PROFESSOR: So let's talk about the transfer of respiratory pathogens, and in particular, contagious pathogens such as viruses and bacteria, that infect the respiratory system.

The way that such pathogens are normally transferred is through droplets which are emitted by respiration, which could be by just normal breathing, coughing, sneezing, et cetera.

And so here is a sketch of an infected person who is undergoing respiration and is emitting droplets into the air.

And so let's think about what is the fate of those droplets, what it could be.

So one possibility is if the droplets are very heavy, they're just going to settle to the ground.

And then they may collect on the ground or on some other surface.

And then somebody else could touch that surface and transmit it, perhaps by touching their eyes or some other-- or their nose or some bodily entrance point.

And that sort of transmission is called fomite transmission.

So these dried up bits of droplets on the surface are called fomites.

And this mode of transfer would involve settling of those droplets to the surface, to a surface, OK?

Now, another possibility is that the droplets kind of float around, and if they're small enough, they might actually evaporate and they might disappear.

So they might evaporate.

And at that point, if there's a pathogen in them, that pathogen may still be around, but perhaps if it loses enough fluid it's going to lose its viability.

And so perhaps those droplets would be eliminated.

And then finally, there are droplets which undergo neither of these and remain floating indefinitely, or at least for long periods of time, let's say for hours, in the space.

And these are called aerosol droplets.

So these are droplets that are very small.

They don't really settle in a reasonable amount of time.

But they're not necessarily evaporating either.

And so they are present.

And if another person is here, they can very easily breathe in those droplets, OK?

Now, how do we know which of these outcomes is possible for droplets that are emitted from respiration?

So what it really depends on at the simplest level is the size of the droplet.

So the droplet fate depends on its size.

So why don't we do some simple estimates of these different processes?

So the first would be looking at settling.

So the settling time from a height L, which might be the height of a person, a typical number that's taken is 2 meters for a settling problem like this.

It's given by the following formula, assuming we have so-called Stokes' law of settling is valid, which it usually is for small droplets.

And that would be that-- I'll just write the formula first.

2 rho g R^2.

So basically, there's a 9/2.

L is the height which they're going to fall.

So basically this is L. And mu_a is the viscosity of the air, rho is the density of the air-- or density the droplet, excuse me, of the liquid.

And g is the gravitational acceleration, and R is the size of the droplet.

So the size of the droplet is R -- or that's the radius.

So what you see here is that when the radius gets bigger, the drops fall faster, and hence the time goes down.

So very large droplets will very quickly settle out.

Others -- as R goes to be smaller and smaller -- they might be suspended and become aerosols.

We also might worry about evaporation, for the smaller droplets especially.

And the evaporation time, again with a fairly simple approximation of pure liquid which is evaporating.

Basically, just as it's getting more highly curved, the molecules will have a bigger driving force to be removed.

And if it's a diffusion-limited process, which is basically water vapor has to diffuse away into the environment, then you can show the evaporation time is the initial size of the droplet, R_0 -- so let's just say R_0 is the initial size.

And maybe here, when it's settling, it could still be evaporating.

So R could be varying.

But why don't we just neglect that for droplets settling quickly.

Maybe that's roughly the initial size.

And here for evaporation, there is a constant, which I'll call D_bar, which is just something that has units of diffusivity.

So length squared per time.

And then (1-RH), where RH is the relative humidity.

So basically, the tendency for the water droplets to be removed from a liquid droplet end up in the air has to do with the relative humidity of the air.

So that's another factor that comes in here.

So if we plot these two results, we arrive at the so-called Wells curve, which was first formulated by epidemiologist Wells in 1934.

And I'll draw that over here.

And the Wells curve is sketched like this.

It says that if we have the drop size R_0 on one axis, and on the other axis we have the time of settling-- the time that the droplet has left the mouth, then you have basically two expressions here.

So the settling is something like this, where it's a function that goes to 0, like 1/R squared.

On the other hand, evaporation is the fastest for the smallest droplets.

You see that it goes like (R_0)^2.

So it has a dependence more like this.

And so basically, these curves intersect at a certain point here.

And if you ask yourself, if I am a droplet of, let's say, this size here, then as time goes on, I hit this point, and this is where I evaporate.

So for just a pure liquid droplet, at that time, that droplet would disappear.

On the other hand, if I have a larger droplet that's going to hit this other curve first, then these droplets will settle, because before they have time to evaporate, which would require all the way going to here, they've already fallen to the ground.

They may continue evaporating on the ground, and you're eventually left with a dried up residue of some of the material that may have been contained in the droplet.

And then there's a crossover.

And so generically, you expect this kind of behavior for droplets that are evaporating and settling.

So the Wells curve was first formulated in 1934.

And if we just want to put some numbers on here, if we're talking about pure water, then this crossover happens around 70 microns.

And the time is around 3 seconds.

So that gives you a sense, basically, of how quickly the larger droplets are settling faster than 3 seconds, and then the small droplets are evaporating a lot faster.

And by the way, to get a sense of how fast they are, if we look at the dependents, each of these is squared.

So if we want to go by a factor of 100, if you go to, let's say, 0.7 microns, which is 700 nanometers, it's a factor of 100.

But the time comes in squared.

So it's 3e-4 seconds.

So we're talking 0.3 milliseconds.

So basically, droplets that are in the 1 micron or below range, if they're pure liquid, they'll evaporate extremely quickly.

And conversely, if we consider much larger droplets, let's say that are bigger by a factor of 10 or 100, that also comes in squared in terms of the settling time being reduced.

