The modes of transmission of SARS-CoV-2: What we know now & how to protect ourselves

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http://tinyurl.com/covid-estimator
http://tinyurl.com/faqs-aerosol

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Cite as: K. A. Prather *et al.*, *Science*
10.1126/science.abf0521 (2020).

Airborne transmission of SARS-CoV-2

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There is overwhelming evidence that inhalation of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) represents a major transmission route for coronavirus disease 2019 (COVID-19). There is an urgent need to harmonize discussions about modes of virus transmission across disciplines to ensure the most effective control strategies and provide clear and consistent guidance to the public. To do so, we must clarify the terminology to distinguish between aerosols and droplets using a size threshold of 100 μm, not the historical 5 μm (*1*). This size more effectively separates their aerodynamic behavior, ability to be inhaled, and efficacy of interventions.

Viruses in droplets (larger than 100 μm) typically fall to the ground in seconds within 2 m of the source and can be sprayed like tiny cannonballs onto nearby individuals. Because of their limited travel range, physical distancing reduces exposure to these droplets. Viruses in aerosols (smaller than 100 μm) can remain suspended in air for many seconds to hours, like smoke, and be inhaled. They are highly concentrated near an infected person, so they can infect people most easily in close proximity. But aerosols containing infectious virus (*2*) can also travel more than 2 m and accumulate in poorly ventilated indoor air, leading to superspreading events (*3*).

Individuals with COVID-19, many of whom have no symptoms, release thousands of virus-laden aerosols and far fewer droplets when breathing and talking (*4*–*6*). Thus, one is far more likely to inhale aerosols than be sprayed by a droplet (*7*), and so the balance of attention must be shifted to protecting against airborne transmission. In addition to existing mandates of mask-wearing, social distancing, and hygiene efforts, we urge public health officials to add clear guidance about the importance of moving activities outdoors, improving indoor air using ventilation and filtration, and improving protection for high-risk workers (*8*).

REFERENCES AND NOTES

1. National Academies of Science, Engineering, and Medicine. "Video 3)—CO| reflection and syntheses: Identifying opportunities and gaps on the path ahead by Kim Prather" (Airborne Transmission of SARS-CoV-2: A Virtual Workshop, 26 to 27 August 2020). www.nationalacademies.org/event/08-26-2020/airborne-transmission-of-sars-cov-2-a-virtual-workshop.
2. J. A. Lednicky *et al.*, *Int. J. Infect. Dis.*, 10.1016/j.ijid.2020.09.025 (2020).
3. S. L. Miller *et al.*, *Indoor Air*, 10.1111/ina.12751 (2020).
4. K. A. Prather, C. C. Wang, R. T. Schooley, *Science* **368**, 1422 (2020).
5. V. Stadnytskyi, C. E. Bax, A. Bax, P. Anfinrud, *Proc. Natl. Acad. Sci. U.S.A.* **117**, 11875 (2020).
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8. L. Morawska *et al.*, *Environ. Int.* **142**, 105832 (2020).

COMPETING INTERESTS

K.A.P. is Director of the National Science Foundation Center for Aerosol Impacts on Chemistry of the Environment. L.C.M. is a member of the Science Advisory Board and holds stock options for Physigen and is a paid reviewer for the Alfred P. Sloan Foundation. R.T.S. is a member of the Gilead Sciences Scientific Advisory Board and chairs Data Safety and Monitoring Boards for VIR, Gilead, and Merck. Honoraria for these activities are paid to the Regents of the University of California. R.T.S. has served as a scientific consultant to Pfizer and to AbbVie. M.A.M. is the (unpaid) Chair of the National Academy of Medicine Committee on Personal Protective Equipment for Workplace Safety and Health.

Published online 5 October 2020
10.1126/science.abf0521

https://science.sciencemag.org/content/370/6514/303.2

2

What do we know about transmission?

- Surfaces not major: e.g. hand-washing reduced 16%

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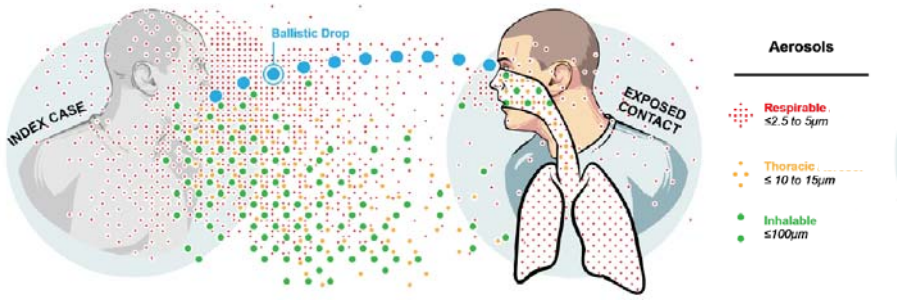
Droplets vs. Aerosols



- Droplets:
  - Ballistic projectiles
  - Infect by impact on eyes, nostrils or mouth
- Aerosols
  - Float in the air
  - Infect by inhalation

From Milton, 2020: https://academic.oup.com/jpids/article/doi/10.1093/jpids/piaa079/5875939

WHO's messaging

FACT CHECK: COVID-19 is NOT airborne

The virus that causes COVID-19 is mainly transmitted through droplets generated when an infected person coughs, sneezes, or speaks. These droplets are too heavy to hang in the air. They quickly fall on floors or surfaces.

You can be infected by breathing in the virus if you are within 1 metre of a person who has COVID-19, or by touching a contaminated surface and then touching your eyes, nose or mouth before washing your hands.

To protect yourself, keep at least 1 metre distance from others and disinfect surfaces that are touched frequently. Regularly clean your hands thoroughly and avoid touching your eyes, mouth, and nose.

This message spreading on social media is incorrect. Help stop misinformation. Verify the facts before sharing.

World Health Organization

March 28 2020

#Coronavirus #COVID19

This message spreading on social media is incorrect. Help stop misinformation. Verify the facts before sharing.

https://twitter.com/WHO/status/1243972193169616898

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WHO's Latest Scientific Brief

Transmission of SARS-CoV-2: implications for infection prevention precautions

Scientific brief

9 July 2020

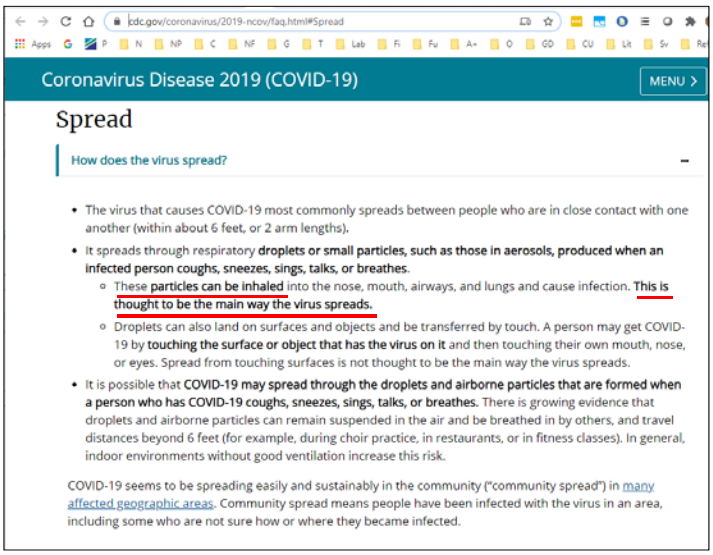
World Health Organization

Transmission of SARS-CoV-2 can occur through direct, indirect, or close contact with infected people through infected secretions such as saliva and respiratory secretions or their respiratory droplets, which are expelled when an infected person coughs, sneezes, talks or sings.(2-10) Respiratory droplets are >5-10 μm in diameter whereas droplets ≤5μm in diameter are referred to as droplet nuclei or aerosols.(11) Respiratory droplet transmission can occur when a person is in close contact (within 1 metre) with an infected person who has respiratory symptoms (e.g. coughing or sneezing) or who is talking or singing; in these circumstances, respiratory droplets that include virus can reach the mouth, nose or eyes of a susceptible person and can result in infection. Indirect contact transmission involving contact of a susceptible host with a contaminated object or surface (fomite transmission) may also be possible (see below).

The physics of exhaled air and flow physics have generated hypotheses about possible mechanisms of SARS-CoV-2 transmission through aerosols.(13-16) These theories suggest that 1) a number of respiratory droplets generate microscopic aerosols (<5 μm) by evaporating, and 2) normal breathing and talking results in exhaled aerosols. Thus, a susceptible person could inhale aerosols, and could become infected if the aerosols contain the virus in sufficient quantity to cause infection within the recipient. However, the proportion of exhaled droplet nuclei or of respiratory droplets that evaporate to generate aerosols, and the infectious dose of viable SARS-CoV-2 required to cause infection in another person are not known, but it has been studied for other respiratory viruses.(17)

https://www.who.int/publications/i/item/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations

CDC accepts aerosols as the main way



- Quietly updated on 9-Oct-2020
- Puts back language from earlier removed update
- Only aerosols (< 100 µm) can be inhaled
- If it can be inhaled, it can reach beyond 1 m
- Therefore close proximity and shared-room transmission are connected through aerosols

https://www.cdc.gov/coronavirus/2019-ncov/faq.html#Spread

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What do we know about transmission?

- Surfaces not major: e.g. hand-washing reduced 16%
- **Easily transmitted in close proximity**

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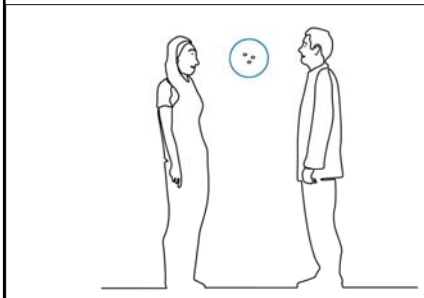
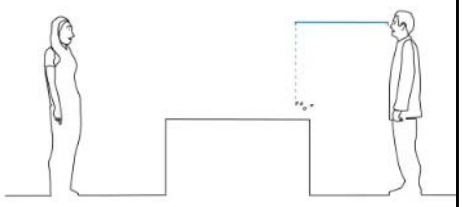
WHO: why social distance helps

Close: droplets can hit eyes / nose / mouth



These droplets can land in the mouths or noses of people who are nearby.

