Disclaimer: Many of the replies below are a matter of opinion, not peer-reviewed scientific facts. For the aerosol-related questions, I also urge you to tune in to the APS COVID Webinar on Dec 2 by Prof. Jose Jimenez. He is a world expert in this area; I am not.

**General questions:**

1. What percentage of transmissions are attributable to aerosols versus droplets?

Reply: The answer hinges on what one considers "aerosol". Following Milton, https://doi.org/10.1093/jpids/piaa079 , I suggest that any droplet smaller than 100 micron must be referred to as aerosol because it almost certainly will dry out before hitting the ground. A droplet that starts out at 100-micron when it exits the mouth will shrink to about 25 micron and then stay in the air for close to a minute and thus can be inhaled. So, when using this definition, I'm positive that the vast majority of transmission results from aerosol. Transmission through even larger, "ballistic" droplets should be comparable indoors and outdoors. Considering that documented outdoor transmission is at least an order of magnitude lower than indoors indicates that ballistic droplets do not play a major role.

2. Are the generic inexpensive paper masks at all useful?

Reply: Some generic masks work much better than others. A key requirement is that the air actually passes through the mask and doesn't get funneled around the edges it as can happen when making a mask out of something like coffee filter paper, that in my experience is not "breathable". Something like a dust-mask, used for decades by workmen, is actually quite effective at stopping all but the smallest droplets from entering the atmosphere, but they offer little protection against inhaling these small speech droplets after they have shrunk by another factor of 20 to 50 in volume due to evaporation of their water.

3. "Based on the ACS-Nano paper: Aerosol Filtration Efficiency of Common Fabrics Used in Respiratory Cloth Masks (Published April 24, 2020) - The bottom line is that a silk lining for a cotton/silk/cotton mask is effective for blocking aerosols. The silk acts as an electrostatic barrier to aerosols. Do you know about this? We have made some prototypes at my university. I would like to talk to someone about our prototypes. And their efficacy. The masks are designed for protecting the wearer from aerosols. That is not breathing the aerosols in.

Reply: Yes, very nice paper that also lists the backpressure generated by each of these materials. In my experience, the air resistance generated is a key factor. It's easy to make a 100% effective mask out of a plastic bag, but hard to breathe through it! The N95 and KN95 (as well as dust masks) solve this problem by having a cup shape, which has a large surface area that the exhaled/inhaled air can pass through while providing excellent filtration. The disadvantage is the "recycle volume": 150-300 mL of exhaled air never leaves the mask, forcing one to take deeper breaths such that the % of recycled breath becomes lower. This is a nuisance when at rest. Surgical and home-made masks tend to leak around the edges, in particular next to the nose, causing glasses to fog up, and lowering protection. They also offer less emission protection against coughing, where the burst speed of exhaled air is high, lifting the mask of the face. But they are perfectly fine for stopping speech droplets, because the flow volume per second while speaking is rather low.

4. The speaker's definitions of aerosols versus droplets?

Reply: I believe people should adopt Donald Milton's definition https://doi.org/10.1093/jpids/piaa079 Droplets larger than ~100 micron diameter will often not fully dehydrate before they hit the ground, and therefore the term droplet (or drop) seems appropriate. Anything smaller than that is likely to fully dehydrate before landing (unless relative humidity is very high) and then hang around for close to a minute or longer, and from a disease transmission perspective therefore must be considered aerosol.

5. What is the conventional definition for disease transmission?

Reply: The conventional definition is found in wiki, but from a COVID perspective it concerns transfer of infectious virus from an index patient to another person, followed by an active infection (at least one round of virus replication, typically resulting in ~1000 new virions). The recipient can remain without symptoms, but the disease has been transmitted. See Y. Bar-On, A. Flamholz, R. Phillips & R. Milo: SARS-CoV-2 (COVID-19) by the numbers, Elife doi:10.7554/eLife.57309

6. How would these experiments be different if they happened outside with no wind or airflow?

Reply: All of our speed measurements are dominated by air convection. Even with no wind or airflow, convection in the presence of a human body, or any other temperature gradient generating object, is enormous. The main difference between indoors and outdoors is that outside “sky is the limit”, whereas inside it’s your ceiling. So, even in the total absence of wind, outside the vertical dilution is far greater. See https://tinyurl.com/covid-estimator

7. Clearly the focus of the study is on droplets of different sizes. What is the (quantitative) knowledge about free virus concentrations (not in droplets) ejected while speaking with vs. without mask?

