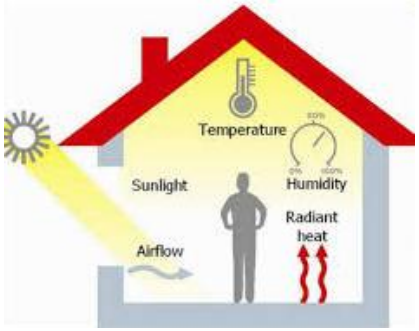
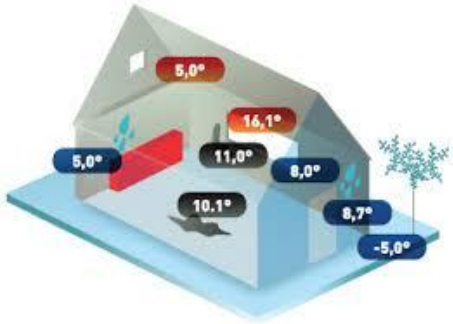
CIVIL 212
Indoor Climate
Fall 2025





Thermal Comfort 2

02 October, 2025

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HOBEL
HUMAN-ORIENTED BUILT ENVIRONMENT LAB

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Update on the course project (not final)

- Last updated on 1 October:

Robin Roux	Noah Walker	Thierry Cajeux	Eliot Ferrari	Pierre Zaninetti	Enzo Weideborg	How the invention of a	Cooling of buildings w
Maria Francisca Marinho F	Milo Heim	Nathan Borer	Marylou Rose Chalas	Hannah Silvia Philine	CÃ©lÃ©na Marie Naika	Cooling of buildings wi	Importance of building
Velson Hajra	Arnaud Wencker	Mathieu Roques	Eva Kupecek	LÃ©onard Gimenez	Anna Billon	Cooling of buildings wi	How the invention of a
Alicia Durand	Sara Maria Cevallos	Elise Hochard	Maria Ana Stanescu	Filip GOGOLEWSKI	Charles Devigny Chavani	How the invention of a	Cooling of buildings w
Paula Tarazona Rodriguez	Lilia Malika Belin	Nina Dufour	Olivia Mahieu	Cleopatra Moroianu	Margot Akel	Thermal Comfort and Pi	Influence of indoor en

- Thank you all for cooperation!
  - Half of the groups will present on 11th Dec
  - Half of the groups will present on 18th Dec
  - Submission deadline for the slides: 19th December by 23:59h

- Also note:
  - Let me know (today!) if you have identified any issue with the groups
  - Current student groups available in Moodle

Today's objectives…

Human thermal comfort assessment:

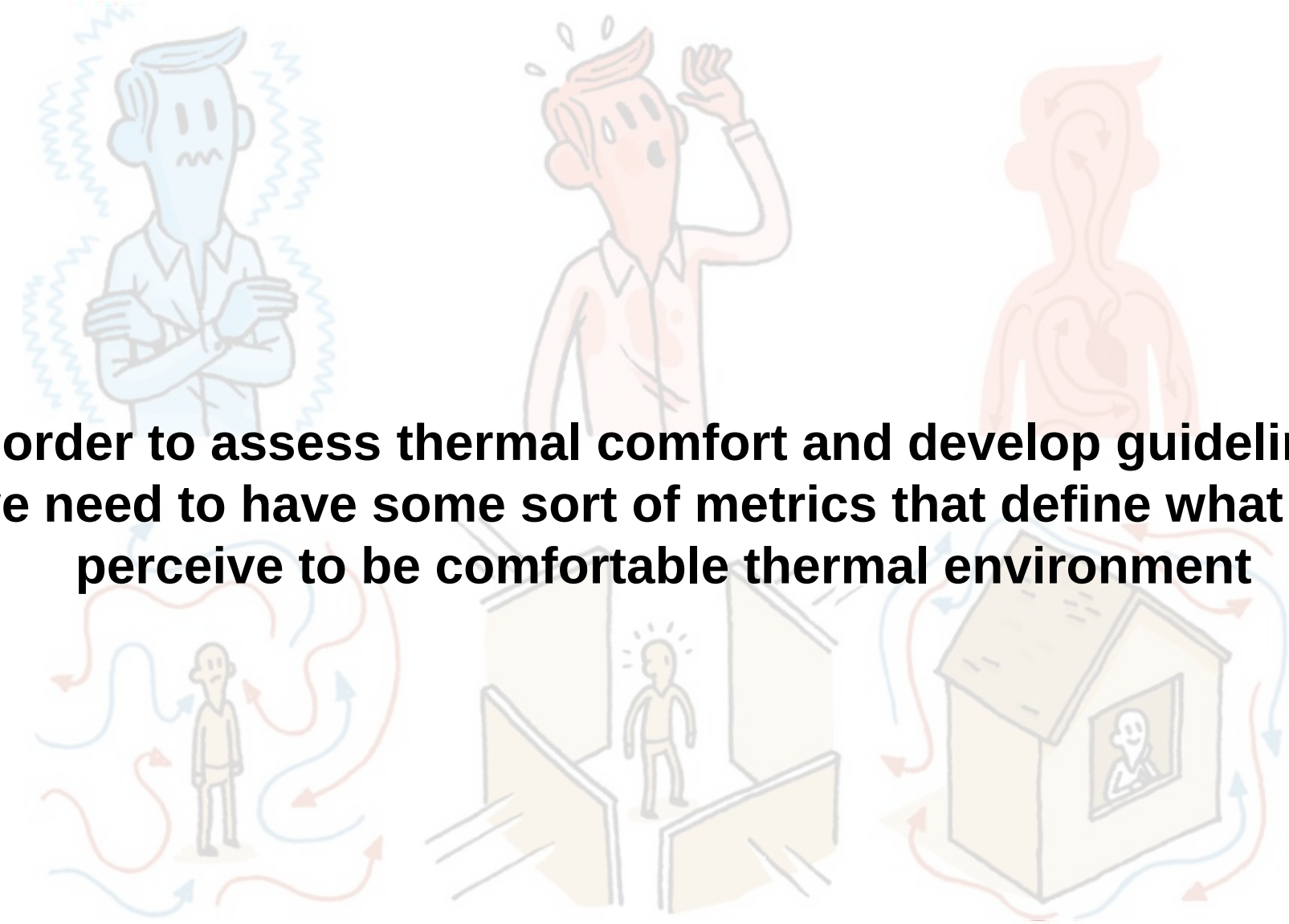
- Actual thermal comfort
- Models (PMV + Adaptive)

45 minutes

- Standards requirements (5 min)
- Exercise
- Quiz time

45 minutes

Thermal Comfort Assessment

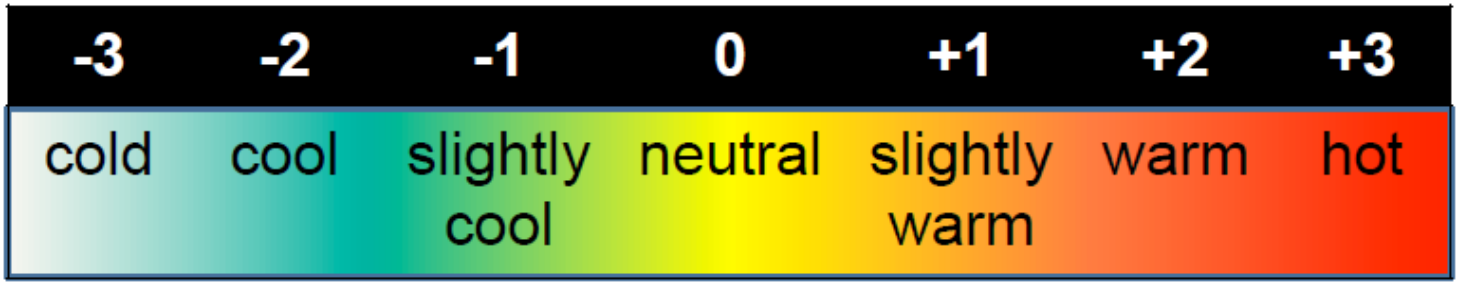


In order to assess thermal comfort and develop guidelines, we need to have some sort of metrics that define what we perceive to be comfortable thermal environment

Thermal Comfort Assessment

Actual thermal comfort analysis is usually done through surveys of users in real spaces and questionnaires that rates comfort on a seven point scale

- The result of the survey is the Actual Mean Vote (AMV)

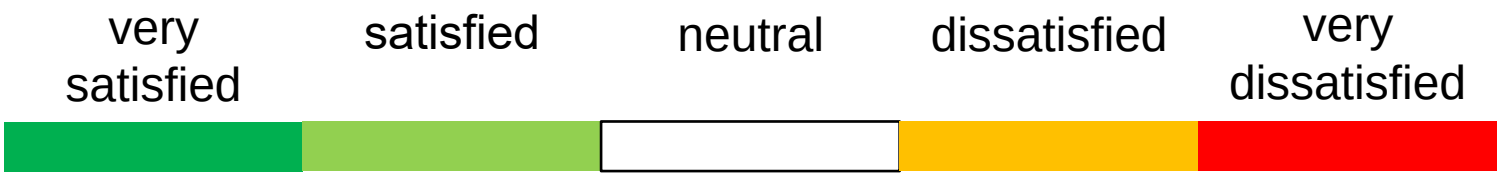


Predicted thermal comfort analysis aims to predict the results of a questionnaire through equations

- It results in a Predicted Mean Vote (PMV)
- PMV is an estimate of the mean value that would be obtained if a large number of people were asked to assess thermal comfort using a seven point scale

Actual thermal comfort: Occupancy surveys

- Subjective measurement - “using occupants as sensors”
- Typically, we ask the following questions
  - satisfaction (very satisfied……neutral.….very dissatisfied)
  - perception (cold…….neutral..…….hot)
  - preference (colder……..just fine……..warmer)
- Can be overall or momentarily
- Examples of surveys: CBE survey, BOMA, Australian National Survey
  - In can also be 5-point scale to evaluate subjective perception of thermal comfort



Post-occupancy evaluation

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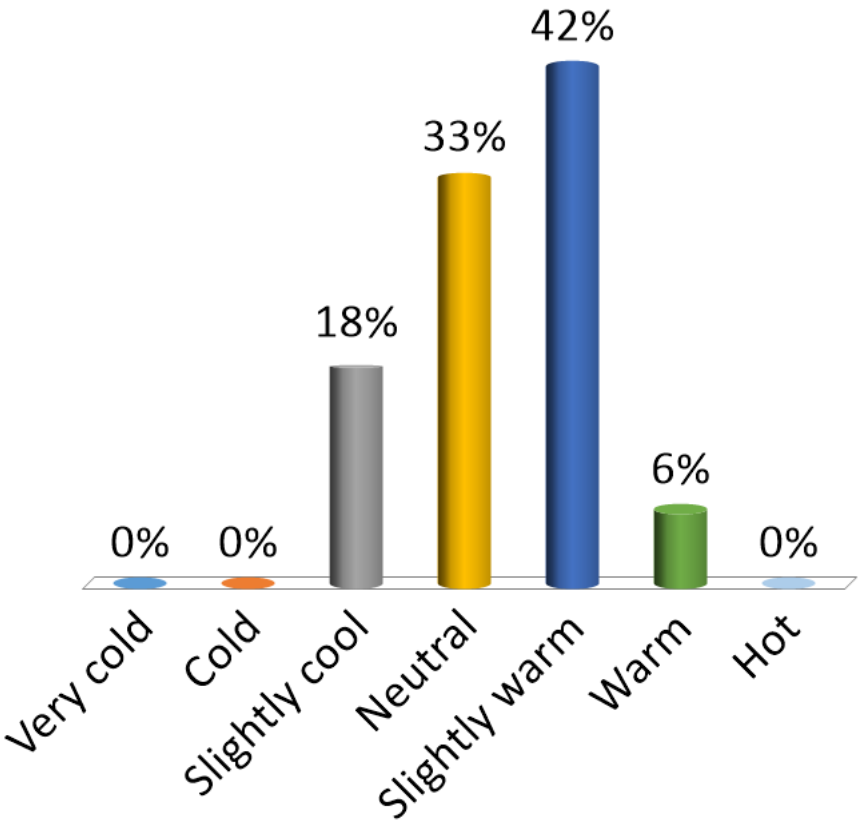
How do you feel right now in this classroom?

