CAE/ENVE 402
Introduction to Environmental Engineering and Sustainable Design
Spring 2020

March 23 and 25, 2020
Introduction to Indoor Air Quality (IAQ)

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Disclaimer and notes

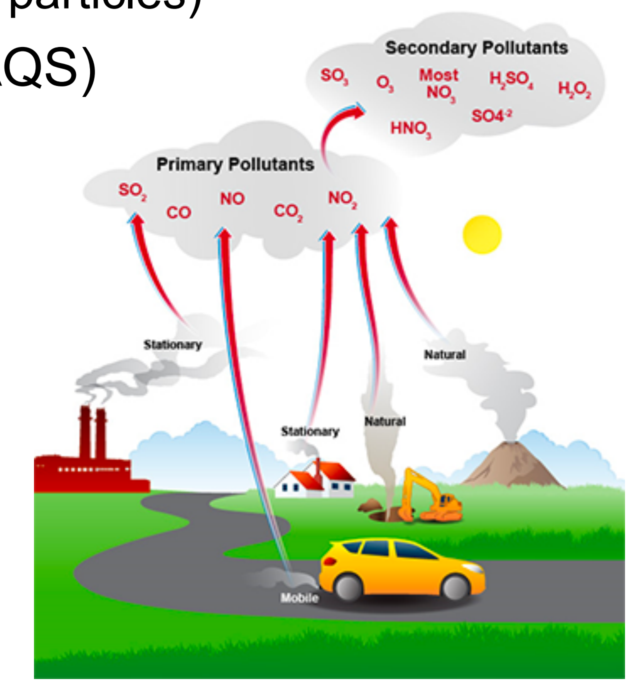
- I have attempted to distill some core concepts of indoor air quality into two days of lectures
  - Including a tangent that is highly relevant today
- I periodically teach a graduate course on the topic: ENVE 576 Indoor Air Pollution
  - Last taught Fall 2017
  - Thinking about teaching it this summer (let me know if interested)
- Some of the content in these slides comes from ENVE 576 as well as CAE 331/513 Building Science
- There is a HW assignment posted on Blackboard
  - Due March 30, 2020

Air quality inside and out

Why should we care about air quality, both indoors and outdoors?

Common outdoor air pollutants

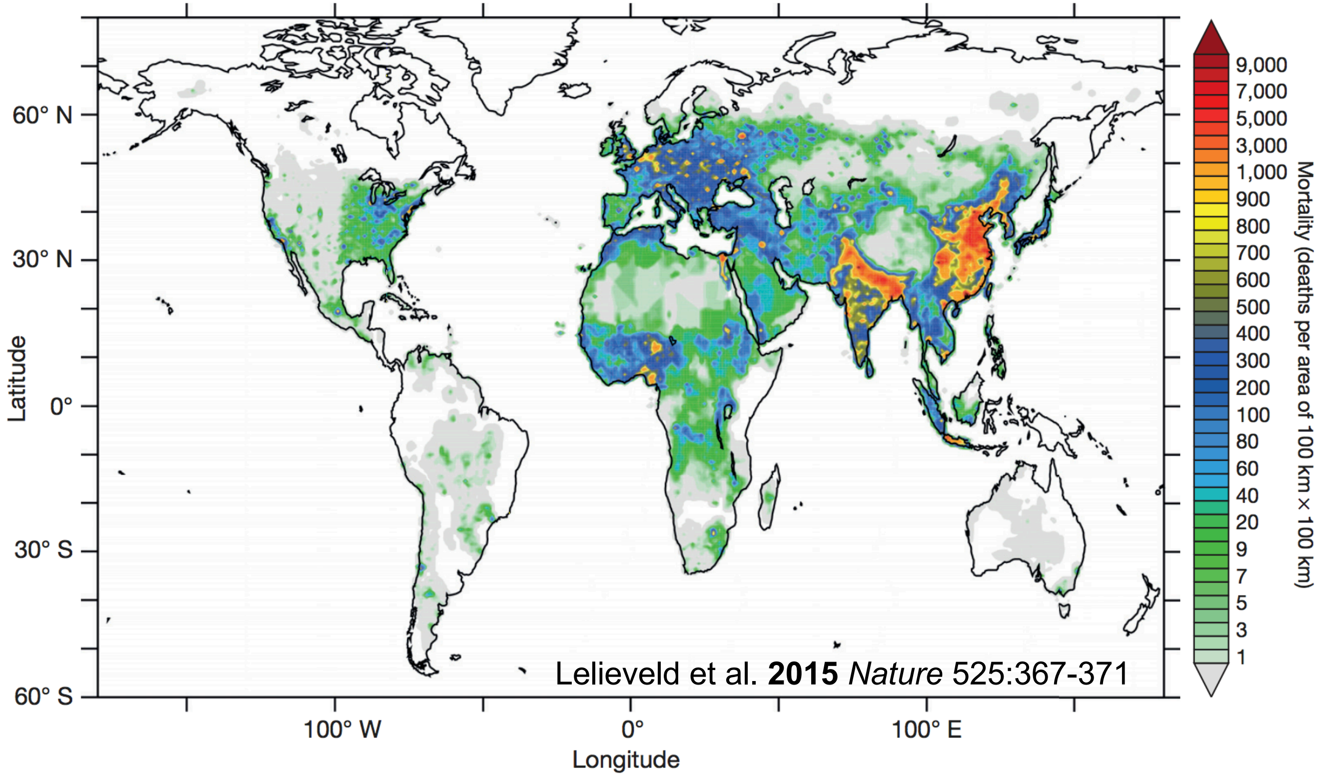
- Common outdoor air pollutants include:
  - Particulate matter
    - Particulate matter less than 10 micrometers (PM_{10})
    - Particulate matter less than 2.5 micrometers ($PM_{2.5}$)
    - Particulate matter less than 0.1 µm (ultrafine particles)
  - Gases (Criteria pollutants regulated by NAAQS)
    - Ozone (O_3)
    - Nitrogen dioxide (NO_2)
    - Sulfur dioxide (SO_2)
    - Carbon monoxide (CO)
    - Lead (Pb)
    - Mercury (Hg)



Outdoor air pollution and health

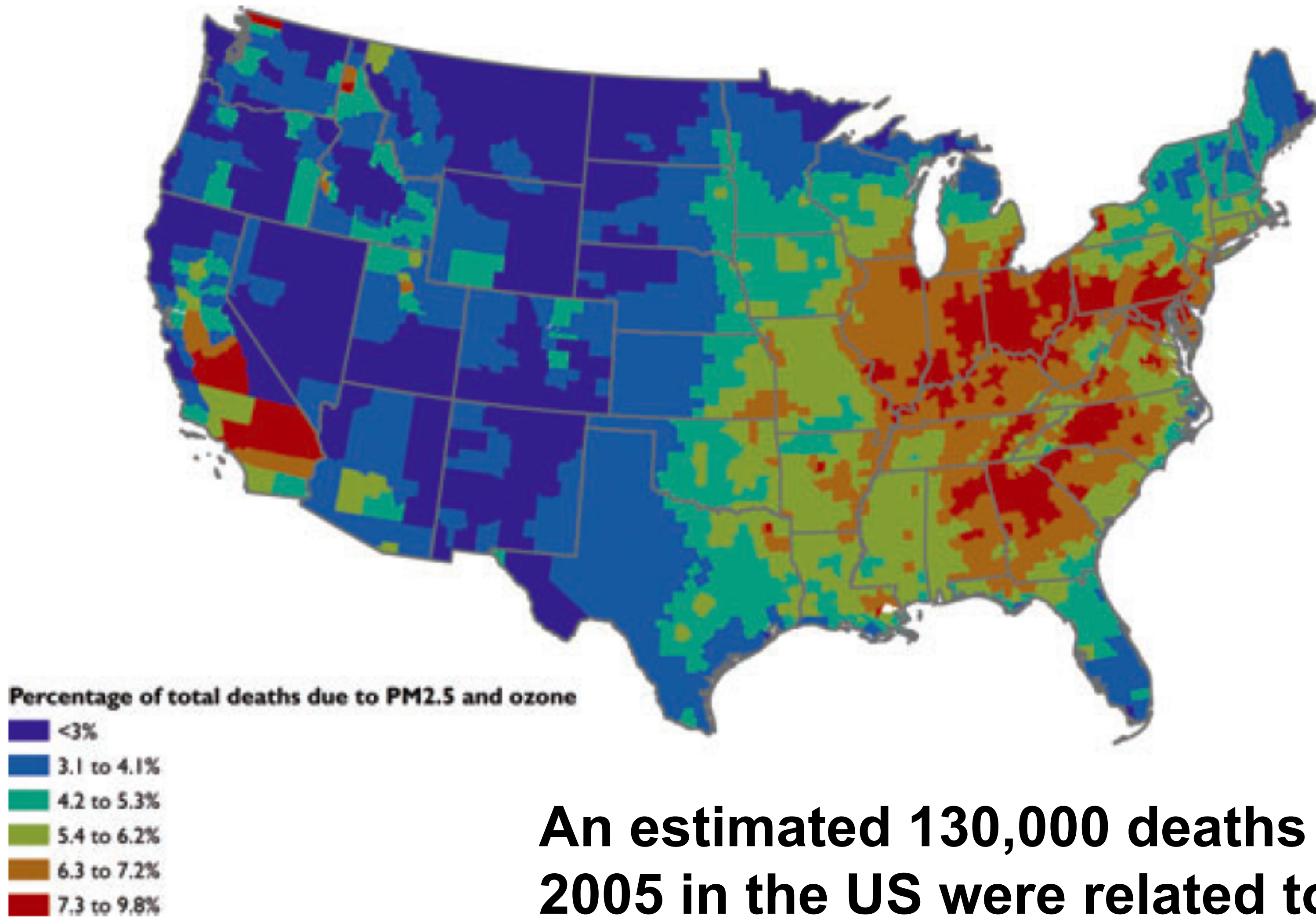
- Documented health effects include:
  - Stroke
  - Heart disease
  - Lung cancer
  - Chronic & acute respiratory diseases (including asthma)
  - Mortality

Outdoor air
3.3 million premature deaths globally in 2010



Lelieveld et al. **2015** *Nature* 525:367-371

Outdoor air pollution and health



An estimated 130,000 deaths in 2005 in the US were related to outdoor $PM_{2.5}$ (and 4,700 w/ O_3)

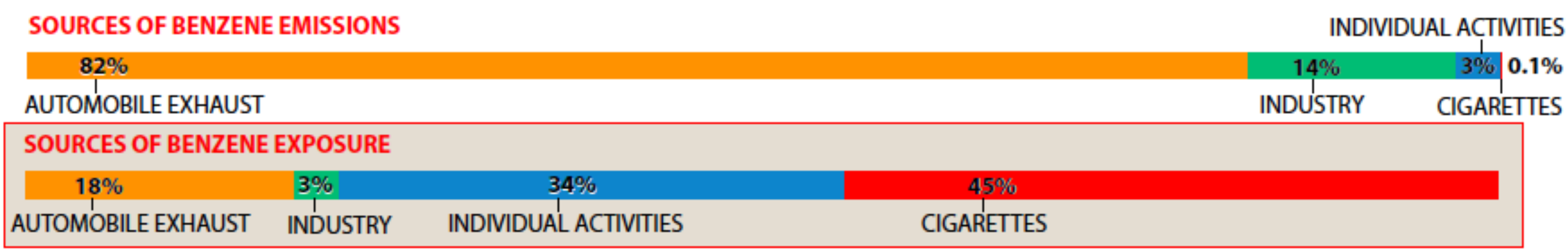
Fann et al., **2012** *Risk Analysis*

Where do we spend most of our time?

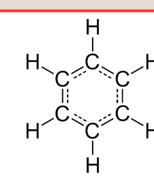
- We spend most of our time indoors
  - Nearly 90% of the time, on average in the developed world
  - Approximately 18 hours indoors for every 1 hour outdoors
- We bring materials, furnishings, appliances, and activities into buildings, many of which emit or release a variety of substances
  - Some harmful, some not
- Buildings also exchange air without the outdoors
  - Outdoor air pollution can both dilute or become indoor air pollution
- Indoor air is a dominant environmental exposure
  - Most of the body’s intake of air is done so inside buildings
  - 80-90% inhaled in buildings generally

Why do we care about indoor air quality?

- Indoor concentrations of most pollutants are higher than outside
  - Global average of ~3:1 indoor/outdoor ratio
    - Large variability between pollutants
- We keep sensitive equipment/precious artifacts inside buildings
- We regulate outdoor air based on emissions
  - No indoor air regulations
    - Other than smoking bans and product emission controls at manufacture stage
    - Canada just initiated residential NO_2 guideline
  - Disconnect between <u>emissions</u> and <u>exposure</u>
    - Benzene example (outdoor sources include auto exhaust and industry):



C_6H_6



Ott and Roberts, **1998** *Scientific American*

A brief history of indoor air

- Since there has been shelter, indoor air has been important
- Greeks and Romans (400 BC) knew of adverse effects of polluted air in crowded cities and mines
- The Bible mentions living in damp (moist) buildings was linked to leprosy
  - Bacterial infection
- Crowded cities and chimney sweeps in 1600s and 1700s highlighted the importance of air pollution indoors and outdoors
- In the 1800s, slaves and prisoners died in very small, poorly ventilated rooms
  - Providing evidence of the importance of ventilation
- Also "bad air" blamed for the spread of disease
  - "deficient ventilation … (is) more fatal than all other causes put together," 1850
- Now, in developed regions of the world, buildings have vented cooking appliances with generally clean fuels, central heating and air-conditioning, new furnishings and materials, lower ventilation rates
  - And a relatively high prevalence of allergies, asthma, and other health issues
- In developing regions of the world we still have burning of biomass on inefficient and unvented stoves
  - And a high prevalence of respiratory disease and other health effects

Sundell, 2004 *Indoor Air*

Methods of studying indoor air pollution

- Indoor air quality (IAQ) is interdisciplinary
  - Involves engineers, public health professionals, analytical chemists, building scientists, architects, contractors, medical professionals, epidemiologists, academics, biologists, psychologists, economists, etc.
  - Many different approaches

- The big picture is that:
  - We are interested in concentrations of pollutants and human exposures
    - Worker productivity/safety
    - Health effects
    - Material degradation
    - Biological growth/disinfection
  - So we need to use and convert concentrations and conduct mass balances to get concentrations, exposures, and doses
    - And to determine what affects those

Who studies indoor air?

- National/state institutions
  - US EPA http://www.epa.gov/iaq/
  - NIOSH/CDC http://www.cdc.gov/niosh/topics/indoorenv/
  - NIST http://www.nist.gov/indoor-air-quality.cfm
  - NRC-Canada http://www.nrc-cnrc.gc.ca/eng/solutions/facilities/indoor_environment.html
  - CARB http://www.arb.ca.gov/research/indoor/indoor.htm
  - LBNL http://energy.lbl.gov/ie/

- Universities
  - Harvard, Berkeley, Penn State, Drexel, University of Texas at Austin, Rutgers, Tulsa, Clarkson, Purdue, Syracuse, Illinois Tech…
  - University of Toronto, Danish Technical University, Tsinghua, National University of Singapore, Hong Kong University…
    - Many others

Who studies indoor air?

- Standards organizations and professional societies
  - ISIAQ (International Society of Indoor Air Quality and Climate)
  - ISES (International Society of Exposure Science)
  - AAAR (American Association for Aerosol Research)
  - ASHRAE (American Soc. of Heating, Refrigerating, and Air-Conditioning Eng.)
  - IAQA (Indoor Air Quality Association)
  - AIHA (American Industrial Hygiene Association)
- Important journals
  - *Indoor Air*
  - *Building and Environment*
  - *Atmospheric Environment*
  - *Environmental Health Perspectives*
  - *Environmental Science and Technology*
  - *Journal of Exposure Science and Environmental Epidemiology*
  - *Science and Technology for the Built Environment*
  - *Aerosol Science and Technology*
  - Many others

Human exposure pathways

- Exposure pathways
  - Ingestion, inhalation, dermal uptake, ocular (eyes), hands

- Inhalation exposure
  - Adults inhale 15-20 m^3 of air per day
  - Adults ingest 1.2 L per day of water, or 0.0012 m^3/day
    - Adults ingest about ~16000 times as much air as water per day!
  - Water is about 800 times as dense as air, so humans ingest about 18 times more mass of air than water per day
  - The point is that we put large amounts of air into our bodies every day by inhalation
    - So what pollutants are contained in air are important!

TYPES AND CHARACTERISTICS OF INDOOR POLLUTANTS

Indoor vs. outdoor atmospheres

- Indoor atmospheric physics and chemistry is much like outdoor atmospheric physics and chemistry
  - With a few important exceptions
- Indoor atmospheres constitute a very small fraction of the planetary atmosphere
  - However, most of that air is breathed by humans on a daily basis

Table 1
Some attributes of the global, urban, and indoor atmospheres[a]

Environment	Mass (kg)	Flow, F ($kg\,d^{-1}$)	Mass breathed, Q^b ($kg\,d^{-1}$)	Ratio, $Q:F$
Global atmosphere	5×10^{18}	—	$\sim10^{11}$	—
Urban atmospheres	$\sim10^{15}$	$\sim3\times10^{15}$	$\sim4\times10^{10}$	$\sim10^{-5}$
Indoor atmospheres	$\sim10^{12}$	$\sim10^{13}$	$\sim8\times10^{10}$	$\sim10^{-2}$

[a] For the urban and indoor atmospheres, attributes are summed over all environments on earth.
[b] For the global and urban atmospheres, the mass breathed includes air inside and outside of buildings.

Nazaroff, Weschler, and Corsi 2003 *Atmospheric Environment*

Indoor vs. outdoor atmospheres

Table 2
Some attributes of urban and indoor atmospheres

Parameter	Urban atmosphere	Indoor atmosphere
Residence time	~ 10 h	~ 1 h
Light-energy flux	$\sim 1000\ W\ m^{-2}$ (daytime)	$\sim 1\ W\ m^{-2}$
Surface-volume ratio	$\sim 0.01\ m^2 m^{-3}$	$\sim 3\ m^2 m^{-3}$
Precipitation	$\sim 10–150$ cm year^{-1}	Absent

- Residence times are lower indoors than outdoors
- Sunlight is much much lower indoors than outdoors
- Surface-to-volume ratios are much much higher indoors
- There is no precipitation indoors (hopefully)

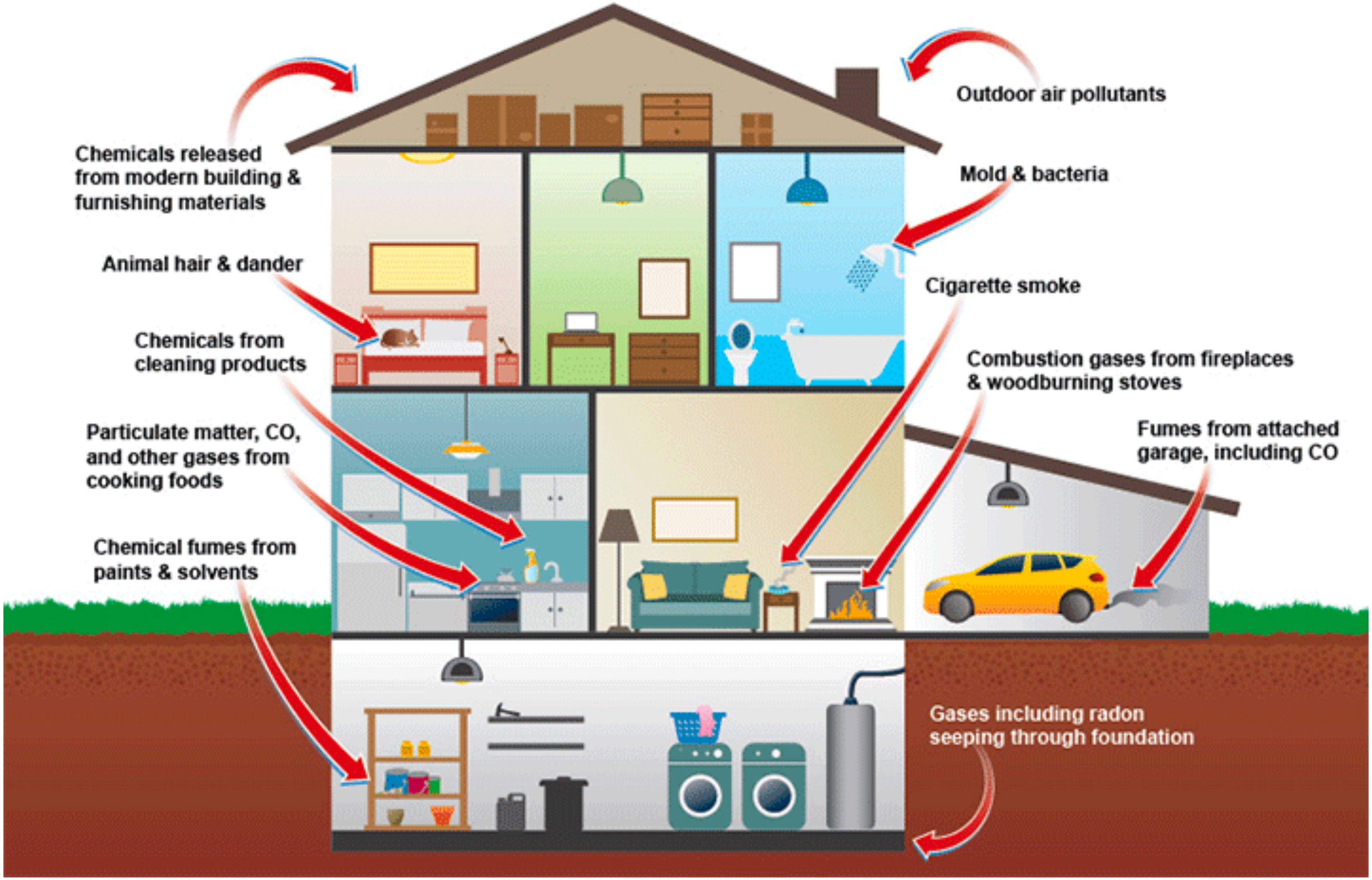
Nazaroff, Weschler, and Corsi 2003 *Atmospheric Environment*

Important classes of indoor pollutants

- Inorganic gases
  - Combustion products: carbon monoxide (CO) and nitrogen oxides (NO_x)
  - Ammonia (NH_3), ozone (O_3), hydrogen sulfide (H_2S), radon, metals
- Organic gases
  - Volatile organic compounds (VOCs)
    - Hundreds of these
  - Aldehydes (e.g., formaldehyde)
  - Semi-volatile organic compounds (SVOCs)
    - Polycyclic aromatic hydrocarbons (PAHs), phthalates, pesticides, brominated flame retardants
- Particulate matter (PM)
  - Solid and liquid aerosols
    - Size, shape, mass, constituents (e.g., chemical species, metals)
  - Fibers (e.g., asbestos)
  - Biological particles
    - Viruses, bacteria, fungi, endotoxins, allergens (pollen, dander)

Godish 2001 *Indoor Environmental Quality*; Spengler et al. 2001 *Indoor Air Quality Handbook*

Types of indoor emission sources



https://www.epa.gov/expobox/exposure-assessment-tools-media-air

Types of indoor emission sources

- Building materials (VOC/SVOC)
  - Wood and composite wood
  - Gypsum wallboard
  - Concrete
  - Carpet
  - Vinyl flooring
- Furnishings (VOC/SVOC)
  - Bedding
  - Tables
  - Couches/chairs
  - Drapes
- Architectural coatings (VOC/SVOC)
  - Paints
  - Stains
  - Varnishes
- Outdoor-to-indoor transport (all)
- Consumer products (VOC/SVOC)
  - Cleaners
  - Fragrances
  - Personal care products
- Combustion (VOC/PM/SVOC/other)
  - Cigarettes, cigars, pipes
  - Gas stoves
  - Space heaters
  - Candles
  - Incense
- Electronics (PM/VOC/SVOC/other)
  - Laser printers
  - Computers
  - Photocopiers
- Volatilization from water (VOC)
- Soil vapor intrusion (VOC/radon)
- People, pets, insects (biological)

Units of measurement for air pollutants

- **Number concentrations** (# per volume of air, #/m^3)
  - # of molecules per m^3 (highly reactive species, e.g., OH radical)
  - # of particles per m^3 (particulate matter)
  - # of cells or colony forming units per m^3 (biological)
- **Mass concentrations** (mass per volume of air)
  - ng/m^3 typical for metals and SVOCs
  - μg/m^3 typical for indoor VOCs and particulate matter
  - mg/m^3 big sources, e.g., ETS, cooking, industrial hygiene
- **Molar concentrations** (variations on $y_i = \mathrm{mol}_i/\mathrm{mol}_{air}$)
  - Mole fraction (y_i) = mol/mol
  - % concentration = moles per 100 moles = 100*y_i
  - Parts per million by **volume** (ppm_v) (or just "ppm")

$$1 \text{ ppm} = \frac{1 \text{ mol of } i}{10^6 \text{ moles of air}} = 10^{-6} \frac{\text{moles of } i}{\text{moles of air}} = 10^{-6} * y_i$$

  - Parts per billion by **volume** (ppb_v) (or just "ppb")

$$1 \text{ ppb} = \frac{1 \text{ mol of } i}{10^9 \text{ moles of air}} = 10^{-9} \frac{\text{moles of } i}{\text{moles of air}} = 10^{-9} * y_i$$

For gases, we can use the ideal gas law to convert between molar and mass concentrations

Inorganic gases: Combustion products

- Combustion for heating, cooking and lighting is a major source of indoor air pollution throughout the world
  - Sources vary greatly by country/region

- Principal combustion products
  - Smoke: mixture of airborne particles (solids + liquids) and gases
    - Composition varies by combustion source and combustion efficiency
  - Water vapor (H_2O) and carbon dioxide (CO_2)
  - Products of incomplete combustion:
    - Carbon monoxide (CO)
    - Oxides of nitrogen (NO_x, NO, NO_2)

- Major sources
  - Gas cooking and heating
    - Particularly heating with unvented appliances
  - Backdraft of vented appliances
  - Vehicles in garages (and transport indoors)

Inorganic gases: Combustion products

- Products of complete combustion
  - Example: combustion of methane (CH_4) in oxygen (O_2)

$$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O + \text{heat energy}$$

- Products of incomplete combustion
  - Example: combustion of CH_4 in oxygen-deprived environment

$$2\ CH_4 + 3\ O_2 \rightarrow 2\ CO + 4\ H_2O$$

$$N_2 + O_2 \rightarrow 2\ NO\ (\textit{at high } T)$$

$$N_2 + 2\ O_2 \rightarrow 2\ NO_2\ (\textit{at high } T)$$

Inorganic gases: Products of incomplete combustion

- Carbon monoxide (CO)
  - Colorless, odorless, poisonous gas
  - Both indoor and outdoor sources (regulated outdoors in U.S.)

- Health effects
  - Combines with hemoglobin (oxygen carrier in red blood cells) in bloodstream to produce carboxyhemoglobin (COHb)
    - COHb hinders delivery of oxygen to the body
    - Combines with hemoglobin with about 250x affinity of O_2
  - Acute: Headache, nausea, vomiting, dizziness, fatigue, and death
  - Chronic: Similar with additional neurological and psychiatric effects

- Typical concentrations
  - Natural outdoors ~0.1-1.0 ppm
  - Average level in homes ~0.5-5 ppm
  - Exhaust from a residential wood fire ~5000 ppm

Inorganic gases: Products of incomplete combustion

- Oxides of nitrogen ($NO_x = NO + NO_2$)
  - Nitric oxide (NO)
  - Nitrogen dioxide (NO_2)
    - NO converted to NO_2 in air
  - Rate of formation depends on:
    - Amount of oxygen; flame temperature

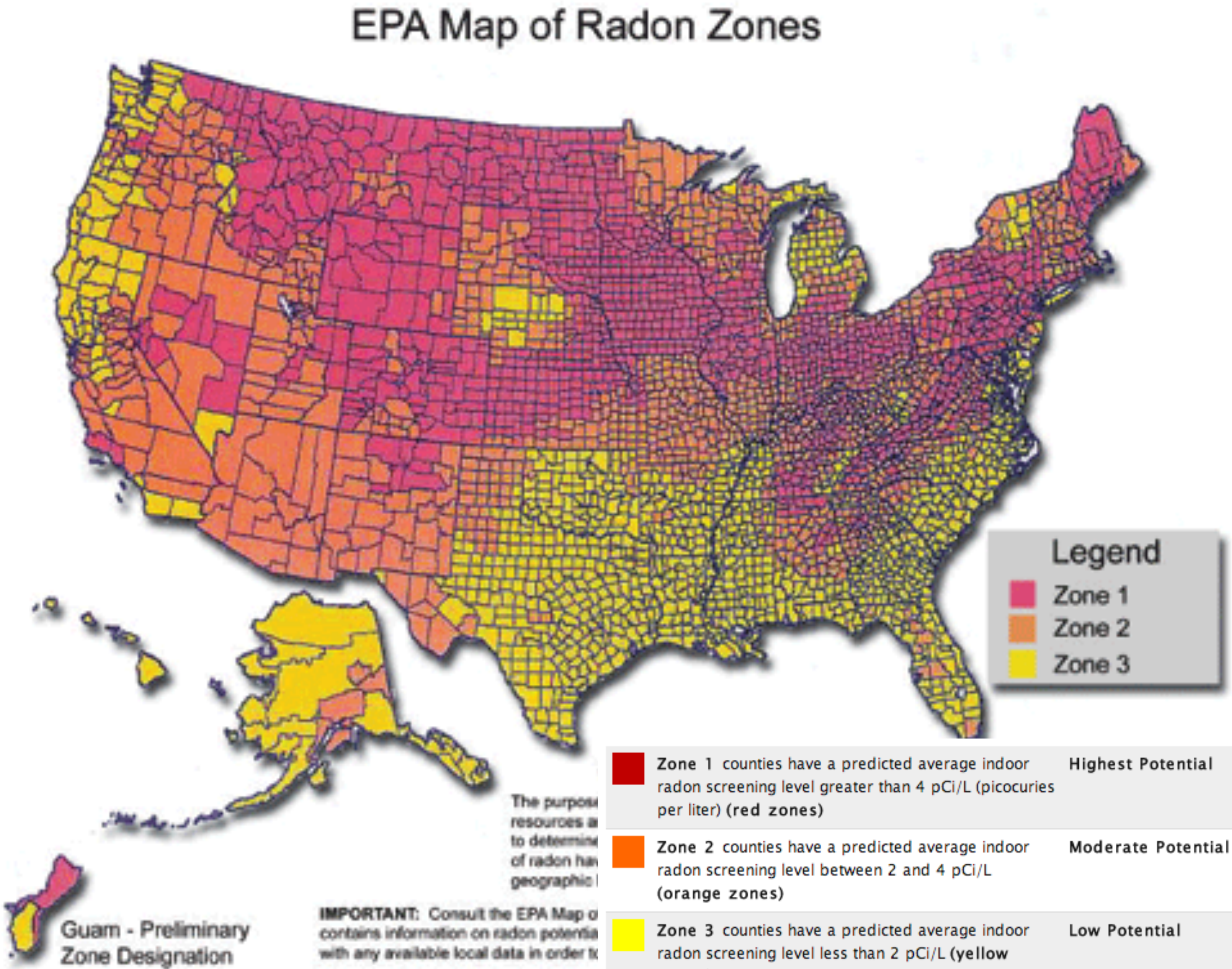
- Health effects
  - NO_2 causes oxidative damage to lining of airways
  - Reduced clearance of respiratory pathogens
    - Increased respiratory illness

- Typical concentrations
  - Average level in homes ~5-20 ppb
  - Peak from gas burner ~500 ppb

Inorganic gases: Others

- Hydrogen sulfide (H_2S)
  - Colorless, poisonous, flammable gas with rotten egg odor
  - Sources: Landfills; volatilization from water; infiltration of sewer gas
- Ozone (O_3)
  - Very reactive, powerful oxidant; causes lung damage
  - Sources: Outdoor photochemistry; indoor electronic “air cleaners”
    - Driver of indoor chemistry
- Ammonia (NH_3)
  - Colorless, corrosive gas with sharp odor; causes irritation
  - Sources: Household cleaners; animal waste and fertilizers (outdoors)
- Radon (Rn-222)
  - Noble, inert gas resulting from decay of naturally occurring uranium (U238); radioactive alpha particle emitter; carcinogen responsible for ~20k lung cancer deaths per year in U.S.
  - Diffuses through rock and soil and enters indoor environments as gas

Radon map of U.S.



■	**Zone 1** counties have a predicted average indoor radon screening level greater than 4 pCi/L (picocuries per liter) **(red zones)**	**Highest Potential**
■	**Zone 2** counties have a predicted average indoor radon screening level between 2 and 4 pCi/L **(orange zones)**	**Moderate Potential**
■	**Zone 3** counties have a predicted average indoor radon screening level less than 2 pCi/L **(yellow zones)**	**Low Potential**

Organic gases: VOCs

- Volatile Organic Compounds (VOCs)
  - Original definition of VOC referred to a class of carbon-containing chemicals that participate in photochemical reactions in outdoor air
    - Excluding CO, CO_2, H_2CO_3, and some others
  - VOCs are also defined according to analytical methods

- Indoor air literature:
  - VOC commonly refers to all organic vapor-phase compounds
    - TVOC = total volatile organic compounds
  - Also:
  - VVOC = very-volatile organic compounds
  - SVOC = semi-volatile organic compounds
  - POM = particulate organic matter
    - Organic compounds associated with particulate matter

Organic gases: VOCs

- VOCs, VVOCs, SVOCs, and POM are all categorized by their boiling points
  - Lower molecular weight (and low boiling point) compounds are more likely in the gas-phase

Table 1. Classification of indoor organic pollutants

Category	Description	Abbreviation	Boiling-point range (°C)[a]	Sampling methods typically used in field studies
1	Very volatile (gaseous) organic compounds	VVOC	<0 to 50–100	Batch sampling: adsorption on charcoal
2	Volatile organic compounds	VOC	50–100 to 240–260	Adsorption on Tenax, carbon molecular black or charcoal
3	Semivolatile organic compounds	SVOC	240–260 to 380–400	Adsorption on polyurethane foam or XAD-2
4	Organic compounds associated with particulate matter or particulate organic matter	POM	>380	Collection on filters

[a] Polar compounds appear at the higher end of the range.

