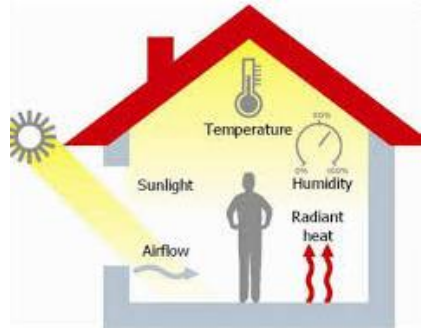
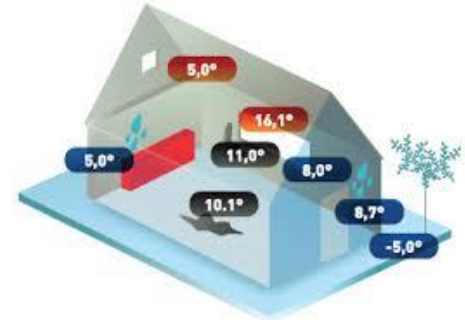
CIVIL 212
Indoor Climate
Fall 2024





Introduction to Ventilation

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Today’s objectives

- **Introduction to ventilation**
- Driving forces of ventilation
- Air exchange rates & ventilation requirements

“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 with building envelope and filtration (when needed)

- **Ventilate well**

(Adapted from: Nazaroff 2013 Indoor Air)

Ventilation – definitions

- **Ventilation**: process of intentional supplying and removing air naturally or mechanically to/from any space
  - Air may or may not be conditioned

Ventilation ≠ **Air-conditioning**

- **Primary aim:** To provide adequate indoor air quality

- **May also be used for:** Regulating thermal comfort ("ventilative cooling") when outdoor conditions are not far from the "comfort zone" (recall the psychrometric chart).

AC began here… with Willis Carrier

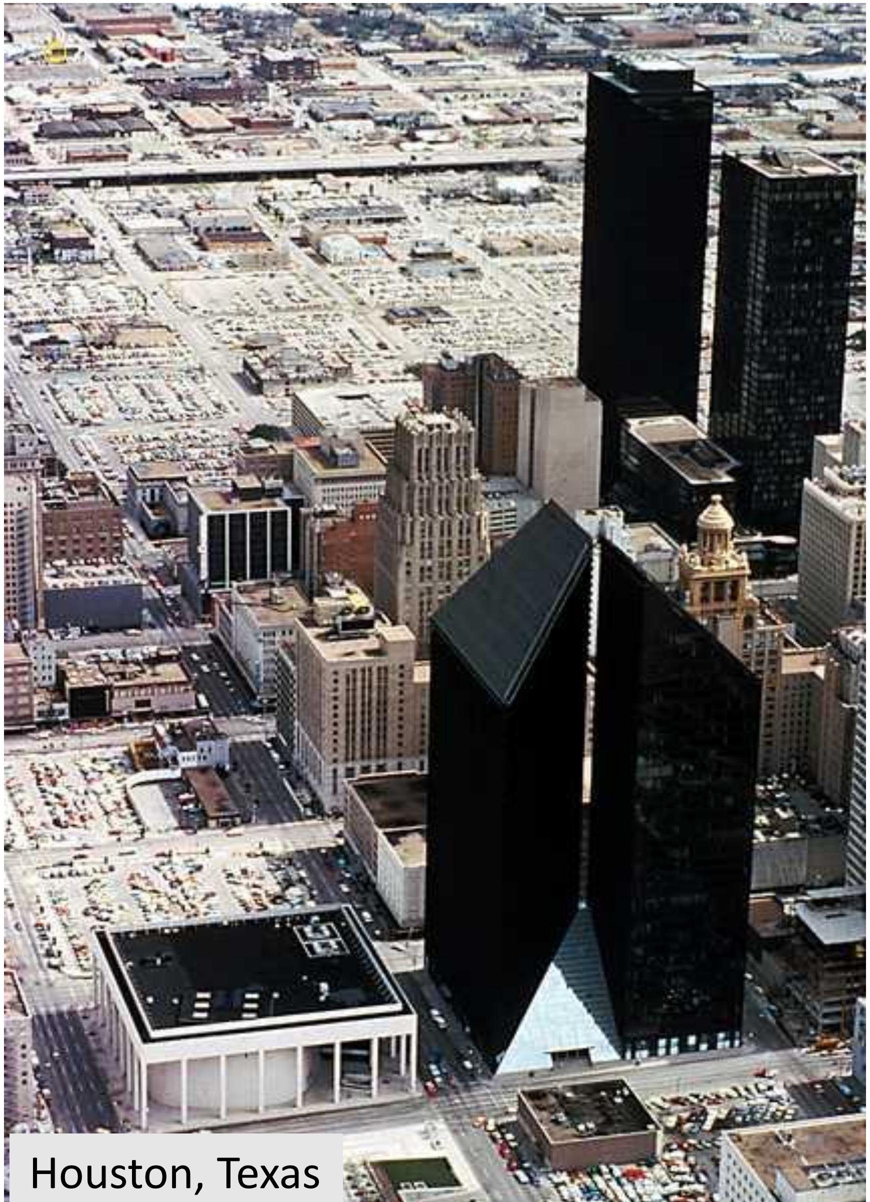
Air-conditioning (AC) invented, Willis Carrier, 1902

Advertisements of 1950's

1950's ads – the role of women, beauty, convenience & nature

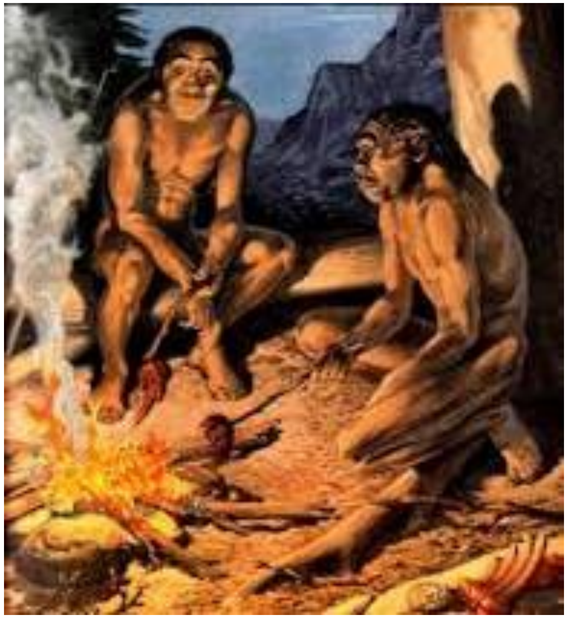
Loss of a porch…cultural & social impact?

AC’s impact on global architecture



History of ventilation

- The first people found that supply of outdoor air is needed in order to reduce smoke and maintain fire in caves



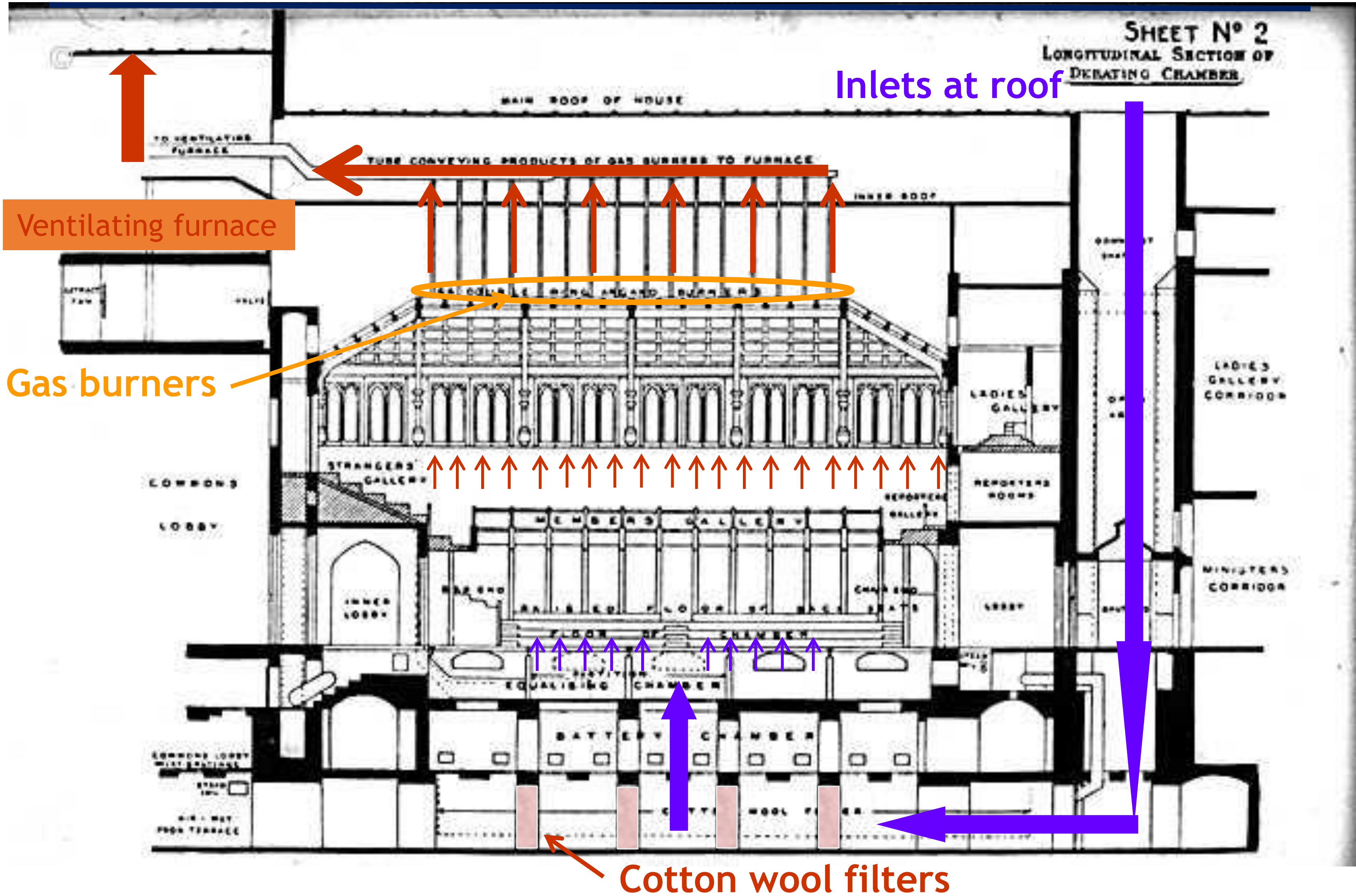
- Ancient Egyptians observed that stone carvers when working indoors had a higher incidence of respiratory diseases compared to when working outdoors. They attributed this to high level of dust in indoor spaces

The 1st centralized ventilation (1830)

- Ventilation as a science begins in 17th century, but the first building with centralized ventilation appears only in 19th century

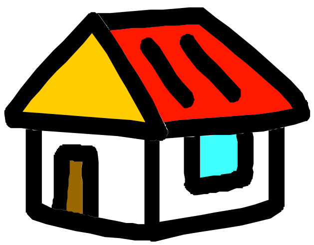
Houses of Parliament, Barry & Pugin, London, 1830.

The 1st ventilation – Houses of Parliament



Impact of ventilation on thermal comfort

- Key parameters influencing thermal comfort



Environmental factors:

1. Air temperature
2. Humidity
3. Air Speed
4. Mean radiant temperature

Personal factors:

1. Activity
2. Clothing

Related to ventilation!

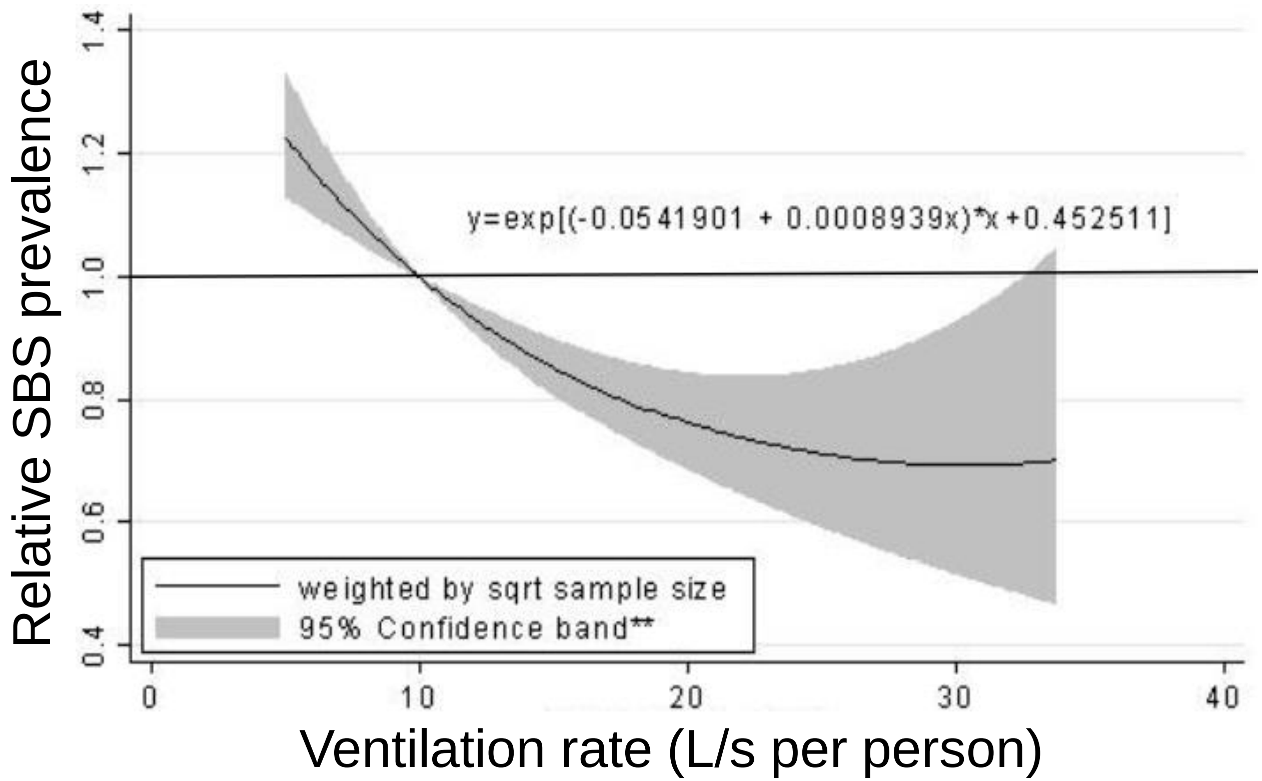
Impact of ventilation on health

- 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)