Reply: I do not believe there to be any "free virus". Virions are tiny particles, covered by a rough ("spiky") hydrophilic (glycosylated and phospholipid headgroup) surface that can only leave the mucosal layer when embedded in a droplet/particle that contains saliva/mucous.

8. In what sense can the bigger droplets ("which would normally fall to the ground") been blown around by ventilation? I hear a lot of people are afraid of that this might happen.

Reply: Yes, the very vast majority (in terms of numbers) of droplets fully evaporate before falling to ground. This even applies for relatively large droplets of diameters up to 100 microns, which then behave like aerosol and will be blown around by ventilation and convection currents. "Ballistic droplets" (larger than ~200 microns) typically fall to the ground prior to dehydration, and since they are still wet, I assume they will mostly stick to the surface on which they land. These would be the primary source for fomite transmission as they constitute a large fraction of the total emitted saliva (See Duguid's table in slide 43 of my presentation).

9. As building engineers we attempt to control relative humidity between 35% to 55% +/-5% for many reasons from comfort to hygroscopic stability to protecting artifacts....can you comment on this range to your understanding of the effects of RH

Reply: Within this range, respiratory particles will fully dehydrate, with the dehydration kinetics roughly scaling with (1 – RH). At higher RH, above ~70%, the kinetics may be impacted by the phase-separation phenomenon discussed by Vejerano and Marr (J. Roy. Soc. Interface, 2018), which could cause a substantially higher fraction of droplets in the 50-200 micron range to fall to the ground before full dehydration. However, from a comfort perspective, such high RH values are probably not feasible.

10. Might you please say more about humidity and infection?

Reply: High humidity will increase the volume fraction of droplets that land prior to dehydration, and thereby reduce airborne exposure. High RH also reduces the time a virion remains infectious, although this time scale is in the hour range and I would expect this latter aspect not to be all that important. The precise relation between dehydration kinetics of oral fluid droplets and relative humidity is not yet known, so I can't give a quantitative number for the RH value where the increase in humidity provides a meaningful reduction in exposure. Based on Vejerano and Marr's numbers, I expect it to be somewhere in the 60-90% range.

11. Is sleeping with masks recommended if a person is infected?

Reply: While asleep, mask use will not prevent self-infection through speech droplets. Although not measured, I anticipate that any droplets generated by snoring will be rather large as they do not originate from the vocal folds, and will not shrink to Milton's “respirable aerosol” size upon dehydration. However, if the infection is in the lungs, breathing particles could carry virus, and mask use while asleep could reduce exposure to others.

12. Watching the videos... I think we need to keep masks mandatory, even after the pandemic is over :D.

Reply: I expect we'll end up in an Asian-like scenario, where mask-wearing will remain fairly wide-spread in urban areas.

13. Why a virus can be airborne and another can't?

Reply: Only respiratory virus will exit the mouth in significant quantities while embedded in respiratory droplets (see D. Musher, N Engl J Med **2003**;348:1256-66) with the high likelihood to become airborne. Other viruses, like hepatitis, Zika, or HIV are transmitted through other routes. Some pathogens, like TB, that predominantly colonize in the lungs (alveolar macrophages are often considered to be the primary host cells) are believed to exit primarily through breathing, not as speech droplets.

14. Since large drops contain most of the total volume, there should be fewer viruses in smaller drops - those that remain in the air for longer. Is there a graph showing the number of viruses vs time (rather than number of droplets)?

