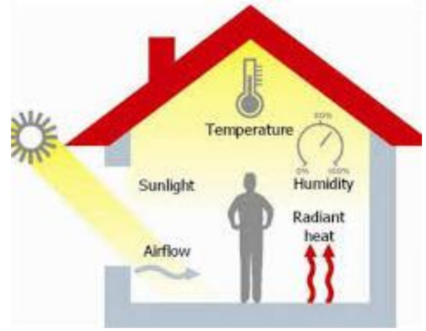
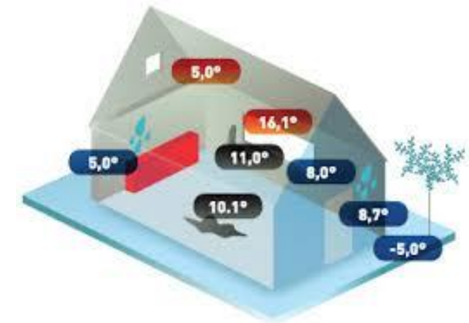
CIVIL 212
Indoor Climate
Fall 2024





IAQ controls

21 November, 2024

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

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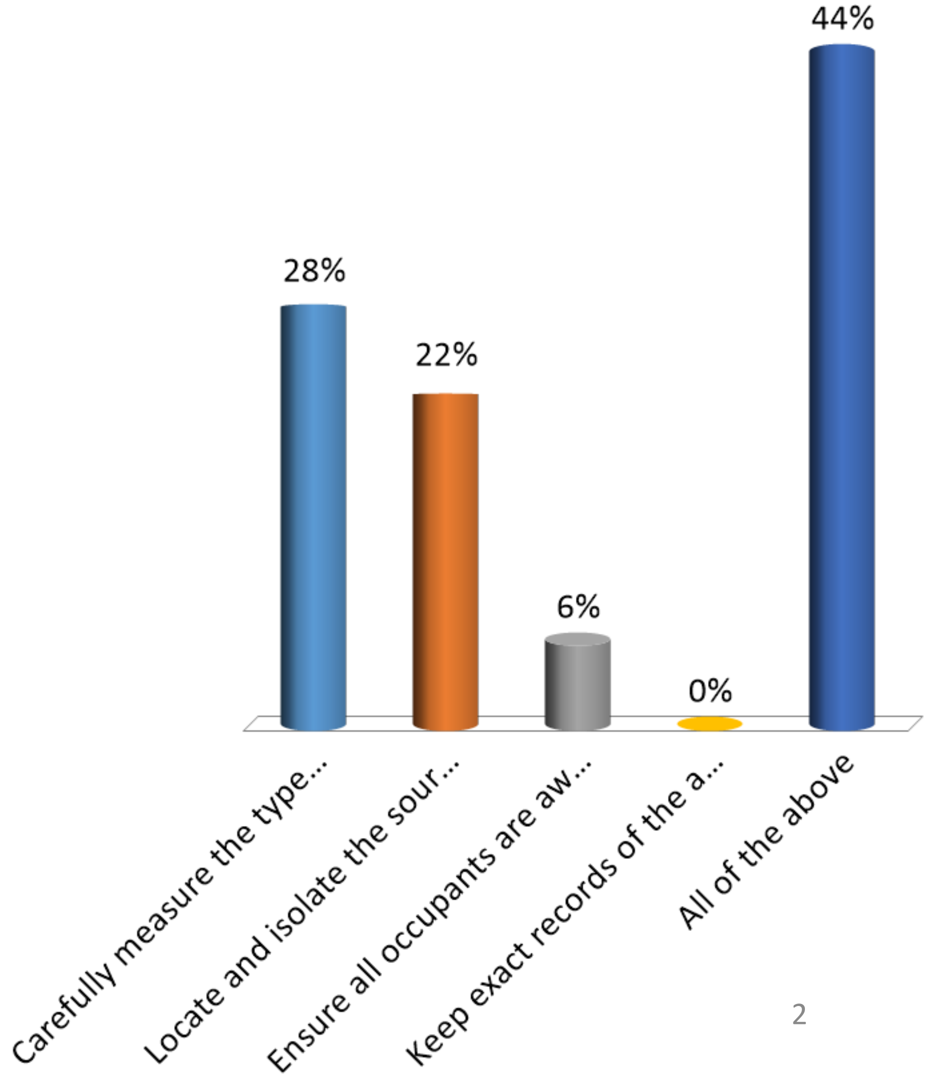
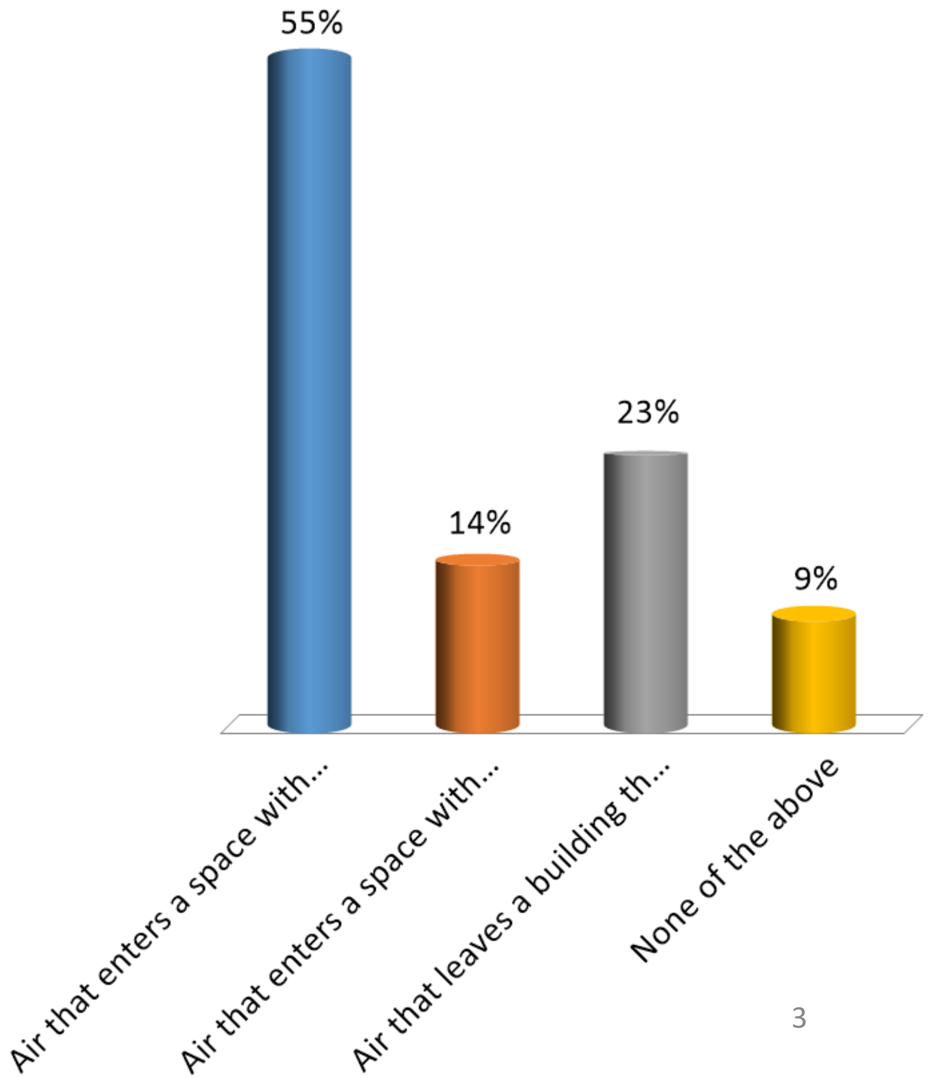
A. Carefully measure the types and quantity of contaminants
B. Locate and isolate the source of the pollution
C. Ensure all occupants are aware of the problem
D. Keep exact records of the actions taken
E. All of the above



“Infiltration” is:

A. **Air that enters a space without filtration or control**
B. Air that enters a space without filtration
C. Air that leaves a building thru cracks and unchecked door seals
D. None of the above



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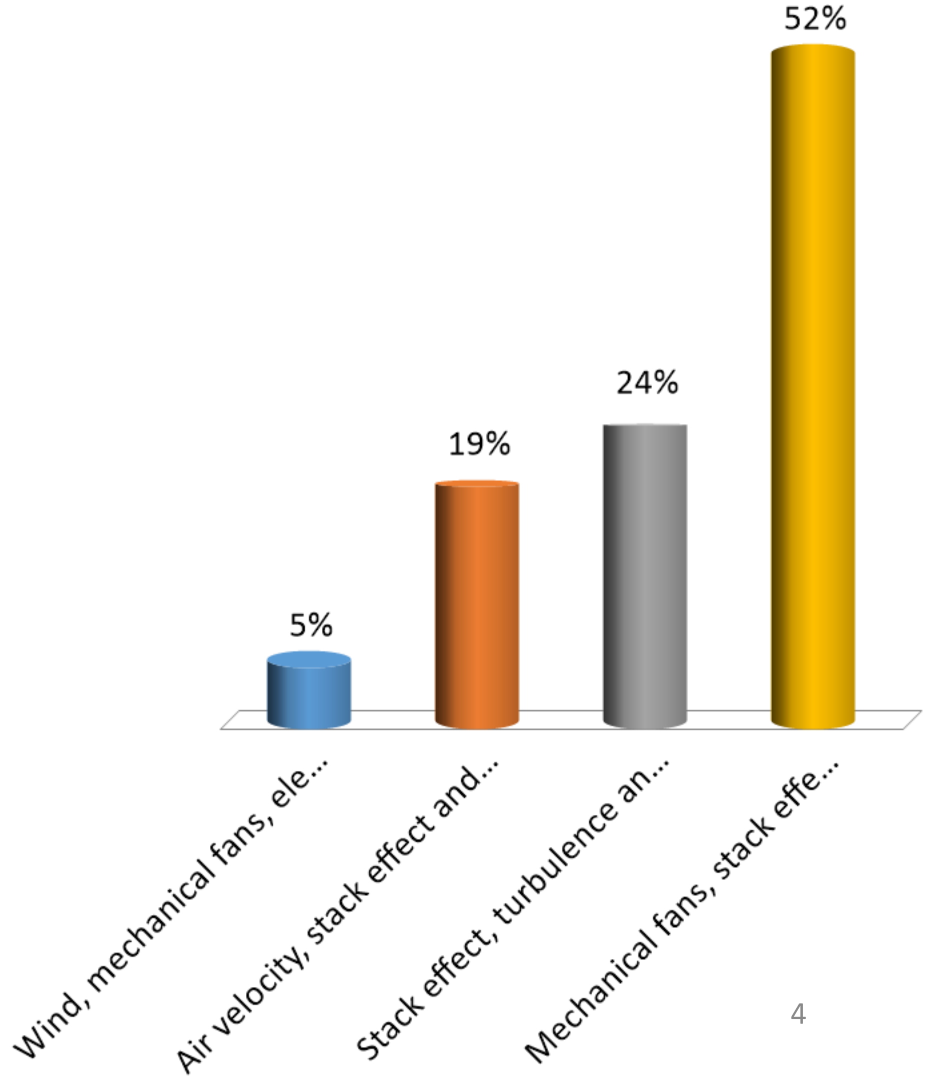
What are the three mechanisms that create pressure differences?

A. Wind, mechanical fans, elevators

B. Air velocity, stack effect and wind

C. Stack effect, turbulence and density

D. Mechanical fans, stack effect and wind



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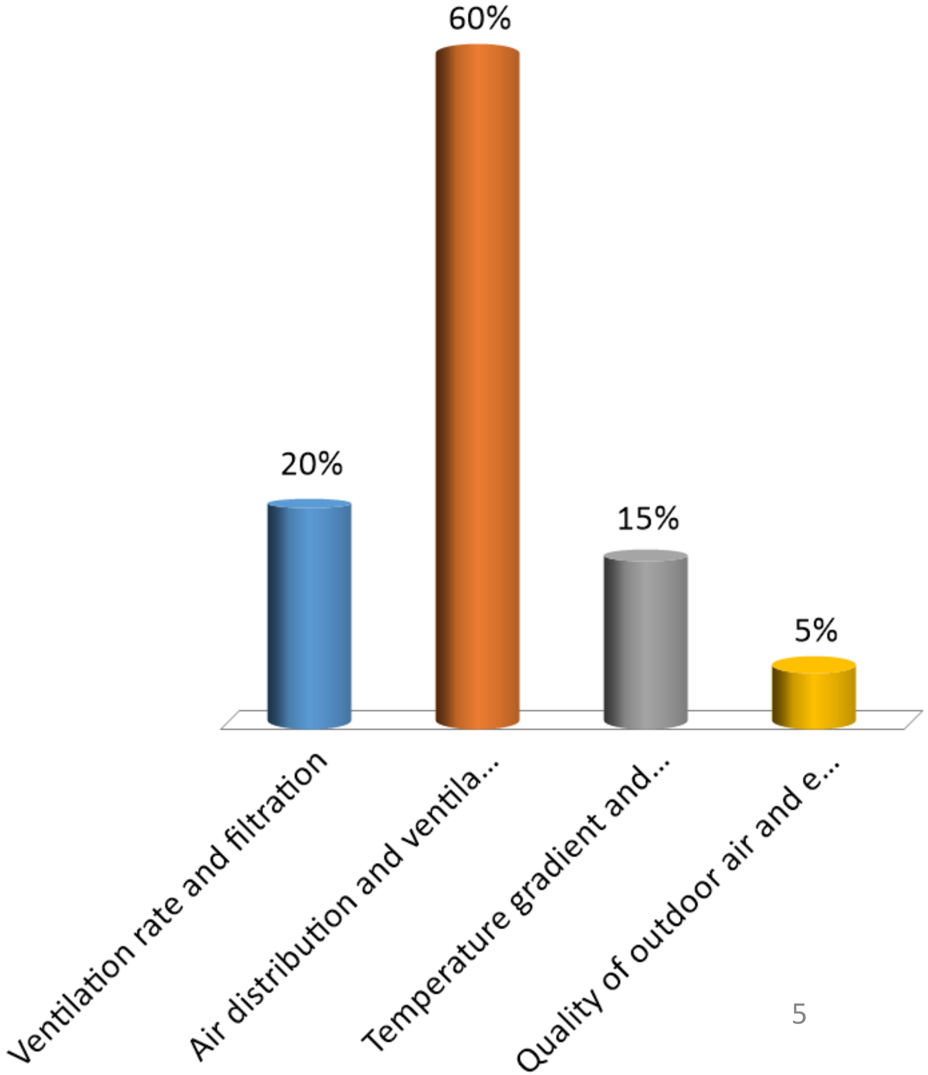
What defines the effectiveness of ventilation?

