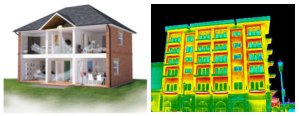
SIMUREX 2018 scientific school

15-19 October, 2018



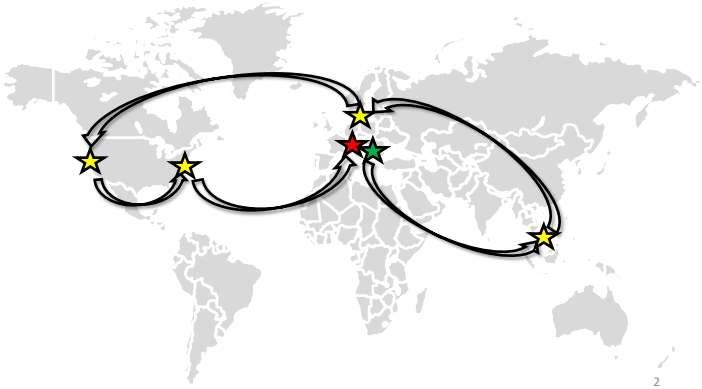
Air quality in buildings – how well can we engineer it?

October 15, 2018

Human-Oriented Built Environment Lab
Website: hobel.epfl.ch
Twitter: @licinadusan

Asst. Prof. Dusan Licina, Ph.D.
School of Architecture, Civil and Environmental Engineering
École polytechnique fédérale de Lausanne
dusan.licina@epfl.ch

My air pollutant exposure trajectory…



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Human-Oriented Built Environment Lab

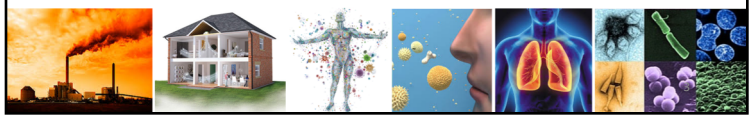
Indoor air quality (IAQ)

Human exposure assessment

Building environmental monitoring

Ventilation systems and energy efficiency

Human thermal comfort, behavior and interactions



Presentation outline

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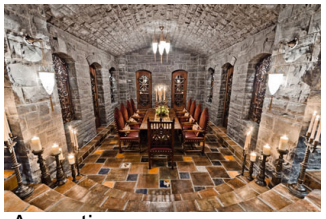
Indoor environmental quality


Thermal comfort


Lighting


Indoor air quality


Acoustics

(Source: Barbara Erwine)

What do you think when you hear "air pollution"

What do I think when I hear "air pollution"

(Source: Sam Falconer/Debut ART)

Interesting facts…

There are 7 Billion people living on the Earth.

There is 714 million kilograms of atmospheric air available per person.

$$\frac{5\times10^{18}\ kg}{7\times10^{9}} = 7.14\times10^{8}\ kg$$

100 metric tons

Mass of all indoor air is about 20'000 times lighter than outdoor air on a per-person basis !

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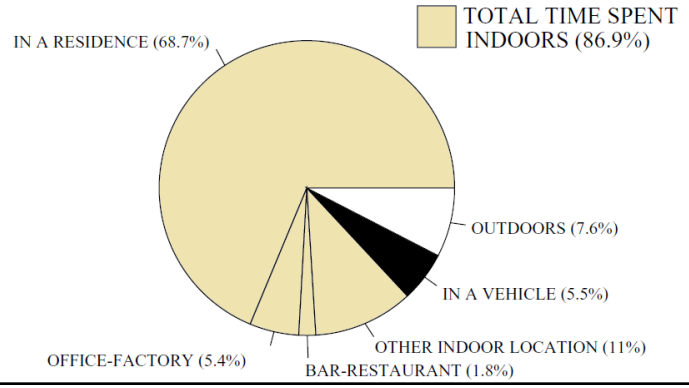
(Adapted from Nazaroff WW, Goldstein AH (2015), Indoor Air, 25: 357-361)

We spend *a lot* of our time in buildings

- Around 90% of the time, on average
  (Source: Klepeis et al., 2001 J Exp Anal Environ Epidem)



The Corsi code

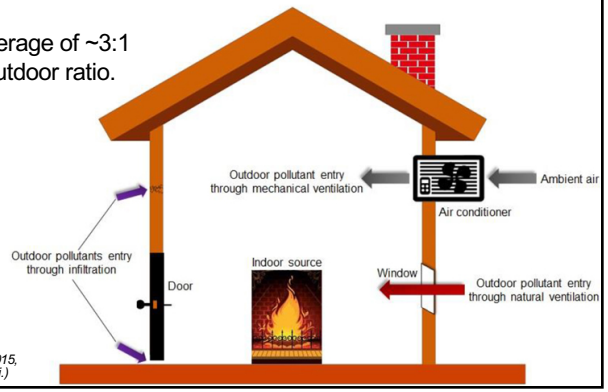
Prof. Richard Corsi, UT Austin, USA

Indoors		In bed		Outside	
79	**70**	**50**	**26**	**5**	**4**
Average life expectancy		**At home**		**In transit**	

Indoor vs. Outdoor air quality

"Indoor air can be 2 to 5 times more polluted than the air outside your house" *(Source: US EPA (United States Environmental Protection Agency))*

Global average of ~3:1 indoor / outdoor ratio.



(Source: Leung 2015, Front. Environ. Sci.)