Reply: You raise a very important point. The volume fraction of emitted droplets that remain airborne is relatively small. We believe that the numbers listed by Duguid are accurate for larger sizes (>~40 microns) but strongly undercount the smallest of particles. Xie et al. (Xie, X.; Li, Y.; Chwang, A. T. Y.; Ho, P. L.; Seto, W. H.: How far droplets can move in indoor environments - revisiting the Wells evaporation-falling curve. Indoor Air 2007, 17, 211) made a serious attempt to provide an improved quantitative evaluation of the small vs large volumes, but even they may not have been able to fully quantify the total numbers of small droplets, considering that we see much larger numbers by laser light scattering.

15. When you say. 6' is not safe indoors: I think you are saying that the smaller droplets will be able to move beyond 6'. Do we have a quantitative estimate of how much virus is in the large vs. small droplets?

Reply: As per above questions, the volume fraction of droplets that transform into aerosol remains ill-defined, with Duguid's ~5% providing a rough estimate. Most of this is "coarse but inhalable" aerosol with an airborne lifetime of at most a few minutes, but that's still more than sufficient to travel well over 6 ft. Consider how far cigarette smoke travels in 1 minute, for example. So, even though the volume fraction that becomes airborne is only a modest fraction of the total emission, it is far more likely to result in disease transmission because it can be inhaled, and therefore likely to dominate the transmission process. Another factor could be that the smallest droplets generated by the vocal folds potentially contain more virus per volume unit when the infection is colonized in the throat.

16. Relatedly question: many people early on noted that tiny droplets could get through masks. Do we conclude from the benefits of masks that the large droplets are a large part of the story?

Reply: I believe penetration through mask material is not the primary limitation for most masks in non-hospital settings. Even **emission** of tiny (~ 1 micron) breathing droplets is substantially reduced when forced to pass through a surgical mask. Whether this conclusion may be extrapolated to all other mask materials (e.g. spandex) remains an open question. Blocking **inhalation** of dehydrated breathing droplets, which have shrunk to well below 1 micron, and may be found in a hospital setting, will require high quality mask material such as KN95 or N95. With our laser setup, we can only easily measure the effect of masks on exhaled particles, however.

17. Would you recommend use of antiseptic mouthwash before bed and during the day to help prevent self-infection? (I know you aren't a "real" doctor, but what are your thoughts?)

Reply: You are correct, I don't feel qualified to comment on the merits of antiseptic mouthwash. One might expect some benefit in terms of reducing emission, but impossible to quantify how much. We hypothesize that self-infection through speech droplets would involve primarily the smallest, vocal-fold generated droplets, which presumably would be little impacted by the use of mouth wash as they originate further down, where the mouthwash doesn't quite reach.

18. Regarding the idea of a "minimum infectious dose": I understand that even one active virion could lead to an infection-but, in practice (i.e., considering the immune

response)-what is known about the threshold number of virons that is required for a person to be infectious (including infectious but asymptomatic)?

Reply: The important thing to remember is that with airborne transmission the virus is delivered in "units of 1", because a single droplet is unlikely to carry more than one **infectious** virion (considering that the vast majority of virions is unable to replicate when dispersed in culture medium containing susceptible cells). My hand-waiving response: It is like buying lottery tickets. The chance that an inhaled virion causes an infection is low, but not zero. The more tickets you purchase, the higher your chances. In terms of the immune system becoming overwhelmed, as clearly applies for many other types of infections: It's difficult to envision how the immune response at one jeopardized cell is impacted by another infectious virion landing on a different cell that on a cellular size scale is many miles apart.

I also want to refer you to the work of Charles Haas (e.g. *Environ. Sci. Technol.* 2015, 49, 3, 1245–1259 or his insightful blog: https://chaasblog.wordpress.com/2020/05/18/its-the-dose-response-stupid/ ). He and his colleagues in the risk analysis community provide a more rigorous answer to this question. They carried out quantitative analyses of viral transmission during earlier epidemics. Warning: Much of the medical community appears to disagree with Haas (and me) on this.

