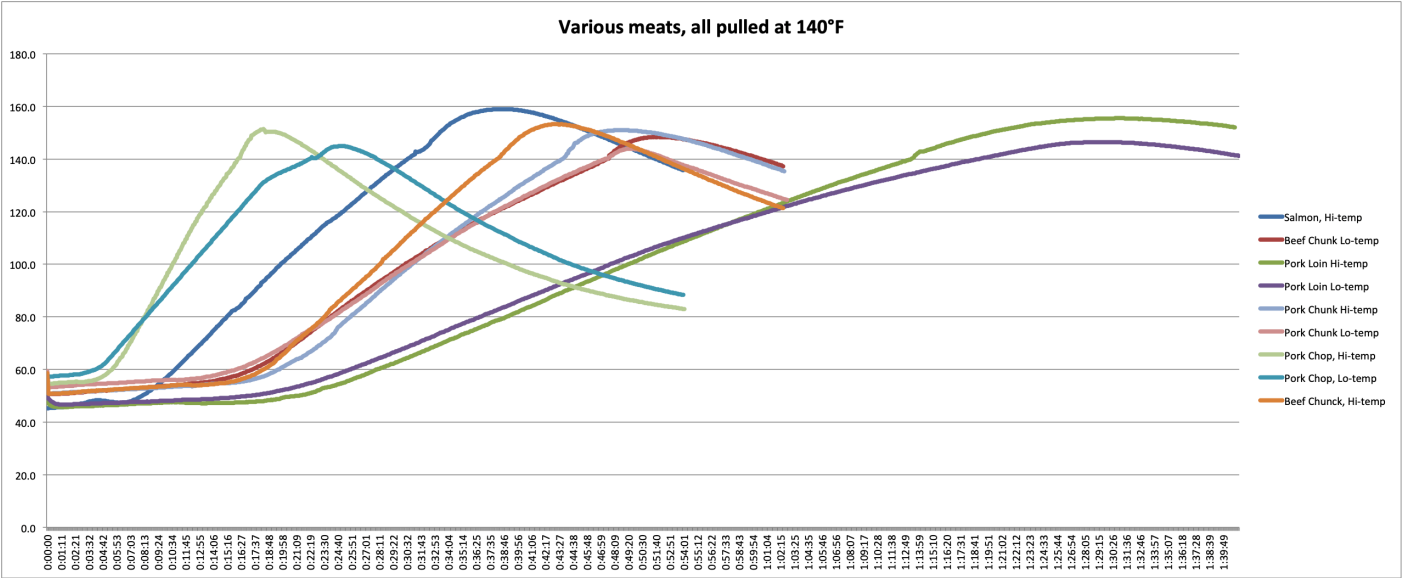




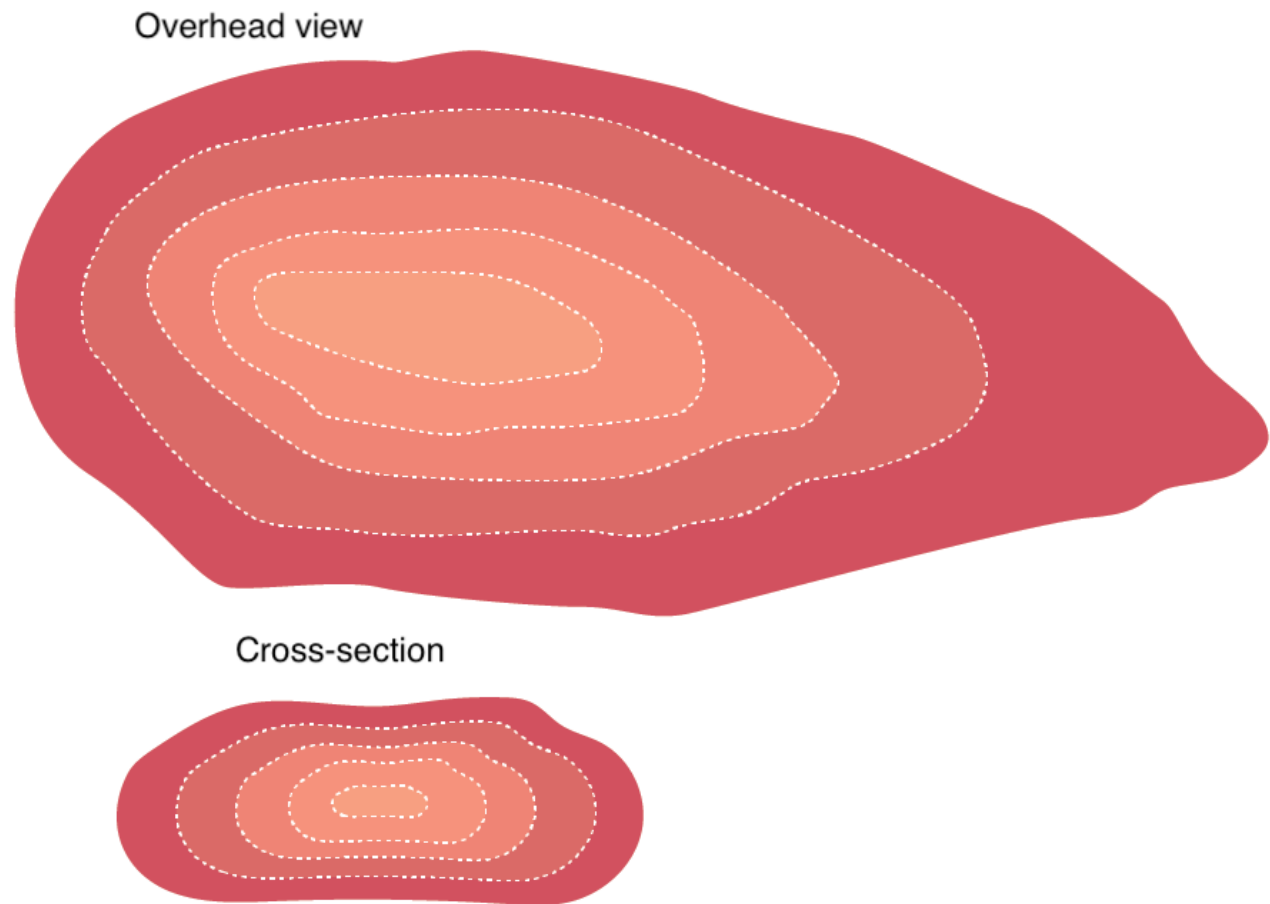
The Science of Carryover Cooking: What Happens After You Cook



Author: Martin Earl

If you pay attention, you'll notice that in most of our blog posts about cooking meat, all the roasts, the whole chickens, the chops, and (almost) all the steaks are pulled at temperatures **below** the final doneness temperatures that we recommend. The reason we typically give for this is something called "carryover cooking."

It's easy enough to say that foods will continue to cook **after** being removed from the oven or smoker and to make allowance for it. But, here at ThermoWorks, we believe that a deeper understanding of the thermal and physical forces involved in cooking will actually lead to more **intuitive** cooking and, yes, even better results. So, this week, buckle your seatbelts and get ready for a quick dive into the world of carryover cooking—what you need to know.



The gradients of cooked chicken breast (as seen in cross-section) about to undergo carryover cooking.

THE PHYSICAL BASIS OF CARRYOVER COOKING

There are a few basic physical laws that govern carryover cooking in foods. And, although they can seem a little daunting, the basic ideas aren't difficult to grasp.

THE SECOND LAW OF THERMODYNAMICS

As you may have learned in middle school, the second law of thermodynamics tells us that the degree of disorder in a system will increase unless work is performed on it. Which is to say that unless you plug something in like a fan or refrigerator, heat can only flow “downhill.”

For example, if you place a cold drink on a hot windowsill on a summer's day, the drink will **not** somehow get **colder**, surrendering its meager heat to further heat the windowsill. Anyone knows

that the drink will heat up. And if, after a few minutes, you pick the glass back up, the spot where it had been sitting will have cooled down—having surrendered some of its heat to warm the drink.