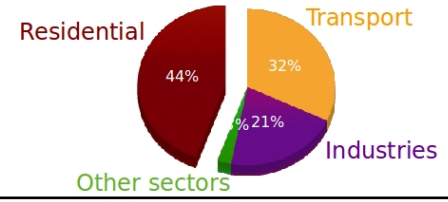
Indoor air quality implications

- Energy use
- Health and well-being
- Cognitive performance
- Cost

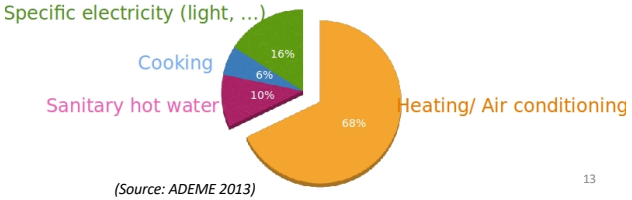
IBN: Institute for Forestry in the Netherlands. *behnisch architekten* .

Energy consumption in France

Total Energy



Building Energy



(Source: ADEME 2013)

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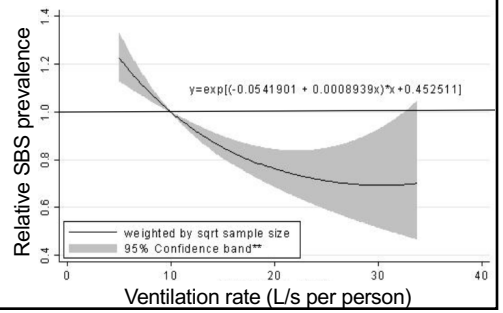
Energy, ventilation and health

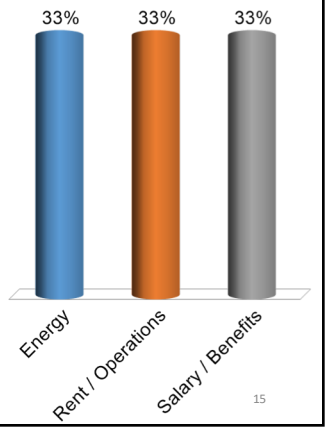
- Low ventilation rates cause an increased risk of allergies, SBS symptoms, and respiratory infections *(Source: Sundell at al. 2011)*
- Low ventilation rates in dwellings increased the risk of allergic symptoms among children *(Source: Bornehag et al. 2005)*

(Source: Fisk et al 2009 Indoor Air)



Commercial buildings: Which of the following operating costs is the highest?

A. Energy
B. Rent / Operations
C. Salary / Benefits



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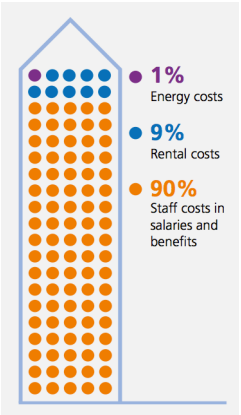
Impact on the 90%

50 %
Drop in Cognitive Brain Function with Elevated CO_2 levels.
Harvard School of Public Health

Lack of fresh air in buildings can cause
35%
of total absenteeism
Milton et al. 2000

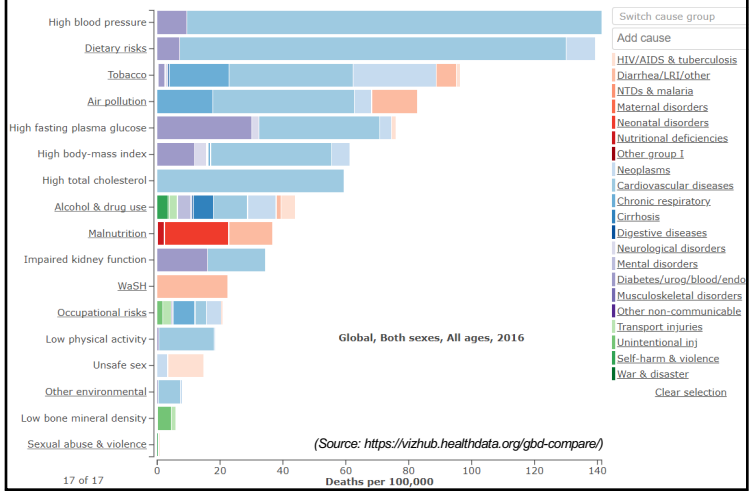
90 %
of Employees are Impacted by the Quality of their Work Environment
Gensler

Productivity Improvements of
8 to 11%
are Common with Better Air Quality
World Green Building Council

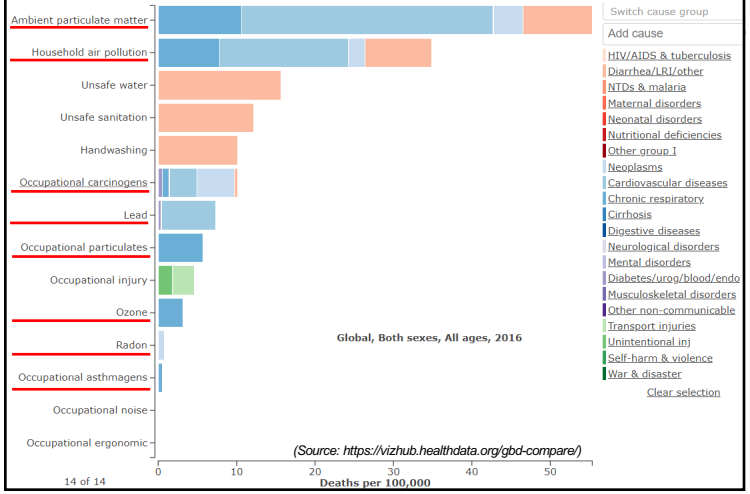


- **1%** Energy costs
- **9%** Rental costs
- **90%** Staff costs in salaries and benefits

Global causes of death – All risk factors



Global environmental and occupational risks



Residential air quality 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)

(Source: Logue et al., Environ. Health Perspect. 2012, 120, 216-222)