And so we would then end up with 100, or up to even 10,000 times smaller settling time.

Although it won't be quite as small, because also, the particles need to accelerate to that speed.

This settling speed here is the terminal velocity of a drop.

And there is a short acceleration time for very small particles.

And for very long particles, you may still be actually in that acceleration time when you hit the ground.

So basically, it might not be that long.

But basically, the time, at large times, is also quite a bit reduced for large particles.

Now, there's also the humidity effect, which can be seen here.

So for example, if we're at 90% relative humidity, this factor here is a factor of 10.

So what was on the order of a few seconds, if we're at higher humidity, then this curve ends up looking more like this.

And we may follow this curve a little bit further and end up with something like this.

This would be high humidity.

I'll say higher, because I haven't gone that far.

There's another curve that I could draw where this even goes further this way, and where this could start turning into, say, 30 seconds where that crossover occurs.

But in any case, there is a crossover at some point.

And at high relative humidity, the evaporation is slower, and so we are more following the settling droplets.

And so this is an important set of concepts in the field of aerosol science involving droplets, and especially for respiratory diseases.

But it's still oversimplified.

So recent research has showed that, in fact, many droplets that are present from respiration do not evaporate on these kind of fast timescales.

And in fact, they can linger and can be way into this small size range of aerosols and not disappear.

And it's possible, then, to breathe them in and transmit disease with them.

So what's missing here is that the droplet fate depends not only on the size of the droplet, but also on solutes.

So what I mean by that is that, of course, a droplet coming out of your lungs and passing through your pharynx, your vocal chords, is not just pure water.

It's even not pure saliva.

In fact, it contains many other molecules.

So of course, it contains the pathogens themselves, which are solids, and they don't evaporate.

So whether it's bacteria or virus, some of that material has to stay behind.

There's all kinds of organic molecules, because in fact, the mucus that comes out of your lungs as a non-Newtonian fluid that's full of macromolecules of different types.

Those molecules are usually charged, as are, in fact, the viruses and other pathogens as well.

And so there could also be hydration, water, so that those water molecules, which are not freely in solution but were strongly interacting with charge services, or charged molecules, and form so-called hydration shells around those molecules.

And finally, there could also be salts, because we all know that our body is, in many cases, similar to seawater, and has fluids which contain a large number of salts.

For example, sodium chloride or calcium.

And salts love water.

So in fact, it's been shown that some respiratory aerosols are actually observed to be growing after they're emitted from the body.

In a humid environment, water may actually be condensing onto those particles and causing them to grow, because it has molecules that love water.

And in fact, these kinds of molecules or particles that attract and hold water are so-called hygroscopic materials.

And many respiratory-- a significant number of respiratory droplets are, in fact, hygroscopic.

So this whole picture of evaporation settling really needs to be modified.

The settling part is going to always be there.

Even a solid particle which is settling in air is going to obey this Stokes settling velocity.

But the evaporation part of it is certainly true for pure water, but is not necessarily the right way to think about respiratory aerosols.

So finally then, I'll just sketch what happens when people have measured respiratory distributions of particles, and focusing on the aerosol range of the really small particles that might remain suspended.

So these are particles like this guy right here, which are around 1 micron, and will have settling times that are on the order of hours.

So those particles that can linger in the air for long periods of time.

And so if we look at the number of droplets that we have at different sizes, and this is for different kinds of respiration-- and I'll draw this to sketch what it would look like on a log scale.

So here I'll put 0.01 microns, which is 100 nanometers.

And then I'll put 1 micron, and then 10 microns, and then 100 microns.

So when you breathe, speak, cough, sneeze, you're letting out a distribution of particles of all these different types of droplets.

And those droplets will typically contain pathogens, such as bacteria or virus.

And the way these things look is because of these hygroscopic solutes, in fact, we don't see that all the little ones are evaporating it away in a tiny timescale like milliseconds, but in fact, they do linger.

And you do have respiratory aerosols that can be observed.

And so what these distributions actually look like, they tend to have a peak around half a micron in diameter, or a radius even smaller than that would be a quarter micron.

And so they look something like this.

And if you're breathing at rest, it might look something like that.

And actually, the volume fraction, if we were to convert this to a volume fraction, ends up being around 1e-16 parts of liquid per volume of air.

So these are very small droplets.

And you can't see them, but they're there.

If you're resting breathing, you might have something like that.

There's also an important effect of the type of respiration.

So if I start talking, then it turns out I'm still releasing quite a few these aerosols, but now I'm also releasing some much larger droplets.

I might even be having-- depending how I'm speaking, and in fact, my personal physiology may vary from person to person, I might be emitting even more of these larger droplets.

Or also, the aerosol droplets as well.

And then there are other activities, such as singing or exercise, where you're breathing very heavily, where you emit even more droplets.

And you can see vocalizations, singing, and this can be, for example, talking, that those lead to more emissions.

But the important thing is that there is a big population of particles.

In fact, the majority of particles, by number or even by volume, is over here in the aerosol range.

So these are particles that do hang around.

And they float around the room.

And they can do so for minutes or even hours, depending on their size and the conditions of the room.

These here are the large drops which will sediment out according to this formula here.

So the Stokes formula is still going to be valid regardless of evaporation.

If we know the size, we have a sense of how quickly the droplets are falling.

But the ones we're really going to want to focus on are these aerosols for viruses, because viruses are small.

Whereas bacteria are big and they might have to be transmitting more of the enlarged drops.

So now let's talk a bit about the biology of viruses and bacteria and see how that might connect to the physics of droplet transmission.