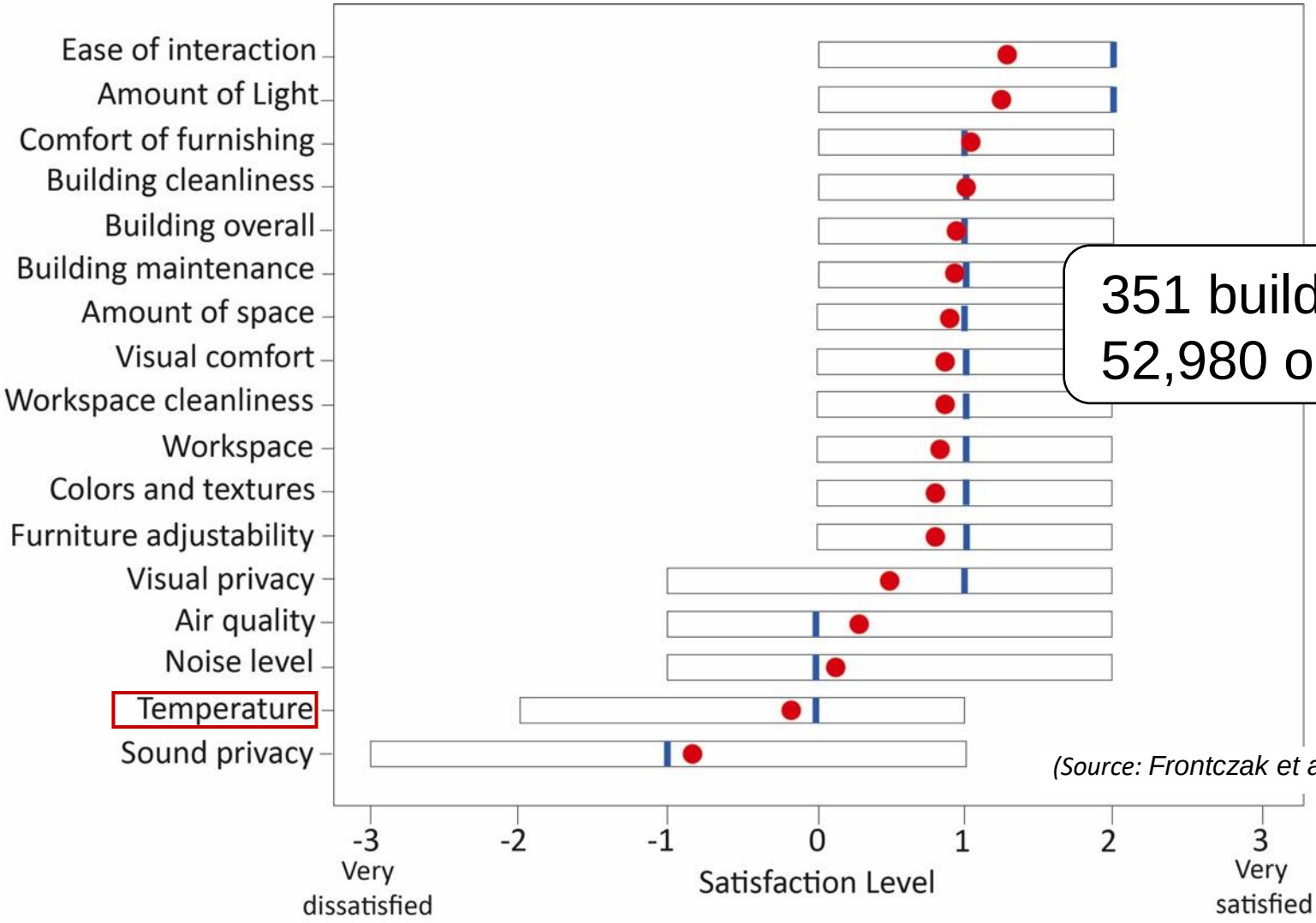
A. Very cold
B. Cold
C. Slightly cool
D. Neutral
E. Slightly warm
F. Warm
G. Hot



very cold | cold | slightly cool | neutral | slightly warm | slightly warm | hot

This could be one of the survey outcomes…

Building occupant satisfaction in offices



351 buildings
52,980 occupants

(Source: Frontczak et al 2011, Indoor Air)

Occupancy surveys: Challenges

- **Overall assessment (long term)**
  - Qualitative category influence by present moment
  - Would change if we know historical replies
  - Make sure occupants understand the question
- **Momentarily assessment (at this very moment)**
  - Requires a large sample which can cause survey fatigue
  - Comfy app – showed that 10% of occupants vote 90% of the time – how representative the sample is?
- **Key drivers**
  - Developer/Owner perspective
    - Rate the buildings to increase the property value
  - Owned and operated building
    - Employees to have better productivity

Predicted thermal comfort: Two models

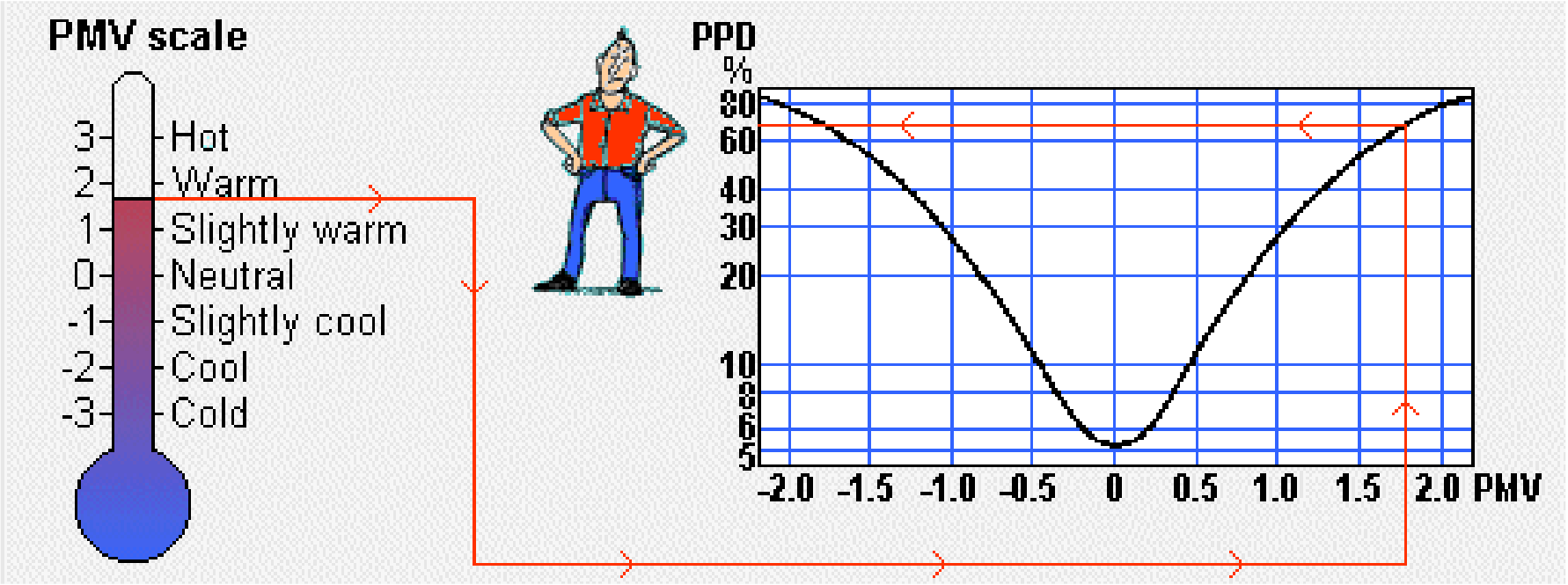
To predict thermal comfort, we can use one of the two models:

- PMV/PPD (Static) model:
  - Considers thermal comfort as a result of steady-state heat balance equation. It's a function of the 4 environmental parameters (air temperature, mean radiant temperature, air velocity and air humidity), and 2 personal factors: activity (metabolic rate) and clothing insulation. Applicable for moderate thermal environments.
- Adaptive model:
  - Considers thermal comfort as a result of occupant adaptation:
    - Behavioral (operating windows, blinds, fans, doors, etc.)
    - Physiological (acclimatization)
    - Psychological (adjusting thermal comfort expectations towards climatic conditions prevailing outdoor)
  - Strong indoor/outdoor temperature relationship in naturally ventilated buildings

PMV/PPD or static model

PMV = f (Ta, MRT, RH, Va, Met, Clo)

- Goal: to estimate of the mean value that would be obtained if many people were asked to vote on thermal comfort using a 7 point scale.



PMV: Predicted Mean Vote

PPD: Percentage of Percentage Dissatisfied

Percent of People Dissatisfied (PPD)

When we know PMV (average results obtained), we need to estimate how many people are satisfied with the thermal conditions for that PMV

- We quantify that as the **percent of people dissatisfied (PPD)**
- Researchers found a non-linear dependence between **PPD** and **PMV** based on numerous experiments in controlled environments

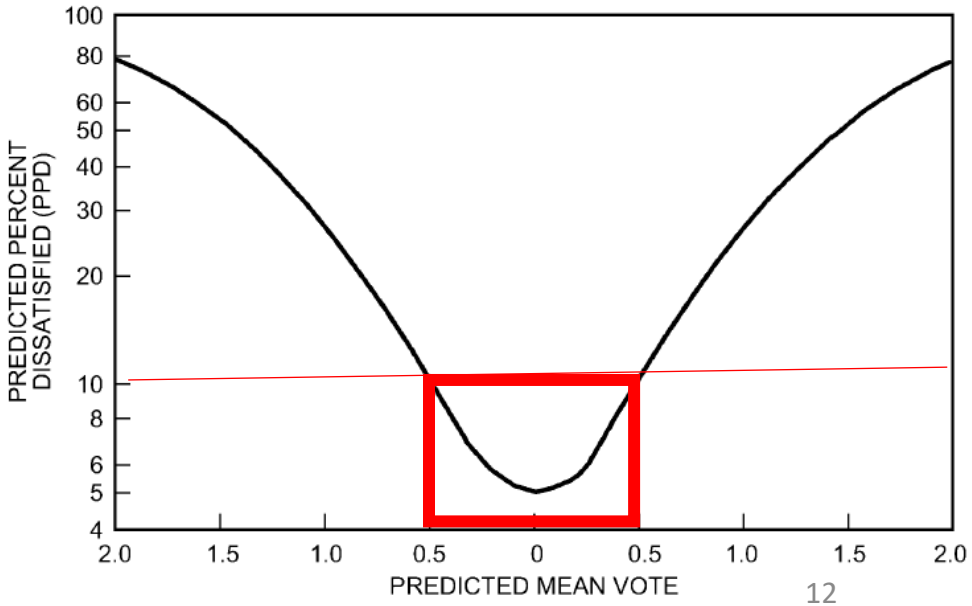
Design target:

$$-0.5 < PMV < +0.5$$

$$\Downarrow$$

$$PPD < 10\ \%$$

Notice that the absolute minimum PPD is 5% showing that you cannot satisfy everyone at the same time!



