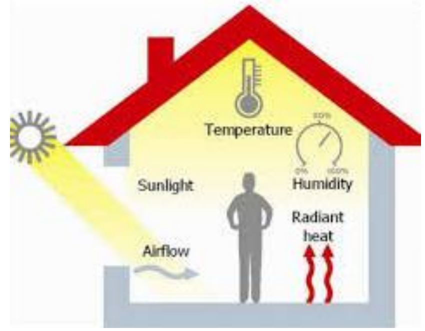
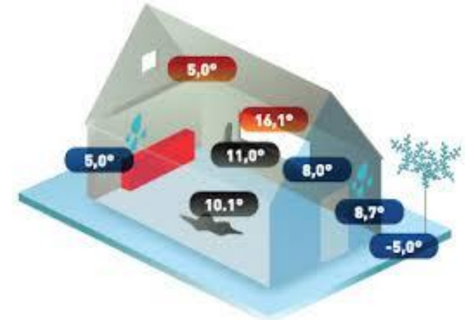
CIVIL 212
Indoor Climate
Fall 2024





Thermal Comfort 1

26 September, 2024

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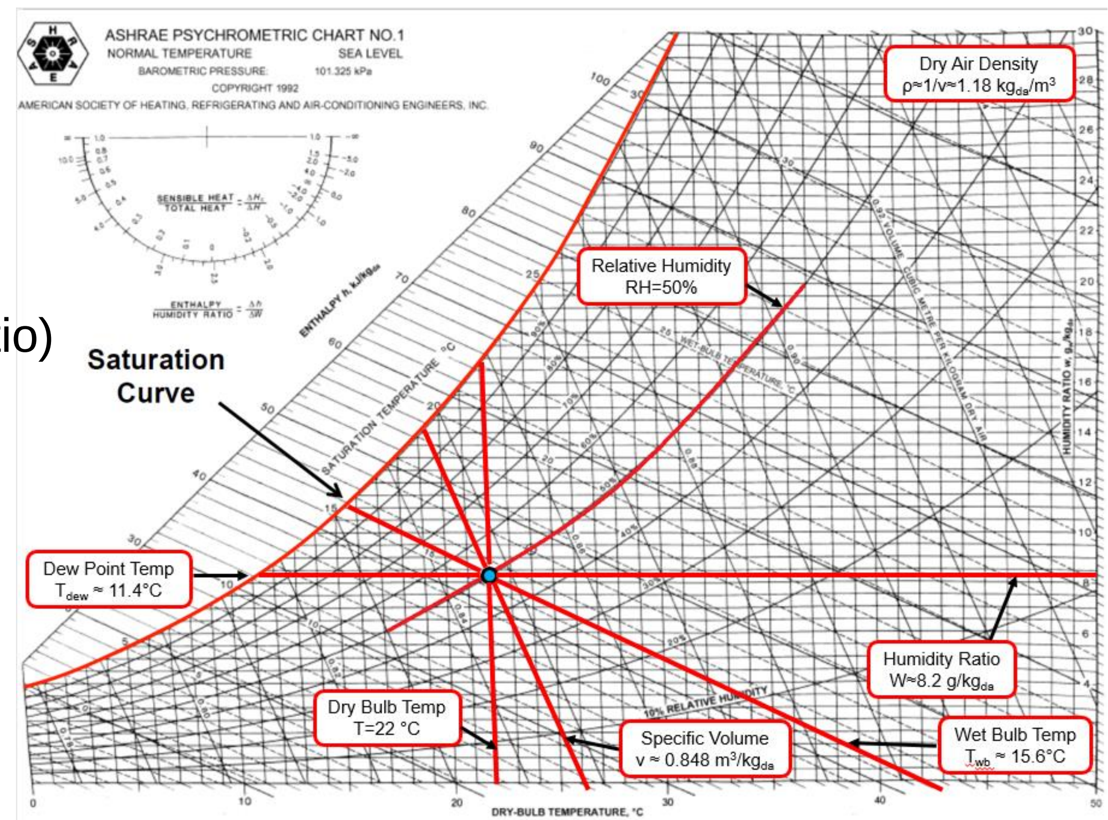
Last time we covered…

- Heat, Air and Moisture Fundamentals
- Psychometric Chart Fundamentals

Key terms that we revised:

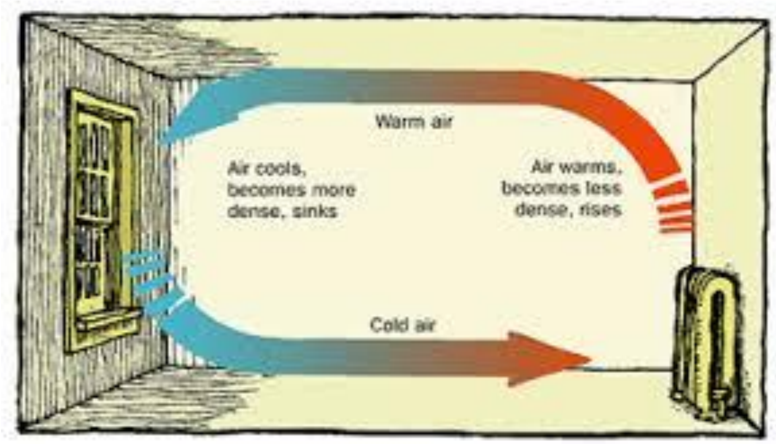
1. Dry bulb temperature
2. Relative humidity
3. Vapor pressure
4. Saturation
5. Absolute humidity (humidity ratio)
6. Dew point temperature
7. Wet bulb temperature
8. Density
9. Specific volume
10. Enthalpy



Last time we covered…

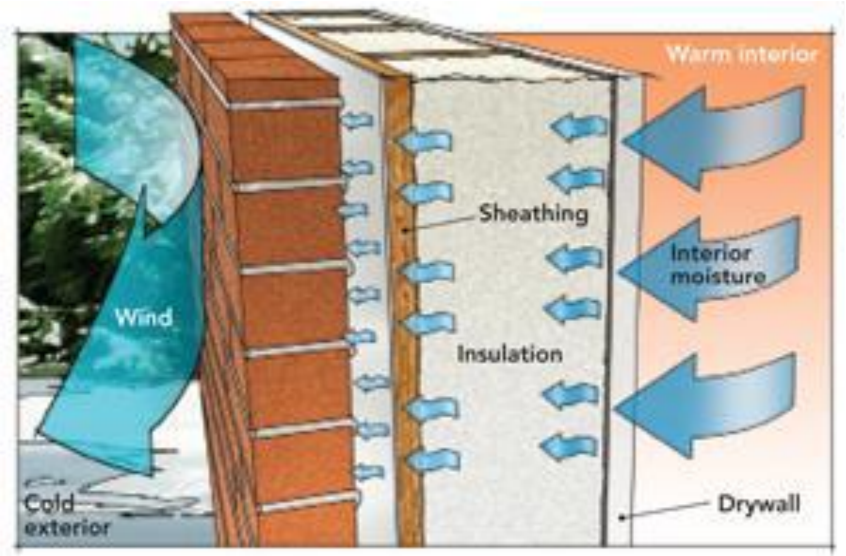
CONDUCTION

CONVECTION



RADIATION

MOISTURE TRANSPORT



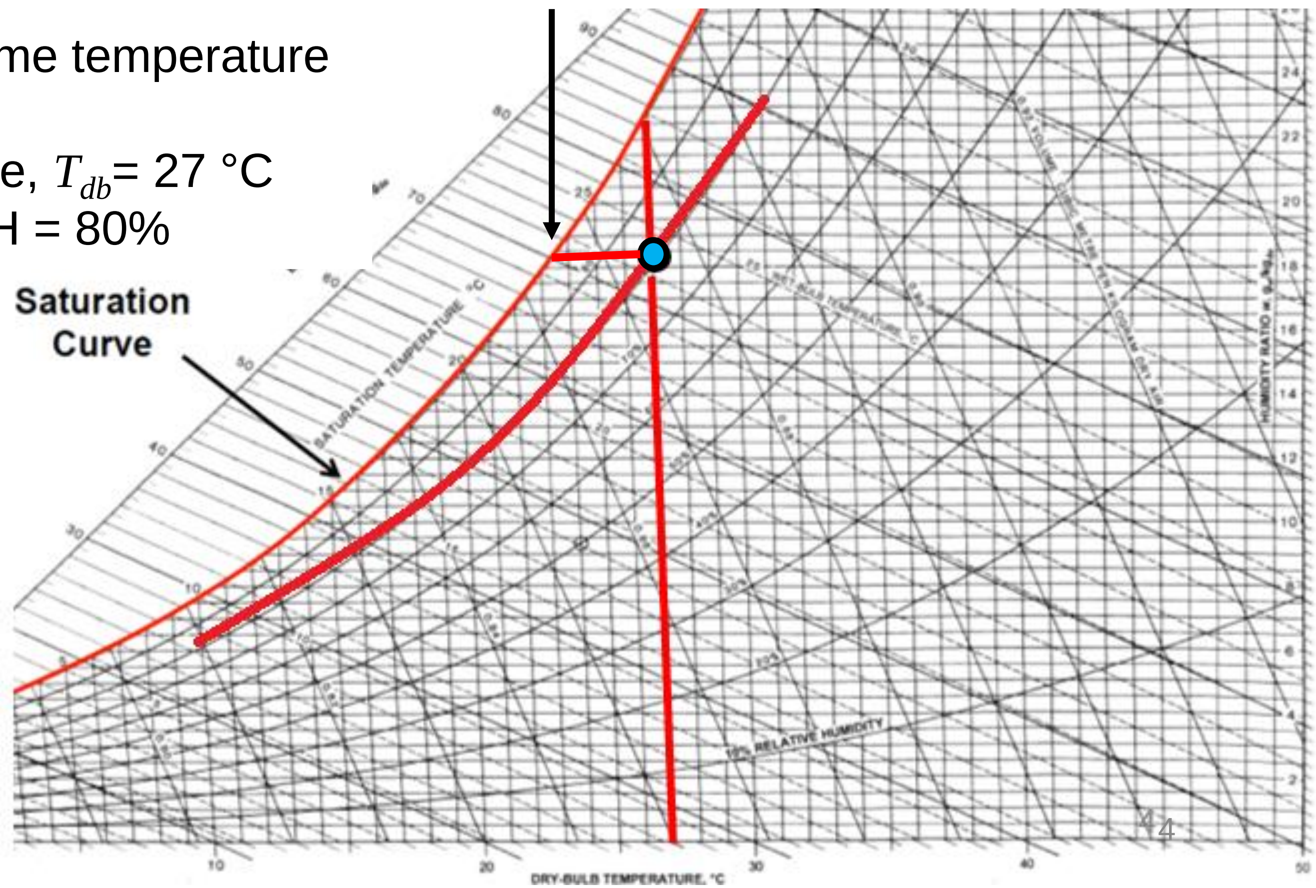
Psychrometric chart: Homework #1

- Condensation on windows when taking a shower
  - How cold does it have to be outside for condensation to form on windows?

Solution: T_{win} = T_{dp} = 23 °C

Assumptions:

- windows are the same temperature as outside air
- dry-bulb temperature, T_{db}= 27 °C
- relative humidity, RH = 80%



Psychrometric chart: Homework #2

By using phychrometric chart, complete the following table of values for a moist air:

Dry-bulb temp °C	Wet-bulb temp °C	Enthalpy kJ/kg	Specific volume m^3/kg_{da}	% saturation (relative humidity)	Moisture content (humidity ratio) kg/kg_{da}
40 °C	22.5	66.5	0.901	22	0.01
40 °C	20 °C	57.8	0.896	14.5	0.0064
40 °C	30.3	102	0.921	50%	0.0237
15 °C	7.1	24	0.82	30	0.0032
25 °C	15 °C	42	0.853	33	0.0066
30 °C	10.3	30	0.858	~0	~0
50 °C	~33.7	120	~0.954	~35	0.0269

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

Today's objectives…

- Thermal comfort fundamentals
- Human body heat balance
- Factors affecting thermal comfort

45 minutes

- Local thermal discomfort
- Quiz time

45 minutes

Note:

I strongly recommend going through the reading material for this week: "Comfort Psychometrics"

What is human comfort?

Human comfort in buildings

Human Comfort ≠ Thermal Comfort

Environmental

Age, Sex
Health and psychological status
Activity, Clothing
Access to food and drink
Safety, etc.

Personal

What is Thermal Comfort?

- **ASHRAE*** definition:
  "…that condition of mind which expresses satisfaction with the thermal environment."

- Building design must ensure the means of achieving comfortable indoor climate

- Engineer's view on comfort:
  = absence of discomfort
  = "thermal neutrality"

* *American Society of Heating, Refrigerating, and Air-Conditioning Engineers (abbreviated as ASHRAE)*

Reduce the negative vs. Enhance the positive

Thermal neutrality or Thermal delight?

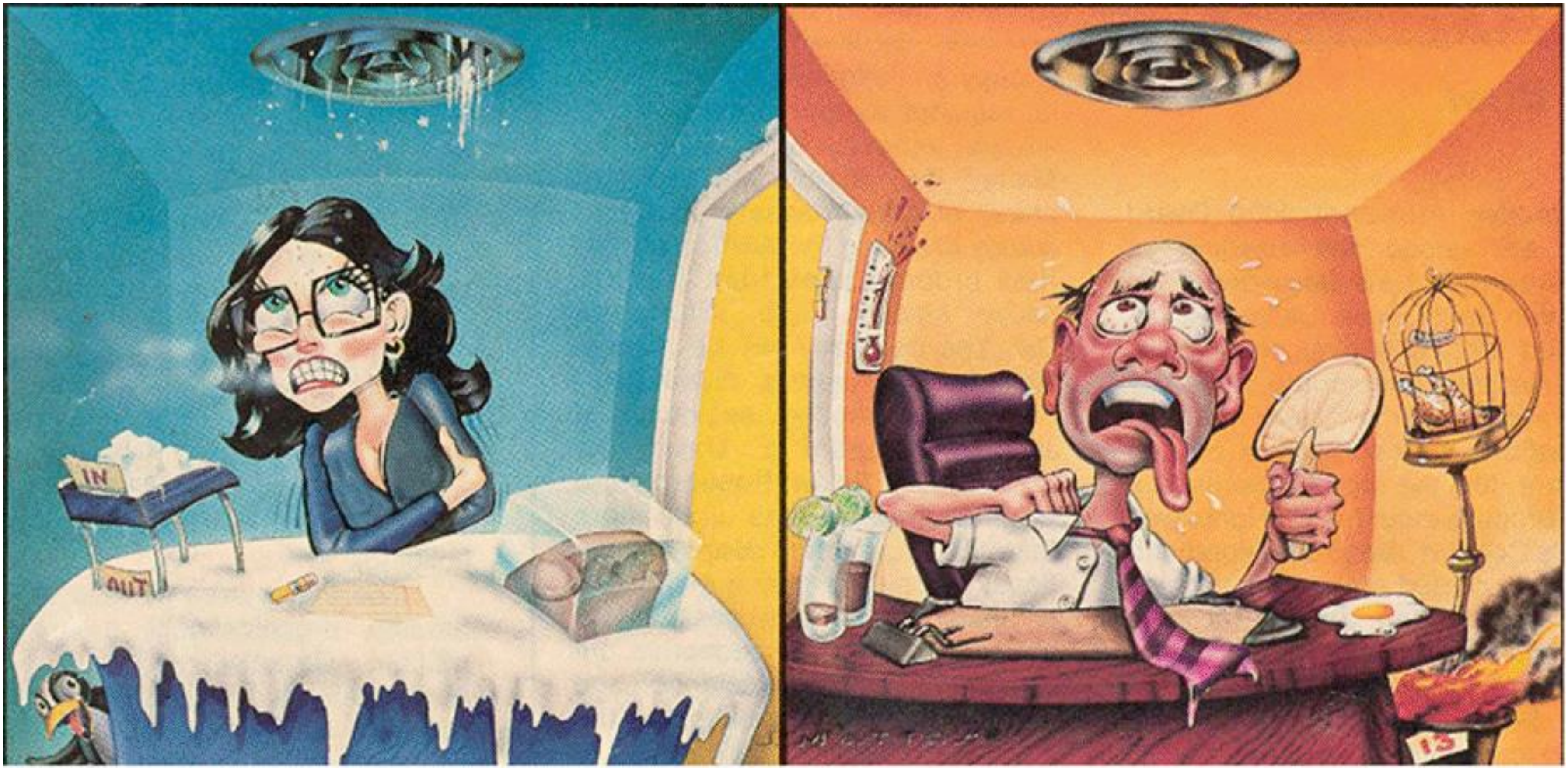
What is the issue?