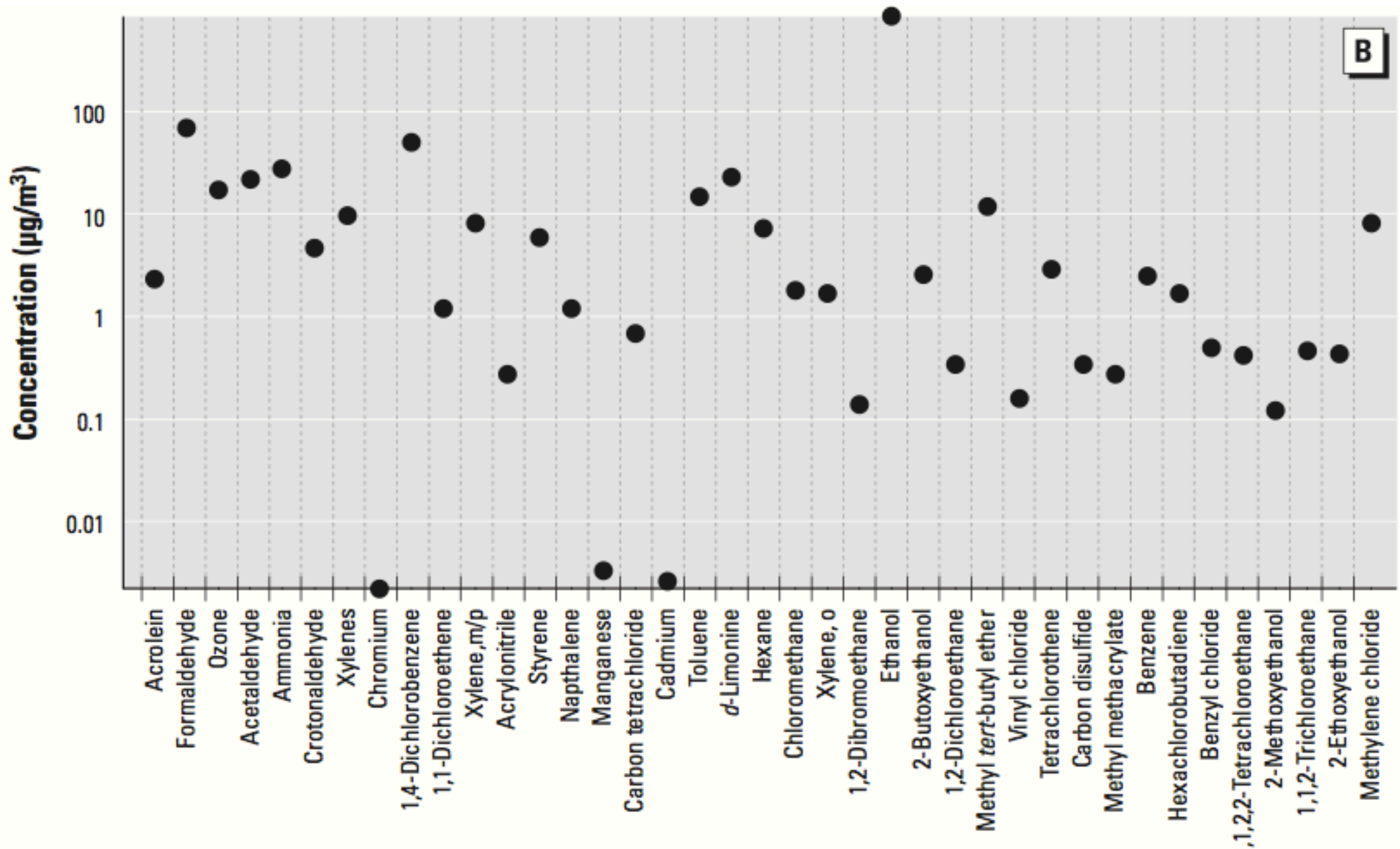
Organic gases: VOCs

- Some VOCs have strong odors, cause sensory irritation (primarily to mucus membranes), or are classified as hazardous air pollutants with carcinogenic or other effects

- VOCs are some of the most prevalent indoor pollutants
  - Also some of the most studied
  - Often dozens if not hundreds of individual compounds present at 1-5 ppb over long periods and can reach hundreds of ppb during peak events

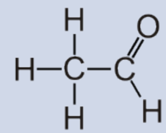
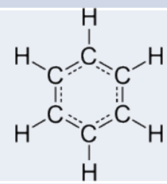
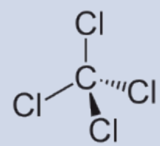
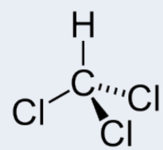
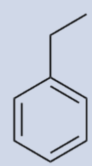
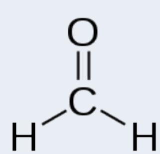
- Concentrations result from a wide variety of synthetic and natural products, and people and their activities
  - Highest concentrations tend to result from solvent application or use of certain personal care products, hobby materials, or cleaning agents

Mean VOC concentrations in U.S. residences



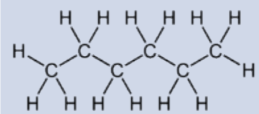
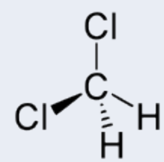
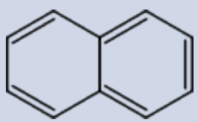
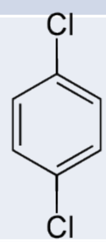
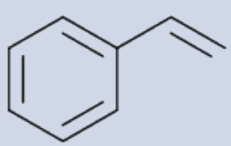
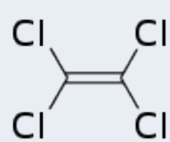
Logue et al. **2012** *EHP*

Hazardous VOCs found indoors

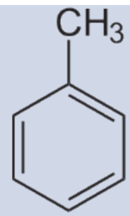
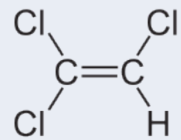
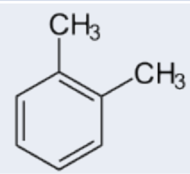
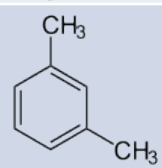
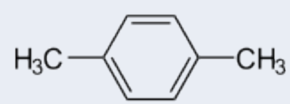
Compound	Formula	Structure	Categories of indoor sources
Acetaldehyde*	C_2H_4O		Floor materials, HVAC systems and components, machines, wood products
Benzene	C_6H_6		Furnishings, paints and coatings, wood products
Carbon tetrachloride	CCl_4		Pesticides
Chloroform	$CHCl_3$		Furnishings, pesticides
Ethylbenzene	$C_6H_5CH_2CH_3$		Floor materials, insulation products, machines, paints and coatings
Formaldehyde*	CH_2O		Cabinetry, floor materials, furnishings, indoor reactions, insulation products, paints and coatings, space heating and cooking equipment, wall and ceiling materials, wood products

*Also classified as aldehydes

Hazardous VOCs found indoors

Compound	Formula	Structure	Categories of indoor sources
Hexane	C_6H_{14}		Floor materials, furnishings, paints and coatings, wood products
Methylene chloride	CH_2Cl_2		Furnishings
Naphthalene	$C_{10}H_8$		Pesticides (moth crystals)
p-dichlorobenzene	$C_6H_4Cl_2$		Pesticides, floor materials
Styrene	C_8H_8		Cabinetry, floor materials, insulation products, machines, paints and coatings, wood products
Tetrachloroethylene	C_2Cl_4		Caulks and sealants

Hazardous VOCs found indoors

Compound	Formula	Structure	Categories of indoor sources
Toluene	C_7H_8		Adhesives, caulks and sealants, floor materials, furnishings, machines, paints and coatings, wall and ceiling materials, wood products
Trichloroethylene	C_2HCl_3		Furnishings
Xylenes (*o*, *m*, *p*)			
o-xylene (1,2-dimethylbenzne)	C_8H_{10}		
m-xylene (1,3-dimethylbenzne)	$C_6H_4(CH_3)_2$		Floor materials, furnishings, machines, paints and coatings, wall and ceiling materials
p-xylene (1,4-dimethylbenzne)	$C_6H_4C_2H_6$		

VOCs found indoors

- Many other VOCs also found indoors but not necessarily classified as hazardous
  - Can still engage in chemistry
  - Can still have other irritating effects

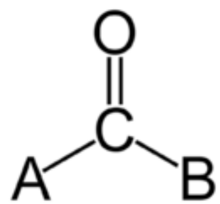
How do we know what is hazardous and what is not?

TOXNET: Toxicology Data Network
http://toxnet.nlm.nih.gov/

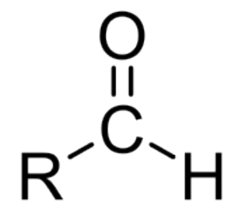
*Look for HSDB in particular

Organic gases: Aldehydes

- Aldehydes belong to a class of organic compounds called carbonyls
  - Carbonyls are composed of a carbon atom double-bonded to an oxygen atom (C=O)



General carbonyl



General aldehyde (functional group)

- Many aldehydes are potent sensory (mucus membrane) irritants
  - Some are skin sensitizers, and a few may be human carcinogens
  - Reactive and soluble

Organic gases: Aldehydes

Compound	Formula	Categories of sources
Formaldehyde	CH_2O	Cabinetry, floor materials, furnishings, indoor reactions, insulation products, paints and coatings, space heating and cooking equipment, wall and ceiling materials, wood products (and cigarette smoke)
Acetaldehyde	C_2H_4O	Floor materials, HVAC systems and components, machines, wood products, auto and diesel exhaust
Acrolein	C_3H_4O	Cooking of oils and fats, wood combustion, cigarette smoke, auto and diesel exhaust
Crotonaldehyde	C_4H_6O	Cooking of oils
Benzaldehyde	C_7H_6O	Cooking (almond flavor)

Aldehydes are also generated as secondary byproducts of reactions between ozone (O_3) and unsaturated hydrocarbons (VOCs) such as d-limonene, α-pinene, α-terpenine, styrene, and isoprene

Organic gases (and particle phase): SVOCs

- **Semi-volatile organic compounds** (**SVOCs**) are higher molecular weight VOCs
  - Usually exist partially in gas-phase and partially in particle-phase
  - Includes:
    - Polycyclic aromatic hydrocarbons (PAHs)
    - Phthalates
    - Pesticides
    - Brominated flame retardants (BFRs)

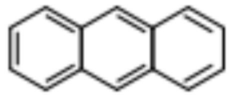
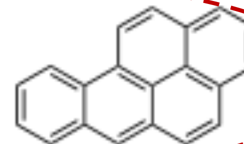
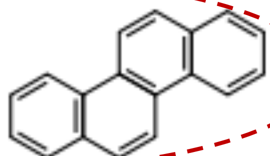
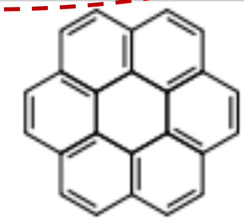
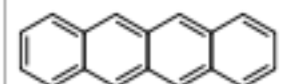
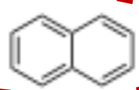
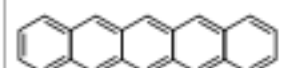
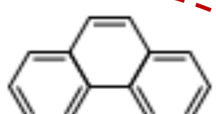
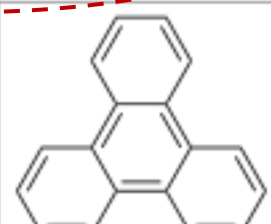
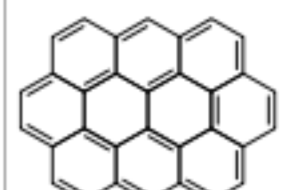
- PAHs are products of incomplete combustion
  - Typical health effect: carcinogenic
- Phthalates are plasticizers used in PVC resins
  - Typical health effect: hormone signaling systems disruptors

Organic gases (and particle phase): SVOCs

- PAHs
  - Multiple benzene rings that share a pair of carbon atoms
  - Three- and four-ringed PAHs (smaller MW) are more volatile and typically exist in the gas-phase
  - Larger five- to seven-ring PAHs occur in the particulate phase

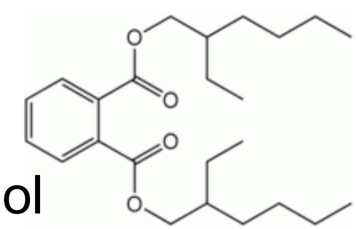
- Major PAH sources
  - Emissions from combustion of wood or other fuel (e.g., kerosene), unvented gas appliances, ETS, and cooking, grilling, and frying
  - Major outdoor sources as well
  - Typically at ng/m^3 levels

Organic gases (and particle phase): PAHs

Chemical compound		Chemical compound	
Anthracene		Benzo[*a*]pyrene	
Chrysene		Coronene	
Corannulene		Tetracene	
Naphthalene		Pentacene	
Phenanthrene		Pyrene	
Triphenylene		Ovalene	

Organic gases (and particle phase): SVOCs

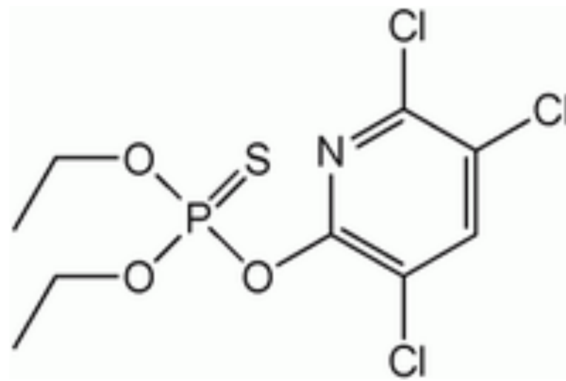
- Phthalates
  - Plasticizers in polyvinyl chloride (PVC) resins used to make building materials and consumer products
    - Vinyl upholstery, shower curtains, food containers, toys, floor tiles, automobile interiors, lubricants, sealers, and adhesives
  - Much higher concentrations indoors than outdoors
    - Although typically at ng/m^3 levels
  - Particle and gas phases → relative fraction depends on MW
- Some common phthalates
  - Diethyl phthalate (DEP) | MW = 222 g/mol
  - Butyl benzyl phthalate (BBP or BBzP) | MW = 312 g/mol
  - Di(2-ethylhexyl) phthalate (DEHP) | MW = 390 g/mol



- Health effects (or at least *associations*)
  - Some cancer evidence; some endocrine disrupting evidence; others
    - e.g. reproductive effects, obesity, diabetes, and allergies

Organic gases (and particle phase): SVOCs

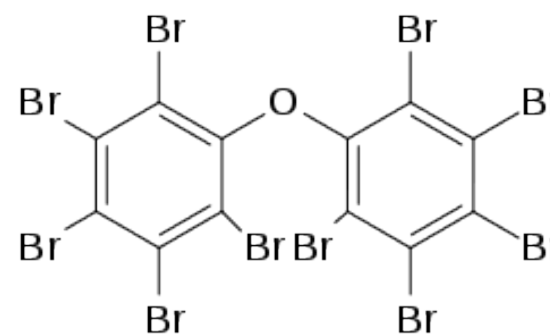
- Pesticides
  - Common pesticides (found in more than ~50% of homes) include:
    - Chlorpyrifos
    - Propoxur
    - *o*-phenylphenol
    - Diazinon
    - Dieldrin
    - Chlordane



- Health effects
  - Acute poisoning
  - Chronic and long-term effects
    - Cancers (many)
    - Neurological development, including Parkinson's
    - Reproductive effects, including birth defects and fetal death
    - Fertility reductions

Organic gases (and particle phase): SVOCs

- Brominated flame retardants (BFRs)
  - Organobromide compounds that inhibit combustion
- Several groups:
  - Polybrominated diphenyl ethers (PBDEs)
    - DecaBDE
    - OctaBDE (not manufactured anymore)
    - PentaBDE (not manufactured anymore)
  - Polybrominated biphenyl (PBB)
    - Also not manufactured anymore



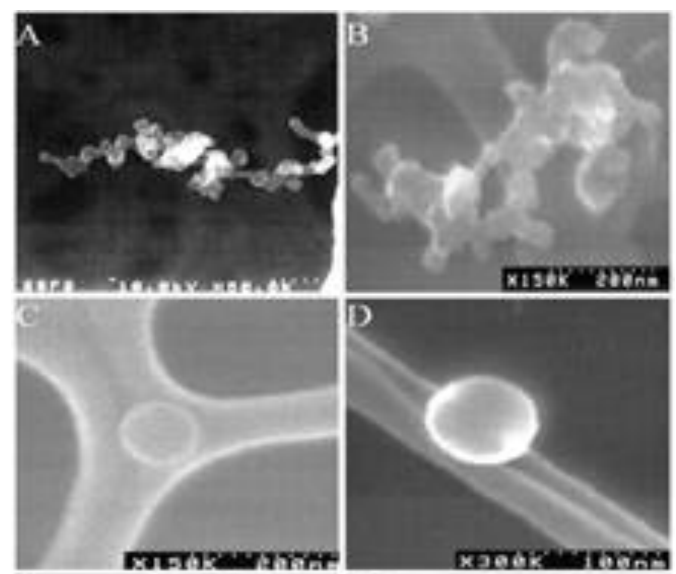
- Health effects (or associations)
  - More endocrine (hormone) disrupting effects
    - Estrogen and thyroid hormones
    - Reproductive and metabolism effects

Particulate matter (PM)

- Particulate matter (PM) is its own class of pollutant
  - PM consists of a mixture of solid particles and liquid droplets suspended in air
  - Primary emissions are emitted directly by sources
    - Outdoors: Industry, construction, roads, smokestacks, fires, vehicles
    - Indoors: Smoking, cooking, resuspension of dust, transport from outdoors
  - Secondary emissions are formed in atmospheric reactions

- Health effects
  - Respiratory, cardiovascular

- Visibility effects outdoors



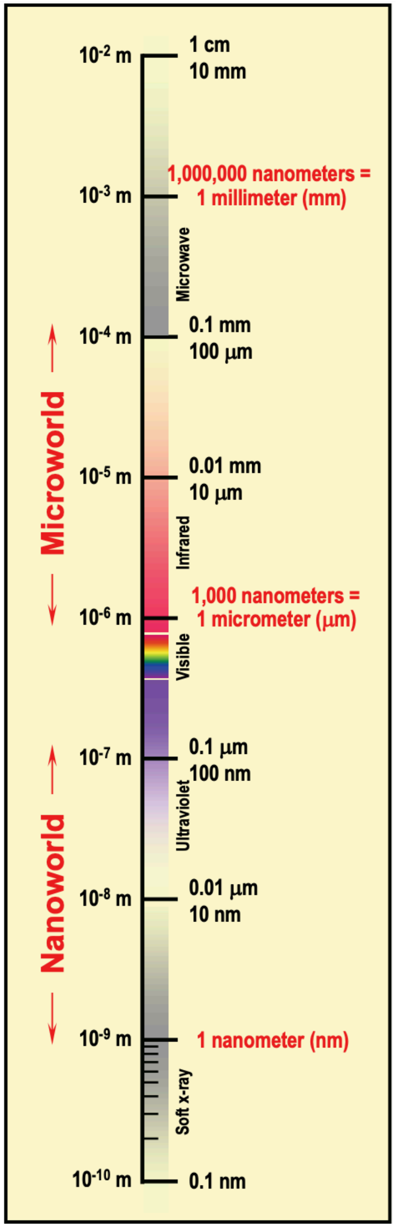
http://www.aerosols.wustl.edu/education/AerosolBasics/What%20is%20an%20aerosol.htm

Particle sizes

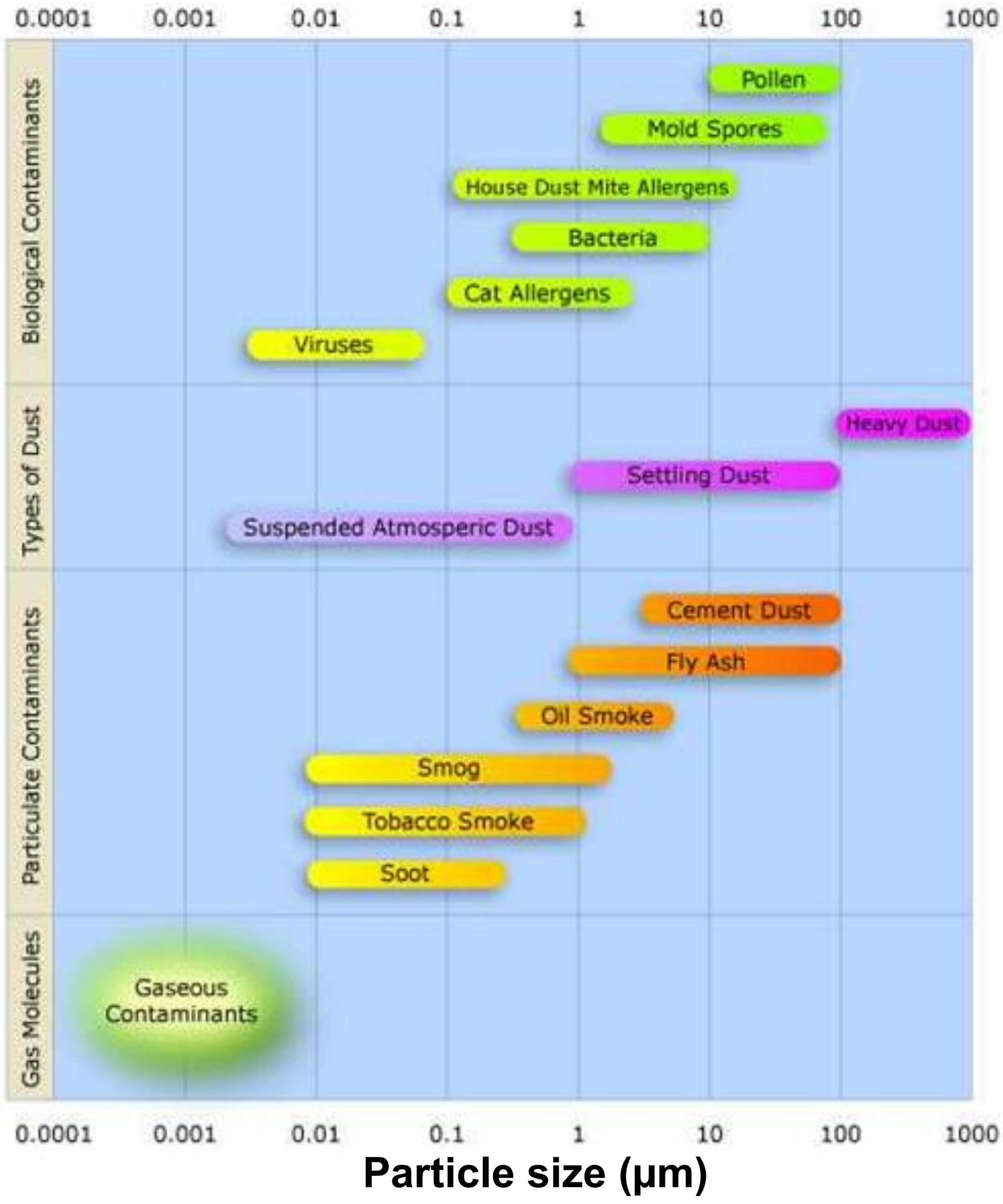
- Usually referring to a characteristic dimension
  - Diameter for sphere
  - Diameter for fibers (e.g. asbestos)
  - Equivalent diameter for non-spherical

- Micrometer (µm)
  - 1 µm = 10^{-6} m

- Nanometer (nm)
  - 1 nm = 10^{-9} m



Particle sizes



Particle sizes

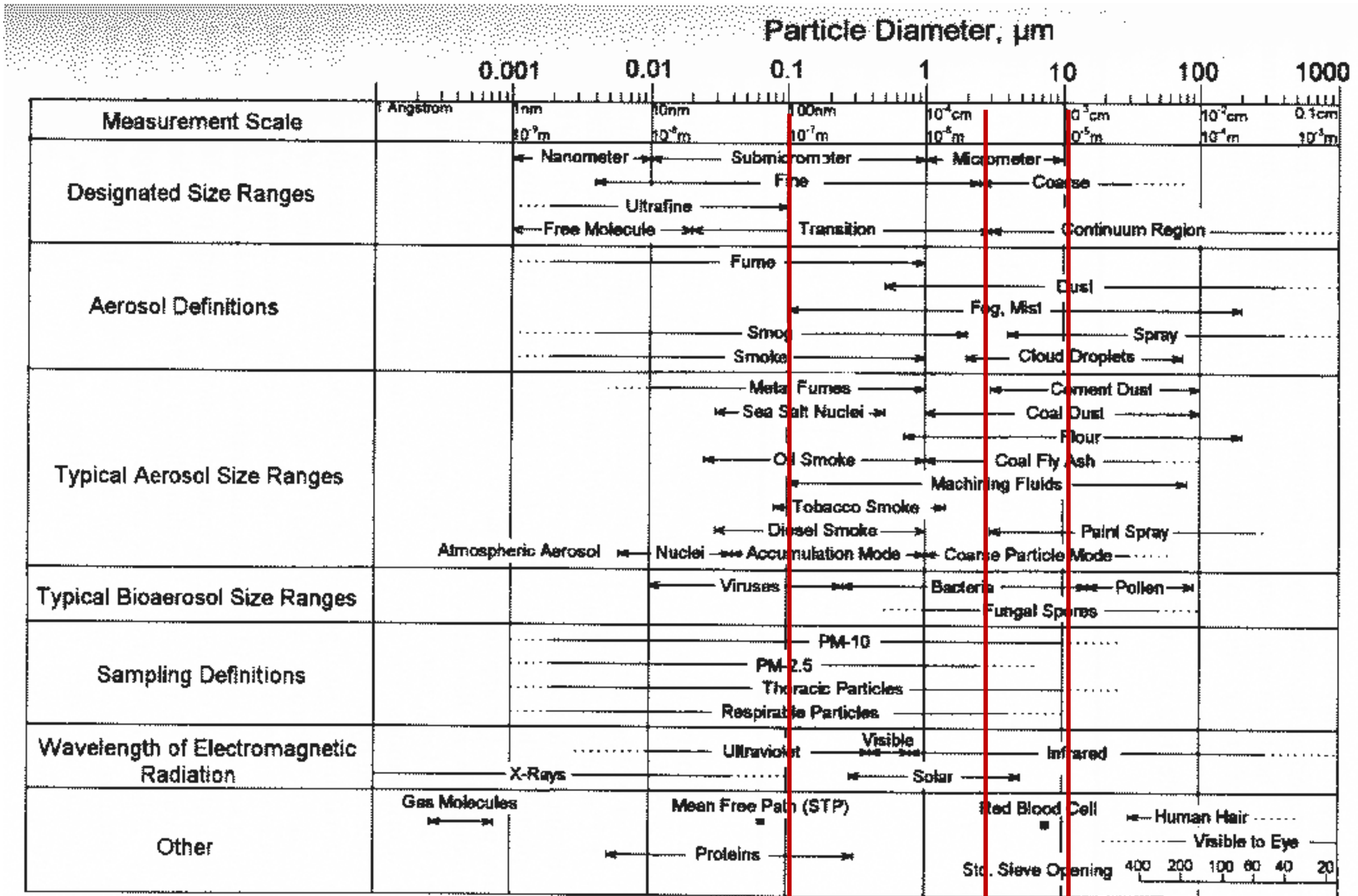
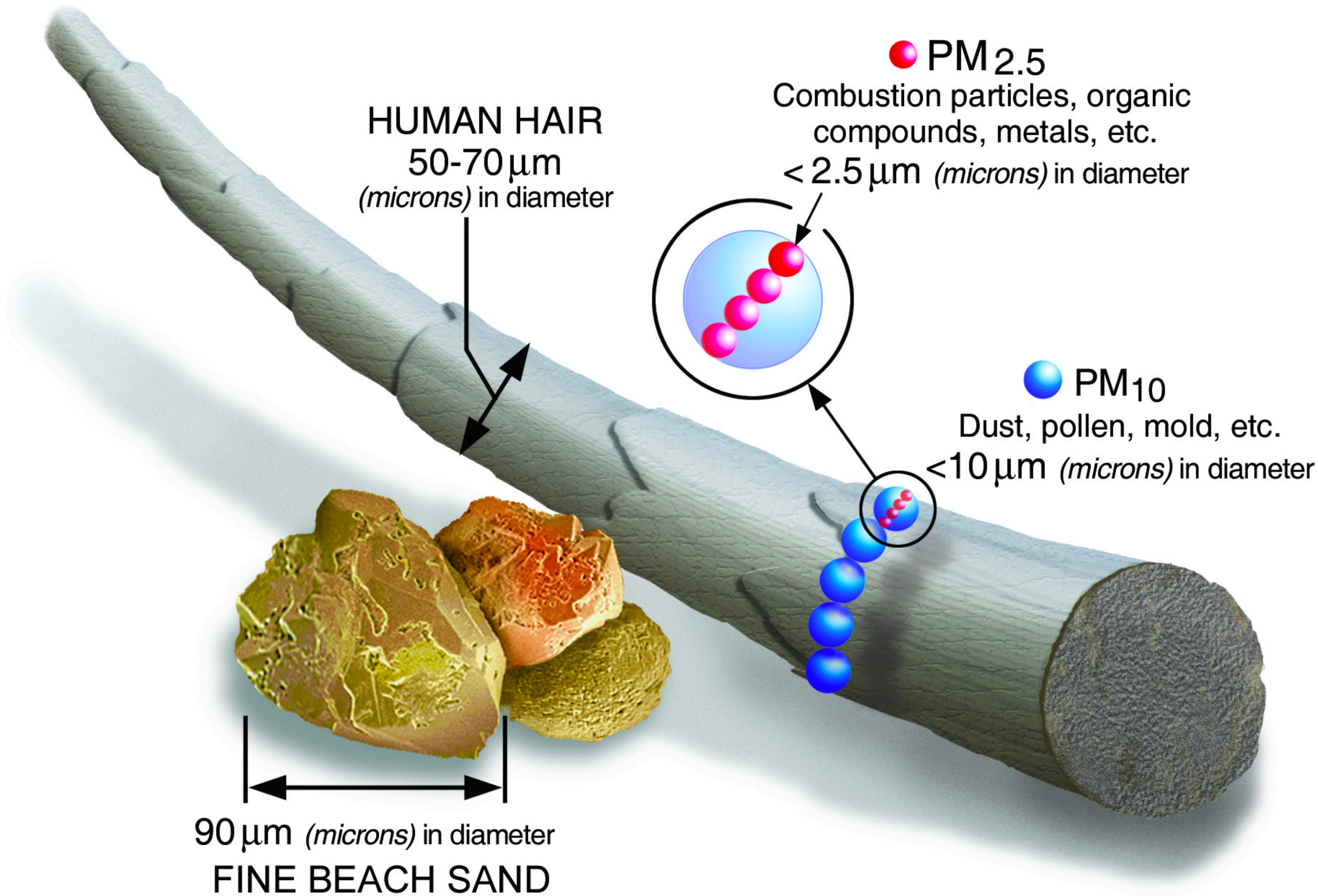


FIGURE 1.6 Particle size ranges and definitions for aerosols.