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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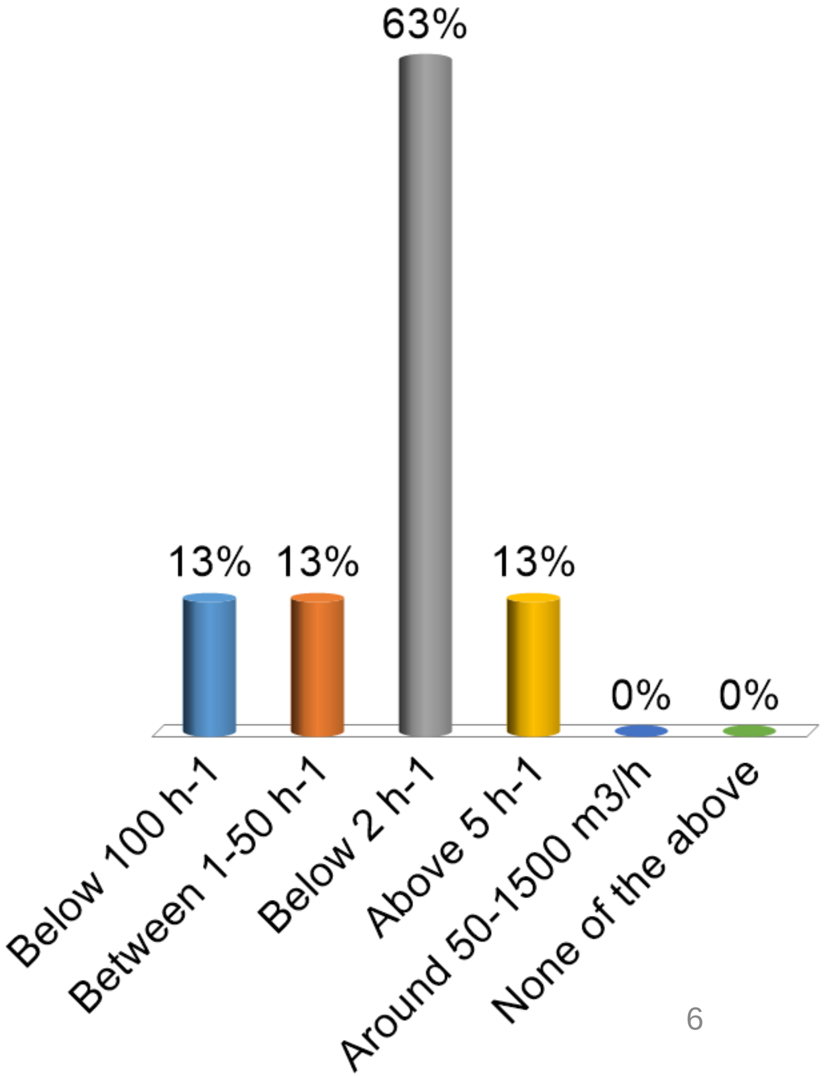
What are typical air change rates in homes?

A. Below 100 h^{-1}
B. Between 1-50 h^{-1}
C. Below 2 h^{-1}
D. Above 5 h^{-1}
E. Around 50-1500 m^3/h
F. None of the above



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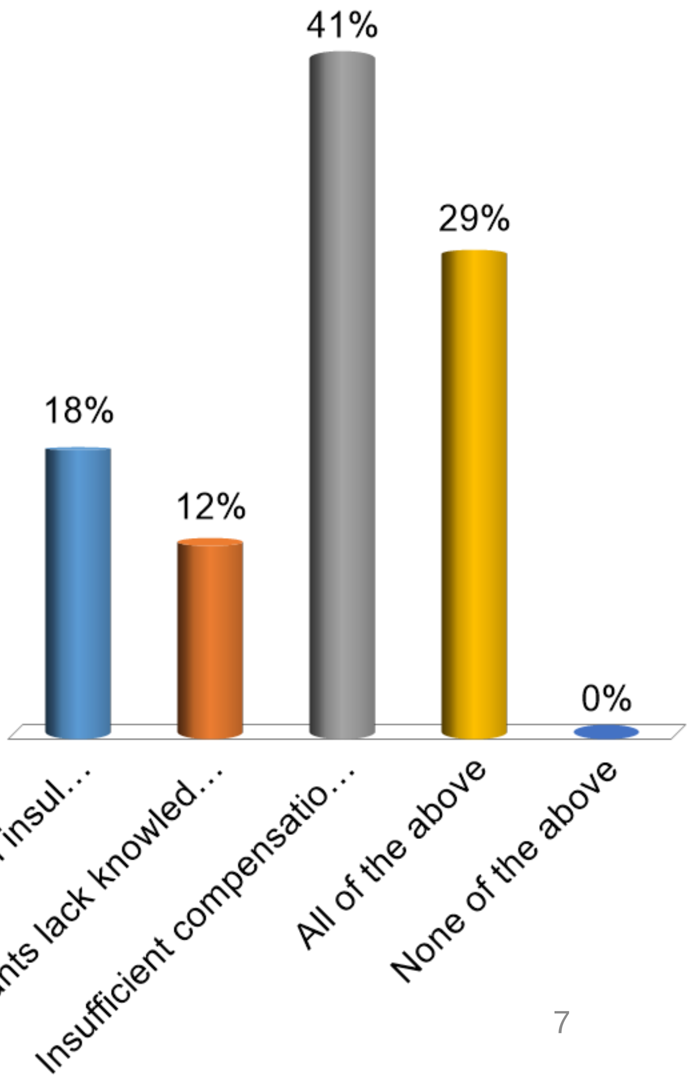
What is the main cause for reducing trend in air change rates over the past decades?

A. Enhanced thermal insulation of building envelopes
B. Occupants lack knowledge on proper ventilation practices
C. Insufficient compensation for air renewal due to reduced infiltration
D. All of the above
E. None of the above



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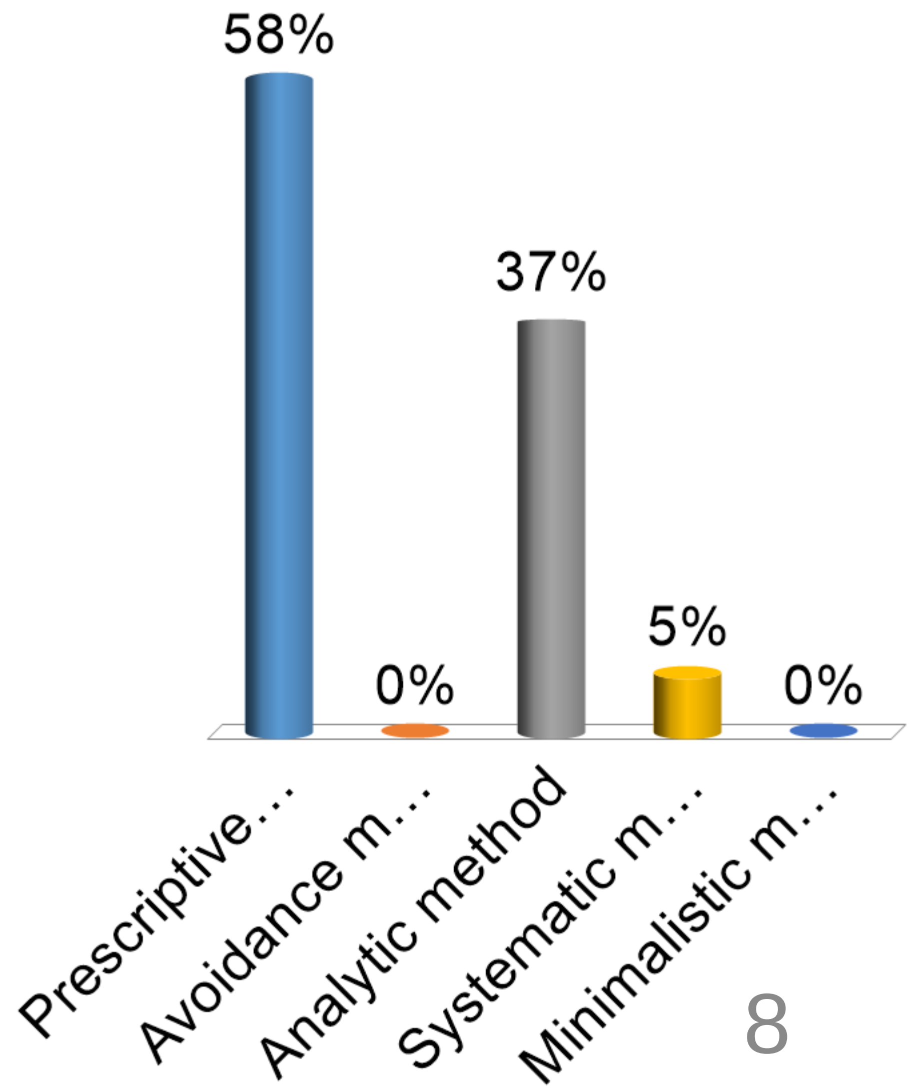
Which of the following corresponds to ventilation design for sufficiency, minimizing health risks and avoidance of complains?

A. **Prescriptive method**
B. Avoidance method
C. Analytic method
D. Systematic method
E. Minimalistic method



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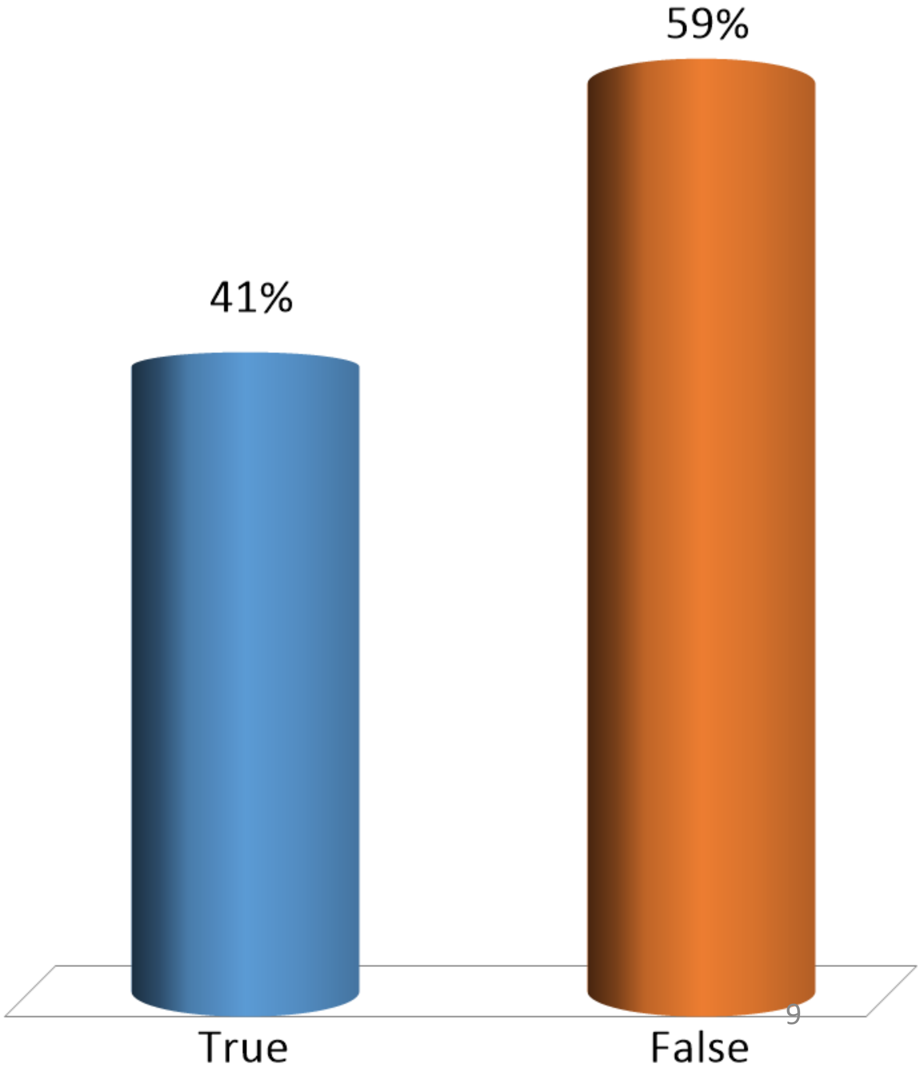
Analytical method for determining ventilation rates is more commonly used?

A. True

B. False



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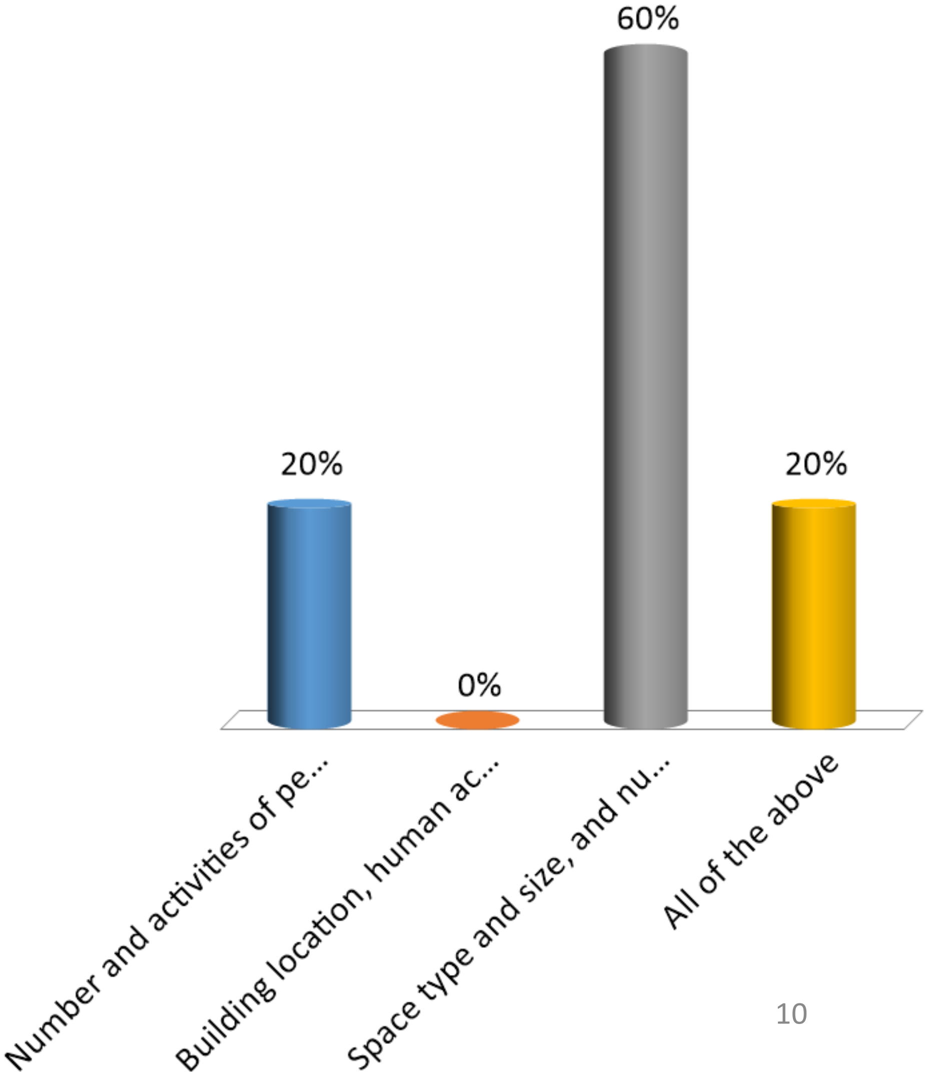
What are the key parameters for the prescriptive ventilation method?

A. Number and activities of people, and space type

B. Building location, human activities and outdoor air quality

C. Space type and size, and number of people

D. All of the above



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More ventilation is always better?