Source: Dilbert cartoon

Due to its subjectivity, **thermal comfort is different for every individual**.

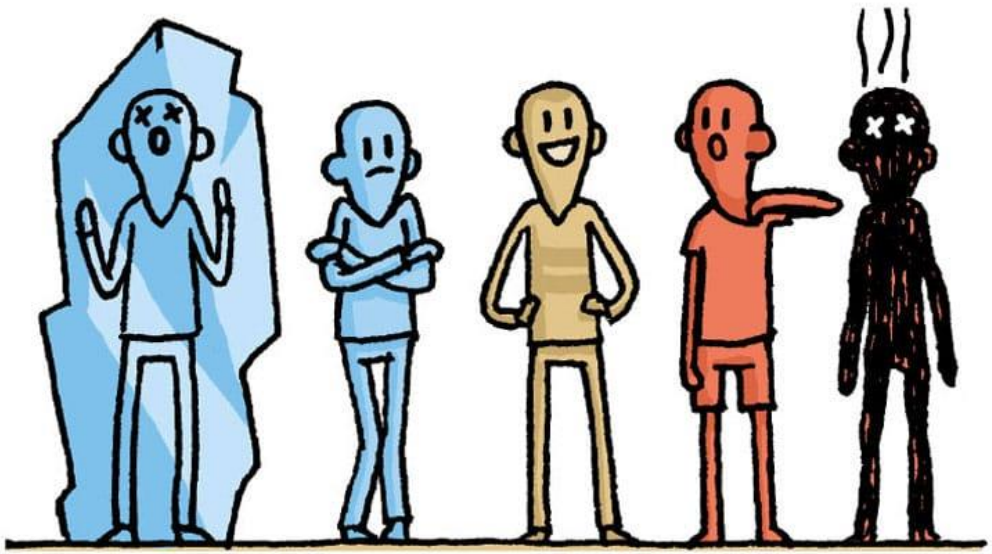
That means that uniform thermal conditions cannot satisfy everyone !!!

Workplace discomfort & individual differences

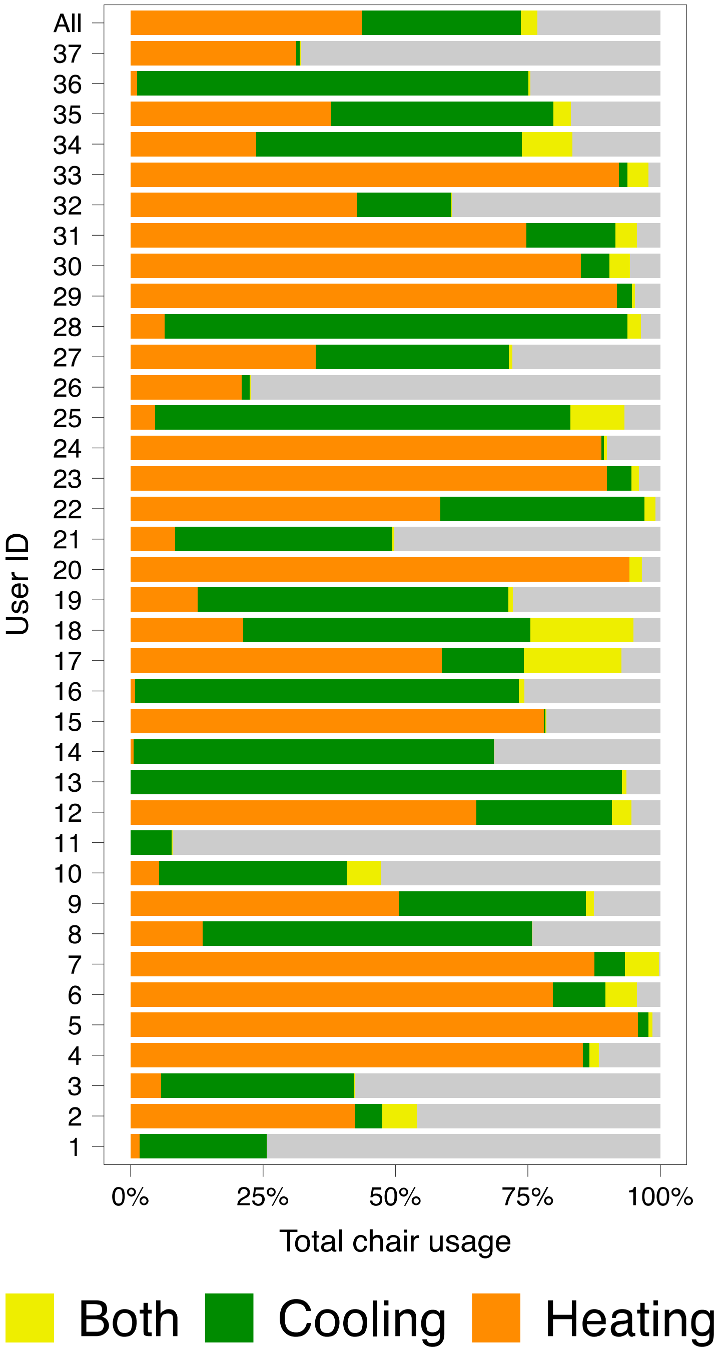


- Physical differences (e.g., age, sex, climatic origin, activity, metabolism)
- Psychological (e.g., thermal experience, perceived thermal control)
- Behavioral (e.g., expectations, culture, thermal adaptation)

Multiple people – thermal preferences vary widely

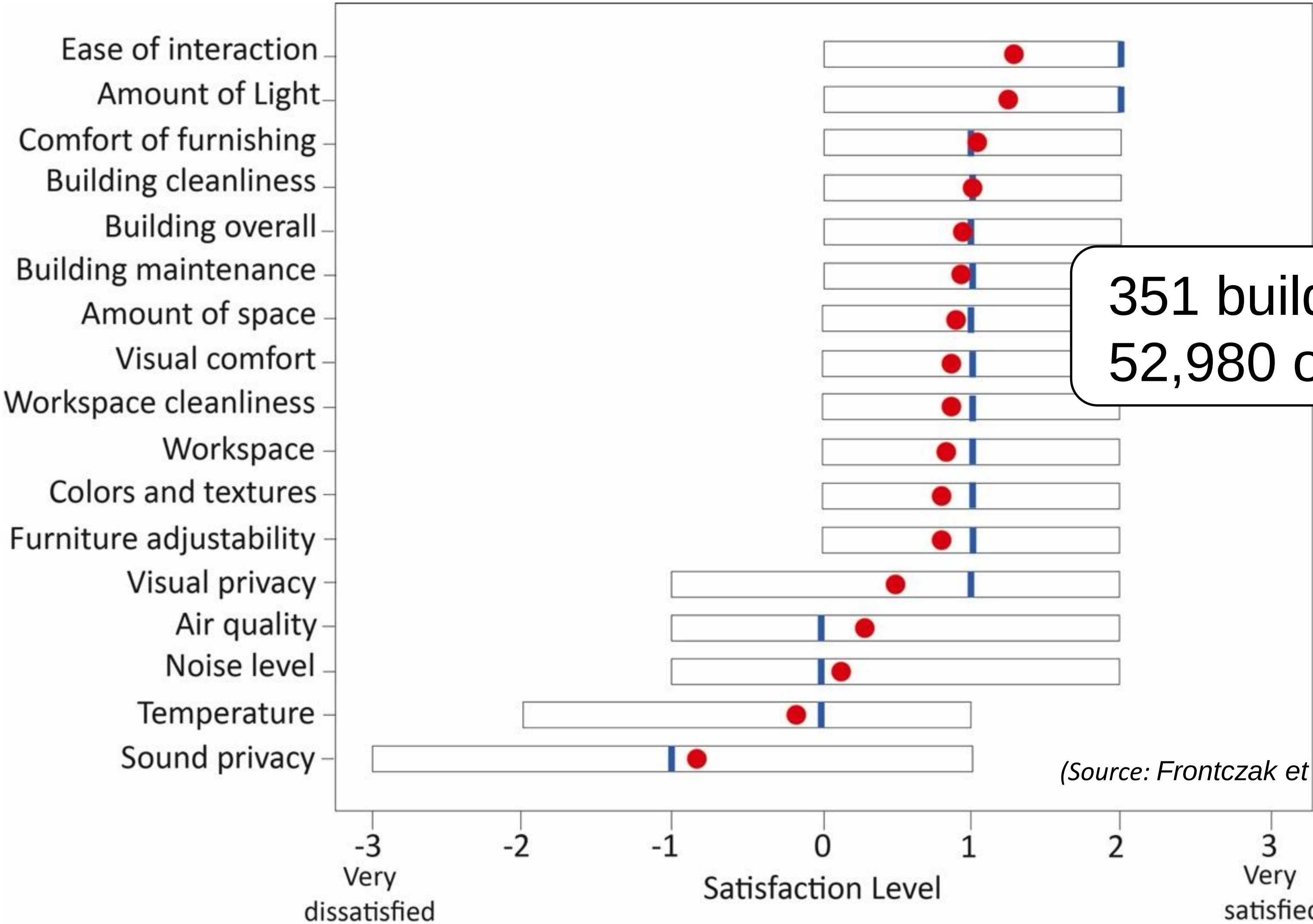


Thermal preferences vary widely even when people are exposed to the same ambient conditions.



Comfort and buildings

Building occupant satisfaction in offices

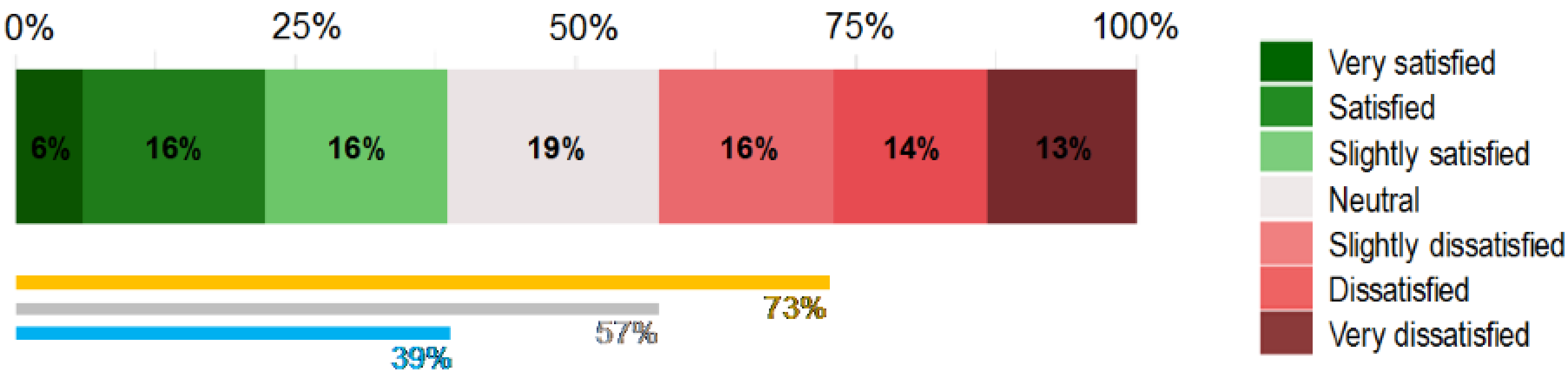


351 buildings
52,980 occupants

(Source: Frontczak et al 2011, Indoor Air)

Air temperature satisfaction in offices

351 buildings
52,980 occupants



(Source: Karman et al 2018, Windsor Conference)

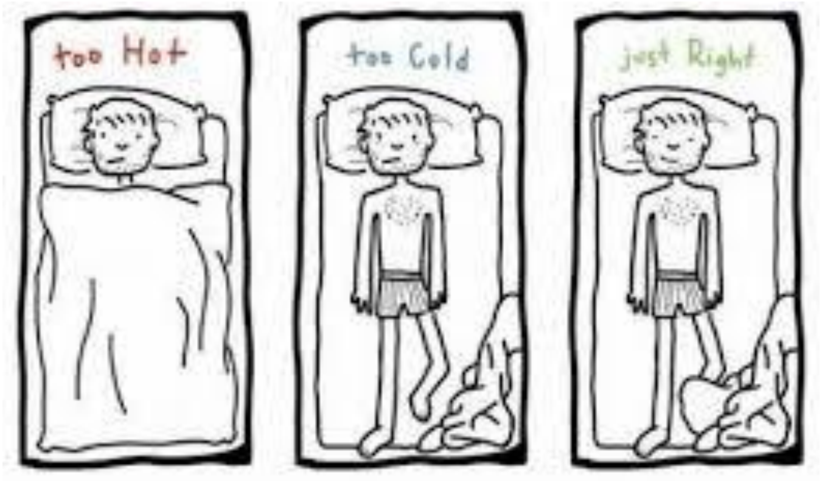
- ~40% of occupants are dissatisfied with air temperature
- Only ~40% of occupants are satisfied
- So we consume so much energy on buildings and still delivering such a poor performance -- what the heck can we do about it?