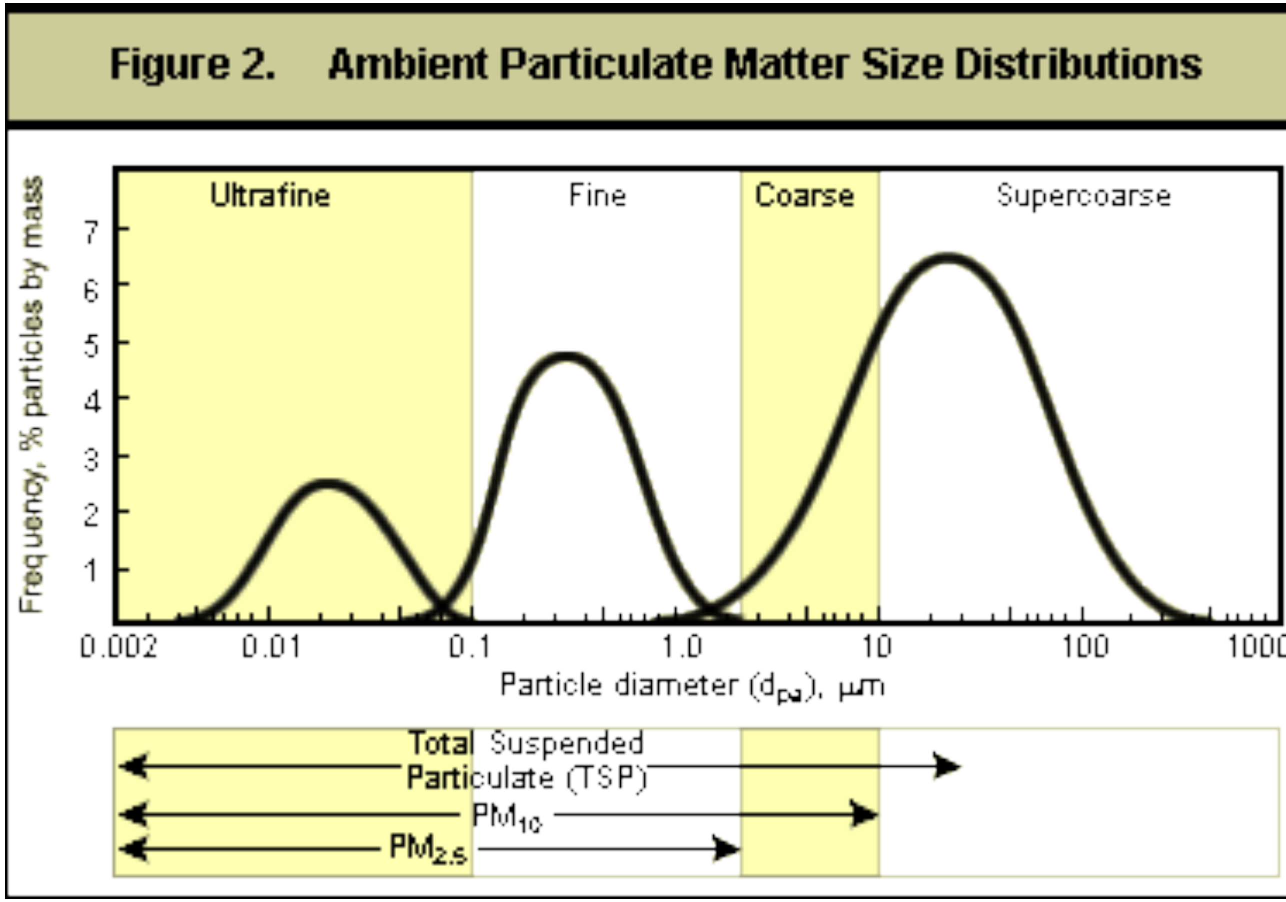
Hinds 1999

Particle sizes



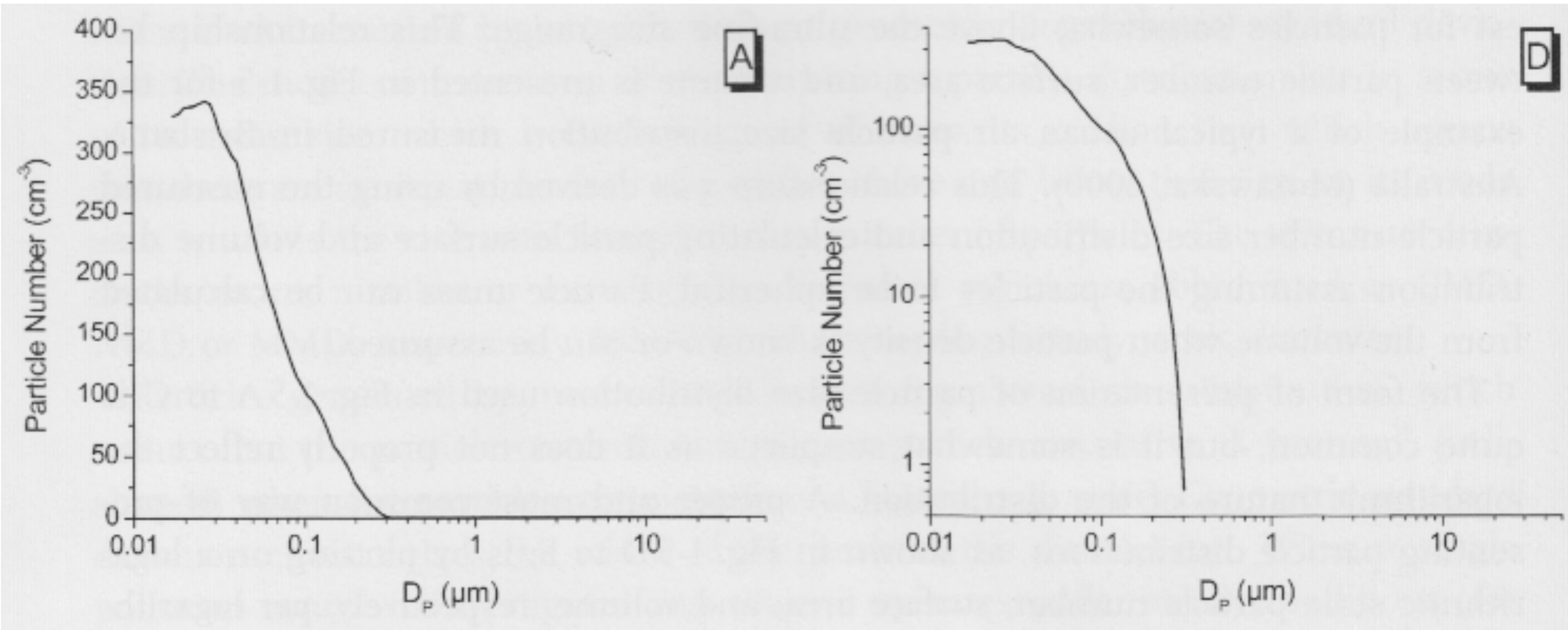
How are particles measured and reported?

- Number
  - #/cm^3
  - UFP <100 nm
- Surface area
  - cm^2/cm^3
- Volume
  - m^3/m^3
- Mass
  - μg/m^3
  - $PM_{2.5}$
  - PM_{10}
  - $PM_{2.5\text{-}10}$
  - TSP
  - RSP



Typical particle size distributions

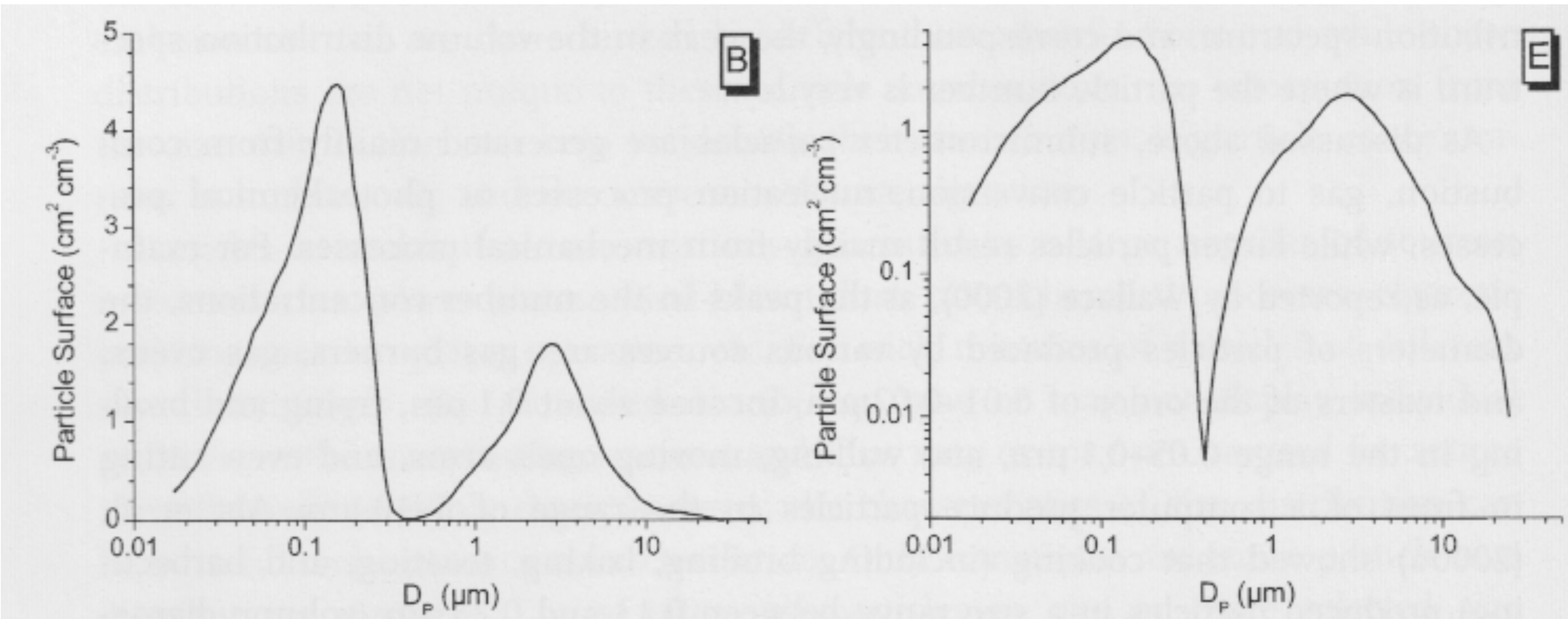
- Number distributions: scales with diameter (d_p)



Morawska and Salthammer 2003 *Indoor Environment*

Typical particle size distributions

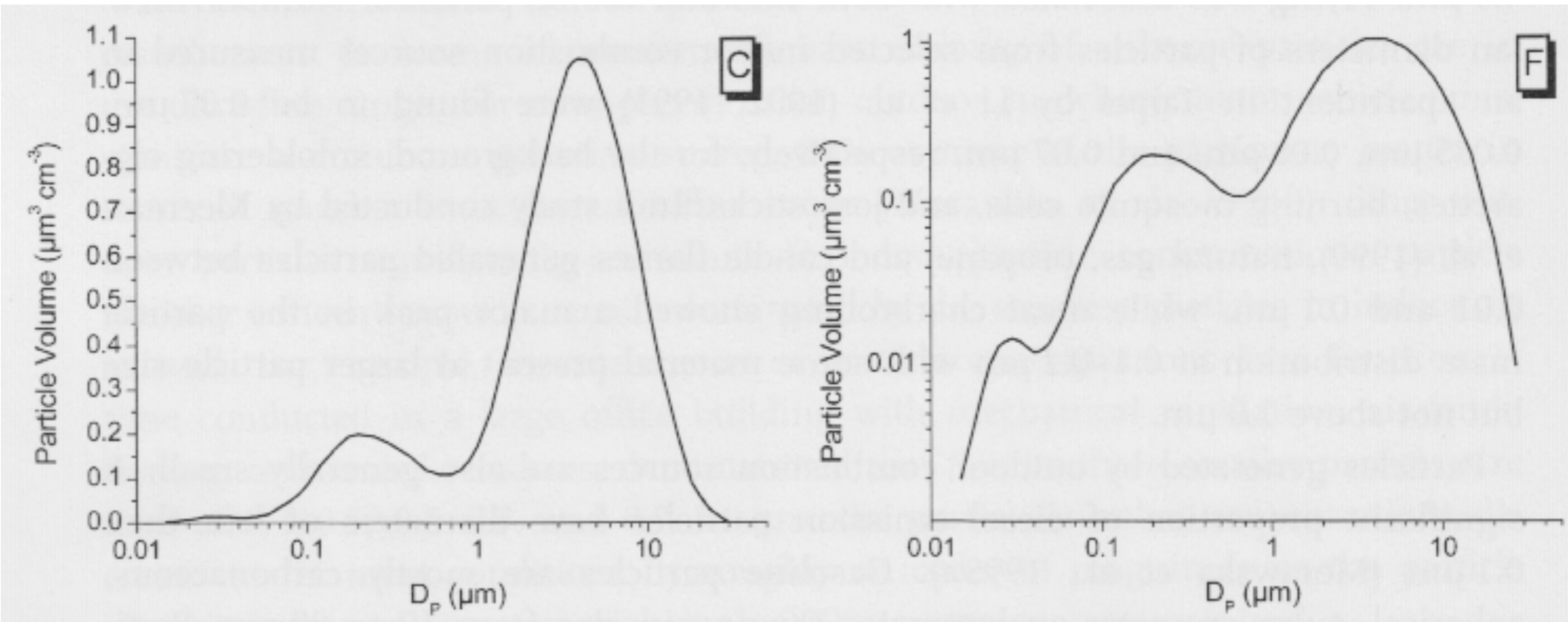
- Surface area distributions: scales with diameter^2 (d_p^2)



Morawska and Salthammer 2003 *Indoor Environment*

Typical particle size distributions

- Volume distributions: scales with diameter^3 (d_p^3)



Morawska and Salthammer 2003 *Indoor Environment*

Particulate matter: ETS

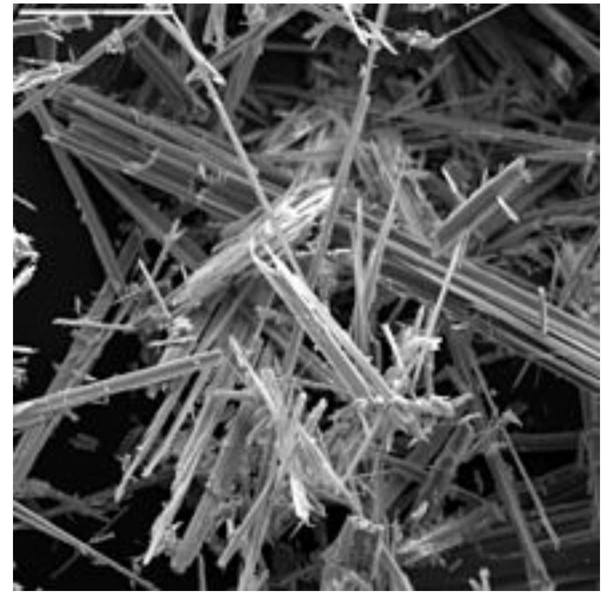
- Environmental tobacco smoke (ETS) is a combination of many of the pollutants we've already mentioned
  - Particles, VOCs, SVOCs, aldehydes, inorganic gases, and metals

- Health effects of involuntary smoking
  - Reduced fetal growth
  - Sudden infant death syndrome
  - Cancer
  - Lower respiratory tract illness
  - Asthma
  - Reduced lung growth
  - Heart disease
  - Odor and irritation

Particulate matter: Fibers/asbestos

- Fibrous products are ubiquitous in buildings
  - Insulating products, ceiling tiles, wall panels, duct linings, etc.
  - L:W ratios of 3:1 or more
- Prior to 1980, these were made with asbestos fibers
  - Asbestos refers to fibrous silicate materials
- Now they are typically cellulose fibers and other less harmful materials
  - Old buildings will still contain asbestos

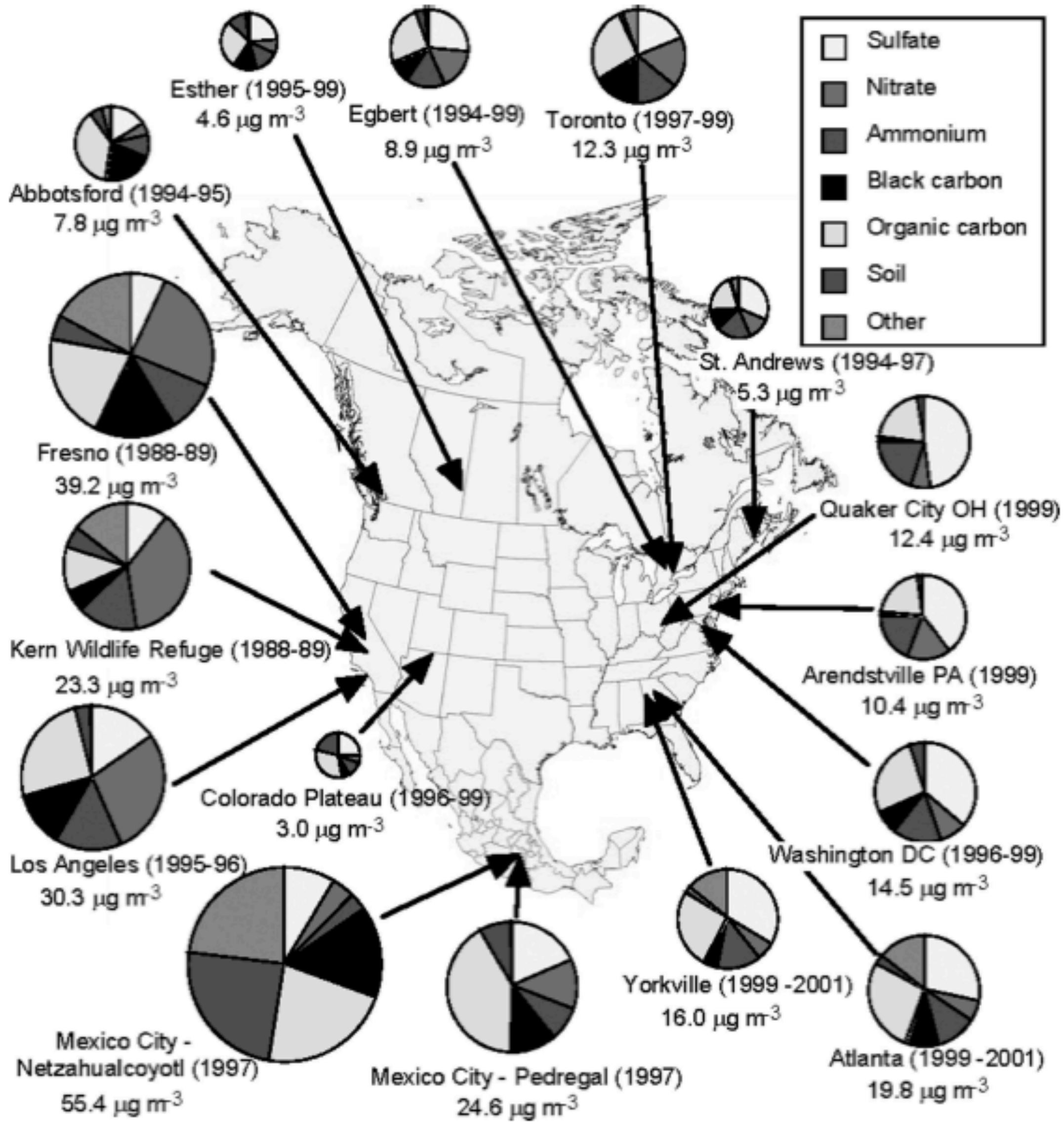
- Health effects
  - Lung scarring and fibrosis
  - Increased incidences of lung cancer



Particulate matter: Biological

- Biological sampling in buildings is an ongoing field of research
  - New analytical techniques are advancing capabilities (DNA)
- Most of the previous biological work involves:
  - Endotoxin: inflammatory substances present in some bacteria
  - Allergens
    - From insects: mice, cats, dogs, cockroaches, dust mites
    - From plants: pollen, certain fungi
      - Existing as complete spores or attached to other aerosols
  - Fungi/molds
    - Can grow on building substrates with the right T/RH/light conditions
  - Viruses and bacterial pathogens
    - Influenza, rhinovirus, tuberculosis, legionella, etc. ← Novel coronavirus?
- New sampling techniques focus on the many organisms that are probably harmless, potentially even *protective*

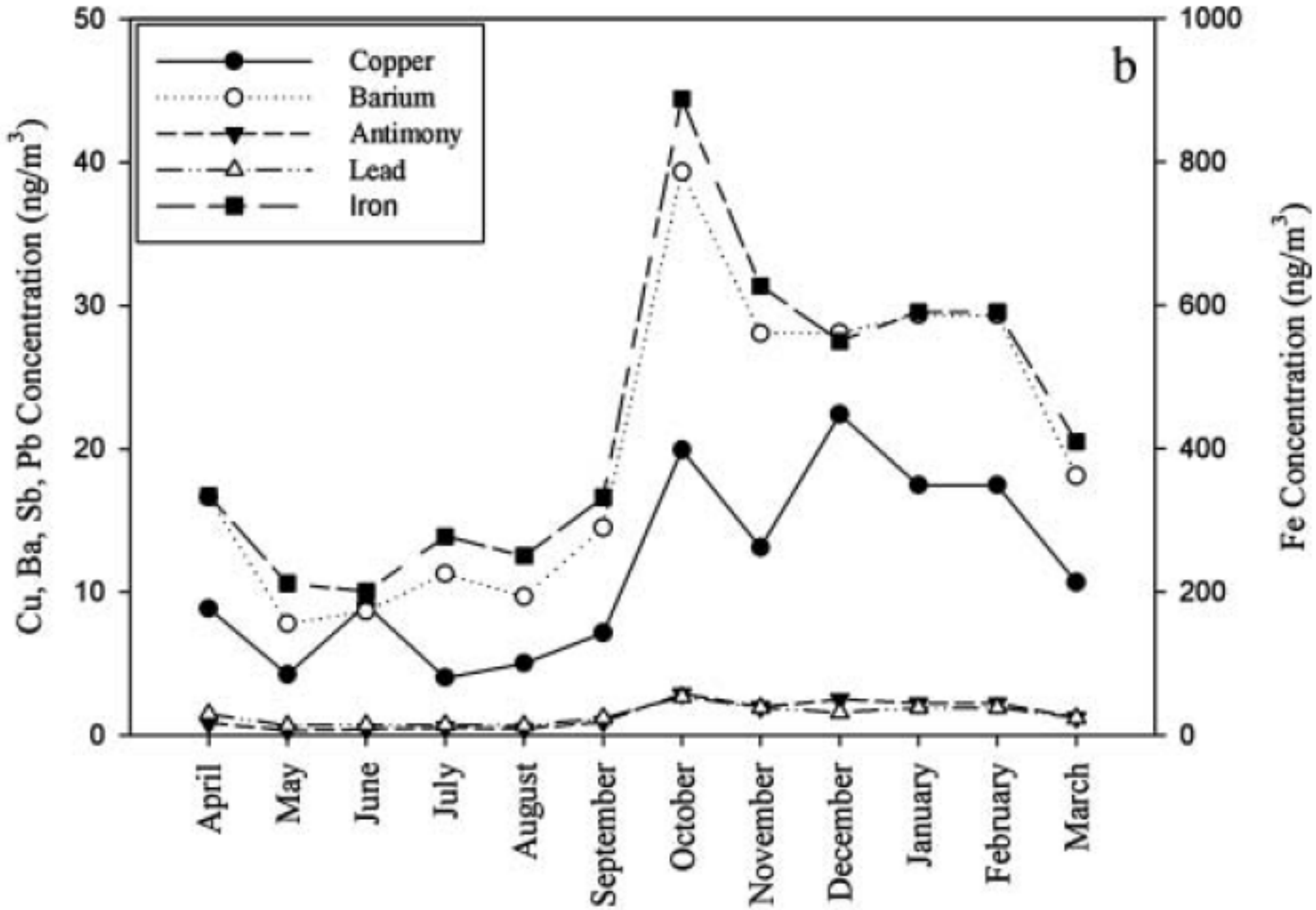
Chemical composition of PM



Davidson 2005 *Aerosol Sci Technol*

Particulate matter: Metals

- Particle-bound metals



Pakbin et al., 2011 *Aerosol Sci Technol*

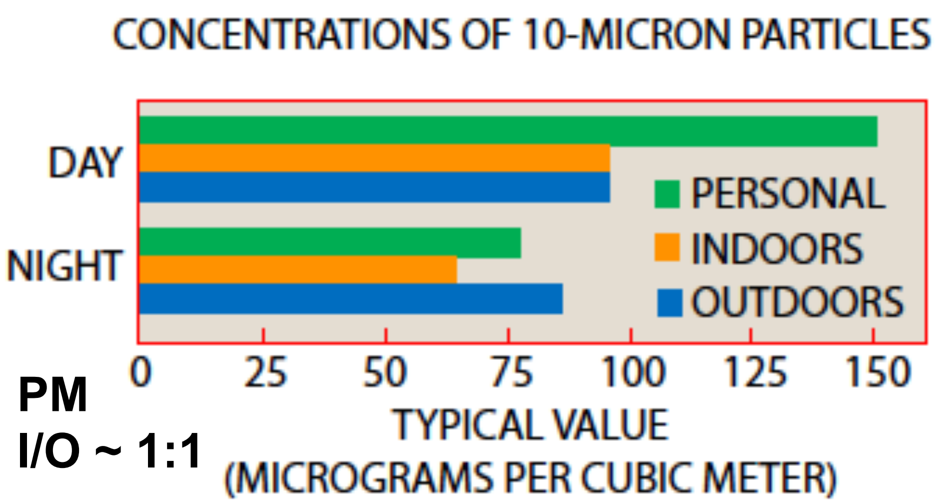
For many pollutants: Personal > Indoor > Outdoor

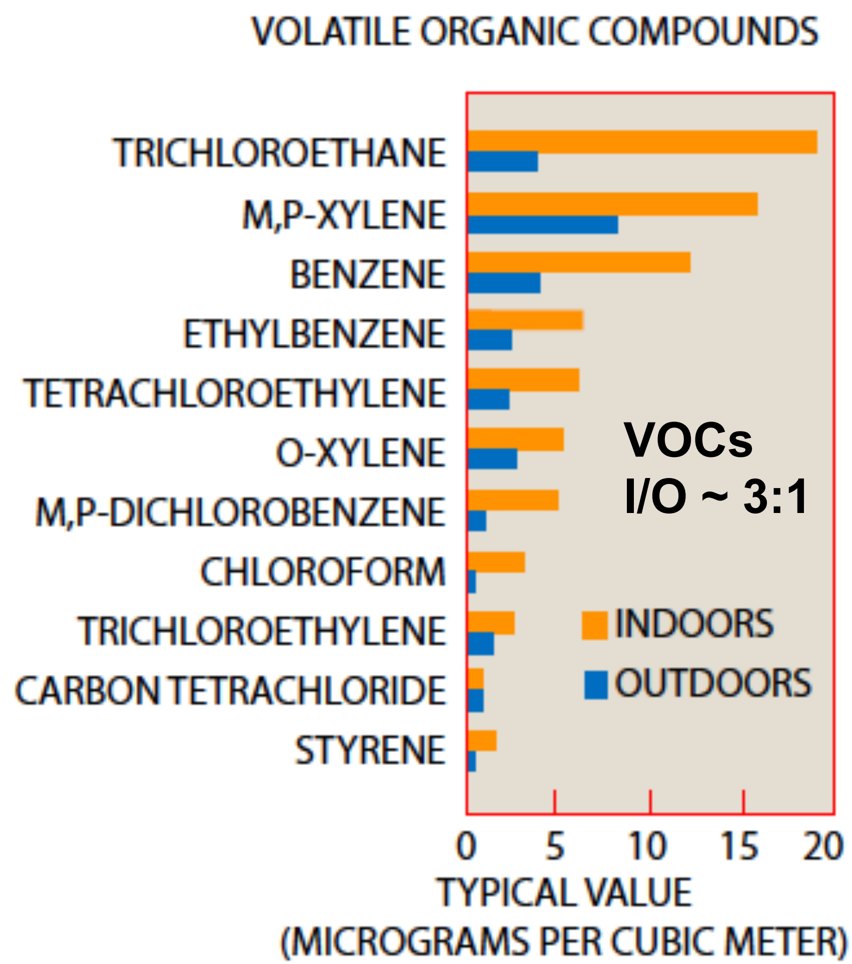
Everyday Exposure to Toxic Pollutants

Environmental regulations have improved the quality of outdoor air. But problems that persist indoors have received too little attention

by Wayne R. Ott and John W. Roberts

SCIENTIFIC AMERICAN February 1998





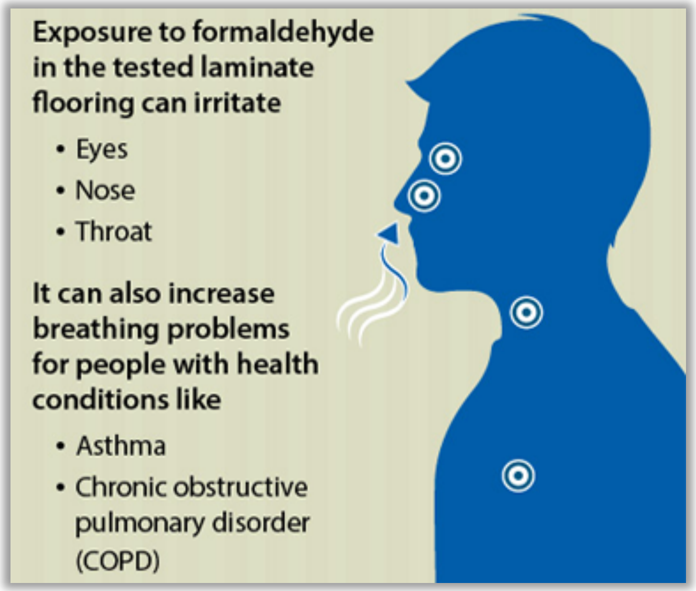
INDOOR AIR AND HEALTH

Indoor pollutant exposures and health

Formaldehyde: a sensory irritant and known human carcinogen (IARC Group 1)

Formaldehyde and Other Volatile Organic Chemical Emissions in Four FEMA Temporary Housing Units

Maddalena et al. **2009** *Environ Sci Technol*



Formaldehyde in the Indoor Environment

Salthammer et al. **2010** *Chem Rev*

Emission Rates of Formaldehyde from Materials and Consumer Products Found in California Homes

Kelly et al. **1999** *Environ Sci Technol*

Indoor pollutant exposures and health

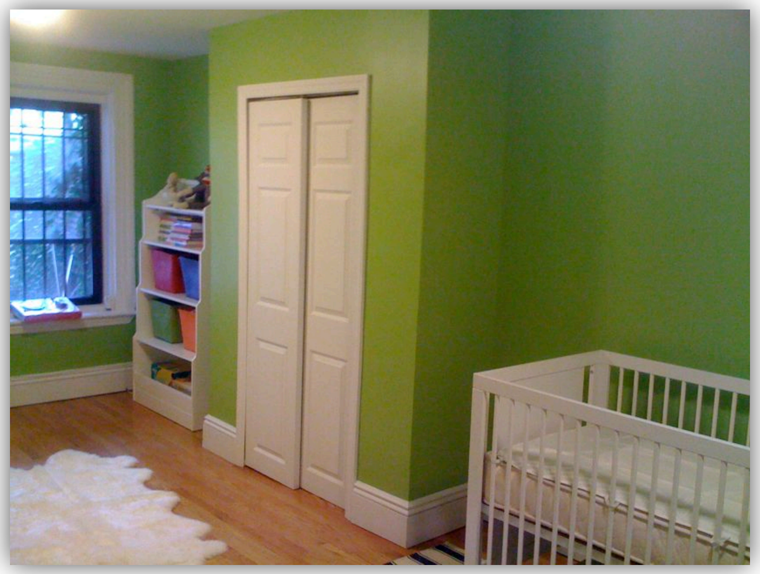
NO_x, CO, ultrafine particles, some organics

Association between gas cooking and respiratory disease in children
Melia et al. **1977** *British Medical Journal*

Indoor Air Pollution and Asthma
Ostro et al. **1994** *Am J Respir Crit Care Med*

Respiratory Symptoms in Children and Indoor Exposure to Nitrogen Dioxide and Gas Stoves
Garrett et al. **1998** *Am J Respir Crit Care Med*

VOCs

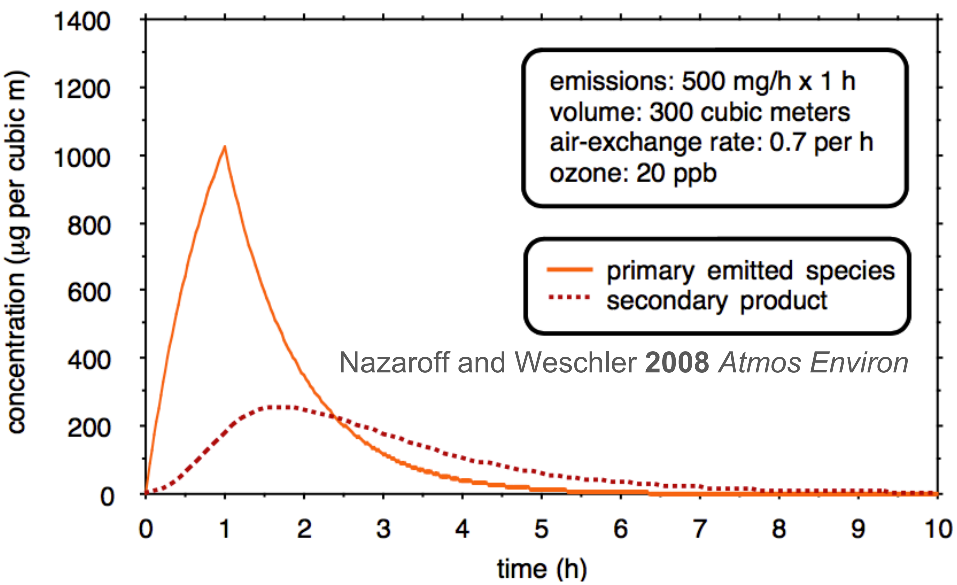


Association of domestic exposure to volatile organic compounds with asthma in young children
Rumchev et al. **2004** *Thorax*

Cancer Risk Disparities between Hispanic and Non-Hispanic White Populations: The Role of Exposure to Indoor Air Pollution
Hun et al. **2009** *Environ Health Perspect*

Indoor pollutant exposures and health

Primary & secondary VOCs + ultrafine particles



Nazaroff and Weschler **2008** *Atmos Environ*

Frequent use of chemical household products is associated with persistent wheezing in pre-school age children

Sherriff et al. **2005** *Thorax*

The Use of Household Cleaning Sprays and Adult Asthma

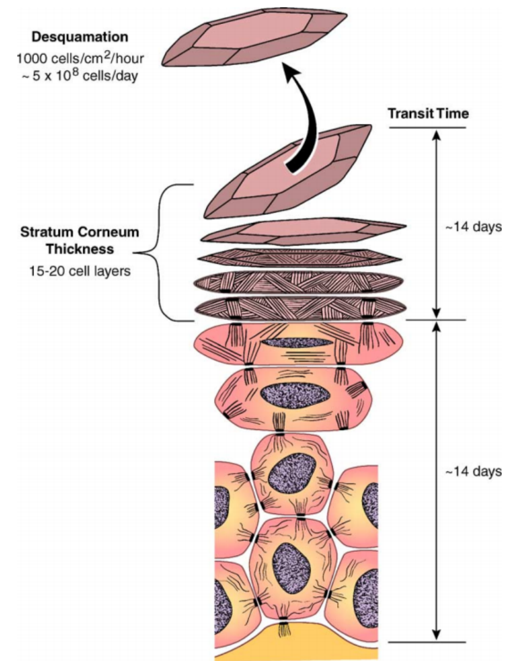
Zock et al. **2007** *Am J Respir Crit Care Med*