Far: droplets fall to the ground



These droplets are too heavy to travel far in the air –
they only travel approximately one metre and quickly settle on surfaces.

https://twitter.com/WHO/status/1244258441880797184

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Another explanation for social distance

- Expiratory plume visualized by smoke
- Avoid breathing exhaled air, can explain social distance works
  - Observation that social distance works *alone* does not prove droplets or aerosols. We need to look at more evidence
- Shared room air?
  - If droplets: safe
  - If aerosols: not safe. With time and low-ventilation, infection can happen

https://www.kunr.org/post/dri-researchers-find-e-cigs-leave-cancer-causing-chemicals-lungs#stream/0
https://www.dailykos.com/stories/2019/11/16/1899711/-The-Smoke-Filled-Room-Unsolicited-Advice-as-Who-Should-Be-Vice

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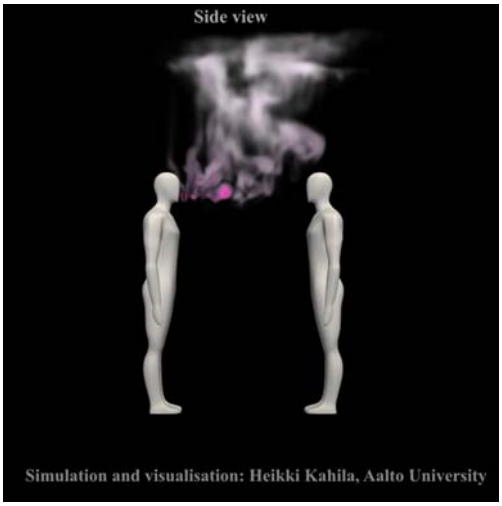
Videos: social distance vs. aerosols

Real exhaled CO_2

CFD Simulation



- Exhaled air when talking loses momentum in <0.5-1 m, starts rising
  - Can explain why social distance works to reduce disease transmission
- Consistent results
  - CO_2 is directly imaged (experiment) but offers less visual contrast and range than simulation

https://twitter.com/SEE_Fluids_UK/status/1314565418980462594
https://www.youtube.com/watch?v=EcpQBxBdr5g

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What do we know about transmission?

- Surfaces not major: e.g. hand-washing reduced 16%
- Easily transmitted in close proximity
- **Indoors >> outdoors**

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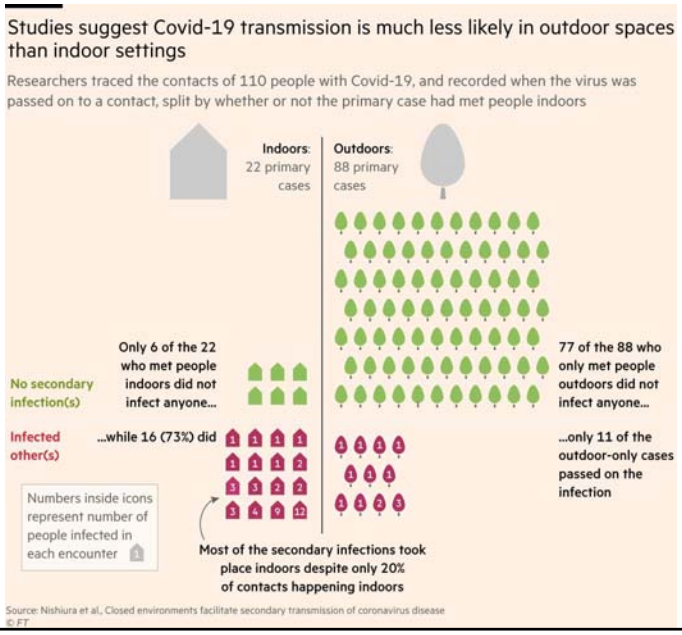
Indoors vs. Outdoor



https://twitter.com/mugecevik/status/1308080074986524672

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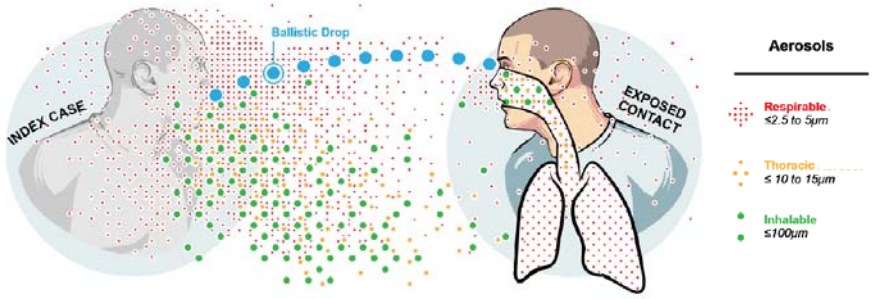
Droplets vs. Aerosols: Indoors vs Outdoors



- Droplets:
  - Ballistic projectiles, not perturbed outdoors in light winds
  - Infection should be similar outdoors
- Aerosols
  - Float in the air, rise & are removed much more efficiently
  - Expect much less infection outdoors

From Milton, 2020: https://academic.oup.com/jpids/article/doi/10.1093/jpids/piaa079/5875939

What do we know about transmission?

- Surfaces not major: e.g. hand-washing reduced 16%
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- Indoors >> outdoors
- "Different" than accepted airborne diseases:
  - Airborne: Measles, tuberculosis, chickenpox
  - COVID-19 more similar to "droplet diseases" such as flu
    - R_0 ~ 2.5
  - High dispersion, "superspreading"
    - 10-20% of infected lead to 80% of new infections (R_0 ~ 10-20)

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Example Superspreading Event: Skagit Choir

- 2.5 hr rehearsal: 1 index case, 52 new infections (13 m behind)
- Fomites?
  - Agreed to be inefficient (e.g. CDC)
  - Index case didn't touch any objects, ~3 people went to same bathroom
- Droplets?
  - Index case didn't talk to others. Others talked to 2-3 ppl in 10 min break
  - No way to impact droplets on eyes, nostrils, mouths of 52 people
    - CDC says "15 min. of close proximity" are needed
- Aerosols?
  - Low ventilation, room well mixed, long time, no masks → easy to explain
  - Amount of virus ~10 times bus and restaurant (singing all the time vs. talking intermittently, consistent with measurements)
- All SS events point to aerosols. **None** point to fomites or droplets

Miller et al., Indoor Air, 2020. https://doi.org/10.1111/ina.12751 17

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  - **Often not very contagious**
    - **Many don't transmit to anybody**
    - **Attack rate in households not very high**
    - **"Droplet precautions" work ok with very ill patients**

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Droplet or Aerosol Diseases?

Disease A	Disease B
• Transmission is through **droplets**. Successful transmission requires close contact within 1 m	• Respiratory **droplet** transmission can occur in close contact (within 1 m) with an infected person
• Following hospitalization of 182 patients, only one secondary case occurred, despite free circulation of air	• No transmission to 41 health care workers exposed for >10 min and <2 m of patient with intense intubation, wearing medical masks (85%) of N95 (15%)
• Outbreaks aboard ships, in school buses, poorly ventilated rooms, and in bars	• Outbreaks aboard ships, buses, poorly ventilated restaurants, bars, choirs

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Droplet or Aerosol Diseases?

Disease A	Disease B
• Transmission is through **droplets**. Successful transmission requires close contact within 1 m **Tuberculosis (1950) & Measles (1985)**	• Respiratory **droplet** transmission can occur in close contact (within 1 m) with an infected person **WHO on COVID-19**
• Following hospitalization of 182 patients, only one secondary case occurred, despite free circulation of air **Measles (1985)**	• No transmission to 41 health care workers exposed for >10 min and <2 m of patient with intense intubation, wearing medical masks (85%) of N95 (15%) **WHO IPC Comm. on COVID-19**
• Outbreaks aboard ships, in school buses, poorly ventilated rooms, and in bars **Tuberculosis**	• Outbreaks aboard ships, buses, poorly ventilated restaurants, bars, choirs **COVID-19**

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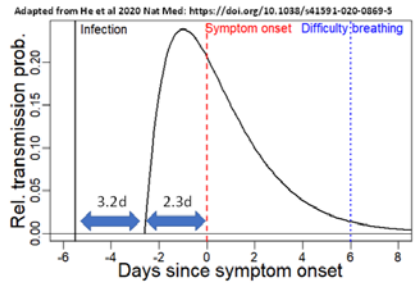
Variability of Infective Aerosol Emission

- WHO mental model: constant & high aerosol emission by all infected
  - When that's not consistent with observations, they conclude aerosols don't transmit!



Courtesy of A. Malm Kilpatrick

OXFORD ACADEMIC

Clinical Infectious Diseases

Coronavirus Disease 2019 Patients in Earlier Stages Exhaled Millions of Severe Acute Respiratory Syndrome Coronavirus 2 Per Hour

Jianxin Ma, Xiao Qi, Haoxuan Chen, Xinyue Li, Zheng Zhang, Haibin Wang, Lingli Sun, Lu Zhang, Jiazhen Guo, Lidia Morawska ... Show more

Another significant discovery from this work is that SARS-CoV-2 emission does not continue at the same rate but rather is a sporadic event.

- Also anisotropic infection, e.g. for flu (Don Milton)
  - Infective dose is x100 lower for small aerosols into lung than nose deposition
  - For the same symptoms, dose is x100000 larger for the nose
- Superspreading?
  - Certainly wrong time in wrong location
  - Superspreading ppl? Some emit x10 more aerosols, also high variability in viral loads
  - Lack of transmission? People only infectious for short period

https://www.nature.com/articles/s41591-020-0869-5 Don Milton's lecture (high recommended): https://t.co/sL6bwRf1u4
https://academic.oup.com/cid/advance-article/doi/10.1093/cid/ciaa1283/5898624 https://www.medrxiv.org/content/10.1101/2020.08.07.20169920v3

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    - "Droplet precautions" work ok with very ill patients
- **"Droplets larger, have many more viruses"**
  - **Is that correct?**

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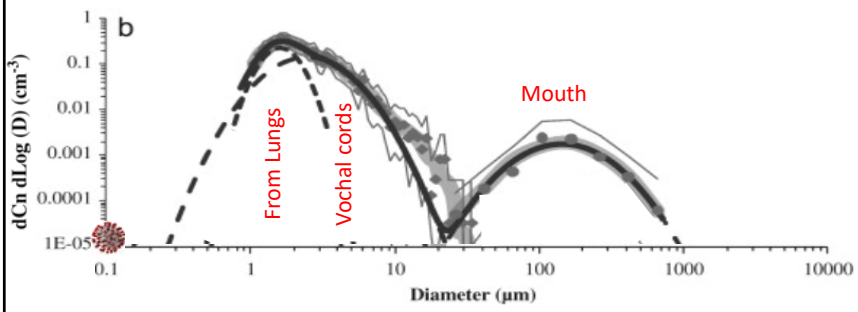
https://www.who.int/publications/i/item/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations

Droplets & aerosols when talking



From Johnson et al., *J. Aerosol Sci.* (2011)
Black line is best estimate
Emitted respiratory particles when speaking

https://doi.org/10.1016/j.jaerosci.2011.07.009

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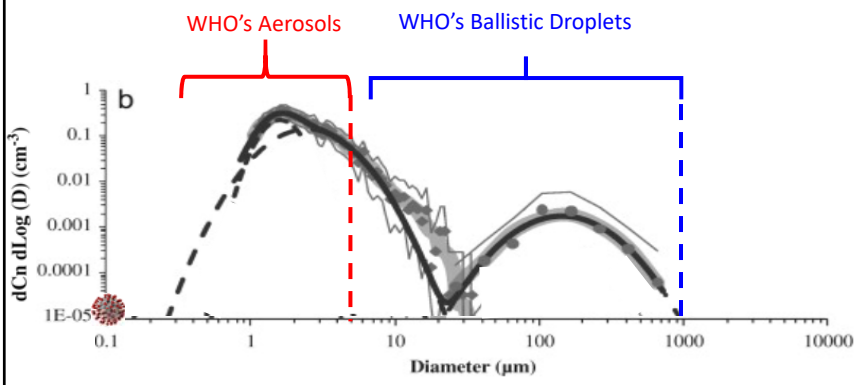
Droplets when talking: WHO's view