Human Thermal Comfort

Generally, state of **thermal comfort** is when (*Prof. Fanger*):

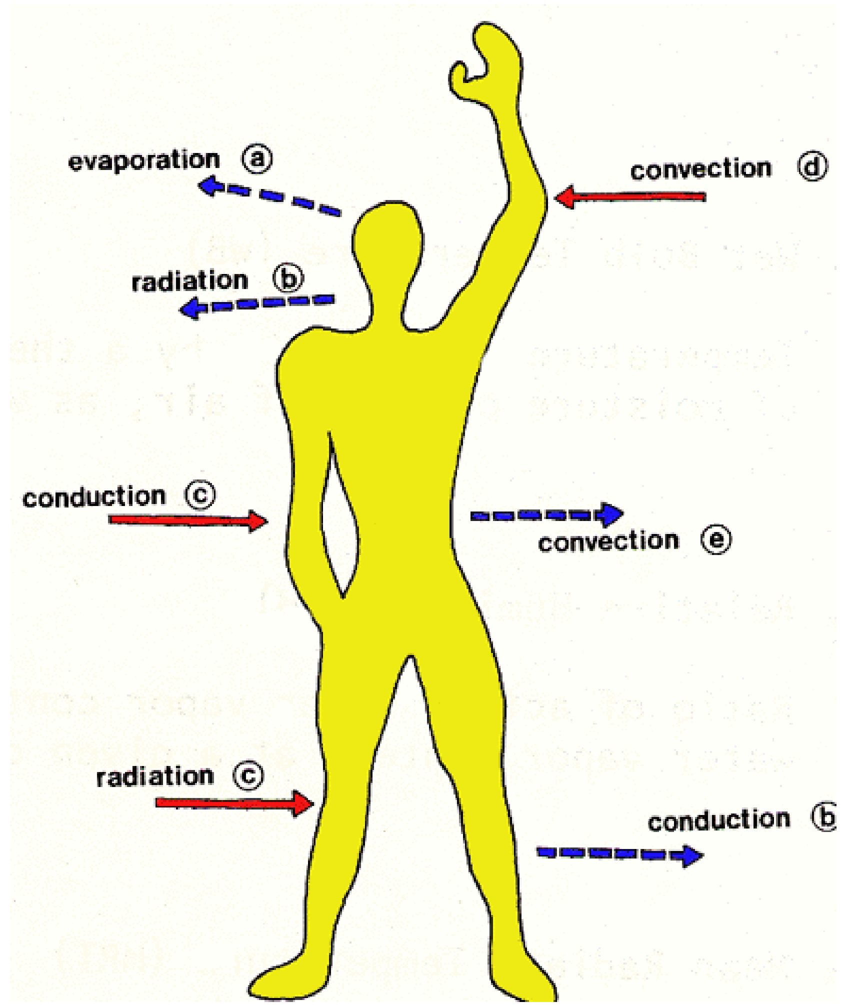
- Body temperatures are held within narrow ranges
- Skin moisture is low
- The physiological effort of regulation is minimized

Metrics for thermal comfort include quantifying the **amount of discomfort** that a space might present to people and what **fraction** of occupants **are dissatisfied** with a space



Human body's heat balance

- **Skin** - Your largest organ which covers ~1.8 m^2 and makes up ~15% of your body weight
- **Metabolism** - Total power produced by the body (1 met = 58 W/m^2_{corps})
- **Thermoregulation** - The response of a person in an attempt to achieve an optimum thermal state

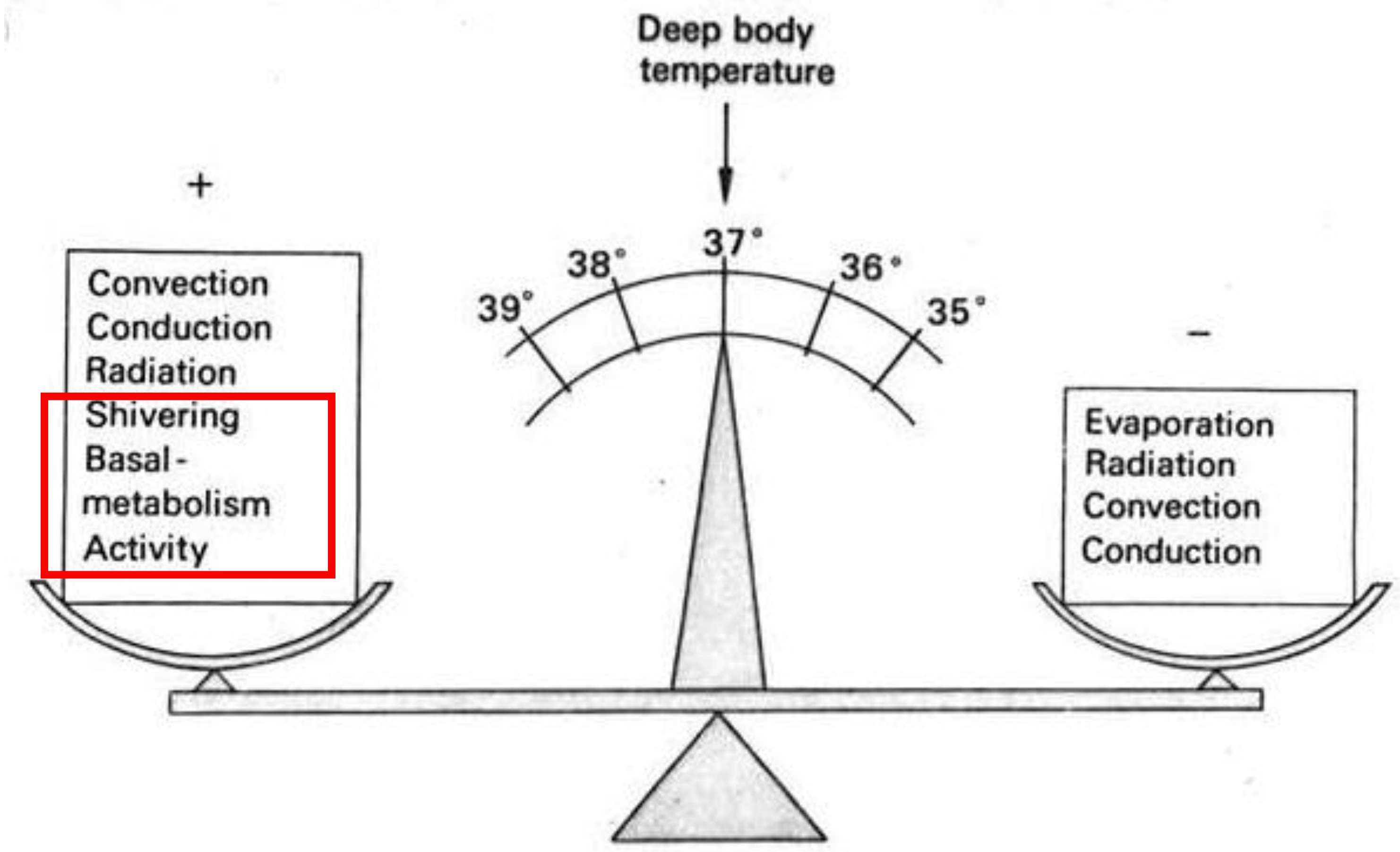


Three external "to" mechanisms; four "from" mechanisms

(Source: https://ssb2012emilyashby.files.wordpress.com/2012/10/metabolism.jpg)

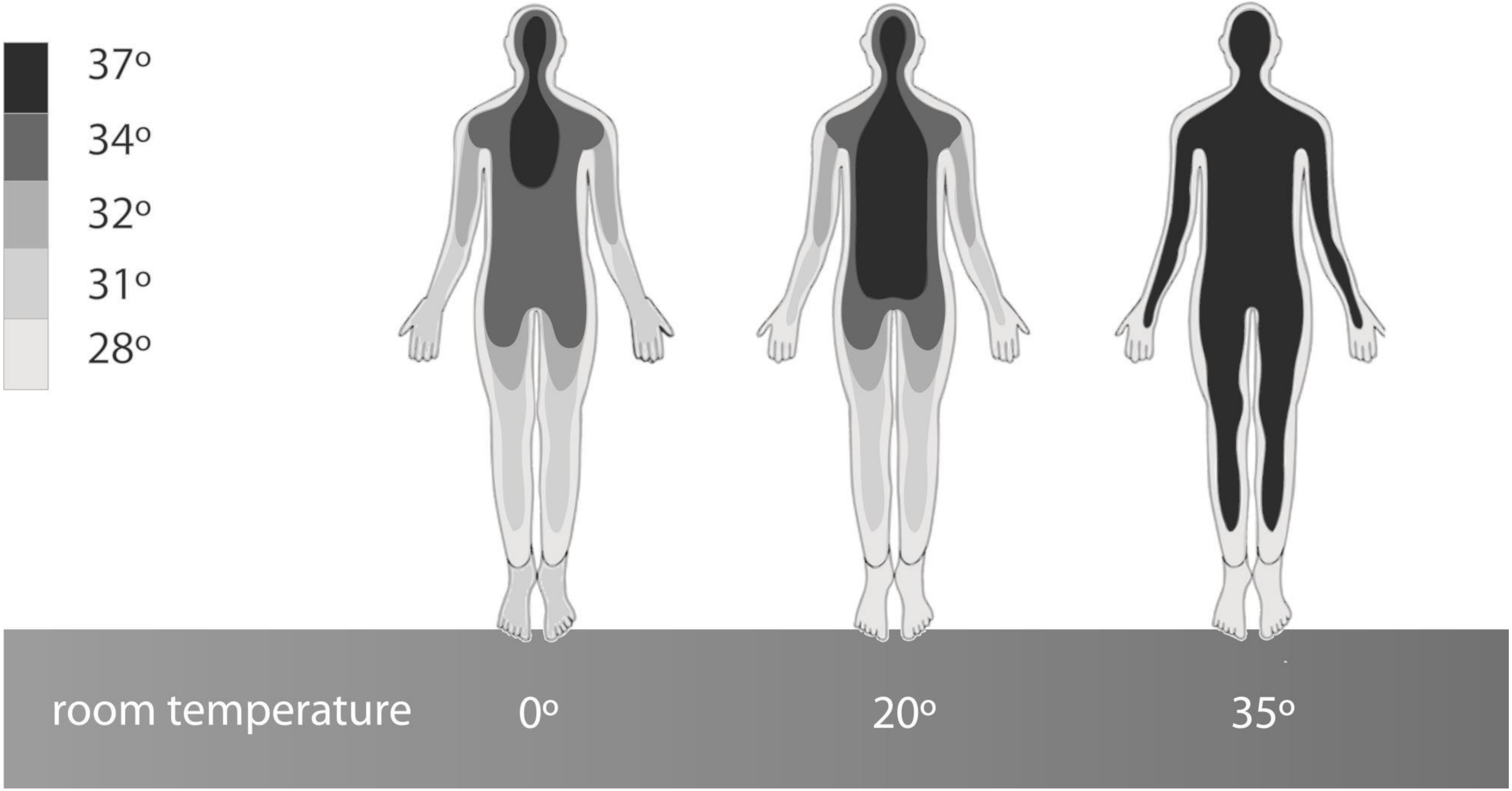
Human body's heat balance

heat in ≈ heat out



Many more (internal & external) "to" mechanisms; four "from" mechanisms.

Human body’s core temperature

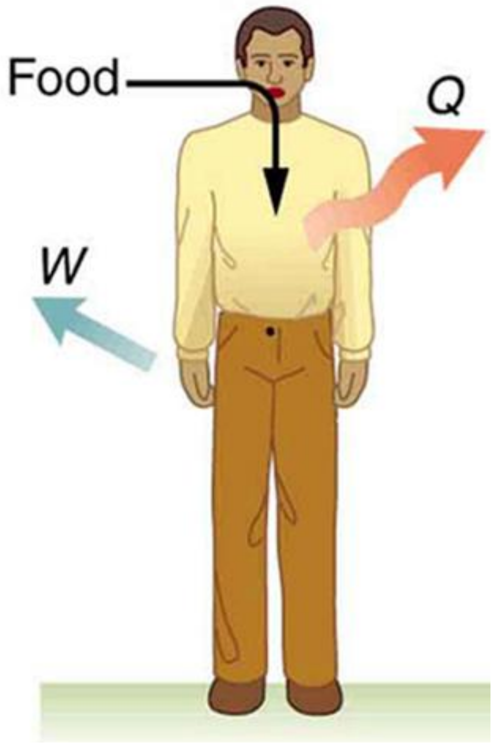


(Source: Emanuele Nabboni)

Indoor climate largely affect our body core temperature and heat output

Human body energy (dis)balance

Fun fact (or not): You are producing a lethal amount of heat ! The heat you produce in your body will kill you unless you get rid of some of it !



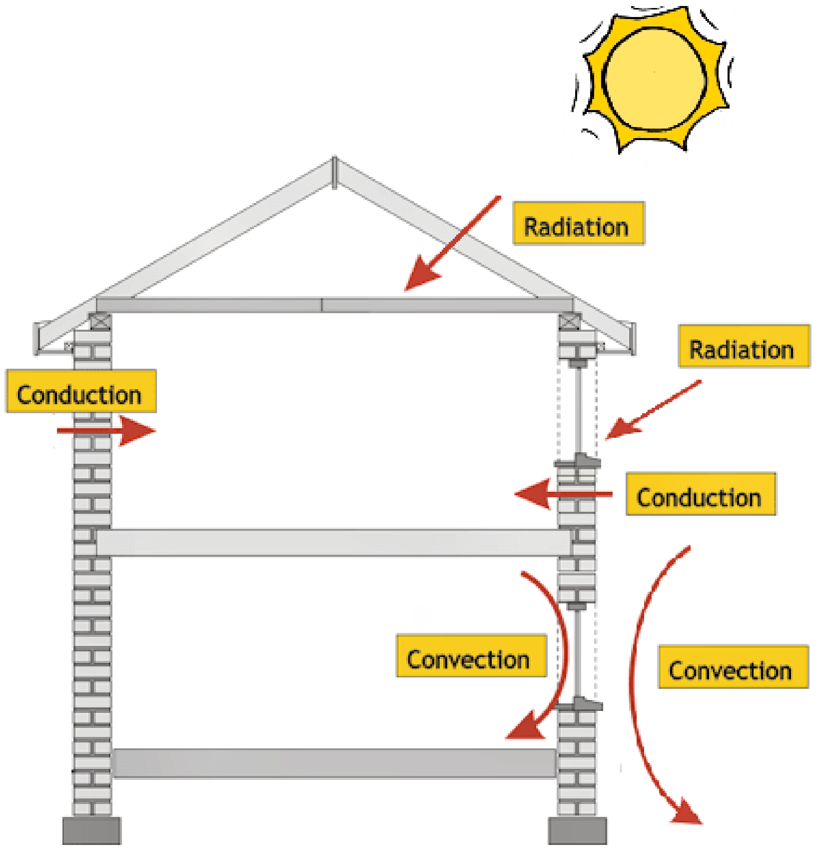
(Source: www.wikipedia.com)

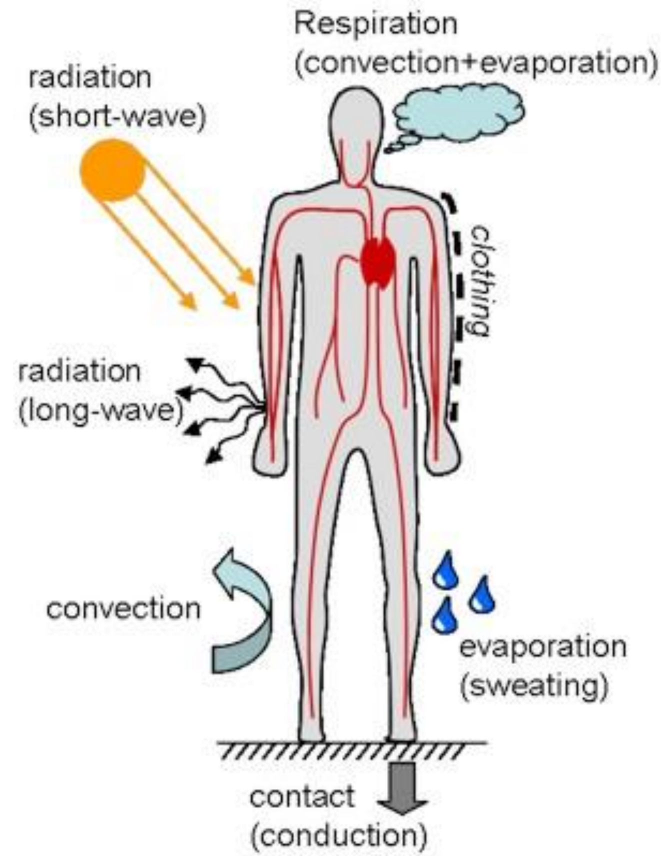
Heatstroke: severe heat illness that results in a body temperature greater than 40.0 °C

Hyperthermia: elevated body temperature when a body produces or absorbs more heat than it dissipates

Hypothermia: reduced body temperature when a body dissipates more heat than it absorbs (core temperature below 35.0 °C)