PMV & PPD: Equation of Fanger

Prof. Ole Fanger

How can we predict PMV and PPD?

- Physically: a relationship between the imbalance between heat flow from the body and the heat flow required for optimum thermal comfort
- Empirically: Correlations derived between sensations of thermal comfort (PMV/PPD) and environmental variables:

$$PPD = 1 - 0.95 \cdot \exp(-0.03353\ PMV^4 - 0.2179\ PMV^2)$$

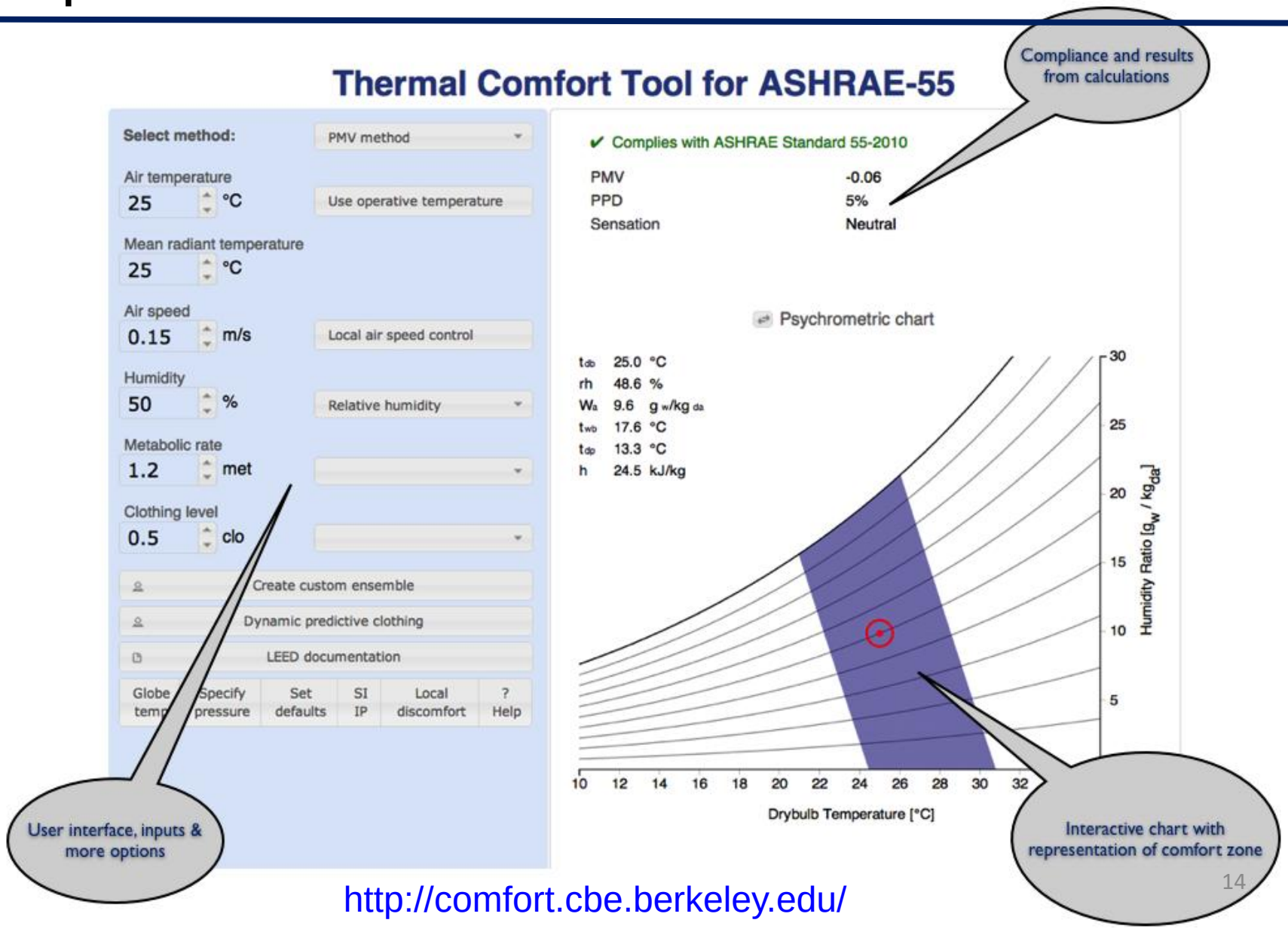
$$PMV = (0.303 \cdot \exp(-0.036M) + 0.028) \cdot L$$

M = metabolic activity (Met)

L = thermal load (difference between actual skin temperature and the skin temperature required for comfort) at a given activity

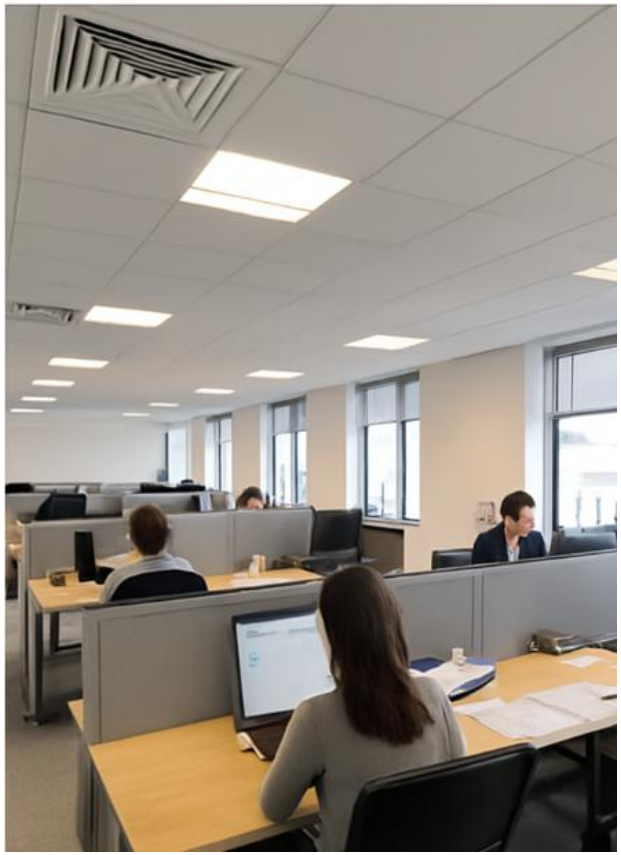
(Source: ASHRAE Handbook of Fundamentals 2019; ASHRAE Standard 55)

In practice: CBE Thermal Comfort Tool



http://comfort.cbe.berkeley.edu/

Case study: When standards aren’t enough…



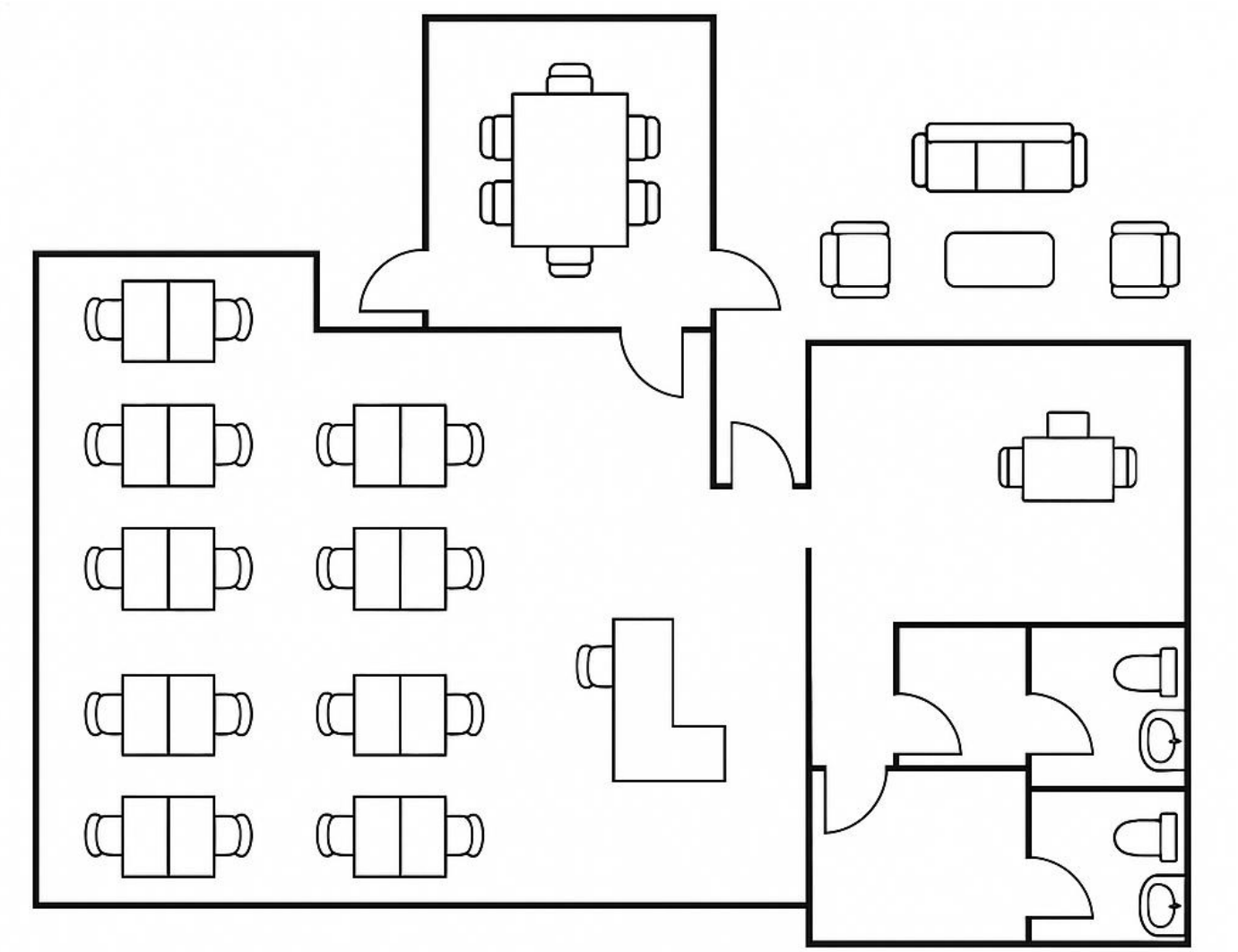
Case study 1: PMV vs. own votes

Case study 2 (actual study):

- PMV ≈ 0 → “predicted comfort” ☑
- Occupant surveys → “too cold / too warm / stuffy” ✖
- What went wrong?

