



Transcending Complexity: Indoor Fine Particulate Matter Measurement, Exposure and Control

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The National Academies of Sciences, Engineering, Medicine
Workshop on Indoor Exposure to Fine Particulate Matter and Practical
Mitigation Approaches

Fine PM is a major contributor to premature mortality

Global Mortality and Global Burden of Disease Results

Cause	2016 deaths (millions)
All deaths	55.5
Air pollution	6.1
Ambient particulate matter pollution	4.1
Second-hand [tobacco] smoke *	0.9

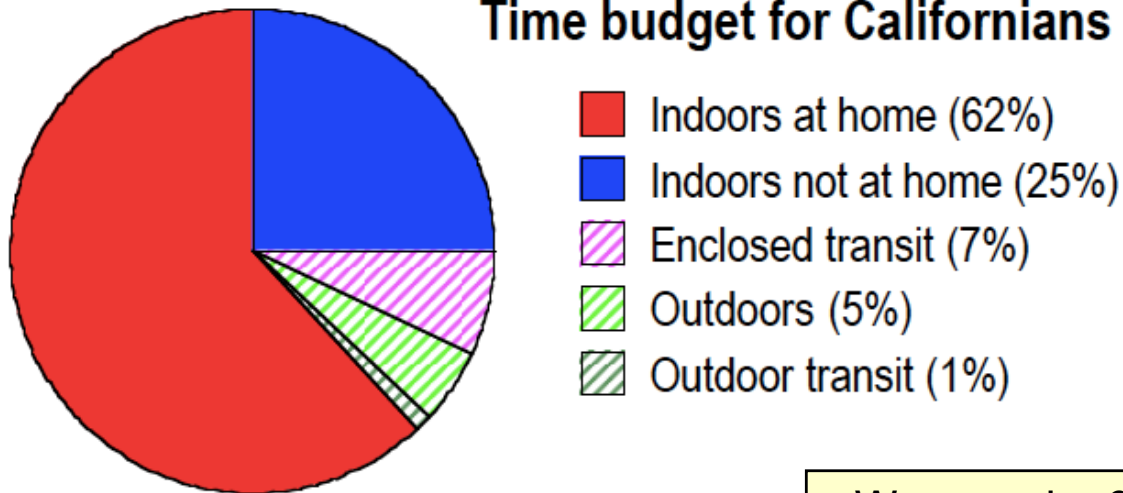
For context, the COVID-19 pandemic is estimated to have caused 2.9 million deaths globally as of 9 April 2021.

(* Premature mortality associated with second-hand smoke is attributed to fine PM.)



Exposures occur where people and pollutants meet

Time budget for Californians



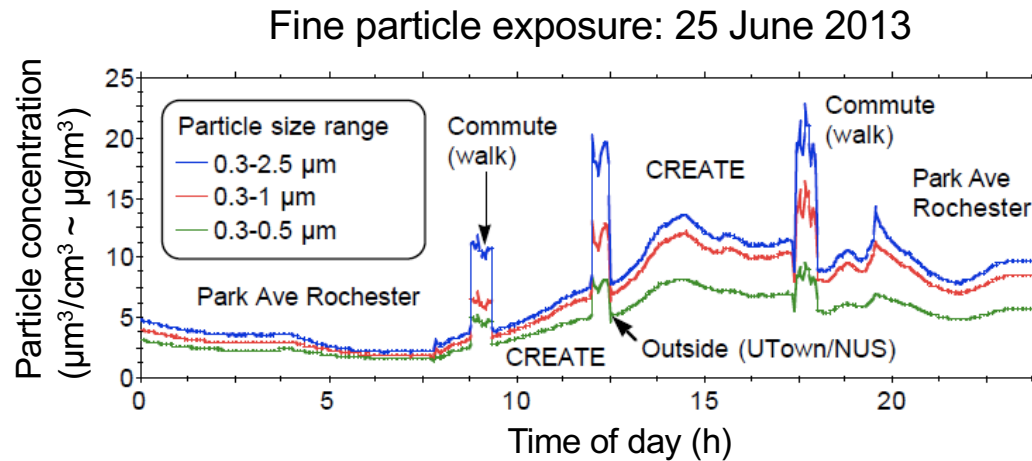
- We spend ~ 90% of our time indoors.
- Most of the air we breathe is indoor air.
- Indoor air $\neq$ outdoor air.



Buildings are partially protective against outdoor PM



Personal monitoring using real-time light-scattering instrument.



Exposure factors (0.3-2.5 μm):
 CREATE Research Building — 52%
 Park Avenue Rochester Hotel — 41%
 $\Rightarrow \sim 2\times$ protection
 (Exposure factor $\sim$ indoor/outdoor ratio)

20 June 2013 (9 AM)



8 July 2013 (9 AM)



Indoor emission sources contribute to PM exposures



Indoor fine PM: Four dimensions of complexity

Size complexity

From 0.01 to 2.5 μm is a range of 250x in diameter and a factor of 16,000,000x in mass. The same mass ratio applies between an Etruscan shrew and a gray whale.

Temporal complexity

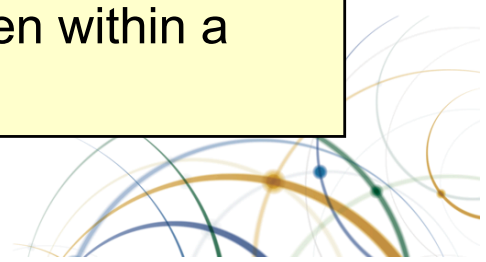
Indoor concentrations can change by 100x or more on a time scale of minutes, e.g., in response to an episodic emission event such as cooking.