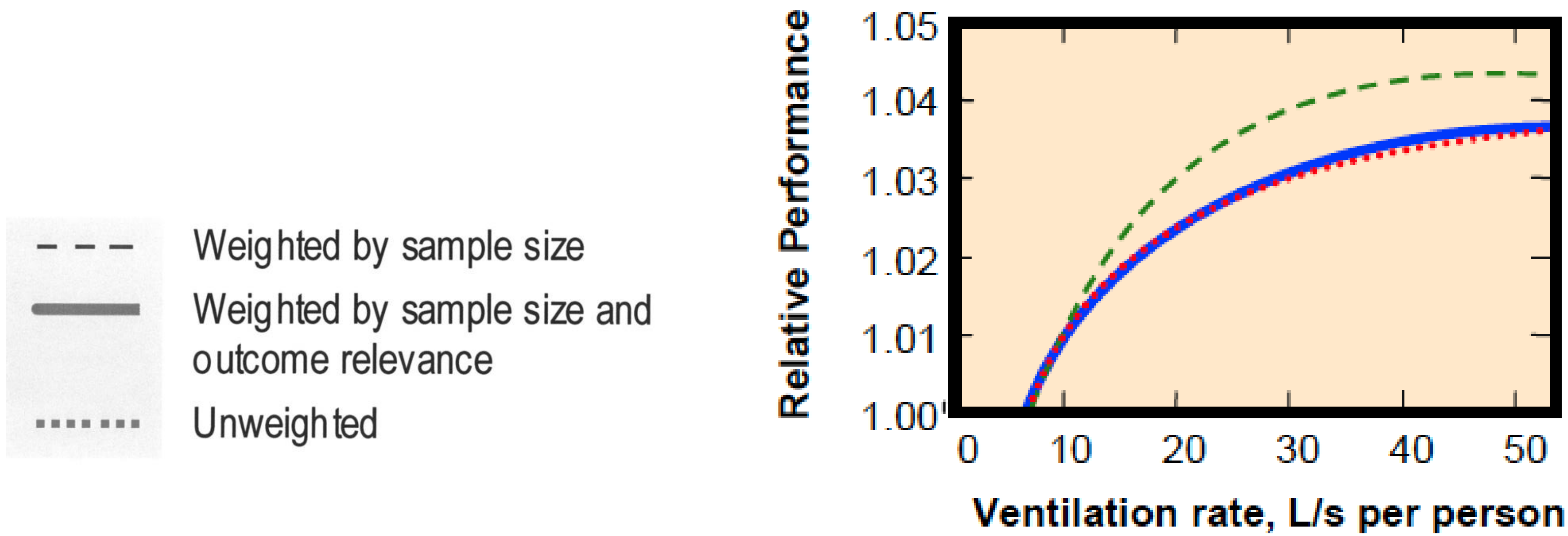
Impact of ventilation on productivity

- Improved ventilation in a manufacturing facility led to reduced sick days

(Source: Milton et al. (2000) Indoor Air)

- Increased ventilation leads to slight increase (5%) in productivity (with potentially enormous cost implications)

(Source: Wargocki et al. (2000) Indoor Air)



Ventilation – definitions

- **Mechanical (forced) ventilation:** The intentional movement of air into and out of a building using fans, intake vents, and exhaust vents
  - Straightforward
  - Fans move air through known openings
  - Flow rates typically known or at least measurable

- **Natural ventilation:** The flow of air through open windows, doors, and other **planned** envelope penetrations, driven largely by natural or artificially induced pressure differences
  - Conceptually straightforward but physically complex
  - Known openings but highly varying wind speeds and directions

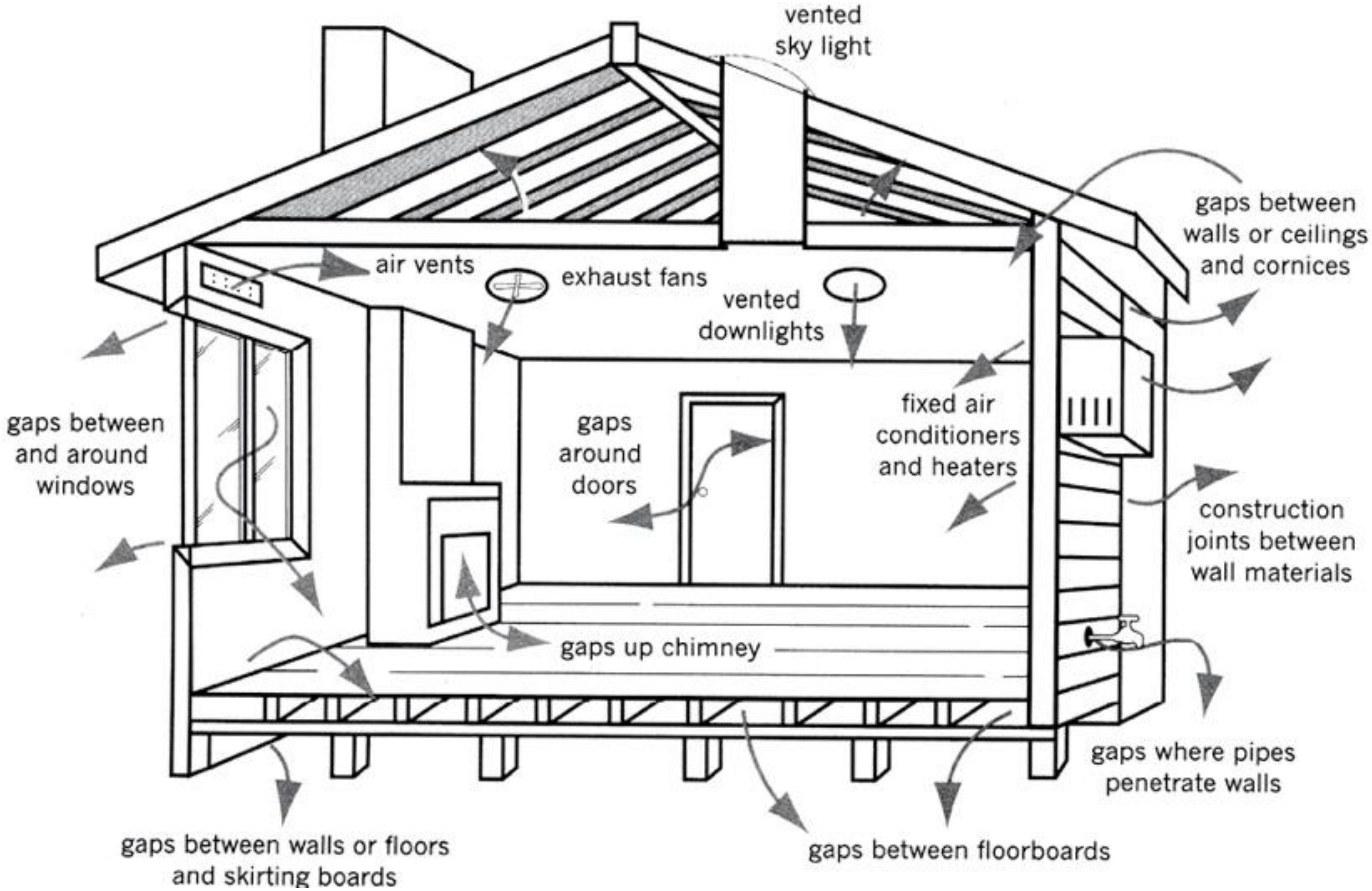
- **Mixed-mode ventilation:** Combination of mechanical and natural ventilation

What impacts air exchange rates (ventilation)?

- Is a result of (often) combined effects of
  - **Intentional ventilation** (The intentional movement of air into and out of a building using fans, intake vents, exhaust vents and natural ventilation)
  - **Unintentional ventilation** – infiltration or air leakage

Unintentional ventilation is very important as if influences the heat balance of buildings (thus energy use), indoor air quality and thermal comfort.

Air leakage paths in a building



Flow of outdoor air into a building through cracks, leaks, and other **unintentional** openings in the envelope (includes normal use of exterior doors) … i.e., air leakage. It is often very complex – We need to know airflows through each opening in order to quantify indoor climate impacts, typically we have unknown openings and multiple driving forces.

Today's objectives

- Introduction to ventilation
- **Driving forces of ventilation**
- Air exchange rates & ventilation requirements

General models for air flows through openings

- Given an opening (i.e., a leak, crack, or intentional opening):

$$Q = AC\Delta P^n$$

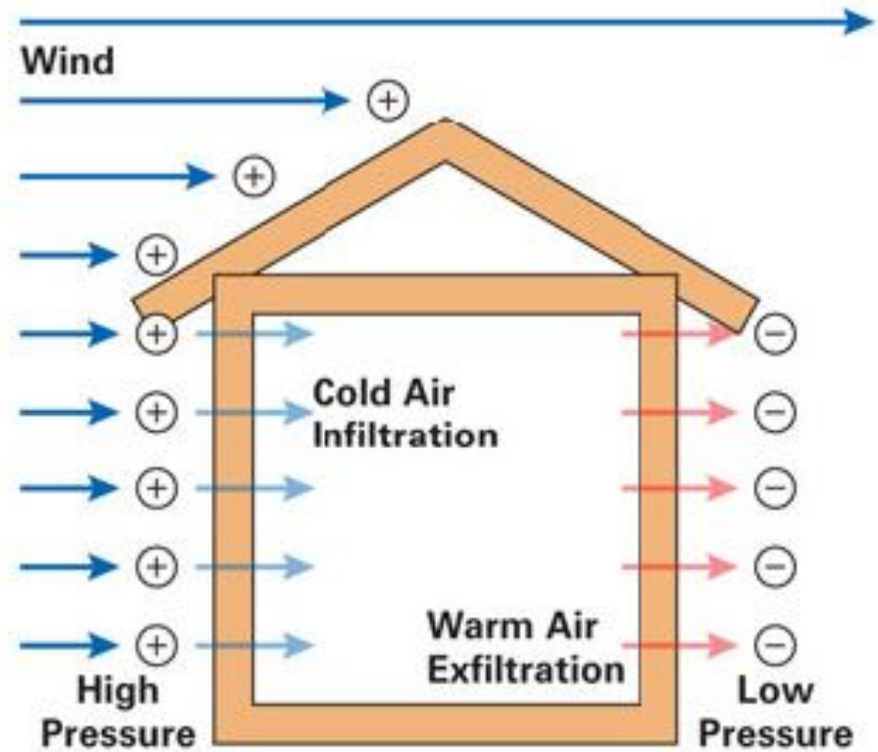
A = area of opening, (m^2)
ΔP = pressure difference between inside and outside, (Pa)
C = flow coefficient that depends on opening geometry and flow path (often determined experimentally), [m/(s Pa^n)]
n = exponent, between 0.5 and 1.0 (depends on opening types)

- For a combination of *i* openings:

$$Q = \sum_i A_i C_i \Delta P_i^{n_i}$$

Driving forces of air exchange (*ΔP*): **Wind**

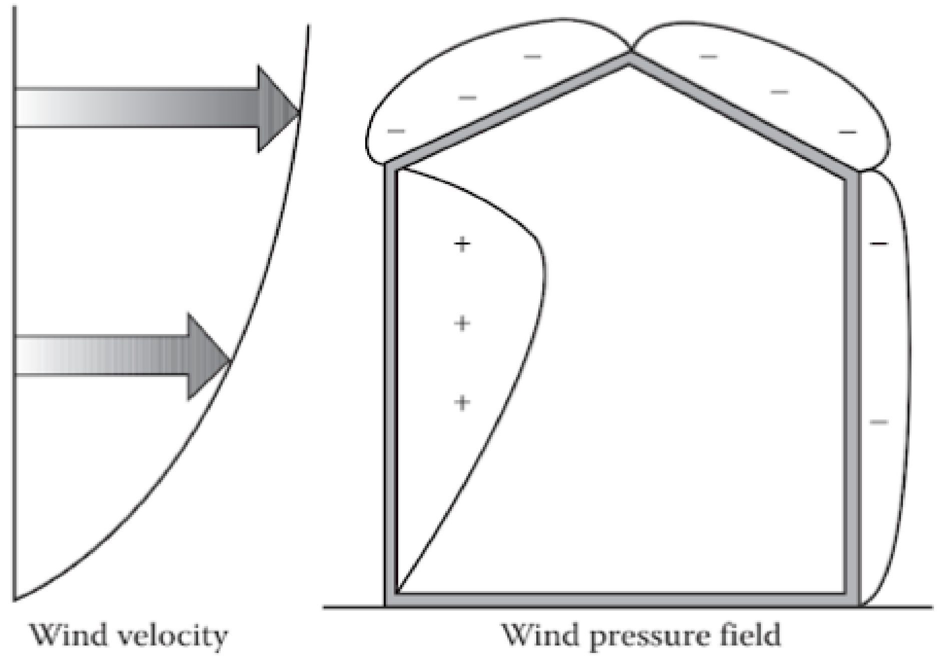
– **Wind**
  - Caused by <u>wind</u> impinging on a building, creating a distribution of pressures on the exterior surface
  - Depends on wind direction, wind speed, air density, surface orientation, and surrounding conditions



Wind-Induced Airflow:
Wind blows on the outside of the home and pushes air through holes (infiltration). An equal amount of air will be pushed out of the holes in other places in the home (exfiltration).

Wind pressures

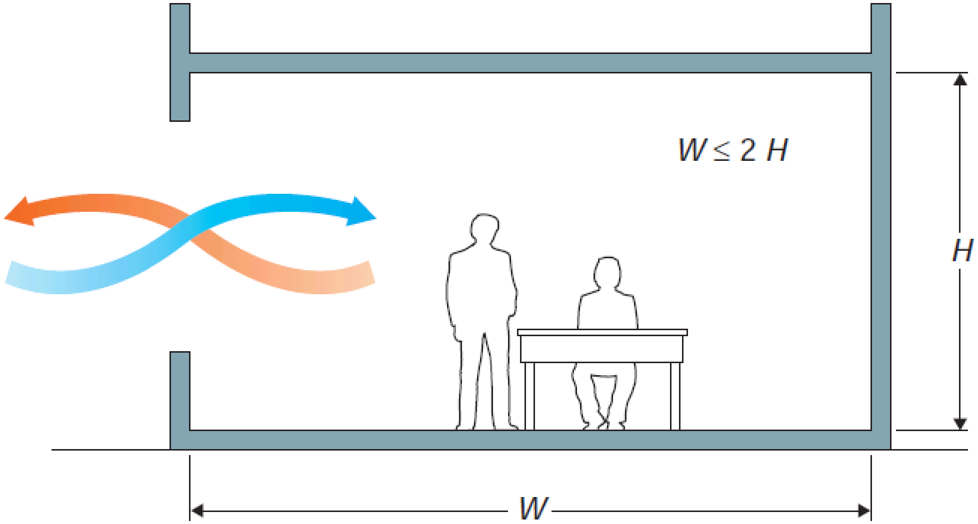
$$\Delta P_{wind} = \frac{1}{2} C_p \rho \vartheta_h^2$$



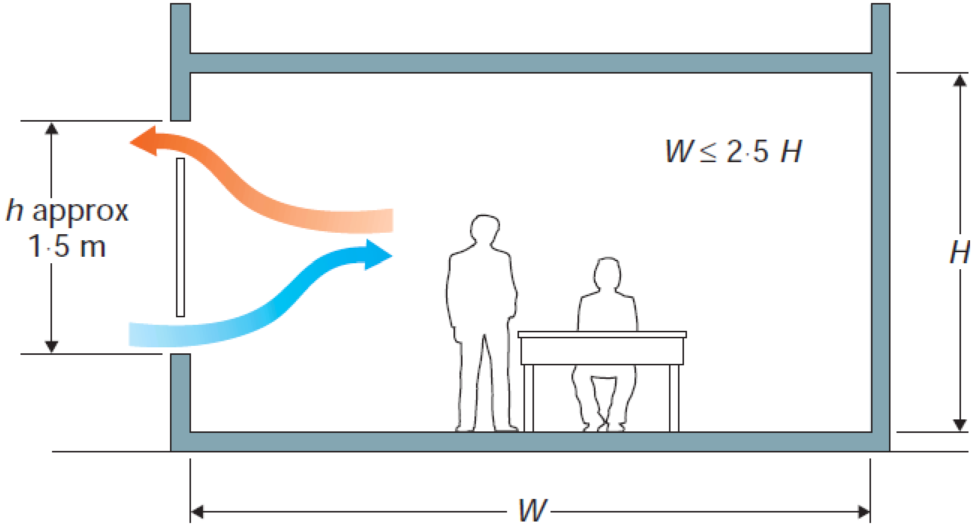
(Source: Reddy et al.2007)

C_p = wind pressure coefficient (f-on of the relative location of the building element with respect to wind direction) – is can be obtained from measurements or from handbooks.
ϑ_h = wind velocity at building height, *h*.
ρ = air density.