What on earth does this have to do with carryover cooking? A lot, actually. It means that the hot outside of a roast will share its heat with the colder inside, and it will do so with absolute physical certainty. This is **the** central principle of carryover cooking. The other principles we mention hereafter are all secondary to it. This tendency of heat to be shared until an equilibrium is reached is exactly what causes carryover cooking, and understanding it on that basic, conceptual level will help you get a more intuitive feel for how carryover works in your own practice. Substances tend **toward** an even temperature, and heat naturally flows from what is hotter to what is cooler.

HEAT CAPACITY

The next concept to understand in carryover cooking is heat capacity. Heat capacity is the ability of a certain substance to store thermal energy. And, by extension, heat capacity is a measure of how much energy it takes to heat a substance up.

Another thought experiment: Imagine, if you will, a piece of aluminum foil inside of a **350°F** (177°C) oven. Without much fear of repercussion, you might reach into that oven and pull out that sheet or wad of foil. You've probably grabbed foil from an oven before. However, if even a single drop of **350°F** (177°C) oil were to splash on your hand while you were deep-frying something, you would scream in pain!

What gives? Weren't the foil and the oil at the same temperature? Well, yes, in fact, they were, but oil carries more **thermal energy per degree of temperature** than does aluminum. Depending on the type, oil can carry as much as 2.2 times the thermal energy of aluminum at the same temperature. And water carries even more! Leaving the units off for the sake of understanding the raw numbers, aluminum has a heat capacity of 0.91, olive oil has 1.97, and water has 4.19! That's why you can heat a pot of oil to **350°F** (177°C) in roughly the same amount of time it takes to heat a pot of water to boiling, **212°F** (100°C).

What those heat capacity measurements represent in physical terms is the amount of energy (measured in Joules) needed to heat one kilogram of each substance one degree Kelvin (1.8°F).^{*} So one kilogram of water takes 4.19 joules to raise its temperature 1°C (1.8°F), but aluminum only takes 0.91 joules for the same temperature change.

^{*}These heat capacities are based on mass. **Volumetric heat capacities** can also be derived that

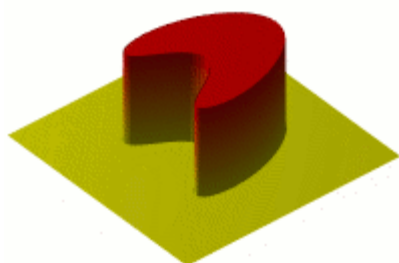
measure the energy required to change a certain **volume** of a substance by 1°C. Water still has a much higher specific heat capacity in that case.

HEAT TRANSFER FORMULA (HEAT EQUATION)

The way that heat distributes itself through a substance is, as noted above, unidirectional. But the movement can be more accurately described by the **heat equation**.

$$\frac{\partial u}{\partial t} = \alpha \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)$$

The heat equation is a handy (if admittedly slightly intimidating) partial differential equation that describes heat moving over time. What it means is not hard to grasp, even if the mathematics themselves may be.