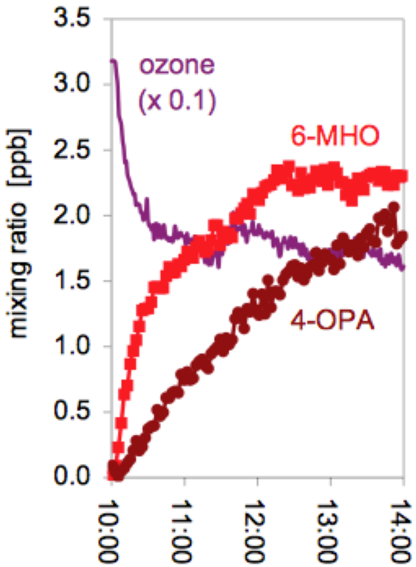
Indoor pollutant exposures and health

Epidermal desquamation

Milstone **2004** *J Dermatol Sci*

We shed our entire outer layer of skin every 2-4 weeks





Ozone + skin oils → organics + ultrafine particles

Reactions of ozone with human skin lipids: Sources of carbonyls, dicarbonyls, and hydroxycarbonyls in indoor air

Wisthaler and Weschler **2010** *Proc Nat Acad Sci*

Indoor pollutant exposures and health

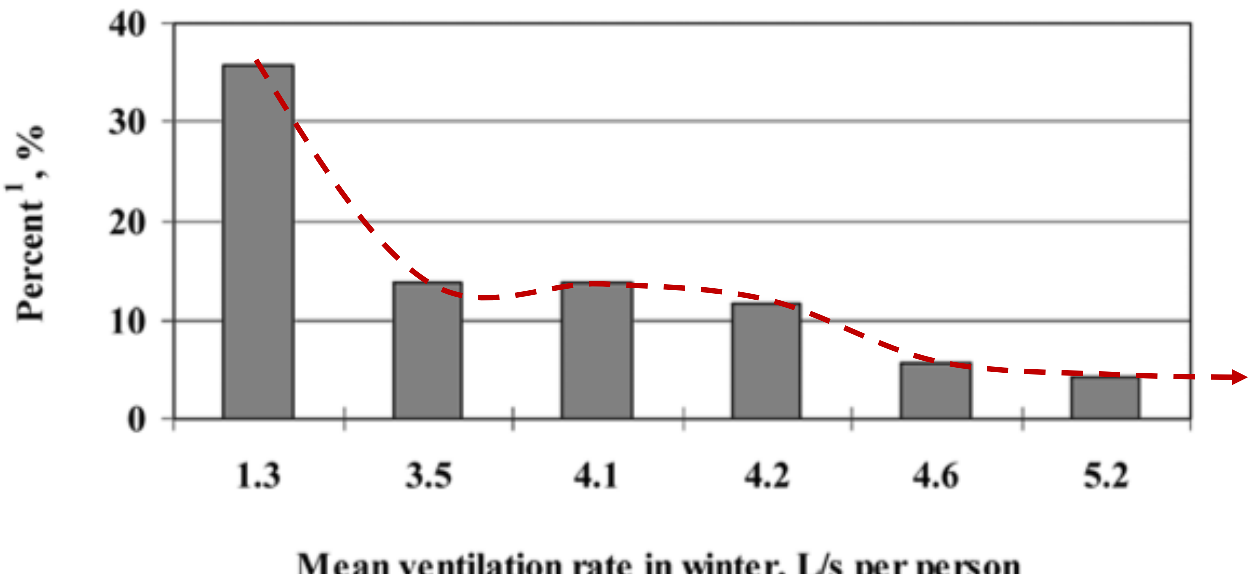
Infectious disease transmission

Evidence of Airborne Transmission of the Severe Acute Respiratory Syndrome Virus

Yu et al. **2004** *New Engl J Med*

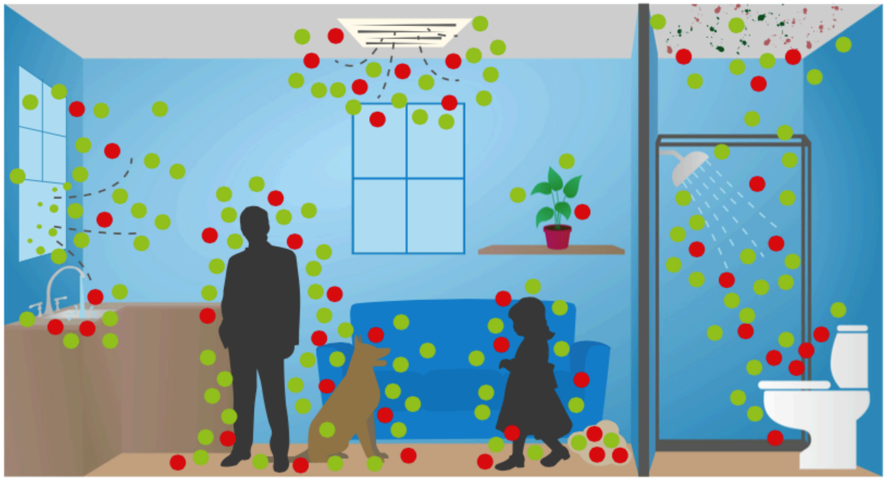
In China, Students in Crowded Dormitories with a Low Ventilation Rate Have More Common Colds: Evidence for Airborne Transmission

Sun et al. **2011** *PLoS ONE*

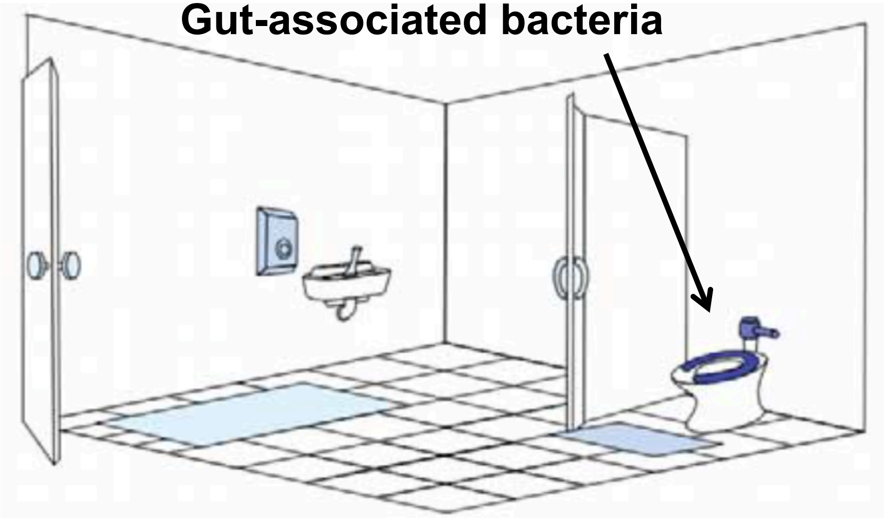


Indoor pollutant **exposures** and **health**

Indoor microbiome

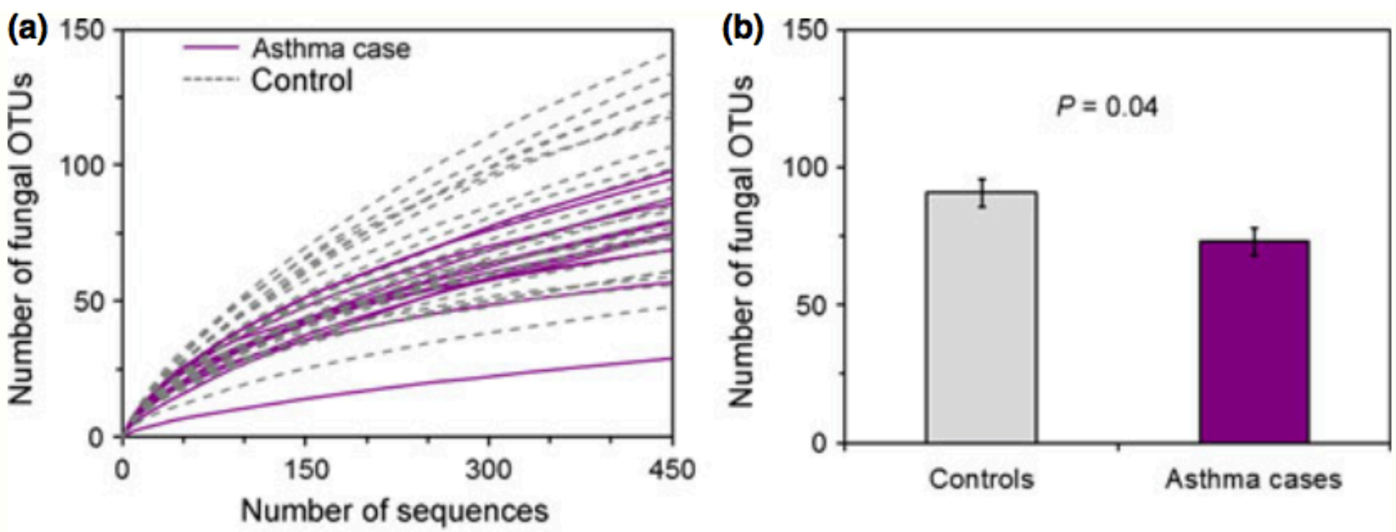


Prussin and Marr **2015** *Microbiome*



Flores et al. **2011** *PLoS ONE*

Exposure to microbial diversity (i.e., the '**right**' **microbes** and the '**right**' **time**) may be **beneficial** for health



Dannemiller et al. **2014** *Indoor Air*

Indoor pollutant **exposures** and **health**

Air cleaning

Health benefits of particle filtration

Fisk **2013** *Indoor Air*

Photo from M.S. Waring and J.A. Siegel

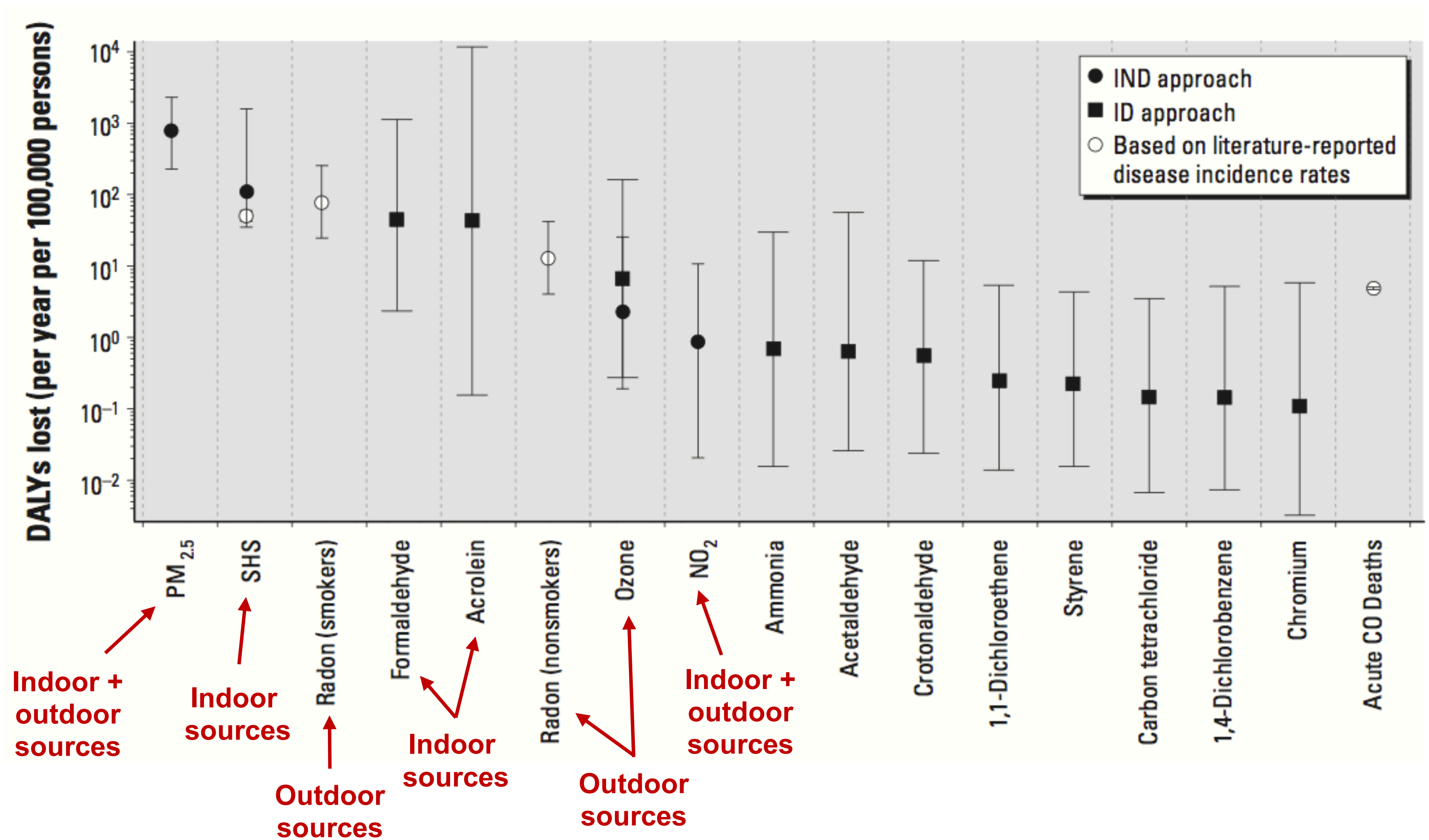
Air cleaners typically reduce indoor PM concentrations by ~50%

Documented health improvements with air cleaners include:

- Improvements in lung function in asthmatics
- Fewer asthma-related doctor visits
- Improvements in cardiovascular and pulmonary function

Indoor air pollution and health (in homes)

The **most harmful indoor air pollutants** inside residences:



Logue et al. **2012** *Environ Health Perspect* 120:216-222

Indoor air pollution and health

- Residential indoor air pollution is estimated to result in **5-14%** of the annual non-communicable, non-psychiatric **disease burden** in the U.S.
  - Excludes SHS and radon

Logue et al., *Environ. Health Perspect.* **2012**, 120, 216-222

- Cumulative lifetime **cancer risks** of **1-10** excess cases **per 10,000** people

Wallace et al., *Environ. Health Perspect.* **1991**, 95, 7-13
Sax et al., *Environ. Health Perspect.* **2006**, 114, 1558-1566
Hun et al., *Environ. Health Perspect.* **2009**, 117, 1925-1931

- Indoor air is a <u>**dominant**</u> environmental exposure!

Costs of poor IAQ/ventilation

- Health and productivity gains from better indoor environments in the U.S.
  - Fisk (2000) *Annual Reviews of Energy and Environment*
  - $6-14 billion from reduced respiratory disease
  - $1-4 billion from reduced allergies and asthma
  - $10-30 billion from reduced sick building syndrome
  - $20-160 billion from direct improvements in worker performance

- $37-208 billion annual savings possible
  - Fisk (2002) *ASHRAE Journal*

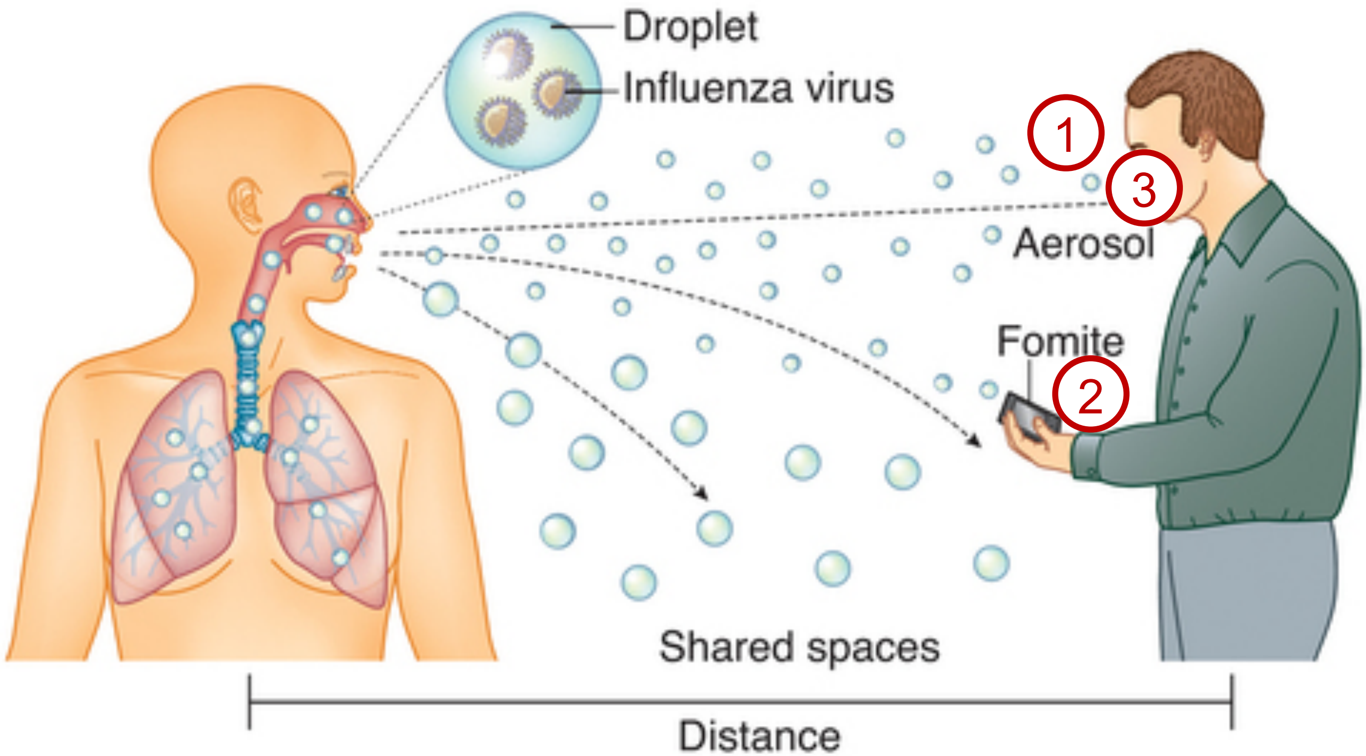
- Improved ventilation in a manufacturing facility led to reduced sick days
  - Milton et al. (2000) *Indoor Air*

- Increased ventilation led to slight increase (5%) in productivity
  - Wargocki et al. (2000) *Indoor Air*

Time for a detour….

INFECTIOUS DISEASE TRANSMISSION IN INDOOR ENVIRONMENTS

Primary modes of disease transmission



1. Direct contact with pathogen sources
2. Contact with contaminated object surfaces (“fomite”)
3. Inhalation of airborne infectious aerosols (often longer distances)

Lakdawala and Subbarao 2012 *Nature Medicine* 18:1468-1470

Diseases spread by airborne transmission

Disease	Organism	Clinical manifestations
Adenovirus	Adenovirus	Rhinitis, pharyngitis, malaise, rash, cough
Influenza*	Influenza virus	Fever, chills, malaise, headache, cough
Measles*	Rubeola virus	Fever, rash, malaise, conjunctivitis
Meningococcal disease	Neisseria meningitides	Fever, headache, vomiting, confusing
Mumps*	Mumps virus	Pain/swollen salivary glands
Pertussis	Bordetella pertussis	Malaise, cough, coryza, “whooping cough”
Parvovirus B19	Parvovirus B19	Rash, anemia, arthritis
Respiratory syncytial virus	RSV	Often asymptomatic
Rubella	Rubella virus	Fever, malaise, rash
Tuberculosis*	Mycobacterium species	Fever, weight loss, fatigue, night sweats, pulmonary disease
Varicella	Human herpes virus 3	Chicken pox

ASHRAE Position Document on Airborne Infectious Diseases (2014)

Evidence of airborne transmission

In China, Students in Crowded Dormitories with a Low Ventilation Rate Have More Common Colds: Evidence for Airborne Transmission

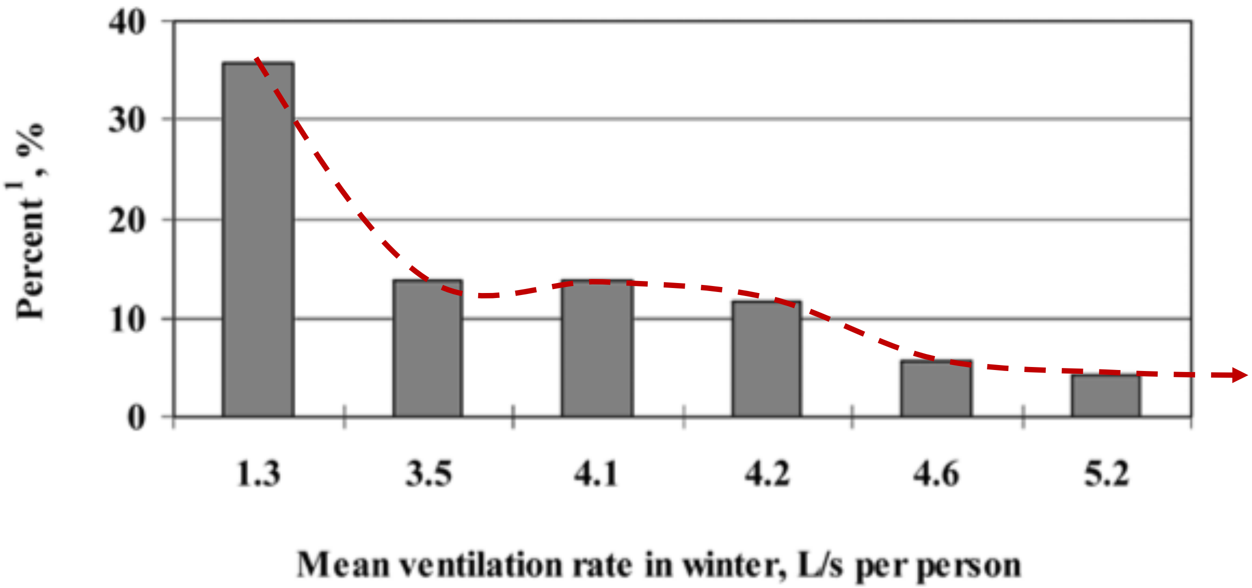


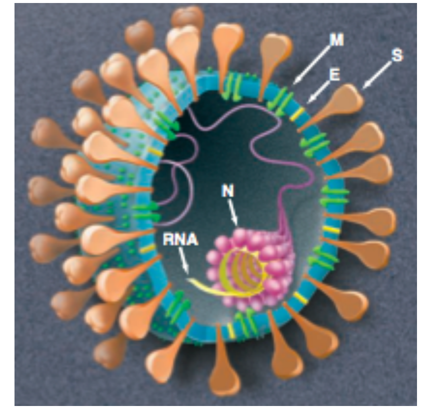
Figure 4. Associations between common cold infection rates and mean ventilation rate in winter in buildings constructed after year 1993. [1] Proportion of occupants with ≥6 common colds in the previous 12 months.

Sun et al. 2011 *PLoS ONE* 6:e27140

Evidence of airborne transmission

Severe acute respiratory syndrome (SARS)

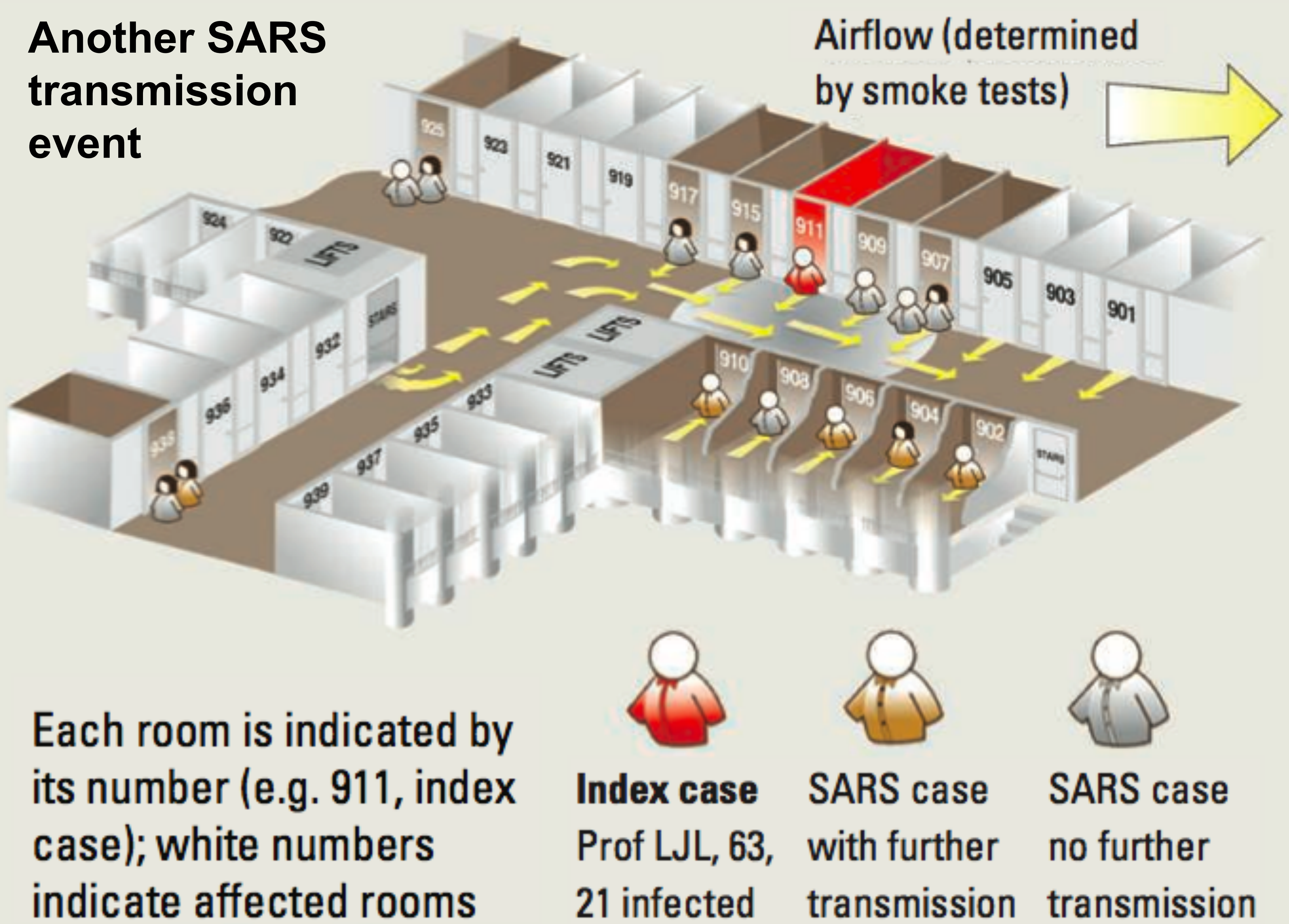
- 10 years ago: global outbreak of SARS
  - In 8 months, 8100 people in 29 countries were infected
    - 774 died
- In one high profile spreading event in Hong Kong, it became clear that transmission by airborne particles was substantial
  - One infected man suffering from diarrhea was linked to 300 SARS cases in one apartment building
  - Investigators concluded that diarrhea from the patient flushed into common plumbing system between units produced aerosols that traveled through piping and into other bathrooms
  - From there, both aerosol and subsequent person-to-person contact transmission likely occurred



SARS-CoV-1 virus

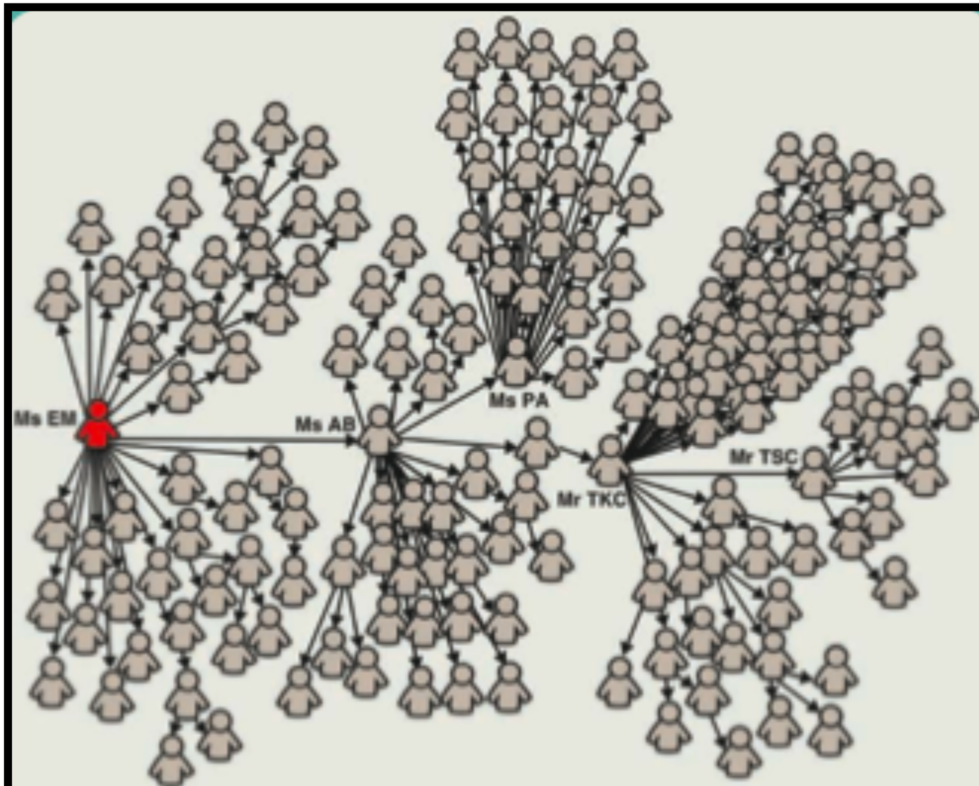
Normile 2013 *Science* 339:1269-1273

Another SARS transmission event



Normile 2013 *Science* 339:1269-1273

Importance of "super spreaders"

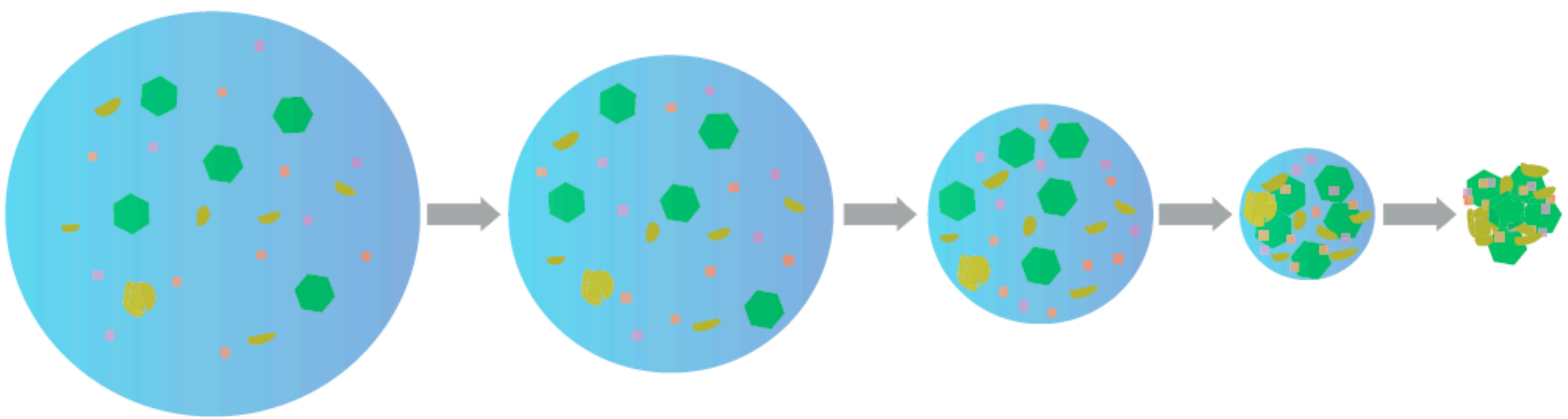


144 of Singapore's 206 SARS cases were traced to 5 individuals

Normile 2013 *Science* 339:1269-1273

“Spreading”: Expulsion of droplets

- When a person coughs, sneezes, speaks or even breaths:
  - Particles of liquid water, proteins, salts, and other matter are expelled
    - These are called droplets
    - These particles may contain smaller infectious organisms
  - Droplets rapidly deposit to surfaces and/or decrease in size as the surrounding liquid evaporates
    - Droplet nuclei remain after evaporation
    - Typically 40-50% smaller diameter (d_p) than original droplets
      - Still contain infectious organisms



Verreault et al. 2008 *Microbiology and Molecular Biology Reviews* 72:413-444; Nicas et al. 2005 *J Occup Environ Hyg* 2:143-154; Chen and Zhao 2010 *Indoor Air* 20:95-111; Yang and Marr 2011 *PLoS ONE* 6:e21481