Single-sided ventilation



- Commonly found in cellular buildings. Wind is the main driving force.
- The "rule of thumb" governing maximum width of a building: W ≤ 2H.



- Multiple ventilation openings can enhance ventilation rate due to buoyancy driven air movement.
- Separating the low level openings can increase ventilation (issue: cold draughts)

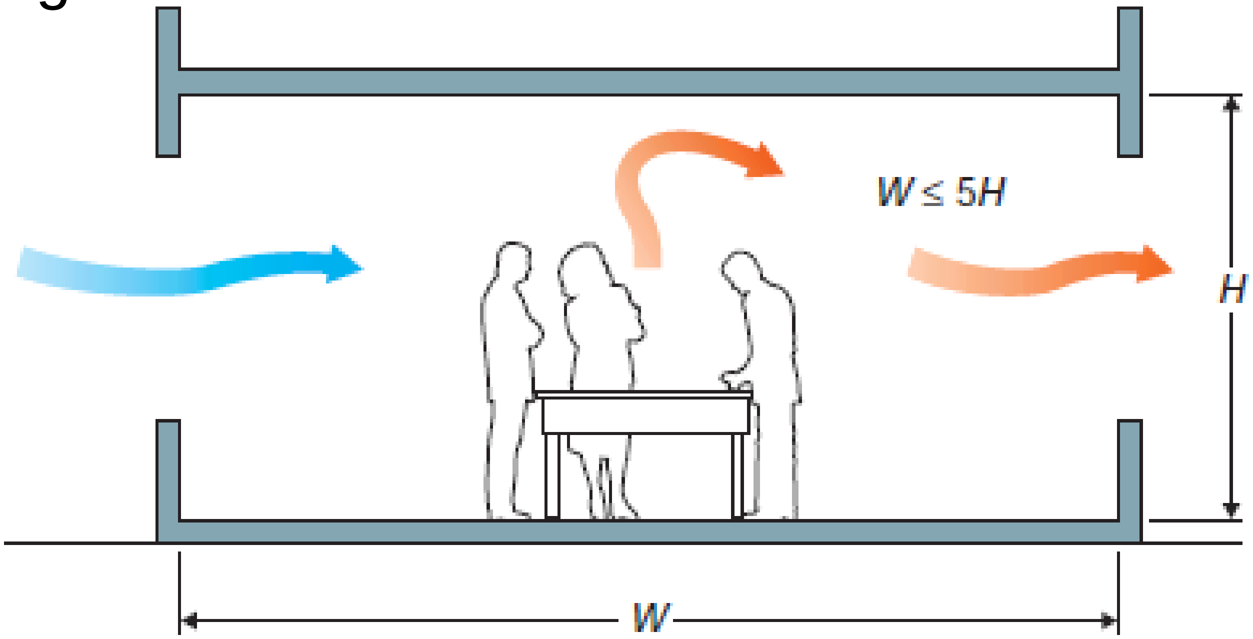
(Source: CIBSE AM10 Natural Ventilation in non-domestic buildings)

Double-sided (cross) ventilation

- The "rule of thumb" governing maximum width of a building: W ≤ 5H

  - however, a similar effect can be achieved in a deep plan layout with a courtyard.

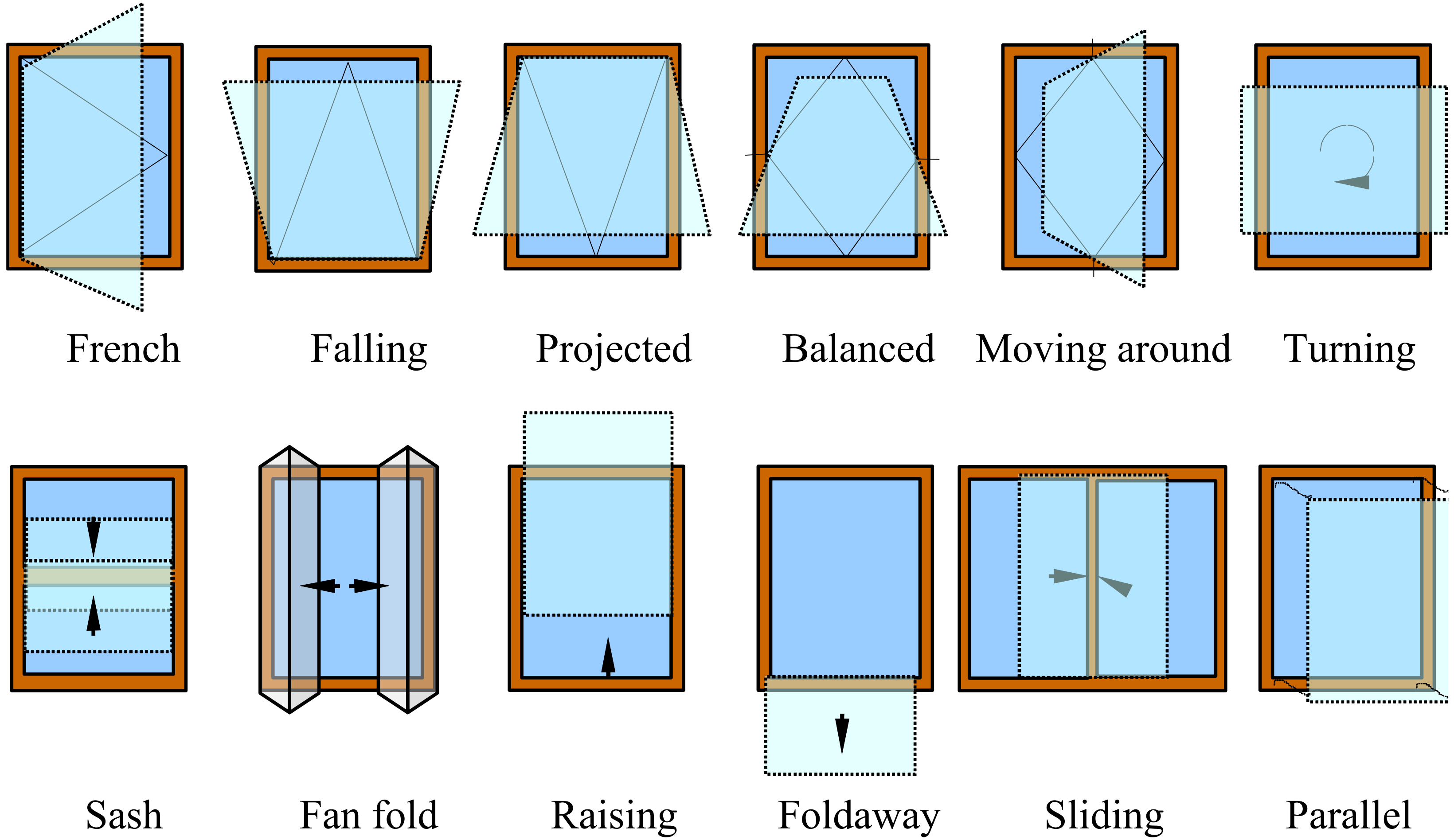
- This approach also enhances the potential for natural lighting



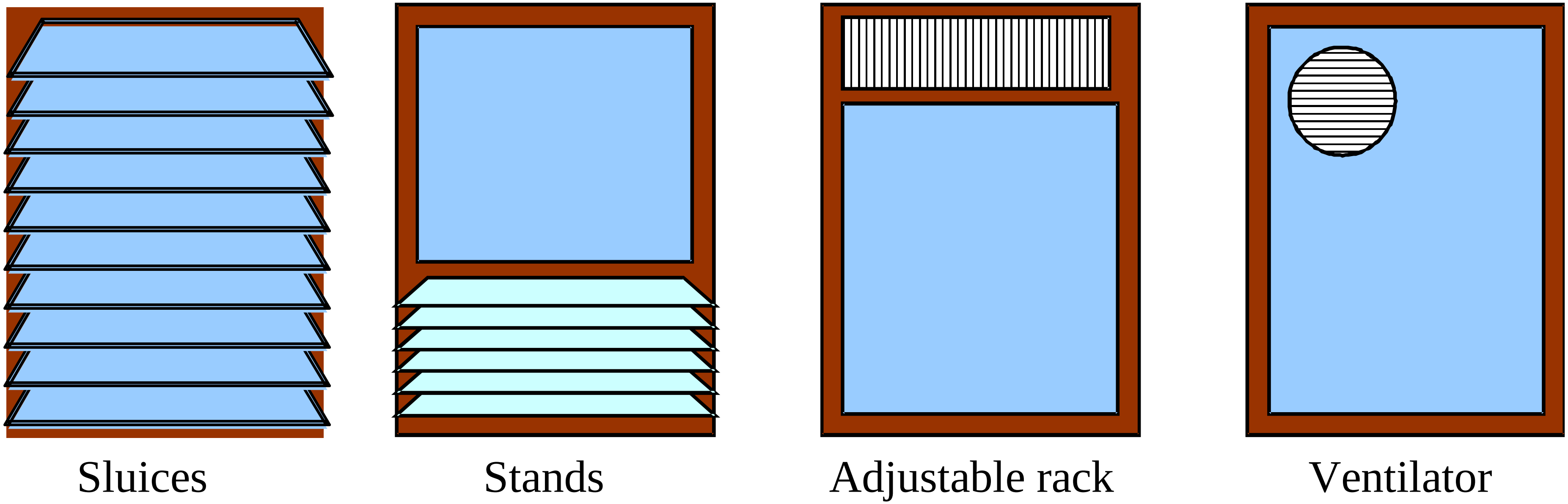
(Source: CIBSE AM10 Natural Ventilation in non-domestic buildings)

Window openings

Window design greatly influences ventilation effectiveness



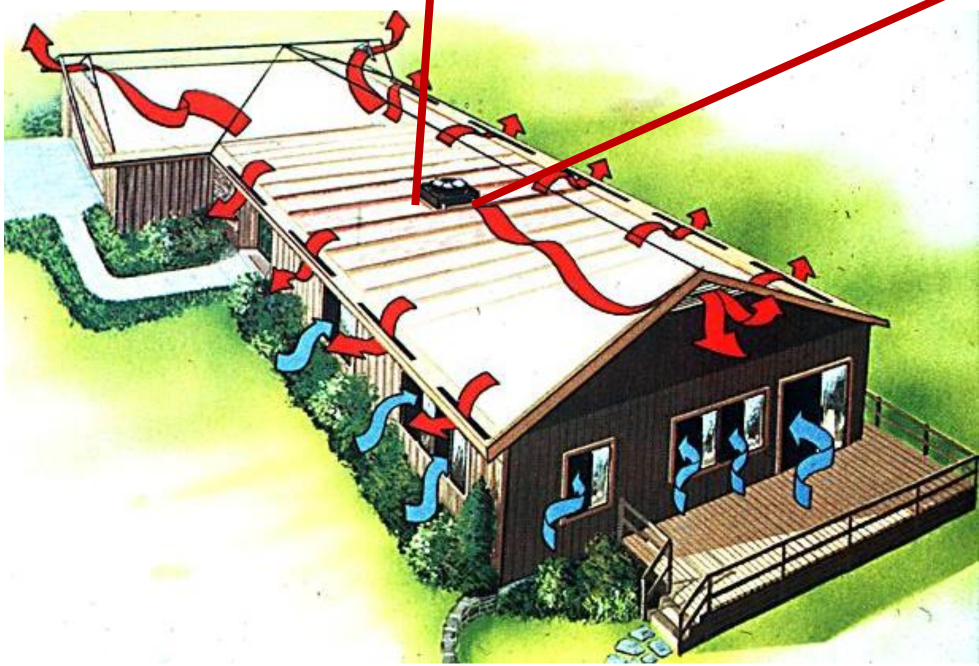
Ventilation openings



- A louver is a ventilation product that allows air to pass through it while keeping out unwanted elements such as water, dirt, and debris
- The potential for cold draughts can be minimized
- Operation can be automated

Cross ventilation with roof-mounted ventilator

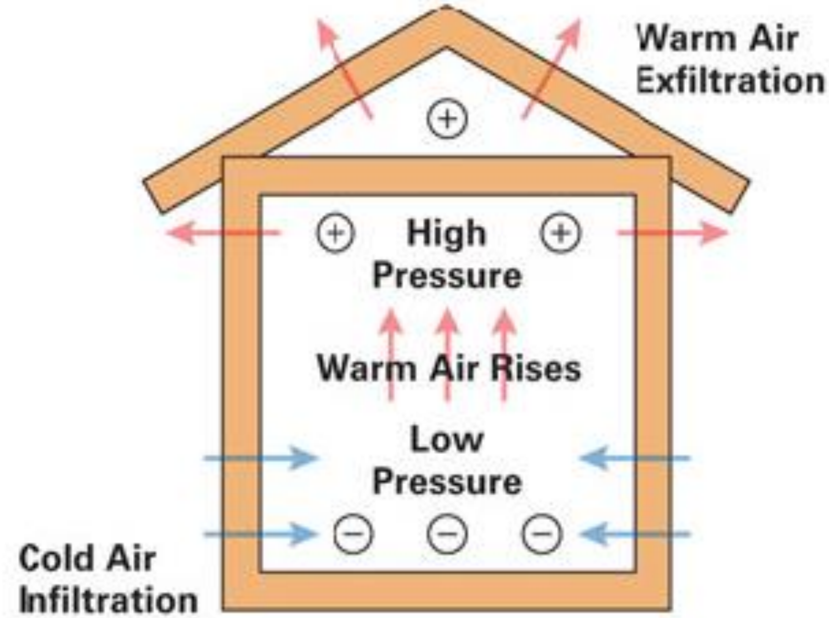
- A multi-directional ventilator draws air through various parts of the house, up through the roof
- Relatively cheap solution but it could be noisy if not properly sized



Driving forces of air exchange (*ΔP*): **Stack eff.**

– Stack effect (natural buoyancy)

- Caused by the weight of a column of air located inside/outside a building
- Depends on air density and height above a <u>neutral reference level</u>
  - – Density is a function of temperature (so this is temperature driven)



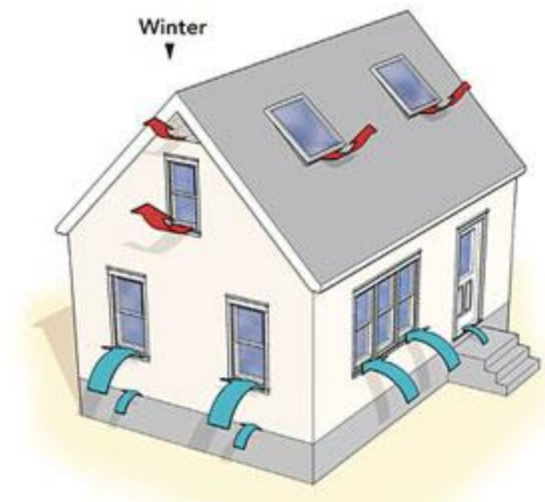
The Stack Effect:
Rising warm air causes pressure differences throughout the building envelope making warm air exfiltrate through ceiling and attic, while cool air infiltrates through crawl spaces and basements.