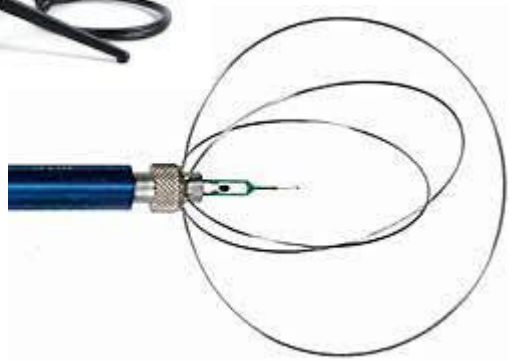
- 👤 Individual differences → sex, age, acclimatization, clothing → PMV assumes “average person.
- ⚙ Model limitations → steady-state, uniform environment; estimates for clo/met; assumptions for MRT & air speed.
- 🧠 Psychological/adaptive factors → expectations, control (e.g., opening windows), cultural norms, prior thermal history.

Where would you place sensors to measure comfort?

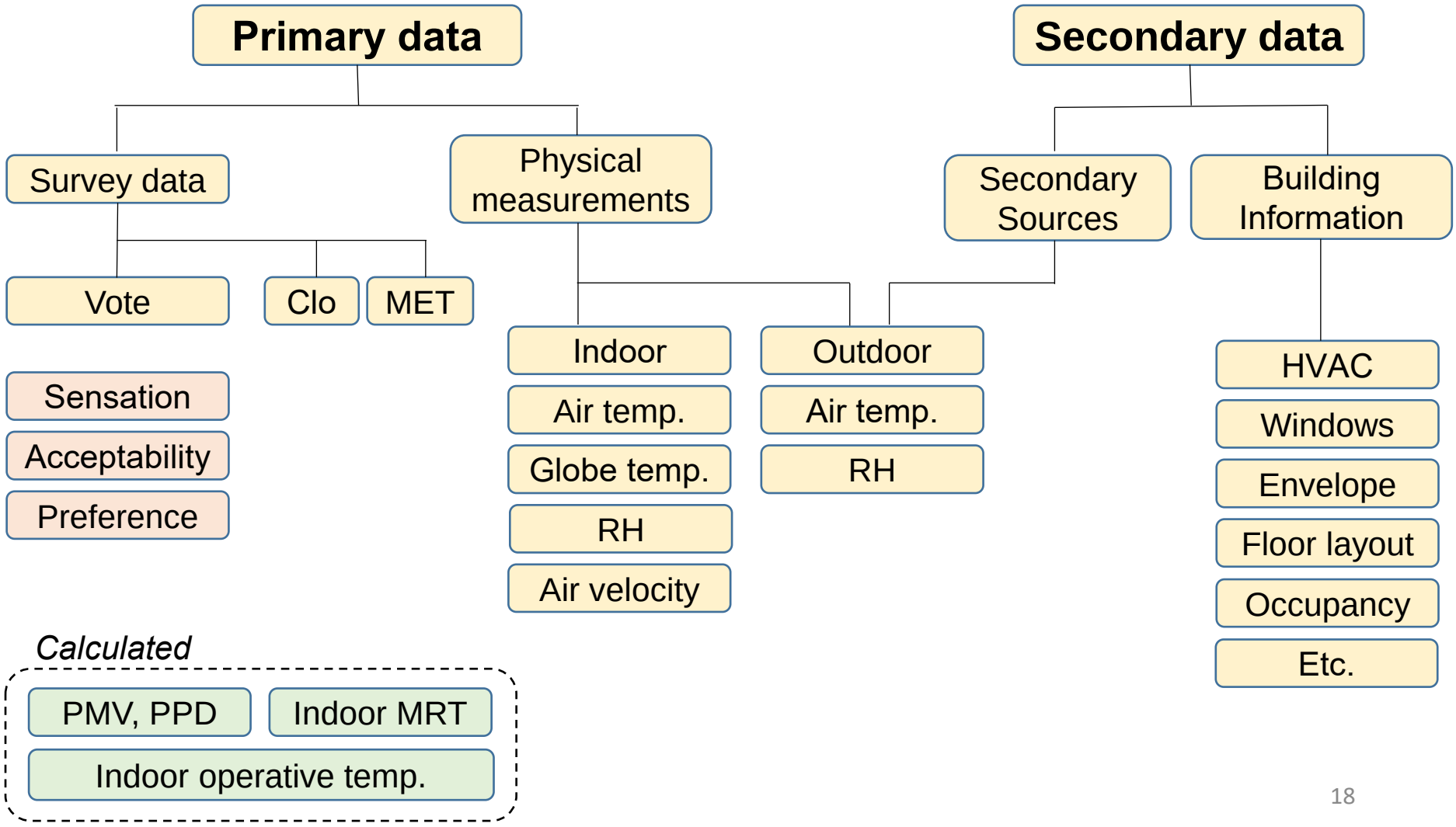


Objective measurements: Questions to consider

- What to measure?
- How accurate?
- Where to measure?
- How many sampling points?
- How long to measure?
- How intrusive equipment is?



Example of thermal comfort analysis design



Adaptive Thermal Comfort Model

- Based on measurements and surveys done in real buildings
- Takes into account human behavior - Assumes that people change their behavior if they experience discomfort
- Applies to naturally ventilated buildings (takes into account outdoor temperature as well)

Darwin:
"It is not the most intellectual or the strongest of species that survives; but the species that survives is the one that is able to ***adapt*** *to and adjust best to the changing environment in which it finds itself."*

Prof. Gail Brager

Prof. Richard de Dear

Where do data come from?

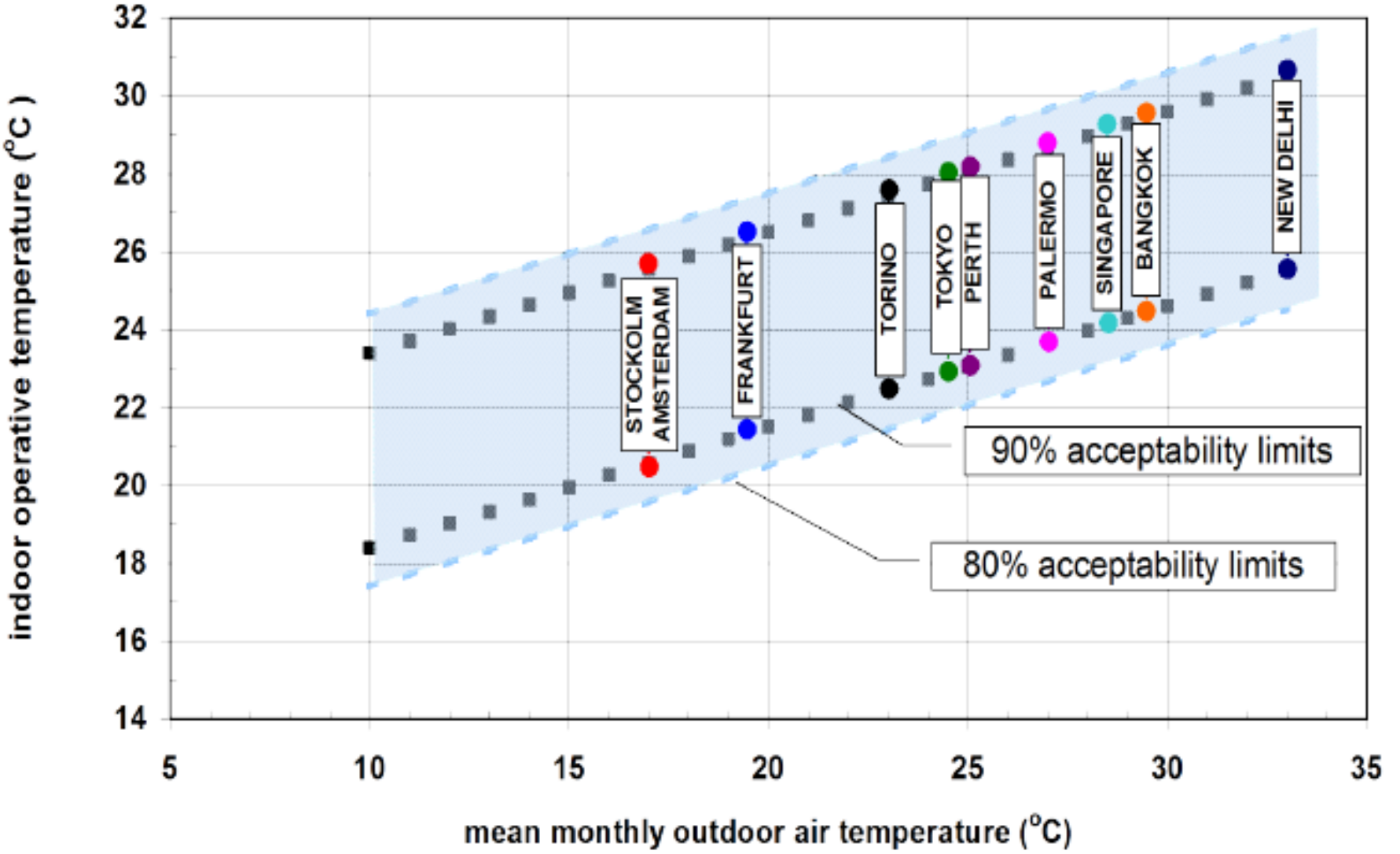
ASHRAE Thermal comfort database

- Database 1 + Database 2
- Building locations: Country (N>23), City (N>65)
- Season: Spring, Summer, Autumn, Winter
- Various climatic zones
- Conditioning types: AC, NV, MM, MV
- Building types: Multifamily housing, Office, Classroom, Senior center, Others

- Includes approximately 76,000 complete sets of thermal comfort data
- Access to the database: http://www.comfortdatabase.com
- Includes web-based interactive visualization tool for end-users
- Access to the visualiz. tool: https://cbe-berkeley.shinyapps.io/comfortdatabase

(Source: Foldvary Licina et al. 2018, Building and Environment)