A. True

B. False

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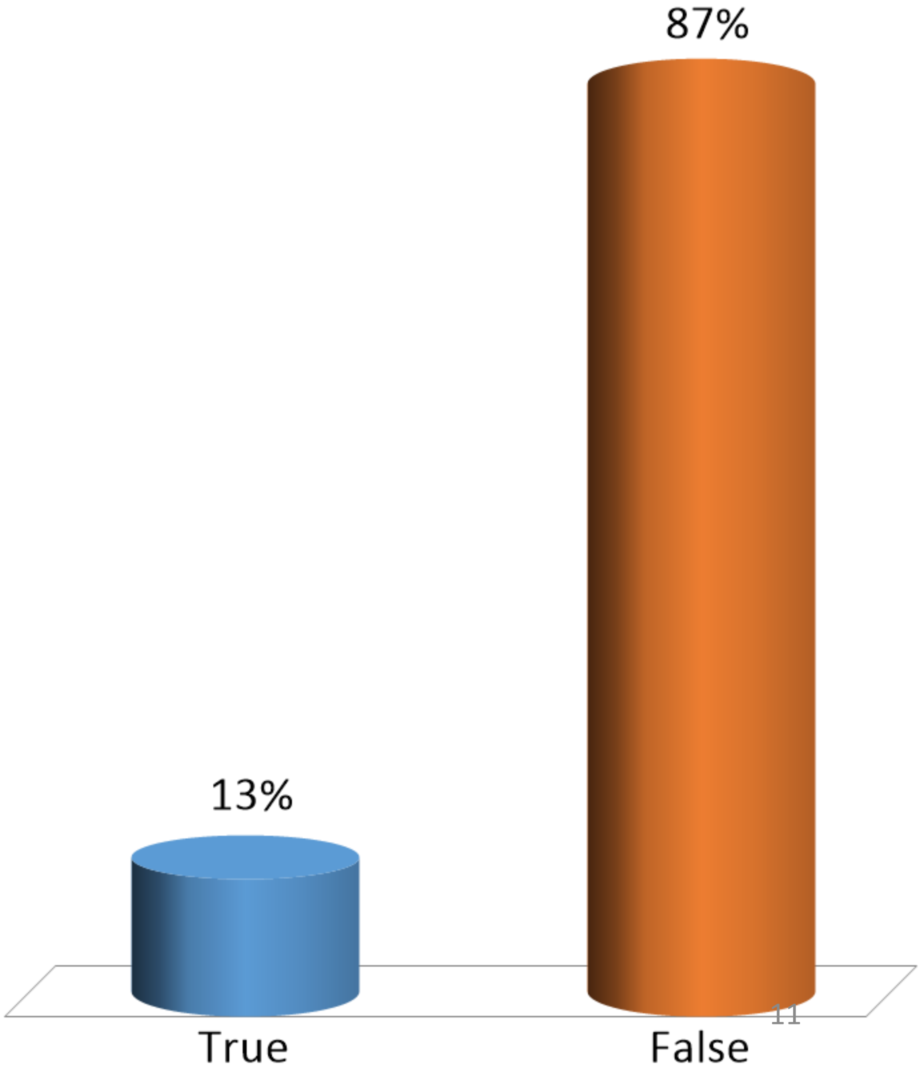


Any problems with the homework?

- As per ASHRAE 62.1, calculate the minimum needed ventilation rate for 60 m^2 classroom that is occupied by 55 students.

Solution: $V_{bz} = q_p P_z + q_b A_z$ = *3.8x55+0.3x60=227 l/s = 817 m^3/h*

TABLE 6.2.2.1 Minimum Ventilation Rates in Breathing Zone
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		Air Class
	cfm/person	L/s·person	cfm/ft^2	L/s·m^2		#/1000 ft^2 or #/100 m^2	cfm/person	L/s·person	
Lecture classroom	7.5	3.8	0.06	0.3		65	8	4.3	1

Any problems with the homework?

- In a room, there are 85 students. They are working on exam questions with each of them generating 23 liters/hour of metabolic carbon dioxide. In order to comply with building standard, carbon dioxide limit must be set to 1000 ppm. Assuming that outdoor carbon dioxide levels are 380 ppm, estimate the required ventilation rate in m^3/h by means of the steady state mass balance model. Assume that the room is well-mixed, ventilation rate is constant, ventilation effectiveness is equal to 1, and that indoor and outdoor carbon dioxide levels are constant.

Solution:

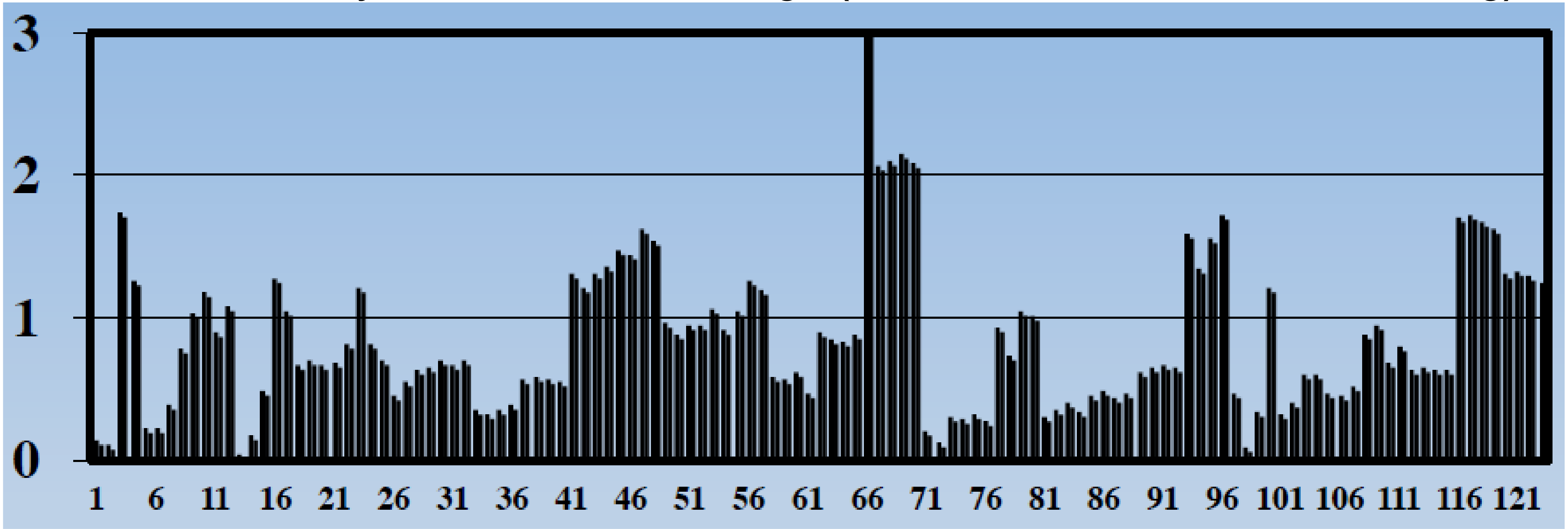
$$Q = E \,/\, (Cin - Cout)\cdot\varepsilon_v =$$

$$= (85 \cdot 23\ l/h) \,/\, (1000 - 380)\cdot 10^{-6}\cdot 1 =$$

$$= 3'153'225 \text{ l/h} = 3'153 \text{ m}^3\text{/h}$$

Air-exchange rates: design vs operation

EPA BASE study of 100 office buildings (4 measurements in each building)



Ratio of Measured/Design minimum outdoor air supply by system

What are the key issues?

Today's objectives…

Controls:

- Room air distribution (Ventilation effectiveness)
- Filtration & air cleaning
- Exercise
- Remaining schedule & course summary

Last time - Ventilation

Ventilate well

Ventilation rate (dilution)

Room air distribution

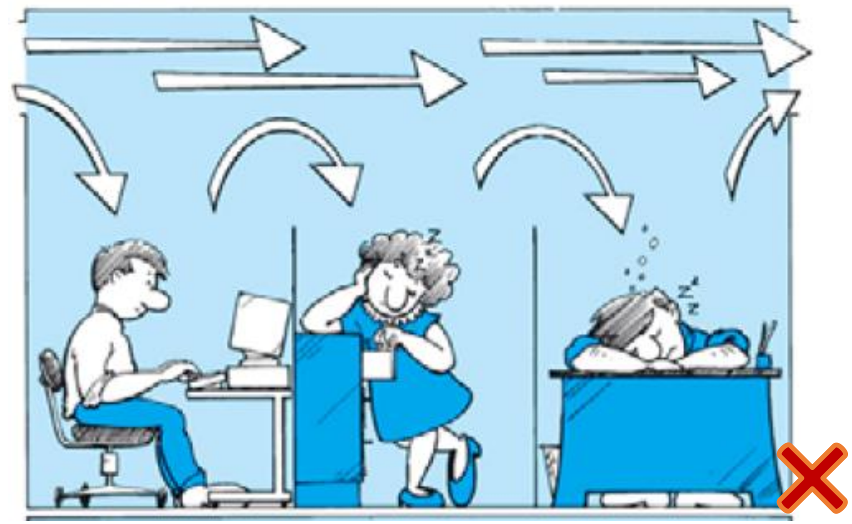
Ventilation Rate

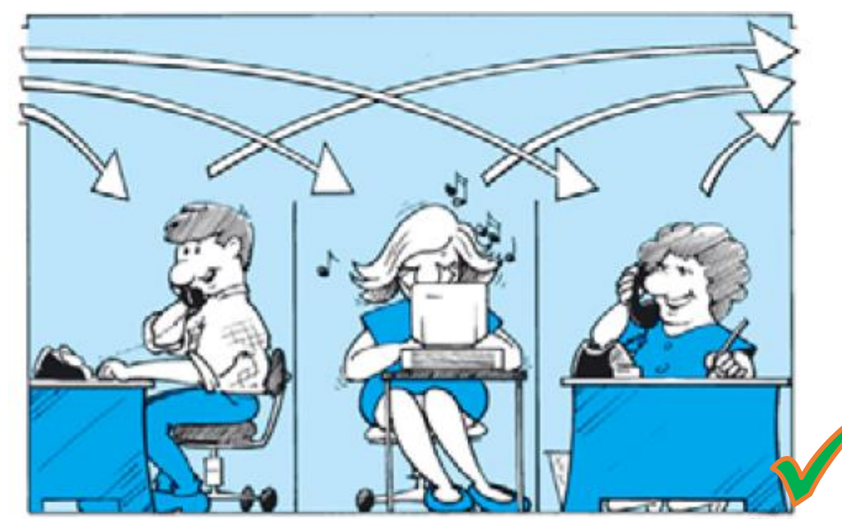
Defines the amount of ventilation air supplied to the space. Often is presented by the number of the space **air volume changes per hour (ACH).**

Air distribution

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

Air distribution is important!



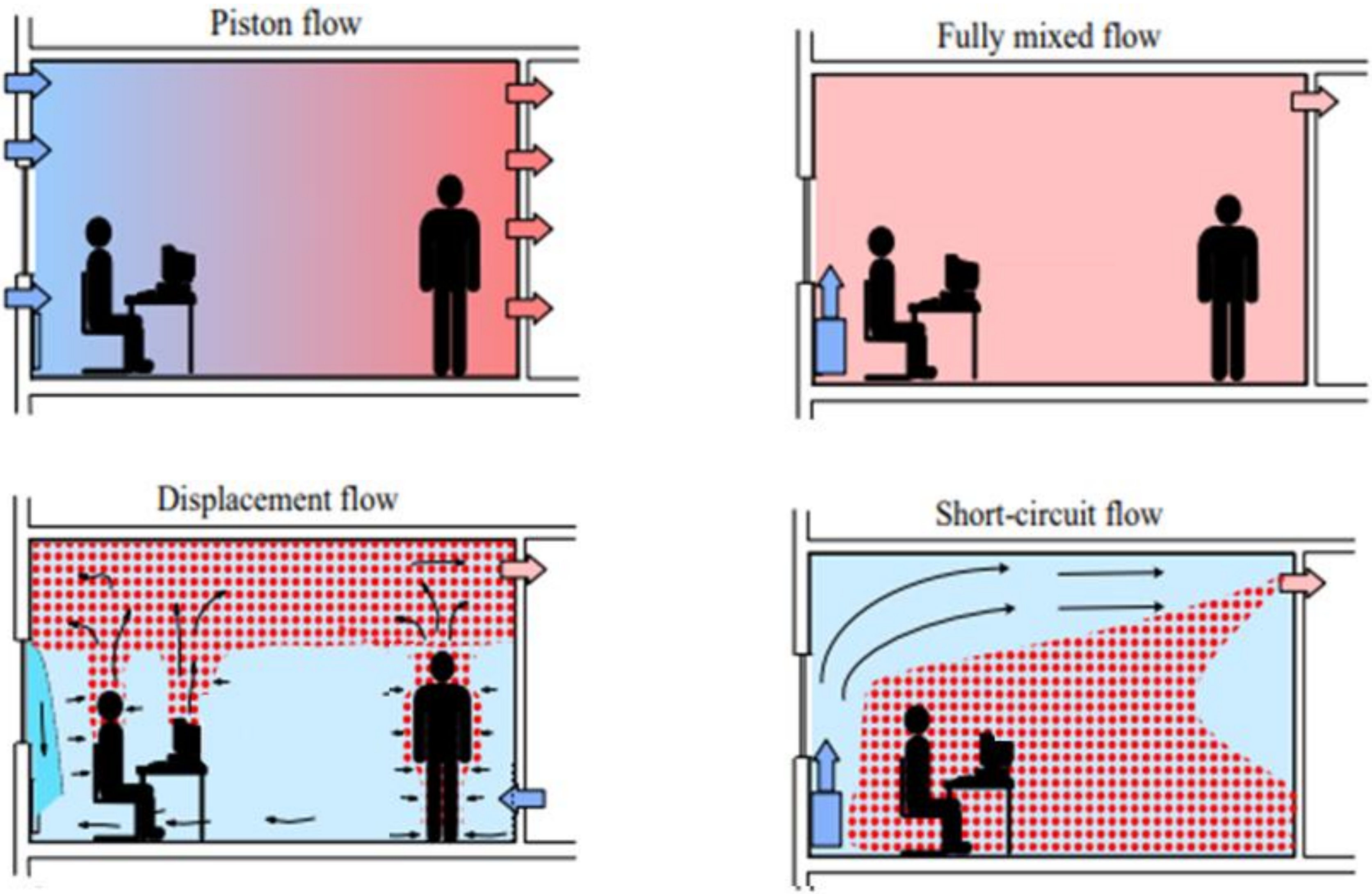


- Room air distribution (ventilation effectiveness) determines **inhaled** air quality
- **Less ventilation** air is needed when it is efficiently distributed

Important notes on ventilation effectiveness

- The total ventilation rate should be calculated by taking into account the ventilation effectiveness: $Q = Q_{table}/\varepsilon_v$
  - In practice, ventilation effectiveness is very seldom taken into account
  - The ventilation rates given in the standards' tables (Q_{table}) are usually based on full air mixing. Last time we assumed that $\varepsilon_v = 1$
- In practice, not all ventilation systems are based on full mixing of the room air. Also, some systems may have a different ventilation effectiveness during summer and winter
  - For example, if the supply air temperature is lower than room temperature the ventilation effectiveness is normally 1 or higher, but if the ventilation system is used for heating in winter the ventilation effectiveness could be as low as 0.5, and the ventilation rates should be even doubled.
  - More information and a greater emphasis on this factor are required!