Stack effect

The result of **density differences** between air inside and outside the building.

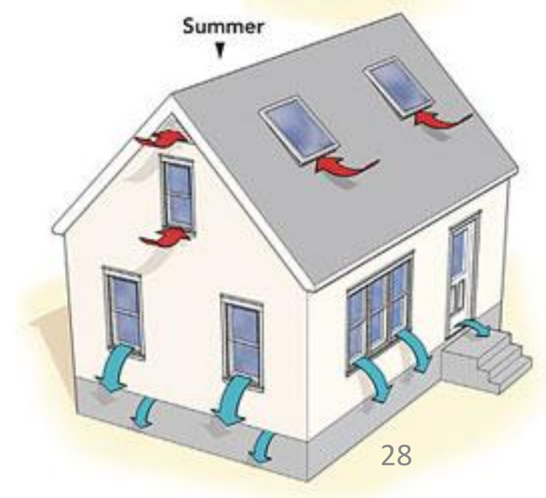
In wintertime

– Air acts like a bubble of hot air in a sea of cold air
– Rises to the top
– Draws **outdoor air in from the bottom**
– Indoor air flows out through openings in the top

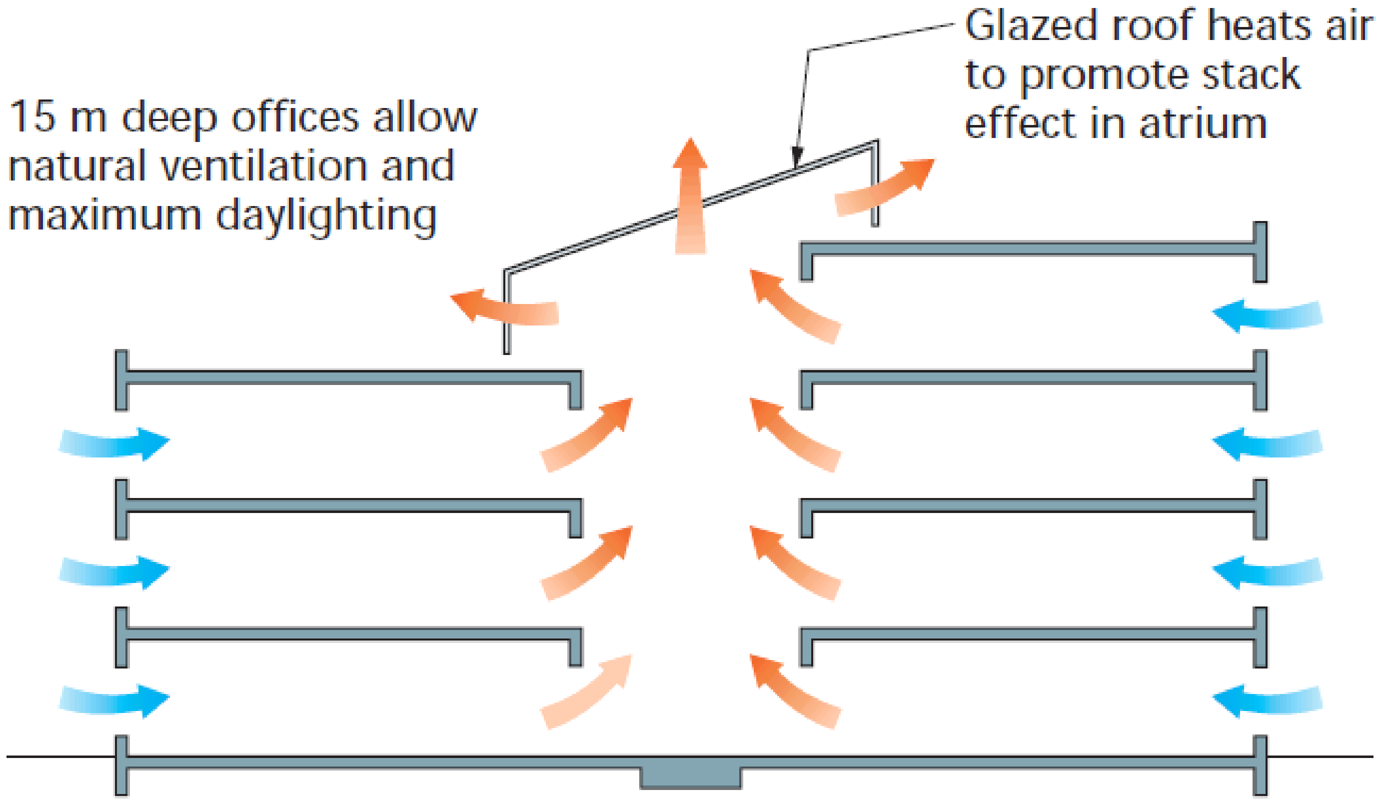


In summertime

– Air acts like a bubble of cold air in a sea of hot air
– Falls to the bottom
– Drives **indoor air out through the bottom**
– Outdoor air is drawn in through openings in the top
– Temperature differences usually lower in the summer time so the amount of flow is smaller



Atrium Stack Ventilation

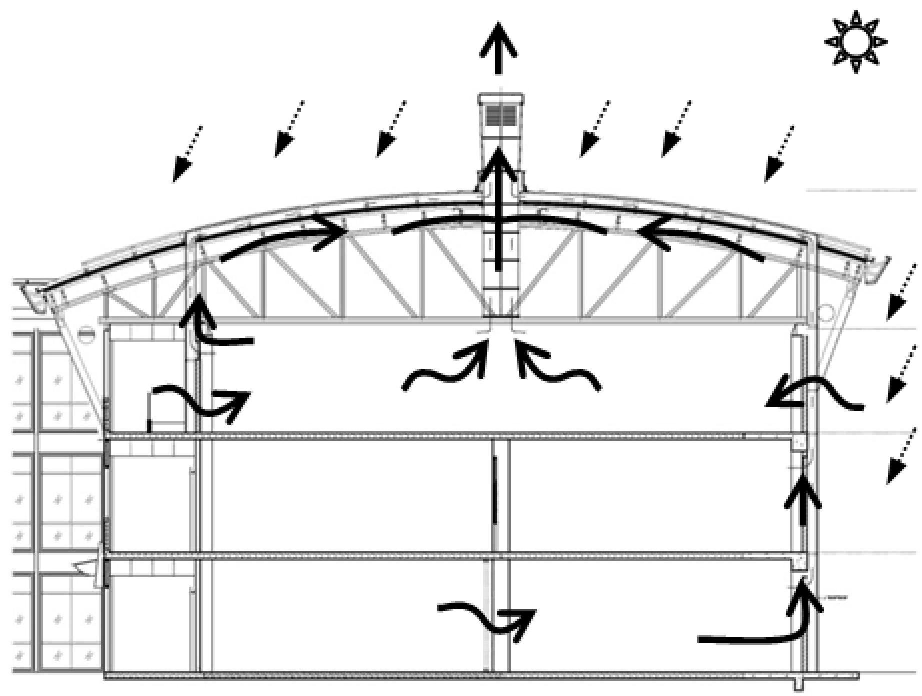


(Source: CIBSE AM10 Natural Ventilation in non-domestic buildings)

- Possesses similar benefits to incorporating a courtyard but solar heating of atrium also provides stack effect and can also be used as year round social and or circulation space.

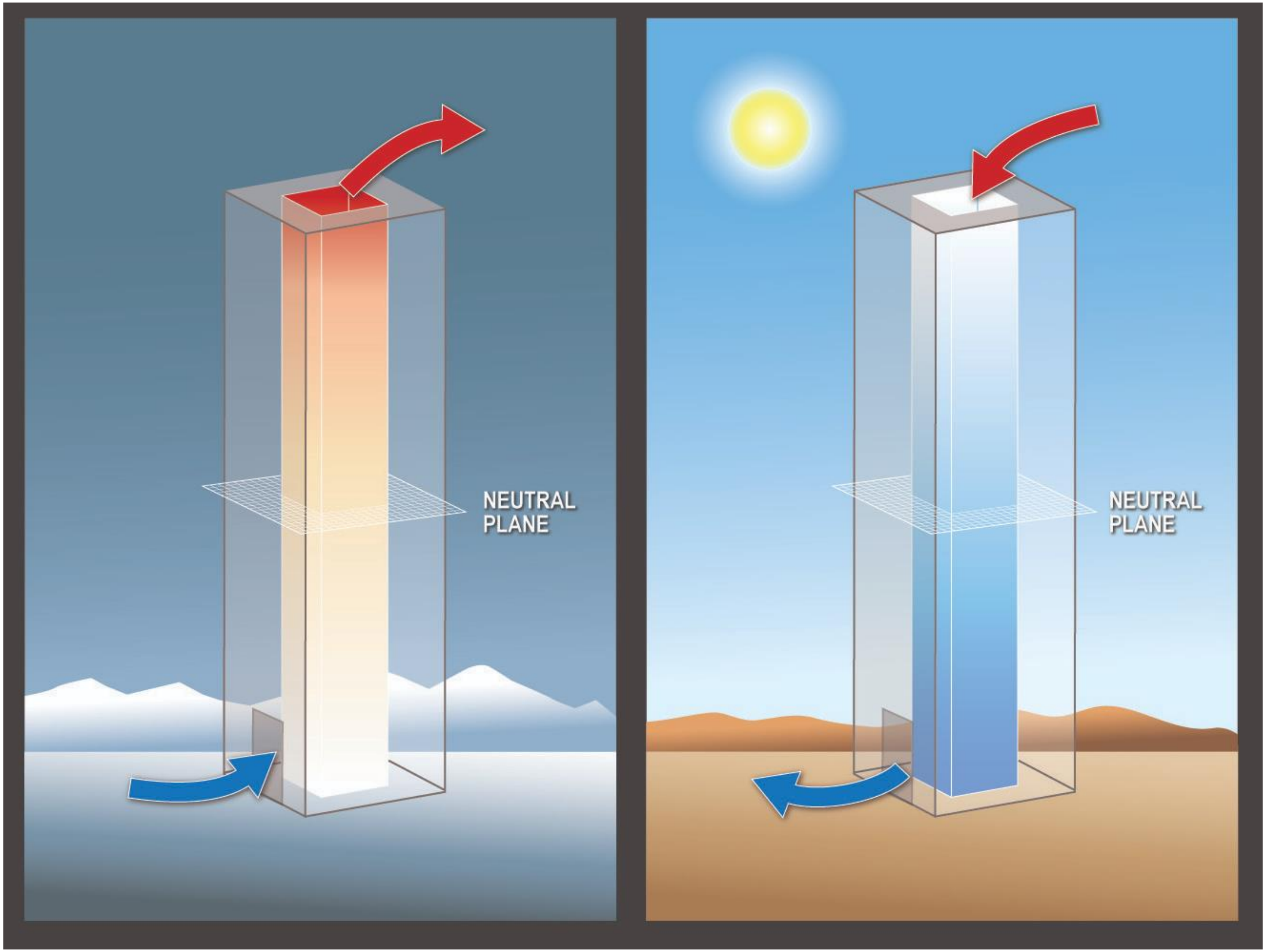
Solar Chimney and Ventilation

A **solar chimney** (thermal chimney)**:** a way of improving the natural ventilation of buildings by using convection of air heated by passive **solar** energy.