Adaptive Thermal Comfort Model



PMV/PPD vs Adaptive model

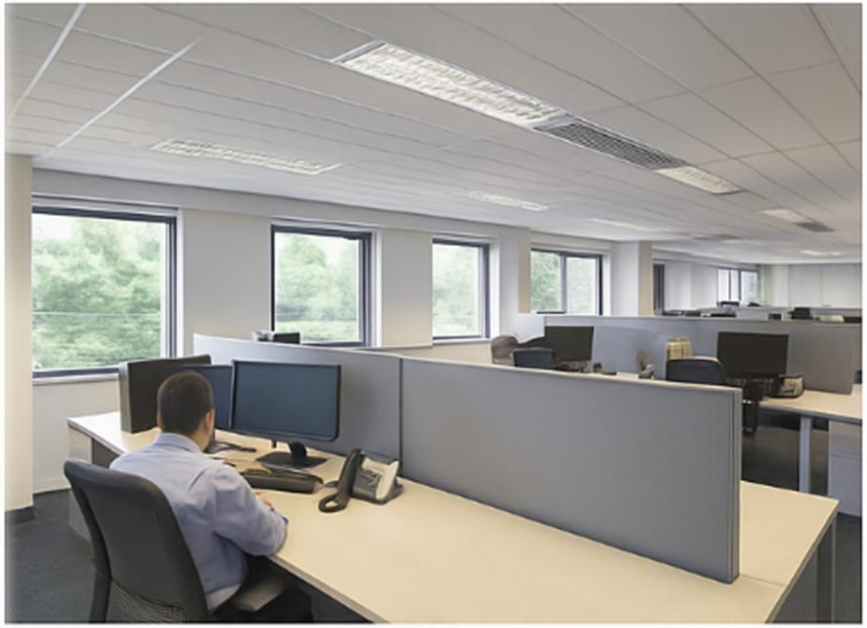
PMV/PPD - based on laboratory studies
(Laboratory ≠ Real buildings)

- **One-size-fits all:**
  Universally applied to all climates, cultures, and building types

Adaptive - Based on field data

- **3 types of adaptation:**
  - physiological
  - behavioral
  - psychological
- **Satisfaction influenced by expectations & context**

Which model (PMV vs. Adaptive) is more suitable?



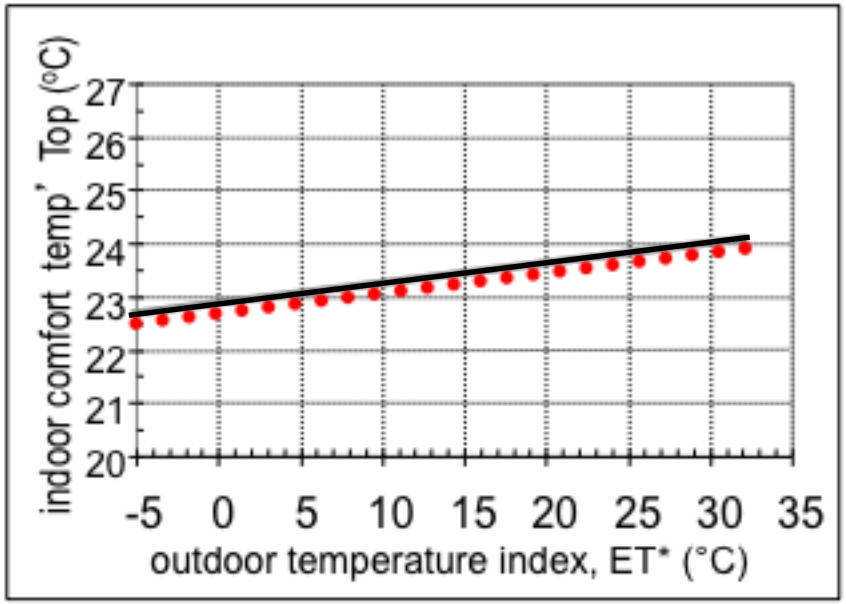
HVAC-controlled

Open windows

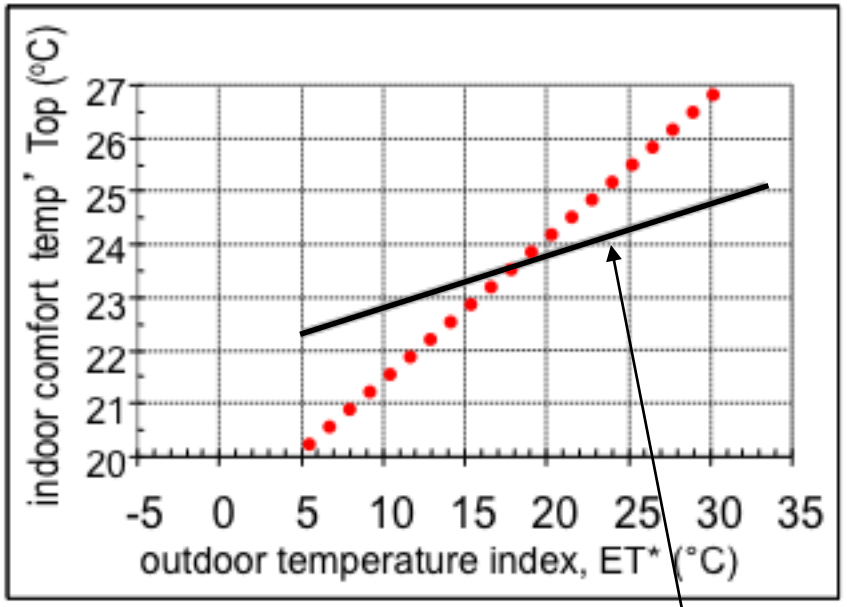
- **HVAC-controlled office** → PMV model (steady-state, assumes control).
- **Naturally ventilated office** → Adaptive model (occupants adjust via windows/clothing).
- Standards (ASHRAE/EN) also make this distinction

Is PMV model suitable for naturally vent. building?

Centrally-controlled HVAC bldgs



Naturally ventilated buildings



— Predicted: Lab-based heat-balance model

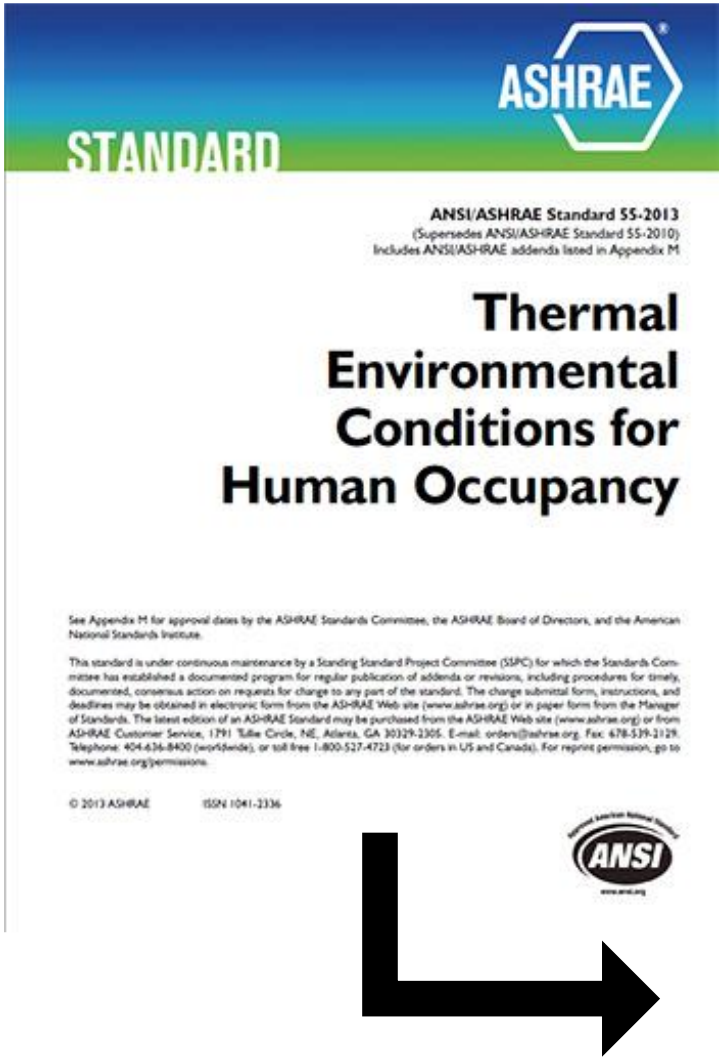
•••• Observed: Field-based adaptive model

Lines are weighted linear regressions through the data points (*not shown*)

Despite drawbacks, the PMV/PPD model has been the dominant paradigm in thermal comfort engineering.

(Source: de Dear and Brager; 1998)

Thermal comfort standards in building design



- ASHRAE Standard 55
- ISO 17772 (new – we will use this one)
- CEN Standard EN-16798
- ISO 7730
- Together, these:
  - Often produce thermal conditions acceptable to **80%** or more of building occupants

1. PURPOSE

The purpose of this standard is to specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space.

Thermal comfort standards: Categories

Standards	Category I	Category II	Category III	Category IV
ISO 17772	**High** For occupants with special needs (children, elderly, handicapped)	**Medium** (typically used) For regular building design and operation	**Moderate** Can provide an acceptable environment with some risk of reduced occupants' performance	**Low** Can be used for a short time of the year or in spaces with a very short time of occupancy
ASHRAE 55	No categorization (defines only "acceptable"/"unacceptable" level)			

Depending on the standard category selected, energy use in buildings can be largely affected:

- Typically, higher category means more narrow indoor air temperature setpoint (e.g., 22-24°C) which requires more energy

In-class exercise #1

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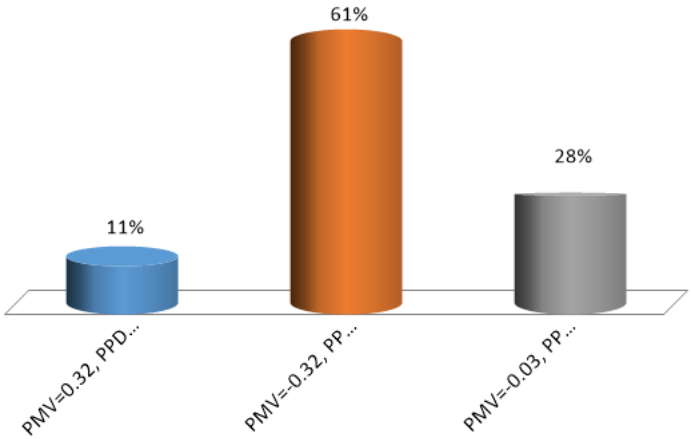
By means of the CBE tool (http://comfort.cbe.berkeley.edu/), determine PMV, PPD and EN-16798 Standard compliance and category for this classroom assuming the following conditions:

- Dry-bulb T = 23 °C
- MRT = 21 °C
- Air speed = 0.05 m/s
- RH = 30%
- MET = 1.1
- Clo = 0.9



A. PMV=0.32, PPD=9%, Cat III

B. PMV=-0.32, PPD=7%, Category II

C. PMV=-0.03, PPD=5%, Category I

Compare the obtained PPD value with the survey result obtained at the beginning of today's class. Discuss any differences.