- Biomass fuels in households are estimated to be responsible annually for **~0.7 to 2.1 million premature deaths** in low-income countries

(Sources: Smith et al. 2004)

Household air pollution – 3rd most important cause of ill health for the world's population

(Source: Lim et al. 2012, Lancet)

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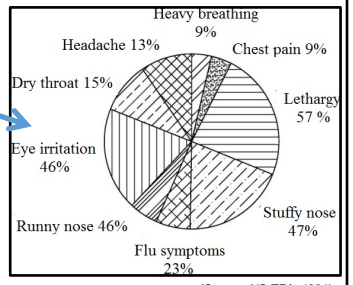
Sick building Symptoms and Building-Related Illnesses

Sick Building Syndrome (SBS) symptoms

Building-Related Illnesses

Exposure to indoor air pollution

- SBS symptoms - Building occupants experience acute health and comfort effects that are linked to the time spent indoors
- BRI - Health problems accompanied by physical signs that persist



(Source: US EPA, 1991)

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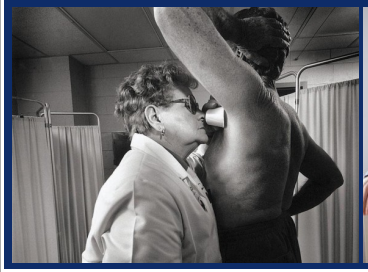
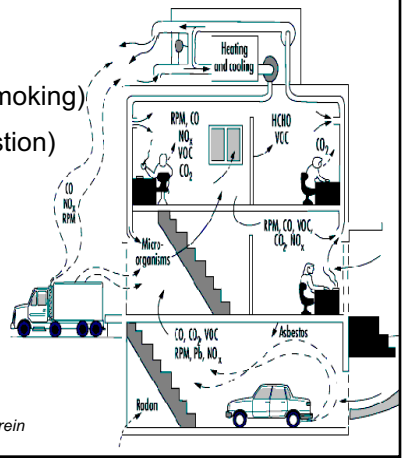



Sources of air pollution in buildings

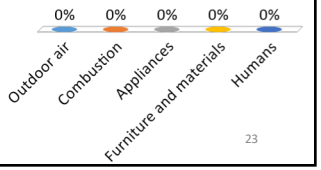
- Outdoor air
- Combustion (cooking, smoking)
- Appliances (non-combustion)
- Furniture and materials
- Consumer products
- Humans, pets



US EPA 2009 and many references therein

What is typically the major air pollutant source in buildings?

A. Outdoor air
B. Combustion
C. Appliances
D. Furniture and materials
E. Humans



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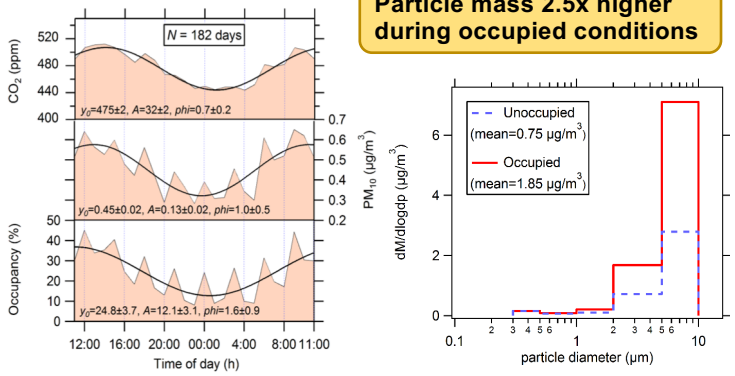
Case Study – Particle Sources in NICU

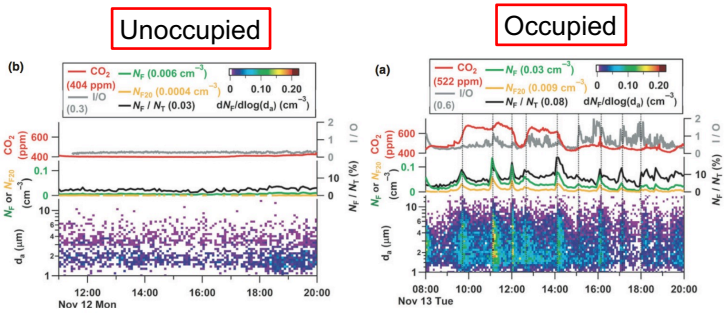
Humans are often major sources of PM



Particle mass 2.5x higher during occupied conditions

(Source: Licina et al. 2016, PLOS One)

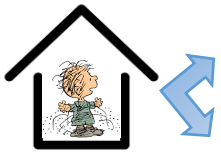
Case Study – Bioaerosol sources in classroom



(Source: Bhangar et al. 2014 Indoor Air 24(6):604-617)

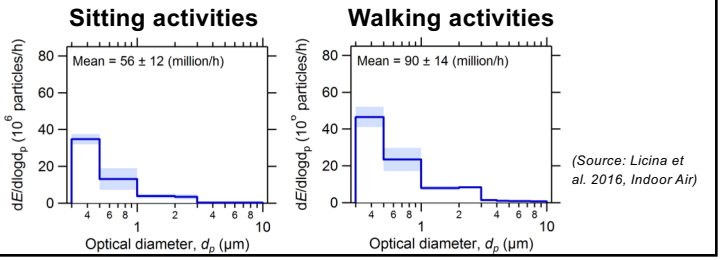
Humans are major sources of bioaerosols in classrooms!

Mechanisms of human particle emission



Exogenous – cooking, vacuuming, making a bed, cleaning, hobbies, etc.

Endogenous – particle release from human skin and clothing.