Rapid evaporation of droplets brought to you by *Mythbusters*

Droplet evaporation is nearly instantaneous

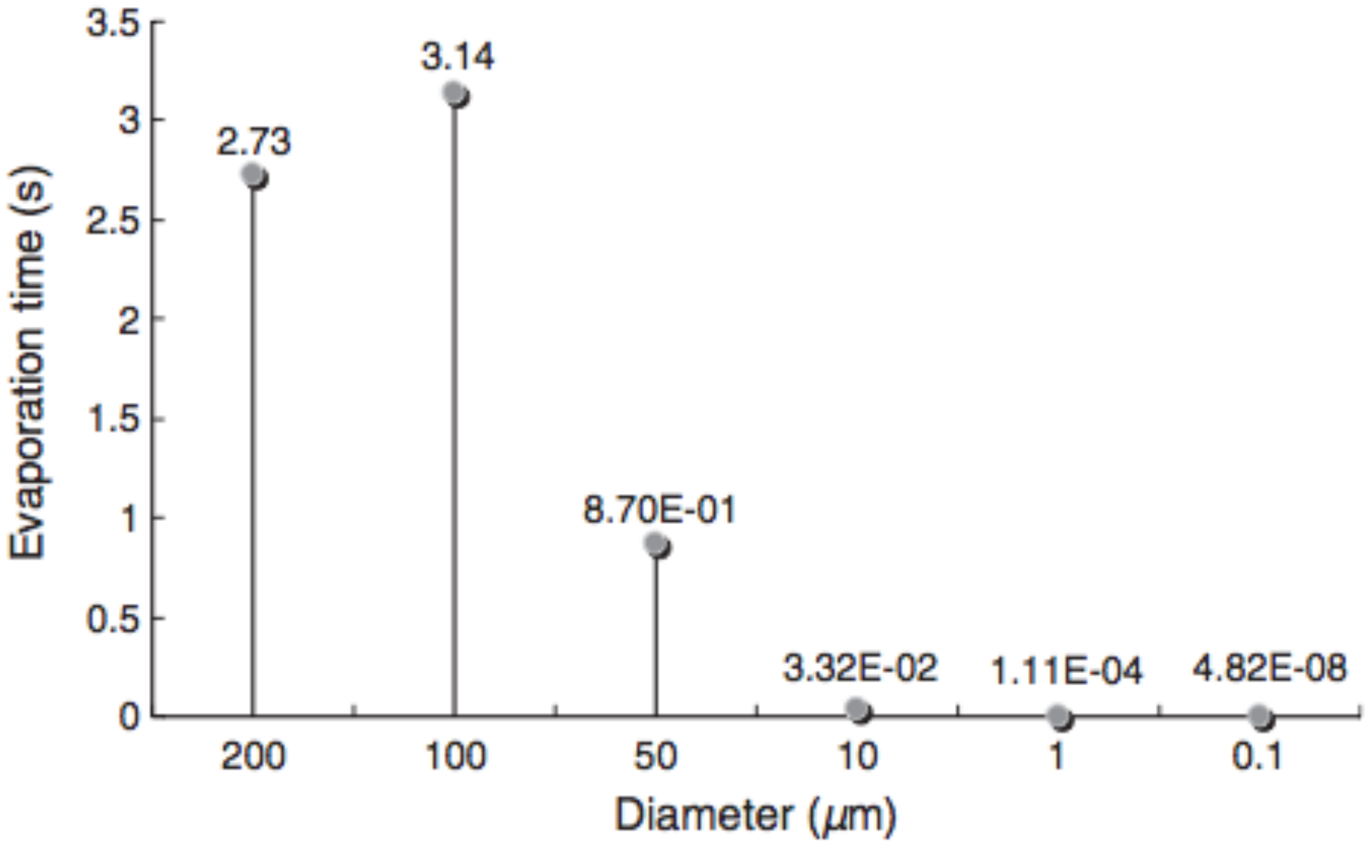


Fig. 5 The evaporation time of droplets with different diameters

Chen and Zhao 2010 *Indoor Air* 20:95-111

Airborne transmission and particle size

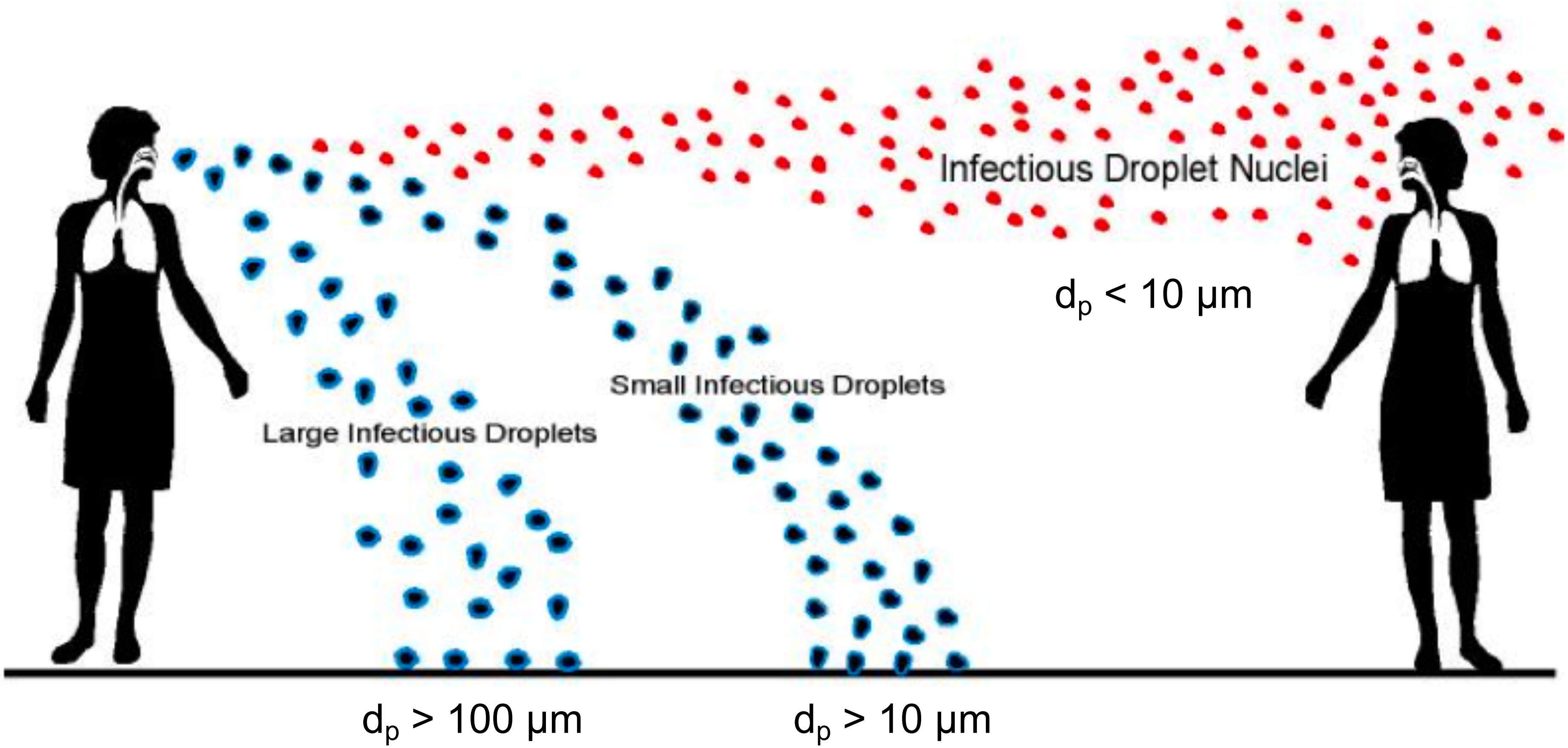
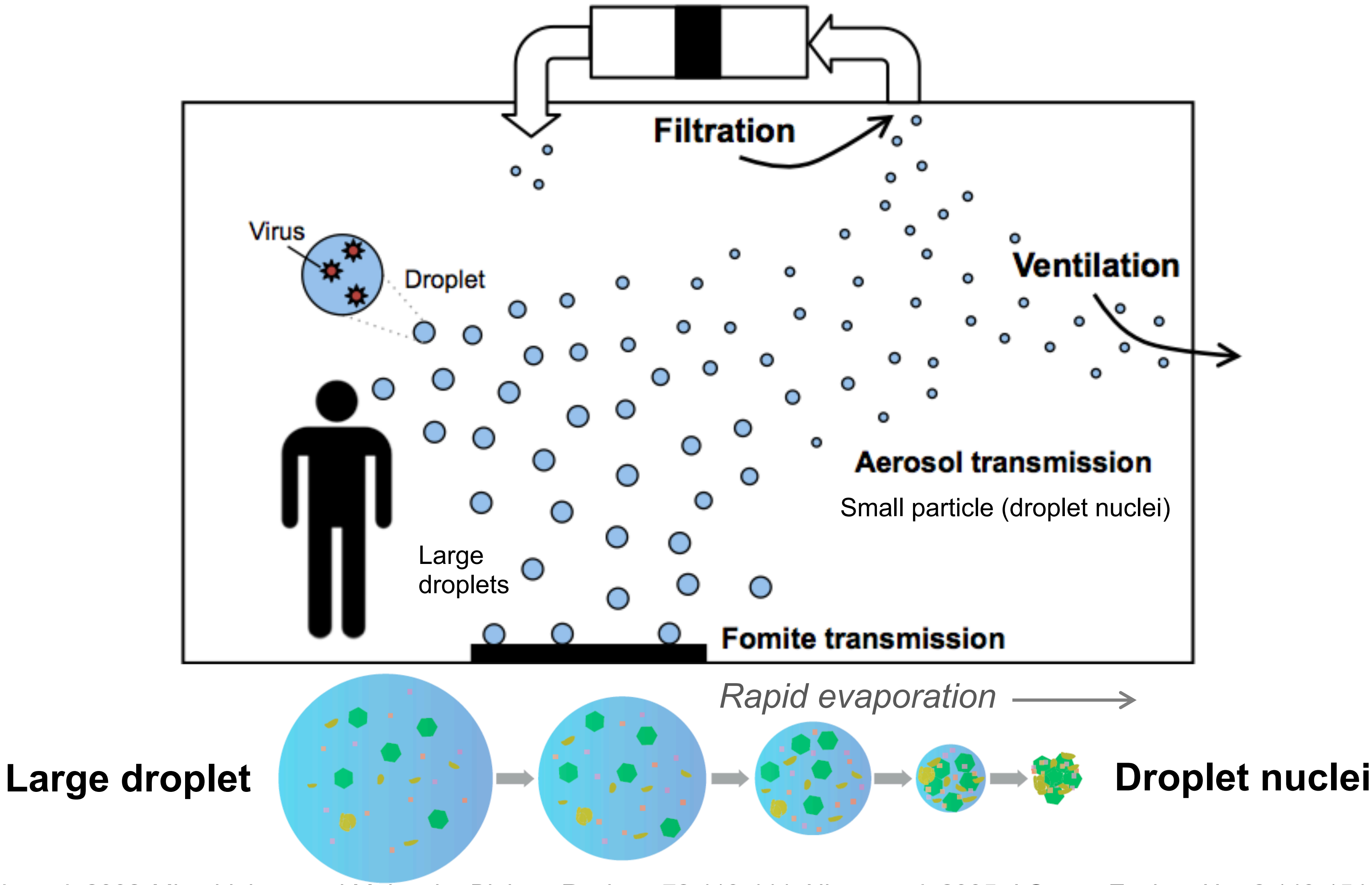


Figure taken directly from Welty 2009 presentation to FIC for IAQ, US EPA

Aerosol transmission: Particle size is crucial



Verreault et al. **2008** *Microbiology and Molecular Biology Reviews* 72:413-444; Nicas et al. **2005** *J Occup Environ Hyg* 2:143-154; Chen and Zhao **2010** *Indoor Air* 20:95-111; Yang and Marr **2011** *PLoS ONE* 6:e21481; Lakdawala and Subbarao **2012** *Nature Medicine* 18:1468-1470

Droplet nuclei can mix rapidly

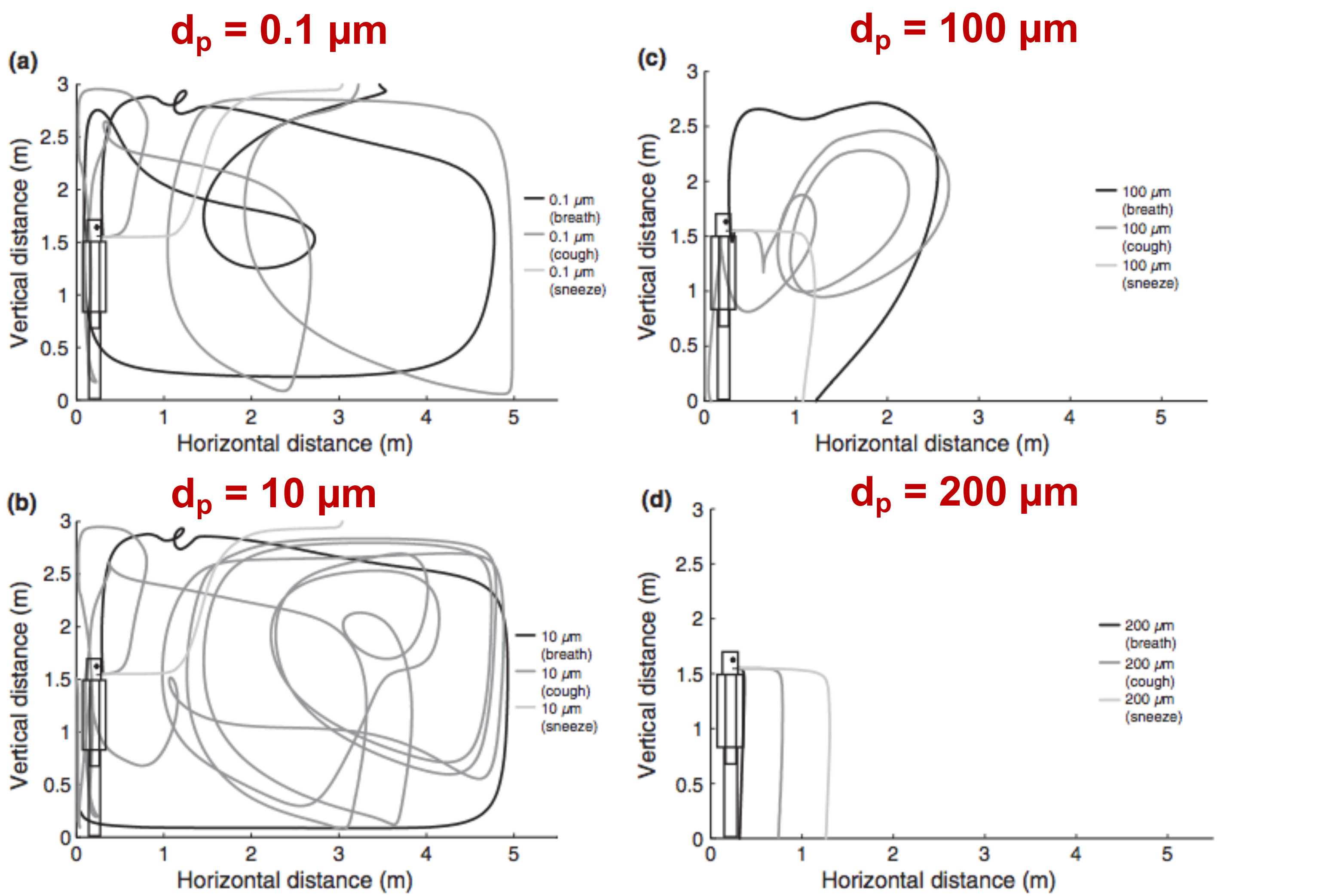


Fig. 13 Comparison of trajectories of droplets at different initial exhaled velocities. (a) initial diameter 0.1 μm, (b) initial diameter 10 μm, (c) initial diameter 100 μm, (d) initial diameter 200 μm. z = 2 m

Chen and Zhao 2010 *Indoor Air* 20:95-111

Evidence of airborne transmission

One of my favorite studies…

Aerosol Transmission of Rhinovirus Colds

Elliot C. Dick, Lance C. Jennings, Kathy A. Mink, Catherine D. Wartgow, and Stanley L. Inhorn

Rhinovirus infections may spread by aerosol, direct contact, or indirect contact involving environmental objects. We examined aerosol and indirect contact in transmission of rhinovirus type 16 colds between laboratory-infected men (donors) and susceptible men (recipients) who played cards together for 12 hr. In three experiments the infection rate of restrained recipients (10 [56%] of 18), who could not touch their faces and could only have been infected by aerosols, and that of unrestrained recipients (12 [67%] of 18), who could have been infected by aerosol, by direct contact, or by indirect fomite contact, was not significantly different ($\chi^2 = 0.468$, $P = .494$). In a fourth experiment, transmission via fomites heavily used for 12 hr by eight donors was the only possible route of spread, and no transmissions occurred among 12 recipients ($P < .00$
results suggest that contrary to current opinion,
occurs chiefly by the aerosol route.

ments. Twenty-seven to 34 men >18 years of age were inoculated intranasally with 560–2,400 $TCID_{50}$ of safety-tested RV16 [5] by pipette and spray on two successive days. On the third day, eight men with the most severe colds (donors) played stud and draw poker with 12 antibody-free (no neutralization of virus by the undilute [1:1] serum specimen against a 20–25 $TCID_{50}$ challenge) men (recipients) between hours of 8 a.m. and 11 p.m. The ending hour was

Dick et al. 1987 *J Infectious Diseases* 156:442-448

INFECTIOUS AEROSOLS

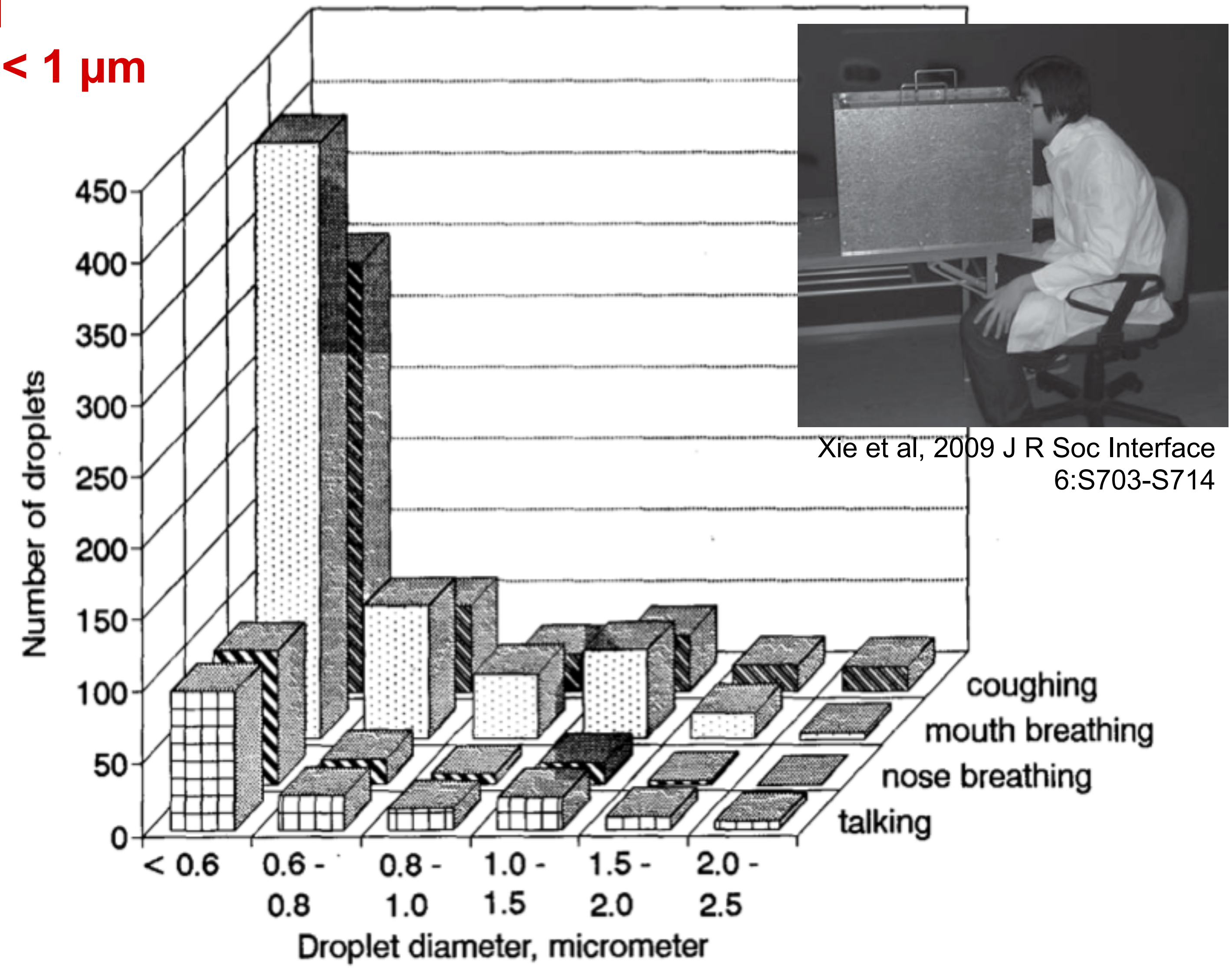
Size distributions and infectious organism content

What particle sizes are actually emitted by humans?

- Commonly believed that droplet nuclei average 1-3 μm
  - Recent studies show that 80-90% of particles expelled during human activities are actually smaller than 1-2 μm
- When considering dynamics of infectious aerosols
  - It is crucial to consider particle sizes of infectious aerosols
  - Particle size governs transport, control (e.g. by filtration), deposition in respiratory tract, and resuspension ability

Emissions from coughing subjects

Nearly all particles < 1 µm

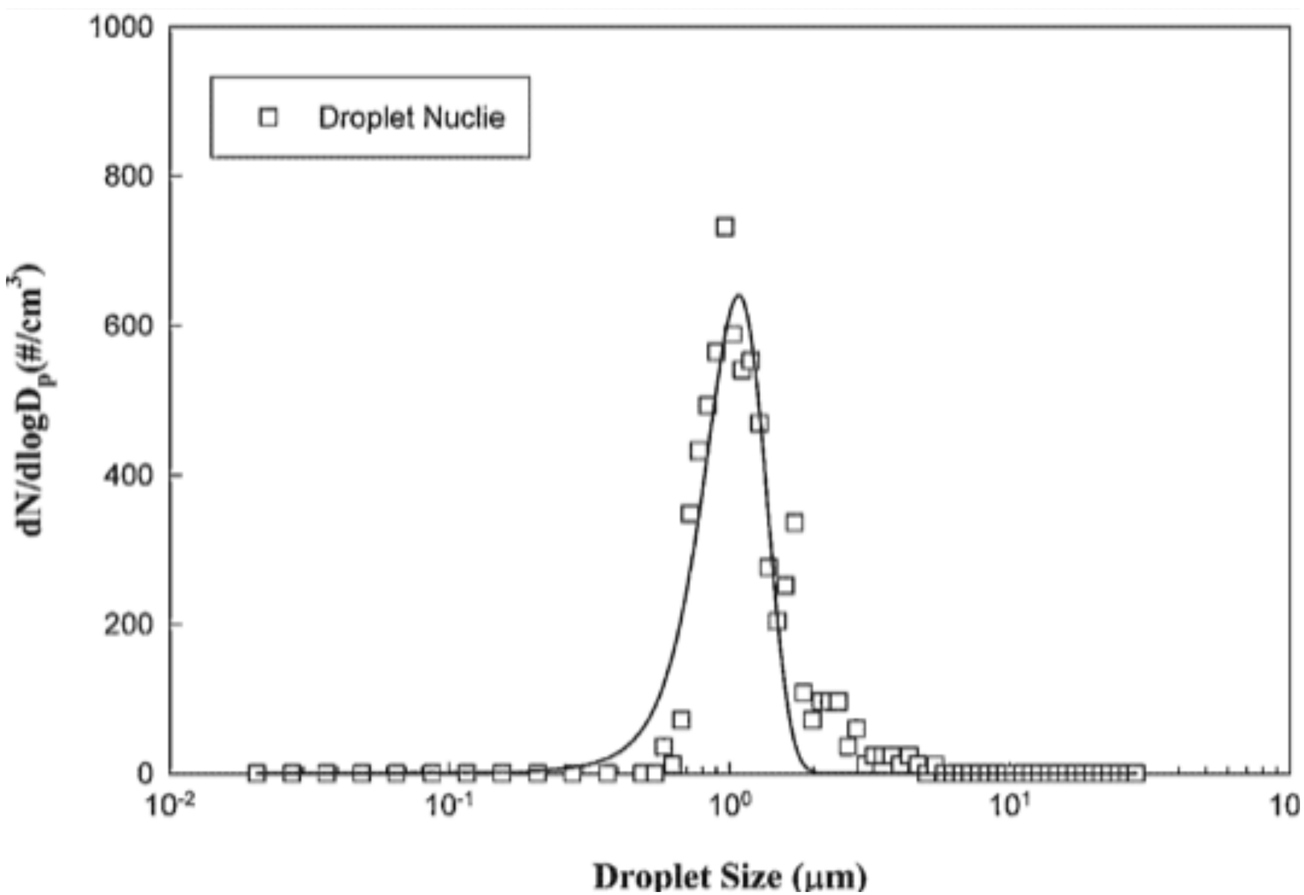


Xie et al, 2009 J R Soc Interface 6:S703-S714

Papineni and Rosenthal 1997 *J Aerosol Medicine* 10:105-116

More emissions from coughing subjects (n = 54)

- 82% of particles in the 0.7-2.2 μm size range

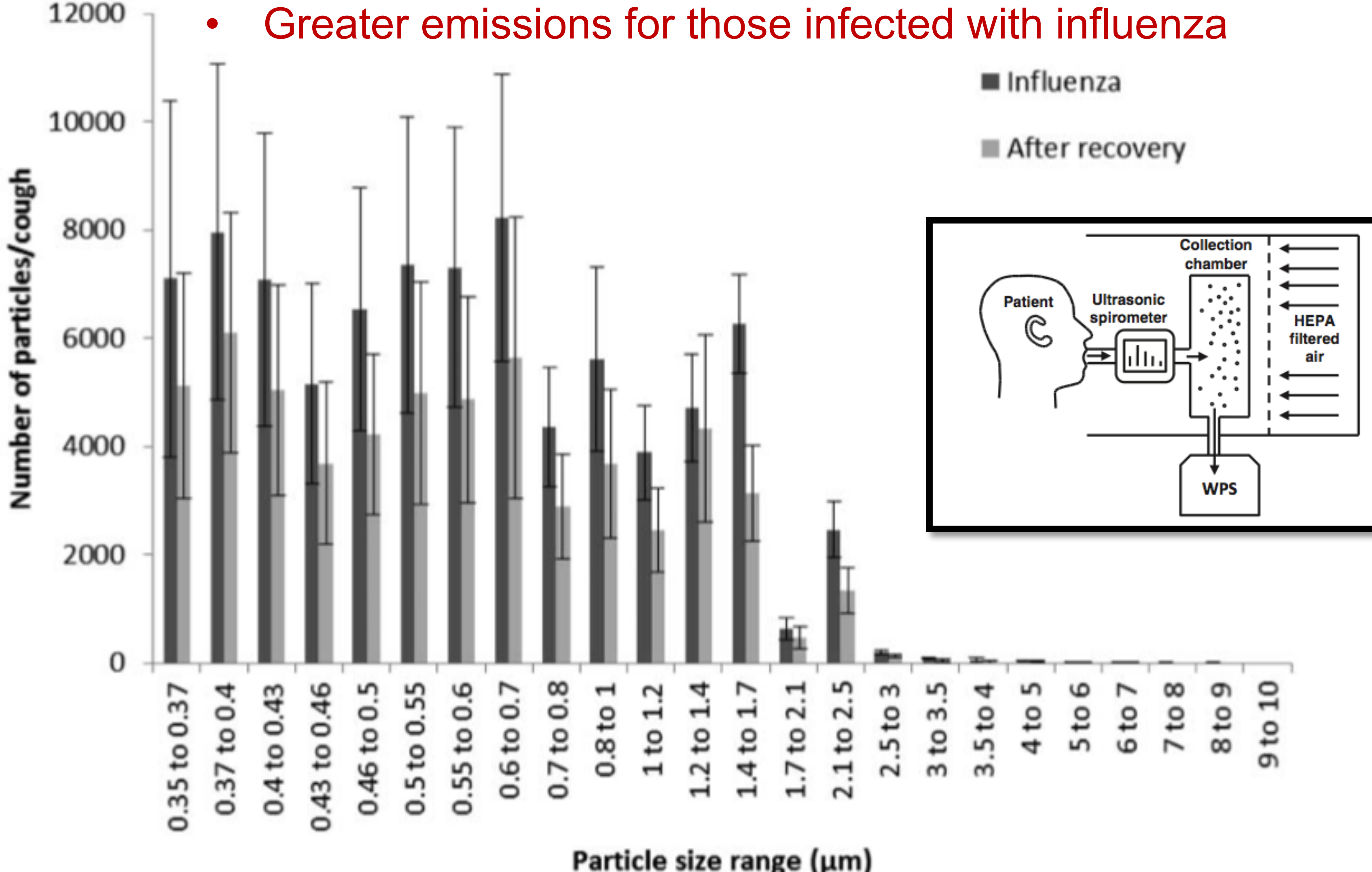


Yang et al., 2007 *J Aerosol Med* 20:484-494

Coughing subjects with and without influenza

Most emitted particles < 1 µm

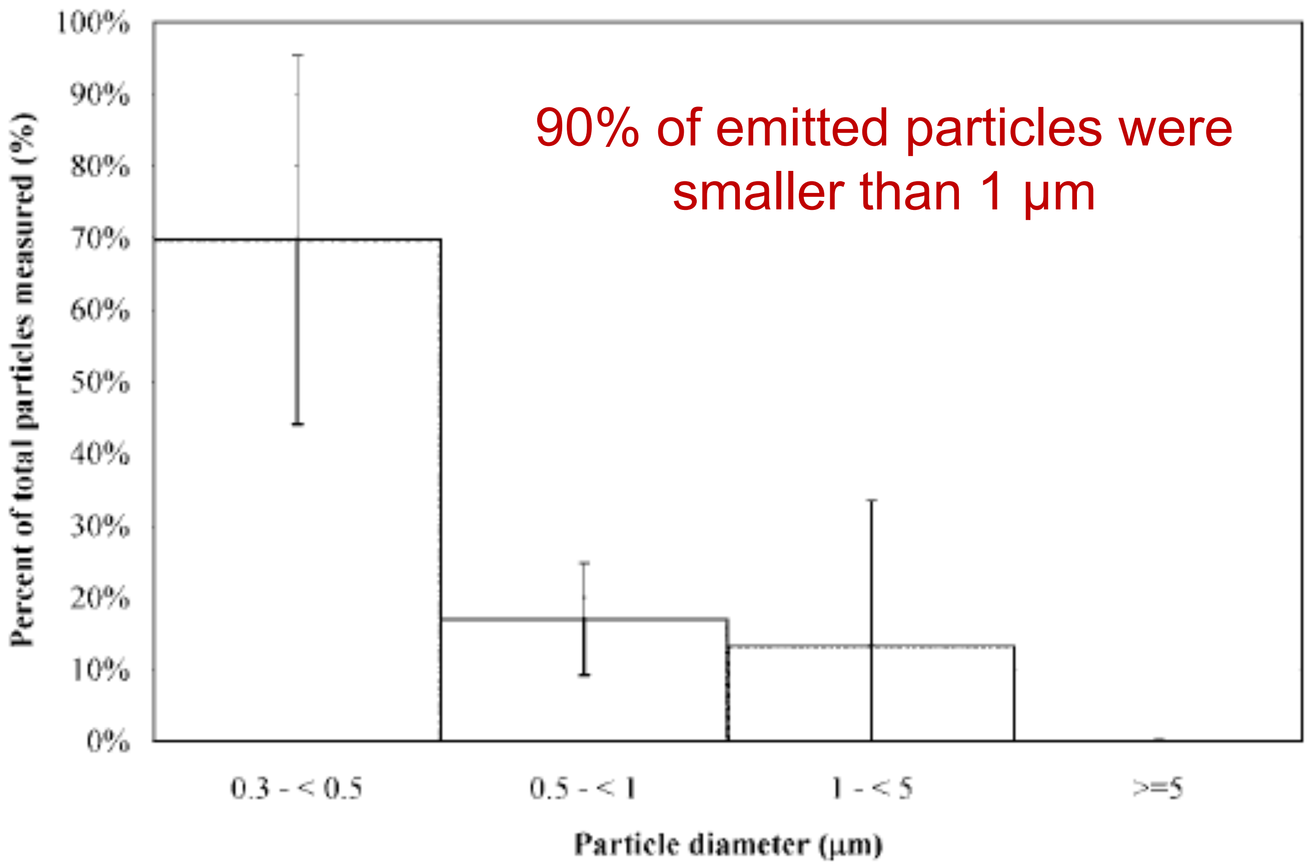
- Greater emissions for those infected with influenza



Lindsley et al., 2012 *J Occup Environ Hygiene* 9:443-449

Emissions from breathing subjects

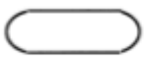
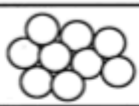
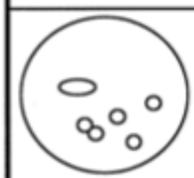
- Typically much smaller number concentrations than during coughing



Fabian et al., 2008 *PLoS ONE* 3:e2691

What about infectious organisms within particles?