Air can be distributed in different ways…



(Source: Rehva)

Ventilation effectiveness – Short circuiting

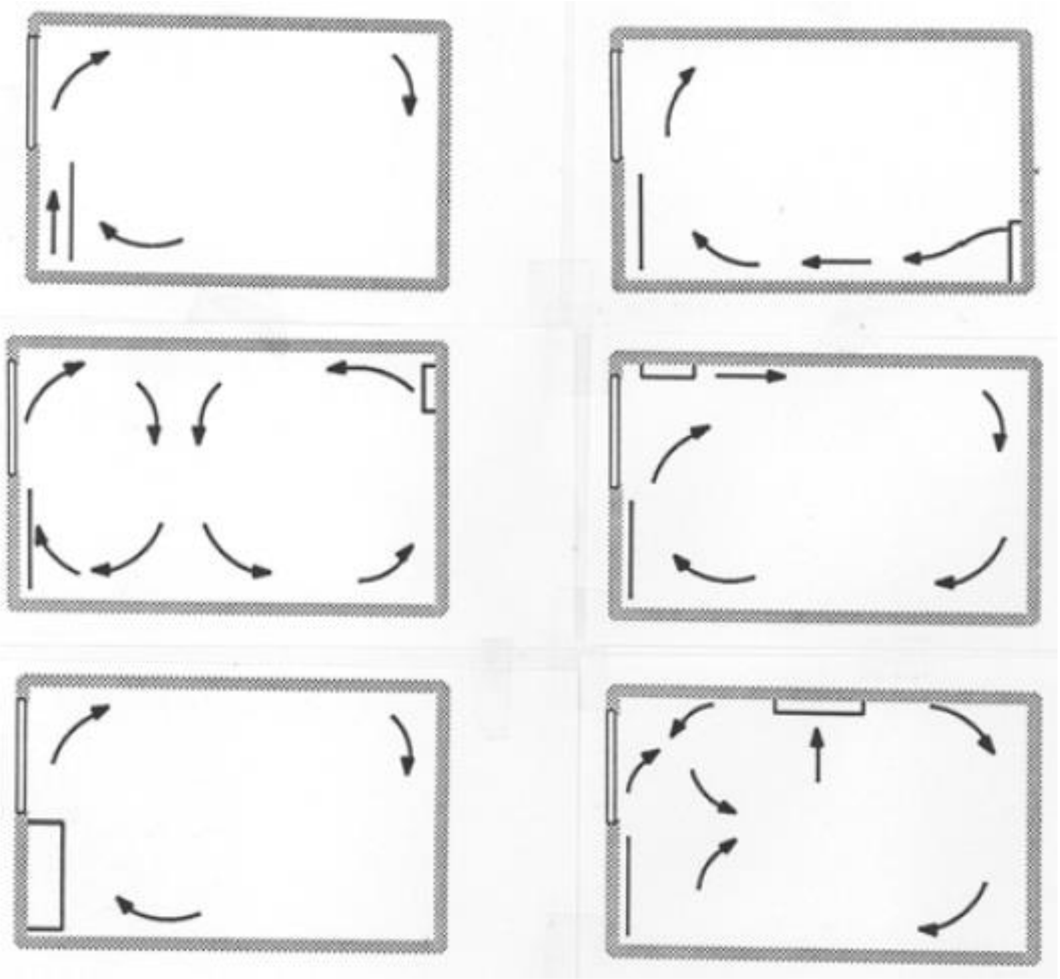
Zero ventilation effectiveness means the ventilation system is short-circuiting which happens if a supply grille and an extract grille are located close together.

(Source: http://www.hvacfun.com/hall-shame-43.htm)

Ventilation short circuiting - A supply grille (nearest) and an extract grille (furthest) can short circuit if located close together (click image to zoom)

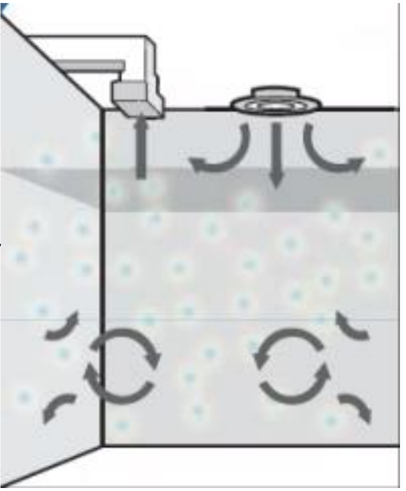
Room air distribution

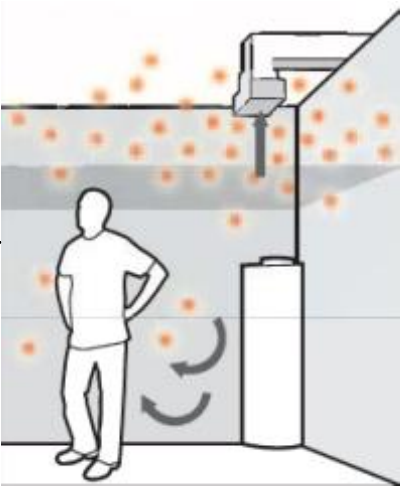
- Two major influencing factors:
  - Type and position of ventilation supply and exhaust diffusers or windows
  - Airflow characteristics in the room



Mechanical ventilation for comfort

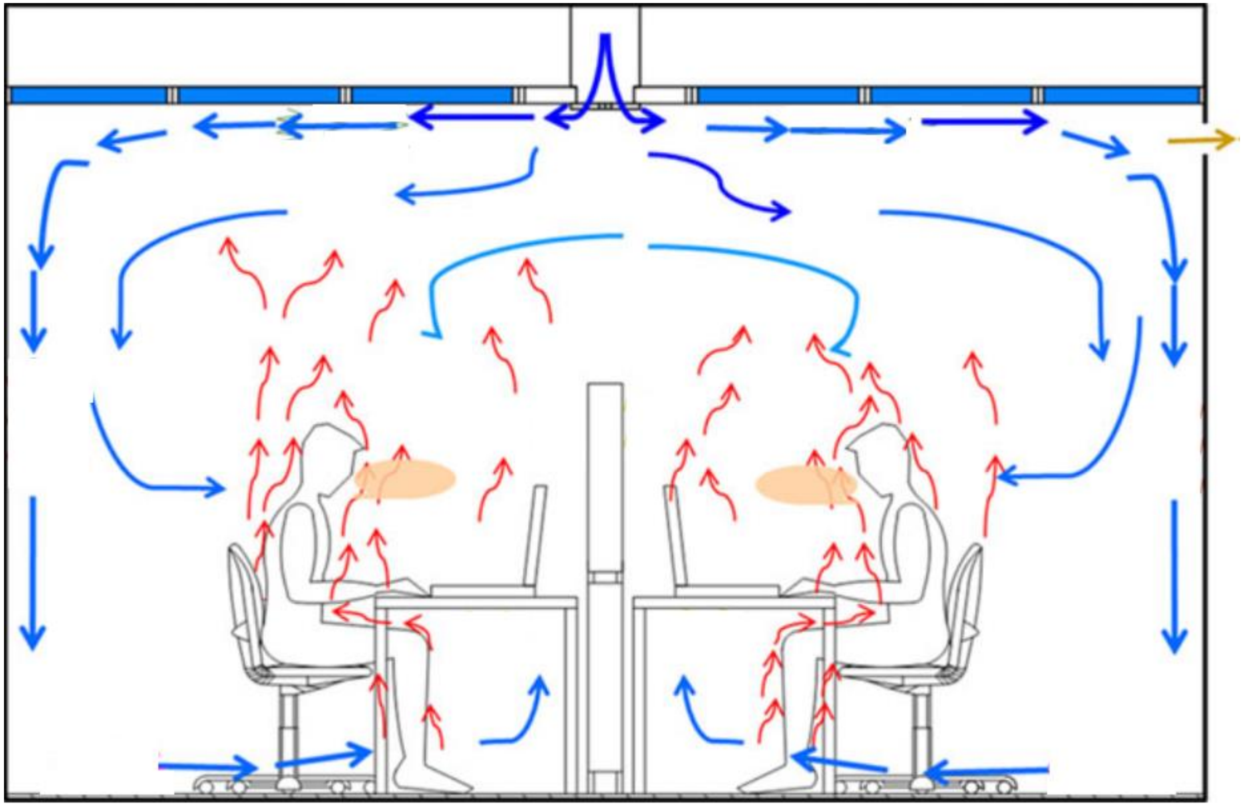
- **Mixing ventilation**
  - Uniform indoor environment
  - Occupants have limited control
- **Displacement ventilation**
  - Stratified indoor environment
  - Occupants have limited control
- **Newest developments (out of scope)**
  - Preferred environment for each occupant
  - Occupants have several degrees of control





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)

Mixing ventilation - drawbacks

- <1% of clean air is inhaled (air supplied far away)

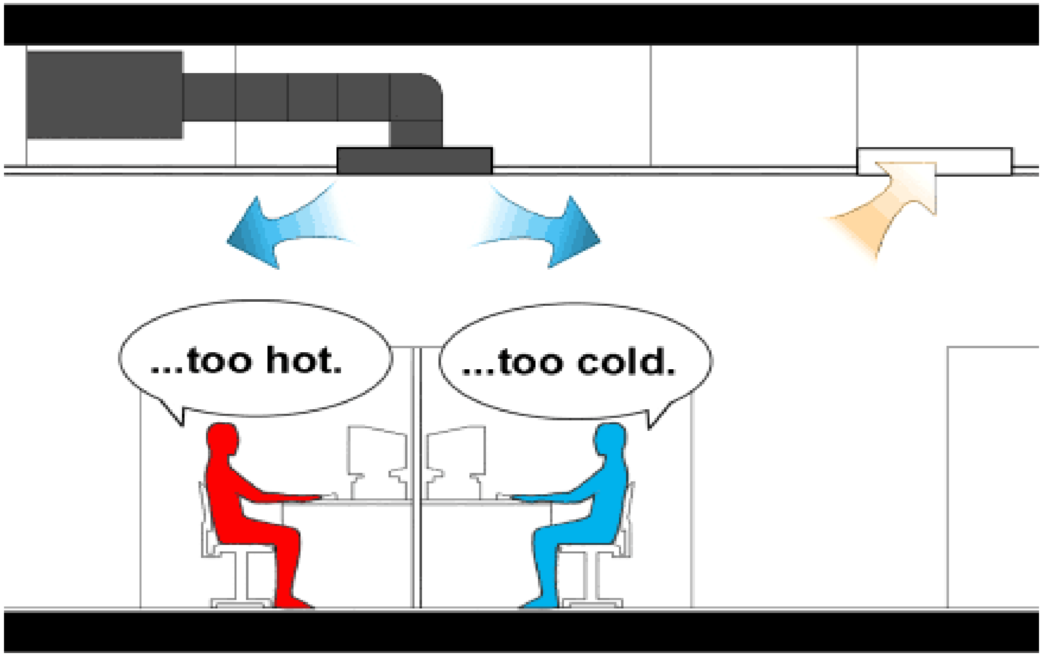
  (Sources: Fanger 2006 Indoor Air; Licina 2017 Build and Environ)

- Difficult to control exposure

- Entire space is ventilated (also unoccupied volume)

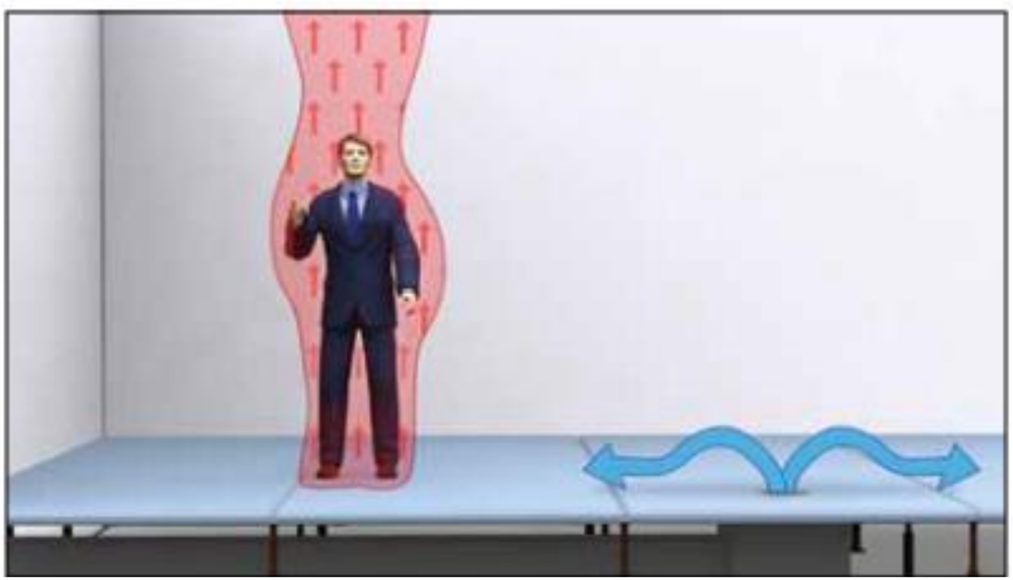
- Large airflow rate required (energy, space, cost!)

- Designed for "average" person (we are all different!)



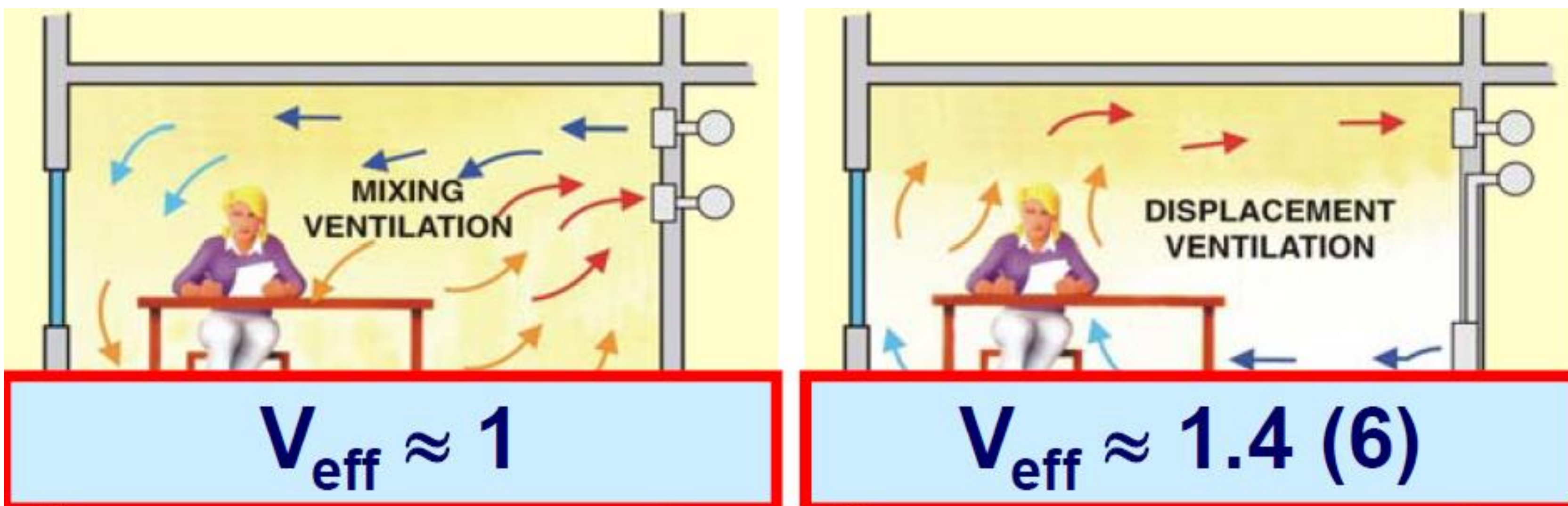
Displacement ventilation

- The idea behind displacement ventilation is to provide a variation in the concentration distribution with a high value below the ceiling and a low value in the occupied zone
- Relatively cool air that is supplied near the floor level, heats up by means of human thermal plume and other heat sources as it moves to the ceiling where it is exhausted



Displacement ventilation effectiveness

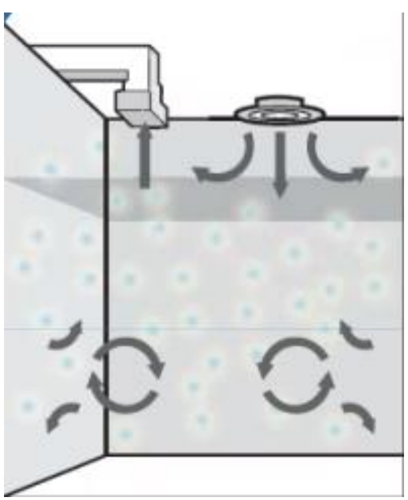
- Displacement ventilation is slowly gaining in popularity
- Displacement ventilation has higher ventilation effectiveness
  - ε_v = 1.2 – 2.0; while for mixing ventilation ε_v = 1.0
- Higher ventilation effectiveness means either less air supplied at the same exposure or the same quantity of air supplied at reduced exposure

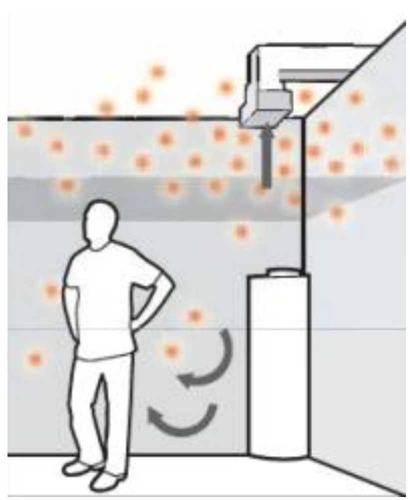


Displacement vs. Mixing ventilation

Mixing

- Mixing of supply and room air
- Temperature and contaminants levels similar throughout room
- Overhead heat gains mixed with room air
- Local discomfort due to draft at the upper body parts
- Perceived air quality?