In-class exercise #2

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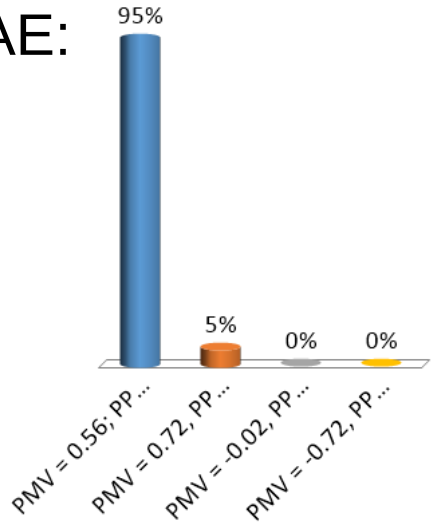
A room is occupied by standing relaxed person (1.2 met) dressed in light summer clothing (0.5 clo). A summer day the indoor temperature (air temperature = mean radiant temperature) is 27 °C, the relative air humidity is 50%, and the air velocity is 0.1 m/s. According to ASHRAE:

- Question a: What is PMV?
- Question b: What is PPD?
- Question c: What is sensation?
- Question d: What is the optimal operative temperature?



A. PMV = 0.57; PPD = 12 %; Slightly Warm; To= 25.08°C (when PMV = 0)

B. PMV = 0.72, PPD = 26%; Warm; To= 26.26 °C (when PMV = 0)

C. PMV = -0.02, PPD = 6%; Slightly cool; To= 26.26 °C (when PMV = 0)

D. PMV = -0.72, PPD = 6%; Neutral; To= 22.62 °C (when PMV = 0)

In-class exercise #3

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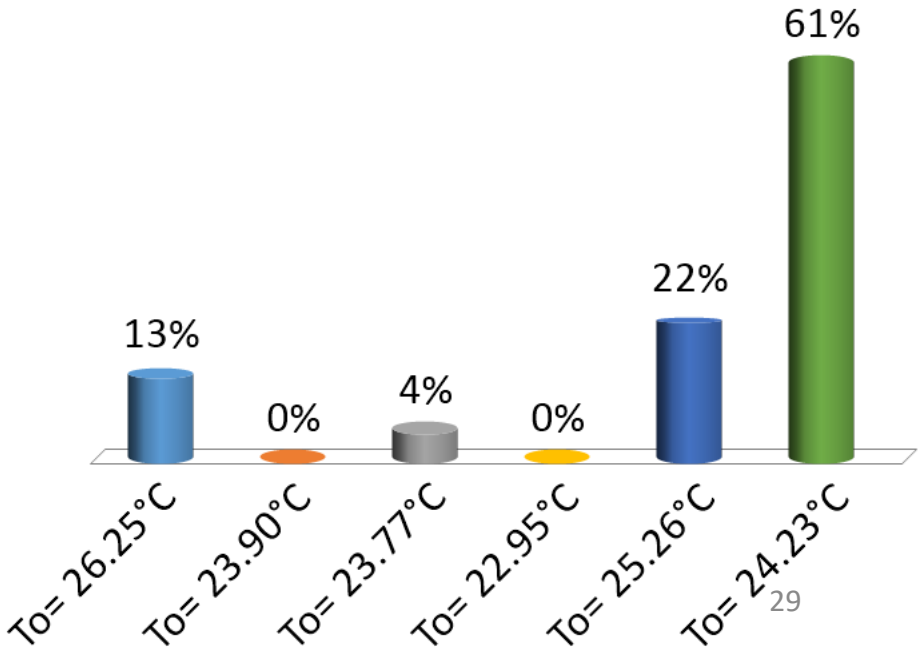
A person is sitting at the desk and typing while wearing typical summer indoor clothing. If air speed is 0.1 m/s and relative humidity is 50%, what is the minimum needed operative temperature in order to comply with ASHRAE-55 Standard?

A. To= 26.25°C
B. To= 23.90°C
C. To= 23.77°C
D. To= 22.95°C
E. To= 25.26°C
F. To= 24.23°C



Homework, exercise #4

A person is exposed to the following conditions according to EN-16798:

- Operat. T = 25.5 °C
- Air speed = 0.1 m/s
- RH = 45%
- MET = 1.1
- Clo = 0.6

What is PPD?

PPD=5%

Homework, exercise #5

During the average summer month, indoor operative temperature is 24.5 °C, while outdoor temperature is 27.5 °C.

Q.1. According to ASHRAE, what is the needed range of operative temperature in order to preserve 90% acceptability limits?

90% acceptability limits = Operative temperature: 23.8 to 28.8 °C

Q.2. According to EN-16798, which category of compliance is met?

II category

http://comfort.cbe.berkeley.edu/

Key takeaways on thermal comfort

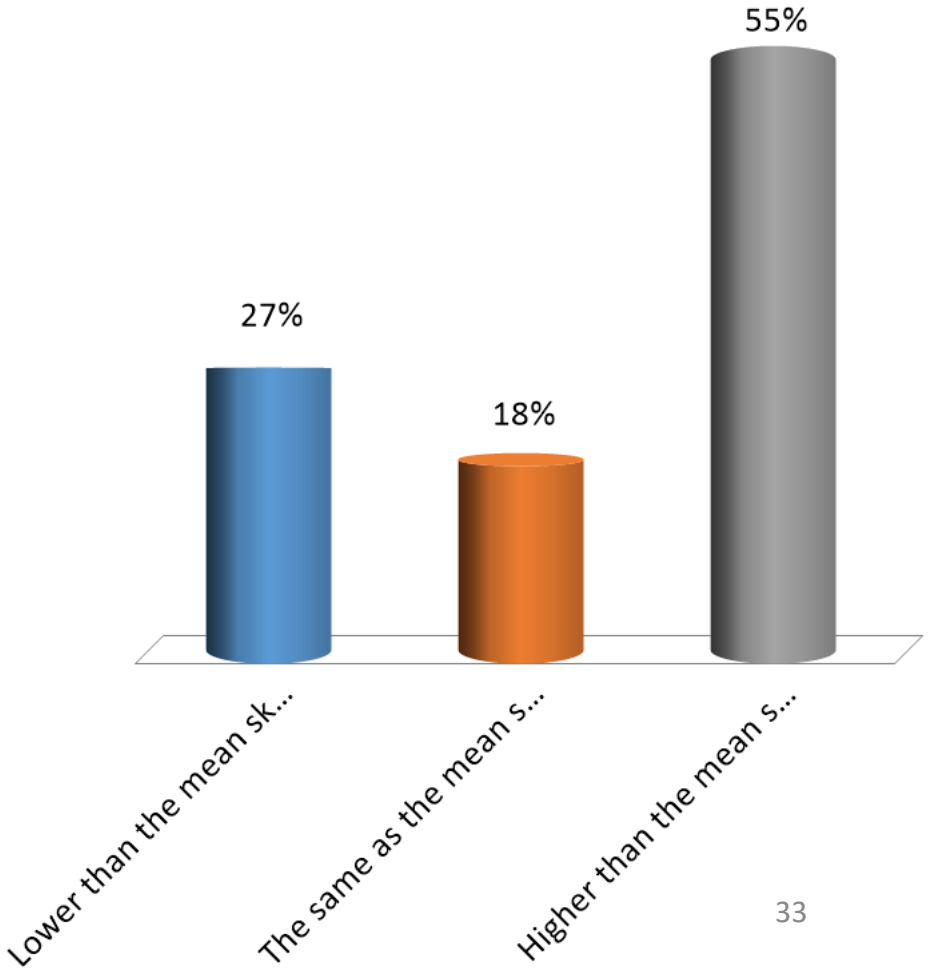
- **Thermal comfort matters** → It influences building design, energy demand, health, well-being, and productivity.
- **Models are tools, not truths** → PMV vs. Adaptive: each fits different building types and contexts.
- **Standards set the baseline** → They acknowledge subjectivity; not everyone will feel equally comfortable.
- **Future challenge** → Moving toward a holistic approach balancing individual diversity and energy efficiency.

A seated person dressed in 1 Clo is thermally neutral at 22 °C. Under these conditions, the core temperature is...

A. Lower than the mean skin temperature

B. The same as the mean skin temperature

C. Higher than the mean skin temperature



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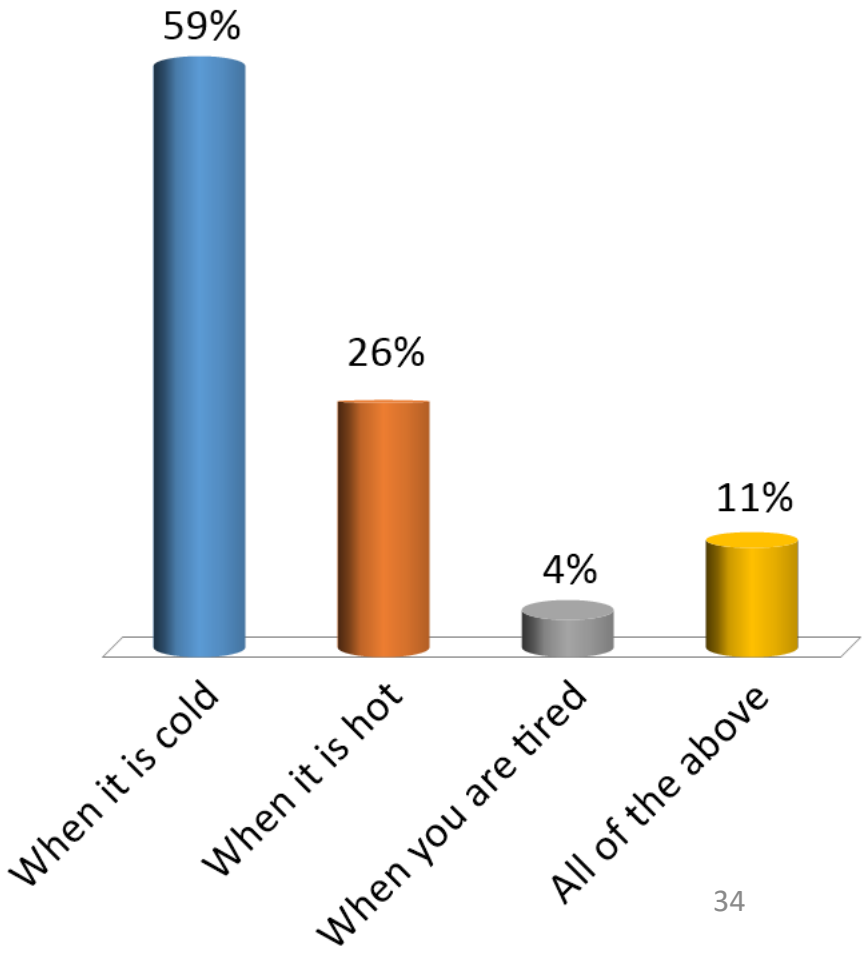
When is vasoconstriction important?

