PROFESSOR: So the transfer of respiratory pathogens is primarily accomplished through droplets that are emitted by an infected person and then either breathed in or ending up on surfaces and touched and incorporated into the body in some other way by a susceptible person.

So let's begin by talking about the formation of droplets during respiration.

So these droplets can form in different parts of the respiratory tract.

So the respiratory tract refers to the whole system of your breathing apparatus in your body.

So that includes, of course, your lungs, which involves a network of passages going from the large bronchus down to the bronchioles and ultimately to the alveolar sacs where the air is exchanged or oxygen gets into the blood and carbon dioxide is picked up, and then you exhale.

In the upper respiratory tract, we have of course the mouth and the nose and the larynx, the voice box where sounds are made.

The nasopharynx is sort of the region behind the mouth and the nose where the passages are connected.

And in all of those different regions of the respiratory tract, when we breathe in, air is coming through in one direction, and of course when we exhale, it's coming back out.

And there is a lot of fluid in the lungs.

So the airways are lined typically with surfactant film and mucus, which is a thick substance we're all familiar with.

It can vary in composition but generally has some large macromolecules and in particular proteins that are called mucins, which give it it's sort of thick consistency.

There are also ions such as sodium and chloride, which are dissolved in the liquid.

And even liquid such as saliva in your mouth have a similar composition but less of the sort of thick mucin proteins that I mentioned compared to the deeper parts the respiratory tract.

Of course, when someone gets sick, also there can be more of the sort of mucus and phlegm that's generated to help the body deal with the pathogen.

So all those liquids and fluids are present in different parts of the respiratory tract.

And so there are a number of mechanisms which are still subject to scientific research and debate by which droplets are created and ultimately emitted when a person is breathing out.

So let's begin by thinking about such processes in the upper respiratory tract.

So in the upper respiratory tract, we can imagine, first of all, that the passages have a little bit larger spacing.

So for example, your mouth might be open by centimeters or millimeters.

If you go into your nose, there's of course various hairs and smaller structures which are often covered with mucus and liquids, which as the air is passing by, could be leading to some breakup of droplets.

And then of course also in the voicebox and other areas of the upper respiratory tract.

So the main mechanism here for generating droplets would be the breakup of viscoelastic filaments in a fluid flow.

So another word for breakup is fragmentation of viscoelastic filaments.

And by that, I mean that the mucus especially is a fluid.

So it has a viscosity, a resistance to shear flow.

But it also can have some elasticity.

If you pull on it, it can pull back a little bit because there are these macromolecules present.

So in general, we have a somewhat complicated reality of that liquid or that fluid.

And a filament refers to the fact that those droplets can be stretched out, and as the air is then blowing past those filaments, it can start to break up.

So this is our basic mechanism.

And this is mainly going to be happening while a person is exhaling, at least in terms of emissions.

It's also possible when you Inhale, there'll be some of those droplets created.

They go into your lungs or get deposited on the surfaces and then manage to somehow come back out again.

But certainly during exhaling, you would imagine more-- or you could see actually that more droplets are created.

So if we think of some examples of that, we might have, for example, when I'm speaking or breathing and my mouth is a little bit open, if I imagine drawing kind of let's say a person's lips and mouth might look something like this.

So I'm kind of exaggerating here, but of course there's saliva present, and there may be little filaments that form.

Of course, we can see this.

And then as we're inhaling, and especially as we're exhaling, then these filaments will kind of bend and they can break, and some of them will be emitted.

And in fact, these have been recently visualized in great detail.

And anyway, so that's one mechanism.

So it's these filaments of saliva in this case could be forming around-- I'll just mention this picture might be, for example, the mouth.

We could also look at the act of speaking.

We will discuss in detail later in this course that the emissions of infectious droplets is very strongly correlated with vocalization.

If you're speaking, there's many more emissions than when you're just simply breathing, and when you're speaking in a louder volume or when you're singing, that rate of emission goes up very significantly.

So there's clearly emissions related to the vocal-- the voicebox and to the vocal folds in the glottis, which is basically the voicebox.

