The development of the incandescent light bulb took many years and relied on the talents of many inventors from around the world. One of the key changes was the use of an inert gas, rather than a vacuum, in the bulb itself. In this video, we'll use the kinetic theory of gases to explain why the addition of an inert gas had such a significant impact on the usability and longevity of the humble incandescent bulb. This video is part of the Governing Rules video series. A small number of rules describe the physical and chemical interactions that are possible in our universe. Hi. My name is Jeff Grossman and I am a professor in the Department of Materials Science and Engineering at MIT. Today, I'm going to talk to you about the development of the incandescent light bulb. In order to understand the topic of this video, you should be familiar with the kinetic theory of gases. After watching this video, you should be able to discuss the physical significance of a gas molecule's mean free path. You should also be able to discuss the physical parameters that affect the mean free path. Imagine that you are a consultant for a light bulb manufacturer. They have a problem with their incandescent light bulbs. After the light bulbs have been operating for a period of time, the inner walls of the bulb begin to blacken. This reduces the light output. Not a desirable outcome for a light bulb. You have been hired to figure out why this is happening and to determine a way to fix the problem. So, what questions do you have? What do you think is going on? What chemical principles might be important here? Take a moment to pause the video and jot down some things that you think might be relevant to the problem. It's okay to brainstorm with a partner. It may be helpful to understand a few things about the construction of the light bulb. Looking inside, we see that there is a coil of metal, called the filament. This filament is typically made of tungsten. What you can't see is that the inside of this light bulb is a vacuum. What would happen if there was air in the light bulb? Because the filament reaches such high temperatures, the filament will oxidize if oxygen is present. Some of you may have been wondering about the temperature of the tungsten filament. When the light bulb is on, the tungsten filament gets very hot, around 3000 Â°C. While this temperature is below the melting and boiling points for tungsten, the occasional tungsten atom sublimes and condenses on the wall of the light bulb. Not only does this reduce the light output of the bulb, but it also causes deterioration of the filament. Knowing what you know about gases, how can you explain what is happening and what solution might you propose? It might help to review some of the assumptions of the kinetic theory of gases. One assumption is that the molecules in a gas are separated by distances that are much larger than the size of the molecules themselves. Another is that the molecules are constantly moving in random directions. The molecules obey Newton's laws of motion and thus continue in straight-line motion until they collide with other molecules or the walls of the container. Gas molecules that are not in physical contact do not exert forces on one another, so between collisions, they move with constant velocity. Collisions between molecules or between a molecule and the wall of the container are assumed to be perfectly elastic. In other words, energy is conserved. What factors do you think affect a molecule's collision frequency? Pause the video and take a moment to think about it. You may have realized that the diameter of a molecule, as well as the number of molecules in the region will affect collision frequency. So when a tungsten atom evaporated off of the hot filament under vacuum, what happened? Pause the video and take a moment to think about it. The atom proceeded in a straight line, and in the absence of other molecules to collide with, condensed on the cool wall of the light bulb. Under vacuum, the mean free path of tungsten atoms in the vapor state is quite large. What is the mean free path? The mean free path is the average distance traveled by a molecule between collisions. The mean free path for a molecule can be approximated by the distance traveled by the molecule in a given time t divided by the number of collisions the molecule experienced. Although the molecule may exhibit a random walk and change direction with each collision it experiences, we are simply interested in the scalar quantity of total distance traveled. The total distance traveled can be found by multiplying the velocity of the molecule by the time. How do we find the number of collisions? Let's break this down. If we assume that the molecule is spherical with diameter d, as it moves, it will sweep out a cylindrical volume equal to pi*r-squared*vt. As a first approximation, let's assume that our molecule is moving through other gas molecules of the same diameter. Any molecule whose center lies within a distance r of this cylinder will collide with our molecule of interest. So to find the number of collisions, we need to look at the volume pi*d-squared*vt and multiply this by the density of gas molecules n sub v. We're not quite done. When looking at the number of collisions, we need to keep in mind that all of the gas molecules are moving, so we should use a relative velocity. The relative velocity is equal to square root of 2 multiplied by the average velocity. It would be good for you to think about how we got this. So now we have this expression for the mean free path. What would happen to the mean free path of a tungsten atom if we introduced other gas molecules into the bulb? Would the mean free path increase, decrease, or stay the same? Pause the video and take a moment to think about it. You might have realized that by introducing other gas molecules into the light bulb, we can increase the number of collisions a tungsten atom will experience and decrease its mean free path. Would this be desirable or undesirable? Why? Decreasing a tungsten atom's mean free path is desirable. While some vaporized tungsten atoms will still condense on the walls of the light bulb, some collisions will result in tungsten atoms re-condensing on the filament. You may have noticed blackening near the top of incandescent bulbs after they have been used for a while. Heat transfer from the filament to the fill gas creates convection currents that carry many of the vaporized tungsten atoms to the top of the bulb where they condense. This localized darkening allows the light output from other regions of the bulb to remain relatively constant. You can see how kinetic theory has helped us think about this problem. Of course, there are some other things we need to think about. For example, what gas should we use? What properties do you think the gas should have? Pause the video here and take a moment to think about it. Well, if we are going to fill our light bulb with gas, we probably want to use something that is inert to avoid undesirable reactions. For common household use, we would also want our fill gas to be non-toxic in case the glass breaks. And of course, low cost is always desirable. Irving Langmuir actually solved this problem when he was working at General Electric in the early 1900s. Langmuir chose argon as the fill gas because it is inert and non-toxic, but if you look at the periodic table you might ask why he didn't chose a more massive inert gas. Argon is much lower in cost compared to other inert gases. Krypton and xenon are used in more expensive light bulbs, but not in household light bulbs. Argon continues to be used in standard incandescent light bulbs, although the use of incandescent light bulbs in general is being phased out. To Review, we saw how kinetic theory can be used to help us analyze a real-world problemâ€”that of light bulb blackening. We derived an equation to allow us to estimate a gas molecule's mean free path. The mean free path provides an estimate of the average distance traveled by a molecule between collisions. We saw that the mean free path is inversely proportional to the density of gas molecules. Realizing that the mean free path of tungsten atoms in a light bulb was too long helped us think about what parameters we might manipulate in order to solve our problem.