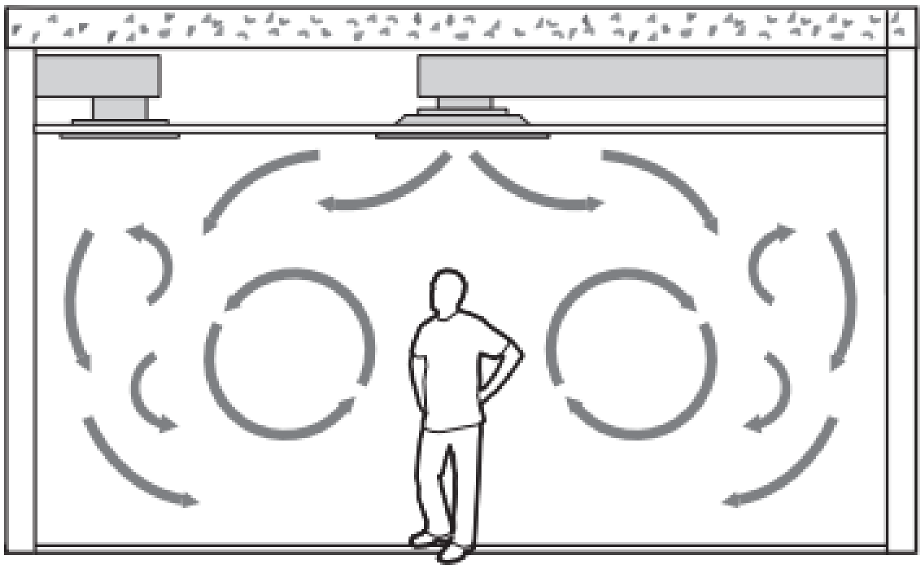


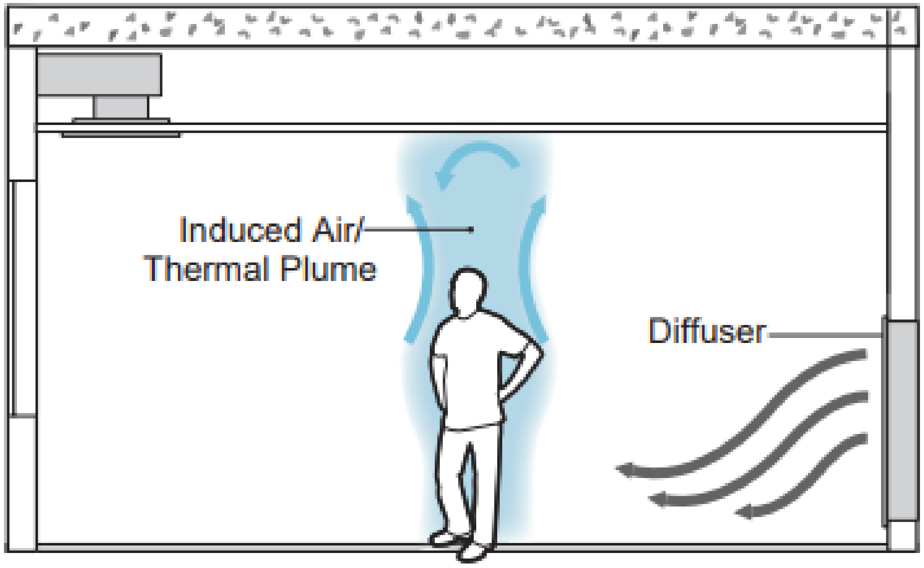
Displacement

- Decreased mixing of supply and room air
- Temperature and contaminant levels increase with the height
- Overhead convective heat gain isolated
- Local discomfort due to draught temperature difference
- Perceived air quality may be better than in the case of mixing ventilation

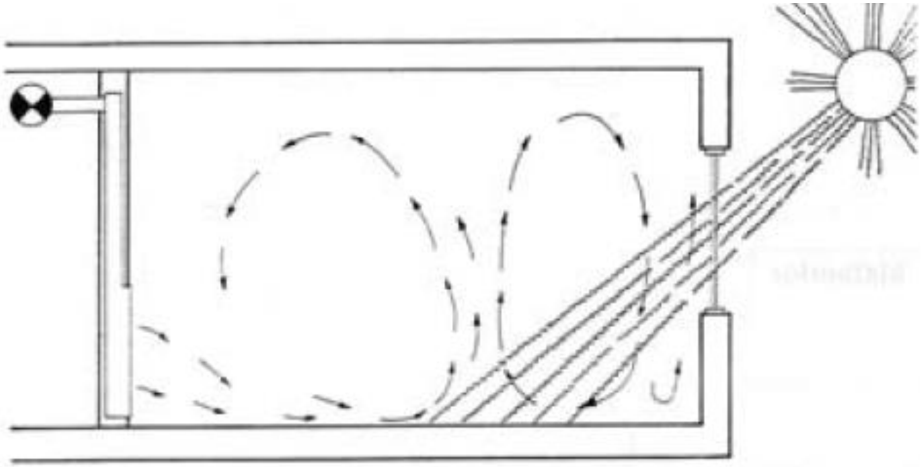
To stratify or not to stratify?

In-class discussion…



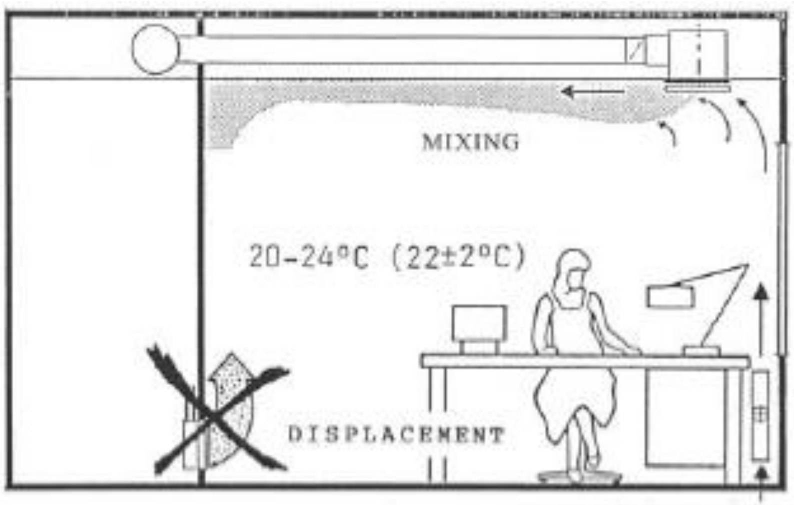


Displacement ventilation – issues

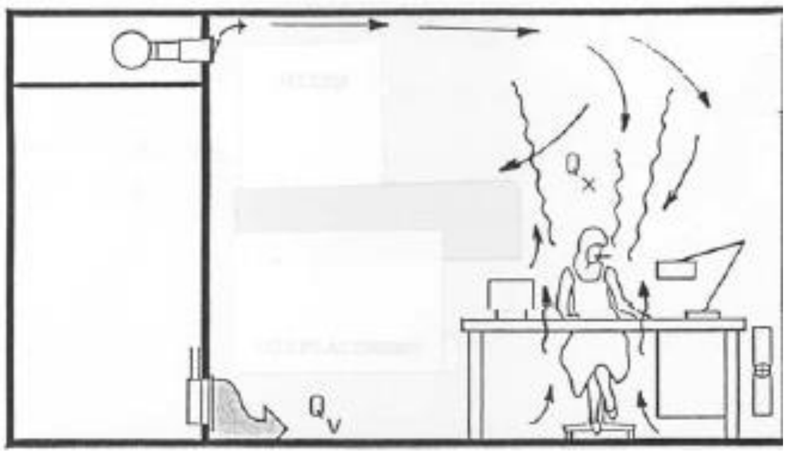


Solar radiation

Cold draft



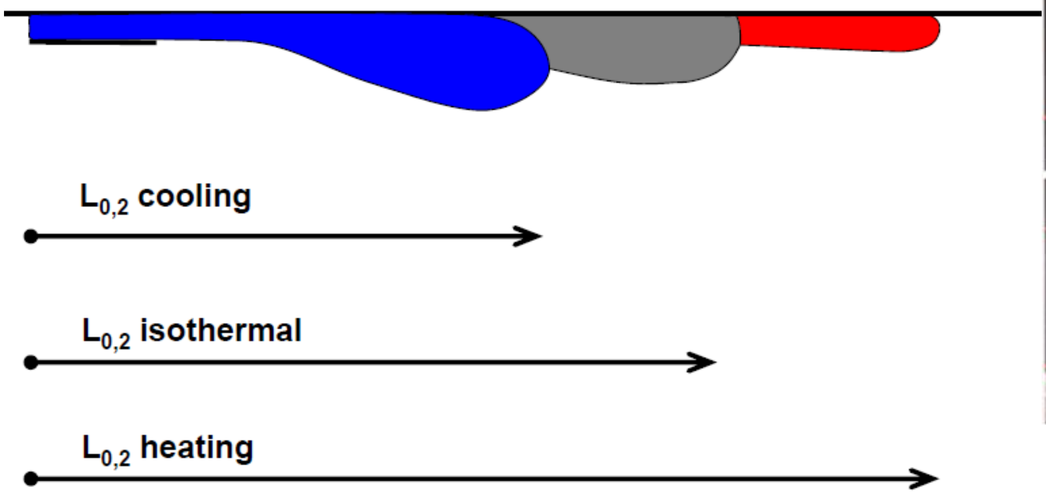
Heating Mode

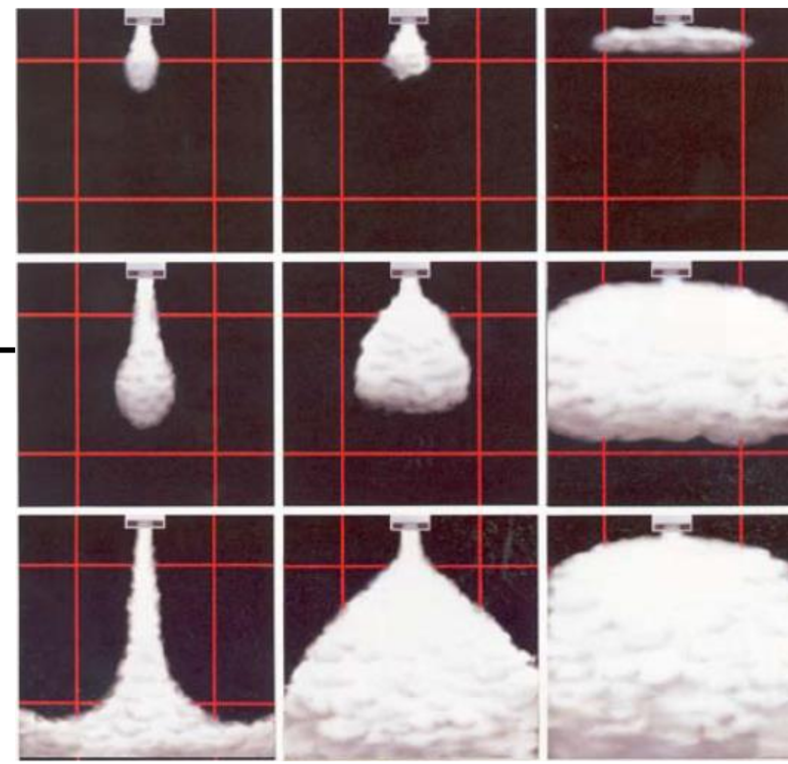


Cooling Mode

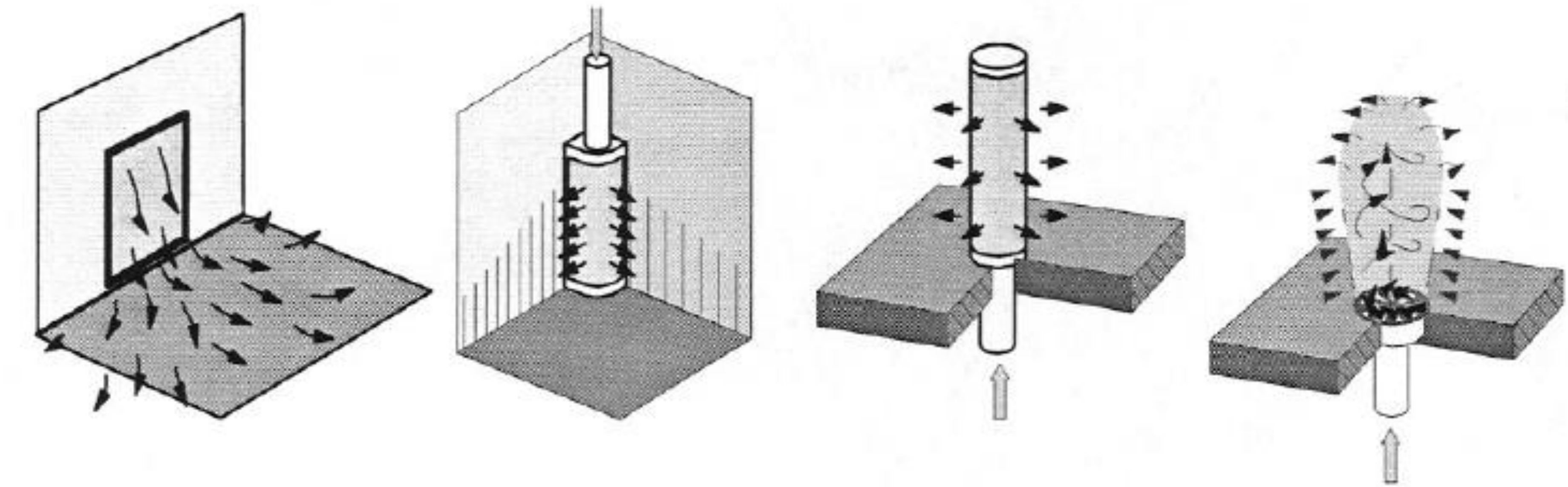
What about supply/exhaust diffusers?