Shape and Aspect Ratios of Microorganisms

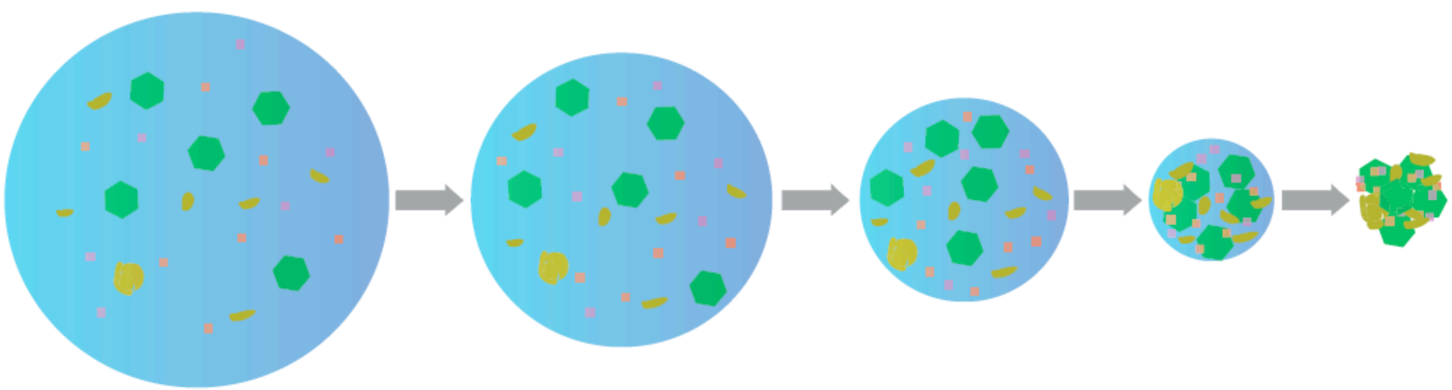
Shape	Type	Description	AR
	Icosahedral Helical	All respiratory viruses, whether icosahedral or helical, are so much smaller than filter fibers that they can be considered spherical for filtration calculations.	1
	Spherical	Most bacteria and spores are approximately spherical.	1
	Ovoid	Some bacteria and spores are ovoid.	1-3
	Rods	Bacteria classed as bacilli are rod-shaped.	1-10
	Diplo-cocci	Certain bacteria normally occur in pairs.	1-3
	Strepto-cocci	Some bacteria occur in strings (i.e. strepto-coccus) but are likely to break up on impact with filter fibers.	NA
	Staphylo-cocci	Some bacteria occur in bunches (i.e. staphylo-coccus) but are likely to break up on impact with filter fibers.	NA
	Flagella	Some bacteria have flagella, enabling motility.	NA
	Capsule	Some bacteria have hydrophobic capsules that can be shed or regenerated depending on the environment.	1-3
	Slime layer	Some microbes produce slime layers in addition to capsules that can be shed at any time.	1-3
	Droplets & Droplet Nuclei	Aerosolized droplets, typically 20-100 microns, may contain numerous microbes and other particles. These evaporate to condensation nuclei that may contain several viable microbes and residue. These will break up upon impact with filter fibers.	1-3

Pathogen	Mean size, µm
Influenza	0.098
Smallpox	0.22
C. burnetti	0.283
R. prowazeki	0.283
L. pneumophila	0.520
M. tuberculosis	0.637
C. diphtheria	0.700
S. pneumoniae	0.707
R. rickettsii	0.85
N. asteroides	1.12
Bacillus anthracis	1.12
H. capsulatum	2.24
Botulinum toxin	2.24
B. dermatitidis	12.6

Kowalski et al., 1999 *ASHRAE Transactions*

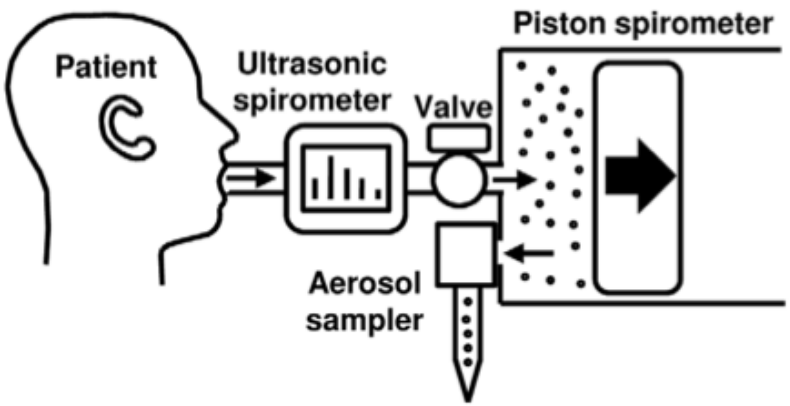
What about infectious organisms within particles?

- Most particles emitted during human activities are smaller than 1-2 µm
  - But particle volume scales with d_p^3
  - Does the amount of viral or bacterial material contained in droplet nuclei scale similarly?



- Recent measurements have shown this to be ~true

Viral RNA contained in size-resolved aerosol samples



qPCR reveals influenza viral RNA size distribution in human coughs:

- 42% < 1 μm
- 23% 1-4 μm
- 35% > 4 μm

Table 1. Influenza viral RNA detected in the NIOSH two-stage aerosol sampler.

Aerosol particle size range (aerodynamic diameter)	*Median # of viral copies per cough*	*% of viral RNA contained in particles in this size range*	*% of subjects whose cough aerosol contained viral RNA-laden particles in this size range*
>4 μm	6.3 (SD 9.0)	35%	90%
1 to 4 μm	3.3 (SD 6.9)	23%	81%
<1 μm	3.7 (SD 23.7)	42%	75%
All particles	15.8 (SD 29.3)	100%	100%

Although ~90% of emitted particles (number concentrations) are < 1 μm

- Only ~40% of viral RNA is contained in that fraction

Lindsley et al., 2010 *PLoS ONE* 5:e15100

Size-resolved influenza virus indoors

Distribution of Airborne Influenza Virus and Respiratory Syncytial Virus in an Urgent Care Medical Clinic

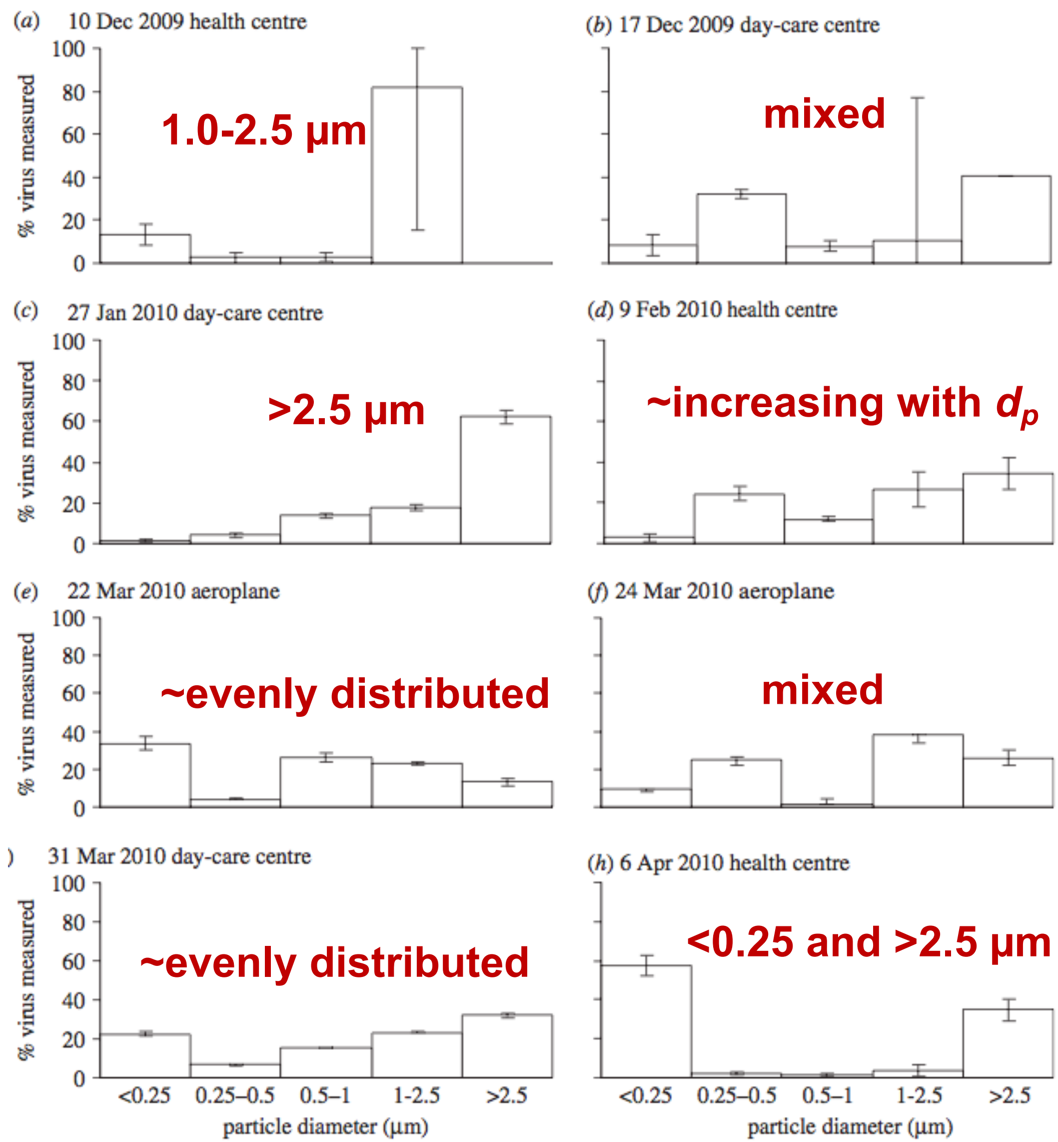
qPCR reveals influenza viral RNA size distribution in an urgent care clinic:

- ~10-20% < 1 μm
- ~20-40% 1-4 μm
- ~50-60% > 4 μm

Sampling Location	Distribution of viral RNA		
Personal samplers	< 1.7 μm 32%	1.7-4.9 μm 16%	> 4.9 μm 52%
Lower stationary samplers	< 1 μm 13%	1-4.1 μm 37%	> 4.1 μm 50%
Upper stationary samplers	< 1 μm 9%	1-4.1 μm 27%	> 4.1 μm 64%

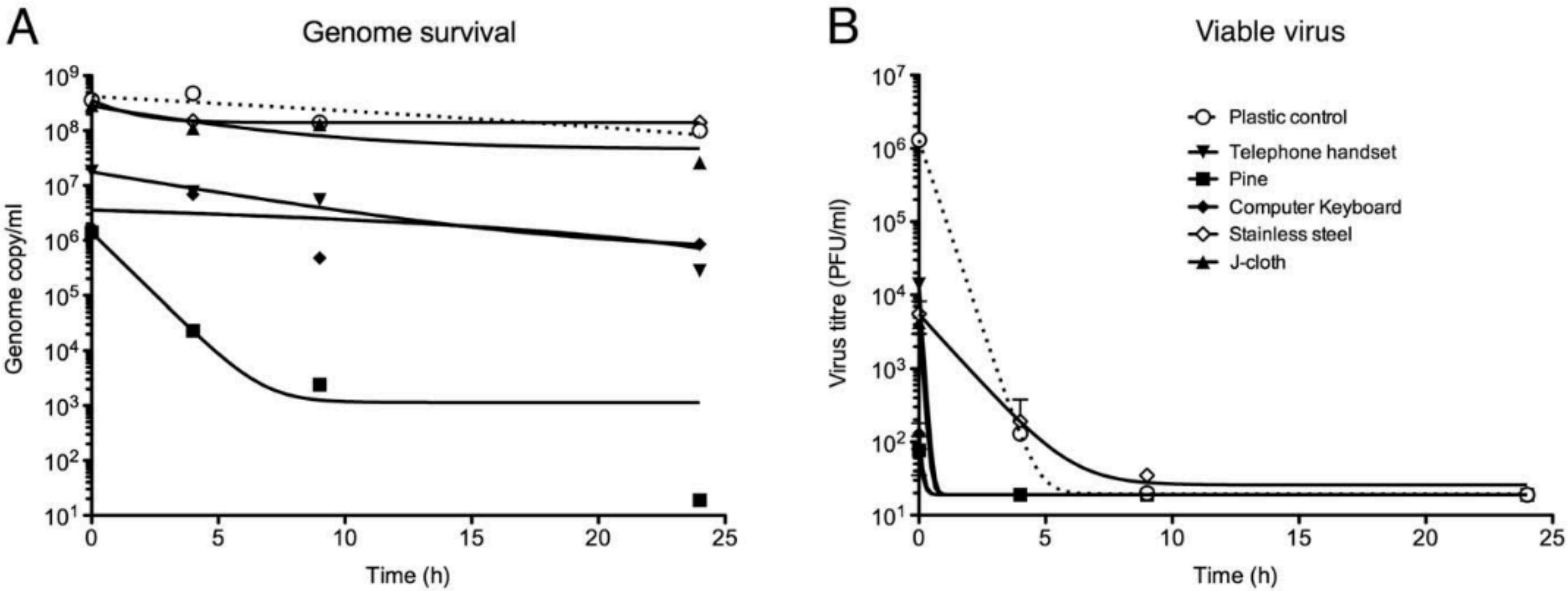
Lindsley et al., 2010 *Clinical Infectious Diseases* 50:693-698

Other mixed results for viral distributions



Yang et al., 2011 *J R Soc Interface* 8:1176-1184

Influenza virus survival on surfaces



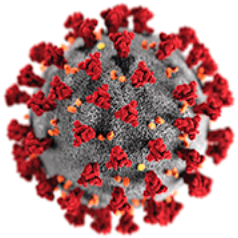
Conclusions/Significance: The genome of either virus could be detected on most surfaces 24 h after application with relatively little drop in copy number, with the exception of unsealed wood surfaces. In contrast, virus viability dropped much more rapidly. Live virus was recovered from most surfaces tested four hours after application and from some non-porous materials after nine hours, but had fallen below the level of detection from all surfaces at 24 h. We conclude that influenza A transmission via fomites is possible but unlikely to occur for long periods after surface contamination (unless re-inoculation occurs). In situations involving a high probability of influenza transmission, our data suggest a hierarchy of priorities for surface decontamination in the multi-surface environments of home and hospitals.

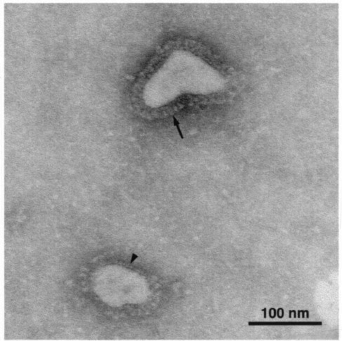
Greatorex et al., 2011 *PLoS ONE* 6(11): e27932

WHAT ABOUT THE NOVEL CORONAVIRUS (SARS-COV-2)?

SARS-CoV-2 and COVID-19

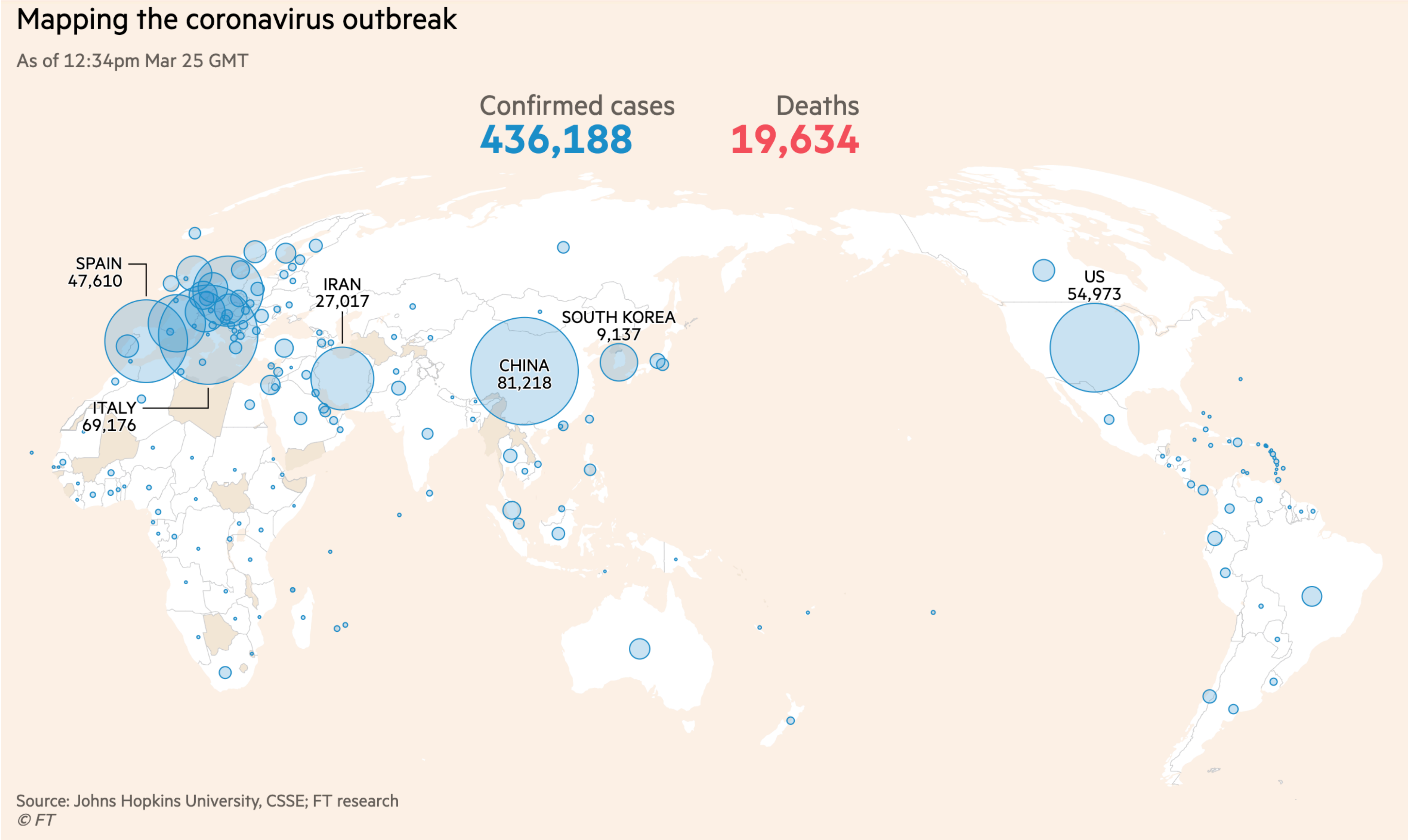
- Coronavirus disease (COVID-19) is an infectious disease caused by a newly discovered coronavirus (SARS-CoV-2)
  - The problem is no one has immunity to a novel virus (yet)
- Most people infected with the COVID-19 virus will experience mild to moderate respiratory illness and recover without requiring special treatment
  - Older people, and those with underlying medical problems like cardiovascular disease, diabetes, chronic respiratory disease, and cancer are more likely to develop serious illness
- There are no vaccines or treatments for COVID-19 (yet)
  - There are many ongoing clinical trials evaluating potential treatments





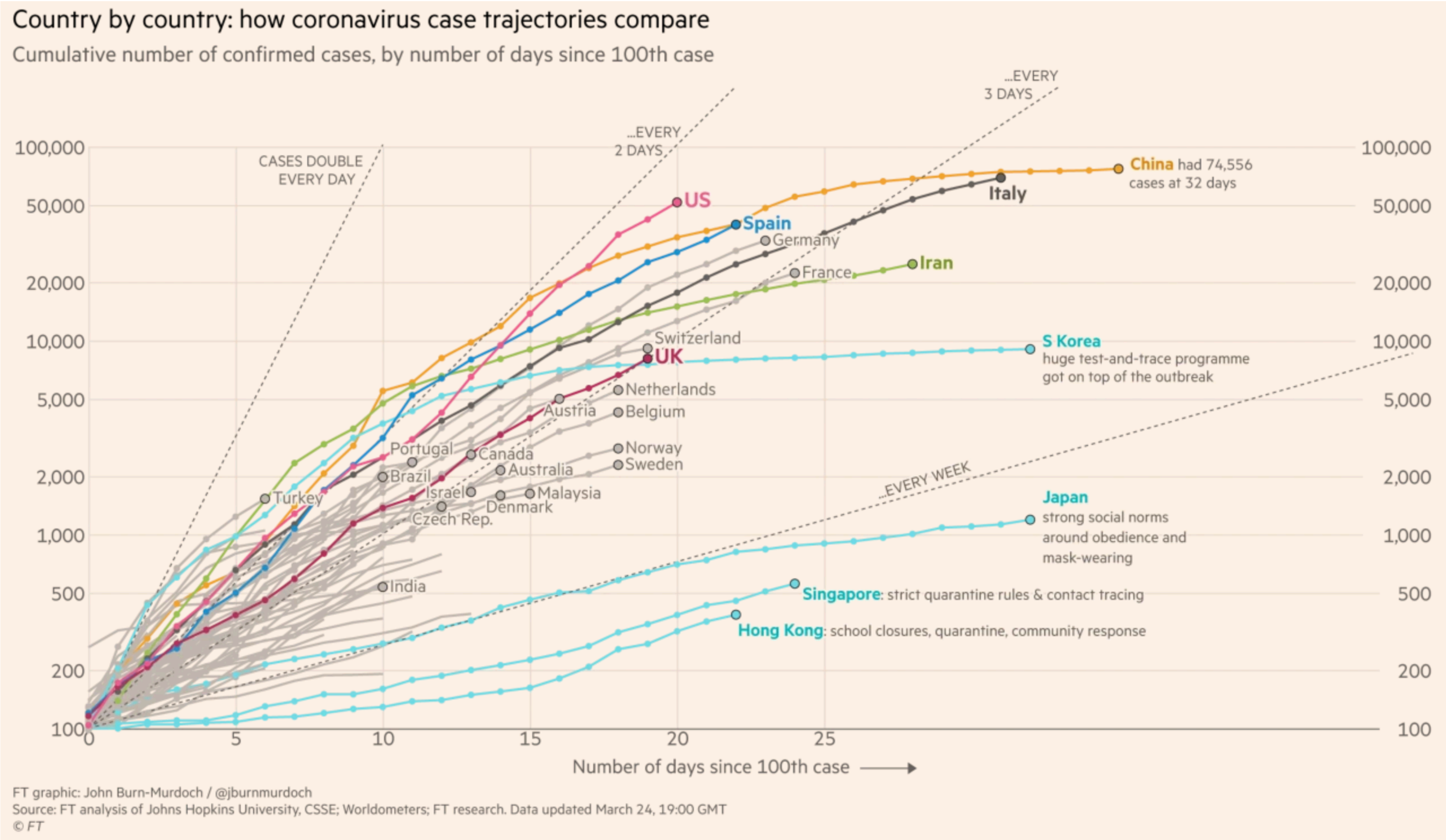
https://www.who.int/health-topics/coronavirus

SARS-CoV-2 and COVID-19



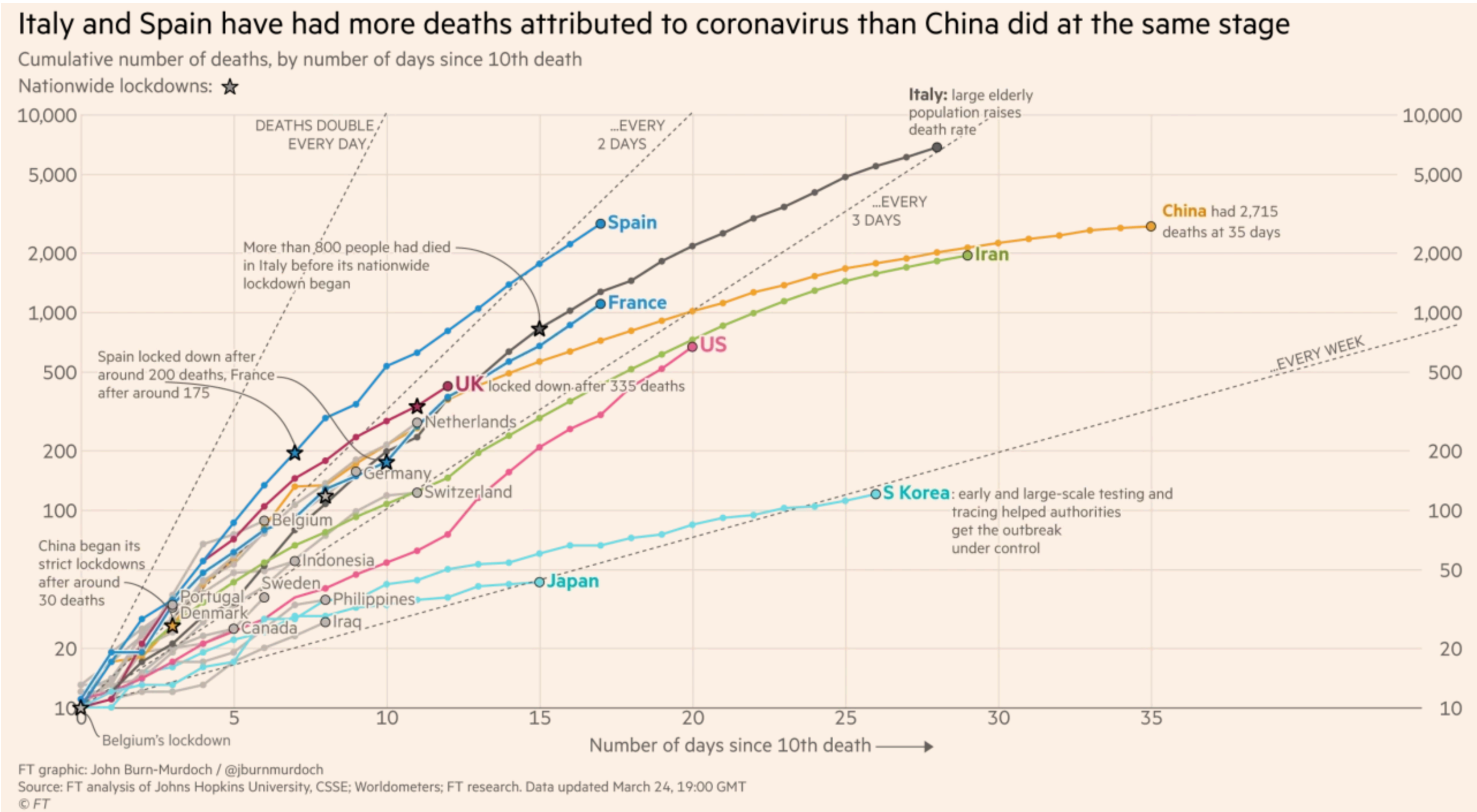
https://www.ft.com/coronavirus-latest

SARS-CoV-2 and COVID-19



https://www.ft.com/coronavirus-latest

SARS-CoV-2 and COVID-19



https://www.ft.com/coronavirus-latest

How is SARS-CoV-2 spread?

- **WHO:** "The virus spreads primarily through droplets of saliva or discharge from the nose when an infected person coughs or sneezes" https://www.who.int/health-topics/coronavirus

- **CDC:** "The virus is thought to spread mainly from person-to-person (Between people who are in close contact with one another (within about 6 feet); through respiratory droplets produced when an infected person coughs or sneezes). These droplets can land in the mouths or noses of people who are nearby or possibly be inhaled into the lungs."
  - "It may be possible that a person can get COVID-19 by touching a surface or object that has the virus on it and then touching their own mouth, nose, or possibly their eyes, but this is not thought to be the main way the virus spreads."

  https://www.cdc.gov/coronavirus/2019-ncov/prepare/transmission.html

SARS-CoV-2 detection in Singapore patient rooms

From January 24 to February 4, 2020, 3 patients at the dedicated SARS-CoV-2 outbreak center in Singapore in airborne infection isolation rooms (12 air exchanges per hour) with anterooms and bathrooms had surface environmental samples taken at 26 sites. Personal protective equipment (PPE) samples from study physicians exiting the patient rooms also were collected. Sterile premoistened swabs were used.

Samples were collected on 5 days over a 2-week period. One patient's room was sampled before routine cleaning and 2 patients' rooms after routine cleaning. Twice-daily cleaning of high-touch areas was done using 5000 ppm of sodium dichloroisocyanurate. The floor was cleaned daily using 1000 ppm of sodium dichloroisocyanurate.

Patient A's room was sampled on days 4 and 10 of illness while the patient was still symptomatic, after routine cleaning. All samples were negative. Patient B was symptomatic on day 8 and asymptomatic on day 11 of illness; samples taken on these 2 days after routine cleaning were negative (**Table 1**).

https://jamanetwork.com/journals/jama/fullarticle/2762692

SARS-CoV-2 detection in Singapore patient rooms

Patient C, whose samples were collected before routine cleaning, had positive results, with 13 (87%) of 15 room sites (including air outlet fans) and 3 (60%) of 5 toilet sites (toilet bowl, sink, and door handle) returning positive results (**Table 2**). Anteroom and corridor samples were negative. Patient C had upper respiratory tract involvement with no pneumonia and had 2 positive stool samples for SARS-CoV-2 on RT-PCR despite not having diarrhea.

Only 1 PPE swab, from the surface of a shoe front, was positive. All other PPE swabs were negative. All air samples were negative.

There was extensive environmental contamination by 1 SARS-CoV-2 patient with mild upper respiratory tract involvement. Toilet bowl and sink samples were positive, suggesting that viral shedding in stool[5] could be a potential route of transmission. Postcleaning samples were negative, suggesting that current decontamination measures are sufficient.

https://jamanetwork.com/journals/jama/fullarticle/2762692

SARS-CoV-2 detection in Wuhan hospitals

Background: The ongoing outbreak of COVID-19 has spread rapidly and sparked global concern. While the transmission of SARS-CoV-2 through human respiratory droplets and contact with infected persons is clear, the aerosol transmission of SARS-CoV-2 has been little studied.

Methods: Thirty-five aerosol samples of three different types (total suspended particle, size segregated and deposition aerosol) were collected in Patient Areas (PAA) and Medical Staff Areas (MSA) of Renmin Hospital of Wuhan University (Renmin) and Wuchang Fangcang Field Hospital (Fangcang), and Public Areas (PUA) in Wuhan, China during COVID-19 outbreak. A robust droplet digital polymerase chain reaction (ddPCR) method was employed to quantitate the viral SARS-CoV-2 RNA genome and determine aerosol RNA concentration.

Results: The ICU, CCU and general patient rooms inside Renmin, patient hall inside Fangcang had undetectable or low airborne SARS-CoV-2 concentration but deposition samples inside ICU and air sample in Fangcang patient toilet tested positive. The airborne SARS-CoV-2 in Fangcang MSA had bimodal distribution with higher concentration than those in Renmin during the outbreak but turned negative after patients number reduced and rigorous sanitization implemented. PUA had undetectable airborne SARS-CoV-2 concentration but obviously increased with accumulating crowd flow.