From Johnson et al., *J. Aerosol Sci.* (2011)
Black line is best estimate
Emitted respiratory particles when speaking

- x50 times more aerosols than droplets
- But droplets are larger, may carry more virus

https://doi.org/10.1016/j.jaerosci.2011.07.009

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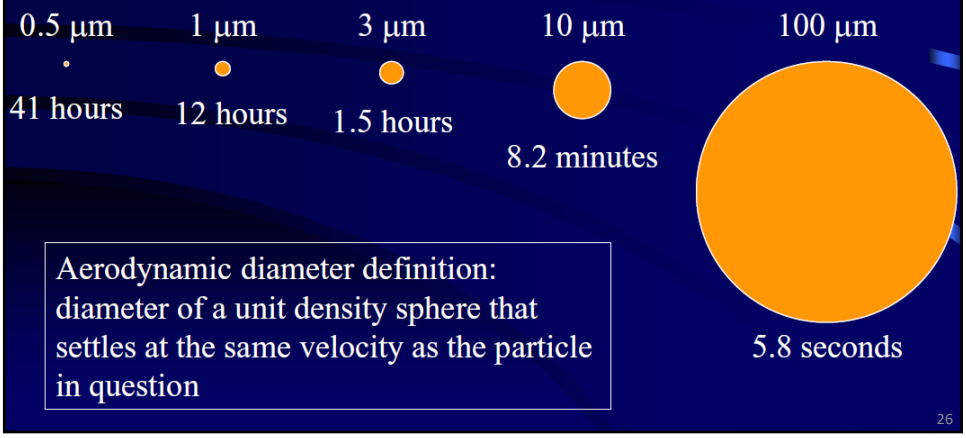
CDC: "Aerosols 101" tutorial on their web page

Particle Settling in Still Air

Time to settle 5 feet by unit density spheres



Aerodynamic diameter definition: diameter of a unit density sphere that settles at the same velocity as the particle in question

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Dr. Anthony Fauci Admitted 5 µm is an Error on 10-Sep

- ”There was some real misunderstanding about respiratory droplets and so-called aerosolised particles. The aerosol and particles physicists that have approached us now have told us that we really have got it wrong over many years and that particles greater > 5 µm still stay in the air much much longer than we have thought when we used to say empirically > 5 µm drops to the ground, 5 µm might be aerosolized, we know now that's just not the case.”
- **“Bottom line is this: there is much more aerosol than we thought”**

https://masscpr.hms.harvard.edu/event/harvard-medical-school-grand-rounds-featuring-dr-anthony-s-fauci

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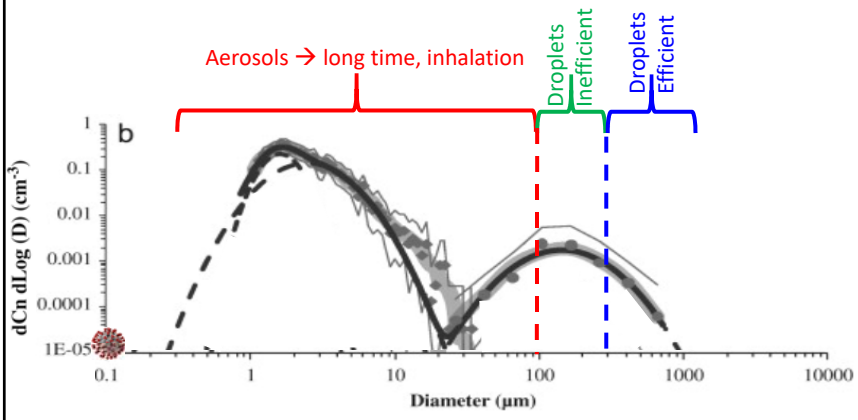
Droplets when talking: few, low prob.



- For every large droplet, there are 1000 aerosols
- Droplets have to hit very small targets
- Aerosols float a long time, many chances to be inhaled

https://doi.org/10.1016/j.jaerosci.2011.07.009

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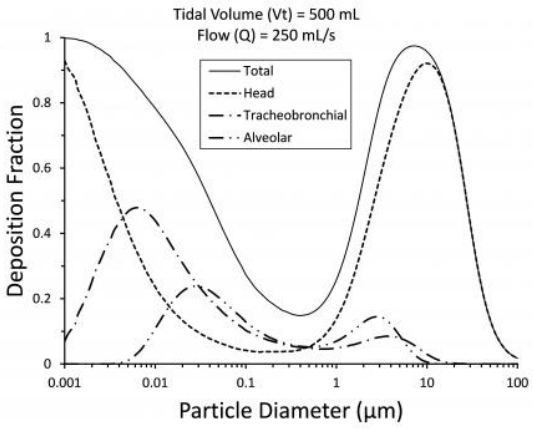
Aerosol Deposition in Resp. Tract

- Studied extensively (cold war biowarfare, pollution, occupational health, tobacco smoke, drug delivery to the lungs etc.
- Only aerosols < 100 µm can be inhaled
  - ➔ **If it can be inhaled, it can reach > 1 m beyond a person!**
- Only aerosols ~< 5 µm can reach deep lung
  - E.g. tuberculosis
- But most aerosols at 5 µm deposited in head region



https://www.epa.gov/pmcourse/particle-pollution-exposure

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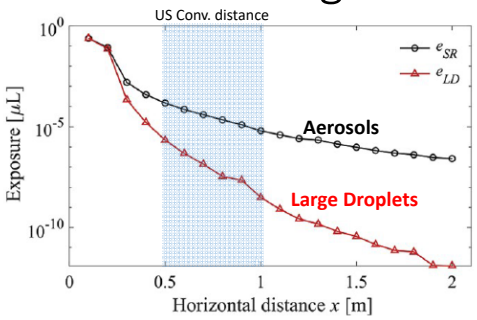
Infectious Dose: droplets vs. aerosols when talking

- Aerosol volume dose is x100-x2000 times larger than for droplets



- For all diseases where measured, pathogens more concentrated in smaller particles (< 5 µm typical)
  - Tuberculosis, measles, flu, RSV

> Reviewing the literature on large droplet transmission, one can find no direct evidence for large droplets as the route of transmission of any disease.

https://www.sciencedirect.com/science/article/pii/S0360132320302183 & https://www.thelancet.com/journals/lanres/article/PIIS2213-2600(20)30323-4/fulltext

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    - "Droplet precautions" work ok with very ill patients
- "Droplets larger, have many more viruses"
  - Is that correct?
- **Difficult to sample infections virus from room air**
  - **True, but never done for measles or tuberculosis**
  - **Impressive technological advances (VIVAS) were needed, has been done by Lednicky et al. (2020)**

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To learn more about aerosol transmission

- Highly recommend watching Don Milton's webinar
  - Medical doctor, aerobiologist
  - https://t.co/sL6bwRf1u4
- For extensive details (11 hrs of talks + discussion)
  - Workshop from the US National Academies of Sciences, Engineering, and Medicine
  - This workshop was the basis for the Prather et al. letter to Science (5-October, https://science.sciencemag.org/content/370/6514/303.2)
  - https://www.nationalacademies.org/event/08-26-2020/airborne-transmission-of-sars-cov-2-a-virtual-workshop

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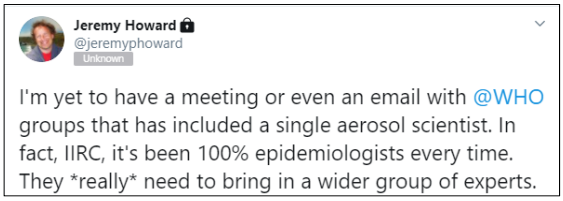
How did we end up here?

- Theory of miasmas, diseases go long distances through air
- 1860s: Pasteur discover germs
  - Evidence accumulates for transmission of different diseases
- 1910: Chapin's *The Sources and Modes of Infection*
  - "Contact Infection"
    - Germs don't live outside the body, in swamps, trash etc
    - Germs live inside of people, contact with other people needed for infection
    - Realizes close proximity leads to infection (correct)
  - Problem: "It is impossible to teach people to avoid contact infection while they are firmly convinced that the air is the chief vehicle of infection"
    - "In air infection, it becomes evident that our knowledge is far too scanty, and that the available evidence is far from conclusive"
  - Solution!
    - Indication of droplets (Flügge 1894). Aerosols not measureable yet
    - "There is no evidence that [air infection] is is an appreciable factor in the maintenance of most of our common contagious diseases. We are warranted, then, in discarding it as a working hypothesis, and devoting our chief attention to the prevention of contact infection."
  - To prove air infection: extraordinary claims require extraordinary evidence
  - Becomes established paradigm, till WHO today
- 1930s on: Wells, Riley & others fight fierce resistance
  - Measles, chickenpox, TB: droplet/fomites for decades
    - Finally demonstrated, but only because so contagious, and/or evidence unequivocal
  - But great progress against diseases w/ vaccines, antibiotics etc. Never a top issue till now
- Now: confusion of artifact of history w/ law of nature!
  - "All aerosol-transmitted diseases must be highly contagious"

https://archive.org/details/sourcesmodesofin00ch & https://books.google.com/books/about/How_to_Avoid_Infection.html?id=vS47AQAAMAAJ 33

How did we end up here? Part II

- Aerosols have never been considered important for disease transmission
  - Not studied by most in medical profession & epidemiology
  - Almost total lack of experts at WHO



  - Key WHO committee is dominated by hand-washing experts
    - Miraculously, the first thing they recommended against COVID-19 was lots of hand washing!
      - Now we know that only cuts transmission ~16% (UK study)
    - They have published a paper, w/ errors and misconceptions about aerosols
      - https://aricjournal.biomedcentral.com/articles/10.1186/s13756-020-00779-6

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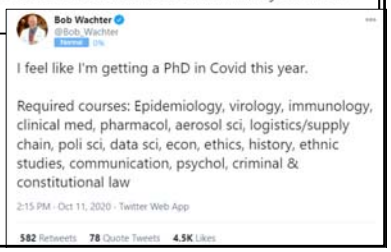
The coming paradigm shift

- Chapin's 1910 error finally becoming obvious
  - Most respiratory diseases go (at least partially) through aerosols
    - Best in close proximity
    - Can transmit in shared room air w/ low ventilation
    - Most contagious diseases can transmit long-range
    - Wide range of contagiousness (COVID = mid-low)
- Huge implications
  - For seasonal flu, future pandemics, others
- Major resistance
  - Shift in infectious disease medicine & epid., pushed by "ignorant intruders"
- Extremely important to collaborate across disciplines
  - Aerosols NOT most important. But crucial error

Wells 1945

The ultimate goal of sanitation set by Lemuel Shattuck a century ago is to guarantee to members of society the same freedom from communicable disease enjoyed by isolated individuals. Water purification, milk pasteurization, and pure food administration during the present century have added several years to the expectancy of life at birth. Does the control of respiratory infection by sanitary ventilation seem more difficult to sanitary science than the conquest of intestinal and insect-borne parasites seemed at the turn of the century?