Mixing Ventilation
air terminal devices (ATDs)





Supply diffusers: Displacement Ventilation



Plane wall-mounted | Semi-circular Corner-mounted | Circular Free standing | Floor-mounted

Supply ATD – Selection

- room load (W/m^2)
- capability to provide the desired flow rate at proper velocity and T distribution in the occupied zone at acceptable pressure loss and noise
- room geometry (obstacles, etc.)

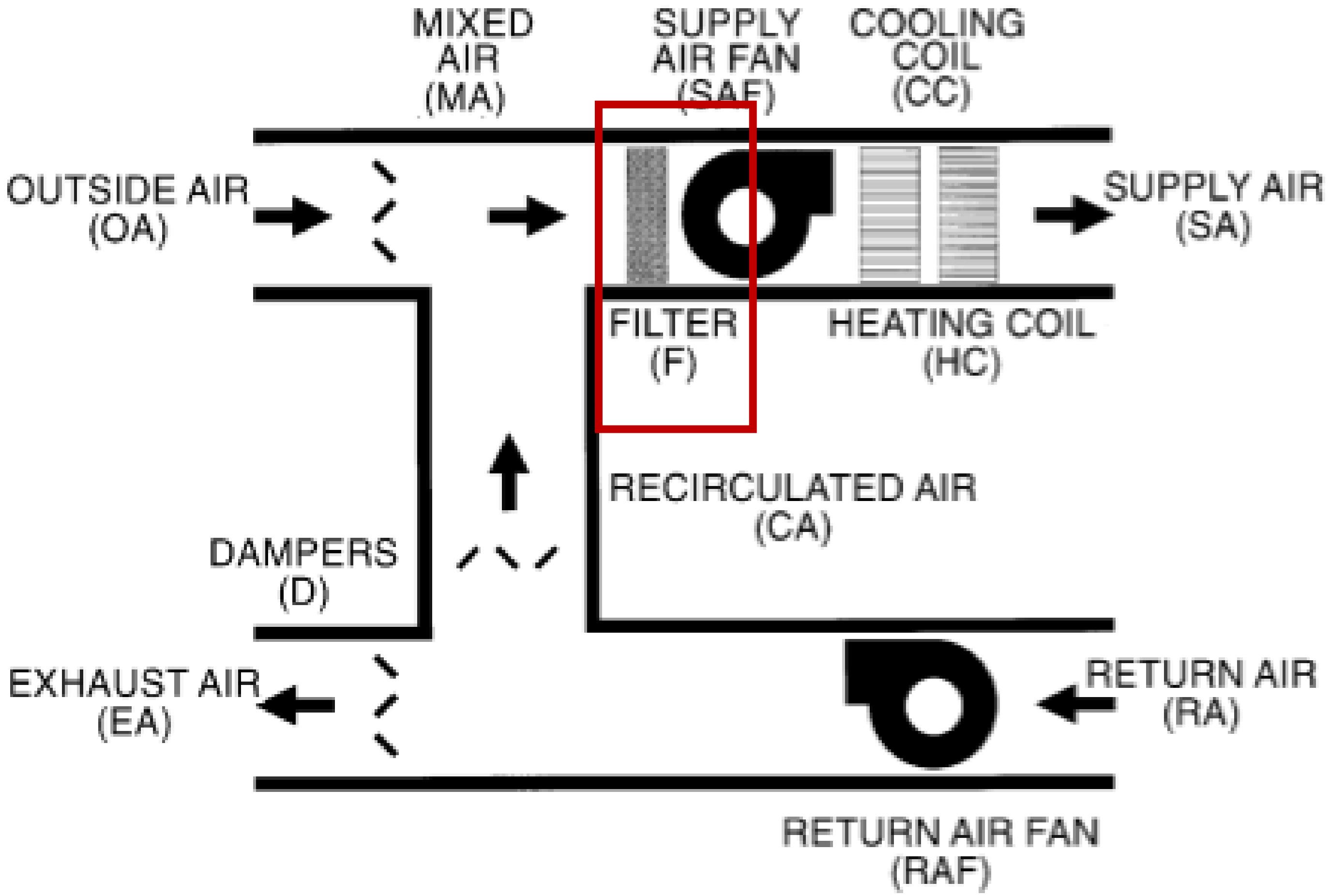
Supply ATD – Positioning

- type of the selected ATD
- air volume capacity
- throw
- drop and spread
- pressure losses and noise

Questions?

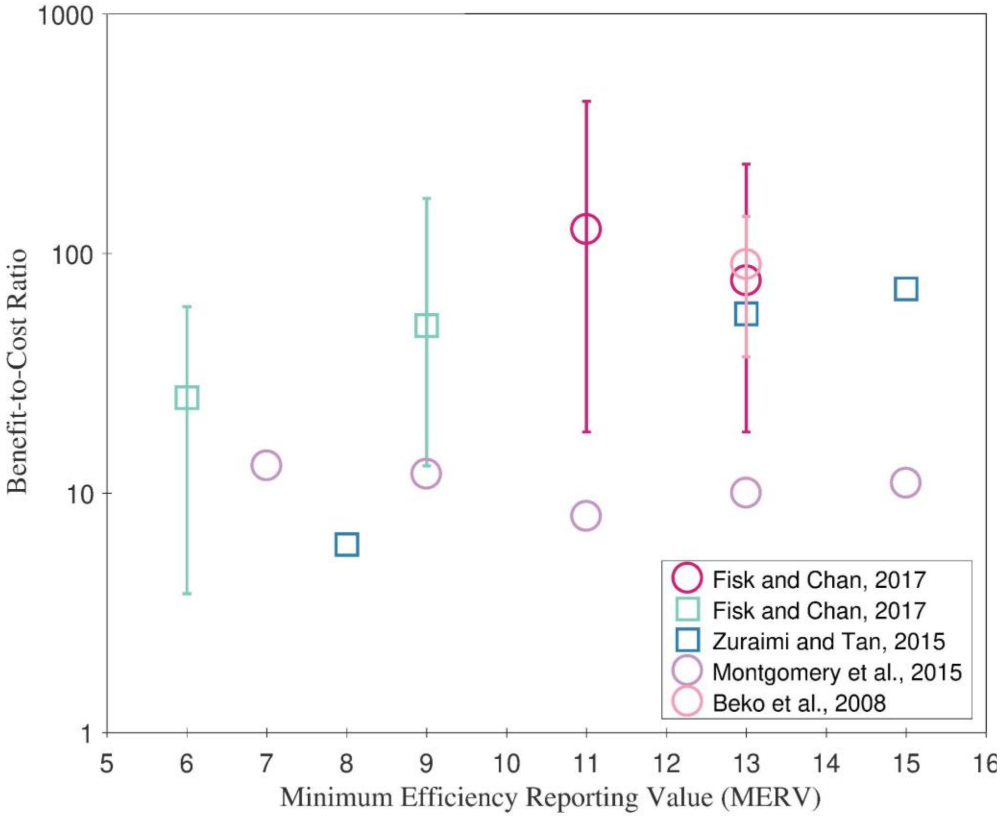
Filtration / Air cleaning

- This is a typical commercial HVAC system:



What is the purpose of a filter?

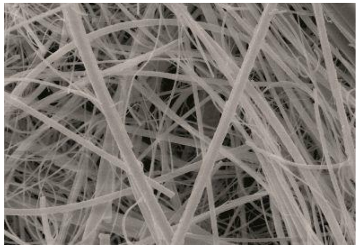
- To protect human health?
- To protect equipment?
  - Both
  - Clear benefit to cost ratio



(Source: Alavy and Siegel (2019) Sci Tech Built Environ)

What can we filter out in our building

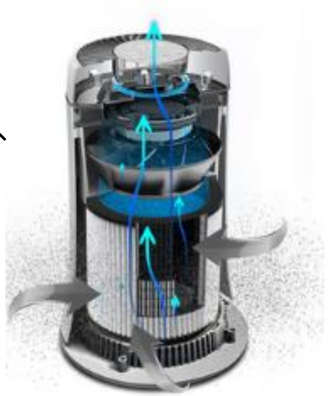
- **Particles**
  - Fibrous filters
  - Electrostatic precipitators
  - Every forced (mechanical) HVAC system will have some kind of particle filter



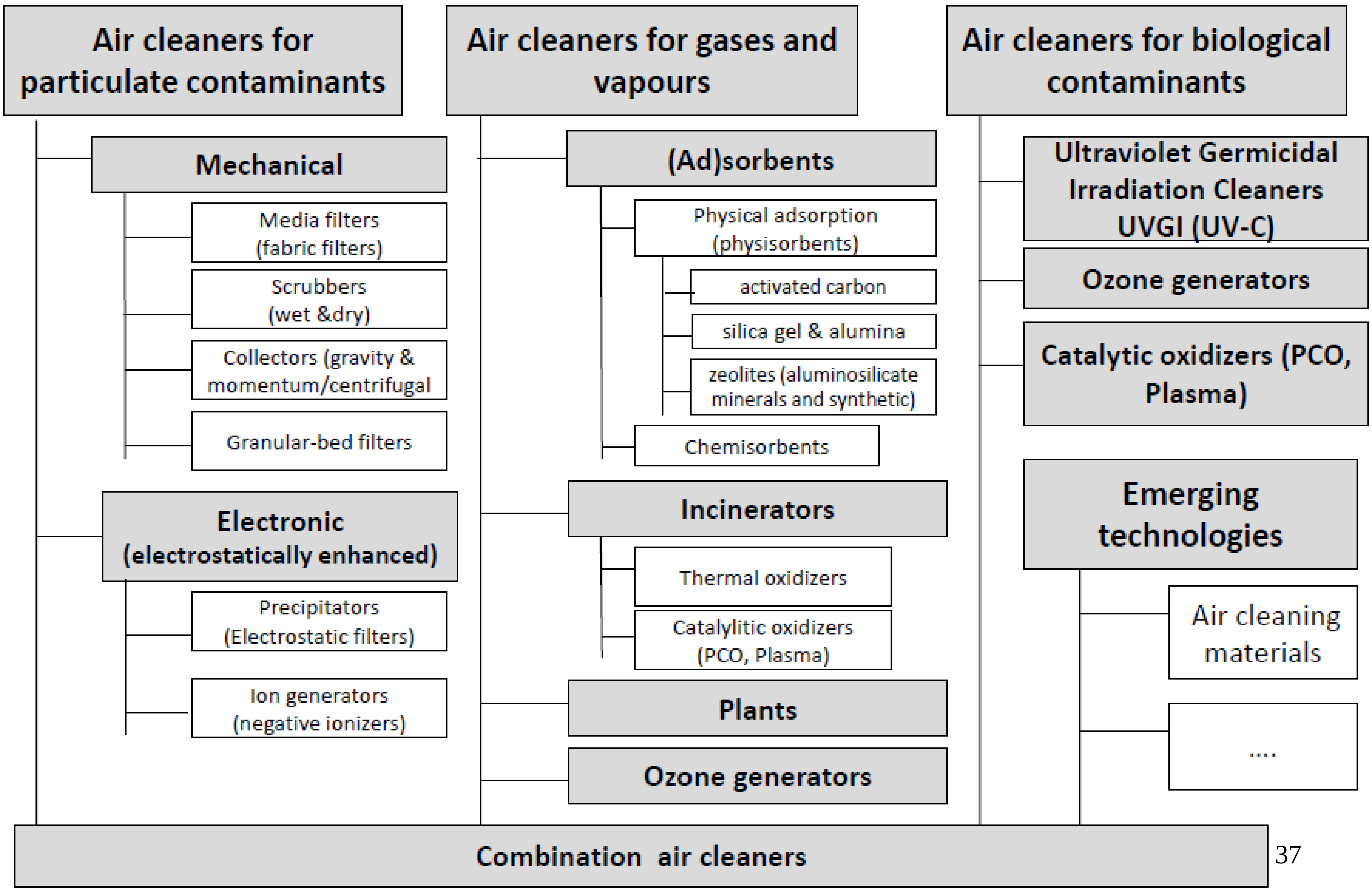
- **Gases (out of scope)**
  - Activated carbon
    - Relies on adsorption of VOCs/other gases to high surface are carbon
  - Very few buildings have gas-phase filtration

Classification of air cleaning devices

- **By pollutants removed:** particle air pollution, gaseous air pollution, biological pollutants: microbes and bacteria, combination of the above
- **By principle of operation:** passive and active
- **By means of principle:** collect, remove/destroy and transform
- **By construction**: in-duct and portable

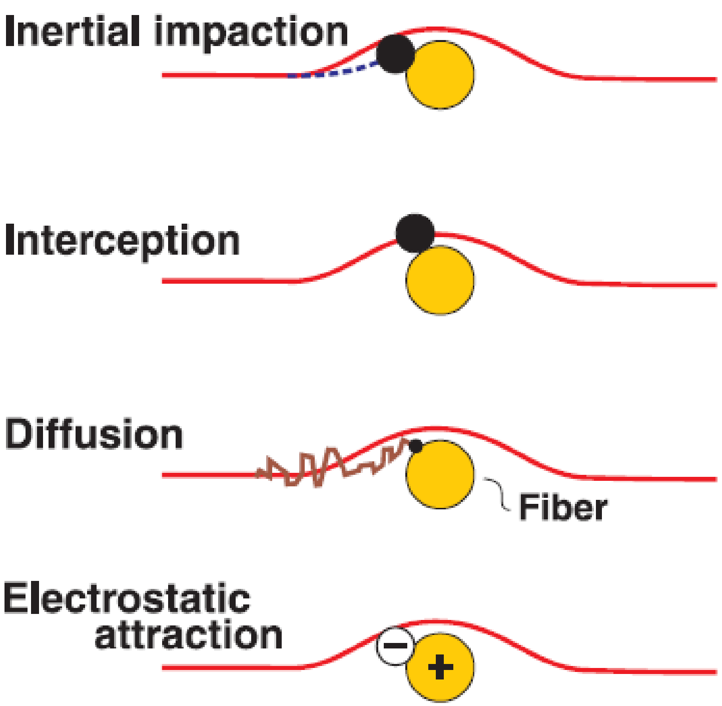


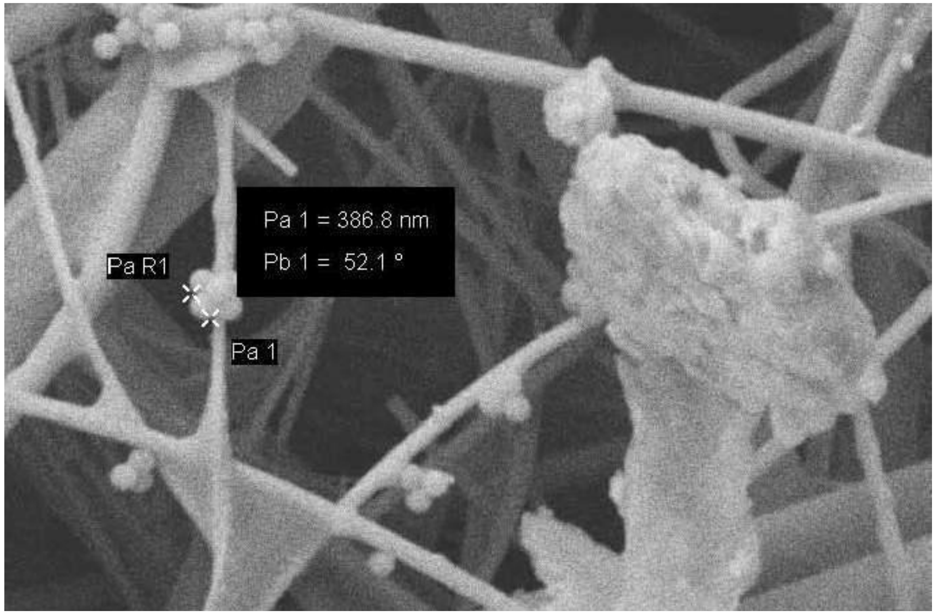
Classification of air cleaning devices



Fibrous filtration (for particles)