19. Apologies for a dumb question: How do masks contribute to reducing the risk of self infection rather than increasing it? (this is not an anti-masker question, I just missed that point)

Reply: Good question and my apologies for having rushed through this too quickly. At the time the small vocal fold droplets are exiting the mouth, they are mostly still too large to be inhaled into the lungs. If one wears a mask, the vocal fold droplets will not get the chance to dehydrate and be re-inhaled as much smaller size particles. If stuck in the mask, they could be inhaled if dislodged, but that doesn't seem to happen considering the empirical observation that mask wearing reduces the severity of disease (Gandhi: DOI:10.1007/s11606-020-06067-8). The explanation by Gandhi does not make a lot of sense to me, because that explanation relies on the dogma "lower exposure causes lower disease severity". If that were true, the opposite result might have been expected: Masks lower disease incidence (by filtering out inhaled particles), but the smallest particles are known not to be well filtered out by generic masks. These smallest particles are associated with severe disease (Gralton: doi:10.1016/j.jinf.2010.11.010 ). So, if their interpretation were correct, one would expect lower incidence of disease, but that lower incidence should apply primarily to the upper respiratory tract, and therefore one would expect mask wearers that do get sick to have a higher degree of severity, contrary to observations.

20. Can you comment on implications of these results on importance of a mask covering one's nose as well as mouth?

Reply:  From an emission perspective, covering the nose is only important when the person has an infection of the lungs, often (but not always!) associated with symptoms.  From a protect-the-wearer perspective, covering the nose is very important.

21. Do droplets affect animals, such as pets, if they are in close proximity to you?

Reply:  Based on the literature, COVID-19 can infect a range of pets, but most seem to be less susceptible to the virus than humans.  Some recent report from Denmark about farmed minks is worrisome because apparently the virus mutated to a strain that is less sensitive to the human immune system.  This is perhaps unlikely to be an isolated event.

22. Do the different speech patterns of different languages change the amount of droptlets and aerosols that get produced? The video with the person speaking do-rei-me-fa... shows different amounts being emitted depending on the sound. Is it possible that different spoken languages lead to different amounts of virus in the air?

Reply:  In principle, yes.  In practice, the effect will not be very strong. My wife (the linguist) suggests cultural differences in language use, and person-to-person variation tend to be far larger than the typical variation in sounds associated with different languages.

23. Regarding the 5um to 100um-factor which is 20, is there a possible 20x20x20 = 8000 factor more virus around a person than "medicine" states or thinks?

Reply:  Yes, it seems that the medical community had forgotten about Wells' 1955 book and had erroneously discounted the ability of virus to remain airborne when embedded in 5-100 micron particles. This may be the reason why much of the medical community had not taken the possibility of airborne transmission through speech droplets seriously.

24. It seems that there is enough experimental information now to work out the risk factor for a patient and a susceptible person as a function of distance and time spent next to each other. But I have not seen published literature on this. The information should be extremely valuable for the general public.

Reply:  Yes, there now is an avalanche of publications that aims to make this semi-quantitative analysis, many based on the Skagitt choir superspreader event where the numbers were fairly well defined.  Most of these analyses are either on MEDXRIV or have just appeared

(https://www.cdc.gov/mmwr/volumes/69/wr/pdfs/mm6919e6-H.pdf; see also the insightful analysis by J.L. Jimenez, COVID-19 Aerosol Transmission Estimator, https://tinyurl.com/covid-estimator )

25. For air purifiers- some have concerns about the purifiers moving air and if not placed properly could function to blow potentially infectious droplets further and towards others in the room - thoughts on that?

Reply: I must defer to Jose Jimenez and his Dec.2 APS webinar for an answer to this question.

26. As a regular group cyclist, if our group is just breathing (hard) but not speaking, is there a significant probability of disease transmission?

Reply: It is difficult to envision a physical mechanism by which exhaled air, which will be in the laminar flow regime,could dislodge virus from the high viscosity upper respiratory tract mucosal layer. If an athlete were having the infection in the lungs, exhaled breath could be infectious. However, outdoors, the quantity of exhaled breath emitted by another infected cyclist or runner that would be re-inhaled by others will be extremely small (despite quadratically increased risk, as both exhalation and inhalation increase with activity). So, I guesstimate this risk to be low, as for virtually all other outdoor activity. Indoor exercise is a different issue, however, and well documented cases of indoor exercise transmission exist. Not clear how much of this was speech or breathing mediated. See also: J.L. Jimenez, COVID-19 Aerosol Transmission Estimator, https://tinyurl.com/covid-estimator

27. What is your reasoning for masks being more effective for exhaled air than inhaled air? Aren't the flow rates and face velocites the same?