(Source: Licina et al. 2016, Indoor Air)

Mechanisms of human particle emission

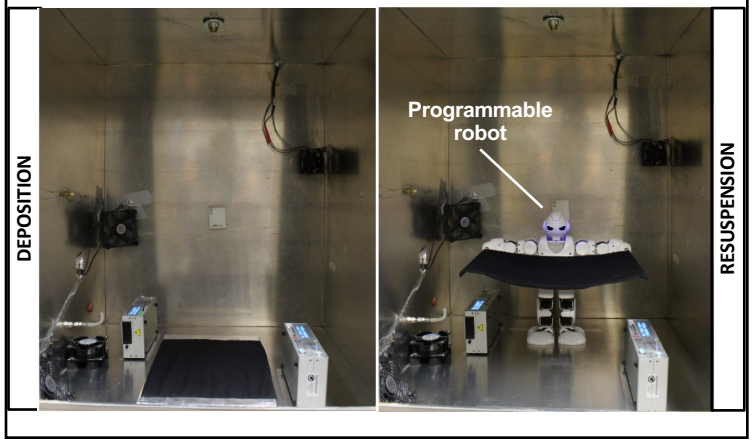
Exogenous – cooking, vacuuming, making a bed, cleaning, hobbies, etc.

Endogenous – particle release from human skin and clothing.

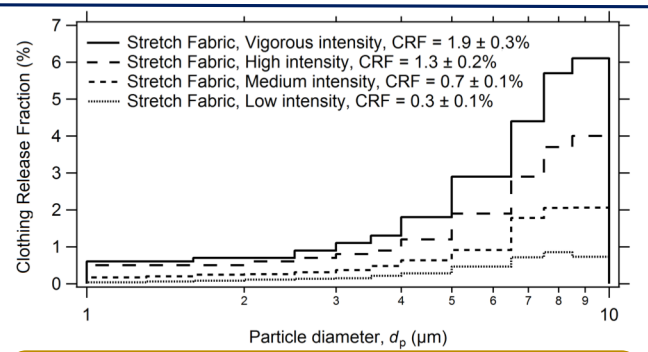
Particle shedding from skin
Exhalation of respiratory particles
→ **Human body**

Shedding of fabric fragments
Transport vector
→ **Clothing**

Clothing as a transport vector for particles



Clothing release fraction (CRF)



- CRF increases with particle size
- CRF increases with the vigor of activity intensity
- Clothing releases ~1% of previously deposited material

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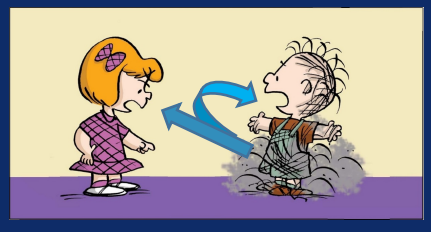

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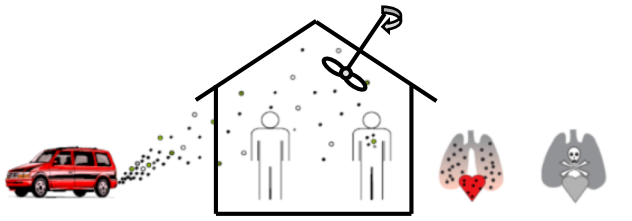
Emissions to health effects paradigm



emissions → concentration → exposure → intake → dose → health effects

emissions ⟶ intake

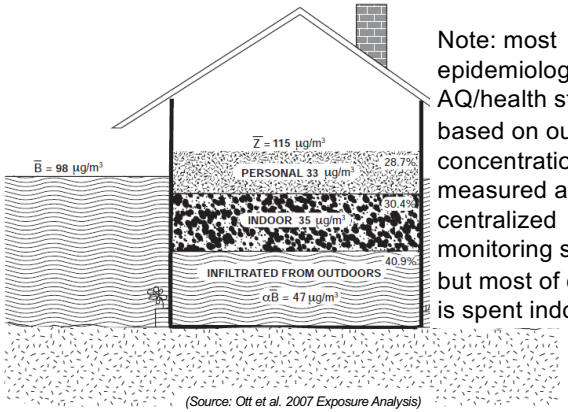
Exposure definitions

- **Exposure:**
  - Contact between an agent and a target at a contact boundary over a specified time period.
- **Routes of exposure:**
  - 3 Primary routes: Inhalation, Ingestion, Dermal.
- **Calculation of inhalation exposure:**
  - Units: Conc. x Time [e.g., µg/m^3 hours]

$$Exposure = \int_{t_1}^{t_2} C(t)dt$$

- **Pathways of exposure:**
  - Many! The exposure pathway describes how agent gets from the source to the target.

Relationship of outdoor concentrations, indoor concentrations and personal exposure



(Source: Ott et al. 2007 Exposure Analysis)

Note: most epidemiological AQ/health studies are based on outdoor concentrations measured at centralized monitoring stations, but most of our time is spent indoors.