Heat flow to/from human body

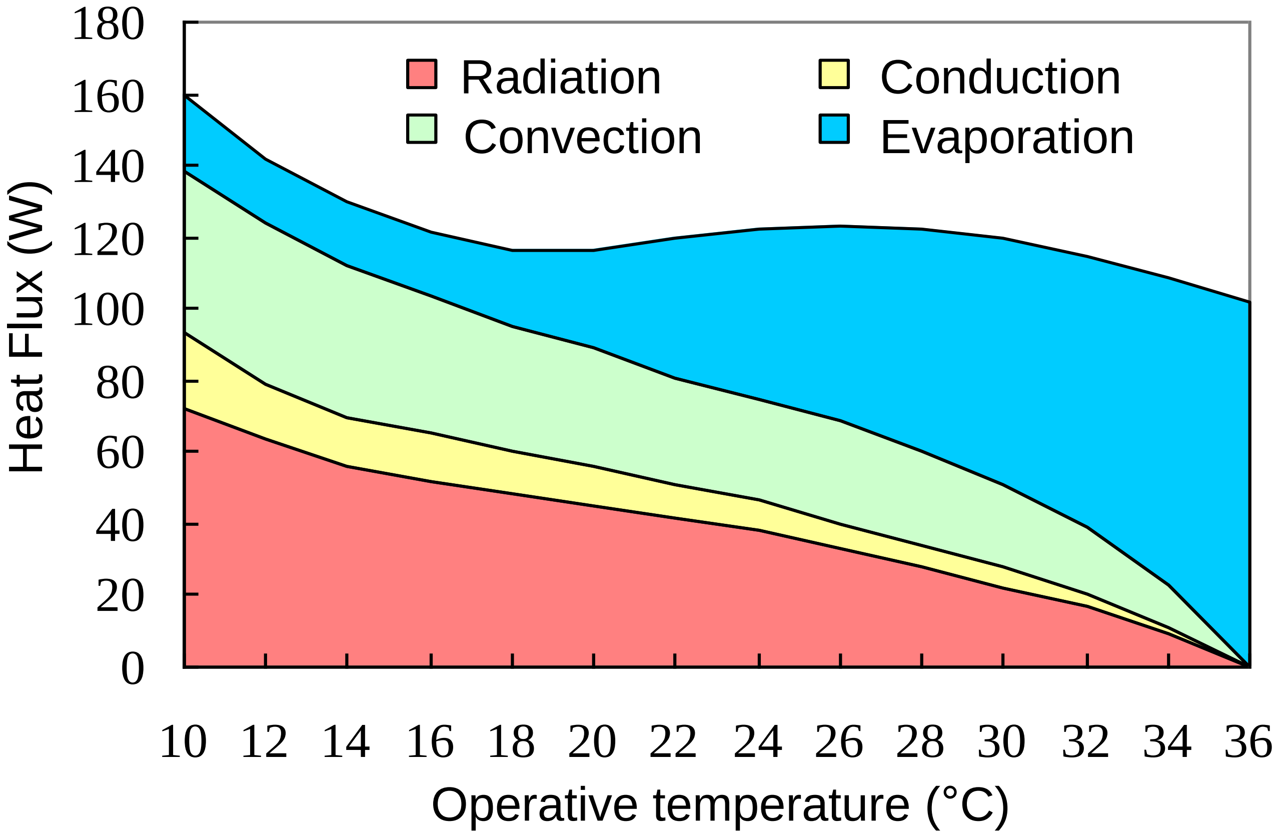




Total Heat Flow = sensible + latent heat

Total Heat Flow = $Q_{conv} + Q_{rad} + Q_{evap} + Q_{resp,sens} + Q_{resp,latent}$

The body's heat loss adaptation

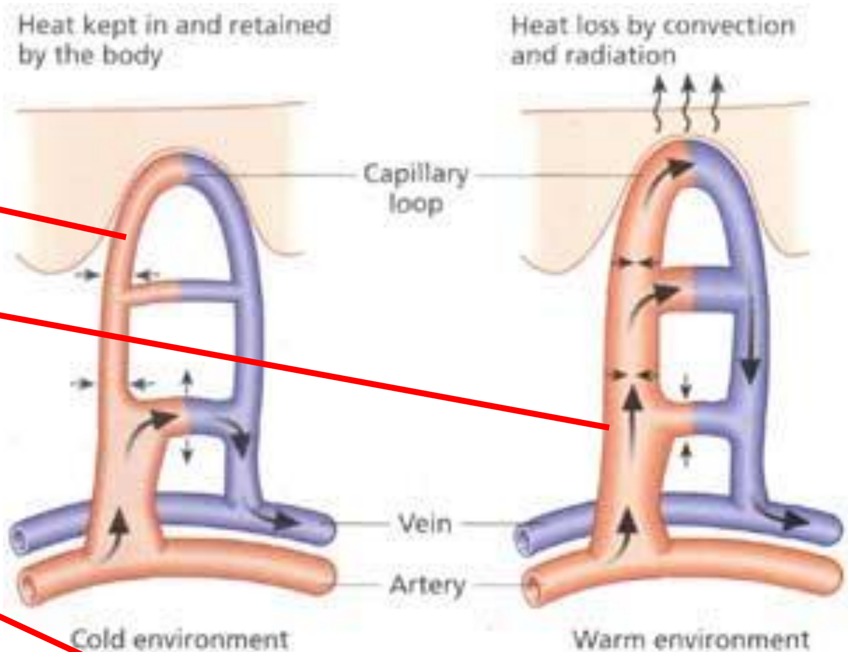


The body automatically adapts to surrounding environmental conditions in its quest for thermal equilibrium; under high temperatures, evaporation becomes critically important.

Physiological Control Mechanisms: Involuntary

Four involuntary adaptations by thermoregulatory system:

1. Blood flow
   - vasoconstriction
   - vasodilation



2. Sweating

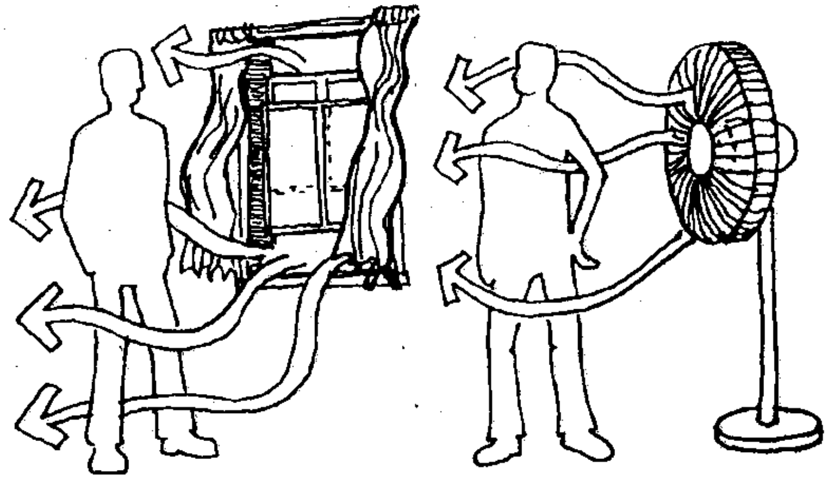
3. Shivering (can be substantial!)

4. Goosebumps

Behavioral Control Mechanisms: Voluntary

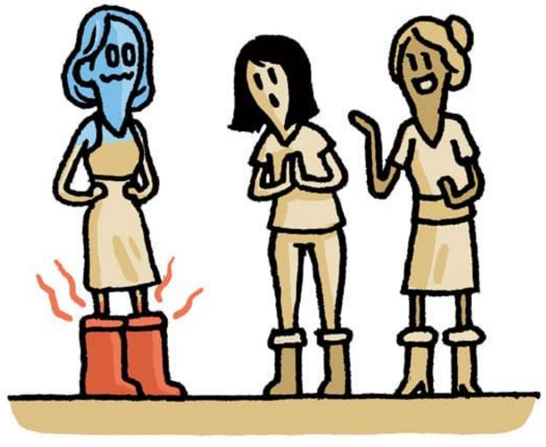
Environmental opportunities

- Turning off/on a fan
- Turning off/on a heater
- Opening/closing:
  - Windows
  - Blinds & shades

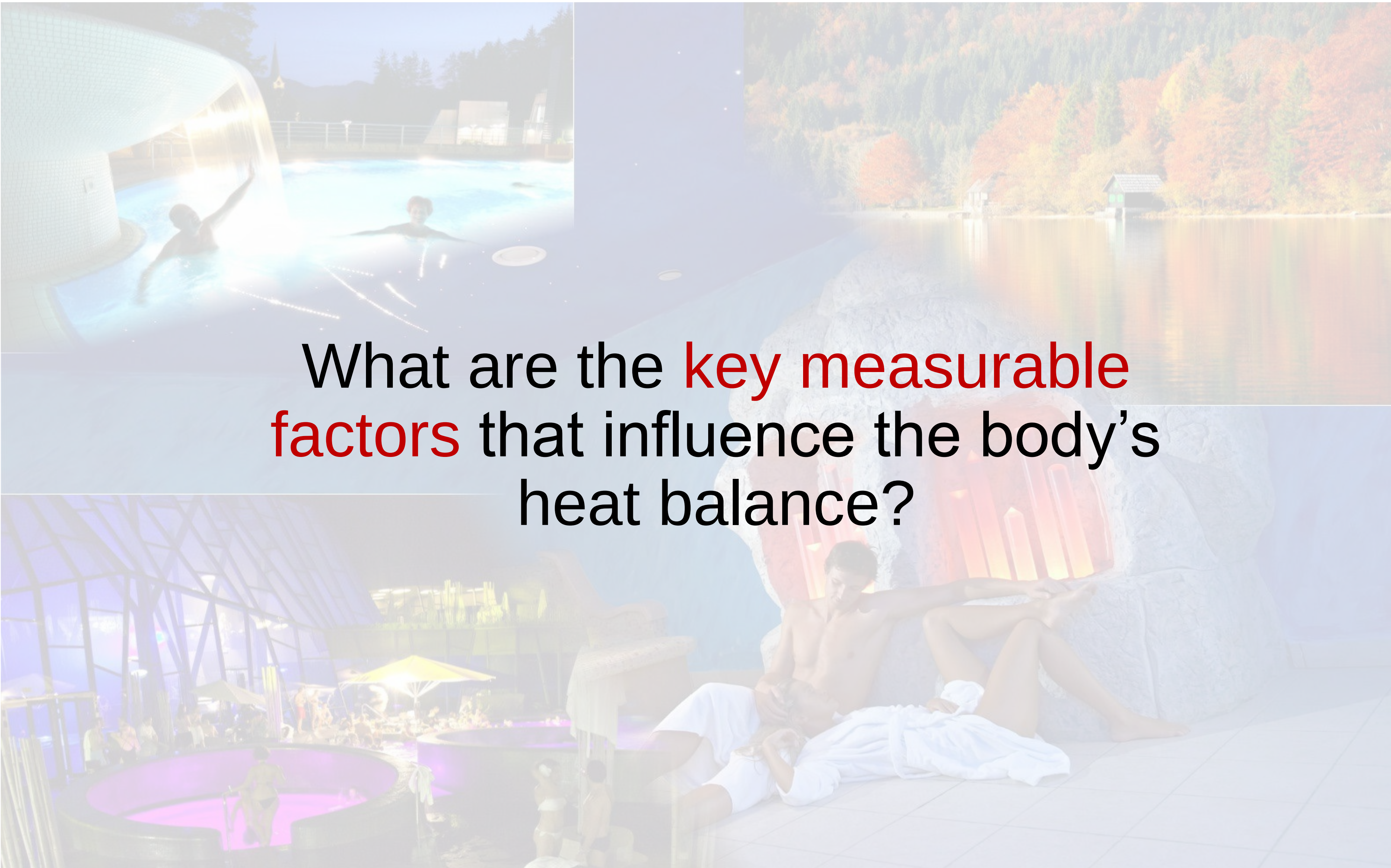


Personal opportunities

- Changing clothing
- Changing activity
- Changing posture, position or location
- Eating/drinking something cold or hot

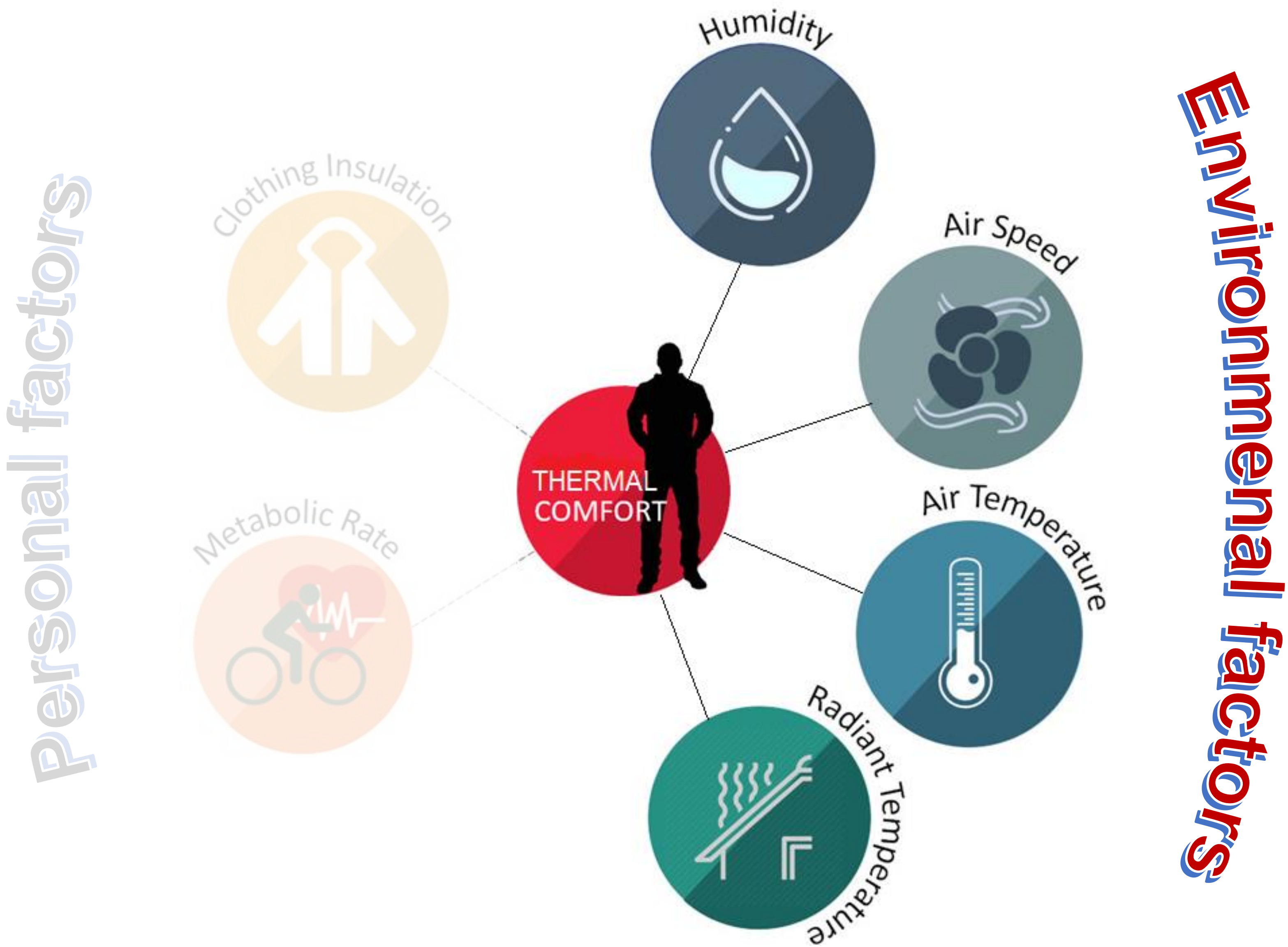


Factors influencing thermal comfort



What are the key measurable factors that influence the body's heat balance?