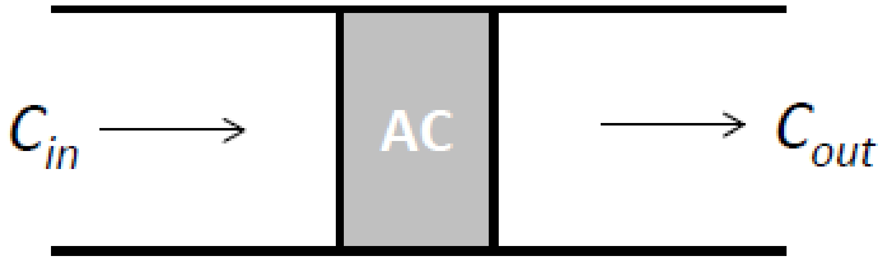
- Particle removal occurs through a combination of forces:
  - Gravitational settling, Brownian diffusion, impaction, electrostatic forces, thermophoretic forces





(Source: http://www.nasa.gov/mission_pages/station/research/experiments/ISS_High_Efficiency_%20Particle_Filter_Analysis1.jpg)

Performance indicator: Single-pass efficiency (η)

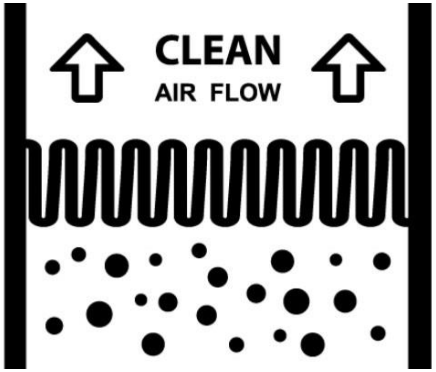


$$\eta = \frac{C_{in} - C_{out}}{C_{in}} \cdot 100\ [\%]$$

- Fraction of pollutants removed as it passes through the device (C_{in}: concentration at the inlet; C_{out}: concentration at the outlet)
- Maximum conversion is 100% indicating that contaminant(s) have been removed completely
- It can be used to estimate the outlet concentration of a pollutant downstream the air cleaner

Performance indicator: Clean air delivery rate (CADR)

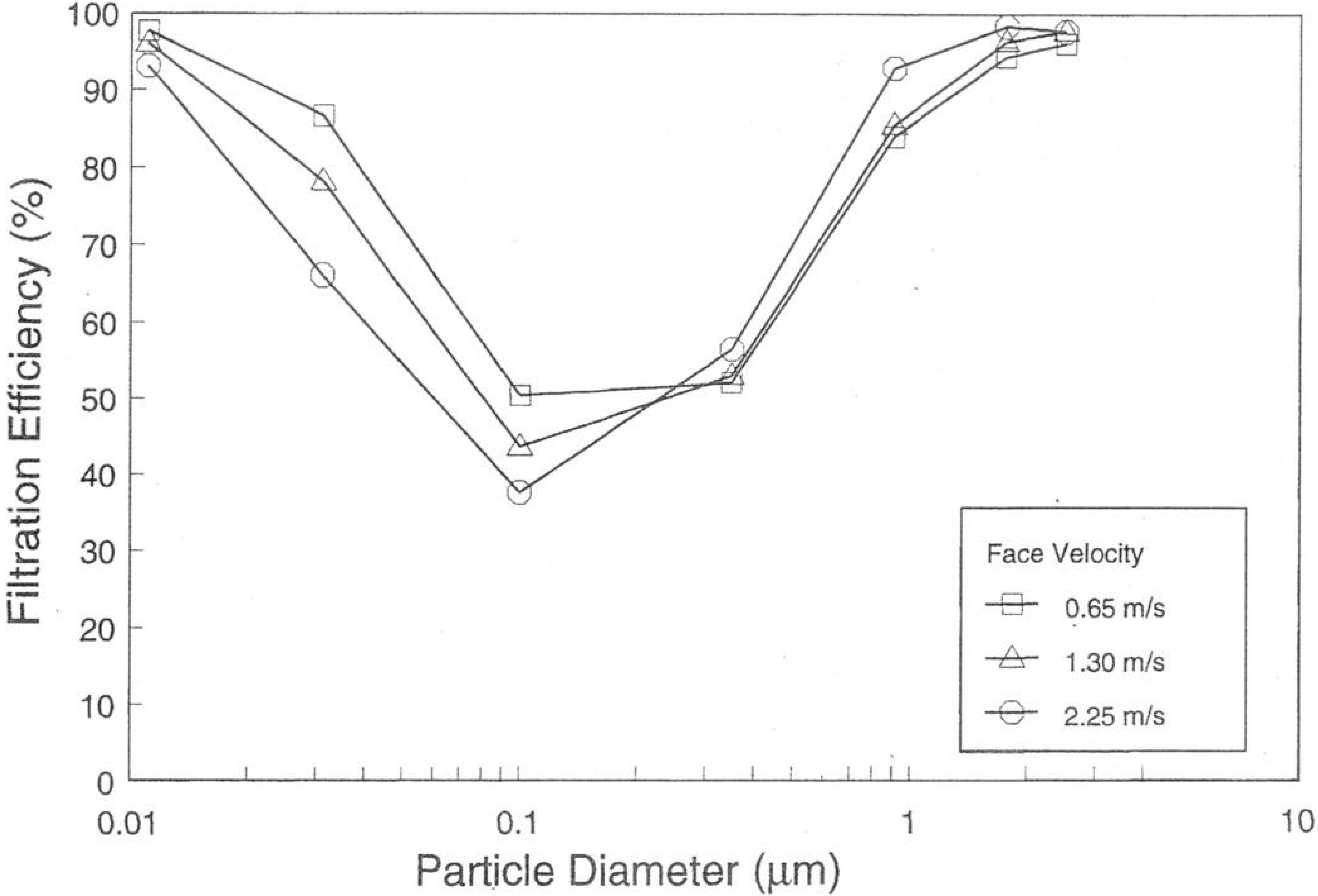
$$CADR = \eta \cdot Q \ (\frac{m^3}{h})$$



- The effective clean airflow rate through air cleaner which is the equivalent of clean air delivered by the air cleaner
  - It basically tells how useful is to have an air cleaner
  - CADR is typically reported by manufacturers
  - If not, the information related to filtration capacity is not reliable

- CADR is typically reported for the challenge pollutant which was used to examine the performance of air cleaner

General efficiency: Classic U-shaped curve



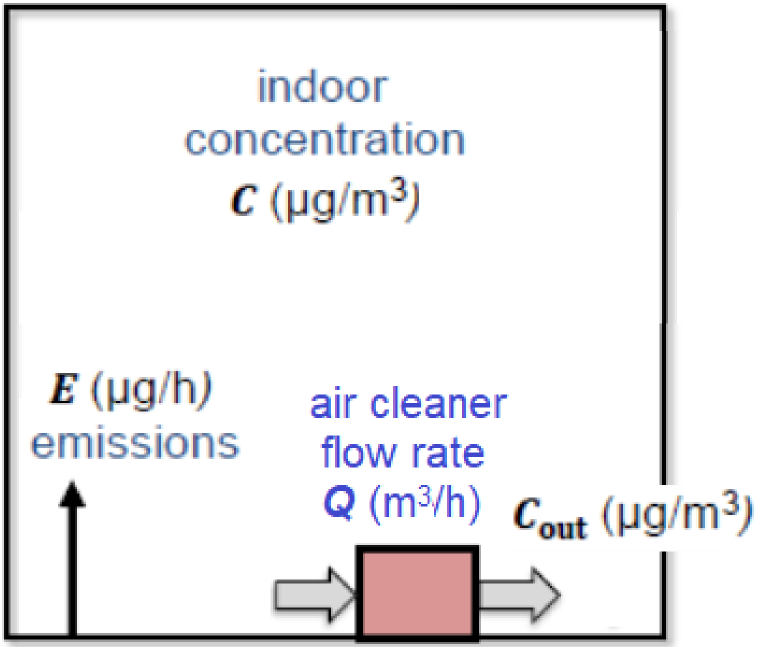
(Source: Hanley et al. (1994) Indoor Air)

Questions?

Example 1

- Determine the single-pass efficiency (η) and clean air delivery rate (CARD) of an air cleaner which is located inside the room. Take these parameters into account:

- Indoor particle concentration is 35 μg/m^3;
- Particle concentration at the outlet of an air cleaner is 12 μg/m^3;
- Air flow rate through the air cleaner is 80 m^3/h.

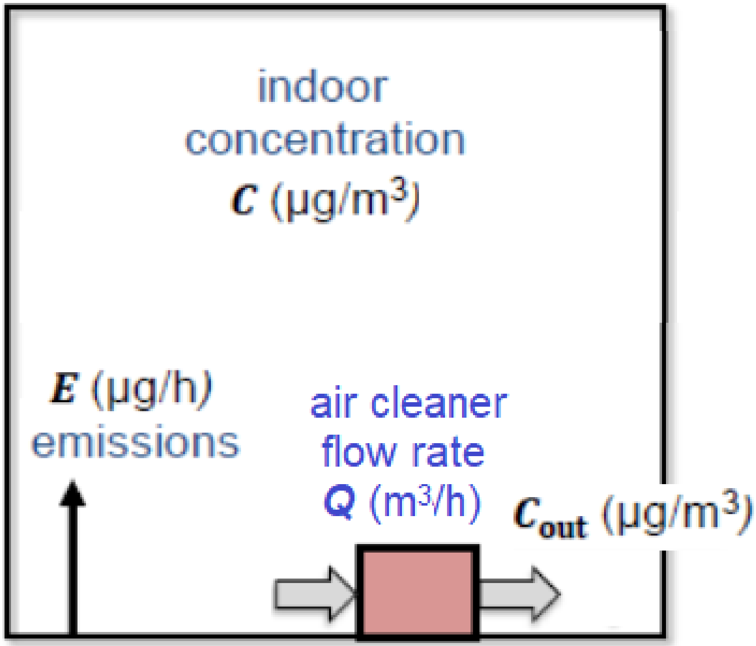


Example 1: Solution

- Determine the single-pass efficiency (η) and clean air delivery rate (CARD) of an air cleaner which is located inside the room. Take these parameters into account:
  - Indoor particle concentration is 35 μg/m^3;
  - Particle concentration at the outlet of an air cleaner is 12 μg/m^3;
  - Air flow rate through the air cleaner is 80 m^3/h.

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} \cdot 100\% = 65.71\%$$

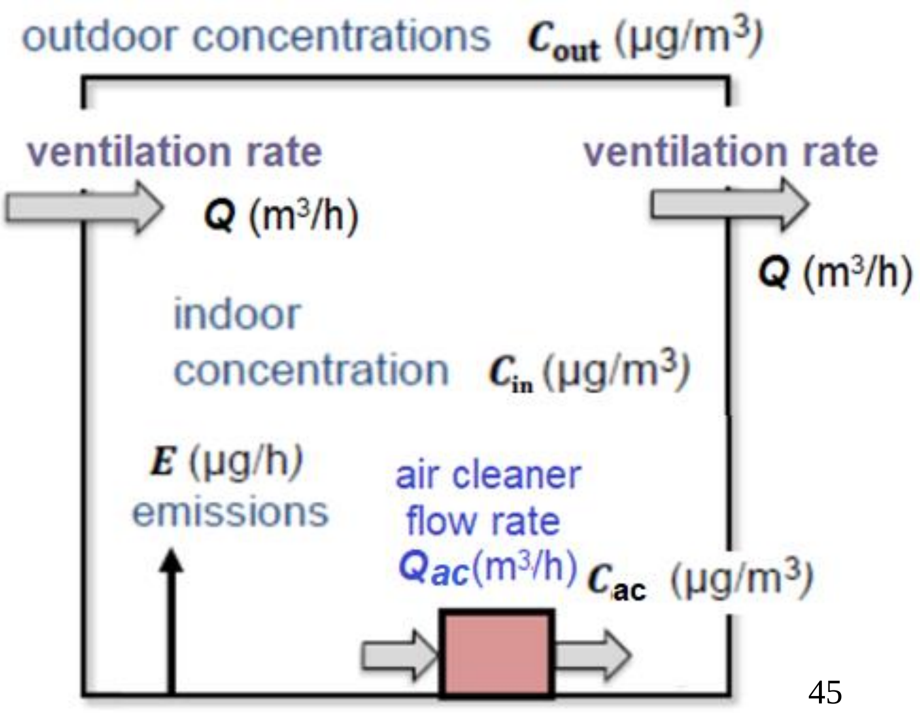
$$CADR = \eta \cdot Q = 0.6571 \cdot 80 = 52.57\ \frac{m^3}{h}$$



- Follow up thought: If ventilation rate in the same room is higher than the CARD of the air cleaner, that means that ventilation is more effective in removing air pollution then the air cleaner, and vice versa…

Example 2

- A person smoking indoors releases particles at a rate of 400 μg/h. Particle mass concentration outdoors is 35 μg/m^3.
  a. Find particle concentration indoors if the outdoor air is supplied at the rate of 7 l/s. Assume ventilation effectiveness to be 1.
  b. If the ventilation effectiveness increases to 1.2, how much ventilation will be needed to keep the same indoor particle level?
  c. What would be the clean air delivery rate of an added air cleaner with the single-pass efficiency (η=0.6) and flow rate Q_{ac} = 35 m^3/h?



Example 2: Solutions

- A person smoking indoors releases particles at a rate of 400 μg/h. Particle mass concentration outdoors is 35 μg/m³.
  a. Find particle concentration indoors if the outdoor air is supplied at the rate of 7 l/s. Assume ventilation effectiveness to be 1.
  b. If the ventilation effectiveness increases to 1.2, how much ventilation will be needed to keep the same indoor particle level?
  c. What would be the clean air delivery rate of an added air cleaner with the single-pass efficiency (η=0.6) and flow rate Q_{ac} = 35 m³/h?