(Source: Wong et al, 2012, Performance Evaluation of Solar Chimney System in the Tropics)

Stack effect – magnified in taller buildings



(Source: https://www.cppwind.com/blogs/get-to-know-a-flow-feature-the-stack-effect)

Stack effect equations

- The stack pressure difference across a horizontal leak at any vertical location can be estimated by:

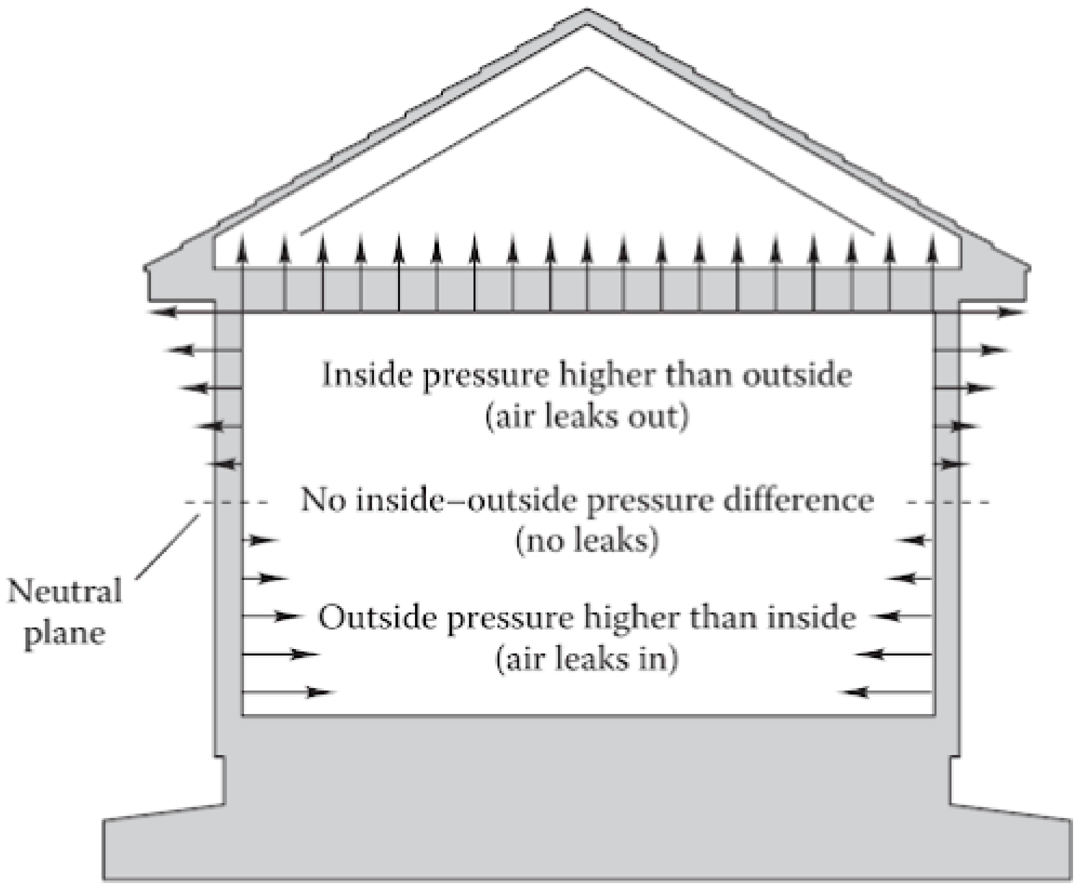
$$\Delta P_{stack} = (\rho_{out} - \rho_{in}) g (H_{NPL} - H)$$

$$\Delta P_{stack} = \rho_{out} \left(\frac{T_{in} - T_{out}}{T_{in}} \right) g (H_{NPL} - H)$$

T_{out} = outdoor air temperature, K
T_{in} = indoor air temperature, K
ρ_{out} = outdoor air density, kg/m^3
ρ_{in} = indoor air density, kg/m^3
H_{NPL} = height of neutral pressure level above reference plane, m
H = height of point of opening, m

Stack effect – neutral level

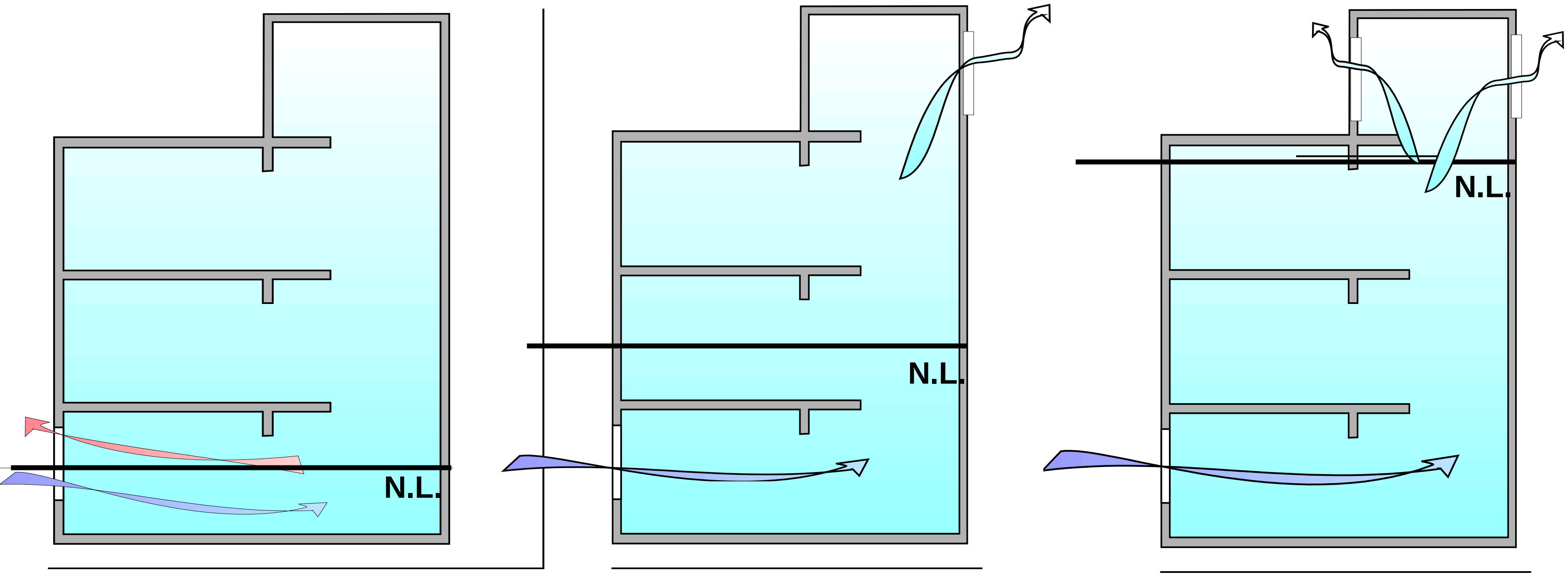
- The neutral level is the level where the internal pressure is equal to the outside pressure



(Source: Reddy et al. 2007)

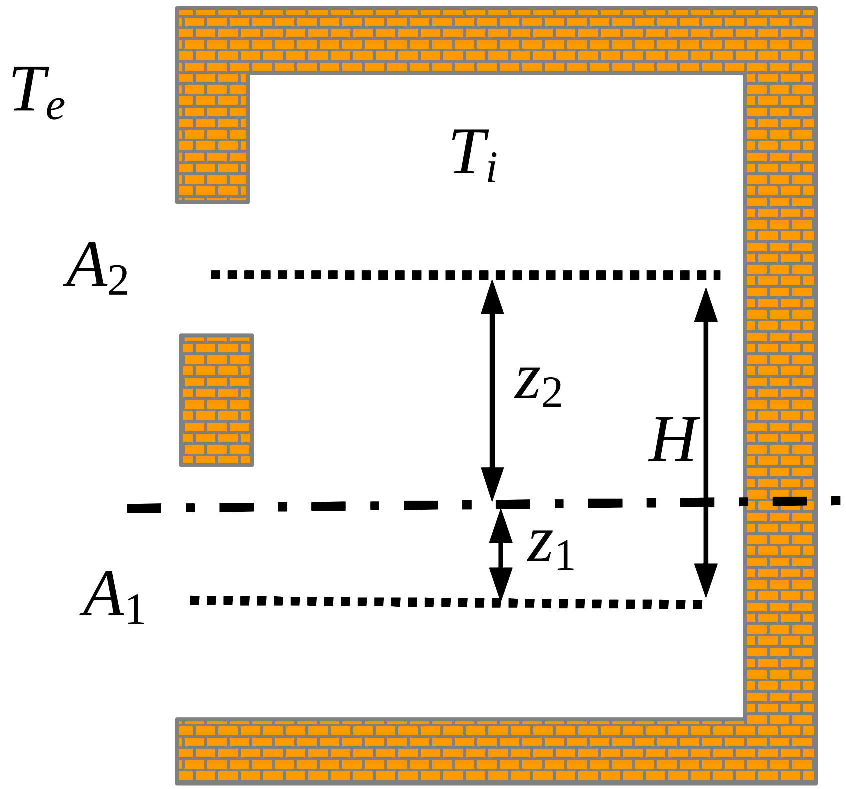
Position of the neutral level

• The position of the neutral level depends on pressures and the position/side of the openings



Position of the neutral level (out of scope)

• The position of the neutral level can be determined with the following equation:



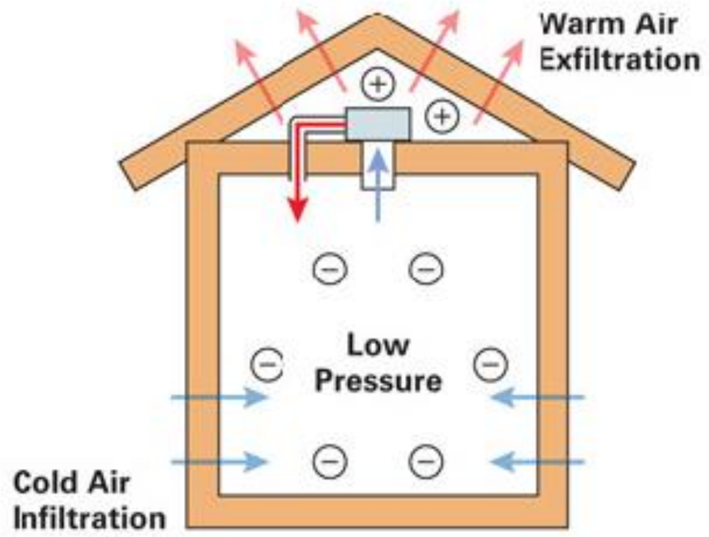
$$\frac{z_1}{z_2} = \frac{\rho_i}{\rho_e}\left(\frac{A_2}{A_1}\right)^2 = \frac{T_e}{T_i}\left(\frac{A_2}{A_1}\right)^2$$

$$h = z_2 = \frac{H}{1 + \frac{T_e}{T_i}\left(\frac{A_2}{A_1}\right)^2}$$

Driving forces of air exchange (*ΔP*): **Fans**

– Mechanical air handling equipment (fans)

- <u>Fans</u> are used to supply, recirculate, exhaust, and otherwise balance pressures and flows in buildings



Mechanical Systems:
Heating and ventilation systems create positive and negative pressures within the building envelope. In this example, the heating/cooling mechanical system is leaking warm air into the attic.

Three primary mechanisms generate pressure differences:

$$\Delta P = \Delta P_{wind} + \Delta P_{stack} + \Delta P_{mech}$$

("+" when causing flow to interior)

Today’s objectives

- Introduction to ventilation
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- **Air exchange rates & ventilation requirements**

Ventilation – moving air in and out of a space

- **Ventilate well**

Ventilation rate (dilution)

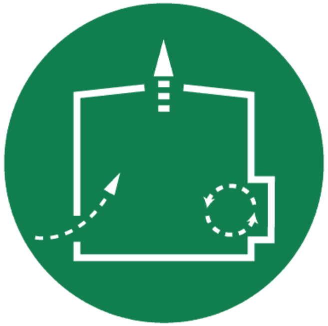
Room air distribution

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).**

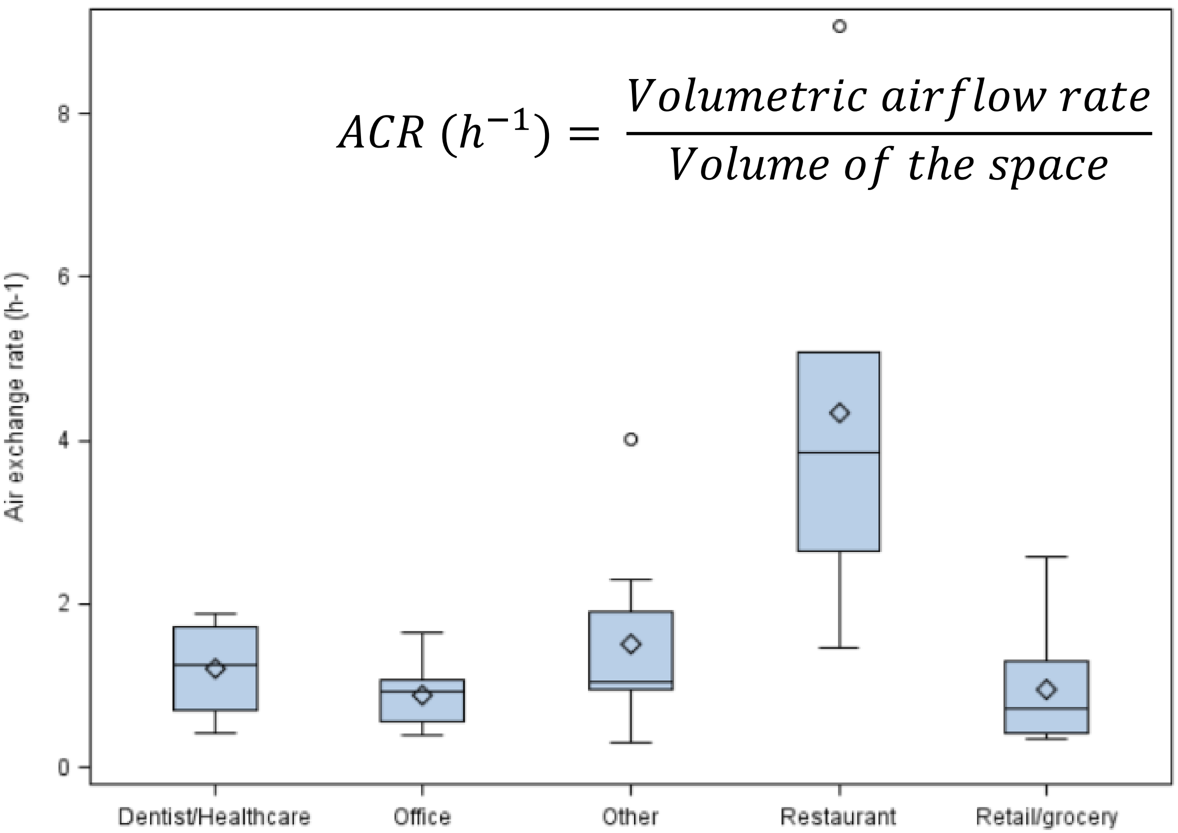
Air distribution

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}



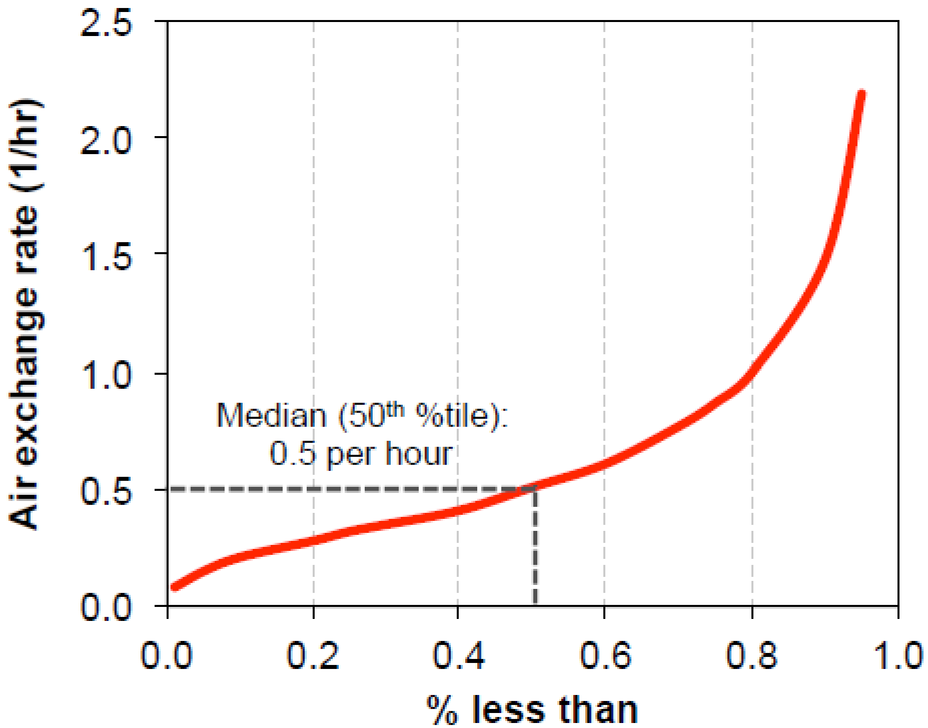
$$ACR\ (h^{-1}) = \frac{Volumetric\ airflow\ rate}{Volume\ of\ the\ space}$$

Recent study of ~40 commercial buildings in California

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

What are typical air exchange rates in homes?

