Heat is transferred between molecules through random collisions, resulting in the diffusion of heat via random walks similar to those discussed previously. Last week's equation can be used to estimate cooking time; the caveats to its application can be understood using this week's equation, described below.

Target temperatures for cooking

High temperatures are required to produce new flavor molecules through changes in covalent bonding, a process called browning. The two major types of brownings are Maillard reactions, which occur when amino acids and carbohydrates react at temperatures in excess of 120°C, and caramelization, results from reactions between sugars and typically occurs above 150°C. Since both types of reactions occur above the boiling point of water at atmospheric pressure, water must evaporate away before browning can occur. (However, in one of this week's videos, Nathan Myhrvold browns boiled carrots by manipulating phase transitions.)

The physical processes that give the interior of cooked meat its desired texture occur at temperatures in the range of 50-70°C. The denaturation and coagulation of proteins increase the meat's elastic modulus: some of the most abundant proteins in muscle, and thus the major contributors to this process, are myosin (denatures around 50°C) and collagen (70°C). Overheating beyond these transitions can result in toughness and dryness, creating a tension between the desire to achieve browning at the surface and to keep the interior moist and tender. Chefs describe their diverse solutions to this problem in this week's lecture videos.

Rules of thumb for cooking times

Last week's equation, $t = L^2/4D$, can be applied to gain a rough estimate of the time required to cook food to a depth L from its surface and to determine the effect of changing food thickness on cooking time. L should be chosen to reflect the shortest path of heat through the food. This equation does not take into account the desired final temperature, or the initial temperature of the food and heat source, leading to inaccuracy in estimates.

Temperature profiles in food

Our equation of the week gives an estimation of the temperature of a food, initially at temperature T_i, after it has been exposed to an external temperature T_e for a time t:

$$T(t) = T_e + (T_i - T_e)\, e^{-t/\tau}$$

The time constant τ reflects how quickly the temperature will change and is situation-dependent. This equation demonstrates how cooking time depends on the initial temperature of the food and that of the heat source. Better estimates of temperature profiles can be calculated by solving the diffusion equation for specific situations, which is beyond the scope of this course but well-illustrated by the (char)MyMeat applet developed by students from MIT. In addition to modeling temperature change on application of heat, you can use (char)MyMeat to visualize the effect of allowing meat to "rest", which allows heat to redistribute more uniformly within the meat before serving.

Additional materials available online

- Newton's law of cooling (advanced)
- ATK video on french fries
- Heat diffusion in spheres (advanced)

Science Review Questions

1. When Carme made Crema Catalana, she put sugar on top of the dish. This was to:
   (a) Sweeten the dish
   (b) Accentuate browning reactions

2. Carme held the burner on the top of the dish for about 4 seconds. According to our equation of the week, the thickness of the heated layer was approximately:
   (a) < 1 mm
   (b) 1-3 mm
   (c) 3-8 mm
   (d) > 8 mm

3. True or False: Given how hot the iron is (900°F), the entire thickness of the heated layer reaches the temperature of 900°F.

4. True or False: Defrosting meat beforehand helps avoid overcooking.

5. Carme's flour balls have a radius of approximately 3 cm. How long does she have to cook them in the hot oil for them to cook all the way through?
   (a) less than 5 minutes
   (b) between 5 and 10 minutes
   (c) between 10 and 15 minutes
   (d) longer than 15 minutes

6. The flour balls are totally immersed in oil when the cook. If you look closely at the oil when it is cooking, you can see little bubbles rising upwards from the flour balls. Where do these bubbles come from?
   (a) The oil is boiling because it is so hot.
   (b) There were air bubbles stuck to the bottom of the pan initially.
   (c) The water within the flour turns to steam and then bubbles to the top.

7. Your pumpkin bread recipe calls for a loaf tin (23 cm x 13 cm x 7 cm), but all you have is a square baking pan (25 cm x 25 cm x 6 cm). How should the cooking time be adjusted?
   (a) Cook about four times as long
   (b) Cook about twice as long
   (c) Use the same cooking time
   (d) Cook about one half as long
   (e) Cook about one fourth as long

8. True or False: The diffusion coefficient for heat in water is greater than the diffusion coefficient for Ca^{2+} in water.