PROFESSOR: So we've just discussed the mass balance that results from considering ventilation and breathing of an infected individual in a room leading to a build up and then steady state of aerosol droplets that are infectious in the indoor air.

We've also briefly talked about masks.

I'd now like to introduce the possibility of filtration, which is actually very common in mechanical ventilation systems.

And then arrive at a very simple comparison of filtration versus mask use as strategies for preventing indoor transmission.

So here's a schematic sketch of the air flows.

So basically, we still have this Q, which is the outdoor air flow.

So that is the air which is coming in from the outdoors.

And for mass balance, it also has to be leaving.

And the air change rate is based on that Q.

And in fact, if I remember, if there's a volume V of the room, then the air change rate was Q/V. So that's of units of inverse time.

So that's the time, roughly, it takes for-- the residence time for the outdoor air, and also for the changing of the air.

Now, in addition to that, though, there could be significant recirculation of air.

Now, if the air is recirculating but not filtering the droplets in any way, then it really doesn't concern our calculation, which is basically just a mass balance.

So if I'm just swirling the air around, or even taking it outside and back in, as long as I'm not losing some droplets in the ducts, then it really doesn't matter if it's recirculating.

But what is of interest to us is if in that recirculation we lose some droplets.

So some droplets could be lost simply to settling on the walls of the ducts or the heating and ventilation and air conditioning, HVAC, unit.

But more interesting is to consider what would happen if we actually placed filters, which is very common in HVAC systems.

So we could either have one of those big filters that you stick into the heating or ventilation ducts.

And those typically are given MERV ratings, which are Mean Efficiency Rating Values.

And we're interested in the filtration of aerosols.

And so if Pf is the fraction of the aerosols that are blocked-- and we roughly would look at a size range, for example, less than 5 micron radius-- then the difference of ratings of filters give you anywhere from 20% to 90% filtration.

And then a very high quality filter would be a so-called Hepa filter, which is a High Efficiency Particle Air filtration unit.

And that would give you even as high as 99.97%.

And also, it's worth emphasizing that you could also have a freestanding filtration unit.

There are a variety of different kinds of filtration units.

It could be a fan which is blowing through a Hepa filter.

And it could be a freestanding unit in the room.

It could also be more exotic systems, such as electrostatic precipitators, where the air is flowing into a chamber that has a very high electric field, and the droplets are basically projected and deposited onto a surface.

It could be flowing the air through a UV-concentrated light treatment to kill the virus.

So you're not actually removing the droplets, per se, but you are removing the virus.

And since we've been keeping track of the concentration of virions, they could be deactivated in that way.

And so all of that can essentially be lumped into this simple picture of a recirculating flow rate Qf, and a filtration efficiency, Pf.

So let's revisit our equations from last time.

So our mass balance is at V dC dt is P, which is the production rate of infectious air by an infected person.

We have the removal of air by the outer flow rate, which we've already discussed.

And now we have the new term which is Pf Qf.

So if Pf is 1, then the entire filtration flow is removing droplets.

On the other hand, if Pf is 0, this term goes away.

And that's the limit where you're simply recirculating air, but you're not actually removing any infectious droplets, and it's playing no role.

So this is basically our only new term here.

And so what this means is we get the same calculation, same as before, but we just have to make a little replacement.

What was before Q is now-- notice we can lock-- oops, I've forgotten, actually, here there should be a C here, actually.

Because the flow rate-- or the flux of infectious air is the concentration of infectious air, so the concentration of virions per volume times the flow rate, that thing gives me the correct value.

So the Pf a dimensionless number between 0 and 1.

So anyway, Q gets replaced by Q plus Pf Qf.

And also, wherever we saw a lambda a, that gets replaced by lambda a just from the outdoor air plus lambda f, where lambda f is Qf over V.

So that's the recirculating or filtration air change.

So it's the recirculation or filtration air change rate, whereas lambda a is the outdoor air change rate.

And we can also talk about the balance between these two.

And so that's also something which is reported or measured for ventilation systems.

And that's sometimes called Z, which is the outdoor air fraction.

So that would be lambda a over lambda a plus lambda f.

Or we could also write it as Q over Q plus Qf.

This is the outdoor air fraction of the ventilation system.

So another way to talk about ventilation is you give the total flow rate.

So as I sketched here, there could be a fan which is in the heating, ventilation, and air conditioning unit, which is just pumping out air at a certain rate.

That air is mixing the recirculated air and the fresh air with a fraction Z, which is the outdoor air fraction.

And so actually, this might be, for example, a typical value is around 20% for many indoor spaces, such as businesses or classrooms.