Major variables influencing thermal comfort

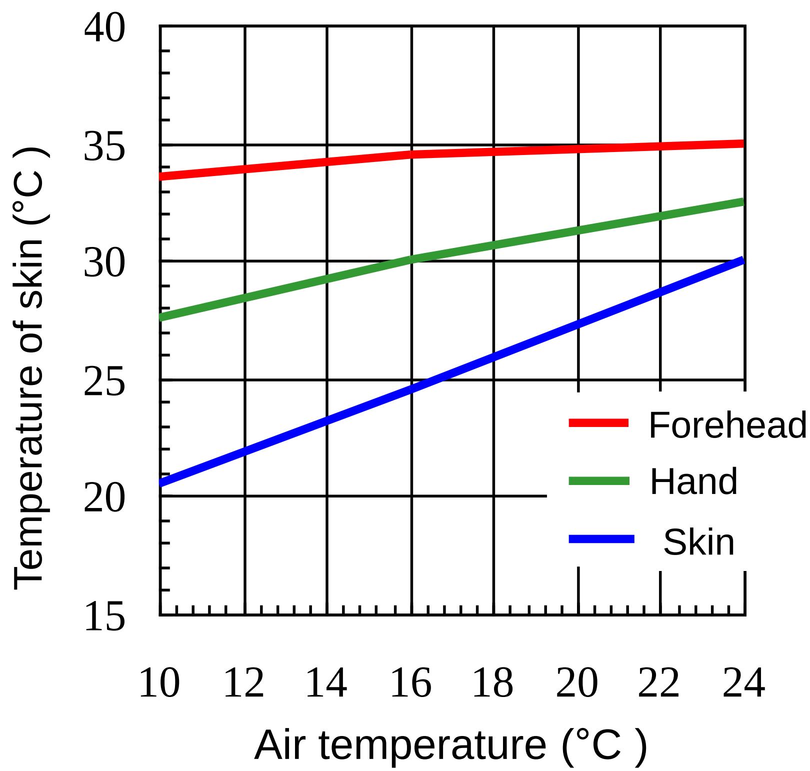


Dry-bulb air temperature (T_{air})

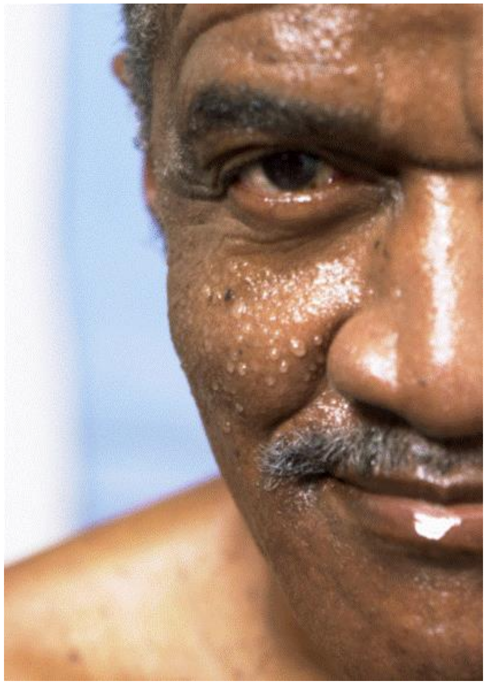
Dry-bulb temperature is the temperature of air measured by a thermometer freely exposed to the air but shielded from radiation and moisture

The body includes two zones:

- Internal zone at 37°C
- Envelope with variable T

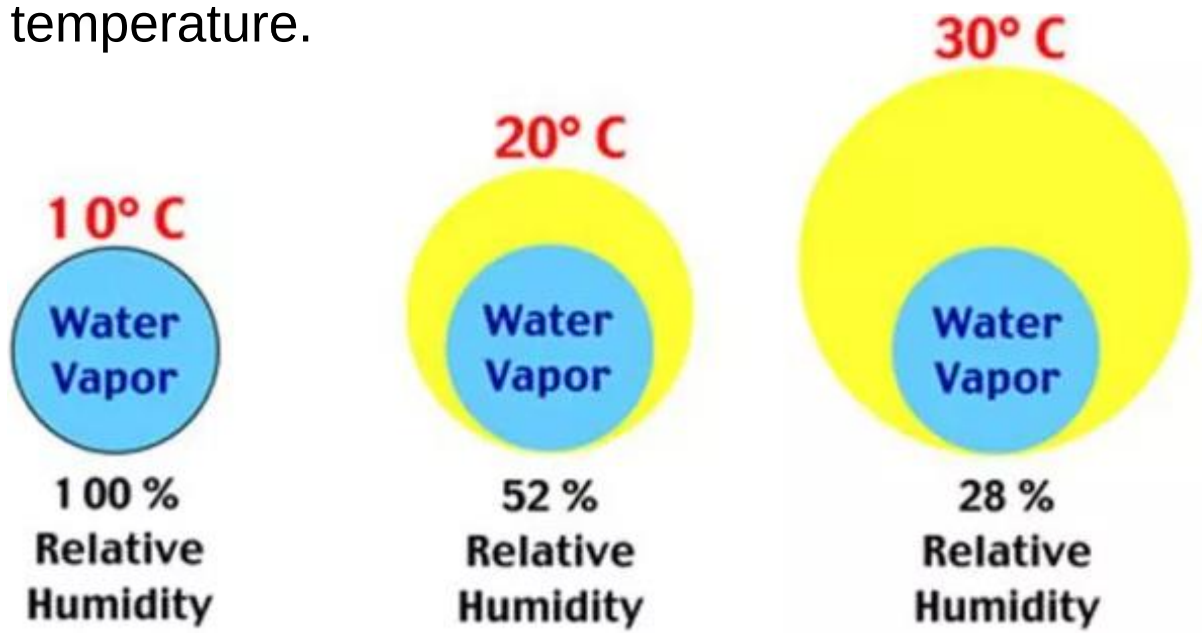


Relative Humidity (RH)



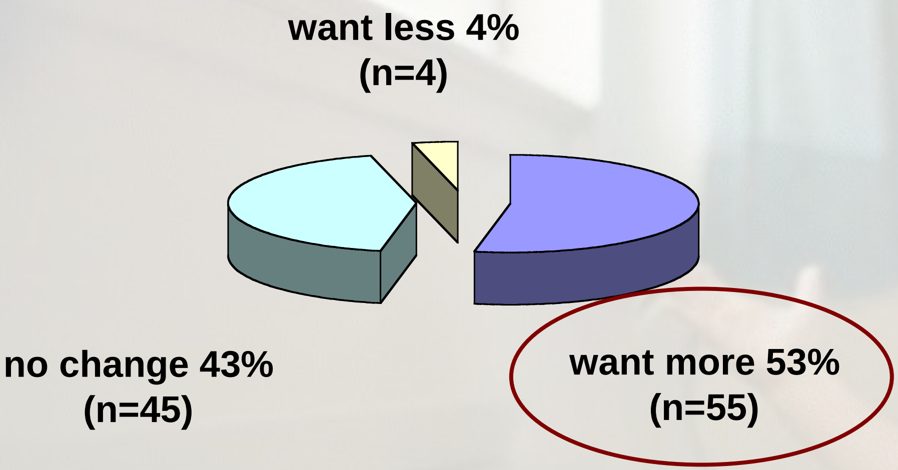
RH - amount of water in the air relative to the saturation amount the air can hold at a given temperature multiplied by 100:

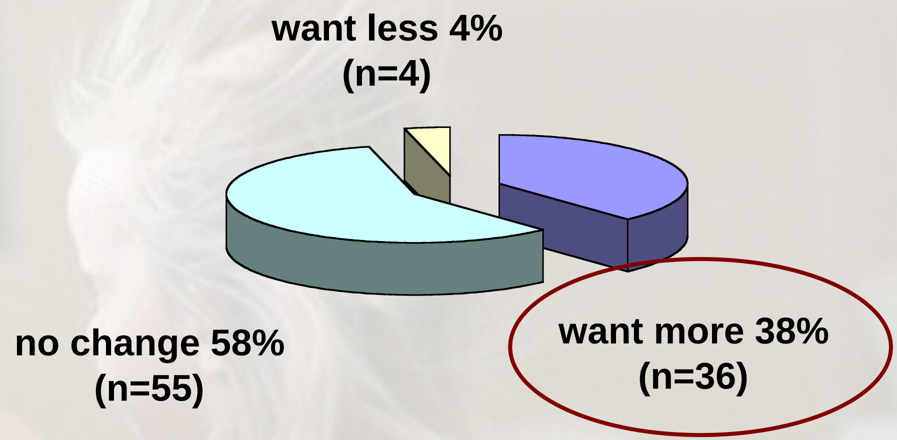
- Dimensionless, usually expressed at percentage.
- Air with relative humidity of 50% contains a half of the water vapour it could hold at a particular temperature.



Air Velocity (v): the most underutilized factor

Air velocity: The rate at which air moves around and touches skin





Summer, n=104

Winter, n=95

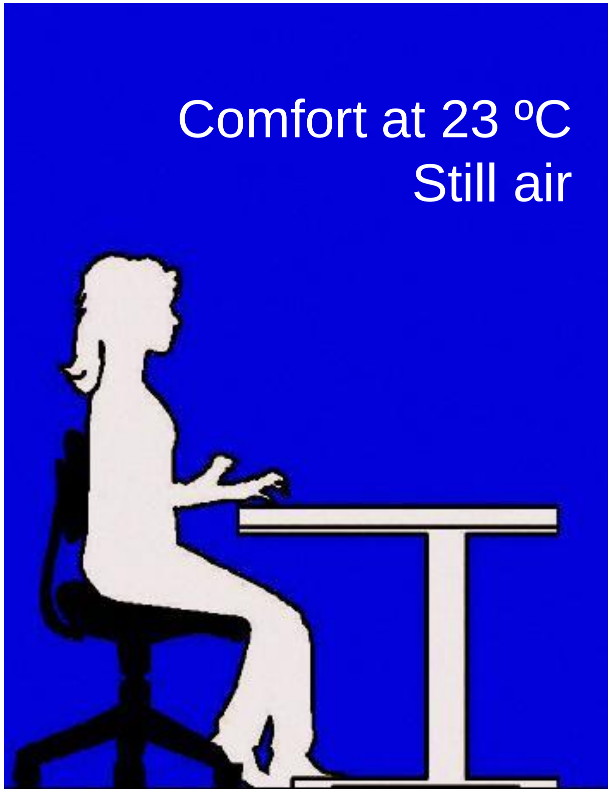
People want more air movement,
not less, even in winter

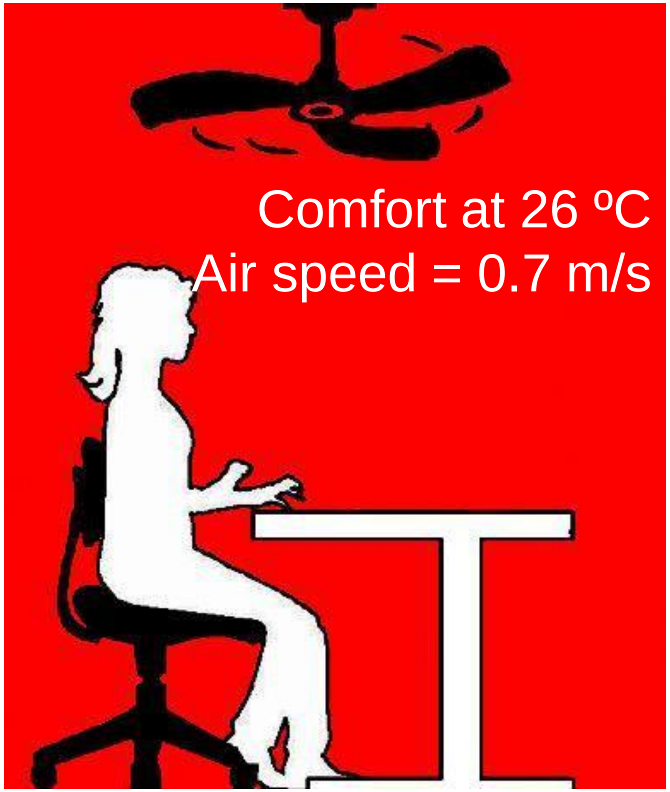
(Source: Zhang et al. (2007) International Journal of Biometeorology, 51(5), 349–360)

Physiological basis for air movement effects

Increased convective heat transfer/ increased airflow:

- Well-established relationship between comfort at elevated temperatures and air velocity
- What are the energy implications?

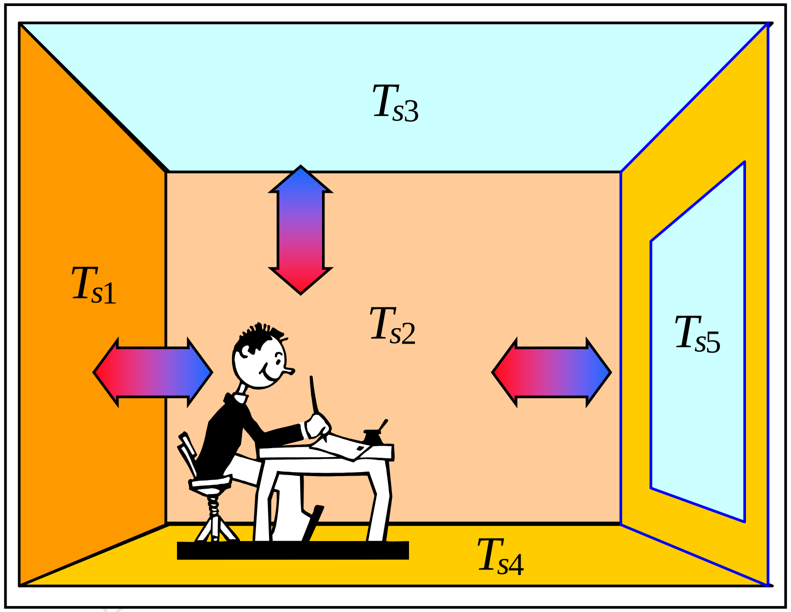




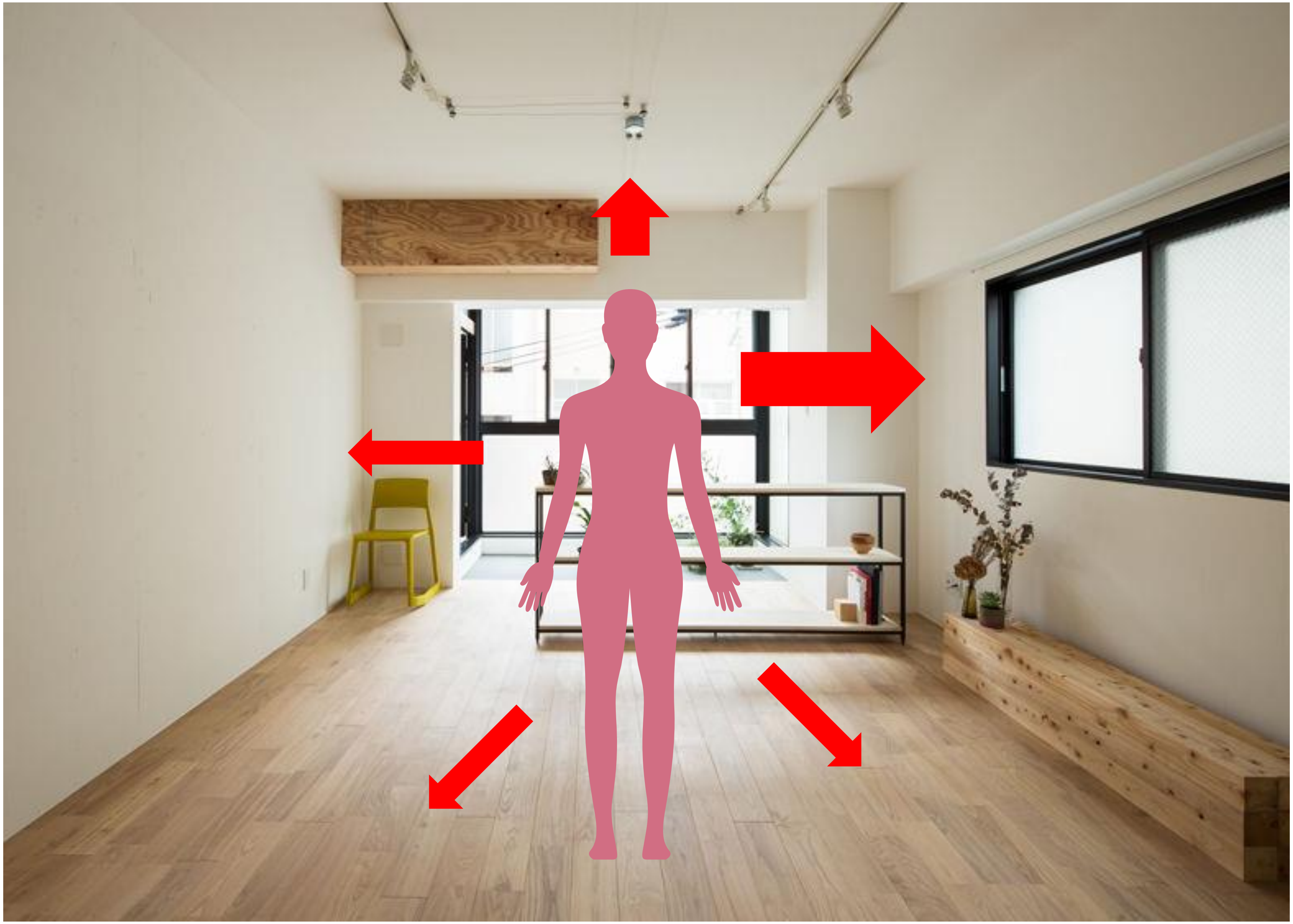
(Source: Schiavon and Melikov, 2008, Energy and Buildings)