So what that looks like is if you take kind of a side view, there are these-- as a cross-sectional view, there's these folds where the air is flowing through, let's say, in this direction.

And these are kind of waving together.

They're vibrating where the frequency could be, for example, 100 hertz depending on the tone of your speech and the type of vowels you're making or other sounds.

And again, what we have is that some here are saying this might be in the glottis.

This could be the vocal folds.

And this is basically the voicebox, is more colloquial term.

And as the air is flowing through there, this part is vibrating.

So there's some kind of maybe motion.

I'll just kind of indicate like this just that this is kind of shaking and vibrating and coming together.

And of course, there's also mucus and other liquids that are here lining all these things.

And when those folds come close together, they touch each other, and they can pull apart and again form these filaments that can break up and generate droplets that will be emitted of different sizes.

Now, one thing to notice is the length scale, so the mouth when it's opening might have a length scale obviously on the order of maybe centimeters but more likely millimeters in the regions where there could actually be emissions of droplets.

If we look at the vocal cords, that scale is also going to be millimeters, but when the vocal cords really come together and pull apart, we might be looking at scales that are much smaller than that.

So some of these filaments that are breaking up could be significantly smaller, and so vocalization may lead to droplets that are quite a bit smaller.

In fact, in the case of the mouth, as I just mentioned, the sort of length scale might be of order of millimeters for the filaments that are breaking up.

And the size of the droplets R might be on the order of 10 to 100 microns or even bigger, actually.

In fact, it can even go up to-- well, maybe not quite millimeters, but in the case of, let's say when you're coughing or spitting, certainly you are spitting out millimeters, but it could be even-- maybe I'll put even here 1 millimeter as sort of a kind of upper bound on the types of droplets that you could be emitting.

In the case of the voicebox, our length scale's a bit smaller.

It might be on the order more like of 100 microns for these filaments that are breaking up.

And the radius of droplets that you're going to form are going to be smaller, and they might be ranging more in the 1 to 10 micron range or possibly larger, again, depending on the details.

If you're coughing and there's a lot of mucus here, certainly you could get maybe larger than that as well.

So breakup of filaments is a primary mechanism of drop formation, especially in the upper respiratory tract.

Now what about in the lower respiratory tract?

So that's really referring to your lungs.

So in the lower respiratory tract, there is significant evidence and also at least qualitative theories and to some extent quantitative theories showing that the main mechanism is not so much the breakup of filaments in a flow, but rather the bursting of filaments of mucus but in much smaller domains, where it's not so much that the fluid is whipping by and breaking apart the droplets, but it's simply breaking up due to surface tension.

Just that it's this instability kind of like in a dripping faucet or a stream of liquid when you start to stretch it out and let surface tension act, it kind of squeezes down, eventually wants to make droplets.

So that's kind of the rupture of a film.

Under surface tension, it's more likely to be the mechanism.

And so this is kind of maybe more generally can be thought of as an elastocapillarity instability of mucosal films, specifically in the deepest part of the lungs and in the smallest passages during during inhaling in the bronchioles and also, to some extent, in the alveola.

During inhaling, that's when the breakup is happening, and then any droplets that are creating, some may deposit on the walls of the respiratory tract, but some fraction of them will be swept back out again.

So let me explain this a little bit more detail.

I should also mention this mechanism is also referred to as the bronchial film burst hypothesis.

And I say it's a hypothesis because despite the fact that there's been a lot of study of the droplets that are produced by different forms of respiration and some theoretical modeling, it's difficult to actually observe this process occurring in the body.

And so it's still-- it's a hypothesis that people are still studying.

So what we're thinking of here is if we zoom in to a bronchiole, which is a passage that looks maybe something like this, it's like basically it's a flexible tube.

And the smallest ones of these now are getting down to the scale of 100 microns or so.

So it is kind of like a typical length scale here of, let's say for the radius, might be 100 microns or less.

And these of course are lined with mucus as well.

And in some places, there's a bridge.