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



(Source: Murray and Burmaster, 1995 Risk Analysis)

Mostly due to infiltration and window opening

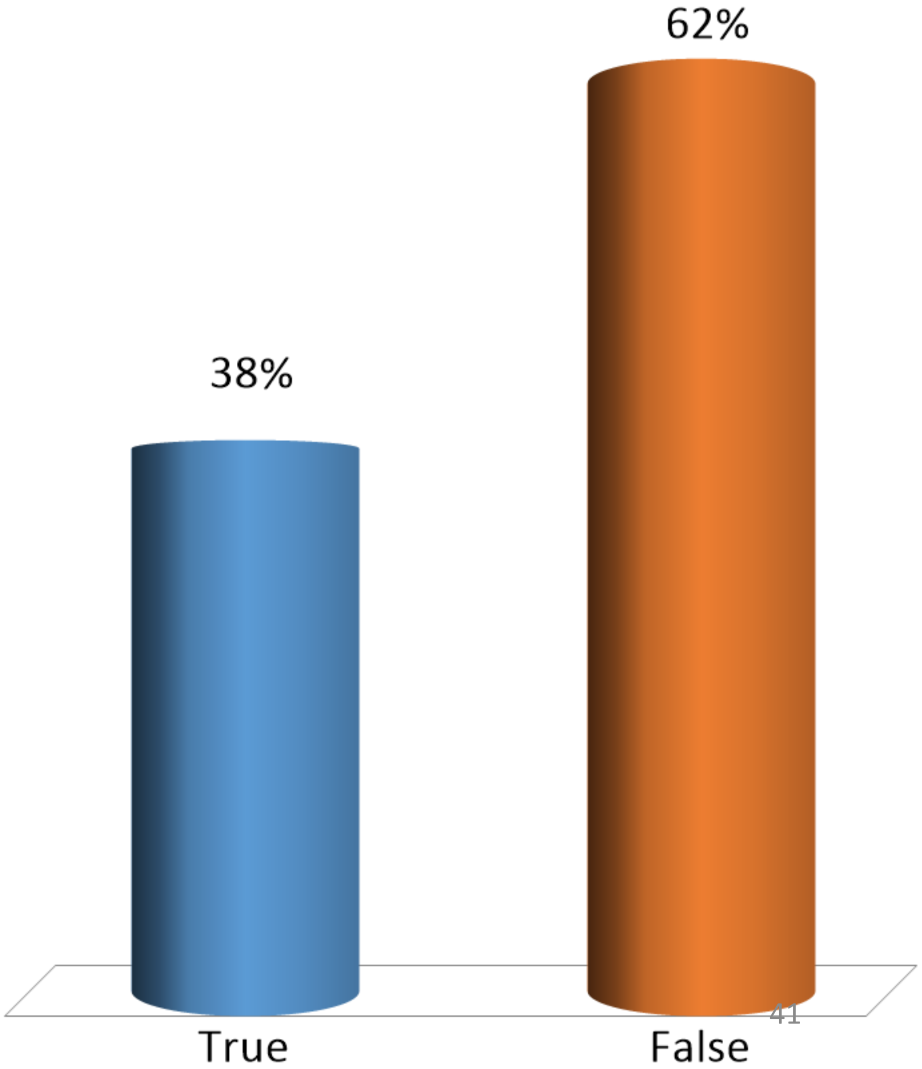
In the past, we seldom used mechanical ventilation systems in single-family homes, but this is changing

- What do you think this curve looks like now?

Over the past few decades, air exchange rate in buildings has been increasing

A. True

B. False



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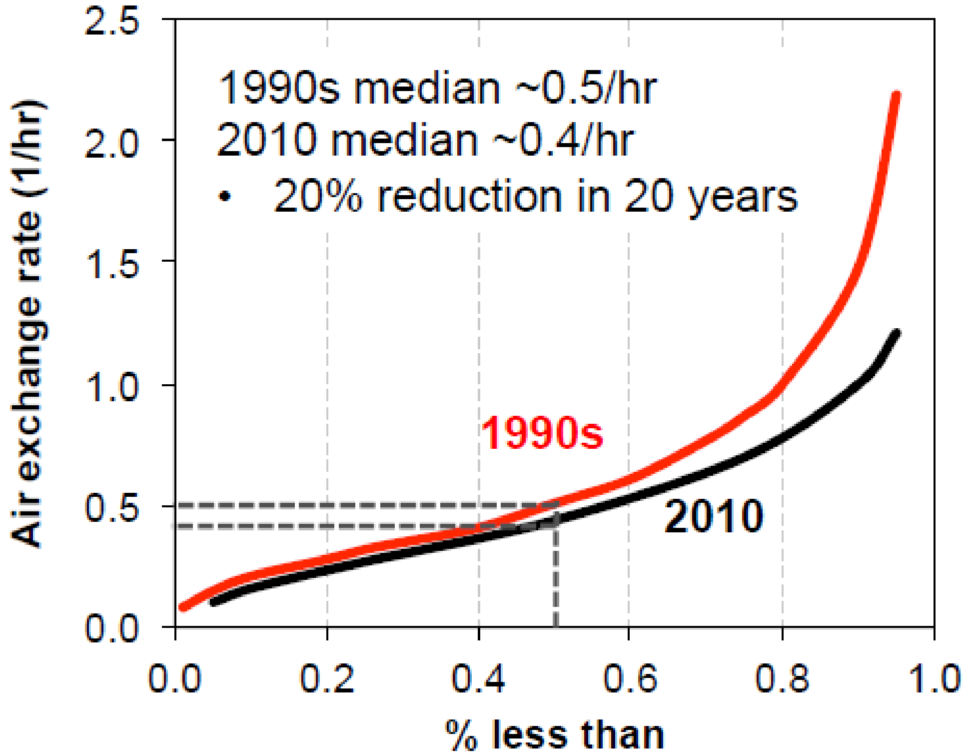
What are typical air exchange rates in homes?

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

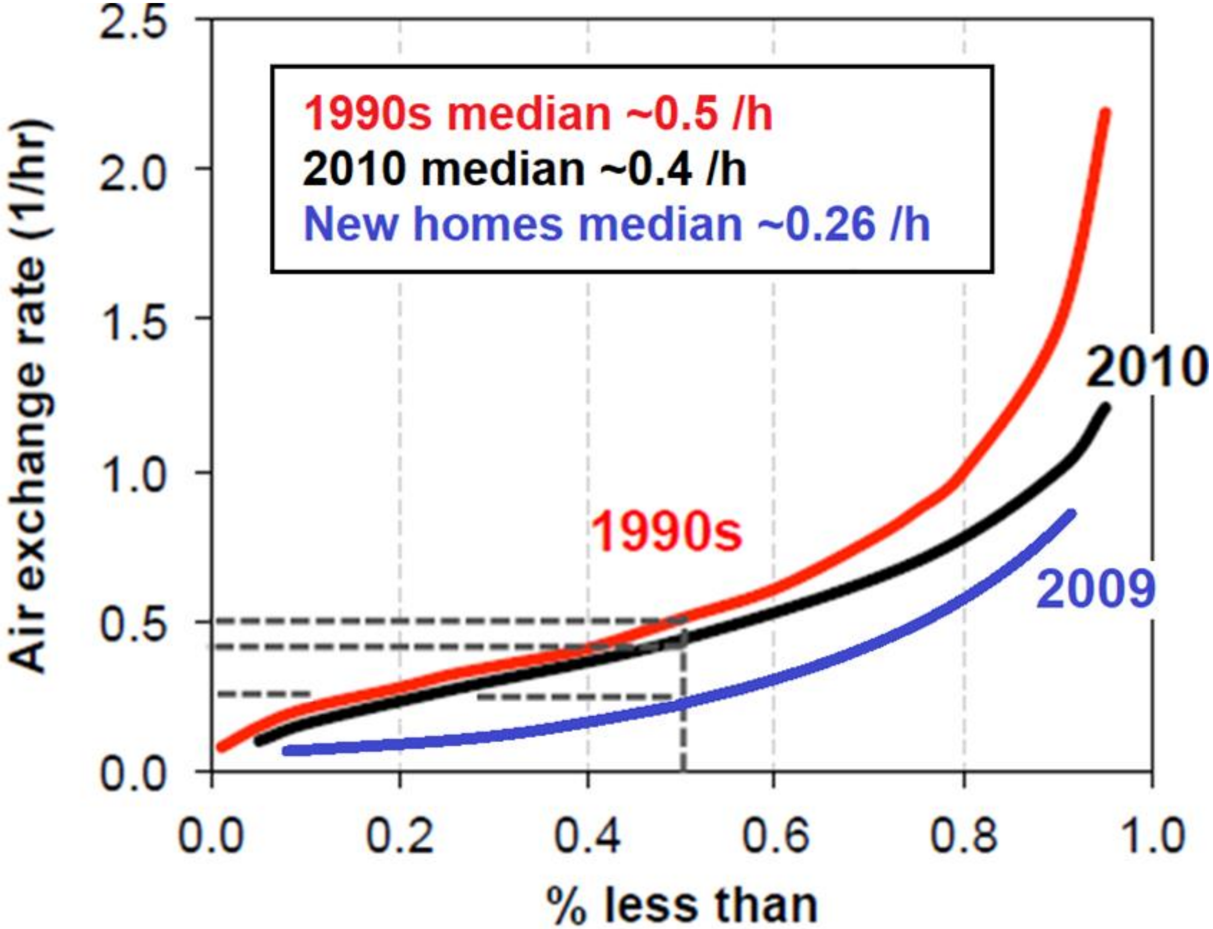


(Sources: Murray and Burmaster, 1995 Risk Analysis; Persily et al. 2010 Indoor Air)

- What about new homes?

What are typical air exchange rates in homes?

- Distribution of AERs U.S. homes
  - 20% reduction between 1990 and 2010



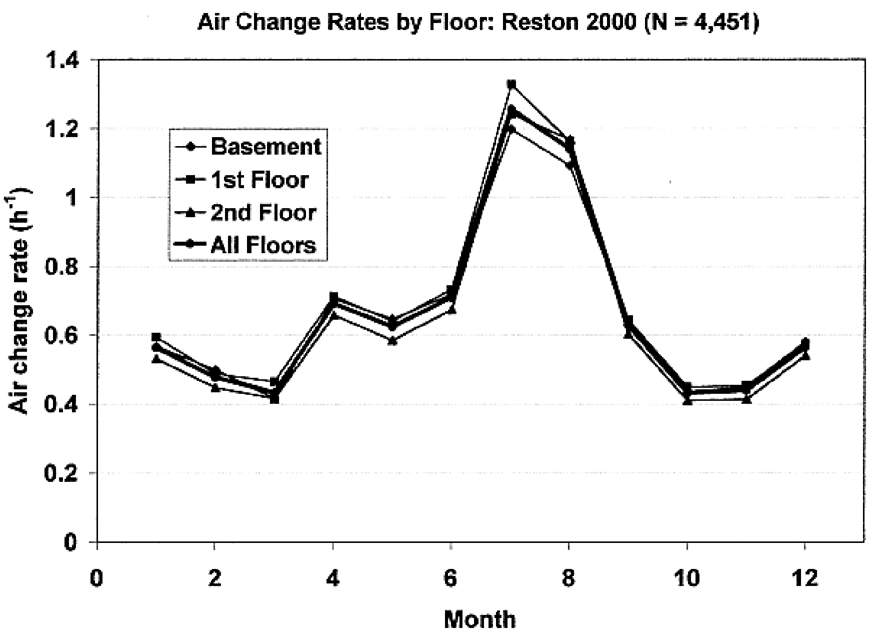
(Sources: Murray and Burmaster, 1995 Risk Analysis; Persily et al. 2010 Indoor Air; Offermann et al. 2009 CEC PIER Report)

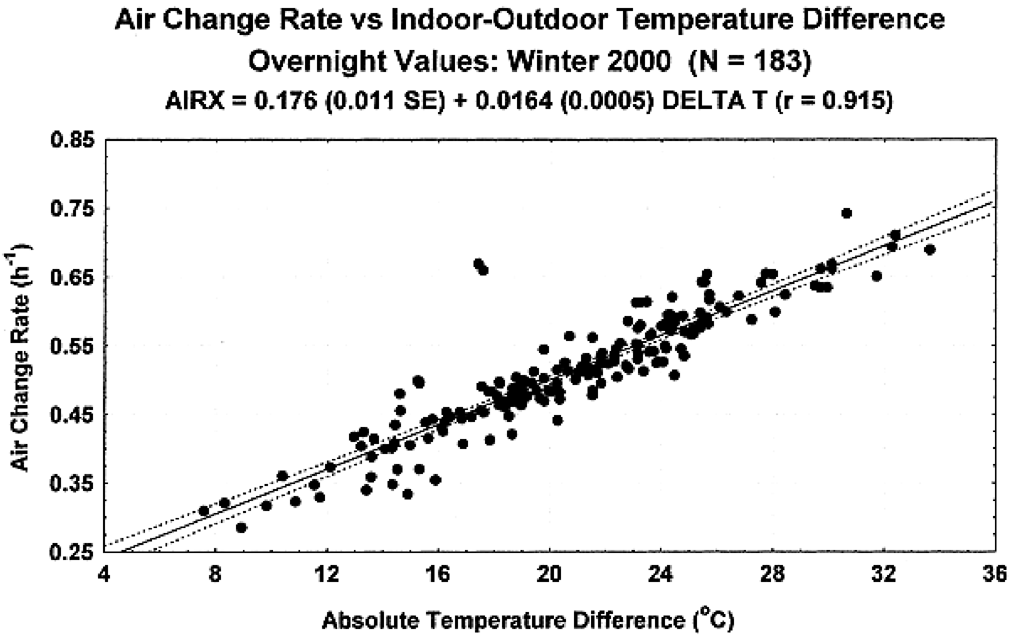
Variation in air exchange rate

Air change rates differ both between buildings and within buildings

– Differences vary by driving forces & building operation (e.g. windows/HVAC)