Exposure Assessment

(Source: Licina et al. 2016 Indoor Air)

- **Direct assessment:**
  - The most accurate method
  - Often neither affordable nor technically feasible
- **Indirect assessment:**
  - Less reliable due to numerous assumptions
  - Required information: personal activities, locations, time in each location, distribution of concentrations

Exposure assessment with low-cost monitors

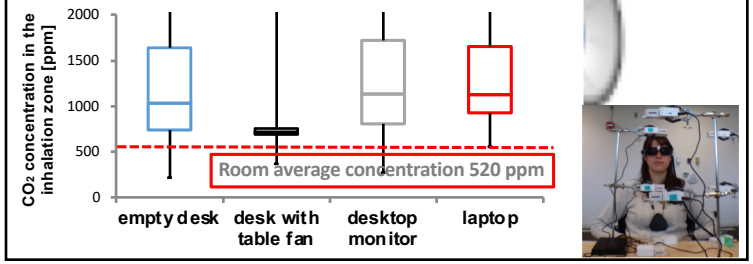
- The recent proliferation of low-cost IAQ monitors is changing the way we assess exposure
- There is a need to characterize these low-cost monitors to determine their accuracy, precision, and limitations

(Source: http://www.citizensense.net/kits/air-quality-sensing/)

Case study – Personal CO_2 cloud

Objective
- Investigate difference between exposure to exhaled CO_2 measured in the microclimate and the room

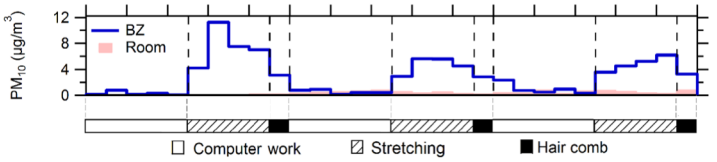
Approach
- Simulated office activities in environmental chamber
- High frequency CO_2 measurement in breathing zone, microclimate, room level
- Computational Fluid Dynamics (CFD)



Case study – The Pig Pen effect

Objective
- Investigate difference between exposure to particulate matter in the breathing zone and the room

Approach
- Simulated activities in environmental chamber with 2 volunteers
- High frequency particle measurements in breathing zone and in the room

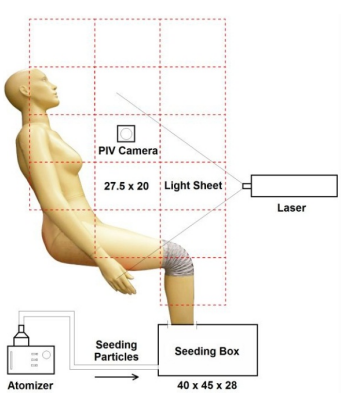


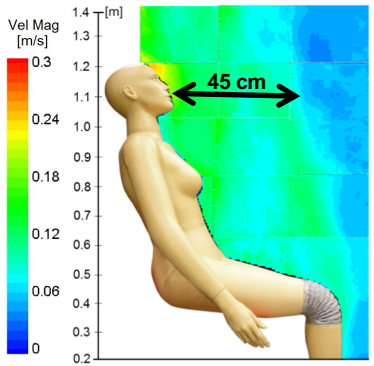
(Source: Licina et al. 2017, Indoor Air)

Where does the pollution go?

Human convective boundary layer in a calm indoor environment at 23 ˚C room air temperature

Human Thermal Plume – Physics of the flow

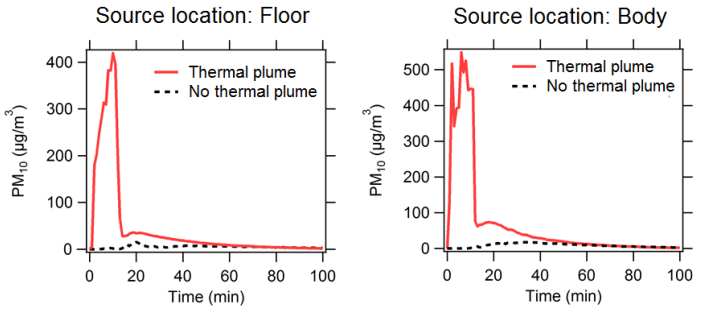




Velocity contours in front of the seating manikin

(Source: Licina et al. 2014 Building and Environment)

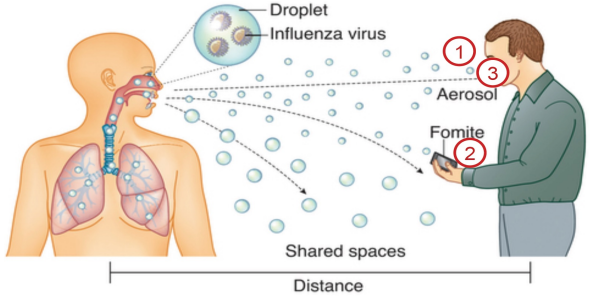
Human Thermal Plume – Personal exposure



- Human thermal plume can increase exposure to pollutants released nearby as much as 6-9 times

(Source: Licina et al. 2017 Building and Environment)

Primary modes of pollutant transmission



(Source: Lakdawala and Subbarao 2012 Nature Medicine 18:1468-1470)

1. Direct contact with pathogen source (large droplet) – for particles
2. Contact with contaminated object surfaces ("fomite")
3. Inhalation of airborne particles (often longer distances)

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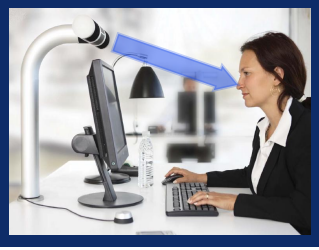

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"Four principles for achieving good indoor air quality"

- Minimize indoor emissions (source control)

  "If there is a pile of manure in a space, do not try to remove the odor by ventilation. Remove the pile of manure."

  (Source: Pettenkofer, 1858)

- Keep buildings dry

  "Eliminating dampness and moisture-related indoor exposures is of major importance for preventing asthma and other respiratory conditions"

  (Source: Kanchongkittiphon et al., 2014)

- Protect against outdoor pollution (when needed)

- **Ventilate well** ⟵

(Adapted from: Nazaroff 2013 Indoor Air)

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Ventilation – moving air in and out of a space

- **Ventilate well**
  - **Ventilation rate (dilution)**
  - **Room air distribution**

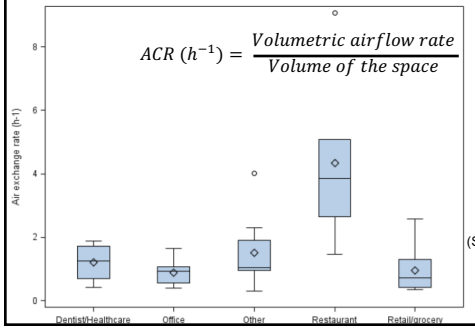
Ventilation Rate
Defines the amount of ventilation air supplied to the space. Often is presented by the number of the space **air volume changes per hour (ACH).**

Air distribution
Reveals how the supplied air is moved within the space, i.e. the airflow pattern.