Chemical complexity

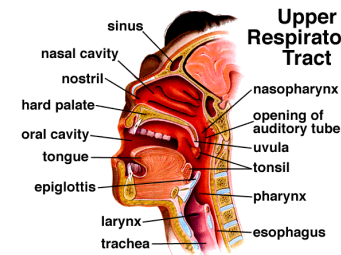
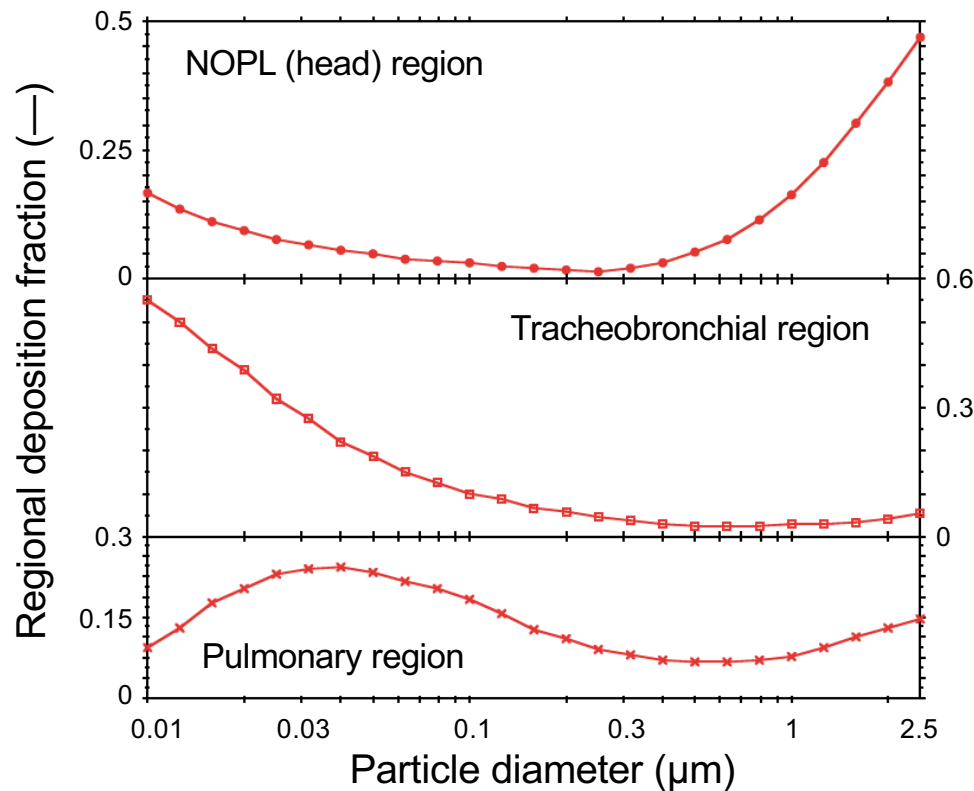
The composition of fine particles includes elemental and organic carbon (with vastly diverse chemical composition), crustal materials, inorganic salts, metals, etc.

Spatial complexity

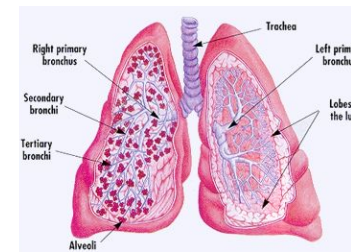
Each building is a distinct entity with its own indoor fine PM level. Within a building, concentrations may vary among rooms and even within a room.



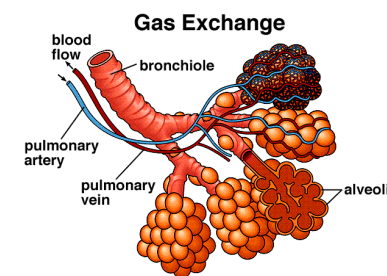
Size complexity: Regional lung deposition