"Most of them are chemists, engineers, owners of ventilation companies," Hunter said. "They do not have a broad understanding of disease transmission mechanisms … this issue is more nuanced than many of them realize."



http://tinyurl.com/preguntas-espanol

https://tinyurl.com/FAQ-aerosols

FAQs on Protecting Yourself from COVID-19 Aerosol Transmission

Shortcut to this page: https://tinyurl.com/FAQ-aerosols
Version: 1.65, 15-Sep-2020

If you want to jump over other details and go straight to the recommendations, click here.

Preventing Transmission of COVID-19

- Some people still think that if they wear a mask and keep 6 ft apart, they are totally safe – this is false!
- Outdoors, distanced, and with masks is almost completely safe. ONLY almost-silver bullet
- Indoors is never completely safe. No silver bullet
  - **A**void or reduce
  - **C**rowding
  - **I**ndoors
  - low **V**entilation
  - **C**lose proximity
  - long **D**uration
  - **U**nmasked
  - **T**alking/singing/shouting
  - (mnemonic: "A CIViC DUTy")

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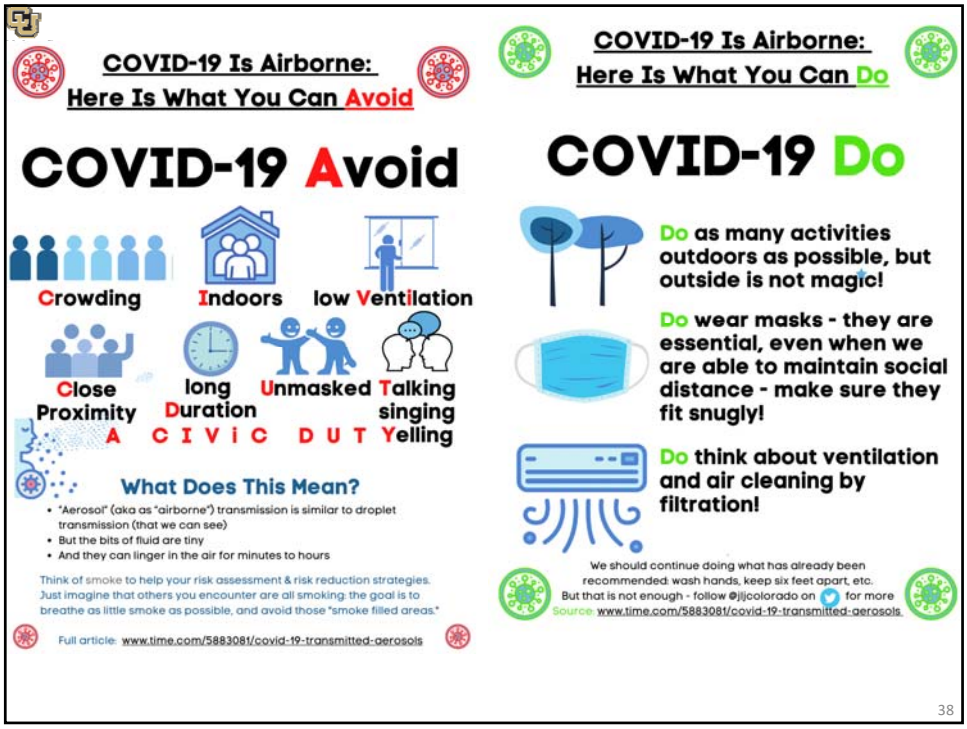

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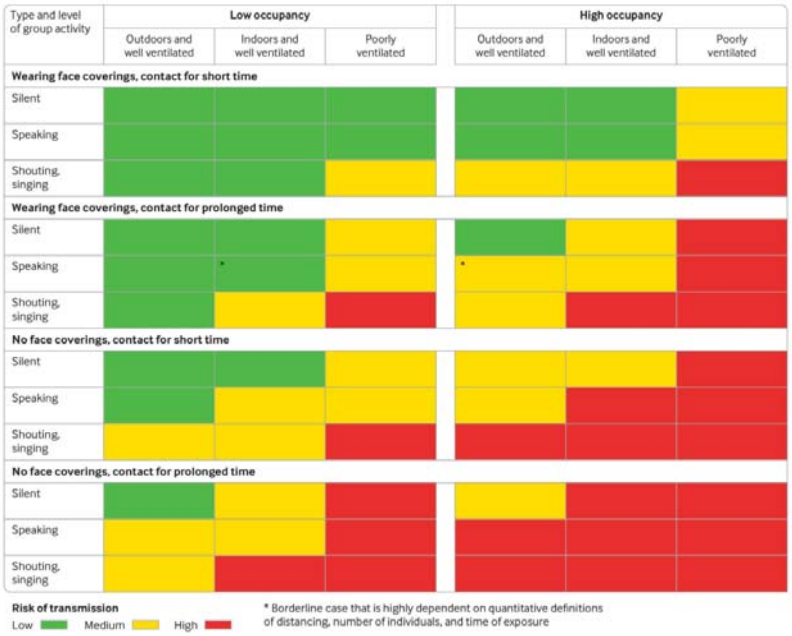
Risk of different situations



Type and level of group activity	Low occupancy: Outdoors and well ventilated	Low occupancy: Indoors and well ventilated	Low occupancy: Poorly ventilated	High occupancy: Outdoors and well ventilated	High occupancy: Indoors and well ventilated	High occupancy: Poorly ventilated
Wearing face coverings, contact for short time						
Silent	Low	Low	Low	Low	Low	Medium
Speaking	Low	Low	Low	Low	Low	Medium
Shouting, singing	Low	Low	Medium	Medium	Medium	High
Wearing face coverings, contact for prolonged time						
Silent	Low	Low	Medium	Low	Medium	High
Speaking	Low	*	Medium	*	Medium	High
Shouting, singing	Low	Medium	High	Medium	High	High
No face coverings, contact for short time						
Silent	Low	Low	Medium	Medium	Medium	High
Speaking	Low	Medium	Medium	Medium	High	High
Shouting, singing	Medium	Medium	High	High	High	High
No face coverings, contact for prolonged time						
Silent	Low	Medium	High	Medium	High	High
Speaking	Medium	Medium	High	High	High	High
Shouting, singing	Medium	High	High	High	High	High

Risk of transmission Low Medium High

* Borderline case that is highly dependent on quantitative definitions of distancing, number of individuals, and time of exposure

https://www.bmj.com/content/370/bmj.m3223

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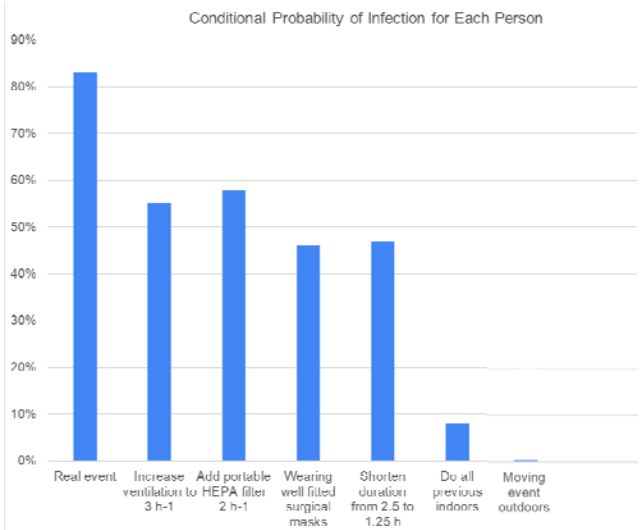
Indoors never totally safe, can mitigate

- What happens if we could change conditions
- All are changing only 1 thing, except "do all previous indoors"



Calculated with: https://tinyurl.com/covid-estimator

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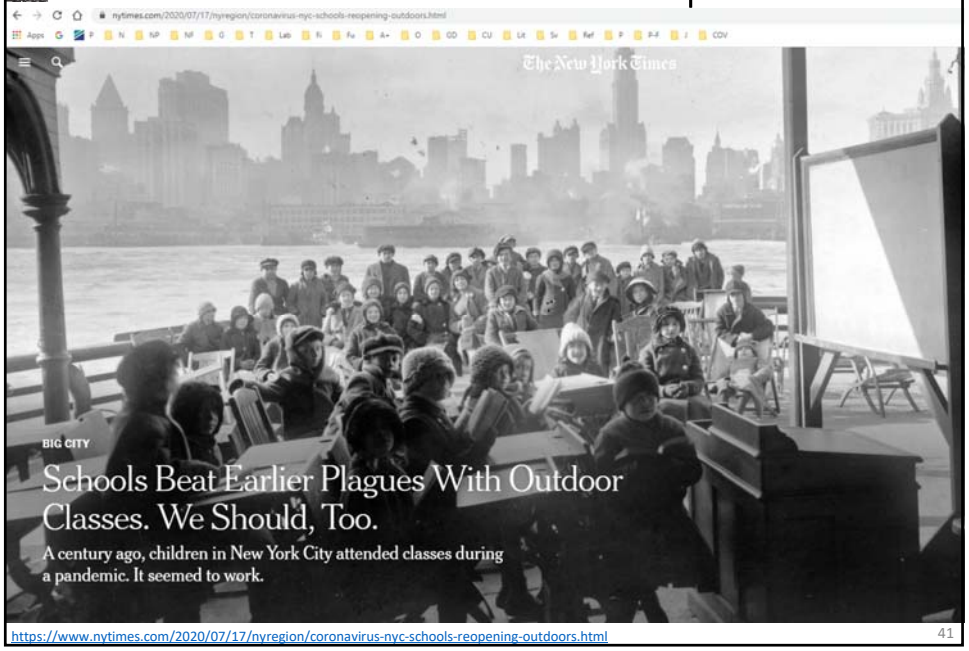
Do activities outdoors when possible



https://www.nytimes.com/2020/07/17/nyregion/coronavirus-nyc-schools-reopening-outdoors.html

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What Ventilation Rate is Needed?