Air change rate (or air exchange rate)

- ACR = 1 h^{-1}, volume of air in the room is replaced in one hour
- WHO recommends ACR=12 h^{-1} to prevent airborne infection
- For offices, typically recommended ACR=4-6 h^{-1}

$$ACR\ (h^{-1}) = \frac{Volumetric\ airflow\ rate}{Volume\ of\ the\ space}$$



Recent study of ~40 commercial buildings in California

(Source: Bennett et al. **2011** CEC Report)

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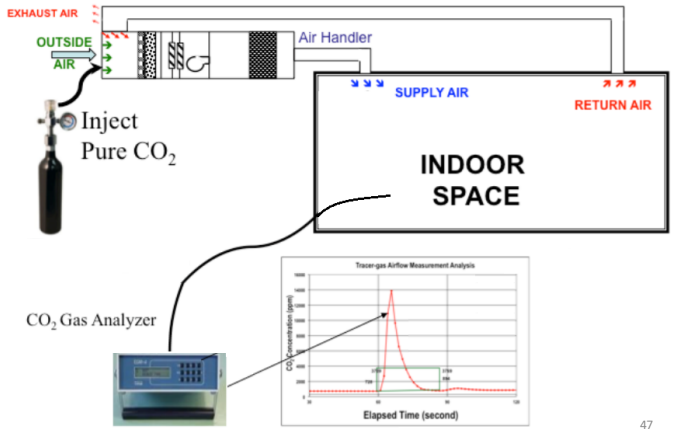
Measuring air change rate – most common method is tracer gas method (but not the only)



(Adapted from: Bennett et al. 2011 CEC Report)

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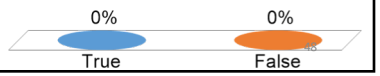
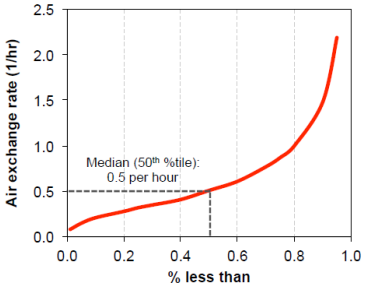
Over the past few decades, air change rate in buildings is increasing

A. True
B. False



What are typical air change rates in homes?

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



Mostly due to infiltration and window opening

In the past, we seldom used mechanical ventilation systems in single-family homes, but this is changing

(Source: Murray and Burmaster, 1995 Risk Analysis)

- What do you think this curve looks like now?

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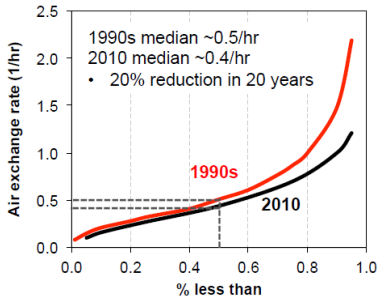
What are typical air change rates in homes?

- New distribution of ACRs U.S. homes
  – Early 1990s and revisited in 2010 by Persily et al. (2010)



(Sources: Murray and Burmaster, 1995 Risk Analysis; Persily et al. 2010 Indoor Air)

- What about new homes?

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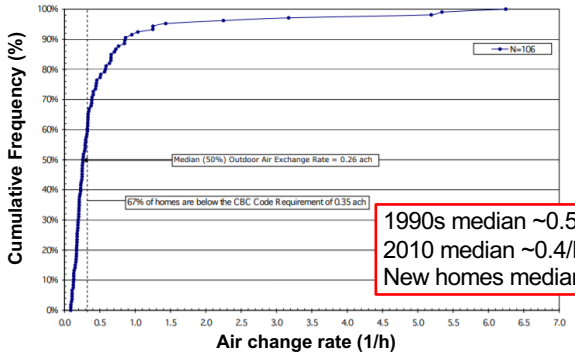
What are typical air change rates in homes?

- Distribution of ACRs U.S. homes: infiltration
  – Addition of 106 new homes (Offermann et al., 2009)



1990s median ~0.5/h
2010 median ~0.4/h
New homes median ~0.26/h

(Source: Offermann et al. 2009 CEC PIER Report

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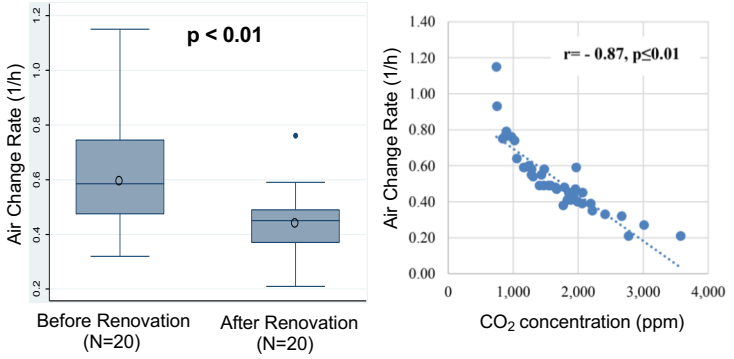
Case Study – Energy renovation and IAQ

- Comparison of air quality before and after renovation



(Source: Foldvary et al, Building and Environment 2017)

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Air distribution is important!