A. When it is cold
B. When it is hot
C. When you are tired
D. All of the above



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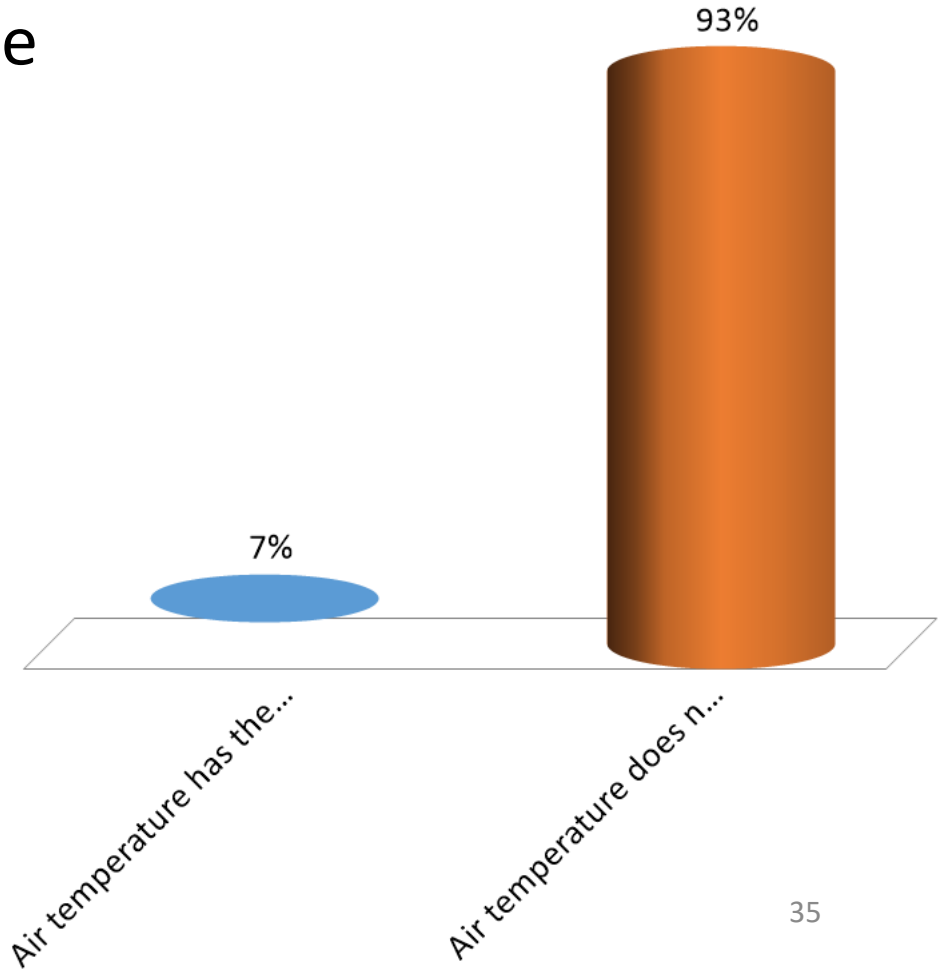
For operative temperature, high air velocity means that ...

A. Air temperature has the equal weight as the mean radiant temperature
B. Air temperature does not have the equal weight as the mean radiant temperature



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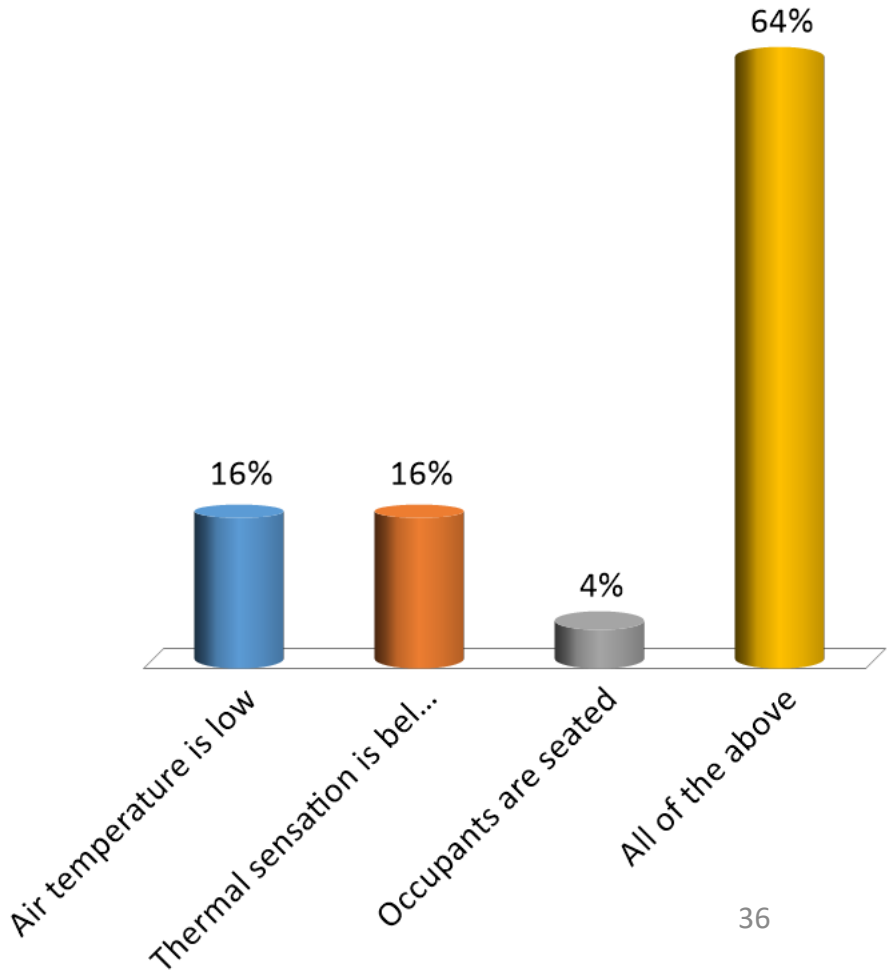
Elevated air velocity is particularly a problem when...

A. Air temperature is low
B. Thermal sensation is below neutral
C. Occupants are seated
D. All of the above



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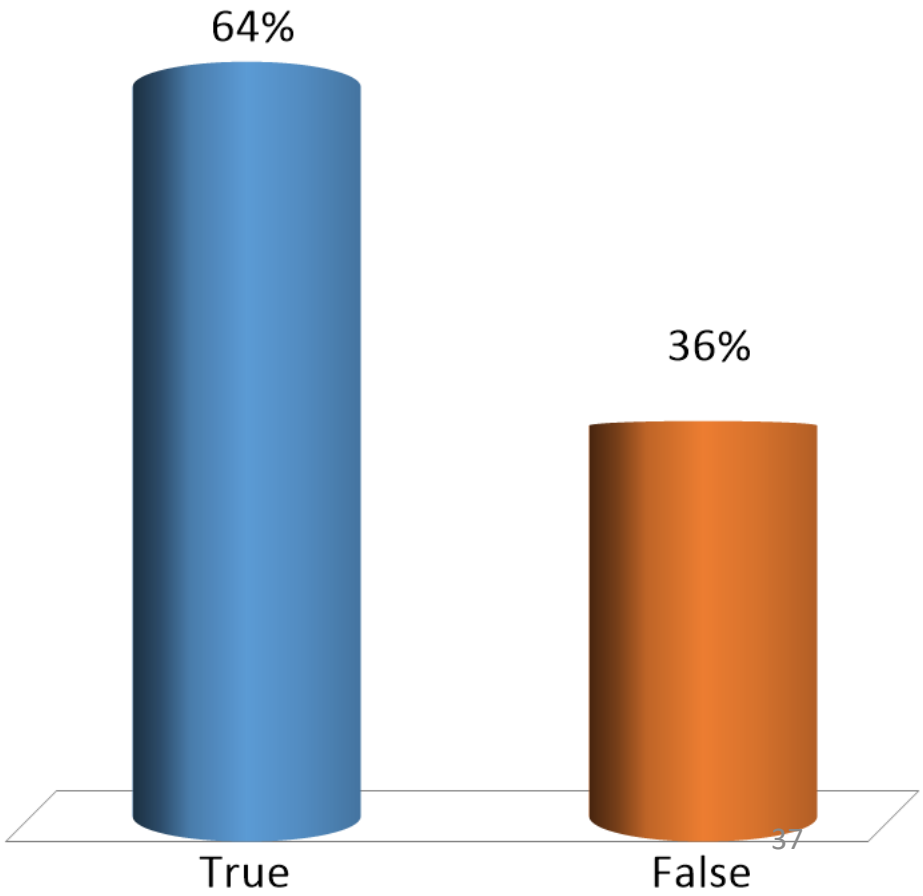
PMV and PPD stand for Predicted Median Vote and Percentage of People Dissatisfied?

A. True
B. False



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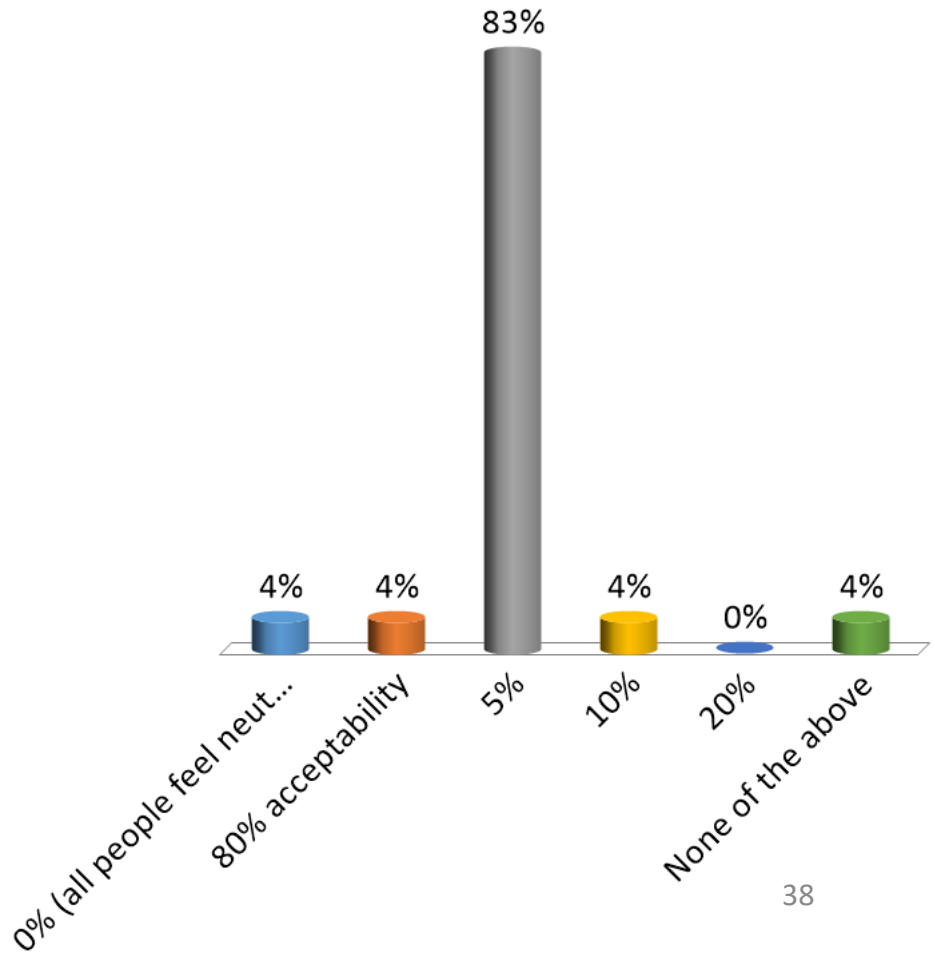
According to standards, what is the minimum achievable PPD?