- Liters/s/person is the best indicator (better than ACH)
- Outbreaks of COVID-19 at ~1-3 L/s/p
- Recommend at least 12.5 L/s/p (REHVA), more if possible

	High Ventilation Dorm	Low Ventilation Dorm
CO2 concentrations in rooms	1230 ppm	1490 ppm
Dorm rooms' ventilation rates	6 L/s/person	2 L/s/person
# ARI cases / total subjects	1 / 11	47 / 109

ventilation rates of < **5 L/s per person** may be impacting acute respiratory infections

Zhu S, Jenkins S, Addo K, et al. Ventilation and laboratory confirmed acute respiratory infection (ARI) rates in college residence halls in College Park, Maryland. *Environment International*. 2020;137:105537. doi:10.1016/j.envint.2020.105537

outdoor air supply rates **< 25 L/s per person** increase the risk of sick building symptoms, increase short-term sick leave, and decrease productivity

Wargocki P, Sundell J, Bischof W, et al. Ventilation and health in non-industrial indoor environments: report from a European Multidisciplinary Scientific Consensus Meeting (EUROVEN). *Indoor Air*. 2
doi:10.1034/j.1600-0668.2

- Prof. Shelly Miller during National Academy of Sciences, Engineering, and Medicine Workshop
- https://www.nationalacademies.org/event/08-26-2020/airborne-transmission-of-sars-cov-2-a-virtual-workshop

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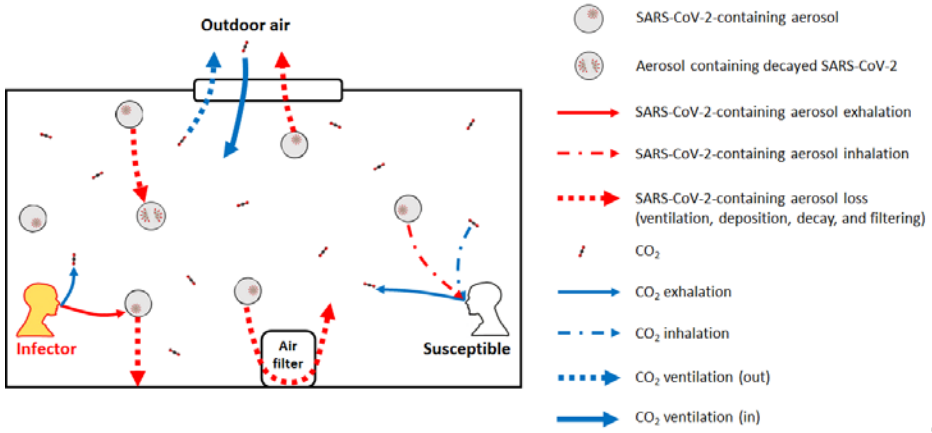
Using CO_2 as a Analog (<700 ppm)



- https://medium.com/@jjose_19945/how-to-quantify-the-ventilation-rate-of-an-indoor-space-using-a-cheap-co2-monitor-4d8b6d4dab44?source=friends_link&sk=6cda52f5682a4a450a10691f07d1ad2c
- Citizen science: see #COVIDCO2 in Twitter, post data there, help your community
- Details of CO2 level: see our paper & estimator; https://twitter.com/iljcolorado/status/1304398049528012800

Slide from Dr. Zhe Peng

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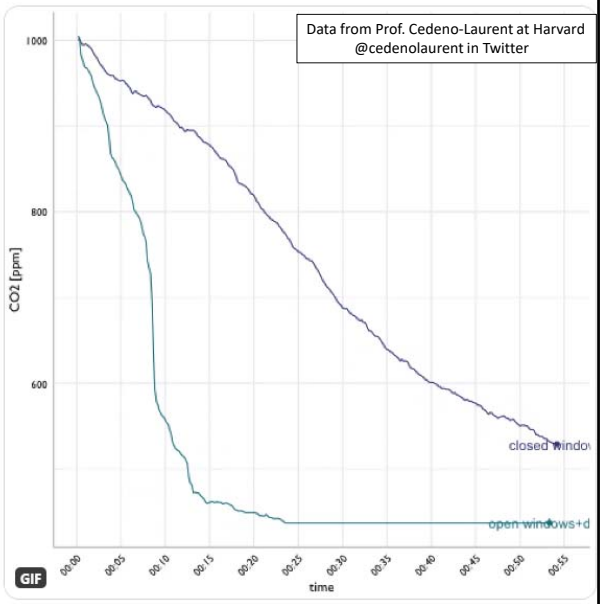
CO_2 w/ open vs closed windows

- Opening windows dramatically increases ventilation rate
- How much to open windows?
  - Depends on room and weather / wind
  - Need to measure CO_2 so that we can be objective



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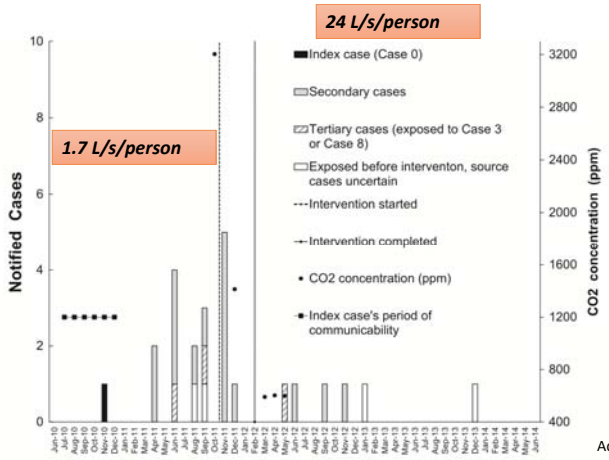
Ventilation stopped TB outbreak

- Many of the rooms had CO_2 levels above 3,000 ppm.
- When engineers improved air circulation and got CO_2 levels under 600 ppm, the outbreak completely stopped
- Increase in ventilation = 97% of the decrease

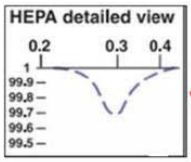


Adapted from Prof. Shelly Miller

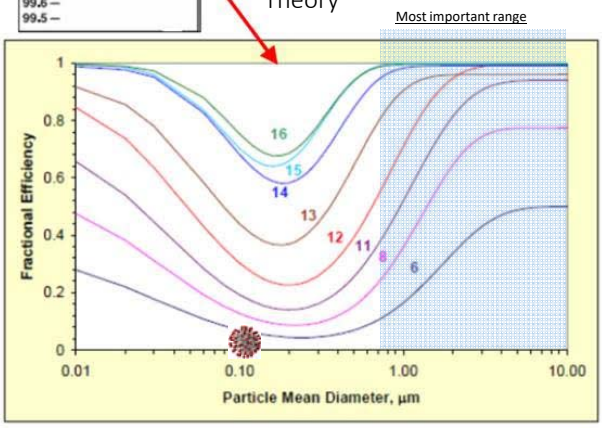
https://onlinelibrary.wiley.com/doi/full/10.1111/ina.12639

Filters & Masks work!

Masks are just filters that we wear



- To say that masks or filters don't remove some virus from the air is like saying that you won't be warmer if you put on a coat. It contradicts basic physics. It is like the Flat Earth Theory



- Virus is not naked in the air
- Supermicron range is likely what matters most
- Going from MERV 8 to MERV 13 is a large improvement
- Most existing HVAC can't tolerate HEPA, fan not strong enough
- What matters is overall removal (flow * efficiency), not 100% in a single pass

https://www.ashrae.org/technical-resources/filtration-disinfection

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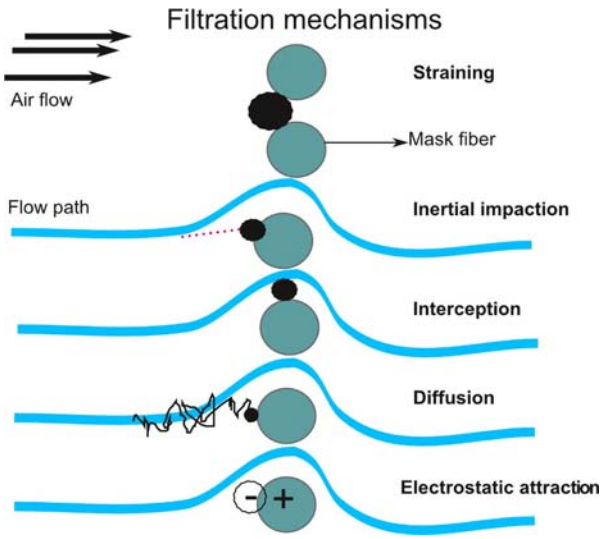
Masks / filters are not sieves!



https://t.co/JPSjST639t?amp=1 https://youtu.be/eAdanPfQdCA

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Mask Fit is Critical

- Pay attention to mask fit: avoid gaps, tight around the nose
  - I see lots of people w/ loose masks
  - Don't stand behind someone with a poorly-fitting mask
- Keep mask on when speaking, x10 times more aerosols than just breathing
  - 50 times more when yelling or singing loudly

Visualization by Prof. Philomena Bluyssen, TU Delft, The Netherlands https://youtu.be/mJ81IBTMvcU

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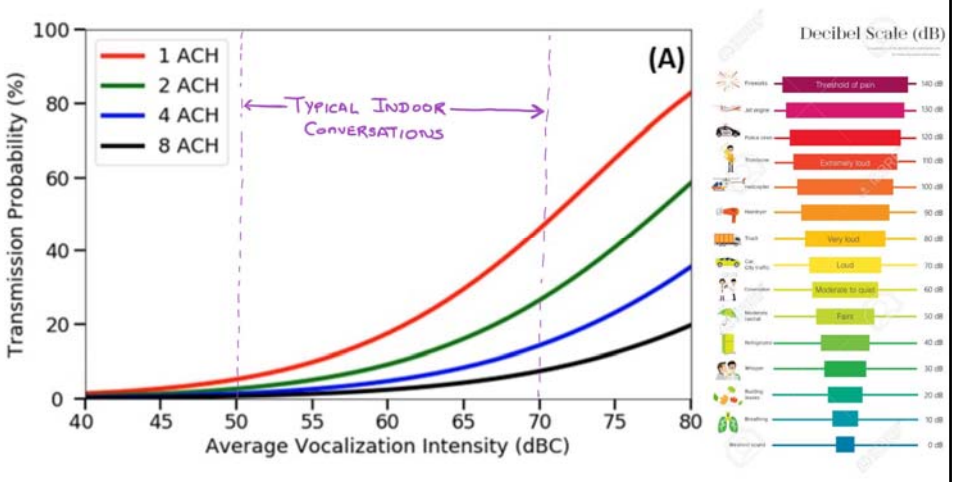
Talking less loudly reduces transmission



- arxiv.org/abs/2009.04060

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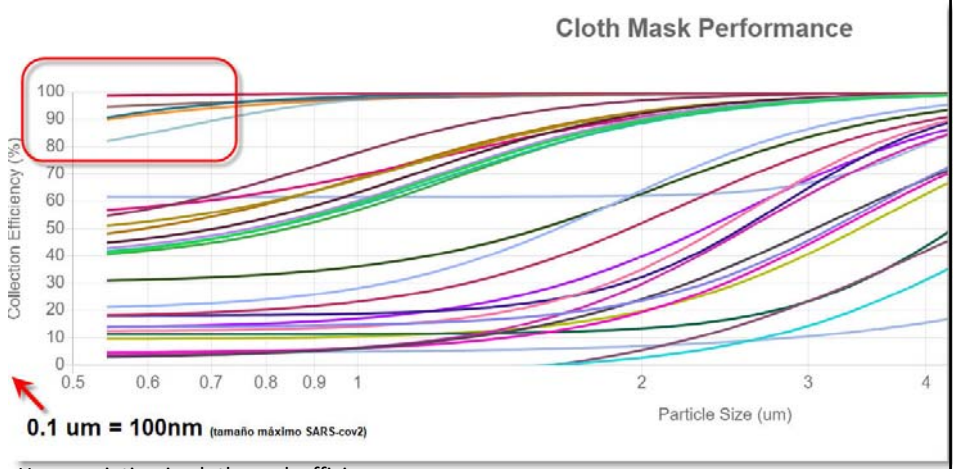
Cloth Mask efficiency: varies widely



Huge variation in cloth mask efficiency:

- Some almost as good as N95
- Others (e.g. bandanas) do something but far less

From John Volckens' CSU mask testing database: http://jv.colostate.edu/masktesting/

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Air Cleaning

- Recommendations in this order:
  1. Ventilation
  2. Filtration
     - Mechanical systems, portable HEPA, or fan + filter
  3. Germicidal UV
     - Only w/ professional design, installation, and maintenance

1. We do NOT recommend
   1. Spraying disinfectants (HOCl, ozone, etc.)
      - ONLY when nobody is present, and when enough time will pass until people arrive for disinfectant to be gone
   2. air cleaners based on chemistry (ions, plasmas, OH, H_2O_2
      - Many of them do kill pathogens
      - The same chemistry that kills the pathogens also reacts with abundant VOCs indoors, and leads to formation of potentially toxic (chemical) aerosols and oxidized VOCs

https://www.sciencedirect.com/science/article/pii/S0160412020317876
https://twitter.com/jljcolorado/status/1291758303089852417
https://medium.com/@dbc007/the-air-chemistry-behind-fogging-for-sars-cov-2-disinfection-ac3df05326bc

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Air cleaners by filtration really work!