Upper Respiratory Tract NOPL region



Tracheobronchial region

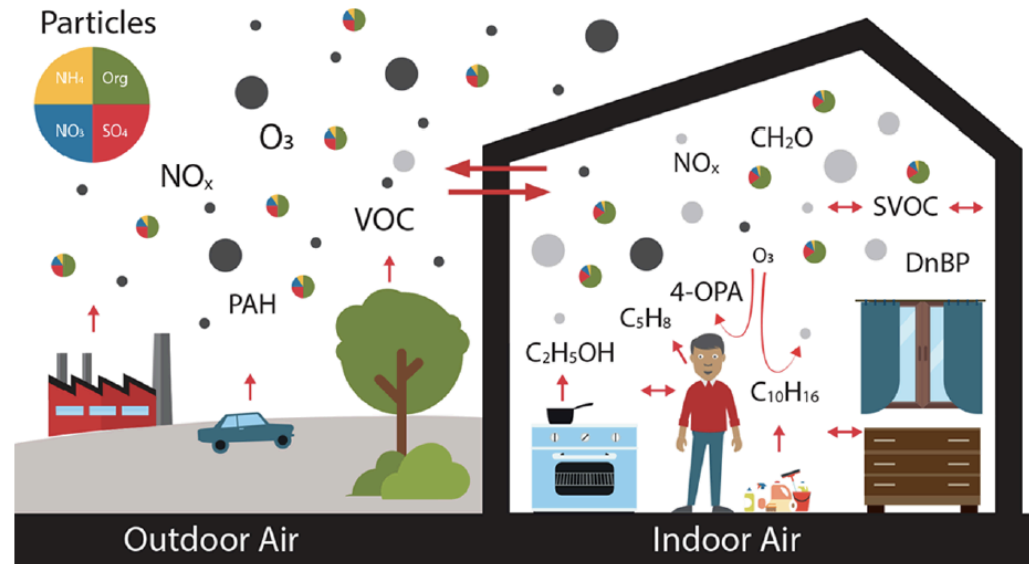


Gas Exchange Pulmonary region

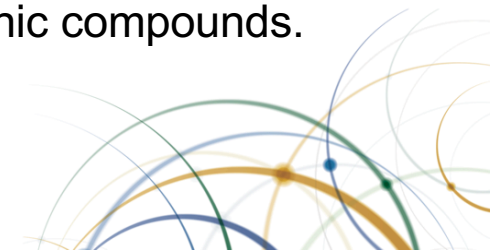
Chemical complexity: Outdoor PM comes indoors

Chemical composition is altered

- Temperature and humidity changes (affects equilibrium partitioning for semivolatile species, including H_2O).
- Surface uptake and emissions of gaseous species (affects condensation to and evaporation from particles).
- Shifts in aerosol liquid water and pH (can alter size and composition).



Prominent semivolatile components of fine PM include NH_4NO_3 and organic compounds.



Temporal complexity: PM time series during HOMEChem

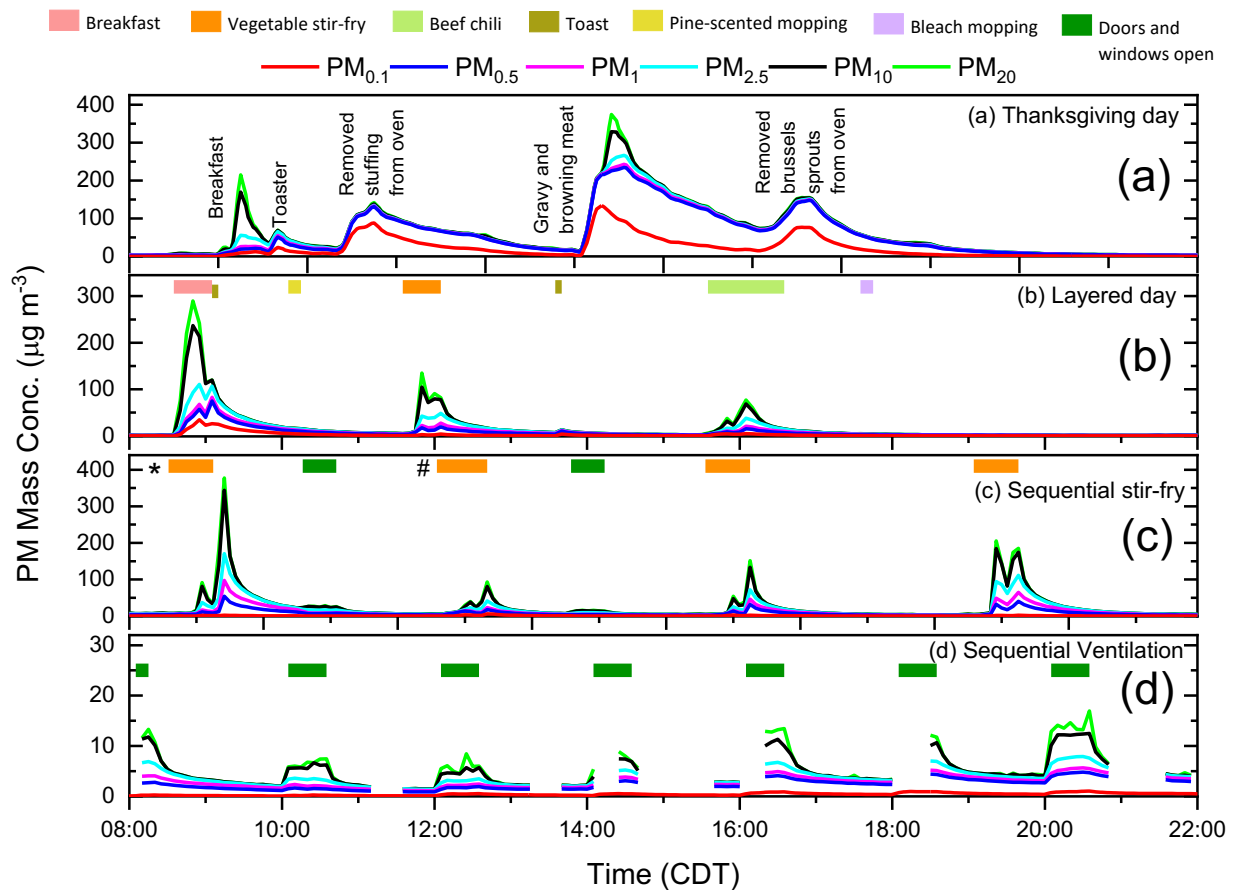
Highlights

- (a) Cooking: a strong indoor source
- (d) Absent indoor sources, I/O is higher with windows open.

PM_{2.5} concentrations (µg/m³)

- (a) Thanksgiving day — 62
- (b) Layered day — 14
- (c) While cooking stir-fry — 25-30
- (d) During high ventilation — 6
- (d) Unoccupied background — 2.3

Reference: S Patel et al., *Environmental Science & Technology* **54**, 7107, 2020.