Reply: Yes, velocities are comparable but sizes are not. The volume of exhaled droplets is 20-50 fold larger than for inhaled, dehydrated particles.

28. If there is little or no evidence for infection transmission in movie theaters, what is the current situation for transmission on commercial airplane flights, especially as a function of duration?

Reply: There are a number of documented airline transmission cases, although some but not all of these could be attributed to transfer inside an airline lounge. https://wwwnc.cdc.gov/eid/article/26/11/20-3299_article There are far more cases of passengers traveling in very close proximity to infected/infectious carriers for more than 8h where no transmission occurred. I note that air turnover on modern jet aircraft is as good as one could hope for. However, note that cough droplets can escape the non N95/KN95 masks relatively easily due to the high burst flow rate of a cough, and exposure will never be zero and increase linearly with duration. Removal of masks during food service, combined with conversation, could be another factor.

29. What percentage of infections can be attributed to aerosols versus droplets?

Reply: Considering that documented outdoor transmission is at least an order of magnitude lower than indoors, whereas large droplet transfer (ballistic droplets in Milton's definition) should be comparable, I believe it is likely that the vast majority is through aerosol. I expect Jose to give you more information on this in his Dec. 2 APS webinar.

30. Is there a difference between mouth and nose breathing?

Reply: Yes, the nose is known to be a fairly efficient aerosol filter, so nose breathing decreases the probability of particles to reach the lungs. Quantitatively, I do not believe it is known by how much for what particle size range, and this percentage is likely to change with inhalation speed.

31. If your glasses are misting up, how much droplets/aerosols are being emitted

Reply: the fogging up of glasses is primarily caused by the supersaturation of the 95% RH 35 deg C air when it hits a cold surface (glasses), not by breathing droplets which are far too small in total volume to yield visible condensation.

32. Can you ask the question on cotton/silk/cotton mask design for protecting against inhaling aerosols?

Reply: we have not tested the efficiency of such masks, but there is a substantial amount of literature that suggests this material to work well. Question really is how breathable the material is and how tight the fit is.

**Technical questions**

33. Could you please tell us the wavelength and power output of the laser that was used?

Reply: I've used several but prefer the 3W 447 nm laser from www.laserglow.com. It has nice safety features and is very robust and fairly well focused. I've also used an 8W 452 nm laser purchased from China on Ebay, but it's too powerful, difficult to regulate, and not nearly as stable.

34. What's the smallest droplet size that can be resolved in the laser scattering experiments? What's the lower-limit that could be realistically achieved (i.e., with higher laser power or a better imaging camera)?

Reply: The optical resolution of my camera (SONY alpha SII, with thanks to Roy Sewall and Richard Chitty for recommending this gem) equipped with a FE 24mm, F1.4 GM lens) is only about 100 micron, so nowhere near good enough to directly observe particle size. However, scattering intensity scales with the square of the particle diameter, and particles with diameters down to ~0.3 micron are easily detected with the 3W blue laser and a 2 mm thickness of the light sheet. Dynamic range (8-bit), and log scale detection on these commercial cameras, with the conversion tables not quite matching the actual photon counts, is a bit of a pain.

35. Why is the CoVID virus less infectious at higher humidity?

Reply: The answer is not really known. Some virus may fare better at high humidity (polio), but most remain infectious longer at low RH and low temperature. Chemical reactions often require water, so it's conceivable that chemical reaction rates are slowed down upon full dehydration. Chemical reactions (e.g. lipid or structural protein oxidation) also slow down with temperature, leaving the virus intact longer.