ACH = CADR / Room Volume
https://calculadora-cadr.web.app/

Cheaper Fan + Filter

- 9.5 in https://tinyurl.com/FAQ-aerosols
- Dr. Javier Ballester, Univ. de Zaragoza
  - tinyurl.com/yc7bpdkg

HEPA adapted from Shelly Miller / Fan + filter from Jim Rosenthal

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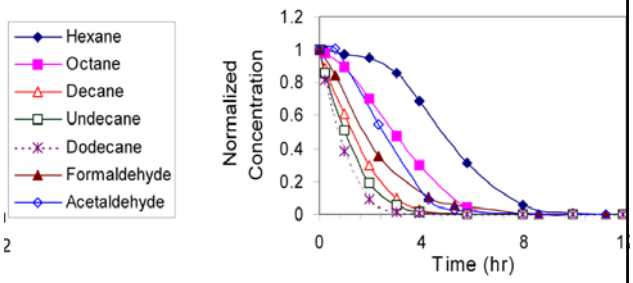
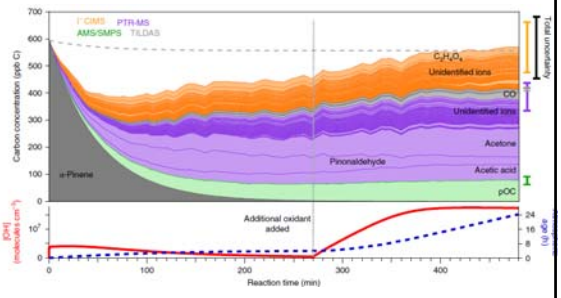
Air cleaners based on chemistry?

Ionizers, plasmas, oxidation, photocat.

- These products destroy VOCs through chemistry
  - VOCs *very* abundant indoors
- They make oxidized VOCs and (chemical) aerosols, more toxic than VOCs
  - Not studied TMK
  - Precautionary principle ➔ can't recommend





https://www.researchgate.net/publication/275344400_Performance_of_Air_Cleaners_for_Removing_Multi-Volatile_Organic_Compounds_in_Indoor_Air
https://www.nature.com/articles/s41557-018-0002-2

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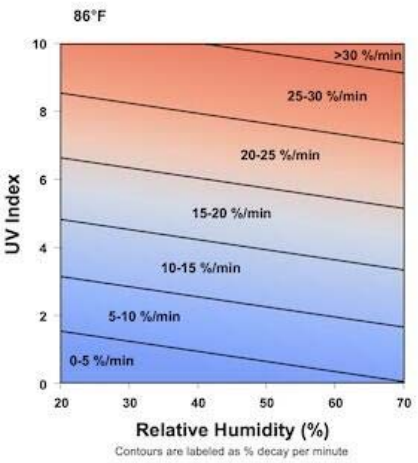
Effect of Temperature, Humidity, UV

- For enveloped viruses, higher survival at low RH
  - Flu, SARS-CoV-2
  - Some differences in results
- Low T increases lifetime
  - Weak effect
  - Important for meat packing (10°C)
- Solar UV decreases lifetime
  - 5 min – 30 min outdoors, depends on latitude etc.



https://www.dhs.gov/science-and-technology/sars-airborne-calculator

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Germicidal Ultraviolet

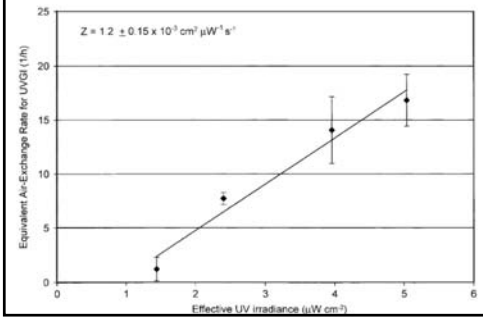
Dec., 1943

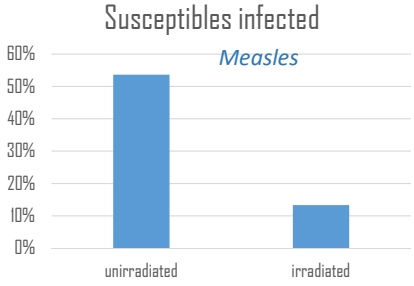
Air Disinfection in Day Schools*

W. F. WELLS

Associate Professor in Research in Air-borne Infection, Laboratories for the Study of Air-borne Infection,† Department of Preventive Medicine and Public Health, University of Pennsylvania School of Medicine, Philadelphia, Pa.

The first sentence of this paper reads: "The prevalence of respiratory infection during the season of indoor congregation suggests a natural relationship between ventilation and communicable disease."



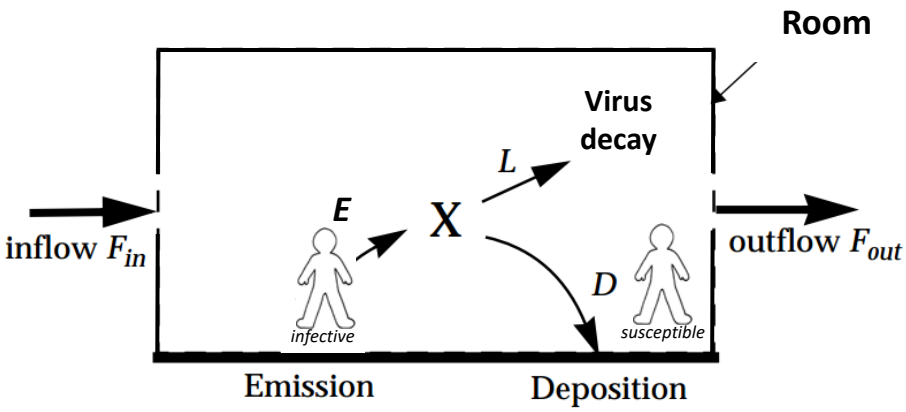


Slide adapted from Prof. Shelly Miller

https://ajph.aphapublications.org/doi/10.2105/AJPH.33.12.1436

https://www.sciencedirect.com/science/article/pii/S1352231002008257#FIG7

Simple "box model" of room-level transmission



- Infective emits virus particles, which mix in the room
  - Ignore details of mixing, which can be important at times, but are very specific to each situation (think or test with smoke)
  - Susceptible breathes in some of those particles over time, some probability of infection (Wells-Riley)
- Same as modeling radon. Ordinary differential equations, solved analytically
  - Numerical solution also possible (maybe in future version, allows more complicated events)
- Implemented in spreadsheet
  - Read "readme" and "FAQs" if you want to use it seriously http://tinyurl.com/covid-estimator

Adapted from Jacob Fig 3-1 http://acmg.seas.harvard.edu/people/faculty/dij/book/bookchap3.html#pgfid=112721

Aerosol Transmission Estimator

http://tinyurl.com/covid-estimator

Estimation of COVID-19 aerosol transmission: master spreadsheet, adapt this one to your case - Default values are for

This is a general spreadsheet applicable to any situation, under the assumptions of this model - *See notes specific to this case (if applicable) at the very bottom*

Important inputs as highlighted in orange - change these for your situation

Other, more specialized inputs are highlighted in yellow - change only for more advanced applications

Calculations are not highlighted - don't change these unless you are sure you know what you are doing

Results are in blue -- these are the numbers of interest for most people

Environmental Parameters

	Value			Value in other units		Source / Comments
Length of room	25	ft		7.6	m	Can enter as ft or as m (once entered as m, changing in ft does
Width of room	20	ft	=	6.1	m	Can enter as ft or as m (once entered as m, changing in ft does
	500	sq ft		47	m2	Can overwrite the m2 one. If you want to enter sq ft, enter "=B1
Height	10	ft	=	3.1	m	Can enter as ft or as m (once entered as m, changing in ft does
Volume				142	m3	Volume, calculated. (Can also enter directly, then changing dim
Pressure	0.95	atm				Used only for CO2 calculation
Temperature	20	C				Use web converter if needed for F --> C. Used for CO2 calcula
Relative Humidity	50	%				Not yet used, but may eventually be used for survival rate of vi
Background CO2 Outdoors	415	ppm				See readme
Duration of event	50	min		0.8	h	Value for your situation of interest
Number of repetitions of event	180	times				For e.g. multiple class meetings, multiple commutes in public tr

- Tutorials in English & Spanish: https://www.youtube.com/channel/UChUCsAMXy8f01R3rWqj4z6A
- Many calculators inspired in this one or derived independently, all consistent to my knowledge

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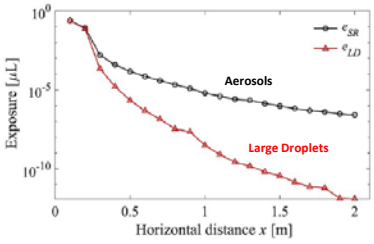
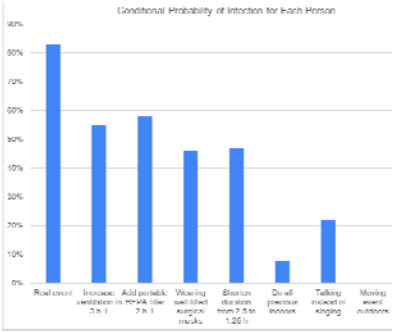
Conclusions

Smoke analogy: proximity & room

Aerosols dominate when talking



Indoors: layers of protection



Need to fit masks well

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BACKUP SLIDES

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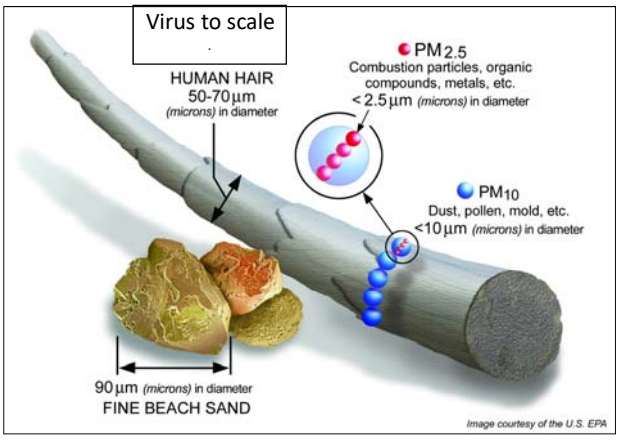
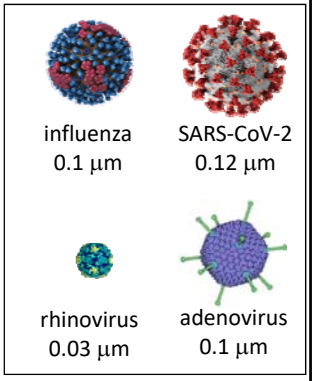
Illustration of Virus Size