And basically, you have to tune this number to make sure that enough fresh air is coming in for the occupants that are present.

And also, you don't want this number too high, because typically the outdoor air is not comfortable air.

It either is too cold or too hot or has the wrong humidity.

And so you save a lot of energy in your heating ventilating system by keeping this number as low as it can be effectively, so that you're just recirculating quality air that is at the right temperature and the right humidity.

However, that desire to save energy, and hence also save carbon emissions and other related things, goes against what we're talking about here, though, is that when you recirculate the air and you don't take in fresh air, it's actually much worse for any airborne pathogens that might be transferred.

So there's a competition here where you design an air ventilation system to make sure that you're saving energy, but also that you're keeping the place safe for potential airborne transmission of disease.

OK, so if we just take this change here, we can replace these quantities in the result that we already derived.

So I don't have to go through all that again, but I can just say that the disease transmission rate-- and this would be in steady state, just to give us something concrete to look at-- that's what I called beta bar.

And let's now write down the same result, but just make this change here.

So we have Qb squared, that's the breathing rate.

We have Cq, that's the concentration of infection quanta per volume in the exhaled breath of a sick individual, an infected individual.

There was Pm squared.

I'll write different colors just to emphasize that.

And then in the denominator, we had lambda a, but now it's going to be lambda a plus Pf lambda f-- and I'll write that in a separate color in just a moment-- times volume.

So here's Pf.

So now, in this formula, we have the effects of masks and the effects of air filtration together.

And so we can ask the question that I posed at the beginning is, which one is more effective in stopping airborne transmission of disease?

So you can see these two factors do come in differently in the equations.

So let's first consider the effect our filtration-- effective air filtration.

So there's a lot of interest today in installing Hepa filters or other high quality filtration systems into vulnerable spaces, such as nursing homes, and also in spaces such as classrooms, where people fear transmission of COVID-19.

So we can ask how effective that can be.

So one way look at that would be to say, well, how does air filtration affect the steady transmission rate?

So that would be looking at the transmission rate with the filter compared to the transmission rate without the filter.

So if we do that, you can see all the terms here cancel except for this one that has Pf in it.

And so what we're left with is, because in the denominator we're left with just-- when Pf is equal to 0, it's just lambda a.

That's in the denominator, so it ends up in the numerator.

And so it's just lambda a over lambda a plus Pf lambda f.

So the benefit of filtration can be immediately seen right here.

If you know the ratio lambda a to lambda v, because I can also write this as 1 plus-- well, actually, I won't even-- I won't do that right now.

But you can see how this is related.

It's related to this quantity Z. but basically, the ratio of the lambda a to lambda v is related to Z.

And that obviously comes in here.

And Pf comes in as well.

But an interesting question we can ask is, well, what if you have a perfect filter?

So let's say we have something even better than Hepa.

Let's say it's 100% filtration.

That's like best case scenario.

So this fraction here is larger than if I just set Pf equals 1.

So this is a perfect filter.

So we have the most expensive filter on the planet, and it's going to definitely filter everything.

And so what we're left with, then, is just lambda a over lambda a plus lambda f.

Now I can make the connection here.

That is simply Z. So basically, the effect of air filtration is never better than the outdoor air fraction itself.

But I already told you, the outdoor air fraction here cannot be too small or you're not delivering enough oxygen to the occupants of the room.

So basically, there are standards for that as well.

For example, you need to have, for outdoor air, there is an additional requirement is that you need, at least in the United States, 15 cubic feet per minute per person.

So basically, this Q can't be too small, because you have to be delivering, essentially, enough oxygen for a person to breathe.

And so this is one way this standard is decided.

And so basically, the Z can't be that small.

And so if I ask myself, what's the effect of filtration, an interesting conclusion to this calculation is that this is not really smaller than about 10 to the minus 1.

So if we just think of an order of magnitude, roughly speaking, gaining a factor of 10, maybe, out of air filtration, but not that much more.

Now, you might say, how is that possible?

My filter is a perfect filter.

I'm filtering everything.

The problem is seen right here, is that in reality, what we really want is we want to protect a person who's over here, maybe who is susceptible, from another person over here who is infected.

And you see the problem is that if it's a well-mixed room, then the infected person is breathing all these infectious droplets everywhere.

And this other person is breathing them.

And even if you perfectly filter the piece of the flow rate that is going through the filter, there's still lots of other air in the room and it's not all being removed.

So unfortunately, you don't get such a benefit from that, unless you could completely choke off the outdoor air and just keep recirculating until you remove all the virus.

But then a problem is, you also run out of oxygen, and you don't have very good air in the room.

So that's not really a solution either.