So it's kind of like there's almost like bubbles of air with sort of little bridges of mucus.

In fact, you may actually have even some places where the passage after exhale has completely collapsed.

And so maybe some parts of it are touching.

Others are not touching.

But there's kind of these little bridges of liquid or films, bronchial films that are kind of extending across at least part or even all of those channels.

Now, imagine we start in this situation, and we start inhaling.

And let's just say this is the direction of inhaling.

Let's imagine that the alveola, which is kind of on the end of this tube, and so let's see what happens if we start inhaling.

So for inhaling, then the air is flowing in.

And so the first thing that happens is that these bubbles are going to start essentially-- this film is essentially going to be pushed.

As that liquid is being pushed, we have some flows occurring.

There's some recirculation flows in there.

Also, there's interaction with the elastic or stretchy walls, which are soft, of the bronchiole, and so it can expand.

So if you go to the next step, you may find as you continue inhaling that now this tube has expanded a bit.

So it might look more like this.

And then this, to some extent, this film would start to get stretched.

And then at some point, as this thing is trying to open, and also it's under some flow, but it's going to burst.

And this bursting again is not quite the same as this situation because the flows are much slower.

So here, these flows are often at so-called high Reynolds number, as we'll talk about later in this class.

High Reynolds number refers to the tendency of the flow to become unstable and for inertial effects and momentum of fluid to become important.

At the scale of the mouth or the nose or even the vocal cords, there can be significant inertial effects and very complex flows.

On the other hand, when we get down to the smallest channels in the lungs, and especially when we reach kind of the dead end, these sort of the alveolas, which is basically a bunch of little sacs, they're kind of at the end here, then it's kind of a dead end.

There can't be any like very fast flow through that system.

And so it's actually a low Reynolds number situation.

So we're not talking about turbulent flows or sprays of liquid at high Reynolds number.

Instead, we're talking about films that are getting stretched out, and then they simply break up under the effect of capilarity, which refers to surface tension.

So basically, when you expose a surface and stretch out a liquid film, it just tends to break up into little droplets, basically in order to minimize its energy.

So what we'll see here is that maybe one of these films over here has already burst and will lead to some droplets that are being created.

So this bursting of the film is what leads to the droplets.

And when you're inhaling, those get swept a little further downstream.

Some of them may deposit on the walls and go back into the film and coalesce into the film, but others will remain suspended in the air.

And now when you exhale, you start pushing back the other way.

The tube is more open now, and we may have a situation like this where there's no more sort of spanning films left, but there's some fraction of these droplets.

A few of them may have deposited and coalesced on the surfaces, but they're going to start getting blown out the other way now.

And so these are the droplet emissions right here.

I'll just say it'll eventually do that.

So some fraction of these will make it all the way out.

Of course, those droplets can deposit anywhere in the respiratory tract.

In fact, some of them, if you're breathing through your nose, may end up getting caught in your nose, actually.

And so there's an exchange of fluids between the different parts of the respiratory tract, but some fraction of those droplets will get out.

And then ultimately, when you're finished exhaling, now the pressure is released.

And this tube kind of relaxes back to its original state where there's some mucus here and there's some places maybe where it's closed and there's these possibly spanning films in some places where it's almost touching.

So these are some of the basic processes by which droplets are emitted.

As you can see by the range of different processes that are possible in the human physiology that we've just described, we can see there's a range of droplet sizes that will depend on the respiratory activity.

Are you breathing lightly because you're sleeping?

Are you breathing heavily at high speeds because you're exercising?

Are you vocalizing and generating droplets in a different way in the larynx?

All those activities play a role.

And also there are variations between individuals.

And finally, if a person is sick and all these fluids I've sketched here as mucus contain pathogens such as virus or bacteria, then of course the degree of infection, the viral load or the total amount of pathogen, the total amount of bacteria plays a role as well in sort of how infectious the emissions are from breathing.

But these are some of the basic principles.

And now we'll move on to ask, what happens to those droplets after they leave the mouth of the infected person?