Mean Radiant Temperature (MRT)

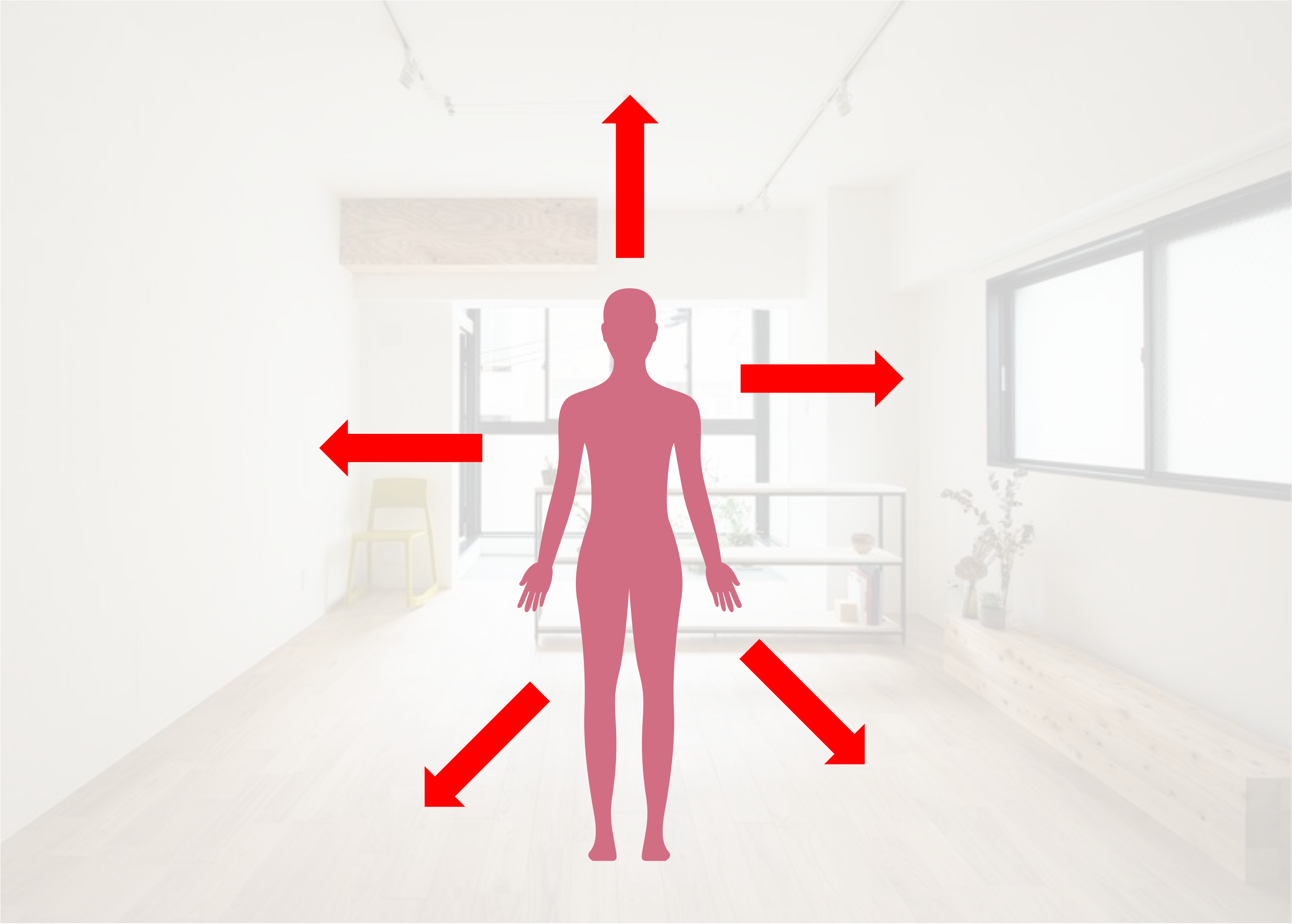
- The MRT is the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space
- In a non uniform thermal environment the MRT change in each point of the room



Surface temperatures in reality



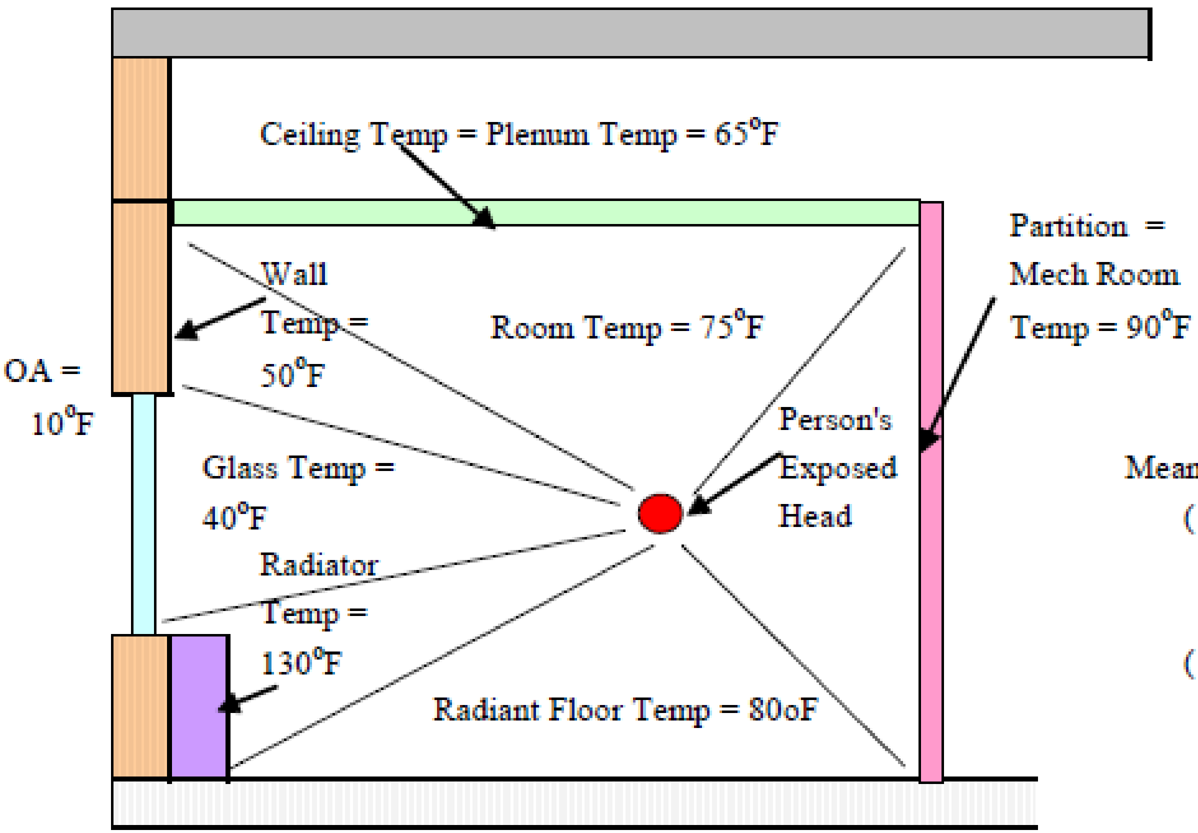
Mean Radiant Temperature (MRT)



How to estimate MRT?

Radiation to/from occupants is an important form of energy exchange – We can estimate its effects using the MRT.

- In practice, we don't calculate MRT – we use a black globe thermometer

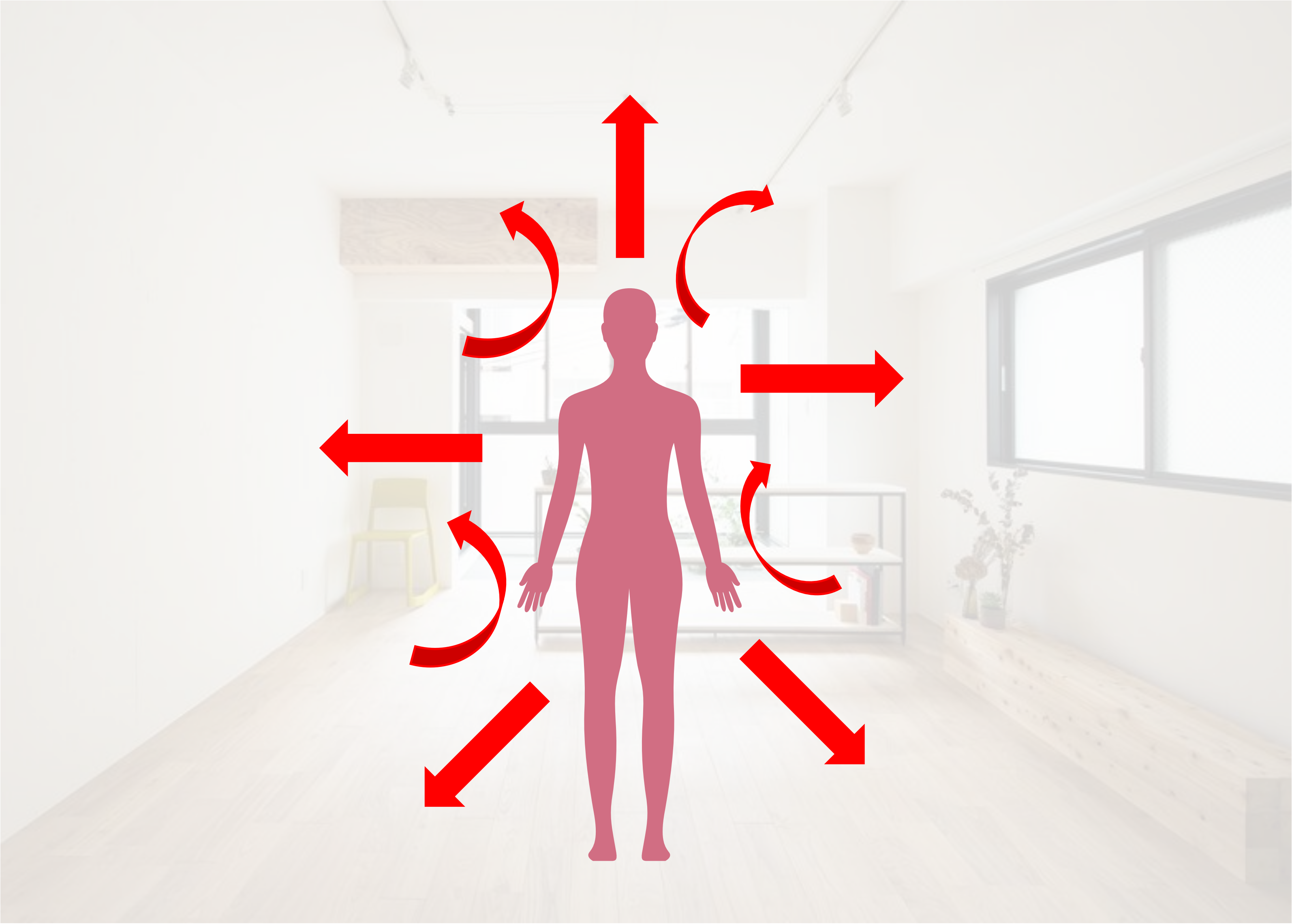


SURFACE		Temp	Angle
Name	No.	°F	degs
Ceiling	1	65	105
Partition	2	90	100
Floor	3	80	110
Radiator	4	130	20
Window	5	40	30
Wall	6	50	20

Mean Radiant Temp (MRT) =
(A1*T1 + A2*T2 + A3*T3 +
A4*T4 + A5*T5 + A5*T5 +
A6*T6) / 360 =
(105*65 + 100*90 + 110*80 +
20*130 + 30*40 + 20*50) / 360 =
29,425 / 360 = 81.74oF

(Source: http://energy-models.com/sites/all/files/resize/advanced-pages-30991/comfort-2-735x326.png)

What combines both air temperature and MRT?



Operative Temperature (T_o)

The uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment.