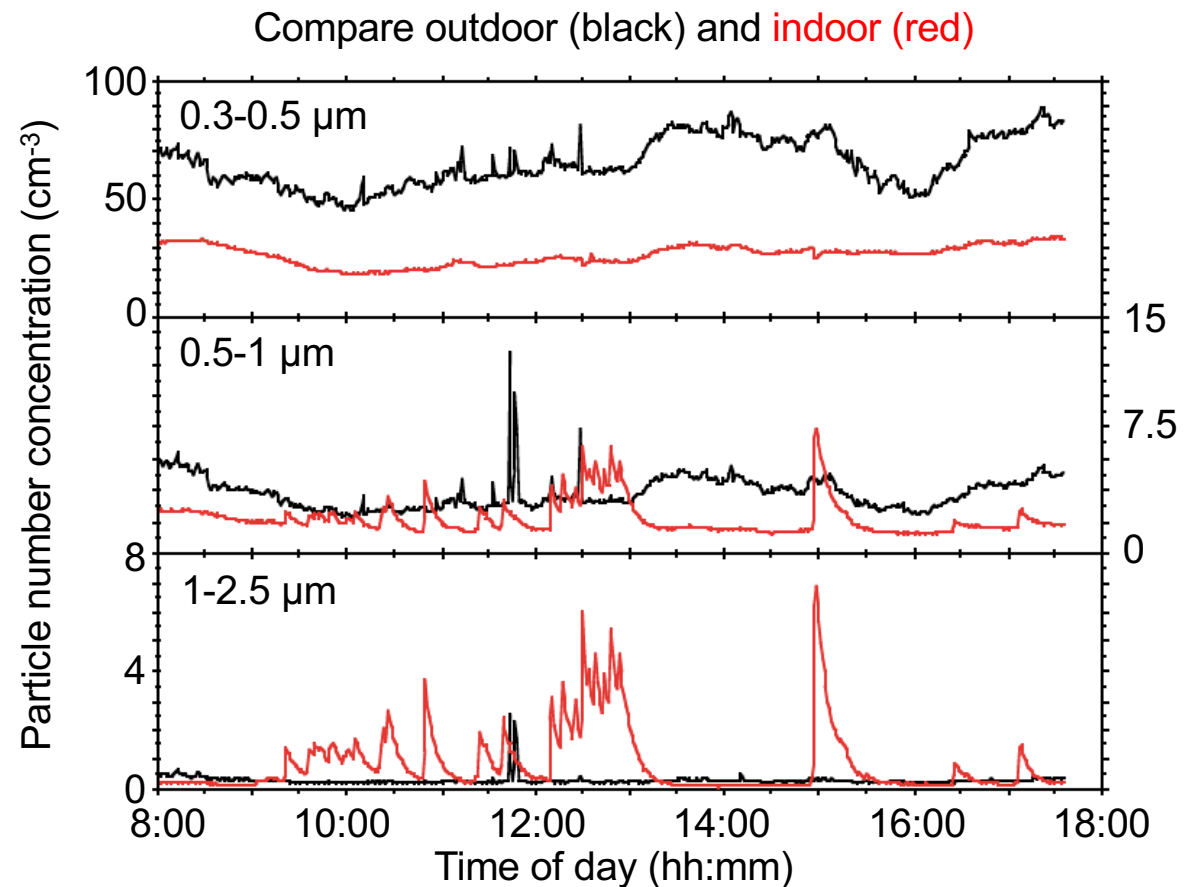


Temporal complexity: Correlation with occupancy

Optical particle counter data from university classroom in normal use.

- $V = 90 \text{ m}^3$
- Air-change rate = 5.5 h^{-1}
- Occupancy levels:
 - Before 9:00: zero
 - 9:00 – 10:15: 4 people
 - 10:15 – 11:00: 14
 - 11:00 – 13:00: 13
 - 13:00 – 15:00: zero
- Peaks after ~ 15:00 caused by sampling activity.

Reference: J Qian et al., *Indoor Air* **22**, 339, 2012.
Data collected on 05 November 2009.



Spatial complexity: Personal cloud

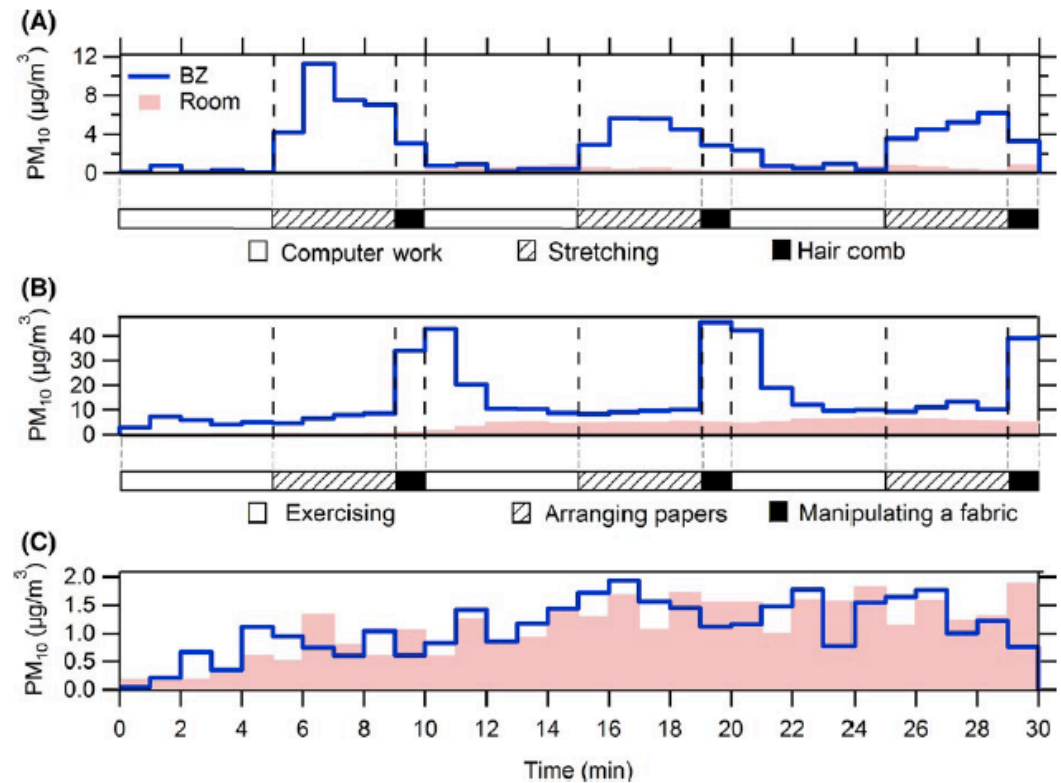
Compare breathing zone to room average PM concentrations during scripted activities in a chamber.