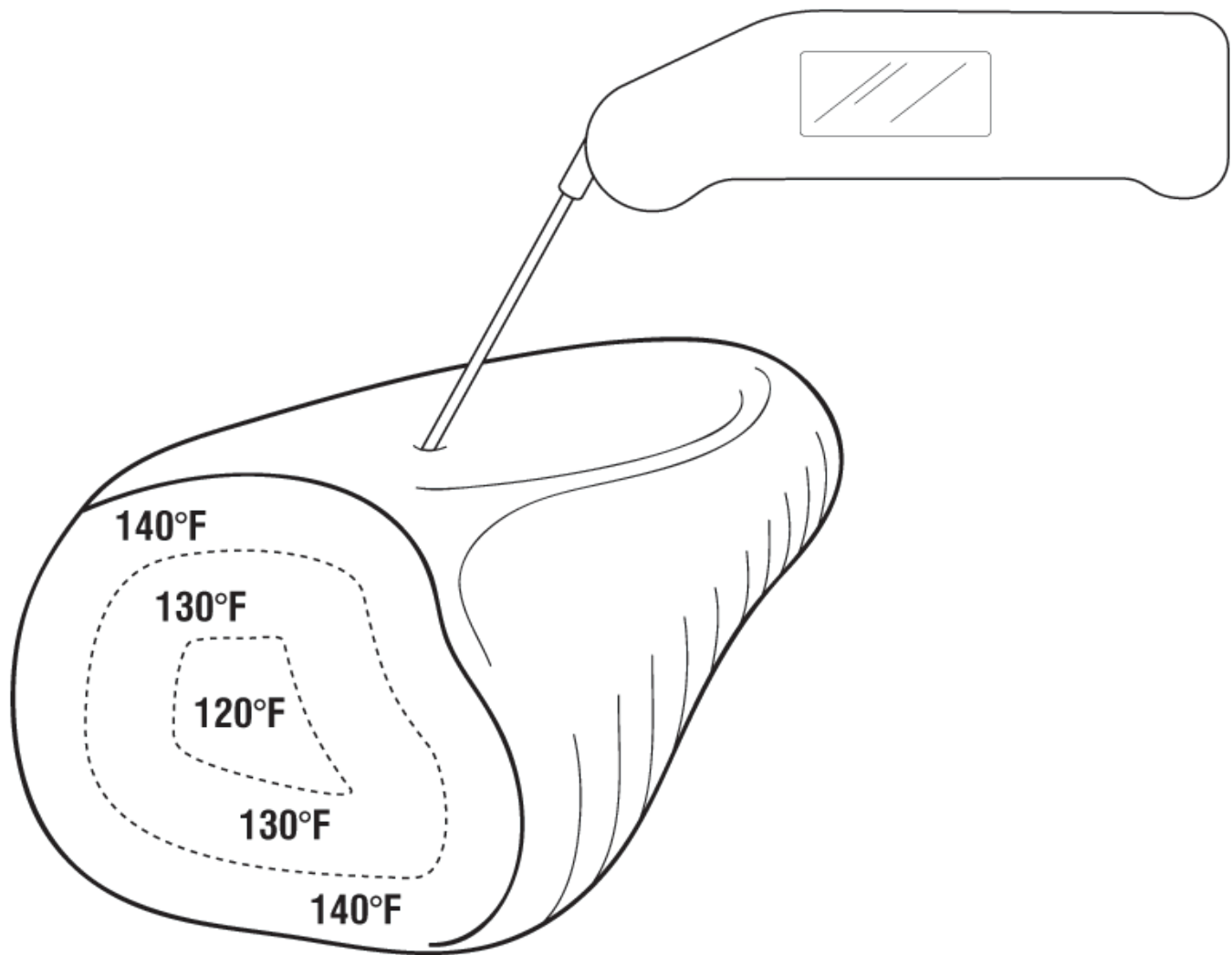
Public domain image of a high-heat area cooling as it warms a lower-heat area.

WHAT THE HEAT TRANSFER FORMULA MEANS, PHYSICALLY

The heat equation says that heat is transferred directly across adjacent points...it doesn't skip around. It also says that areas with a greater temperature difference will change more quickly—a 100°F plate stacked on top of a 40°F plate will heat the cooler plate faster than a 50°F plate stacked on top of it. That's basically it: Adjacent heating, faster with a greater differential.

This is one of the most important physical principles in carryover cooking. It explains the heat flow inside a piece of steak, a roast, or even a loaf of bread. Heat is passed down the line from particle to particle, each bumping into the next and averaging out their energy, with more energy being pumped in from the oven/grill/pan each moment. This is what causes the phenomenon we call **temperature**

gradients, the differences in temperature that exist between the hot surface of your food and the cooler thermal center. Temperature gradients explain why you see a grey band around a cross-section of improperly cooked steak: the outside was hotter than the inside and cooked faster.



Temperature gradients

The second law of thermodynamics says that the energy being pumped into the food can only flow to an area of lower energy, and heat capacity tells us how much energy is necessary to raise the temperature of the food by a certain amount, and the heat equation tells us how heat moves and where the temperature gradients come from.