Most accurate:

$$t_o = \frac{(h_r t_{mr} + h_c t_a)}{h_r + h_c}$$

Less accurate:

$$t_o = \frac{(t_{mr} + (t_a \times \sqrt{10v}))}{1 + \sqrt{10v}}$$

Least accurate:

$$t_o = \frac{(t_a + t_{mr})}{2}$$

h_c = convective heat transfer coefficient

h_r = linear radiative heat transfer coefficient

t_a = air temperature

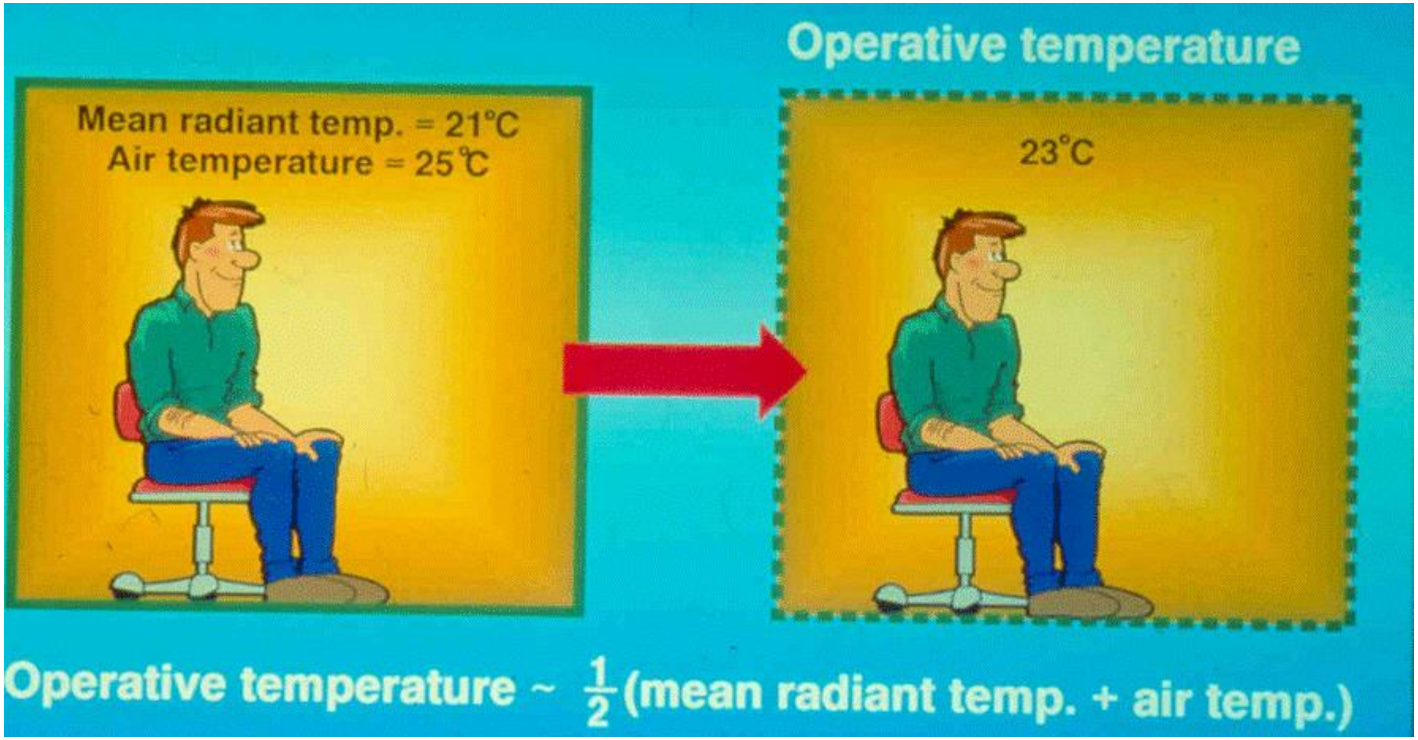
t_{mr} = mean radiant temperature

These are all reasonable to use depending on your application

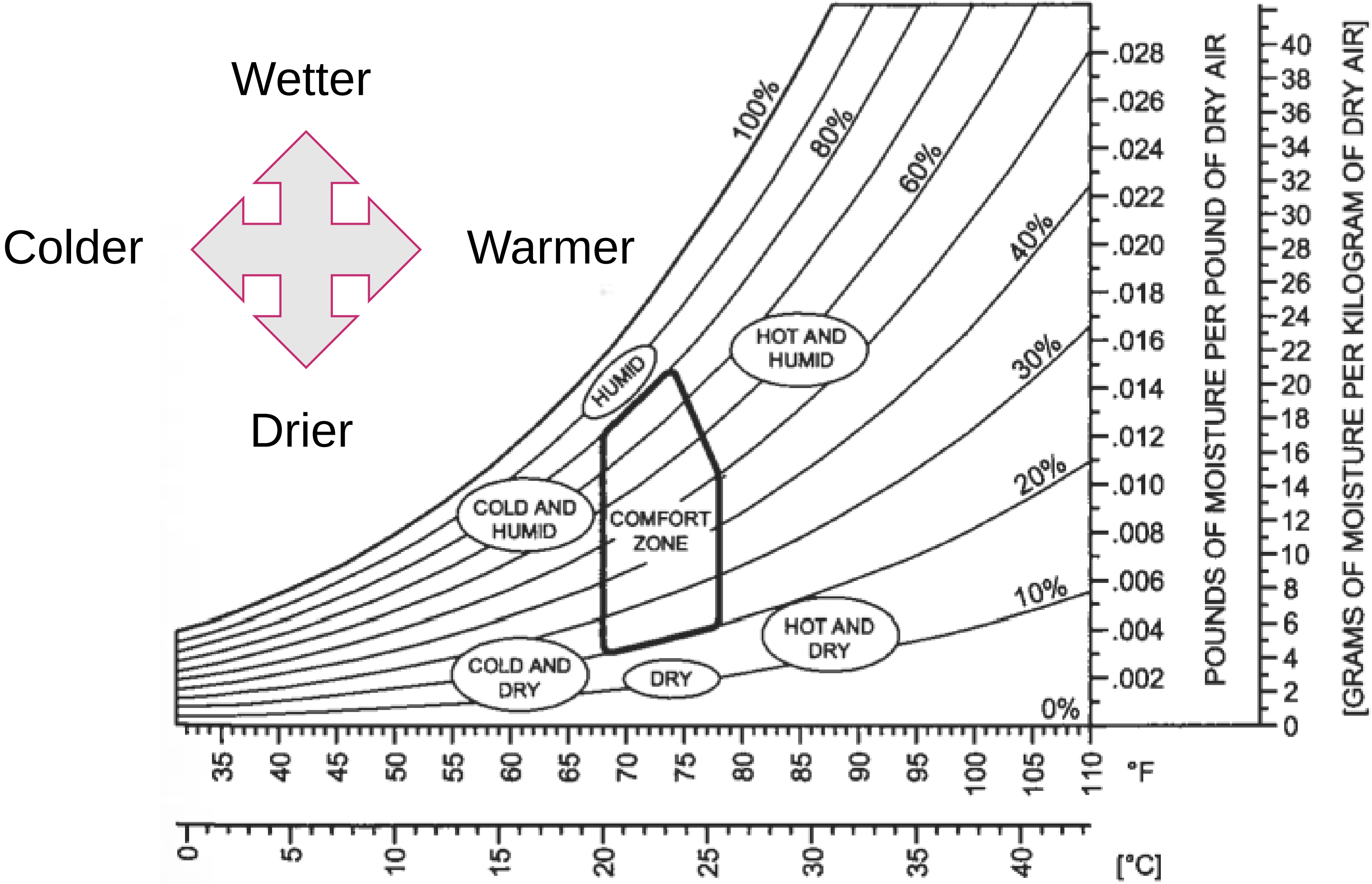
Operative Temperature (T_o)

The operative temperature is essentially the average value between the air temperature and the mean radiant temperature, adjusted for air velocity effects.

Commonly used method for T_o ($v < 0.2$ m/s):

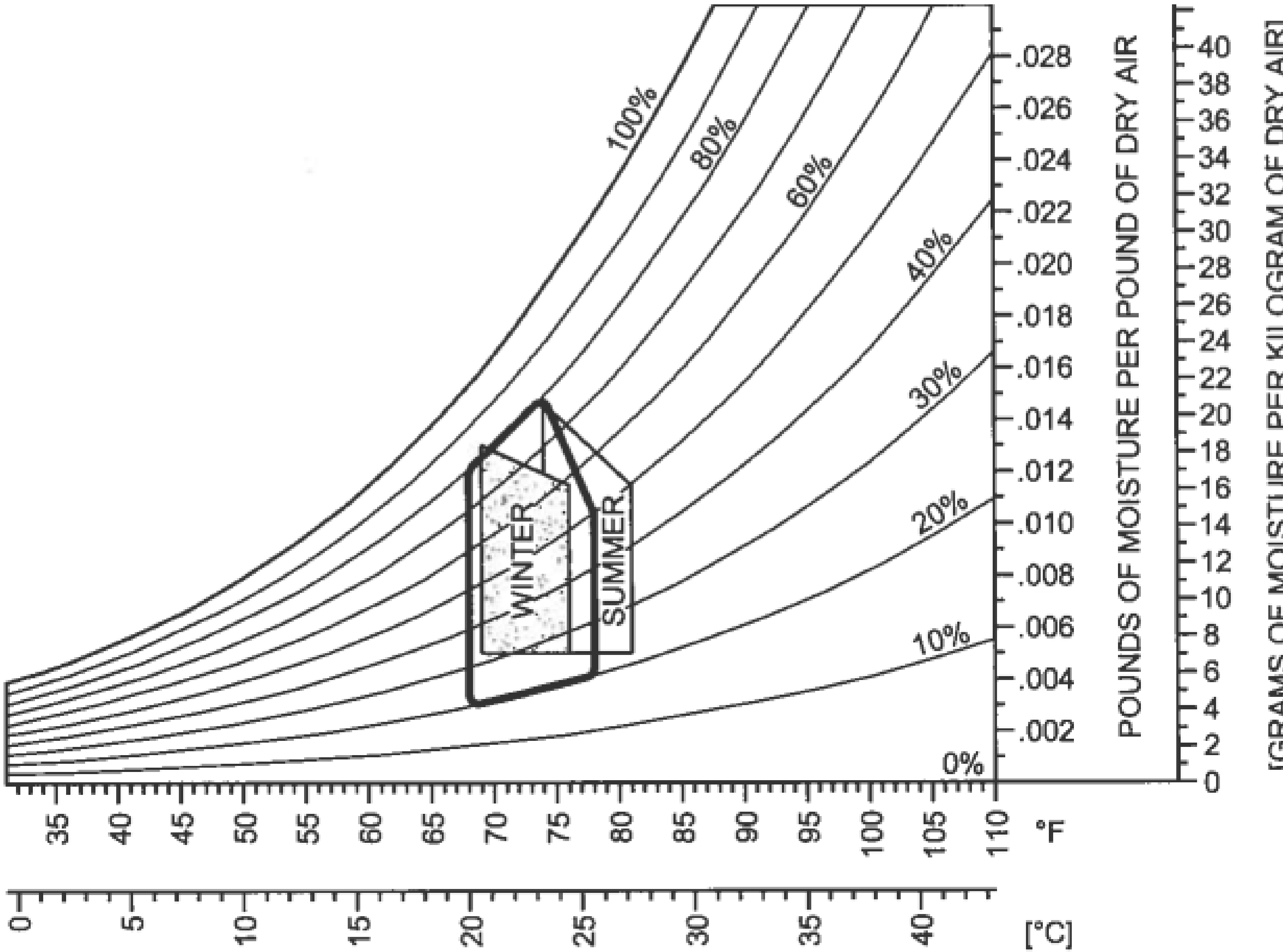


Thermodynamics of human thermal comfort



(Source Norbert Lechner, Heating, Cooking, Lighting: Sustainable Design Methods for Architects, Wiley, 2008)

Seasonal variation of the thermal comfort zone



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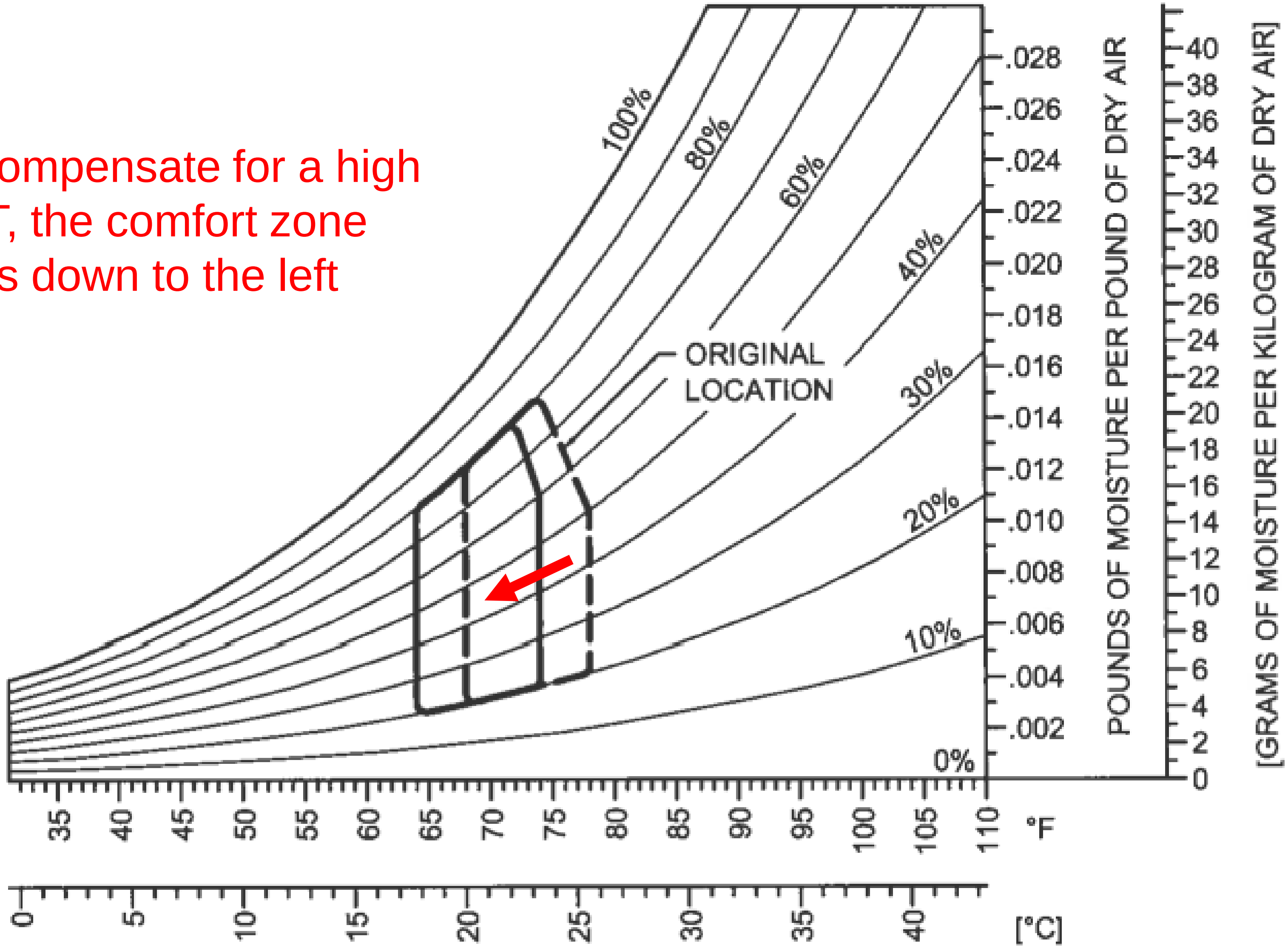
Shifting the thermal comfort zone: MRT