- Air distribution determines **inhaled** air quality
- **Less ventilation** air is needed when it is efficiently distributed

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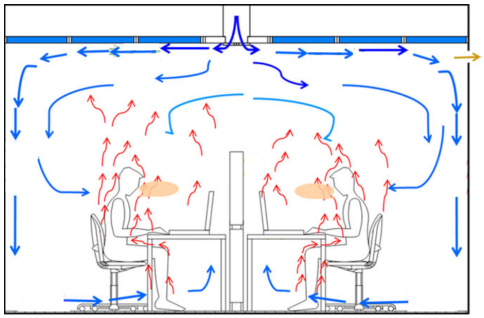
Mixing (forced / traditional) ventilation

- The most common air distribution method
- Warm contaminated air migrates toward the ceiling and mixes with incoming supply air



(Source: Melikov 2015 Indoor Air)

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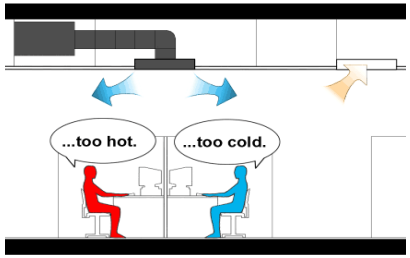
Mixing ventilation - drawbacks

- <1% of clean air is inhaled (air supplied far away)
  (Sources: Fanger 2006 Indoor Air; Licina 2017 Build and Environ)
- Difficult to control exposure
- Entire space is ventilated (also unoccupied volume)
- Large airflow rate required (energy, space, cost!)
- Designed for "average" person (we are all different!)



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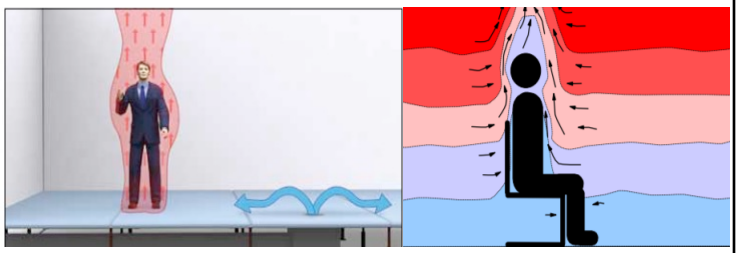
Displacement vs. Mixing ventilation

- Displacement ventilation is slowly gaining in popularity
- Displacement ventilation has higher ventilation effectiveness
  - Ev = 1.2 – 2.0; while for mixing ventilation Ev = 1.0



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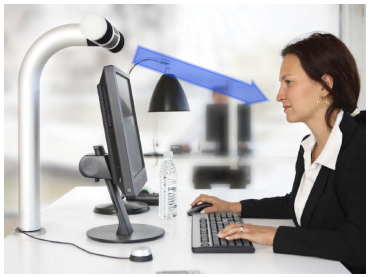
Personalized Ventilation

This systems delivers clean air directly to the breathing zone of a user. User has an individual control.



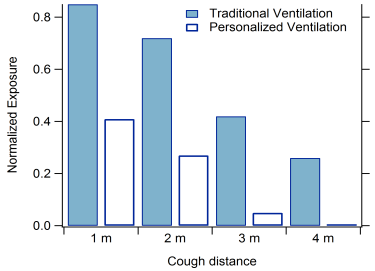
(Source: Exhausto and Techinical University of Denmark)

Benefits:

- Increase occupant satisfaction
- Improve inhaled air quality
- Improve occupants' performance
- Decrease risk of spread of infectious diseases
- Energy savings

Traditional vs. Personalized Ventilation

- Advanced air distribution can mitigate exposure to cough released droplets from a nearby person

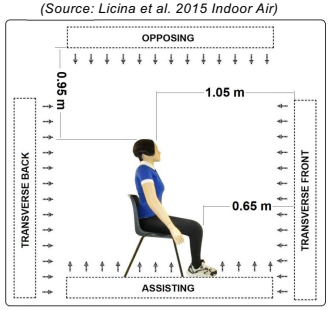


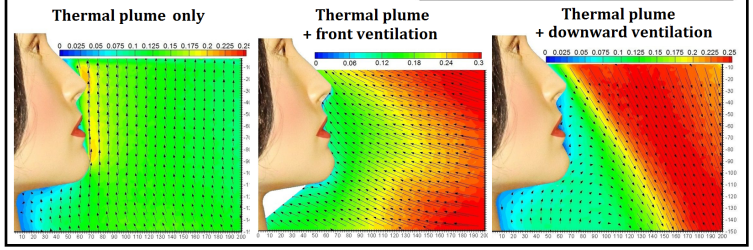
(Source: Pantelic et al. 2015 Indoor Air)

Case study

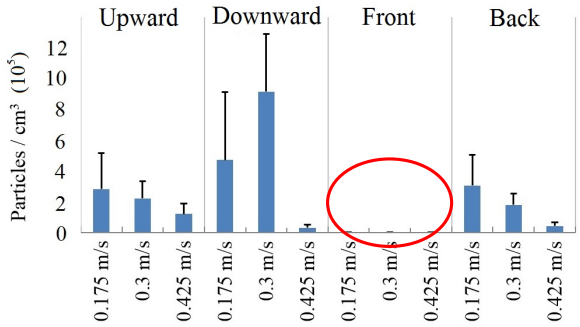
- Air distribution and thermal plume
- Thermal manikin
- Artificially generated pollution

(Source: Licina et al. 2015 Indoor Air)





Ventilation strategy vs. personal exposure



(Source: Licina et al. 2015 Indoor Air)

- Ventilation air supplied from the front of a person delivers the cleanest air at the minimum energy input