(A) Seated, with moderate movement.

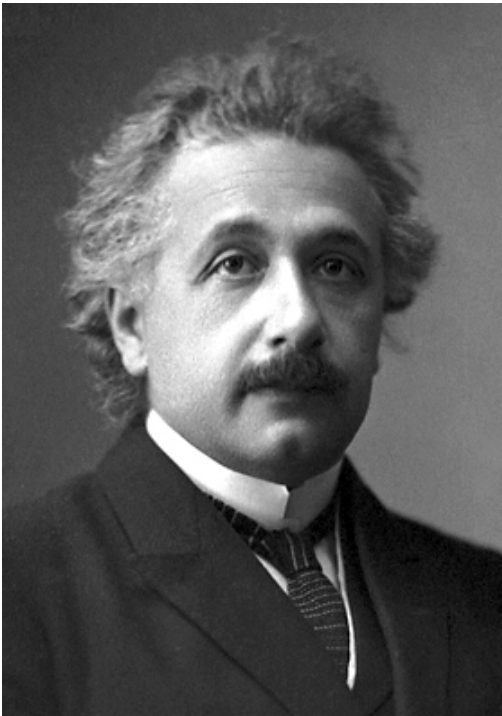
(B) Seated, with vigorous movement.

(C) Pacing.

Caveat: Most of the effect is observed in the coarse mode ($PM_{10} - PM_{2.5}$).



Transcending complexity



“Everything
should be
made as
simple as
possible, but
not simpler.”
— A Einstein



Simplifying the complexity: inhalation exposure to fine PM

Size complexity

- Use PM_{2.5} mass concentration or suitable proxy
- Use number concentration for ultrafine particles (< 0.1 µm)
- Ongoing challenge

Temporal complexity

- Be mindful so that indoor measurements effectively represent conditions during occupancy.

Chemical complexity

- Evidence to date does not implicate any compositional factors as a primary reason for adverse health consequences of PM exposure.

Spatial complexity

- Personal monitoring is better than stationary monitoring.
- Indoor data are better than outdoor data.



Some metrics for indoor particulate matter

PM_{2.5} — mass concentration of particles ≤ 2.5 μm diameter

PM₁₀ — mass concentration of particles ≤ 10 μm diameter

UFP — (typically) number concentration of particles

I/O ratio — indoor to outdoor ratio of a particle measure

Infiltration factor — I/O ratio in the absence of indoor sources

Penetration factor — proportion of particles entering with infiltration

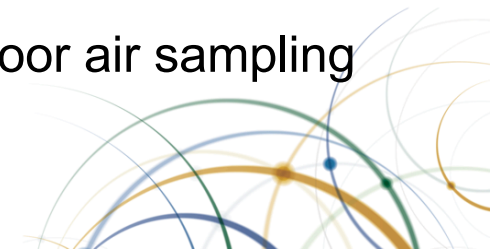
Filtration efficiency — fractional removal of particles through a ventilation filter

Air-cleaner effectiveness — fractional reduction of particle measure



Measurement methods for indoor PM

- No instrument is capable of measuring everything
- Key issues to consider
 - Particle size range and size resolution
 - Time-resolved versus time-integrated sampling
 - Chemical composition information or composition insensitive
 - Cost, portability, performance stability ...
- Some major alternatives
 - Light scattering: Good for particle sizes 0.3 – 10 μm
 - Electrical mobility can provide size-resolved data for ultrafine particles (UFP)
 - Condensation particle counters are excellent for UFP number concentration
 - Filter-based sampling is a standard method for time-integrated mass concentration and some chemical composition information
- Practical constraints are different for personal monitoring vs indoor air sampling



Guideposts for improving indoor air quality



Minimize indoor emissions

A room containing a rotting dung heap will, despite all the ventilation, remain a disgusting dwelling place, a stove for bad air. Only when cleanliness can no longer be achieved by the rapid removal or careful closure of air-polluting substances does the field of ventilation begin.