So basically, air filtration is helpful, but I would say it's not super helpful.

A factor of 10 is good, we like factors of 10.

But it's not a factor of 100.

And we might actually rather have a factor of 100.

So then we can ask ourselves, well, what do we get from masks And by this, I mean everybody's wearing a mask.

So keep in mind, we never know who's the infected person ahead of time.

So we want to consider a case where everybody's wearing a mask.

And so then by assumption, the infected person is wearing a mask, and any susceptible person is also wearing a mask.

So that's our assumption here.

OK, so this is good mask compliance here.

And so we can ask ourselves again, what is the transmission rate with mask compared to the transmission rate when there are no masks?

And the way my notation works here, Pm is the mask penetration factor.

So that would actually-- Pm equals 1, actually.

That would be the case where, basically, there is no mask, because all the airflow goes in and out of the mouth without any kind of filtration.

So this is just Pm squared.

And the important thing is that it's squared.

So one argument you will hear, which even influenced the World Health Organization back in January at the beginning of the pandemic, is that the virus is so small, as we've already discussed, and probably is going to be carried in very small droplets.

And therefore, any filtration, even a mask, is not really that helpful, because masks are not going to be filtering at the scale of 120 nanometers, which is a virus.

And even the smallest aerosol droplets, many of them do get through.

In fact, when you get to about 1/10 of a micron, or 100 nanometers, most mask materials don't have good filtration.

The very simple reason is they also have to allow good airflow.

So if you have such tiny pores that you're catching things at that scale, the problem is there's a very high resistance to flow and you can't breathe.

In fact, you've probably experienced that if you're wearing a good mask that you can't wear it for too long, because after a while you can't breathe anymore.

So you need to have some big enough pores to allow flow.

And that makes it really hard to filter the smallest particles.

But the interesting thing is this thing comes in squared.

So we can ask ourselves, well, what about different qualities of masks?

So a really good mask material that is perfectly fitting, so like a high quality surgical or N95 mask, if you don't have any leakage of air, you have a really good fit, and you're just going right through the material, this could be as high as 99% filtration for aerosols, for the aerosols that we care about.

And this would be like a high quality surgical mask material, like not even factoring for the fit.

So if it's 99% filtration, what that means is Pm is 0.01, but it comes in squared.

And so this factor is actually 10 to the minus 4.

Four orders of magnitude compared to one order of magnitude you get from the filter.

Now, that's for perfect masks, really good masks.

What if our mask is not so good?

So actually, we have an N95.

N95 actually is guaranteed to filter about 95% of the aerosols.

And so if you take 0.05 and square it, you're getting a number of order 10 to the minus 3 for Pm squared.

And what about cloth masks?

So this is where the debate comes in, because these days people are wearing cloth masks, which makes a lot of sense.

It's way better than nothing, as we'll see in a moment.

But yeah, one could argue, well, a lot of the cloth masks might be letting through these aerosol droplets.

They're not really that great.

In fact, if you look at the cloth masks, they could give you a range, but it might be anywhere from-- I mean a really bad cloth mask is 10%.

That'd be like just a single, thin, cotton, very loose weave, like on a bandana.

That's pretty bad.

But most of the multi-layer cloth masks, or the silk masks, they can actually do pretty well.

They can even get as high as 90%, which is pretty high, but it's possible.

And maybe a lot of them, depending on maybe they're not fitting so well, they might be more like, let's say, 50%.

But the thing is, this comes in squared.

And interestingly, even the 90% case, that's 10% get through, so Pm is 10%.

But when you square 10%, it's still 10 to the minus 2.

And if you take these lower numbers and square them, you're still talking about something which is on the order of 10 to the minus 1.

So what this calculation tells you is that even like some of the worst masks you can wear, as long as there's good compliance and everybody is actually wearing those masks indoors, then the fact that this comes in squared means that you get at least a factor of 10 reduction in the transmission compared to having no masks in a well-mixed room.

And in fact, decent masks will do way better.

You could get a factor of 100, 1,000, or potentially 10,000 in reducing the transmission rate by wearing masks, whereas with filtration, even with the most expensive and highest quality filters, you can barely get better than a factor of 10.

So this is a really important concept to keep in mind.

And it comes out of a really simple calculation.

And the simple reason that I mentioned before is that air filtration is only filtering part of the air, and the rest is just out there for you to breathe.

But masks are much better because they capture the source and they also block the target.

So that basically, every droplet has to go through the mask on one end and it has to go through it again on the other end.

Whereas the filter is missing most of the droplets.

They're floating around the room.

They're not going through the filter.

Unless you choke off the outdoor air, and you can't do that.