Conclusions: Room ventilation, open space, proper use and disinfection of toilet can effectively limit aerosol transmission of SARS-CoV-2. Gathering of crowds with asymptomatic carriers is a potential source of airborne SARS-CoV-2. The virus aerosol deposition on protective apparel or floor surface and their subsequent resuspension is a potential transmission pathway and effective sanitization is critical in minimizing aerosol transmission of SARS-CoV-2.

https://www.biorxiv.org/content/10.1101/2020.03.08.982637v1

SARS-CoV-2 detection in Wuhan hospitals

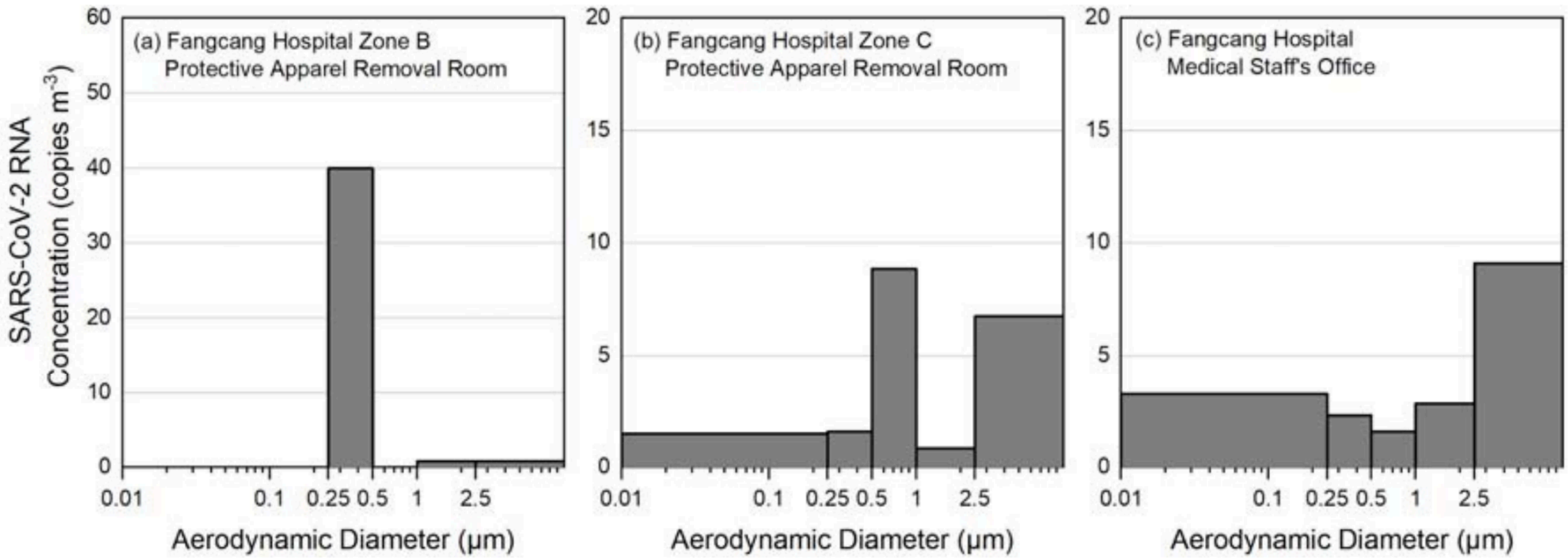
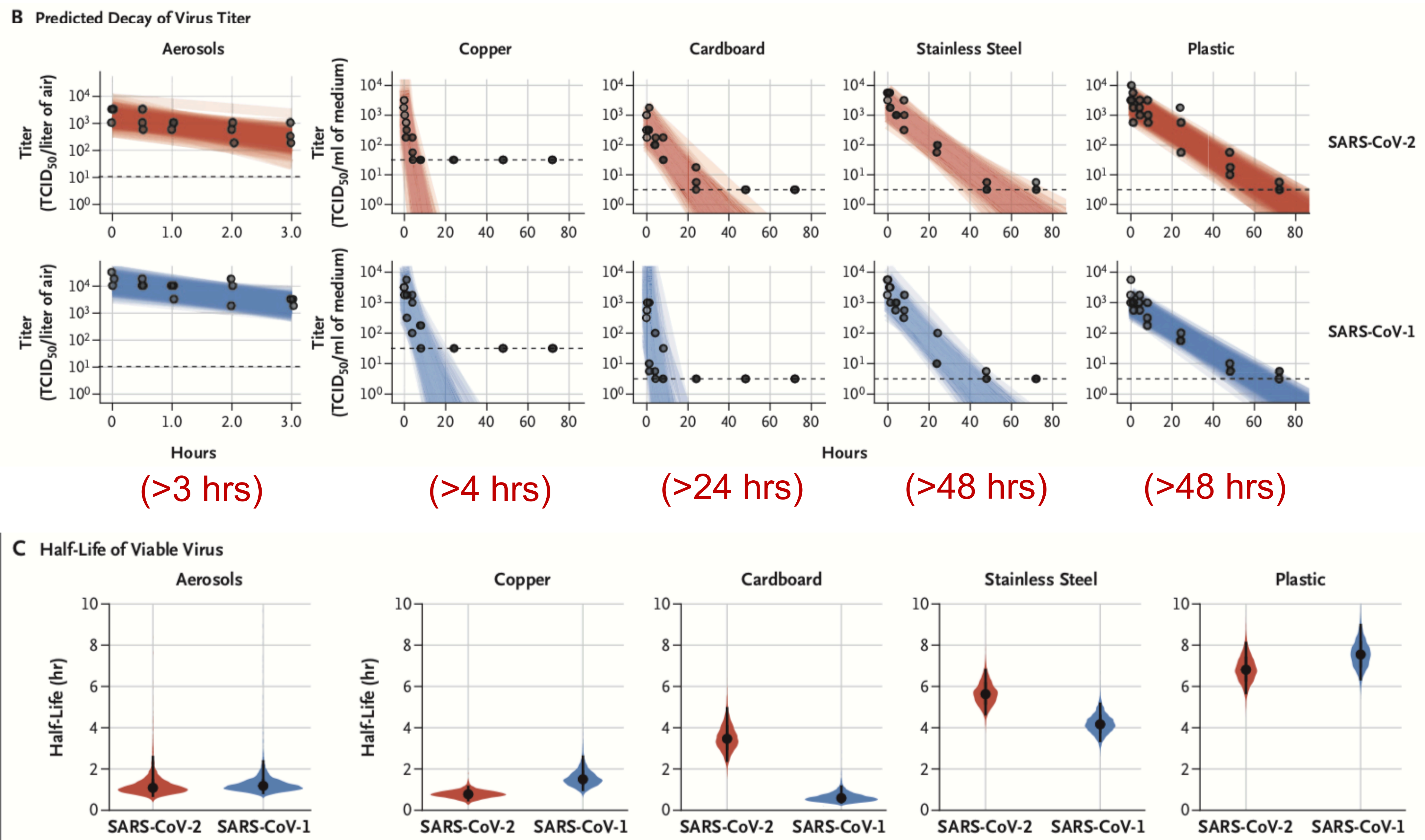


Figure 1 Concentration of airborne SARS-CoV-2 RNA in different aerosol size bins

https://www.biorxiv.org/content/10.1101/2020.03.08.982637v1

SARS-CoV-2 survival in aerosols and on surfaces



van Doremalen et al., 2020 *NEJM*

How is SARS-CoV-2 spread?

- We may be able to learn from SARS-CoV-1:

Routes of transmission of influenza A H1N1, SARS CoV, and norovirus in air cabin: Comparative analyses

H. Lei[1] | Y. Li[1] | S. Xiao[1] | C.-H. Lin[2] | S. L. Norris[2] | D. Wei[3] | Z. Hu[4] | S. Ji[4]

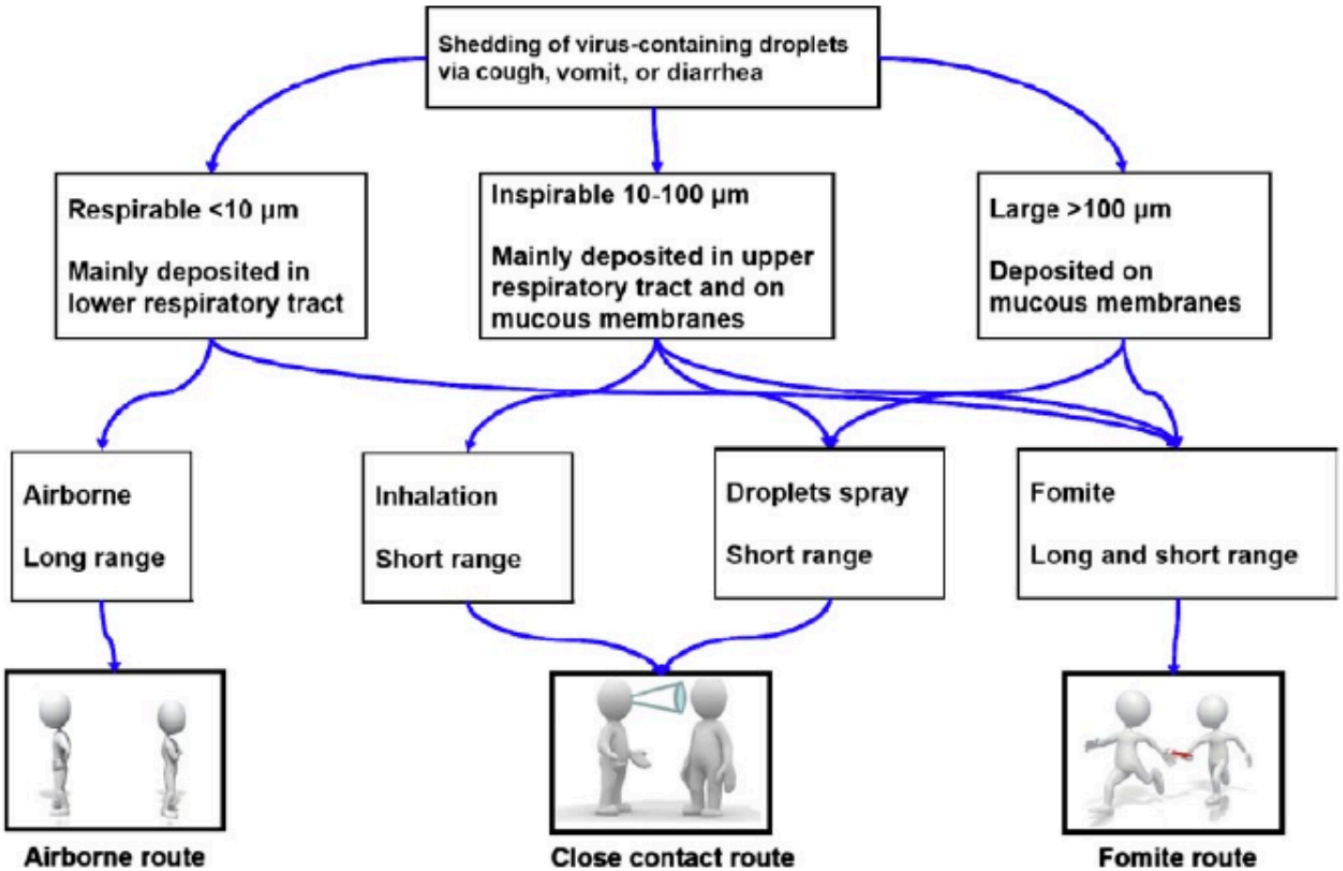
Abstract

Identifying the exact transmission route(s) of infectious diseases in indoor environments is a crucial step in developing effective intervention strategies. In this study, we proposed a comparative analysis approach and built a model to simulate outbreaks of 3 different in-flight infections in a similar cabin environment, that is, influenza A H1N1, severe acute respiratory syndrome (SARS) coronavirus (CoV), and norovirus. The simulation results seemed to suggest that the close contact route was probably the most significant route (contributes 70%, 95% confidence interval [CI]: 67%-72%) in the in-flight transmission of influenza A H1N1 transmission; as a result, passengers within 2 rows of the index case had a significantly higher infection risk than others in the outbreak (relative risk [RR]: 13.4, 95% CI: 1.5-121.2, $P = .019$). For SARS CoV, the airborne, close contact, and fomite routes contributed 21% (95% CI: 19%-23%), 29% (95% CI: 27%-31%), and 50% (95% CI: 48%-53%), respectively. For norovirus, the simulation results suggested that the fomite route played the dominant role (contributes 85%, 95% CI: 83%-87%) in most cases; as a result, passengers in aisle seats had a significantly higher infection risk than others (RR: 9.5, 95% CI: 1.2-77.4, $P = .022$). This work highlighted a method for using observed outbreak data to analyze the roles of different infection transmission routes.

https://onlinelibrary.wiley.com/doi/epdf/10.1111/ina.12445

How is SARS-CoV-2 spread?

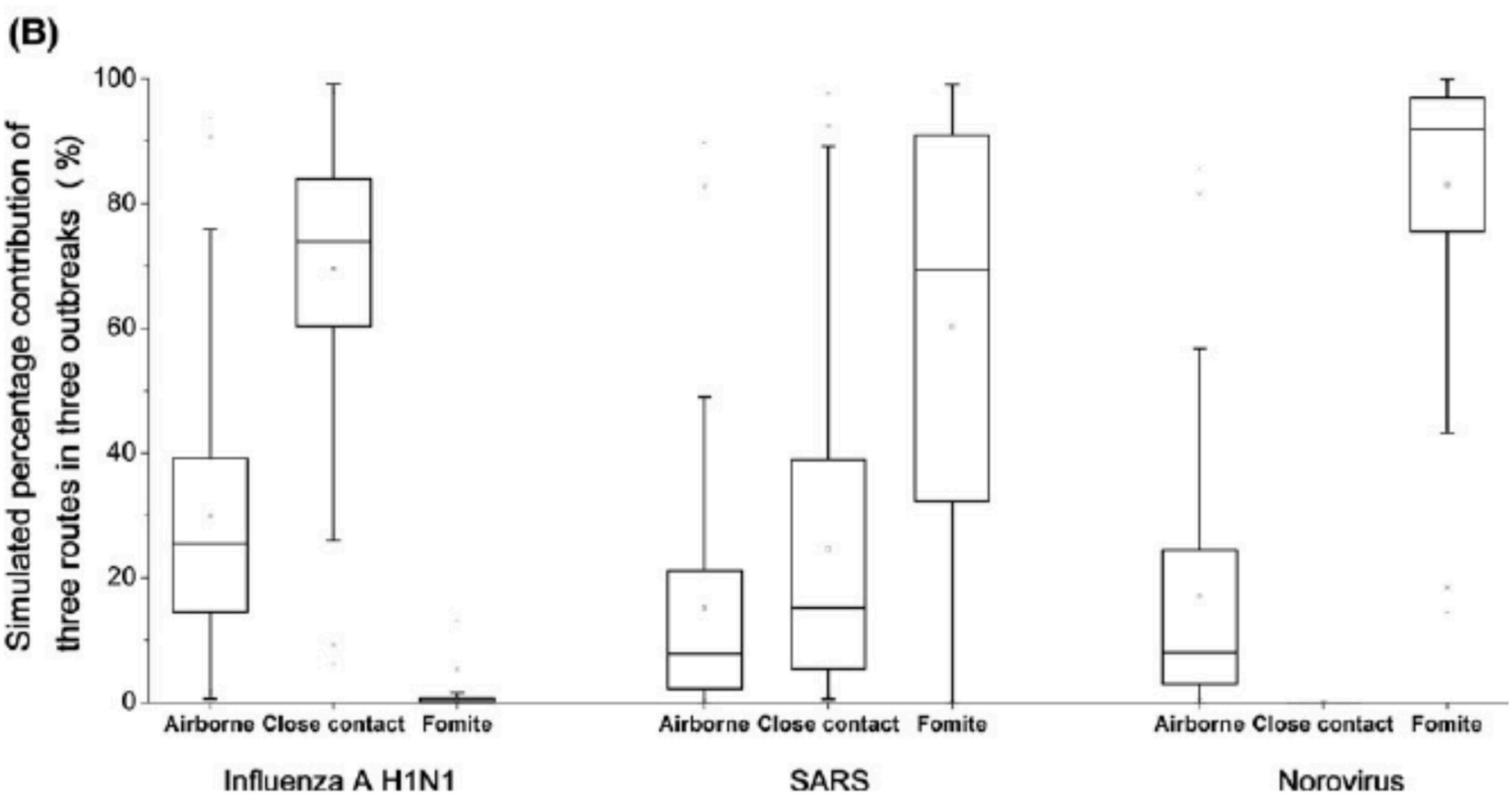
- We may be able to learn from SARS-CoV-1:



https://onlinelibrary.wiley.com/doi/epdf/10.1111/ina.12445

How is SARS-CoV-2 spread?

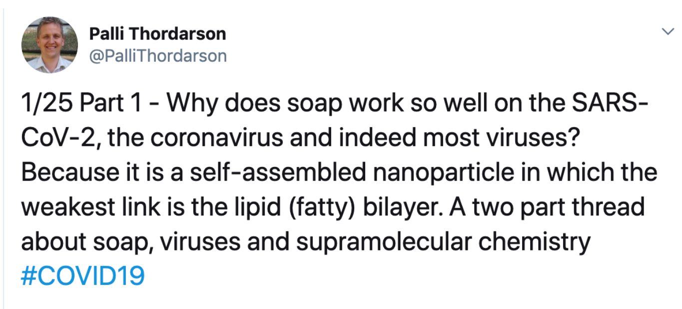
- We may be able to learn from SARS-CoV-1:



https://onlinelibrary.wiley.com/doi/epdf/10.1111/ina.12445

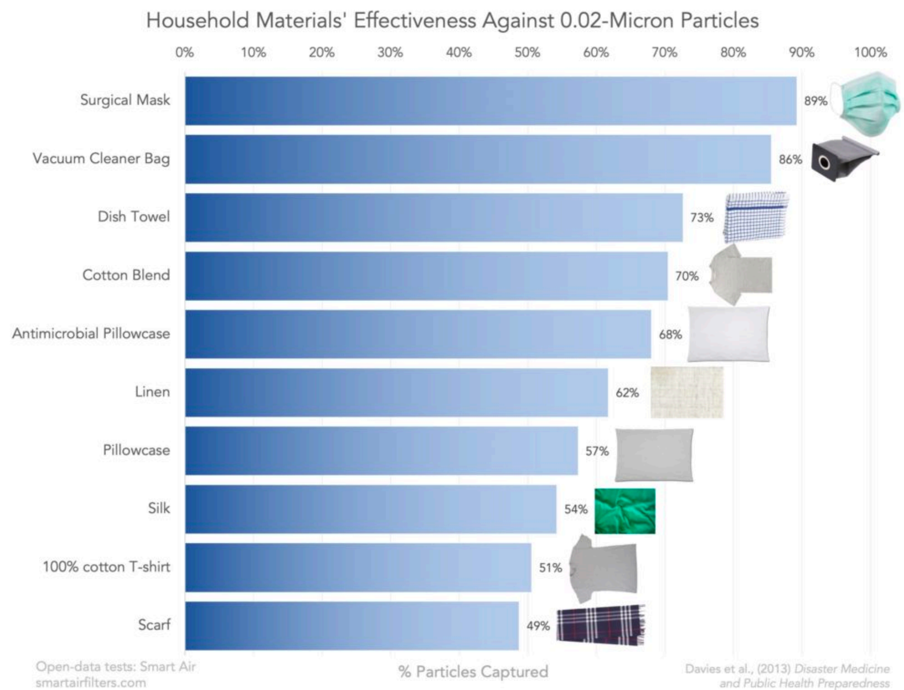
Recommendations SARS-CoV-2 and COVID-19

- Wash your hands (with soap, 20 secs)
- Keep your distance
- Wear a mask if in close contact with a person with a suspected SARS-CoV-2 infection (save them for healthcare workers)
  - Or make your own:


Palli Thordarson
@PalliThordarson

1/25 Part 1 - Why does soap work so well on the SARS-CoV-2, the coronavirus and indeed most viruses? Because it is a self-assembled nanoparticle in which the weakest link is the lipid (fatty) bilayer. A two part thread about soap, viruses and supramolecular chemistry #COVID19

https://twitter.com/PalliThordarson/status/1236549305189597189

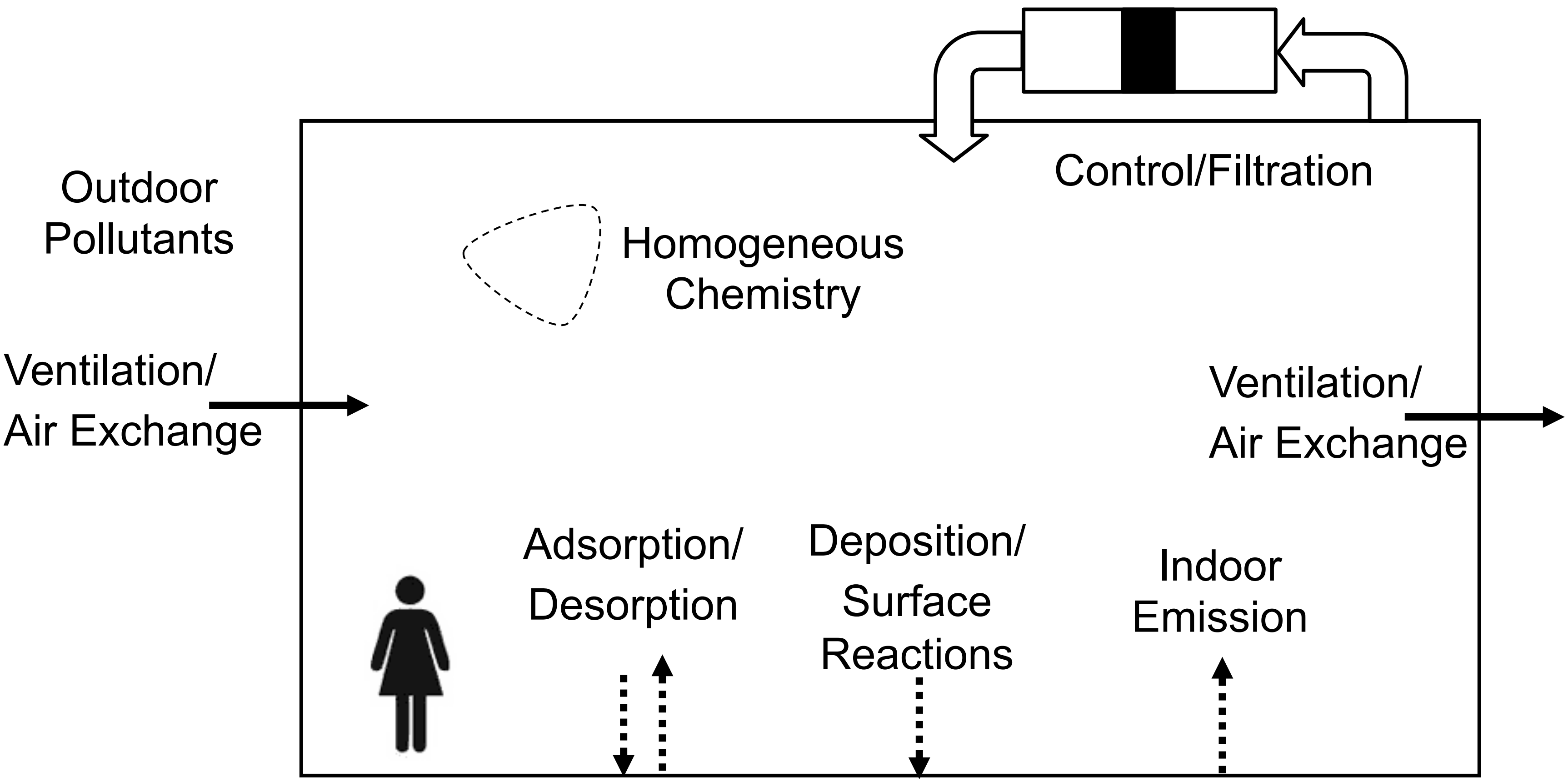


https://smartairfilters.com/en/blog/best-materials-make-diy-face-mask-virus/

QUANTIFYING IAQ: MASS BALANCES

Indoor environment: Mass balances

To understand the levels of airborne pollutants that we are exposed to, we need to understand the underlying physical, chemical, and biological mechanisms that drive pollutant emission, transport, and control



Indoor environment: Mass balance

- Simplest case (**inert gas**)
  - Neglecting indoor physics/chemistry
    - No deposition, no reaction

$$\begin{pmatrix} \text{Mass} \\ \text{accumulation} \\ \text{rate} \\ \text{[mass / time]} \end{pmatrix} = \begin{pmatrix} \text{Mass flow in} \\ \text{[mass / time]} \end{pmatrix} - \begin{pmatrix} \text{Mass flow out} \\ \text{[mass / time]} \end{pmatrix} + \begin{pmatrix} \text{Mass emitted} \\ \text{[mass / time]} \end{pmatrix}$$

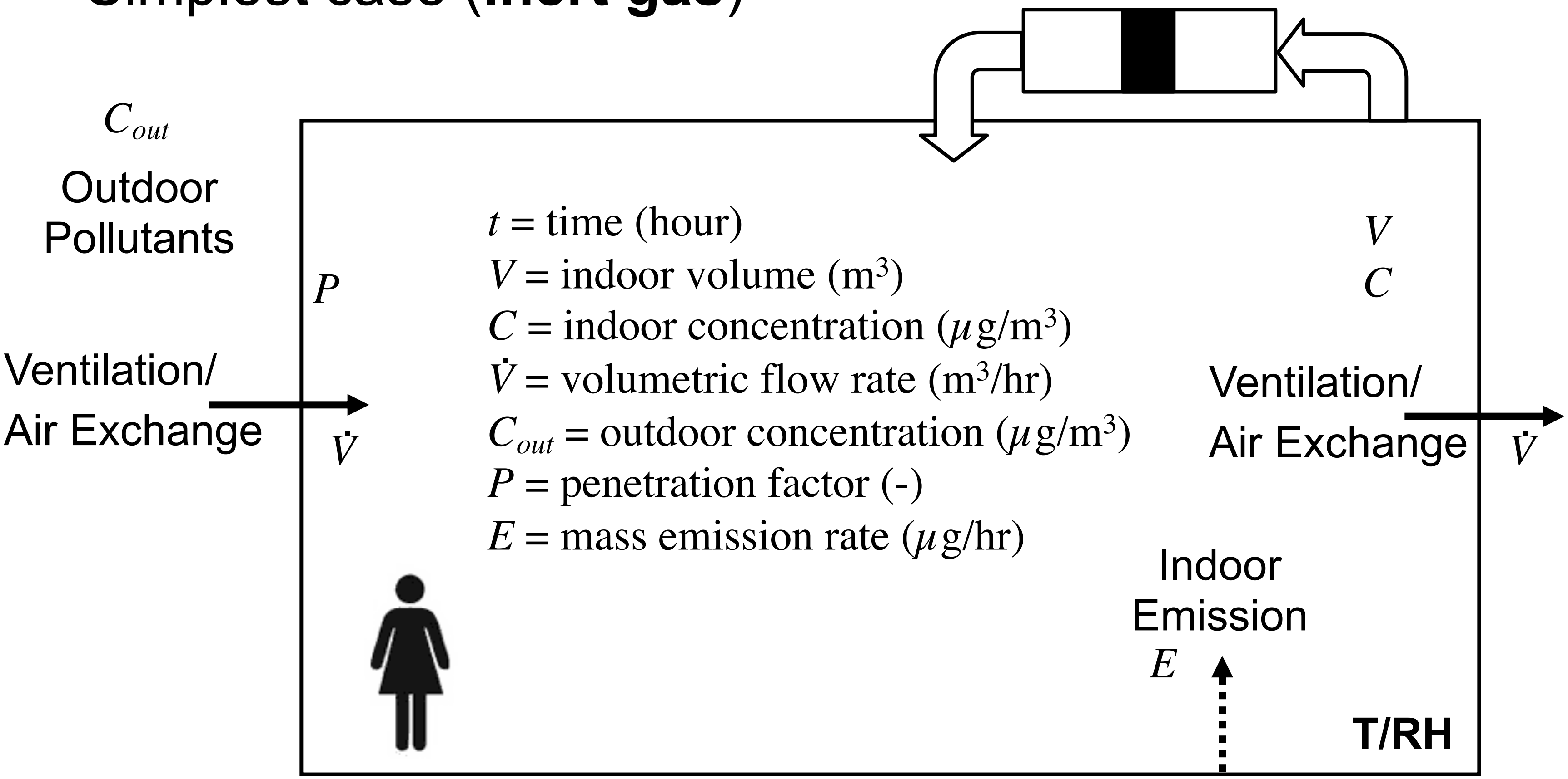
$$\frac{dm}{dt} = \frac{dCV}{dt} = V\frac{dC}{dt} + \underset{0}{C\cancel{\frac{dV}{dt}}}$$

Assumptions:

- Building/room can be treated as well-mixed

Indoor environment: Mass balance

- Simplest case (**inert gas**)



$$V\frac{dC}{dt} = P\dot{V}C_{out} - \dot{V}C + E$$

Indoor environment: Mass balance

- Simplest case (**inert gas**)

$$V\frac{dC}{dt} = P\dot{V}C_{out} - \dot{V}C + E$$

- Divide by volume:

$$\frac{dC}{dt} = P\frac{\dot{V}}{V}C_{out} - \frac{\dot{V}}{V}C + \frac{E}{V}$$

$$\boxed{\frac{dC}{dt} = P\lambda C_{out} - \lambda C + \frac{E}{V}}$$

$$\lambda = \frac{\dot{V}}{V} = \text{air exchange rate } \left(\frac{1}{\text{hr}}\right)$$

Indoor environment: Mass balance

- Assume steady-state conditions:

$$\underbrace{\cancel{\frac{dC}{dt}}}_{0} = P\lambda C_{out} - \lambda C + \frac{E}{V} \longrightarrow \boxed{C_{ss} = PC_{out} + \frac{E}{\lambda V}}$$

Assumptions:
- Building/room can be treated as well-mixed
- Ventilation/air exchange rate is constant
- Outdoor pollutant concentration is constant
- Indoor sources emit at a constant rate

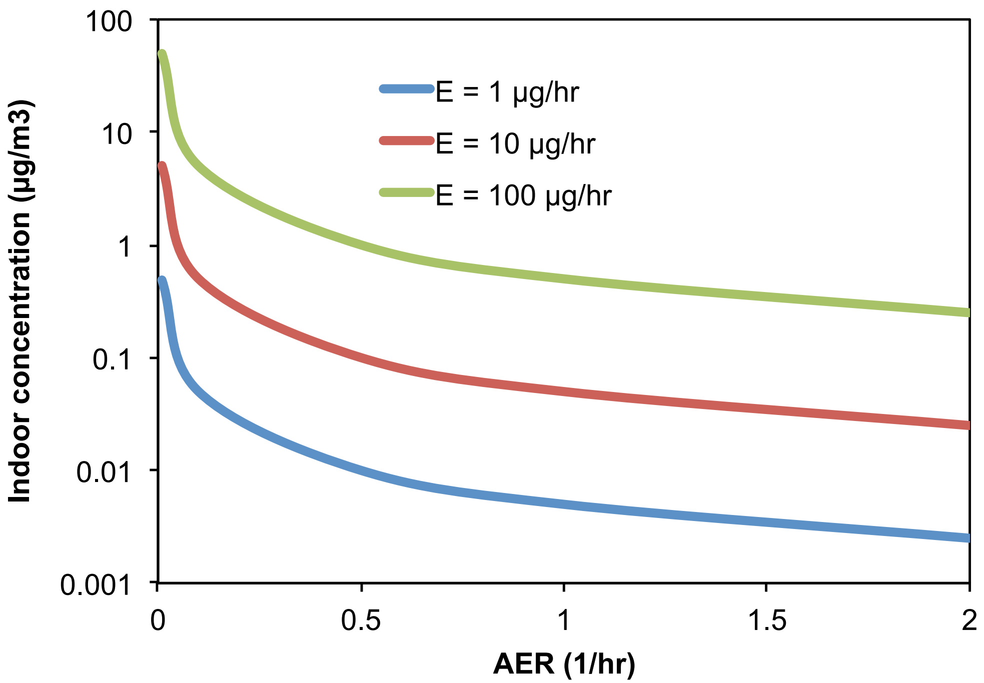
- If λ is large (and/or E is small): $PC_{out} >> E/\lambda V$
  - C approaches C_{out} (depending on P)
  - This means outdoor sources are relatively more important
- If λ is small (and/or E is large): $PC_{out} << E/\lambda V$
  - C approaches E/λV
  - This means indoor sources are relatively more important

Steady state mass balance

- Example steady state calculations: $C_{ss} = PC_{out} + \frac{E}{\lambda V}$

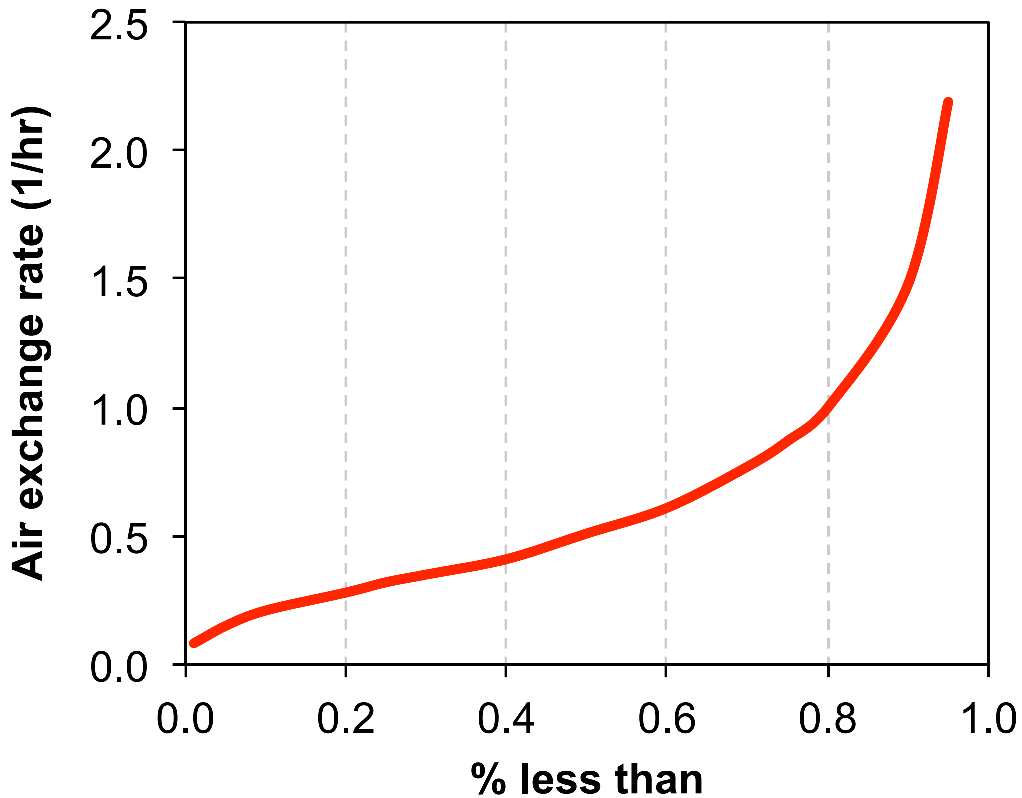
- Assume $C_{out} = 0$: $C_{ss} = \frac{E}{\lambda V}$

- Assume V = 200 m^3, how are C, E, and λ related?



What are typical values of λ (AER)?