— Max von Pettenkofer (1858)

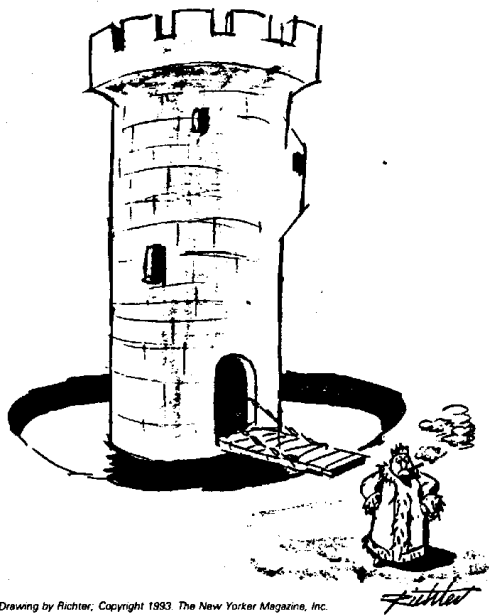


von Pettenkofer (1818-1901)



Minimize indoor emissions: Target major sources

Tobacco smoke



Cooking emissions



Masking for SARS-CoV-2

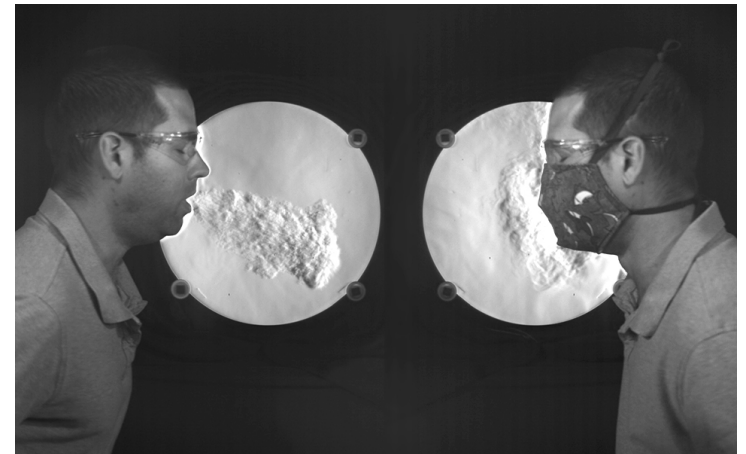
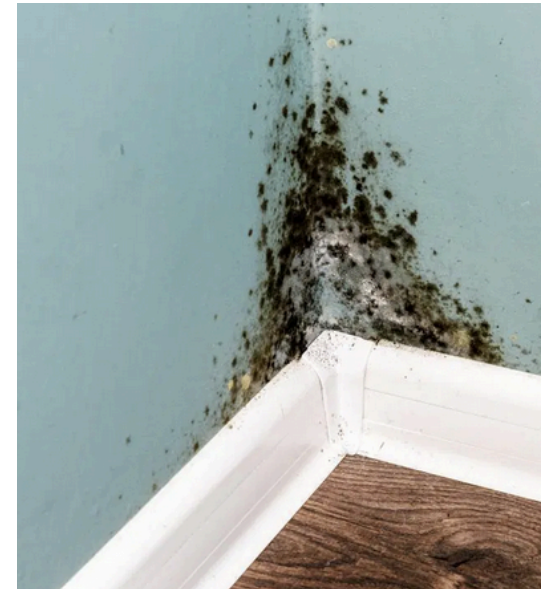


Image sources: M Richter, *New Yorker*, 1993;
<https://www.prolinerrangehoods.com/blog/range-hood-duct-sizing-guide/>; <https://www.nist.gov/blogs/taking-measure/my-stay-home-lab-shows-how-face-coverings-can-slow-spread-disease>