FACTORS THAT AFFECT CARRYOVER COOKING

With that grounding in the physics of heat, we can look more closely at how heat operates in food

while cooking. And one of the first things to think about in that regard is ***thermal mass***.

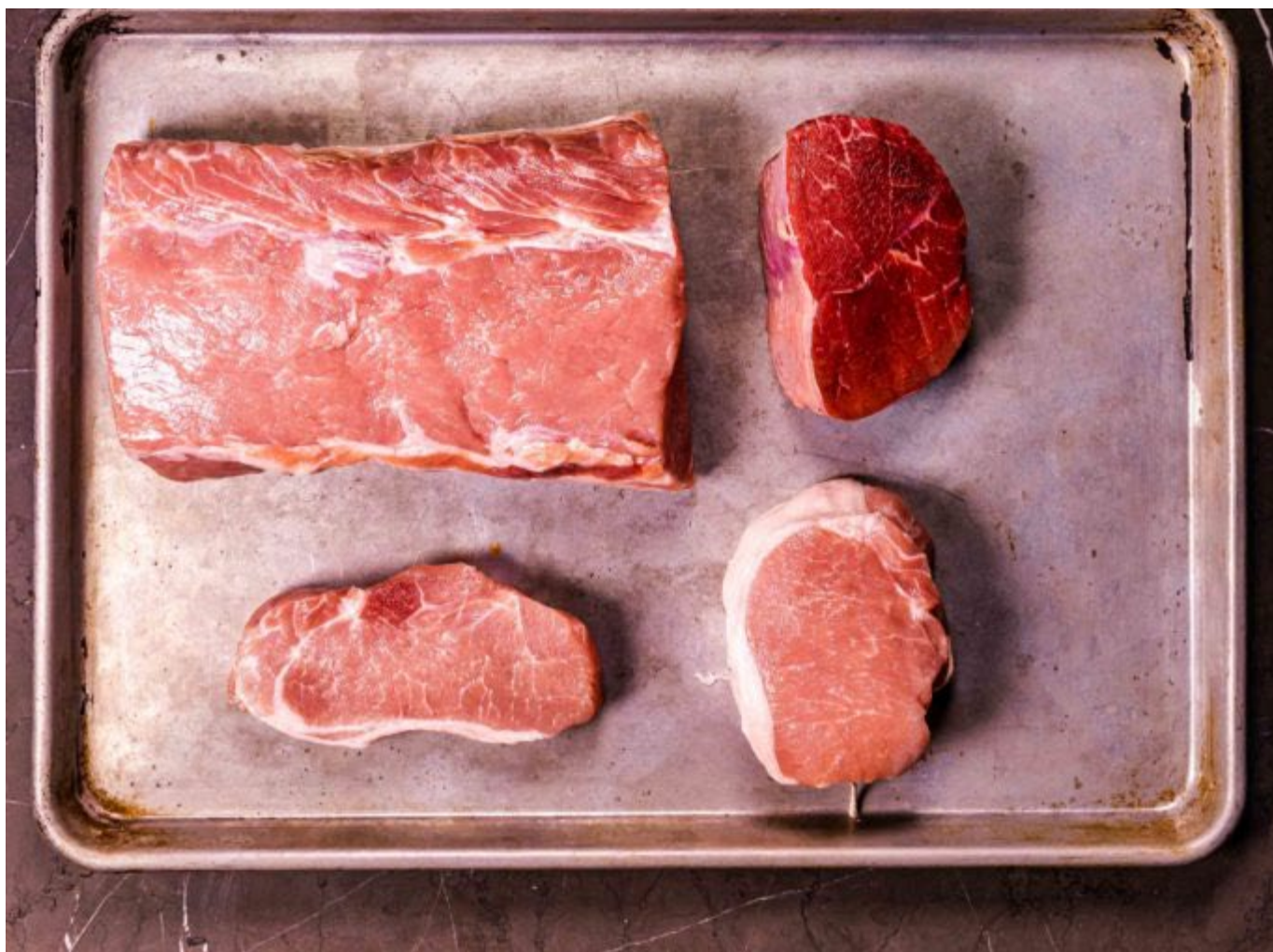
THERMAL MASS

Thermal mass is ***roughly*** equivalent to total heat capacity—not the capacity per kilogram, but the capacity of the entire piece of food (or cookware) as a whole. (A New York strip steak has the same heat capacity ***per gram*** as a whole short loin, but nowhere near the total capacity of ***the whole*** because the short loin is bigger.) A whole loin has more thermal ***mass*** than a steak, and that means there's more heat to go around when the loin is removed from the cooking environment. So the size of any given piece of food has a role to play in carryover cooking.

GEOMETRY: THE SHAPE OF THE FOOD

How the food is cut matters, too. A single steak has a lot of surface area, compared to its volume. That means there is a lot of space to vent heat into the air, cooling a larger portion of the meat much faster. Think of a steak compared to five steaks stacked together (like a loin). The amount of space available for heat to escape is proportionally much smaller for the loin.