Solution a):

$$Q = \frac{E}{(C_{in} - C_{out}) \cdot \varepsilon_v} \qquad 25.2\,\frac{m^3}{h} = \frac{400\,\frac{\mu g}{h}}{\left(C_{in} - 35\,\frac{\mu g}{m^3}\right) \cdot 1} \qquad C_{in} = 50.6\,\frac{\mu g}{m^3}$$

Solution b):

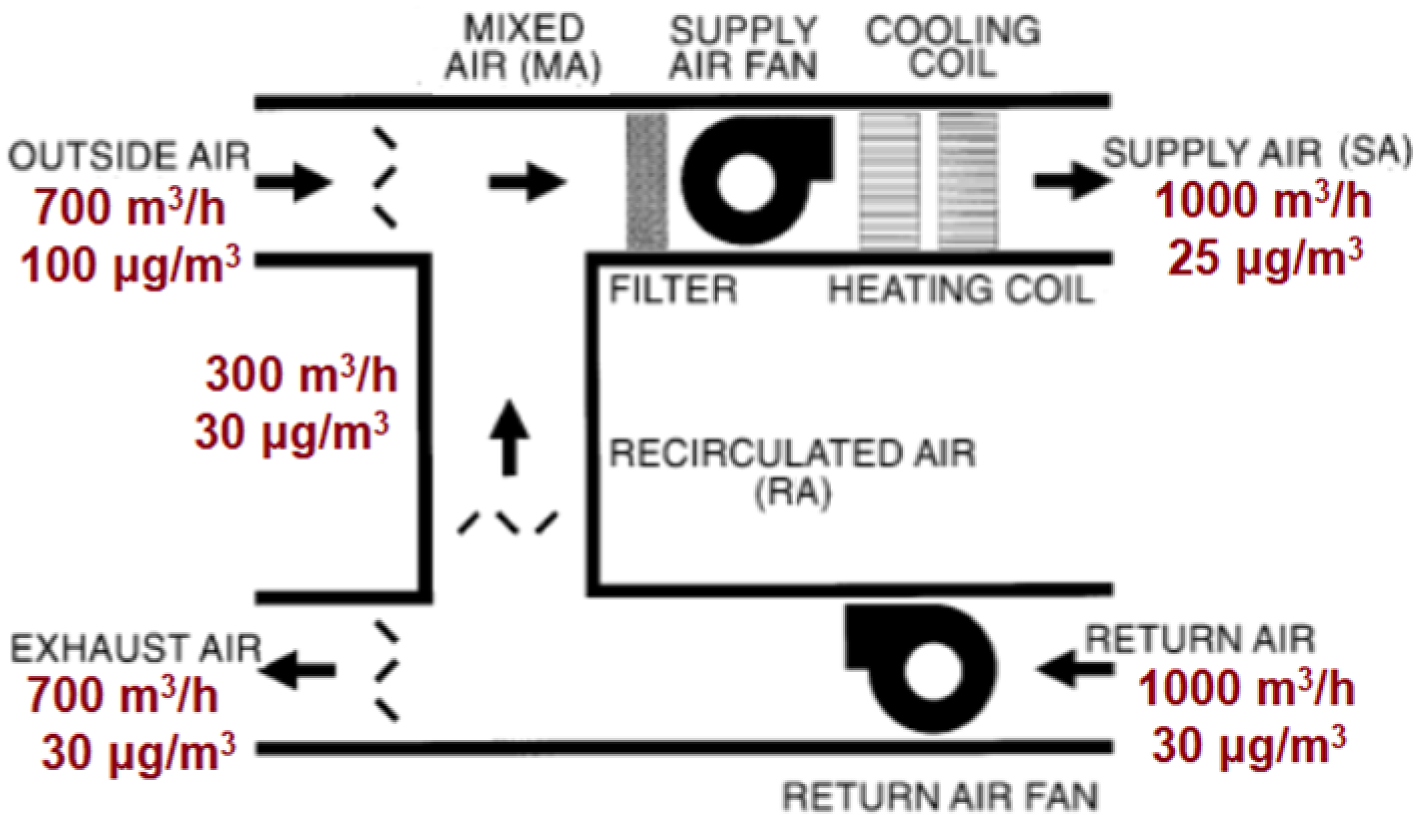
$$Q = \frac{400\,\frac{\mu g}{h}}{\left(50.6\,\frac{\mu g}{m^3} - 35\,\frac{\mu g}{m^3}\right) \cdot 1.2} = 21.36\,\frac{m^3}{h} = 5.94\,\frac{l}{s}$$

Solution c):

$$CADR = \eta \cdot Q_{ac} = 0.6 \cdot 35 = 21\,\frac{m^3}{h}$$

Example 3

- Determine the single-pass efficiency (η) and clean air delivery rate (CARD) of the filter in the air handling unit for the conditions summarized on the figure below.



Example 3: Solutions

- The key is to determine the particle mass concentration at the inlet of the filter
  - We can do that with a simple mass balance of mixing

$$C_{inlet} = \frac{Q_{ao} \cdot C_{oa} + Q_{ro} \cdot C_{ra}}{Q_{oa} + Q_{ra}} = \frac{700\,\frac{m^3}{h} \cdot 100\,\frac{\mu g}{m^3} + 300\,\frac{m^3}{h} \cdot 30\,\frac{\mu g}{m^3}}{700\,\frac{m^3}{h} + 300\,\frac{m^3}{h}} = 79\,\frac{\mu g}{m^3}$$

$$\eta = \frac{C_{ma} - C_{sa}}{C_{ma}} \cdot 100\% = \frac{79\,\frac{\mu g}{m^3} - 25\,\frac{\mu g}{m^3}}{79\,\frac{\mu g}{m^3}} \cdot 100\% = 68.35\%$$

$$CADR = \eta \cdot Q = 0.6835 \cdot 1000 = 683.5\ \frac{m^3}{h}$$

In the next several weeks…(check syllabus)

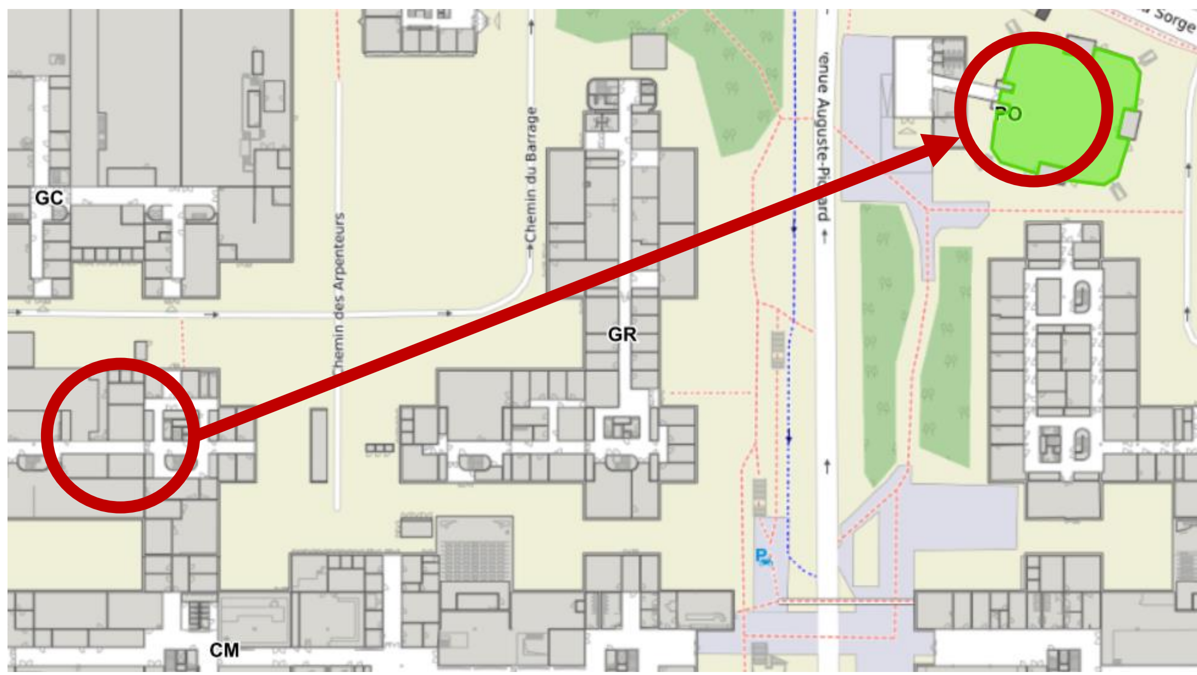
- Next week - No lecture!
  - I will be in the classroom at 17:15 am to take any questions that you may have about the project or lecture notes. Your attendance is optional.
- In two weeks is the final exam – What to study?
  - Focus on IAQ and Ventilation lectures and exercise
  - The exam questions of similar format as for the midterm:
    - Calculations (be sure that you fully understand all the calculation examples from the classes, including mass balance model, general psychrometrics, methods for determining ventilation rates, unit conversion.
    - Open-ended questions (those you cannot answer with a simple "yes" or "no", and instead require to critically think and to elaborate on your point). These question won't necessarily have a single correct answer but will rather examine your perspective described in your own words.
    - A few quiz questions with multiple choice answers based on theory. This will count for less points compared to other questions.

Update on the next exam – Info & Tips

- This will be an open book exam. You are free to use the lecture materials or computers, but you must work on your own. No internet allowed.
- Make sure that your calculators and psychometric charts are ready.
- Please be sure to show as much work as possible. I may give partial credit for it (in case your end result is incorrect).
- Some of open-ended questions won’t have necessarily a single correct answer. For some of these questions how you set up the problem is just as important as whether or not you ultimately get the right answer.
- Please use English language only.
- If you have any questions about the wording of the questions, please raise hand.

Other information about the exam

- When will the exam take place?
  - 05 December 2024, at standard time 17:15 – 19:00h
  - Please try to come a bit earlier if possible (~17:00h)
- Where will the exam take place?
  - PO 01
  - Same place as the last time!



In the next several weeks…(check syllabus!)

- Weeks 14 and 15 (12th and 19th December)
    - Course project presentations! Who to attend?
    - All of you should attend.
    - Who will present their projects?

Student 1 Full N	Student 2 Full N	Student 3 Full N	Student 4 Full N	Student 5 Full N	Student 6 Full N	Student 7 Full N	Name of the selected (or proposed) topic:	Presentation
Martin Gaudry	Eloi Borlet	Jeanne Benoist	Margaux Fustinoni	Arthus Duval	Lil Jost-Dalifard	Victor Denner	**Impact of Indoor Air Quality on Human Productivity**	**12 December**
Maxima Laetizia W	Luis Lippert	Berta Leach	Clara Balcells	Laura Bosch Galde	Lino Davila	Gaist Cyril Alexand	**Do green buildings have better indoor climate**	**12 December**
ClÃ©mentine Bauc	Linda Popovic	Ninon Perot	Inacio Vieira	Marion ChÃªne	Kieran Sharp	Russo Ivan	**Cooling of Buildings Without Air-Conditioning: Feasible or Not?**	**12 December**
Clarisse Anthamatt	Rosa Puopolo	Camille PagÃ¨s	Riwa Naoura	Stefan Mignerey	Giona Ghezzi	Künzli Nicolas Antc	**Influence of indoor environment on sleep quality**	**12 December**
Maja Monika Now	Garman Meyler	Sacha Magnollay	Rika Ota	Olivia Scarlett Sieb	Akvile Seleviciute		**Why does mold grow and how to remediate it?**	**12 December**
Lorenzo Natal	Gauthier Ordonnez	Joaquin Valls	Selma Mkinsi	Mohamed Amine S	Petrillo Kylian		**Mechanical or Natural Ventilation?**	**12 December**
Amirmohammad A	Pedro Henrique Mc	Matthieu Greiner	Corentin Nagel Bo	Gabriel Leclercq	Nolan Bohler	David Aron	**How has architecturale Evolution Impacted indoor Climate?**	**19 December**
RaphaÃ«l Bixente I	Hugo Gebel	Zahed Assad	Arnaud Nicoud	Lucas Tufo	Ines cometti	Ludovic Bourdin	**Influence of indoor environment on sleep quality**	**19 December**
Leo Nalou ZÃ¼rche	Bruttin Diego	Benzoni Zeno	Mehalaine Yacine	Kaitouni Ali Idrissi	Braillard Eloi	Luo Mingyang	**Overheating of Buildings: Why we Should Tackle Overheating Early in**	**19 December**
Serena Fares	Christy Chivi	Omar Maghur	Jolien Van de Wall	Martha Boosten	Michiel De Backer	Ruben Hoeven	**Role of Indoor Climate in Combating the Spread of Airborne Virus**	**19 December**
Charlotte Maitre	Dina Mouden	Margot Chapalain	Malak Jria	Naya Arboleda	Wiam Airad		**Role of occupant behaviour on indoor climate control.**	**19 December**

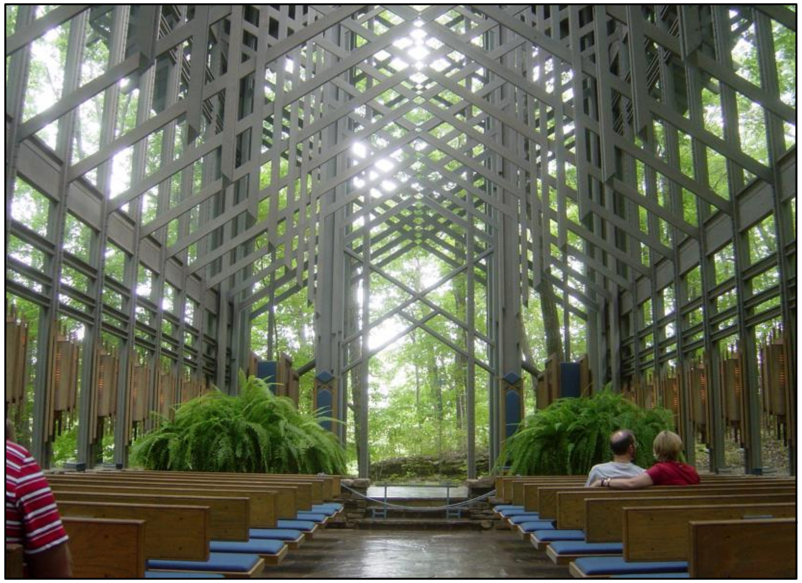
- Please don't forget to revisit the course syllabus to gain information about the presentation formatting and submission!

Course objectives (in my own words)

To understand important concepts of indoor environmental quality parameters which concern indoor climate: Thermal comfort and indoor air quality. By the end of the course, you are expected to be able to:

- Have a fundamental understanding of indoor climate theory and contemporary issues encountered in the building design and operation cycles. ✓
- Talk about determinants and assessment methods for human thermal comfort and indoor air quality, and to understand their impact on humans. ✓
- Assess thermal comfort and indoor air quality control mechanisms and determine their effectiveness. ✓
- Read and critically analyze articles in the technical literature on thermal comfort, indoor air quality and ventilation. ongoing
- Prepare informative oral presentation. ongoing

What do ~~I~~ *WE* think when ~~I~~ *WE* hear "climate"



Summary thoughts and the big picture

- Indoor climate isn’t really a standalone discipline
  - Involves engineers, architects, public health professionals, analytical chemists, building scientists, architects, contractors, medical professionals, epidemiologists, academics, biologists, psychologists, economists, etc.
  - Many different approaches
  - In this course, you have gained the fundamental understanding

- The big picture is that:
  - We are interested in indoor climate because of its impact on:
    - Worker productivity/safety
    - Human comfort
    - Health effects
    - Material degradation
    - Biological growth/disinfection
    - Energy use

Summary thoughts and the big picture

Buildings are complex systems and are trending toward greater complexity. This is not necessarily a good thing.

Indoor climate has profound influence on occupants, and vice versa. We must not think of buildings without primarily thinking of people!

We have an ample opportunity to reduce energy use and its associated external costs. The challenge is to improve the quality of the indoor climate at the same time.

General notion is that building energy use and good indoor climate are always in conflict. However, if a building is well designed and operated, this will not be the case. More to learn in ENG-445 course.

Bravo for surviving the course (so far) and thank you for being a good class!!!

"We should design indoor environments that are better than the best environment found in nature" — *Ole Fanger*