36. Are particle counts coming from a simple image analysis or something like Mie scattering calculations?

Reply: It's really MIE scattering that we're observing, so there is a very sharp angular dependence. However, unless fully spherical (glycerol droplets) the angular dependence in practice is fairly smooth, in particular for the larger particles, speculatively attributed to deviation from spherical shape of the tumbling particles.

37. Is it possible that you are observing condensed droplets instead of droplets generated from breathing or speech, at least for the smaller droplets?

Reply: For sure, the observed droplets are not spontaneous nucleation of supersaturated exhaled air, because they are not seen when the same volume of air is exhaled through N95 mask material. However, 2 days after the presentation I discovered that the (battery-supplied) reference voltage on the hygrometer chip had dropped, causing the readout voltage (and reported relative humidity) to be lower than it should have been by about 0.5V. Difficult to tell how much that may have affected the RH values I reported for the measurements at 90% RH (made a week earlier). If the real RH was close to 100%, it indeed is likely that after exhalation of saturated 35C breath into the colder air, the particles may have become enlarged due to nucleating condensation rather than shrunk through evaporation. These particles at very high humidity showed the type of “flickering” expected for MIE scattering of spherical objects.

38. What is the assumed relationship between intensity and droplet size?

Reply: To a good approximation, photon counts scale with the square of the particle diameter. So does the terminal velocity, so the relation between velocity and photon counts is fairly linear.

39. How to distinguish between air borne particle versus the speak particle while doing laser scattering experiment. How much the air particle will affect your overall results?

Reply: Removal of background aerosol is a critical aspect of all speech or breathing particle measurements, and even HEPA-filtered air is rich in particles in the 100-300 nm range. We are using about 10-20 air exchanges through two sequential high-pressure air filters to get the background down to non-detectable levels.

40. How do you determine the size of particles from the light scattering method? I would think that a commercial phone does not have enough resolution to accurately determine particles (ex)smaller than a micron)?

Reply: You are correct, direct viewing of the size of droplets is impossible with a cell phone or other commercial camera without using a high degree of magnification. However, Stokes law allows measurements down to a few microns and below that, the correlation between scattered light intensity and particle size provides an approximate measure for size.

41. Do droplets break-up or coalesce? And how does this effect infectivity?

Reply: The probability of coalescence once emitted is extremely small considering the volume fractions we are dealing with (making a collision very unlikely). I defer to the fluid dynamics experts on commenting about break-up but have been told that this is not an easy/likely process.

42. What is the current status of CFD modeling of the spreading of viral droplets? Are models reliable?

Reply: Computational fluid dynamics modeling should be very good for homogeneous droplets, but if phase separation (e.g. formation of an oil-like monolayer of phospholipid on their surface) is found to be important (e.g. Vejerano and Marr J. Roy. Soc. Interface, 2018), there may be problems with such modeling as phase separation seems mostly not to be accounted for.

43. I'm very much aware of the work of Mr. Jimenez and colleagues. One thing that keeps circling in my head (which I read a lot in my twitter bubble) is this: How can we distinguish 'proper' ventilation from possible 'dangerous' ventilation? People (often with medical backgrounds) keep on saying: don't blow the larger droplets ("which would fall to the ground if there weren't any ventilation") around in the room to infect others. Then they point at the slaughterhouse examples and the restaurant example(s) in China in which ventilation was thought to be the cause of trouble. I think I have read that you cannot blow larger particles around. But perhaps there can be any comment on this topic?

Reply: It seems unlikely that large particles that hit the ground within seconds will be blown around much by ventilation. Exposure to medium sized particles that remain airborne for say 1 minute, will vary depending on prevailing airflow direction, which competes with regular convection currents. The restaurant superspreader event is an example where the directional ventilation flow overwhelmed the regular convection flow and shifted the fraction of infectees in a non-random fashion relative to the index case. Recirculation of ventilated air (if not passed through a HEPA filter) should be minimized, as has long been known: https://pubmed.ncbi.nlm.nih.gov/665658/ Also see https://tinyurl.com/covid-estimator, and I'm very much looking forward to see Jose's take on this in his APS webinar on Dec. 2