These different shapes, sizes, and surface areas will affect carryover cooking

Ultimately, a sphere is the shape **most** prone to carryover cooking (i.e. least prone to cooling) of all, because it has the **least** surface area for a given volume. Interestingly, a stuffed turkey is roughly spherical in shape. That's why it's a good reason to not stuff your turkey and to [cook it to a slightly lower temperature!](#)

COOKING TEMPERATURE

Possibly the most straightforward factor for carryover cooking is the temperature of the cooking surface or oven itself. A high oven will pump more heat into any cut than a low oven will, and the extremes in temperature differential from the cooler center of the meat compared to the hotter surface will be much greater, causing more carryover cooking once you remove it from the oven.

CARRYOVER COOKING EXPERIMENT

To demonstrate how carryover cooking is affected by mass, cooking temp, and the makeup of the

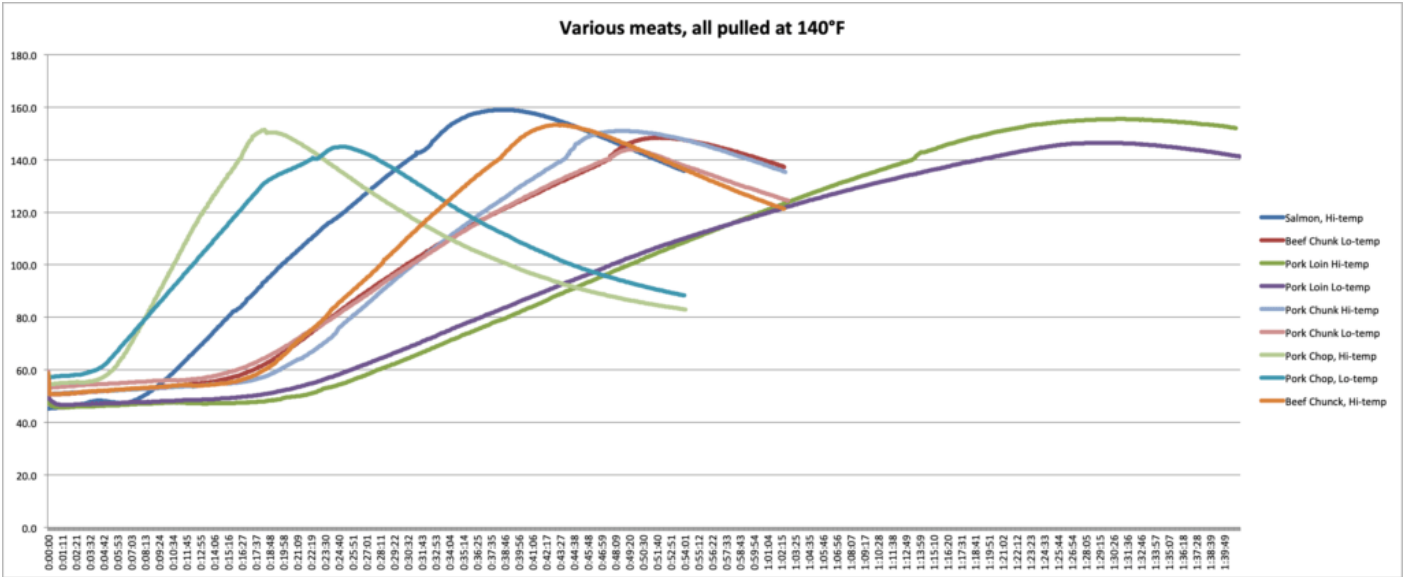
food, we performed an experiment in our kitchen. We cooked two sets of meat, one in an oven set to **300°F** (149°C), the other in an oven set to **425°F** (218°C). Each set of meat consisted of a pork chop, a large chunk of pork and a large chunk of beef of comparable mass and shape to each other, a chicken breast, a fillet of salmon, and a section of pork loin.