I. INTRODUCTION
II. SOURCES OF AIR POLLUTION
III. EXPOSURE AND TRANSMISSION
IV. CONTROL STRATEGIES
V. WHERE ARE WE NOW?

(Source: Construction Climate Challenge)

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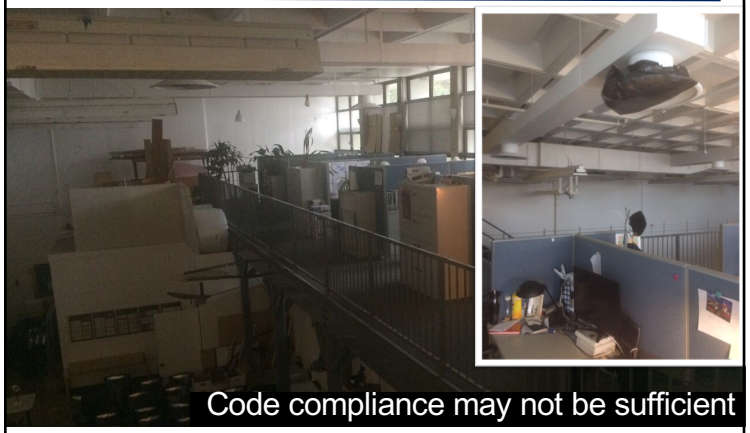
Comfort and buildings



Code compliance may not be sufficient

Center for the Built Environment, UC Berkeley, California

"High" performance building with good design

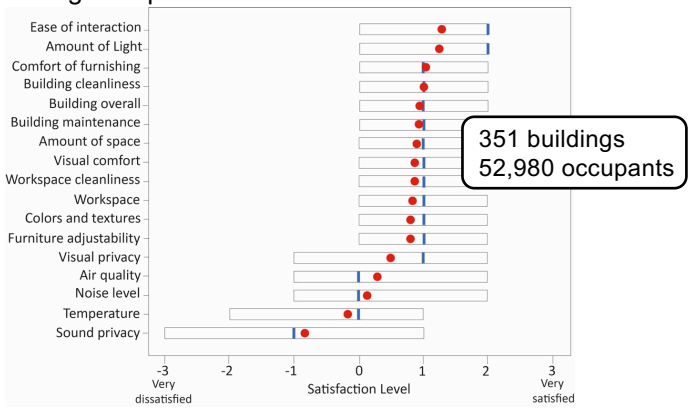
Kresge Foundation HQ, Michigan, US

Good design may not be sufficient

Kresge Foundation HQ, Michigan, US

Comfort and buildings

Building occupant satisfaction in offices



(Source: Frontczak et al 2011, Indoor Air)

New principles reflected in dozen of languages

Where are we now?

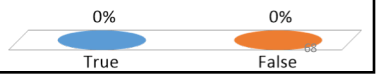
High market penetration with exponential increase

Currently - Thousands of ongoing projects from 200 certification programs around the world

Air quality indoors is always worse than outdoors.

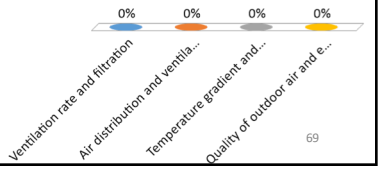
A. True

B. False



What defines the effectiveness of ventilation?

A. Ventilation rate and filtration
B. Air distribution and ventilation rate
C. Temperature gradient and airflow interactions
D. Quality of outdoor air and efficient mechanical fan



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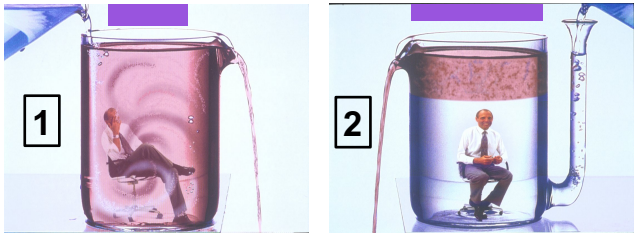
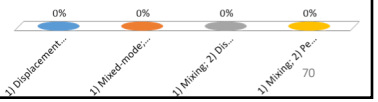
What type of ventilations do the pictures below represent?



A. 1) Displacement; 2) Mixing
B. 1) Mixed-mode; 2) Displacement
C. 1) Mixing; 2) Displacement
D. 1) Mixing; 2) Personalized



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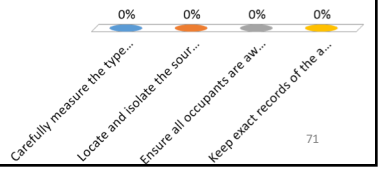
A key factor in solving indoor air quality problems is to:

A. Carefully measure the types and quantity of contaminants
B. Locate and isolate the source of the pollution
C. Ensure all occupants are aware of the problem
D. Keep exact records of the actions taken



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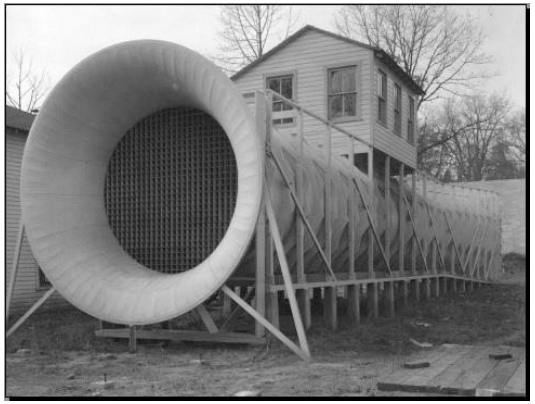
I wish you good air and lots of it



Contact: dusan.licina@epfl.ch

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