4600 AERs measured by automated SF_6 system in a house for 2 years:





AER can vary by season - driving forces are temperature, wind speed

AER can vary by I/O temperature within seasons

(Source: Wallace et al. 2002 J Expo Anal Environ Epidem)

Ventilation requirements in standards

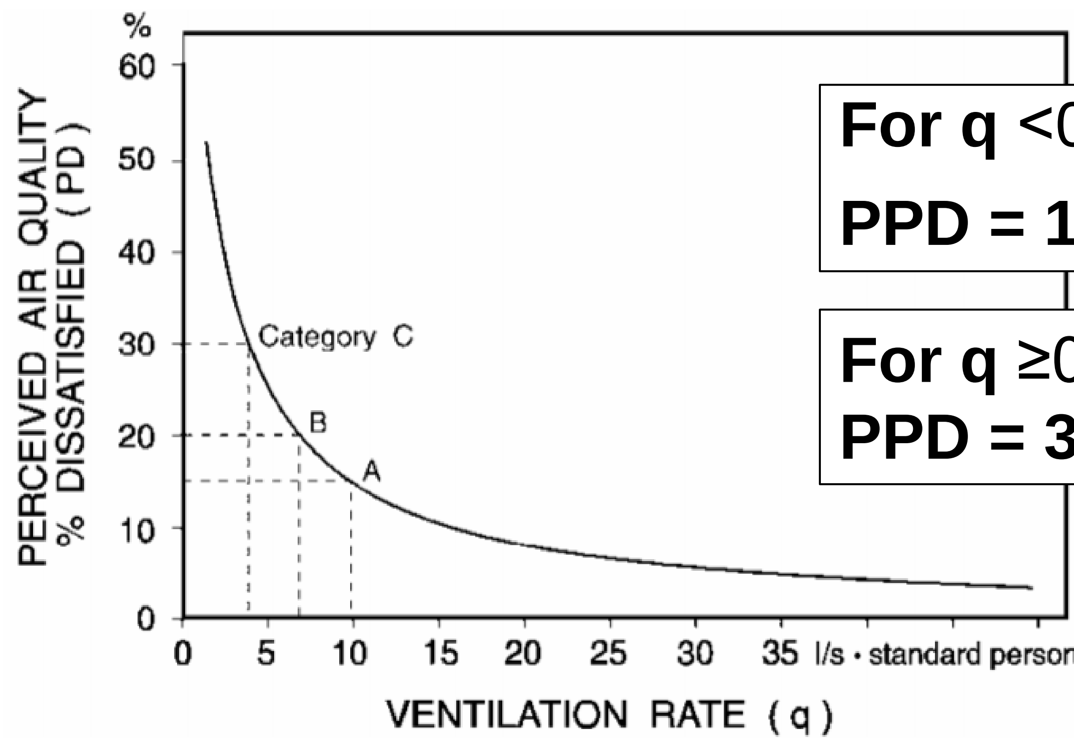
- Some ventilation standards: ISO 17772, EN 16798, ASHRAE 62.1 and 62.2, SIA 382.1….

In all of the standards, more than one procedure for calculating ventilation rates is included:

- One of them is a **prescriptive method**, where the minimum ventilation rates can be found in a table listing values for different space types
  - This method is widely used
- Other method for calculation of the required ventilation rate is an **analytical method** based on a mass balance
  - In this method, the ventilation rates can be calculated on the basis of pollutant type, emission rates and acceptable concentration

Prescriptive procedure

- In ASHRAE 62.1 this procedure is called “Ventilation rate procedure”
- In EN 16798, the values are given for four classes (I=15% dissatisfied; II=20%, III=30%, IV>30% dissatisfied)
  - These results are obtained based on **human subject tests**



For q <0.32 l/s per person:

PPD = 100%

For q ≥0.32 l/s per person:
PPD = 395 x exp(-1.83 x $q^{0.25}$)

Prescriptive procedure

- Typically in standards, a required minimum ventilation rate is given **per person** and **per m² floor area**, and the values are added.

- Outdoor airflow required in the breathing zone:

$$V_{bz} = q_p P_z + q_b A_z$$

- q_p = Outdoor airflow rate required per person - **these values are based on adapted occupants**
- q_b = Outdoor airflow rate required per unit area
- A_z = Zone floor area: the net occupiable floor area of the zone m^2
- P_z = Zone population: the greatest number of people expected to occupy the zone during typical usage.

Minimum ventilation rates as per ASHRAE 62.1

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/ft²	L/s·m²		#/1000 ft² or #/100 m²	cfm/ person	L/s·person	
Correctional Facilities									
Cell	5	2.5	0.12	0.6		25	10	4.9	2
Dayroom	5	2.5	0.06	0.3		30	7	3.5	1
Guard stations	5	2.5	0.06	0.3		15	9	4.5	1
Booking/waiting	7.5	3.8	0.06	0.3		50	9	4.4	2
Educational Facilities									
Daycare (through age 4)	10	5	0.18	0.9		25	17	8.6	2
Daycare sickroom	10	5	0.18	0.9		25	17	8.6	3
Classrooms (ages 5–8)	10	5	0.12	0.6		25	15	7.4	1
Classrooms (age 9 plus)	10	5	0.12	0.6		35	13	6.7	1
Lecture classroom	7.5	3.8	0.06	0.3		65	8	4.3	1
Lecture hall (fixed seats)	7.5	3.8	0.06	0.3		150	8	4.0	1
Art classroom	10	5	0.18	0.9		20	19	9.5	2
Science laboratories	10	5	0.18	0.9		25	17	8.6	2
University/college laboratories	10	5	0.18	0.9		25	17	8.6	2
Wood/metal shop	10	5	0.18	0.9		20	19	9.5	2
Computer lab	10	5	0.12	0.6		25	15	7.4	1

Minimum ventilation rates as per ISO 17772

Examples of recommended ventilation rates for nonresidential buildings with default occupancy density for three categories of pollution from the buildings itself

Type of building or space	Cate-gory	Floor area m^2/per-son	q_p	q_p	q_B	q_{tot}		q_B	q_{tot}		q_B	q_{tot}	
			Minimum ventilation rate										
			l/(s m^2)	l/s pers.	l/s, m^2	l/s, m^2	l/s,pers	l/s, m^2	l/s, m^2	l/s,pers	l/s, m^2	l/s, m^2	l/s,pers
			For occupancy only		**For very low-polluted building**			**For low-polluted building**			**For non-low polluted building**		
Single office	I	10	1	10	0,5	1,5	15	1	2,0	20,0	2	3,0	30
	II	10	0,7	7	0,35	1,1	11	0,7	1,4	14,0	1,4	2,1	21
	III	10	0,4	4	0,2	0,6	6	0,4	0,8	8,0	0,8	1,2	12
	IV	10	0,25	2,5	0,15	0,4	4	0,3	0,6	5,5	0,6	0,9	9
Landscaped office	I	15	0,7	10	0,5	1,2	18	1	1,7	25,0	2	2,7	40
	II	15	0,5	7	0,35	0,8	12	0,7	1,2	17,5	1,4	1,9	28
	III	15	0,3	4	0,2	0,5	7	0,4	0,7	10,0	0,8	1,1	16
	IV	15	0,2	2,5	0,15	0,3	5	0,3	0,5	7,0	0,6	0,8	12

Based on the previous table, what is the minimum ventilation rate needed for non-low polluted 35 m^2 open-space office occupied by 4 persons, as per ISO 17772 Category II?

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responseware.eu

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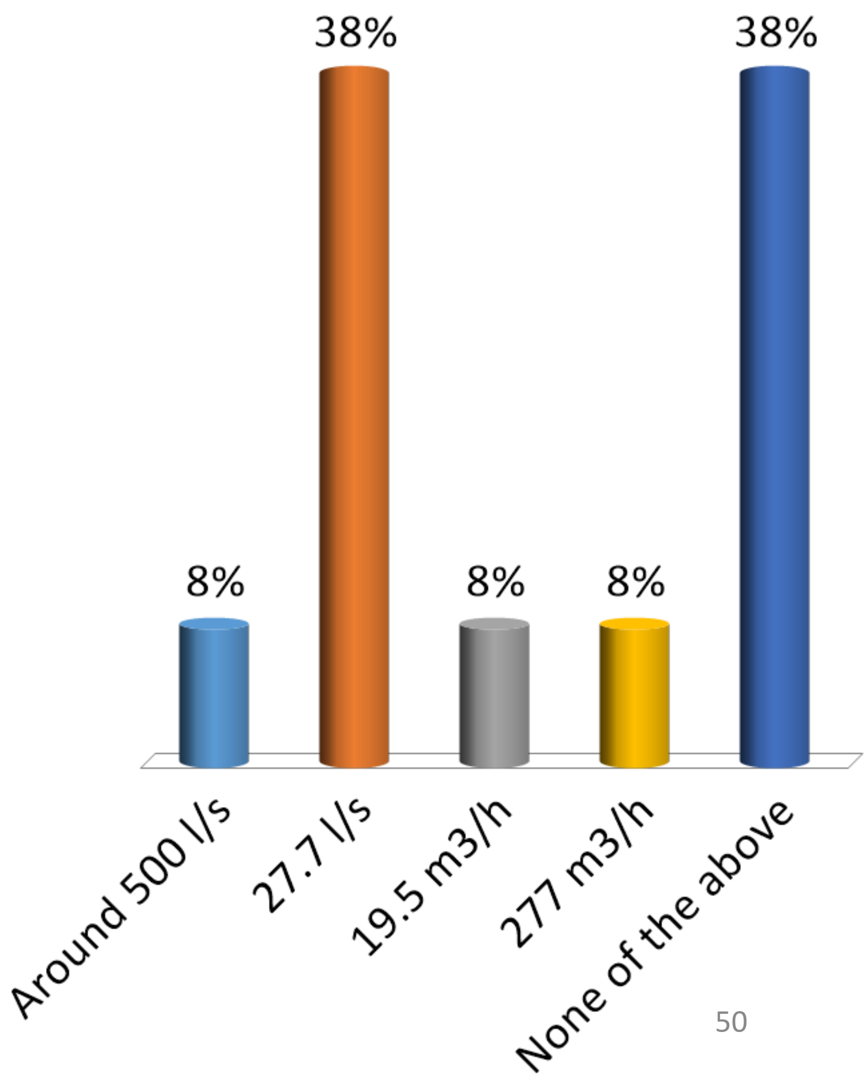
A. Around 500 l/s
B. 27.7 l/s
C. 19.5 m^3/h
D. 277 m^3/h
E. None of the above



Solution: $V_{bz} = q_p P_z + q_b A_z$

=7x4+1.4x35=77 l/s = 277 m^3/h

Do-it yourself after the class

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

Solution:

Analytical method

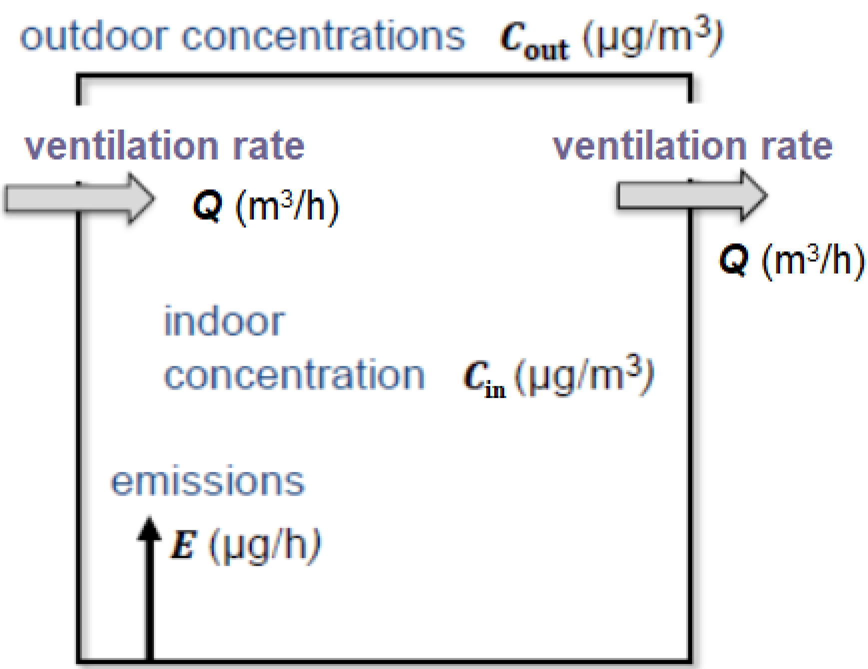
- Some key features:
  - Ventilation rate is calculated on a comfort basis (perceived odour and/or irritation) and health basis. The highest calculated value, (usually comfort value), is then used as the required ventilation rate
  - Analytical procedure allows reduction of ventilation rate if it’s compensated by other control systems to remove contaminants
  - The basis for the calculation is in all standards based on a **mass balance calculation**
    - It can predict pollutant concentrations as a function of time using parameters such as the volume, ventilation, etc.
    - We will do the most fundamental examples that aim to quantify the needed ventilation rate in order to keep IAQ at acceptable level
    - In practice, we typically run analytical method based on the mass balance equation for the CO_2 concentration (as indicator of human bioeffluents)

Analytical method (single zone model)