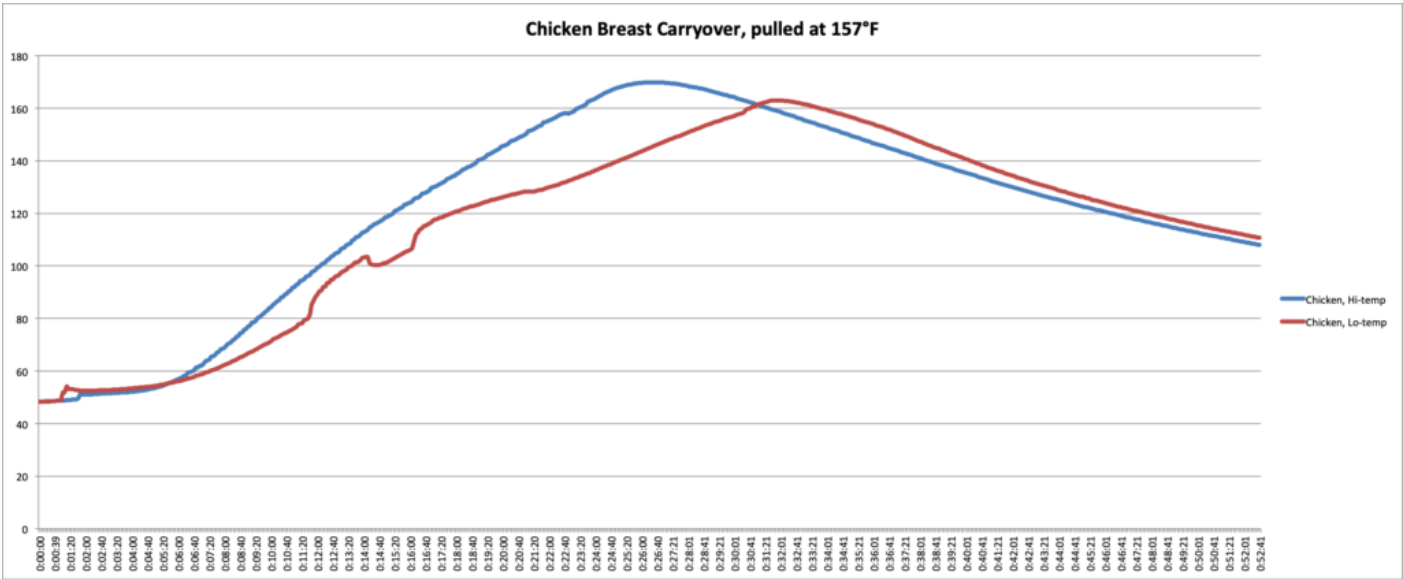
We probed each piece of meat with a needle probe from a [ThermaQ® Blue](#) and cooked them. As each piece reached its target temperature, we removed it from the oven and placed it on a tray, leaving the probes in to monitor the carryover. We allowed each item to rest undisturbed until after their temperatures started to fall.



In the graphs and chart below, you can see the data we collected.