A. 0% (all people feel neutral)
B. 80% acceptability
C. 5%
D. 10%
E. 20%
F. None of the above



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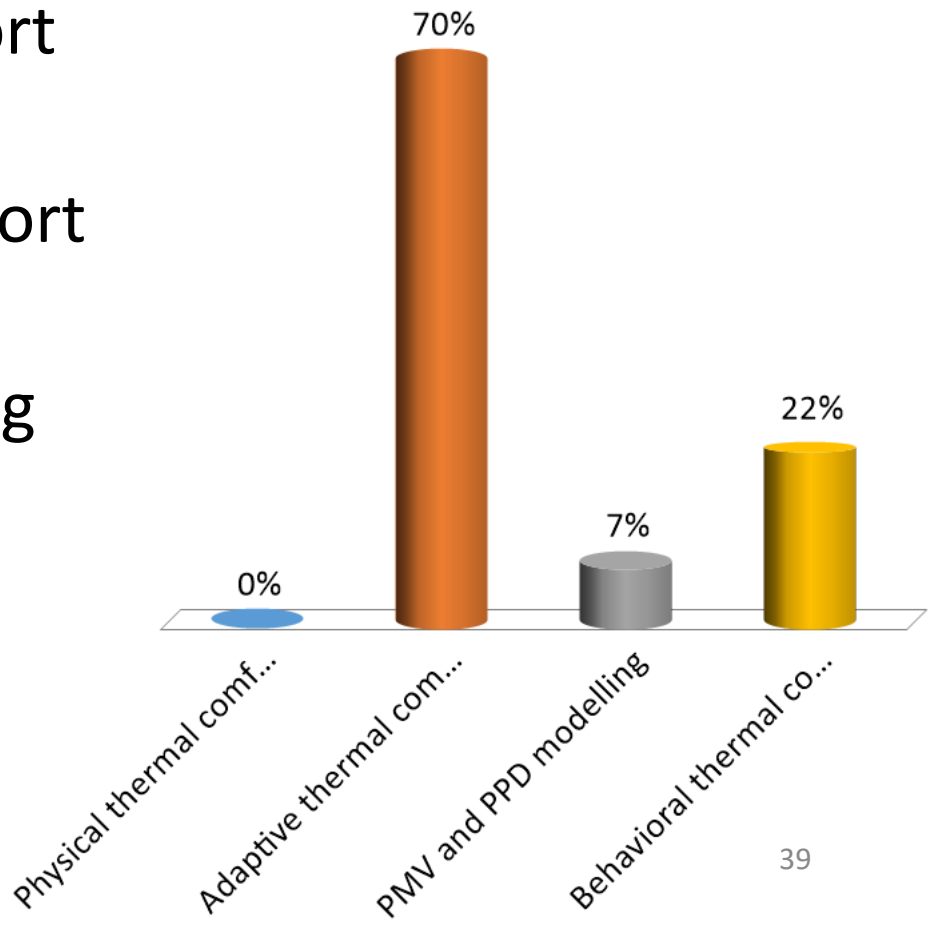
What is the type of thermal comfort modelling called where people change behaviour or respond to thermal conditions as opposed to assuming that they will be passive?

A. Physical thermal comfort modeling
B. Adaptive thermal comfort modelling
C. PMV and PPD modelling
D. Behavioral thermal comfort modelling



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Match the building type to the most appropriate EN category for indoor environmental quality (IEQ). Which of the following combinations is correct?

Building types:

A. Hospital ward
B. Office building
C. Warehouse / storage space
D. Temporary site office used only a few weeks per year

Categories:

I. Category I
II. Category II
III. Category III
IV. Category IV

A. A–III, B–I, C–II, D–IV

B. A–II, B–III, C–IV, D–I

C. A–I, B–II, C–III, D–IV

D. A–I, B–III, C–II, D–IV

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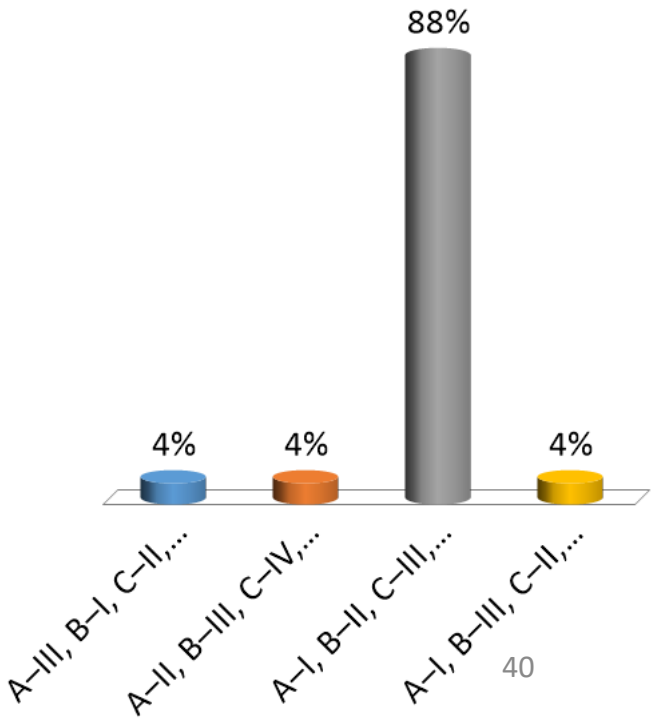
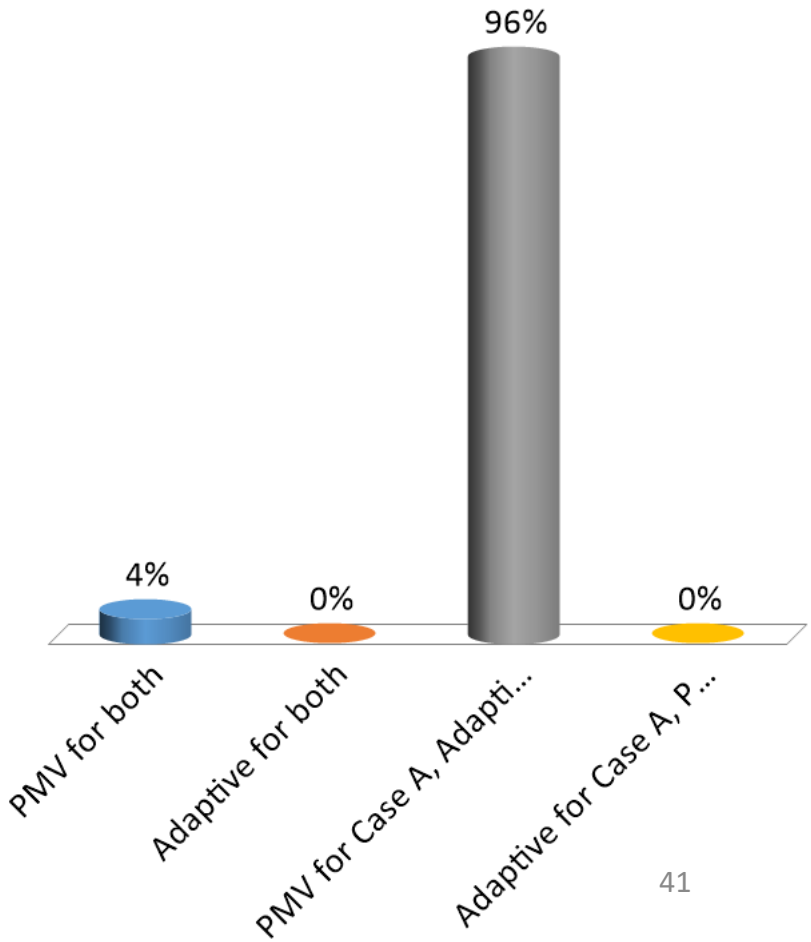


Which model would you apply?

Case A: Sealed, air-conditioned office tower in Dubai.
Case B: Naturally ventilated university classroom in Lausanne.

A. PMV for both
B. Adaptive for both
C. PMV for Case A, Adaptive for Case B
D. Adaptive for Case A, PMV for Case B



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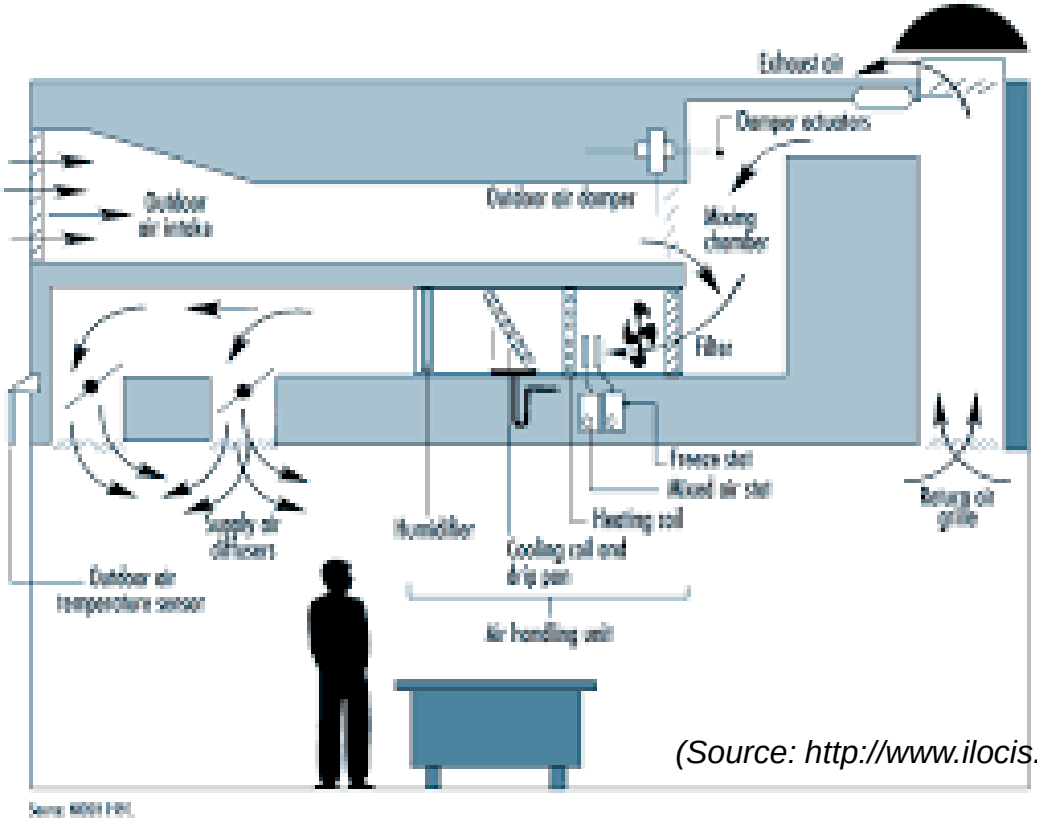
Next time…

- Introduction to HVAC systems
  - Psychometric processes
  - Exercises
- Mid-term exam briefing



(Source: http://www.ilocis.org/documents/chpt45e.htm)