- Distribution of AERs in ~2800 homes in the U.S.
  - Measured using PFT (perfluorocarbon tracer) in the early 1990s

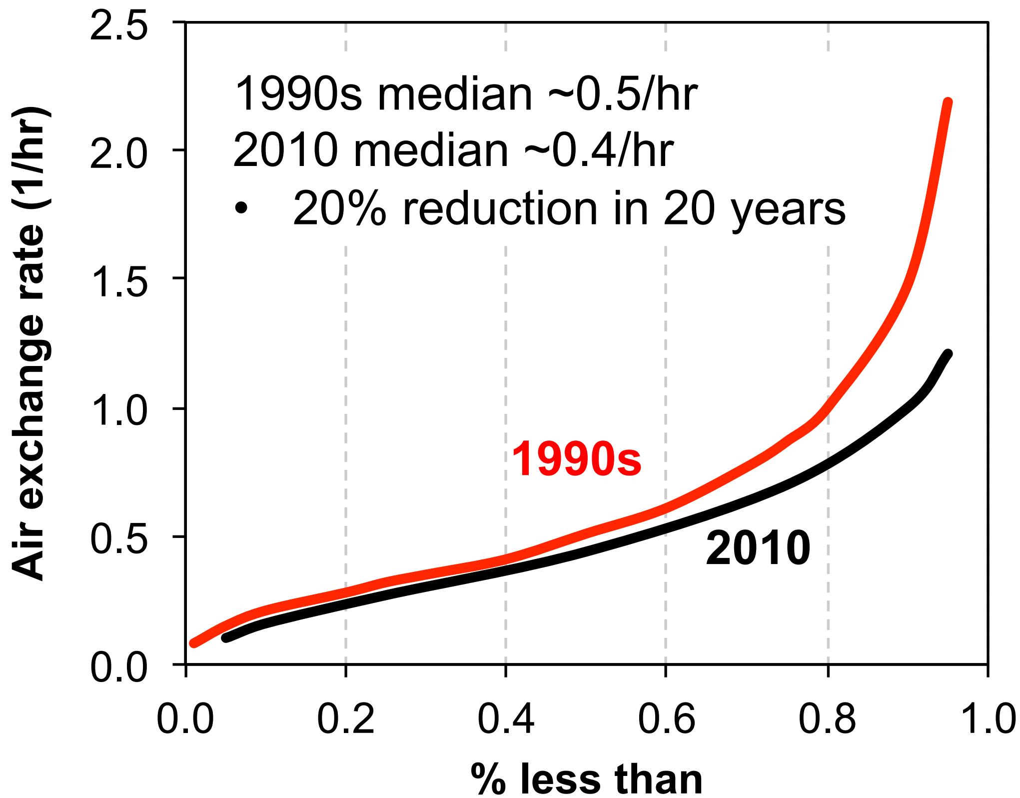


- What do you think this curve looks like now?

Murray and Burmaster, 1995 *Risk Analysis*

What are typical values of λ (AER)?

- Distribution of AERs U.S. homes
  - Early 1990s and revisited in 2010 (Persily et al. 2010)

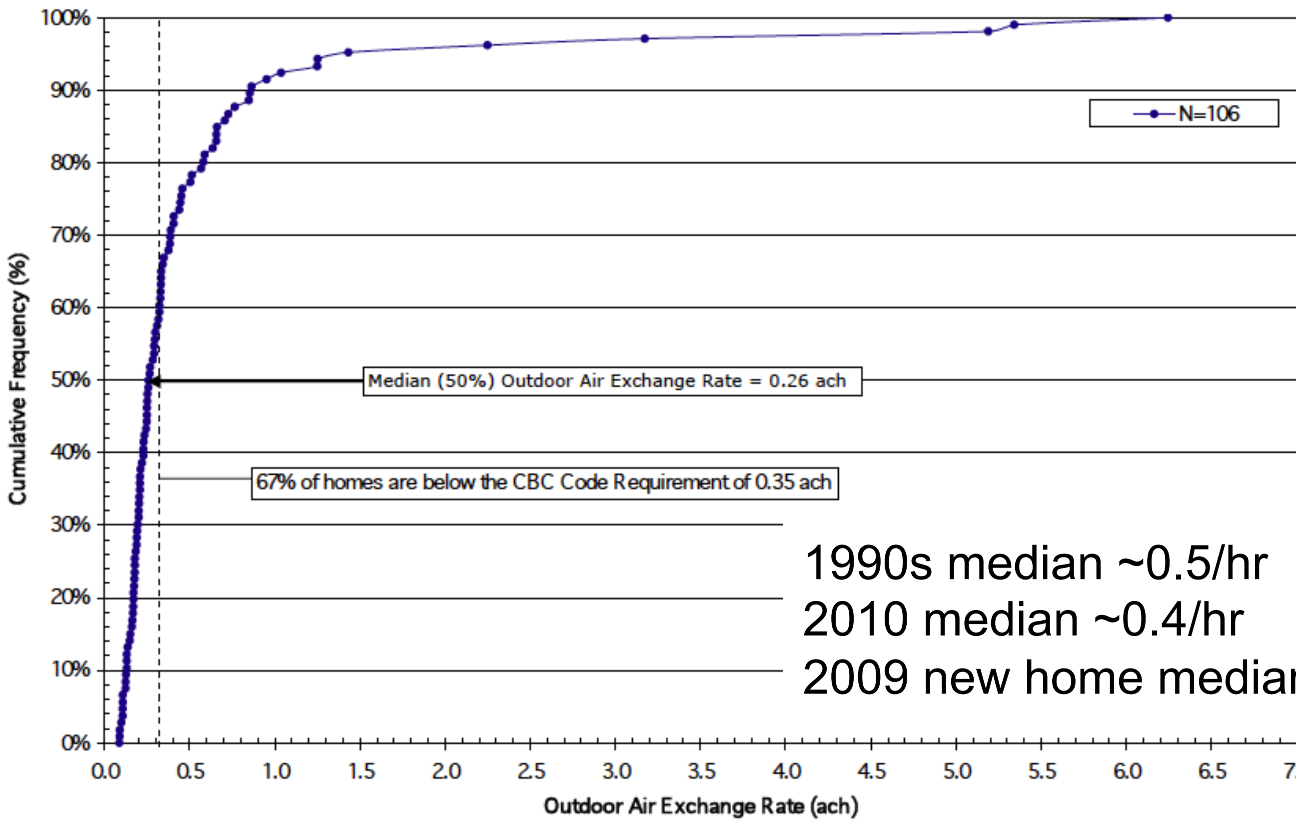


- What about new homes?

Murray and Burmaster, 1995 *Risk Analysis*; Persily et al. 2010 *Indoor Air*

What are typical values of λ (AER)?

- Distribution of AERs U.S. homes
  - Addition of 106 new homes (Offermann et al., 2009)



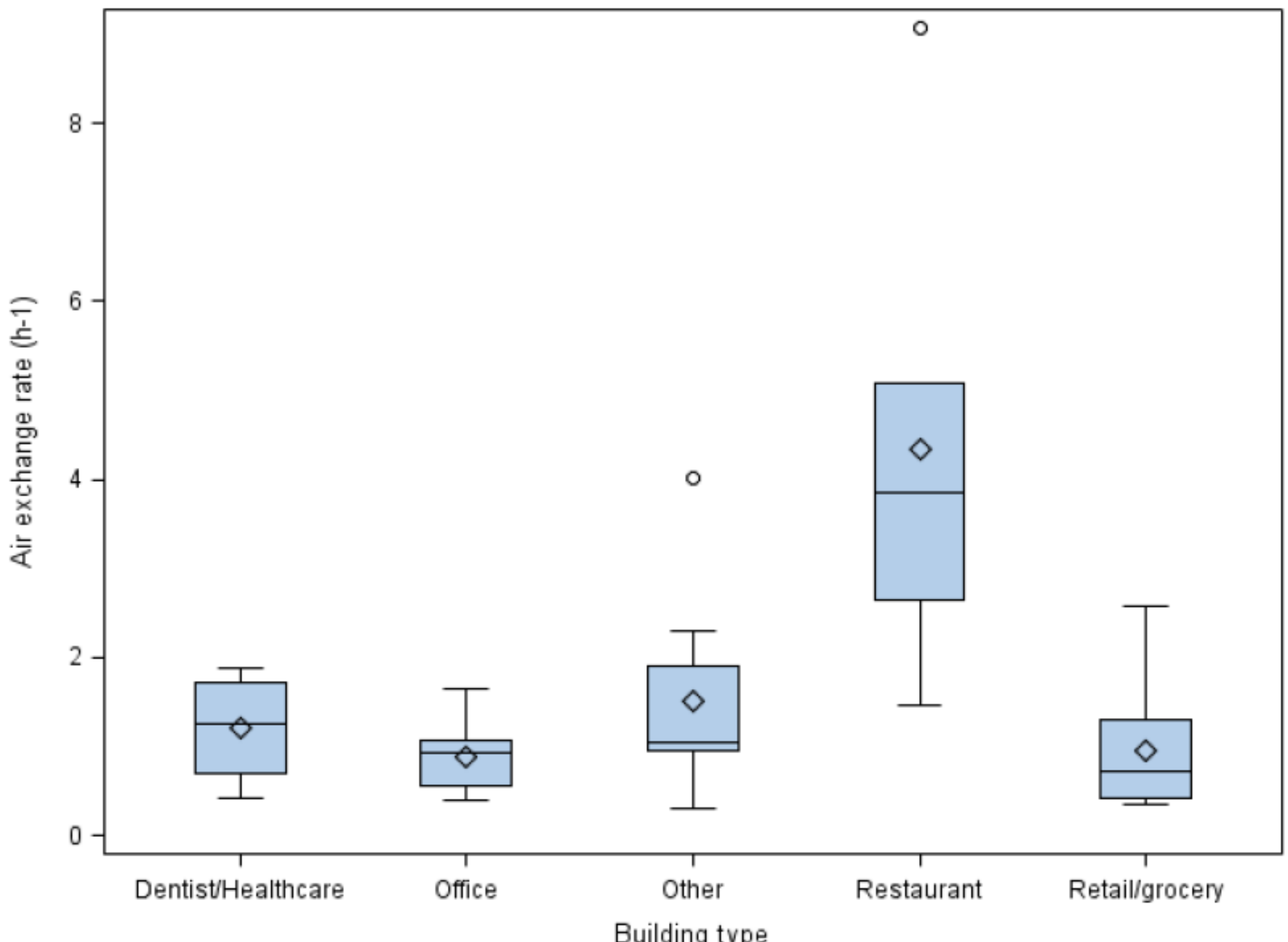
1990s median ~0.5/hr
2010 median ~0.4/hr
2009 new home median ~0.26/hr

- Not uncommon for new homes to have AER = 0.05-0.20 per hour

Offermann et al. 2009 CEC PIER Report

What are typical values of λ (AER)?

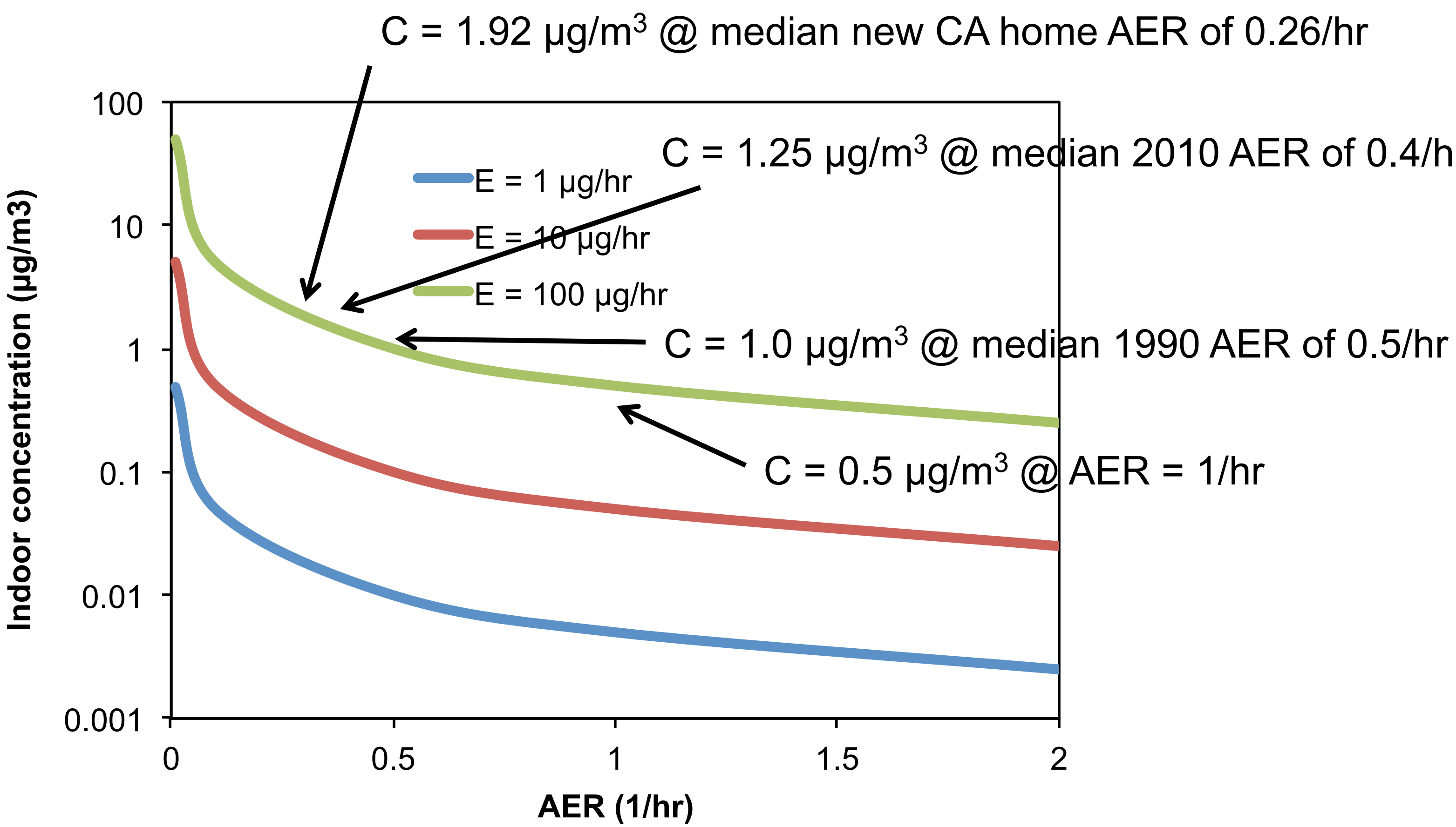
- Recent study of ~40 <u>**commercial**</u> buildings in California



Bennett et al. **2011** CEC Report

Steady state mass balance with AER

- What do trends in AERs mean for indoor concentrations?
  - Nonreactive pollutants at steady date (without an outdoor source)



Limitations to previous mass balance

- Well-mixed assumption
  - Occupant exposure can be much higher than estimated near source
  - Cooking, cleaning, vicinity of smoker
  - Personal cloud or "Pig-Pen" effect is where:

$$C_{personal} > C_{indoor}$$

- Assumption of no sinks or transformations
  - Adsorption, desorption, deposition, and reactions all ignored (for now)
- Assumption of no control of pollutants
  - No whole building filtration or portable air cleaner (for now)
- Also assumed steady-state
  - What about a dynamic solution?

DYNAMIC MASS BALANCES

Dynamic solution to mass balance

- Start with basic mass balance:

$$\frac{dC}{dt} = P\lambda C_{out} - \lambda C + \frac{E}{V}$$

- Rearrange:

$$\frac{1}{P\lambda C_{out} - \lambda C + \frac{E}{V}} dC = dt$$

- Factor out (-1):

$$\frac{1}{\lambda C - P\lambda C_{out} - \frac{E}{V}} dC = -dt$$

- Substitute: $\text{Let } x = \text{denominator} = \lambda C - P\lambda C_{out} - \frac{E}{V}$
  - So that: $\frac{dx}{dC} = \lambda \longrightarrow dC = \frac{1}{\lambda} dx$

Dynamic solution to mass balance

Letting $x = \lambda C - P\lambda C_{out} - \dfrac{E}{V}$ and thus $\dfrac{dx}{dC} = \lambda$ transforms:

$$\frac{1}{\lambda C - P\lambda C_{out} - \dfrac{E}{V}} dC = -dt \xrightarrow{\text{into}} \frac{1}{\lambda}\left(\frac{1}{x}\right) dx = -dt$$

- We can now solve this simpler equation

Rearrange:

$$\left(\frac{1}{x}\right) dx = -\lambda dt$$

Integrate both sides:

$$\int_{x_0}^{x} \frac{1}{x} dx = -\lambda \int_0^t dt$$

Solution with x:

$$\ln(x)\Big|_{x_0}^{x} = -\lambda t$$

Substitute back in for x:

$$\ln\left\{\frac{\lambda C - P\lambda C_{out} - \dfrac{E}{V}}{\lambda C(t=0) - P\lambda C_{out} - \dfrac{E}{V}}\right\} = -\lambda t$$

Dynamic solution to mass balance

$$\ln\left\{\frac{\lambda C - P\lambda C_{out} - \dfrac{E}{V}}{\lambda C(t=0) - P\lambda C_{out} - \dfrac{E}{V}}\right\} = -\lambda t$$

- Raise *e* to both sides:

$$\frac{\lambda C - P\lambda C_{out} - \dfrac{E}{V}}{\lambda C(t=0) - P\lambda C_{out} - \dfrac{E}{V}} = e^{-\lambda t}$$

- Rearrange:

$$\lambda C - P\lambda C_{out} - \frac{E}{V} = \left\{\lambda C(t=0) - P\lambda C_{out} - \frac{E}{V}\right\} e^{-\lambda t}$$

Dynamic solution to mass balance

- Solve for C:
  - Which is *C* at time *t*, or *C(t)*

$$\lambda C - P\lambda C_{out} - \frac{E}{V} = \left\{ \lambda C(t=0) - P\lambda C_{out} - \frac{E}{V} \right\} e^{-\lambda t}$$

$$\boxed{C(t) = C(t=0)\underbrace{e^{-\lambda t}}_{0} + \left(PC_{out} + \frac{E}{\lambda V} \right)\left(1 - \underbrace{e^{-\lambda t}}_{0}\right)}$$

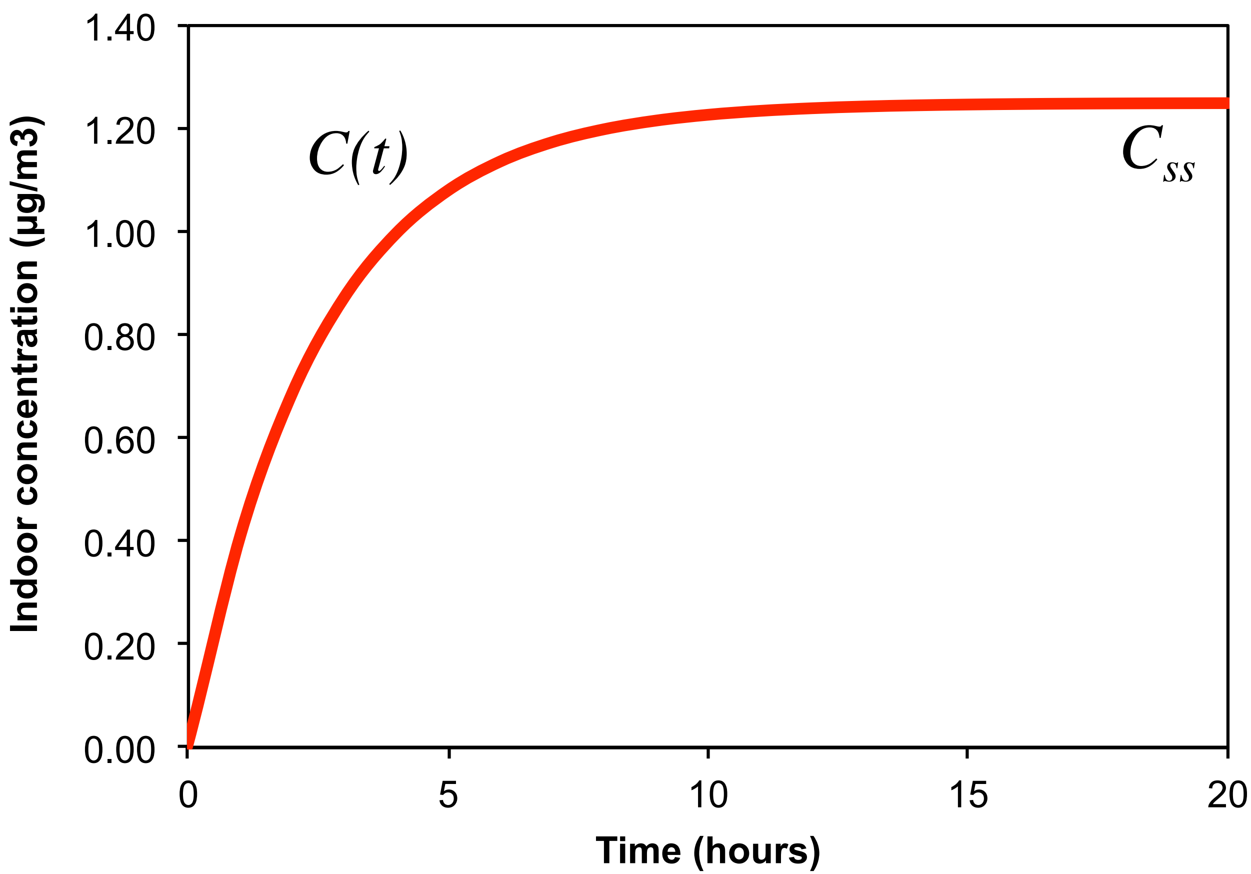
- What do these two terms represent?

- What happens as t → ∞ ?

$$\boxed{C(t \to \infty) = PC_{out} + \frac{E}{\lambda V} = \text{our steady state solution}}$$

Dynamic solution to mass balance

- Example concentration profile
  - $V = 200\ m^3$, $E = 100\ \mu g/hr$, $\lambda = 0.4/hr$, $C_{out} = 0$, $P = 1$



Time to reach steady state

$$C(t) = C(t=0)e^{-\lambda t} + \left(PC_{out} + \frac{E}{\lambda V}\right)\left(1 - e^{-\lambda t}\right)$$

- If we assume an inert pollutant emitted indoors with an initial concentration of zero, how long would it take to achieve 95% of steady state?
- 95% of steady-state is reached when:

$$\left(1 - e^{-\lambda t}\right) = 0.95 \longrightarrow e^{-\lambda t} = 1 - 0.95 = 0.05$$

$$-\lambda t = \ln(0.05) \longrightarrow \lambda t = -\ln(0.05) = 3$$

$$\boxed{t = \frac{3}{\lambda}}$$

Consider λ = 0.1 hr^{-1}

t to 95% steady state = 30 hours

Consider λ = 1 hr^{-1}

t to 95% steady state = 3 hours

Generalized steady and dynamic mass balance solutions

$$\frac{dC}{dt} = S - LC$$

$$S = sources = \lambda P C_{out} + \frac{E}{V}$$

$$L = losses = \lambda + \frac{CADR}{V} + k_{deposition} + k_{rxn} + \ldots$$

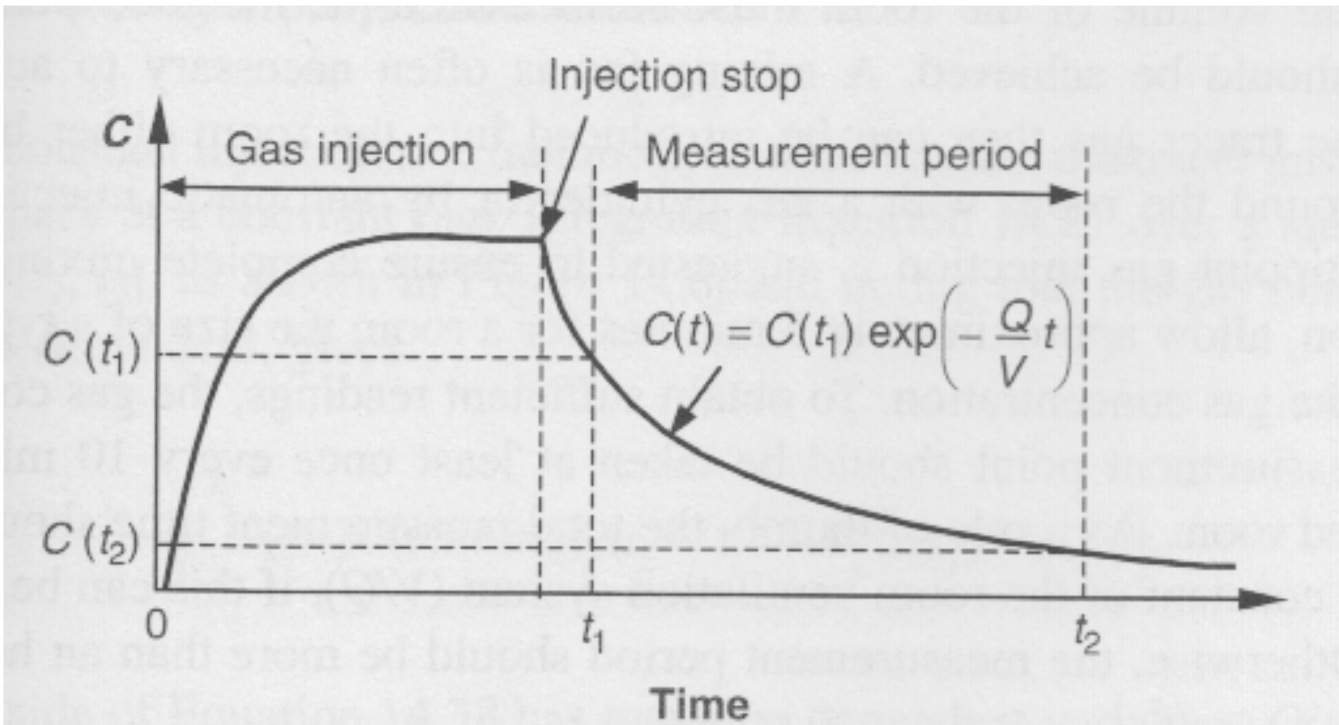
General steady-state solution: $$C_{ss} = \frac{S}{L}$$

General dynamic solution: $$C(t) = C_0 e^{-Lt} + \frac{S}{L}\left(1 - e^{-Lt}\right)$$

MEASURING AIR EXCHANGE RATES

How do we measure λ?

- One method is to inject an inert tracer gas, and measure the decay from C(t=0) after time t=0



How do we measure λ?

- One method is to inject an inert tracer gas, and measure the decay from C(t=0) after time t=0
  - In this case, E = 0
  - Assume P = 1 (reasonable for inert gas)

$$C(t) = C(t=0)e^{-\lambda t} + \left(PC_{out} + \cancelto{0}{\frac{E}{\lambda V}}\right)\left(1 - e^{-\lambda t}\right)$$

$$C(t) = C(t=0)e^{-\lambda t} + C_{out}\left(1 - e^{-\lambda t}\right)$$

$$C(t) = C(t=0)e^{-\lambda t} + C_{out} - C_{out}e^{-\lambda t}$$

$$C(t) - C_{out} = \left\{C(t=0) - C_{out}\right\}e^{-\lambda t}$$

How do we measure λ?

$$C(t) - C_{out} = \{C(t=0) - C_{out}\} e^{-\lambda t}$$

$$\frac{C(t) - C_{out}}{C(t=0) - C_{out}} = e^{-\lambda t}$$

- Take the natural log of both sides:

$$-\ln\left\{\frac{C(t) - C_{out}}{C(t=0) - C_{out}}\right\} = \lambda t$$

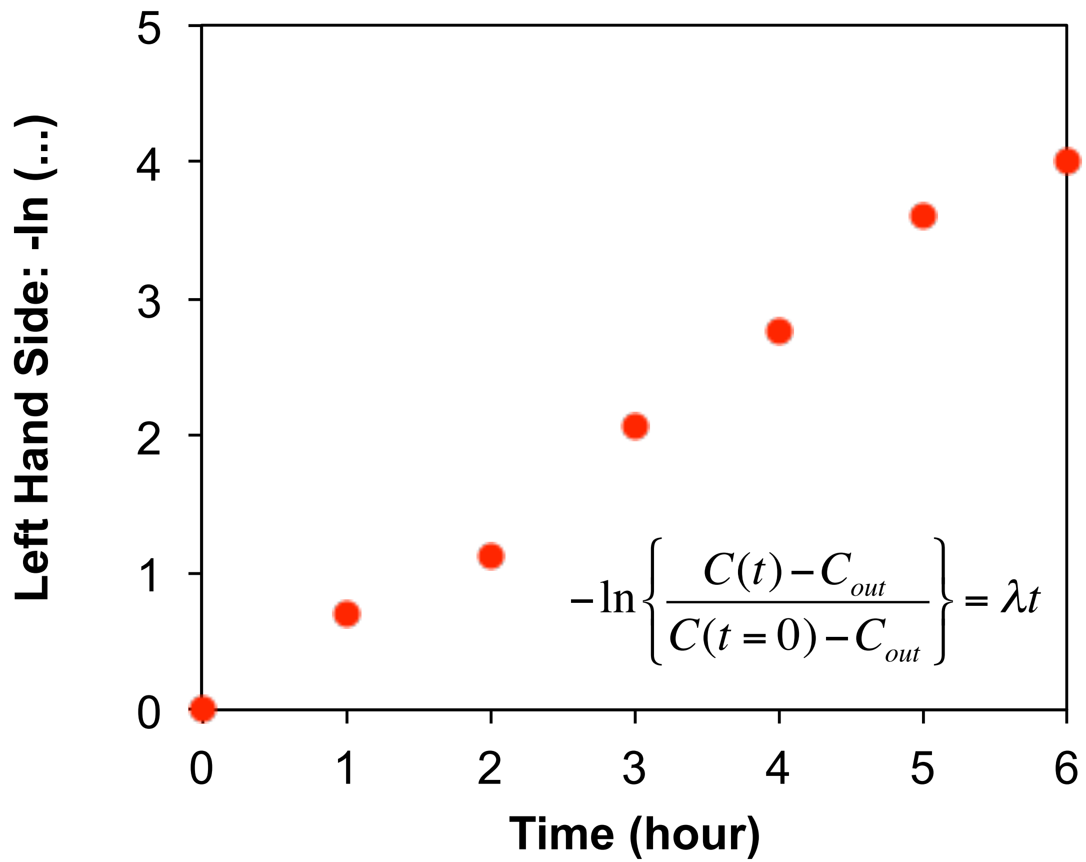
- To find λ, plot left hand side versus right hand side
  - Slope of that line is λ

How do we measure λ?

- **Example:** You perform a tracer test with CO_2
  - You measure a constant outdoor concentration of 400 ppm
  - You elevate indoors to 2000 ppm, then leave for 6 hours
  - You record these data:

Time (hr)	C(t) (ppm)
0	2500
1	1450
2	900
3	660
4	530
5	460
6	430

Plot the LHS vs time



$$-\ln\left\{\frac{C(t)-C_{out}}{C(t=0)-C_{out}}\right\}=\lambda t$$

How do we measure λ?

- **Example:** You perform a tracer test with CO_2
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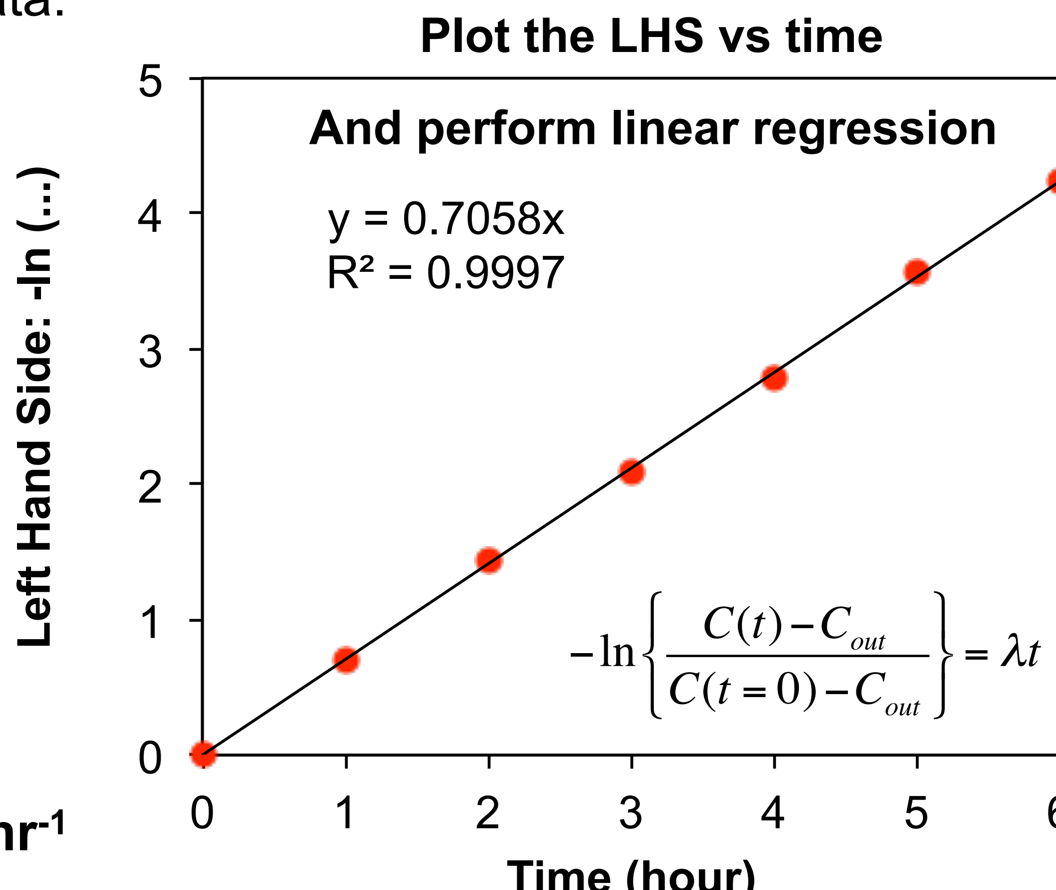

$$-\ln\left\{\frac{C(t)-C_{out}}{C(t=0)-C_{out}}\right\} = \lambda t$$

AER = λ = slope = 0.71 hr^{-1}

What makes a good tracer gas?

Characteristics

- Non-reactive (inert)
- Non-toxic
- Low detection limits
- Portable

Commonly used gases

- Carbon dioxide (CO_2)
  - People are a source
  - Need to account for E/V
- Sulfur hexafluoride (SF_6)
  - Global warming potential

I went 20+ minutes long today because I just wanted to finish (kind of nice not having to stop because it's all online!)