The graph of our pork, beef, and salmon—all pulled from the ovens at 140°F



The same type of graph, but for two chicken breasts, pulled at 157°F

Item	Mass	Pull temp	Highest temp achieved	Total carryover
Pork chop, cooked at 300°F	150 g	140°F	144.9°F	4.9°F
Pork chop, cooked at 425°F	150 g	140°F	151.5°F	11.5°F
Beef chunk, cooked at 300°F	260 g	140°F	148.4°F	8.4°F
Beef chunk, cooked at 425°F	286 g	140°F	153.2°F	13.2°F
Pork chunk, cooked at 300°F	274 g	140°F	143.9°F	3.9°F
Pork chunk, cooked at 425°F	340 g	140°F	151.0°F	11.0°F
Pork loin, cooked at 300°F	1229 g	140°F	146.5°F	6.5°F
Pork loin, cooked at 425°F	1329 g	140°F	155.5°F	15.5°F
Salmon, cooked at 300°F	276 g	140°F	147.3°F	7.3°F
Salmon, cooked at 425°F	314 g	140°F	159.0°F	19°F
Chicken, cooked at 300°F	198 g	157°F	162.9°F	7.9°F
Chicken, cooked at 425°F	245 g	157°F	169.9°F	12.9°F

We can make several key observations by examining this data.

- **First, we can see the effect that cooking temperature has.** In every case, the meat that was cooked at the higher temp experienced more carryover than meats cooked at the lower temps. A pork loin cooked at **425°F** (218°C) experienced **9°F** (5°C) more carryover than a loin cooked at **300°F** (149°C). If you want a pork loin that is not overcooked and you’re cooking at that higher temperature, you’ll need to pull it several degrees earlier!

- **Second, we can see how mass affects the carryover.** For the three pieces of pork cooked at each temperature, you can see the carryover increasing as mass increases. In the **300°F** (149°C) oven, the chop had **4.9°F** (2.7°C) of carryover, while the loin had **6.5°F** (3.6°C). In the **425°F** (218°C) oven, the carryover increased from **11.5°F** (6.4°C) in the chop to **15.5°F** (8.6°C) in the loin. (I don't think the chop and the chunk were different enough to overcome experimental error in this experiment. Hence the chunk experiencing slightly lower carryover.)
- **And third, we can see how the *kind* of meat affects the carryover.** The beef chunks and the pork chunks had very similar masses and shapes but had very different carryover in each case. In the cooler oven, the beef carried over by **8.4°F** (4.7°C) while the pork only carried over by **3.9°F** (2.2°C). In the hotter oven, that gap remained: the beef had **13.2°F** (7.3°C) of after-cooking carryover and pork had only **11.0°F** (6.1°C).

Sometimes, after publishing a post that mentions carryover cooking, I get questions in my email or on the post itself about why we don't publish a carryover cooking table. A close look at the factors above should help to answer that question. With so many variables in a cook, publishing a chart that shows carryover times would be practically impossible. We'd need an entry for every cook temp, for every mass, for every shape, and for every kind of meat or bread. That doesn't mean you should give up hope of mastering your cook. It just means you'll have to get a feel for how much carryover to expect given the specific circumstances of each cook.

Using tools such as the ChefAlarm[®], with its Min- and Max-temp display can help you establish the carryover for any given recipe. Use it on a roast chicken to find out how much the meat cooks **after** you take it out of your oven, and then adjust your pull temp accordingly. [Write the proper pull temp in your recipe](#) so you can get it right again next time. With a little practice, you'll be nailing temperatures each and every time you cook.

CONCLUSION

When cooking, temperature **matters**. Using a thermometer to gauge your pull temps is in every way better than using physical artifacts to check doneness. And if pressing a steak or cutting a chicken is the wrong way to hit an exact temperature, how much worse are they for determining a temperature **you have not yet arrived at**? If you want to perfect your dish, you have to account for carryover cooking, and the only way to do that is to use accurate, [reliable temperature instruments](#). Yes, there is a learning curve as you account for cook temp, the size of your food, and the kind of food you are cooking. But as you learn how those variables operate in your own kitchen, you'll start to elevate your cooking in ways you've never imagined.