- The required ventilation rate (m^3/h) is calculated as:

$$Q = \frac{E}{(C_{in} - C_{out}) \cdot \varepsilon_v}$$

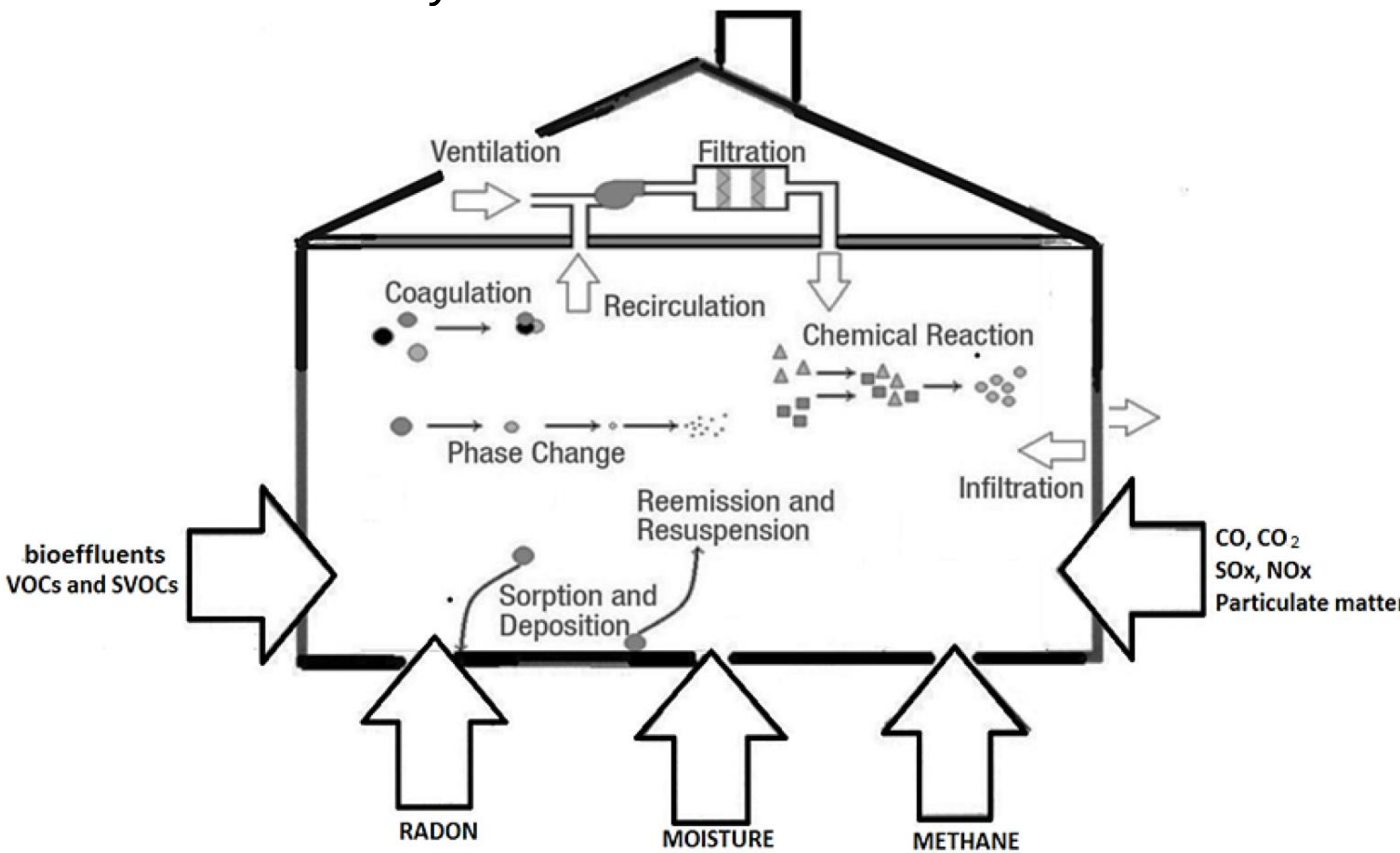
- E = Total emission rate (μg/h)
- C_{in} = Concentration limit indoors ($\mu g/m^3$)
- C_{out} = Concentration in outside air ($\mu g/m^3$)
- ε_v= Ventilation effectiveness (-)
  (how effectively is air delivered to us)



Assumptions:
- Building/room can be treated as well-mixed
- Ventilation/air exchange rate is constant
- Outdoor pollutant concentration is constant
- Indoor emissions (*E*) are constant

Note on simplification

- The problem can easily become more complex (outside the scope of this course), but often the most simple mass balance equation is sufficient to determine needed ventilation rates with reasonable accuracy.



Mass balance example problem with CO_2

- In a 150 m^3 room with 30 people present, what would be the required (a) outdoor airflow rate to keep the indoor CO_2 concentration below 1000 ppm (standard requirement), (b) air change rate, and (c) per person ventilation flow rate to keep the indoor CO_2 concentration below 800 ppm (standard requirement)?
  - Assume outdoors is 400 ppm
  - And CO_2 production (activity level of 1.1 met) = 21 l/h per person
  - ε_v can be neglected for now by assuming well-mixed conditions (we didn't study air distribution yet)

Solution a):

$$\#\ of\ \frac{mg}{m^3} = \#\ of\ \text{ppm} \times \frac{MW_i}{24}$$

$$1000\ ppm = 1833.75\ \frac{mg}{m^3}$$

$$800\ ppm = 1467\ \frac{mg}{m^3}$$

$$400\ ppm = 733.5\ \frac{mg}{m^3}$$

$$Q = \frac{E}{(C_{in} - C_{out}) \cdot \varepsilon_v} = \frac{30 \cdot 21\ l/h}{(1833.75 - 733.5)\frac{mg}{m^3} \cdot 1}$$

$$Q = \frac{630\ l/h}{1100\ \frac{mg}{m^3}} = \frac{1.187 \times 10^6 \frac{mg}{m^3}}{1100\ \frac{mg}{m^3}} = 1071\,\frac{m^3}{h}$$

CO_2 density at 20 °C is 1.87 kg/m^3

Wait – can I do the same calculation with CO_2 without converting molar to mass concentration?

- In a 150 m^3 room with 30 people present, what would be the required (a) outdoor airflow rate to keep the indoor CO_2 concentration below 1000 ppm (standard requirement), (b) air change rate, and (c) per person ventilation flow rate to keep the indoor CO_2 concentration below 800 ppm (standard requirement)?
  - Assume outdoors is 400 ppm
  - And CO_2 production (activity level of 1.1 met) = 21 l/h per person
  - ε_v can be neglected for now by assuming well-mixed conditions (we didn't study air distribution yet)

Solution a): $$Q = \frac{E}{(C_{in} - C_{out}) \cdot \varepsilon_v} = \frac{30 \cdot 21\ l/h}{(1000 - 400) \cdot 10^{-6} \cdot 1} = 1'050'000\ \frac{l}{h} = 1'050\ \frac{m^3}{h}$$

Solution b): $$ACR = \frac{Q}{V} = \frac{1050 \frac{m^3}{h}}{150\ m^3} = 7\ h^{-1}$$

Solution c): $$Q = \frac{30 \cdot 21\ l/h}{(800 - 400) \cdot 10^{-6} \cdot 1} = 1'575\ \frac{m^3}{h} \qquad Q_{per\ p} = 52.5\ \frac{m^3}{h}$$

Mass balance example problem with vapour

- What ventilation rate is required to eliminate the water vapour emitted by the same 30 persons (vapour emission rate per person 80 g/h) so as to limit the relative humidity at 51% and indoor air temperature at 23 °C? Assume the following outdoor conditions: 5°C and 91% relative humidity.
  - *Tip: At the end, try to convert the ventilation rate into m^3/h unit based on the density, 1.2 kg/m^3*

You can download the chart here: https://www.ashrae.org/File%20Library/Technical%20Resources/Bookstore/UP3/SI-1.pdf

A. $100\ \frac{m^3}{h}$

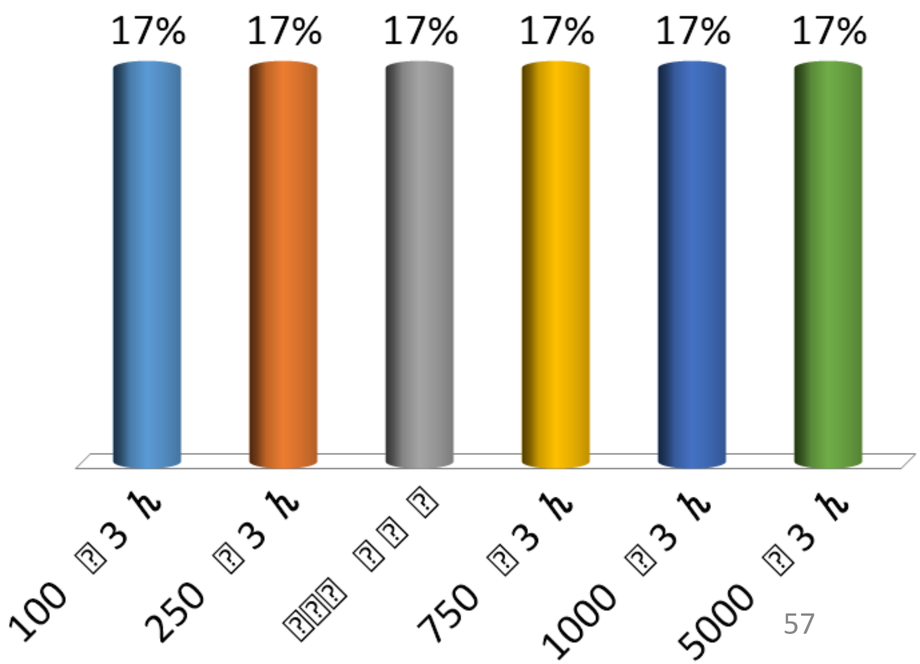
B. $250\ \frac{m^3}{h}$

C. $\mathbf{500\ \frac{m^3}{h}}$

D. $750\ \frac{m^3}{h}$

E. $1000\ \frac{m^3}{h}$

F. $5000\ \frac{m^3}{h}$



Mass balance example problem with vapour

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  - *Tip: At the end, try to convert the ventilation rate into m³/h unit based on the density, 1.2 kg/m³*

Solution:

23°C and 51% RH corresponds to 9 g/kg of air

5°C and 91% RH corresponds to 5 g/kg of air

$$Q = \frac{E}{(C_{in} - C_{out}) \cdot \varepsilon_v} = \frac{30 \cdot 80 \; g/h}{(9-5) g/kg \cdot 1} = 600 \; \frac{kg}{h} = 500 \; \frac{m^3}{h}$$

Summary analytical method

- Compare the last two exercises. Based on which air pollutant are we going to dimension our ventilation system (water vapour or carbon dioxide)?

Solution: $Q_{CO2} = 1'050\ \frac{m^3}{h}$ **>** $Q_{vapour} = 500\frac{m^3}{h}$

- In analytical method, we dimension the ventilation system based on the highest air pollutant.

- In practice, we often use much less analytical method and much more prescriptive method
  - There is a lack of information on emission rates from materials and other sources. This makes it very difficult today to use the analytical methods
  - If analytical method is used, often we focus on CO_2 only

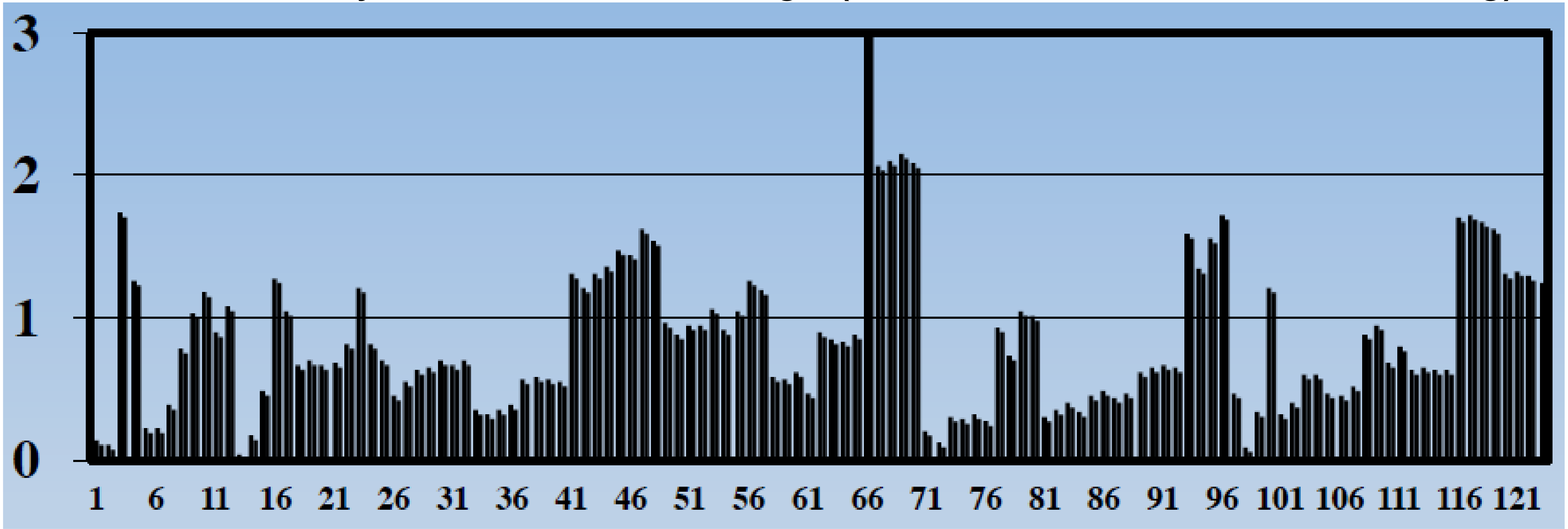
Do it yourself at home…

- 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:

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

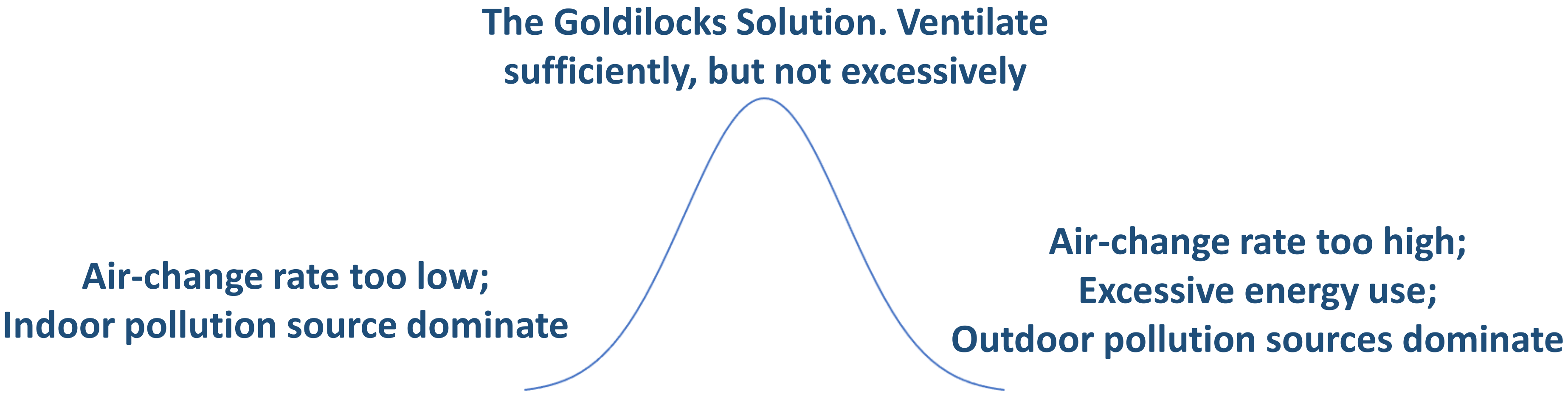
What are the key issues?

In-class discussion…

Is more ventilation always better?

How do we ventilate in a polluted city?

- More ventilation doesn't work in this case
- Adequate ventilation still reduces indoor pollution level



- Strive to limit outdoor-to-indoor transport of ozone & PM
  - Mechanically ventilated buildings: filtration
  - Naturally ventilated buildings: nighttime cooling & passive removal
- Avoid pockets of stagnant air in building design & operation. In other words, pay attention to room air distribution!

Next time… (last lecture for this course)

Controls:

- Room air distribution
- Ventilation strategies
- Mechanical ventilation
- Infiltration & Natural ventilation
- Filtration & air cleaning