Virus Sizes



https://www.cdc.gov/flu/resource-center/freeresources/graphics/images.htm, http://solutionsdesignedforhealthcare.com/rhinovirus, https://phil.cdc.gov/Details.aspx?pid=23312, https://pdb101.rcsb.org/motm/132

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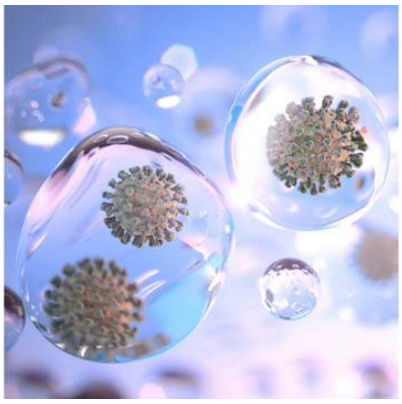
Many visualizations are incorrect

Incorrect

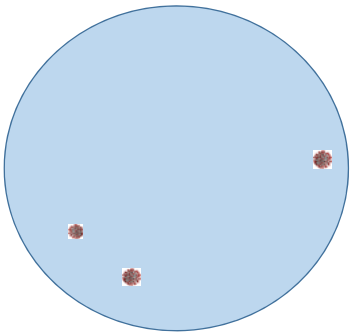
- Aerosols too small relative to the virus (look like 0.2-0.3 µm)
- Looks like water + virus only
- Mass fraction of virus very high



From Klompas et al., JAMA (2020)
https://jamanetwork.com/journals/jama/fullarticle/2768396

More correct

- More typical: few micron aerosol
- Mucin, NaCl, water + sprinkle of virus
- Mass fraction of virus very low



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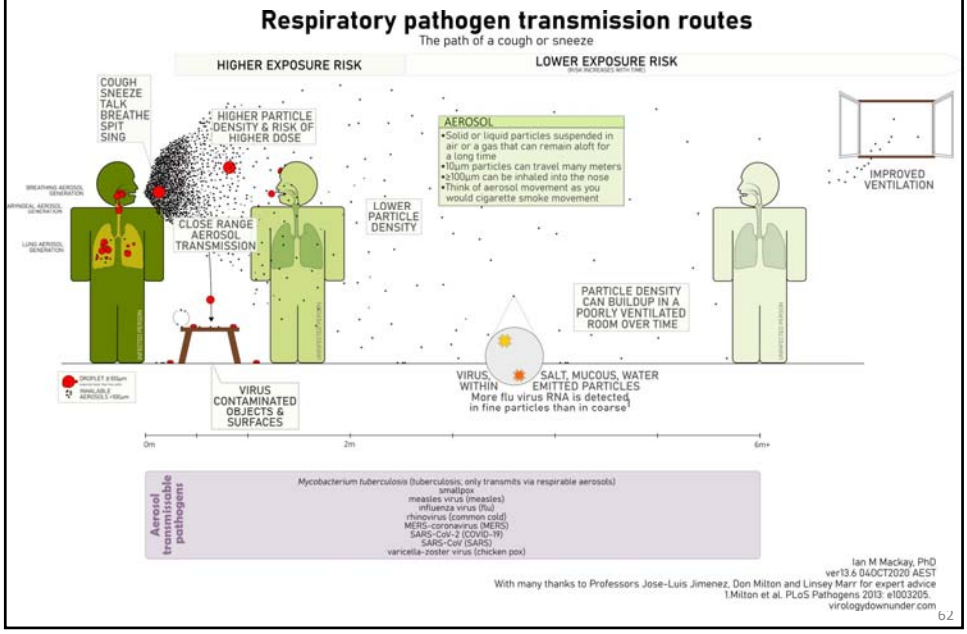

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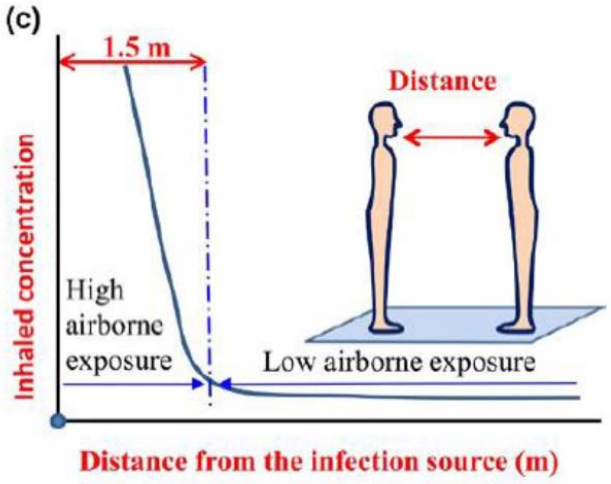
Close proximity: aerosol most concentrated



Exposure from droplet nuclei (aerosols) in rooms with sufficient ventilation

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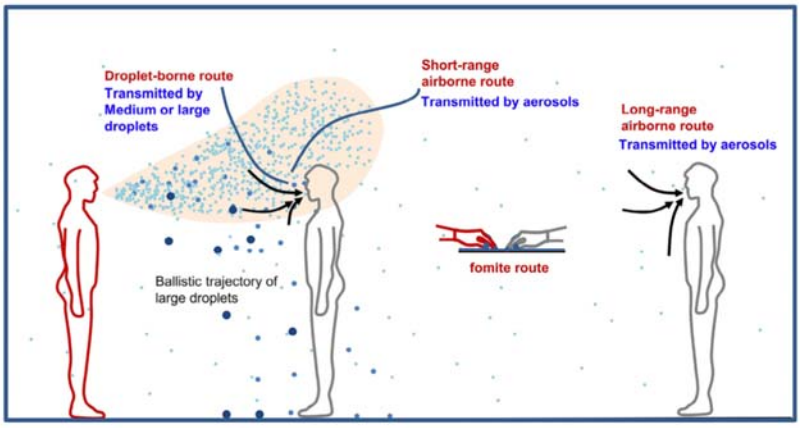
Why social distance most likely works

Wei, J., Li, Y., 2016. Airborne spread of infectious agents in the indoor environment. American Journal of Infection Control 44, S102–S108



- Large droplets (>100 μm) : Fast deposition due to the domination of gravitational force
- Medium droplets between 5 and 100 μm
- Small droplets or droplet nuclei, or aerosols (< 5 μm): Responsible for airborne transmission

2 m = 6 ft can keep you out of the short-range aerosol transmission plume

Courtesy of Shelly Miller

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Meteorology: falling droplets for rain

SEPTEMBER 1969 K. V. BEARD AND H. R. PRUPPACHER

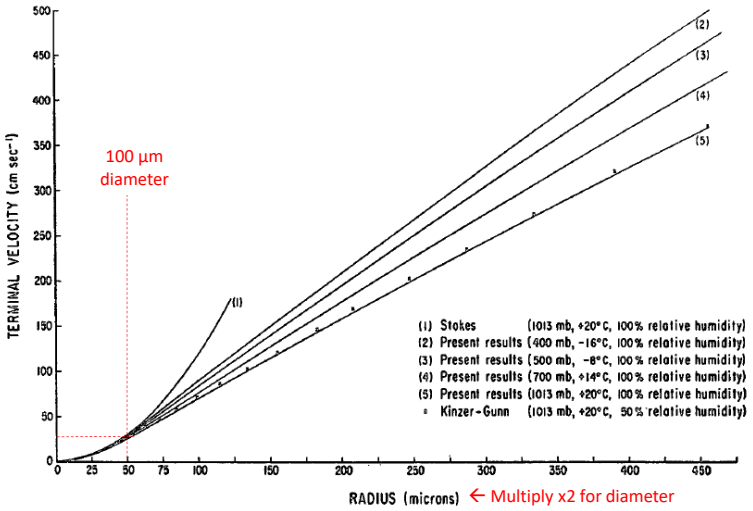

FIG. 5. Terminal velocity of water drops of various sizes and under various environmental conditions.

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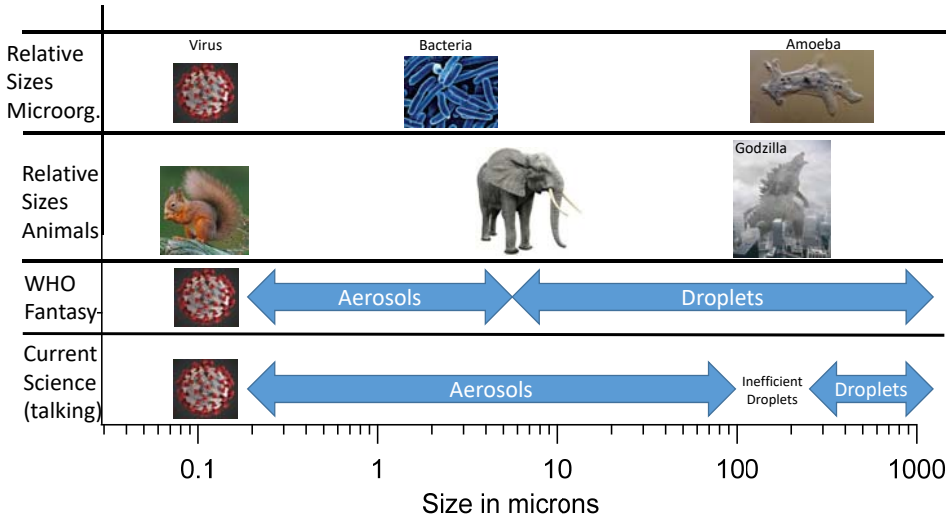
WHO's Massive Error on A / D Sizes



https://twitter.com/jljcolorado/status/1295518786951319552

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Aerosol Myths

(a) If it's aerosol, it has to be like measles
(b) If it's aerosol, it has to infect at long range
(c) If it's aerosol, R0 must be very high
(d) If infects at close proximity, it proves droplets and disproves aerosols
(e) If it's aerosol, then surgical masks are useless

- *All false, see e.g. Medscape perspective*
- ***a, b, c: confusing an artifact of history with a law of nature***
- *d, e: out-of-date with the science*

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Summary of evidence for different modes

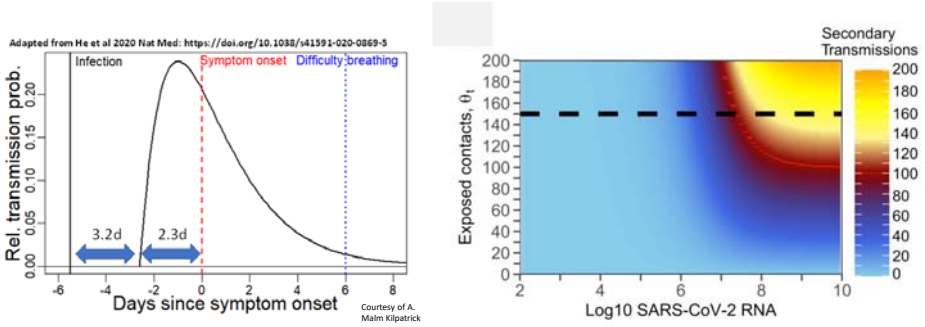
More detail & references at http://tinyurl.com/aerosol-pros-cons
Preliminary, being written up for publication; feedback most welcome

Key:
✓: evidence
✓✓: very strong ev.
X: no evidence
X: evidence against
n/a: not applicable
(v1.47, 18-Sep-2020)

	Droplets	Fomites	Aerosols
Outdoors << Indoors	X	✓	✓✓
Similar viruses demonstrated	X	✓	✓
Animal models	?	✓	✓
Superspreading events	X	X	✓✓
Supersp. Patterns similar to known aerosol diseases	n/a	n/a	✓
Importance of close proximity	✓	X	✓✓
Consistency of close prox. & room-level	X	X	✓
Physical plausibility (talking)	X	✓	✓
Physical plausibility (cough, sneeze)	✓	✓	✓
Impact of reduced ventilation	X	X	✓
SARS-CoV-2 infectivity demonstrated in real world	X	X	✓
SARS-CoV-2 infectivity demonstrated in lab	X	✓	✓
"Droplet" PPE works reasonably well	✓	✓	✓
Transmission by a/pre-symptomatics (no cough)	X	✓	✓
Infection through eyes	✓	✓	✓
Transmission risk models	✓	✓	✓

What causes superspread?