Keep it dry: Avoid mold and related bioaerosol problems

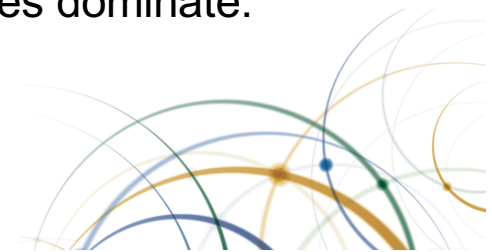


Ventilate well: Sufficiently, but not excessively

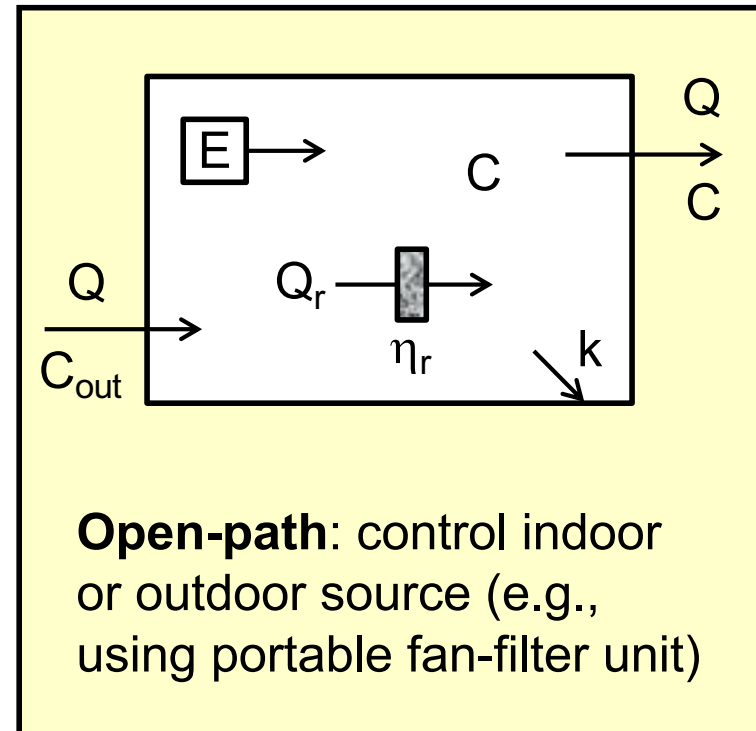
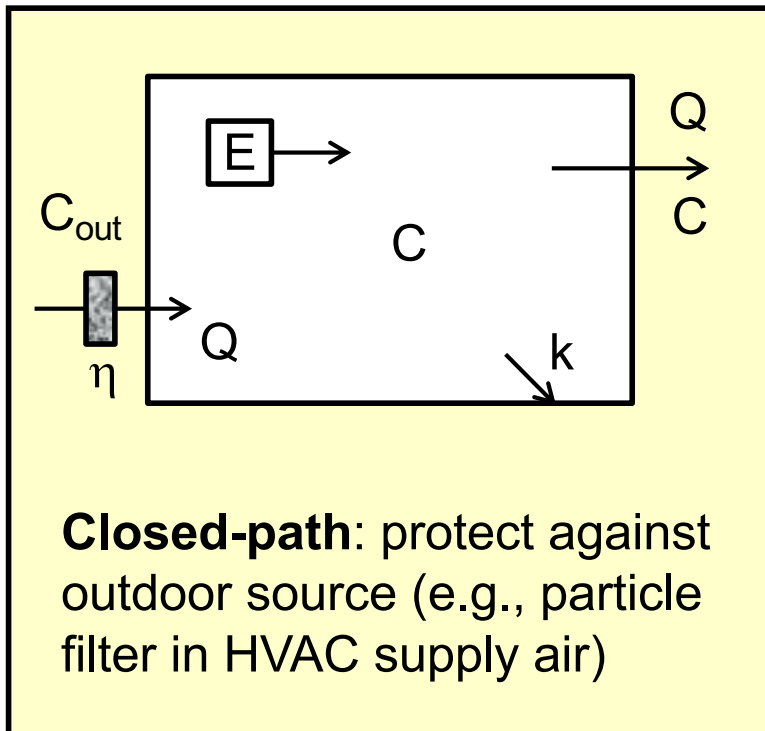
The Goldilocks Solution. Ventilate sufficiently, but not excessively.

Air-change rate too low; Indoor pollution sources dominate.

Air-change rate too high. Excessive energy use. Outdoor pollution sources dominate.

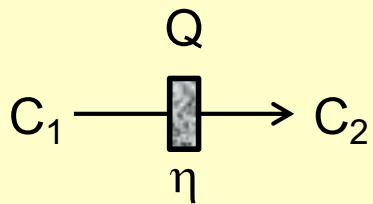


Filtration for PM control: Closed versus open path



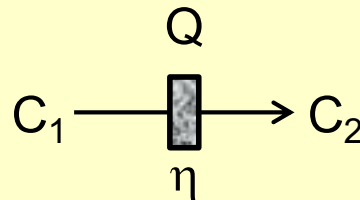
Performance metrics for indoor PM filtration

- Efficiency (η)



$$\eta = \frac{C_1 - C_2}{C_1}$$

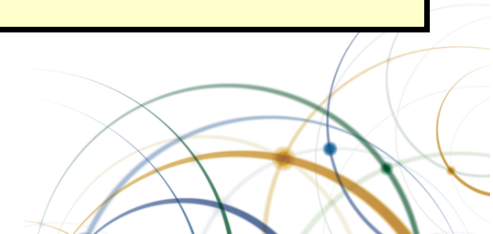
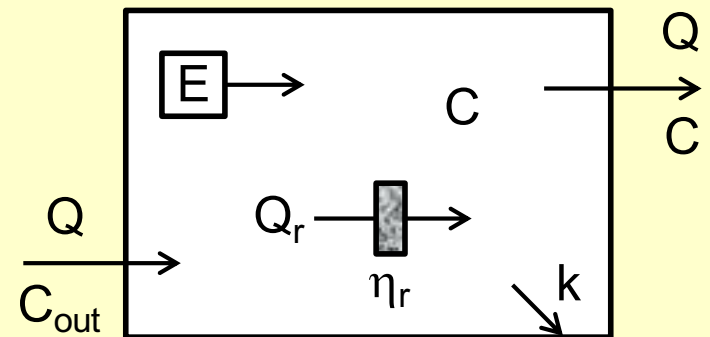
- Clean-air delivery rate (CADR)



$$\text{CADR} = \eta \times Q$$

- Effectiveness (ε)

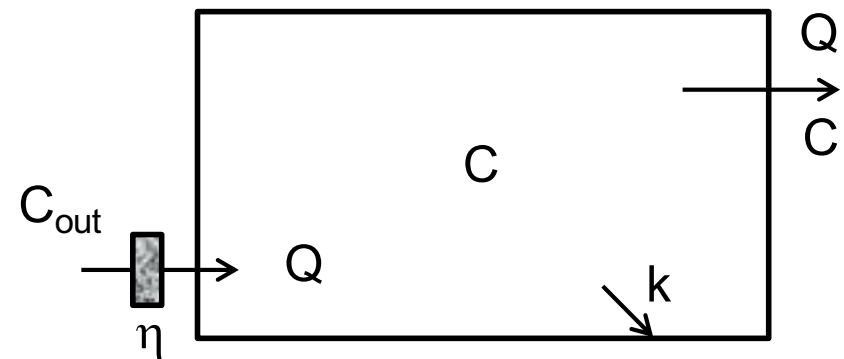
$$\varepsilon = \frac{C_{\text{uncontrolled}}}{C_{\text{uncontrolled}} + C_{\text{controlled}}}$$