Goyal, A., Reeves, D. B., Cardozo-Ojeda, E. F., Schiffer, J. T. & Mayer, B. T. **Wrong person, place and time**: viral load and contact network structure predict SARS-CoV-2 transmission and super-spreading events. *medRxiv* (2020).



- Superspreading people? Some emit x10 more aerosols, also higher viral loads
- Lack of transmission? People only infectious for short period

Slide adapted from Prof. Shelly Miller

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Chapin's motivations

- Not enough evidence
- Belief in air infection is very problematic
- Interpret absence of evidence as evidence of absence
  - Say that airborne infection is almost impossible

In reviewing the subject of air infection it becomes evident that our knowledge is still far too scanty, and that the available evidence is far from conclusive. Yet it is of the greatest practical importance that we should know definitely just what danger there is of air-borne infection and in what diseases it is to be feared. Infection by air, if it does take place, as is commonly believed, is so difficult to avoid or guard against, and so universal in its action, that it discourages effort to avoid other sources of danger. If the sick-room is filled with floating contagium, of what use is it to make much of an effort to guard against contact infection? If it should prove, as I firmly believe, that contact infection is the chief way in which the contagious diseases spread, an exaggerated idea of the importance of air-borne infection is most mischievous. It is impossible, as I know from experience, to teach people to avoid contact infection while they are firmly convinced that the air is the chief vehicle of infection.

While it is not possible at present to state with exactness the part played by aerial infection in the transmission of the different infectious diseases, we are by the evidence forced to the conclusion that the current ideas in regard to the importance of infection by air are unwarranted. Without denying the possibility of such infection, it may be fairly affirmed that there is no evidence that it is an appreciable factor in the maintenance of most of our common contagious diseases. We are warranted, then, in discarding it as a working hypothesis and devoting our chief attention to the prevention of contact infection. It will be a great relief to most persons to be freed from the specter of infected air, a specter which has pursued the race from the time of Hippocrates, and we may rest assured that if people can as a consequence be better taught to practice strict personal cleanliness, they will be led to do that which will more than anything else prevent aerial infection also, if that should in the end be proved to be of more importance than now appears.

History of measles & TB

Measles (1985)

Most public health authorities believe that the primary mode of transmission is by large respiratory droplets which remain suspended in air for short time intervals.[2] Successful transmission in this manner requires close contact between susceptible individuals and a source patient, usually within 1 m (3 ft). Data supporting respiratory droplet spread come from studies conducted in the early 20th century.[3] Following hospitalization of 182 patients with measles at two hospitals, only one secondary case of measles occurred. Transmission was limited despite free circulation of air in both hospitals, presumably because measures were taken to prevent direct contact between patients with measles and others who were susceptible.

COVID-19 (WHO IPC)

Another report in a clinical setting in which 41 health care workers (HCWs) were exposed for over 10 min and within 2 m of a patient with confirmed COVID-19 during an intense and difficult intubation and non-invasive ventilation scenario, involving multiple AGMPs, revealed no transmission events of SARS-CoV-2 with repetitive testing of all the HCWs [23]. The majority (85%) of the HCWs were wearing a medical mask and other appropriate PPE while the remainder wore an N95 respirator.

Tuberculosis

The other sources of information regarding ventilation are various reports on ''accidents of nature'' leading to outbreaks [9]. Most notable among these are outbreaks aboard ships [66–71] and among persons on school buses [72, 73], in poorly ventilated classrooms [74], and in bars [75]. Perhaps the best-studied incident occurred aboard the USS *Byrd*, where 139 (46%) of 308 crew members tuberculin-converted (i.e., converted to tuberculin positivity) and disease developed in 7 (2.3%) [66–68]. Infection was spread by recirculation of contaminated air along closed ventilatory circuits, and high conversion rates were noted in specific sleeping compartments along a ventilatory system. In one compartment housing 6 crewmen with tuberculosis, 52 (79%) of 66 personnel tuberculin-converted; in the next compartment, which shared ventilation with the first, 46 (57%) of 81 tuberculin-converted. This compared to a rate among new recruits of 3.4%.

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Impact of outdoor schools in winter

- News of the school quickly spread, with newspapers across the country running an identical report shortly after the school opened: “Little faces that were sallow and pinched a few weeks ago have a healthy flush, and children who were too tired to play are beginning to show some interest in life. All of this … is what the fresh-air school has accomplished.”
- https://www.washingtonpost.com/history/2020/09/14/open-air-schools-outdoor-coronavirus/

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Masks less different above 1 micron

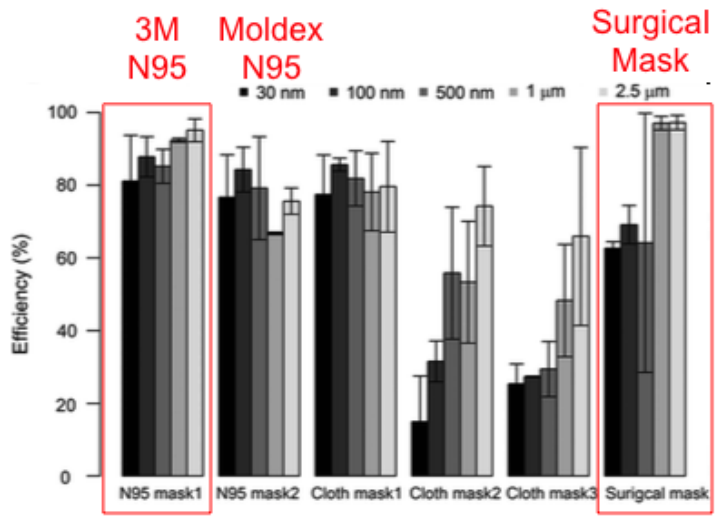

Figure 2. Efficiency of masks in removal of five polystyrene latex (PSL) particle sizes at a flow rate of 19 L/min. Error bars are the standard deviation from three experiments.

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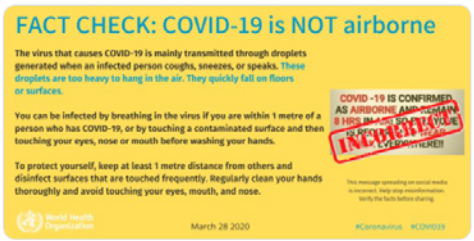
For now we are on our own!

World Health Organization (WHO) @WHO

FACT: #COVID19 is NOT airborne.

The #coronavirus is mainly transmitted through droplets generated when an infected person coughs, sneezes or speaks.

To protect yourself:
-keep 1m distance from others
-disinfect surfaces frequently
-wash/rub your 👐
-avoid touching your 👀👃👄



From experience talking to governments, schools, companies, and inviduals: as long as aerosol transmission is effectively denied by the major organizations, it is extremely difficult to get measures to control it in place. E.g.:

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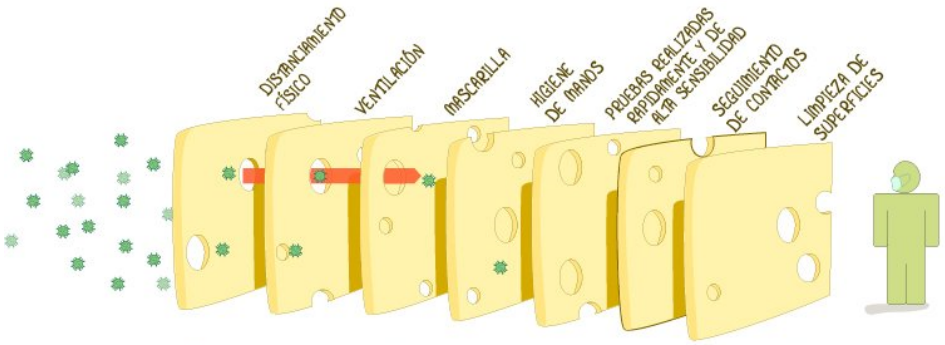
Defensa Contra Virus Respiratorios: El Modelo De Queso Suizo

Reconocer que ninguna intervención por sí sola es perfecta para prevenir la propagación.



Cada intervención (capa) tiene imperfecciones (agujeros).
Múltiples capas mejoran la probabilidad de éxito.

Ian M Mackay
virologydownunder.com
Derivado de @sketchplanator
Basado en "The Swiss cheese model of accident causation", by James T Reason, 1990
Version 1.3.ESP
Actualizado al: 12Oct2020
Traduccion ESP: @DescoladoEn

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University of Colorado Boulder

Chapin on "Reasons for Belief" in Airborn Transmission

- The real reasons why people generally attach so much importance to this mode of infection are, first, the hearty belief in the general **theory of aerial infection which has prevailed from remote antiquity**, and, secondly, because infection so often takes place when there has not been any known contact. **Contact is the most certain and obvious mode of infection, and other modes should not be assumed without good reason. The burden of proof rests on those who make the assumption**.

School of Public Health

Chapin CV. The sources and modes of infection. 1st ed. New York,: J. Wiley & Sons; 1910

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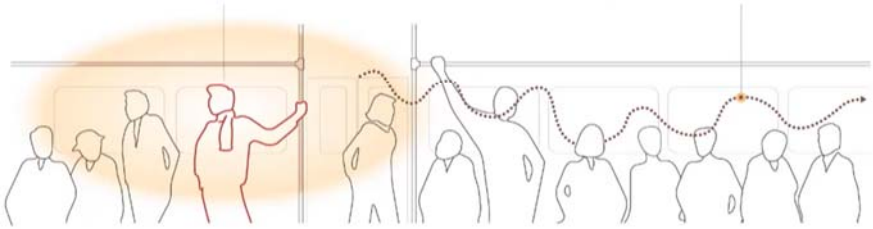
CDC's view of droplets vs aerosols

Droplet Transmission and Airborne Spread

Droplet: infectious particles are projectiles; spread limited by gravity

Airborne: infectious droplet nuclei; remain airborne minutes to hours, potential spread by air currents (e.g., via HVAC)



New York Times, January 31, 2020

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