Filtration to protect against outdoor pollution

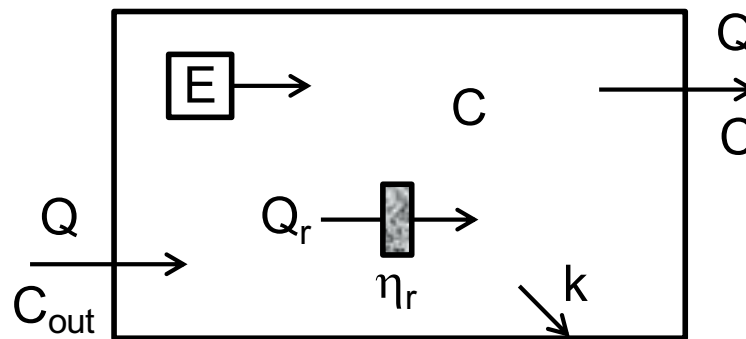
- Efficiency (η) = effectiveness (ε)
- Outdoor source: $CADR = Q \times \eta$
- Time-varying performance is the same as for steady-state conditions.
- Another key to effectiveness:
Avoid bypass

Key for high performance:
 $\eta \rightarrow 1$

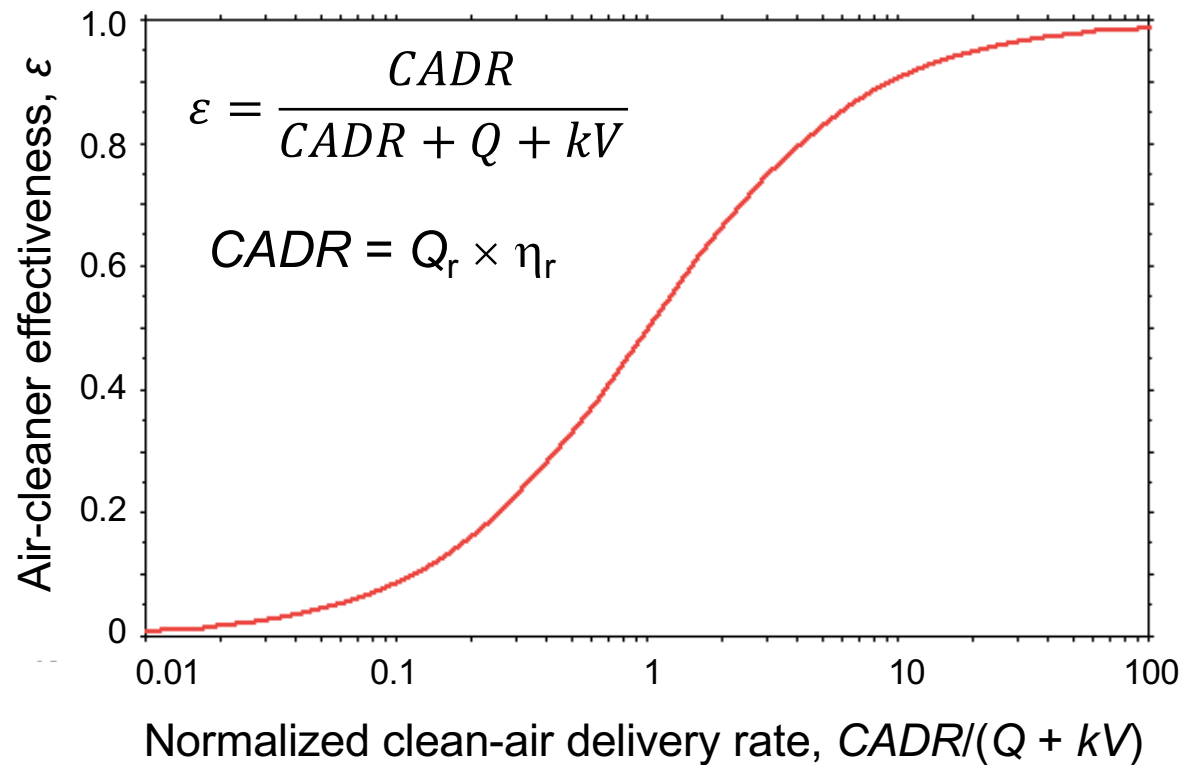


Recirculating filter units: Effectiveness $\neq$ efficiency

- $CADR = Q_r \times \eta_r$
- Effectiveness (ε) versus efficiency (η) :
 - Steady-state: compare removal by air cleaning ($Q_r \times \eta_r$) to removal by ventilation (Q) plus deposition (kV).
 - Effectiveness for transient peaks is less than for steady-state or time-averaged concentrations.



Open-path performance: Effectiveness $\neq$ efficiency



Key for high performance:
 $CADR \gg Q + kV$

Significance: Effective particle filtration can trade off higher flow rate for somewhat lower efficiency to obtain good effectiveness.

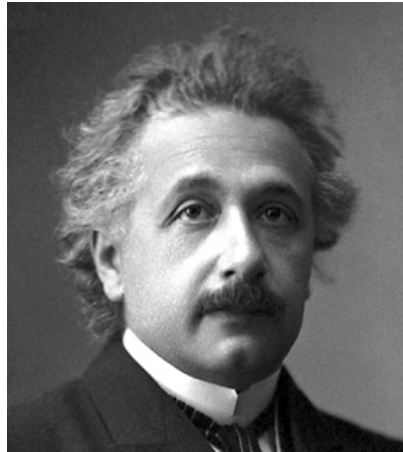


Transcending complexity for indoor fine particulate matter

- Complexity is real
- Sometimes it is important
- Complexity need not impede effective action

Indoor PM: 4D complexity

- Broad range of sizes
- Chemically complex
- Temporally variable
- Spatially variable



“Everything should be made as simple as possible, but not simpler.”
— A Einstein