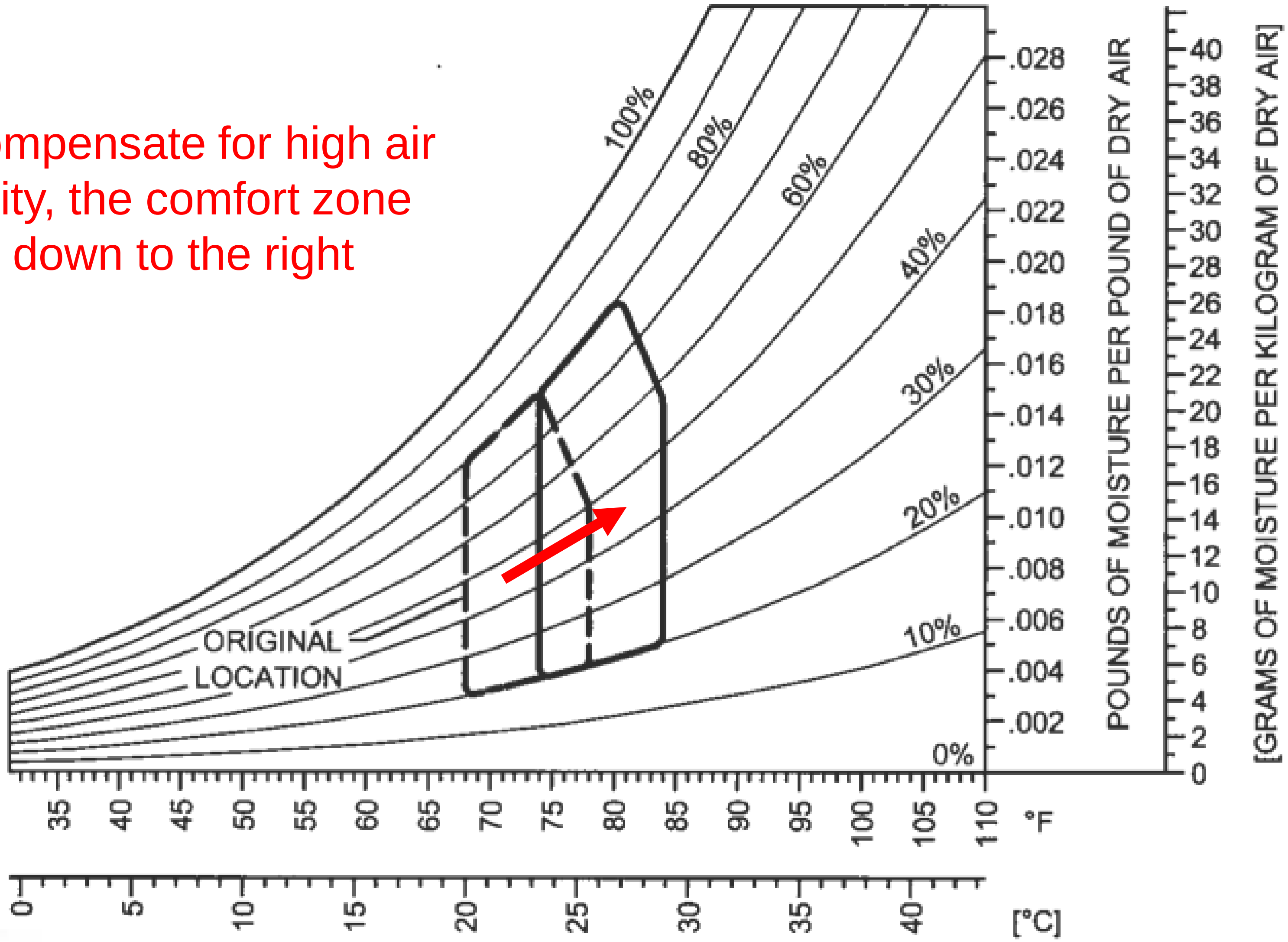
To compensate for a high MRT, the comfort zone shifts down to the left



(Source Norbert Lechner, Heating, Cooking, Lighting: Sustainable Design Methods for Architects, Wiley, 2008)

Shifting the thermal comfort zone: Velocity

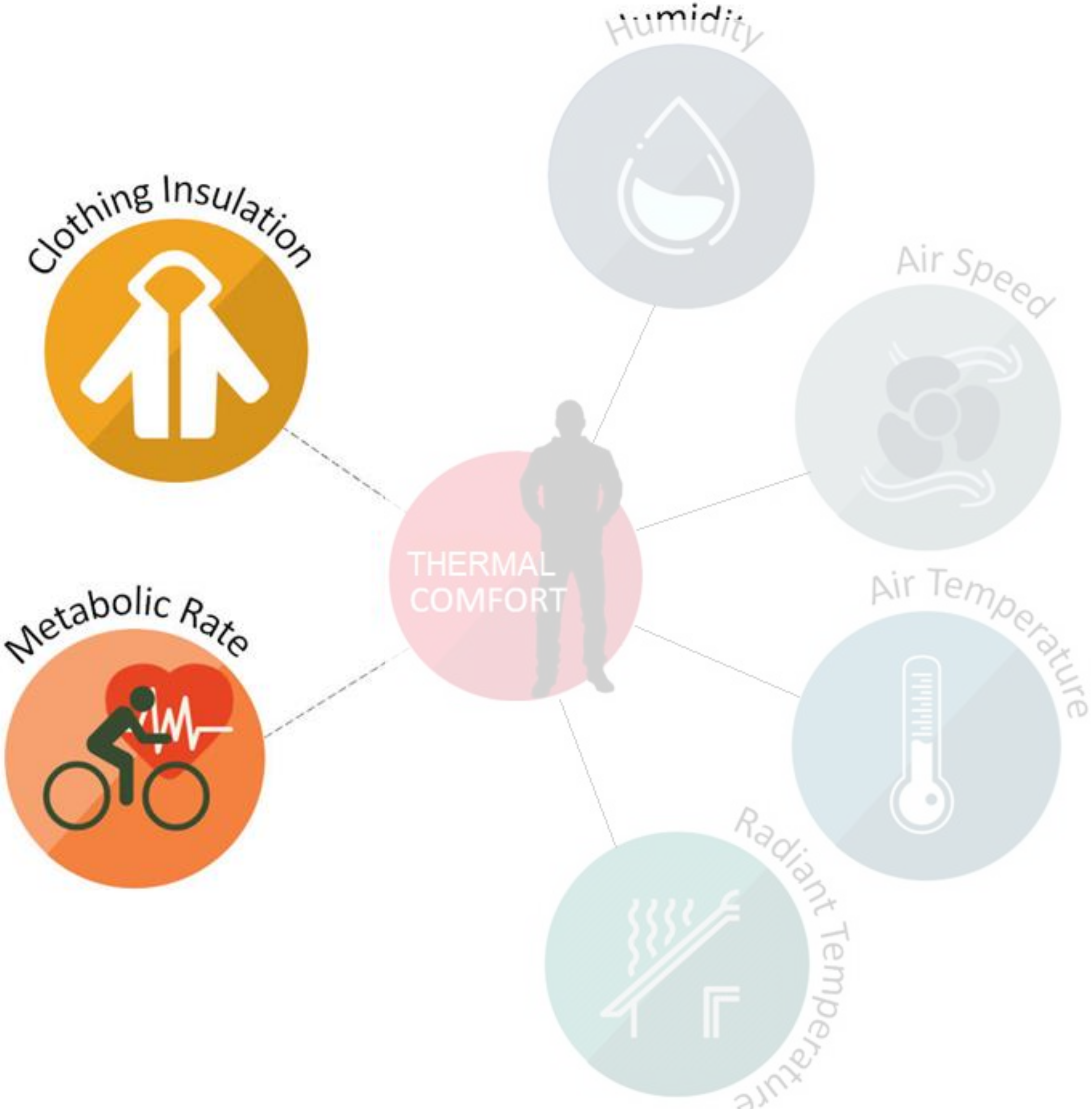
To compensate for high air velocity, the comfort zone shifts down to the right



(Source Norbert Lechner, Heating, Cooling, Lighting: Sustainable Design Methods for Architects, Wiley, 2008)

Major variables influencing thermal comfort

Personal factors



Envirommenal factors

Metabolic Rate (Met)

- Activity = Metabolic Heat Production
- 1 MET = 58.15 W/m^2, sedentary activity
  - *approx. equivalent to a 100 W light bulb*

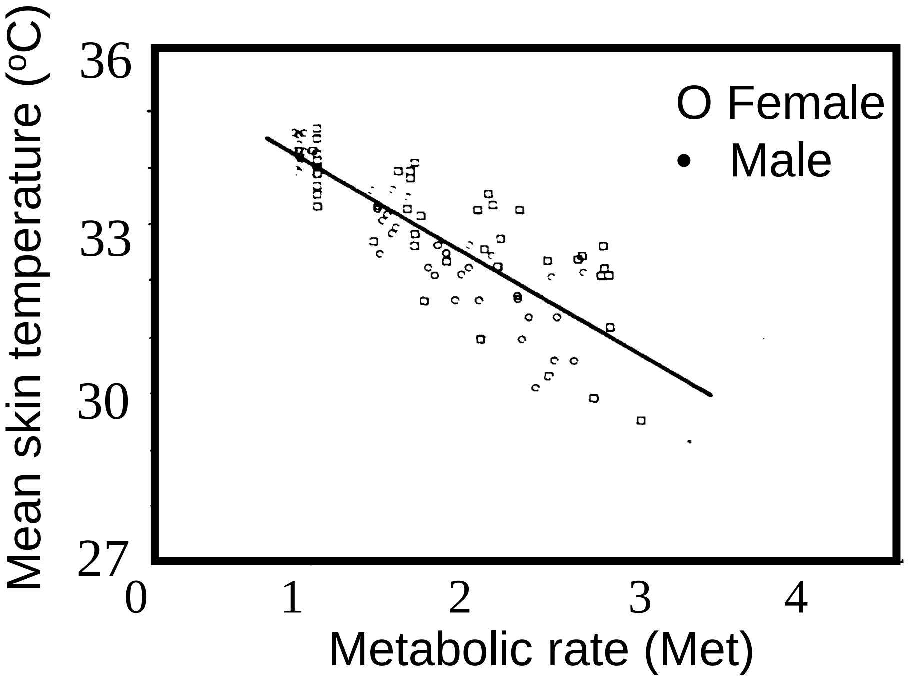
1 met 1.4 met 3.0 met 4.0 met

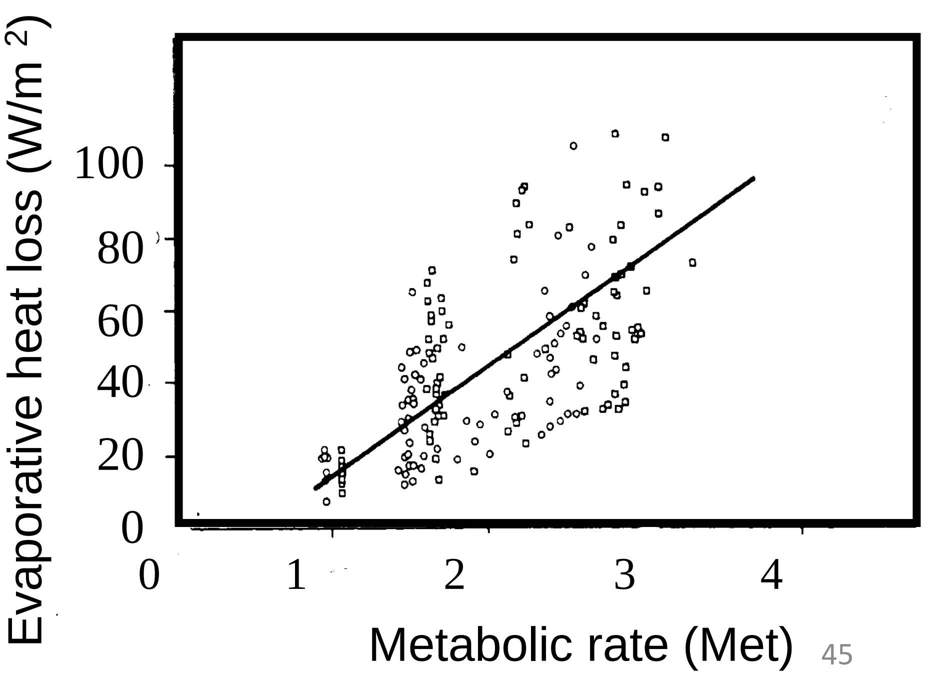
http://cbe.berkeley.edu/comforttool/

MET, Skin temperature, Evaporative heat loss

Questions for the class:

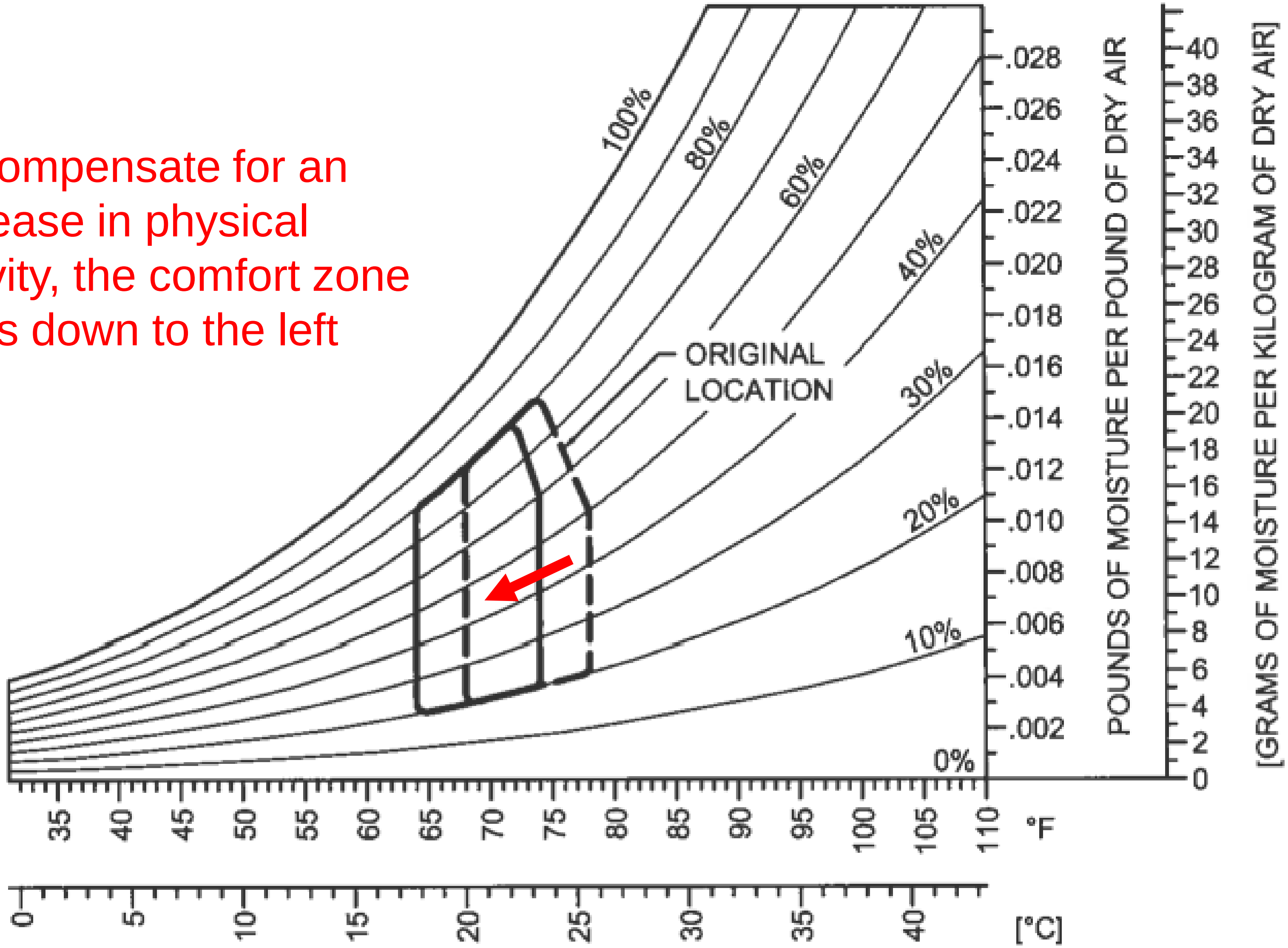
1. What is the correlation between MET and the skin temperature?
2. What is the correlation between MET and evaporative heat loss?





Shifting the thermal comfort zone: MET

To compensate for an increase in physical activity, the comfort zone shifts down to the left



(Source Norbert Lechner, Heating, Cooking, Lighting: Sustainable Design Methods for Architects, Wiley, 2008)

Clothing level (Clo)

Clothing = Insulation Value (like an "R-value")

1 Clo = 0.155 m^{2}K/W

0.2 clo　　0.8 clo　　1.0 clo　　3.0 clo

(Source: Table of clothing & clo values – See http://cbe.berkeley.edu/comforttool/)

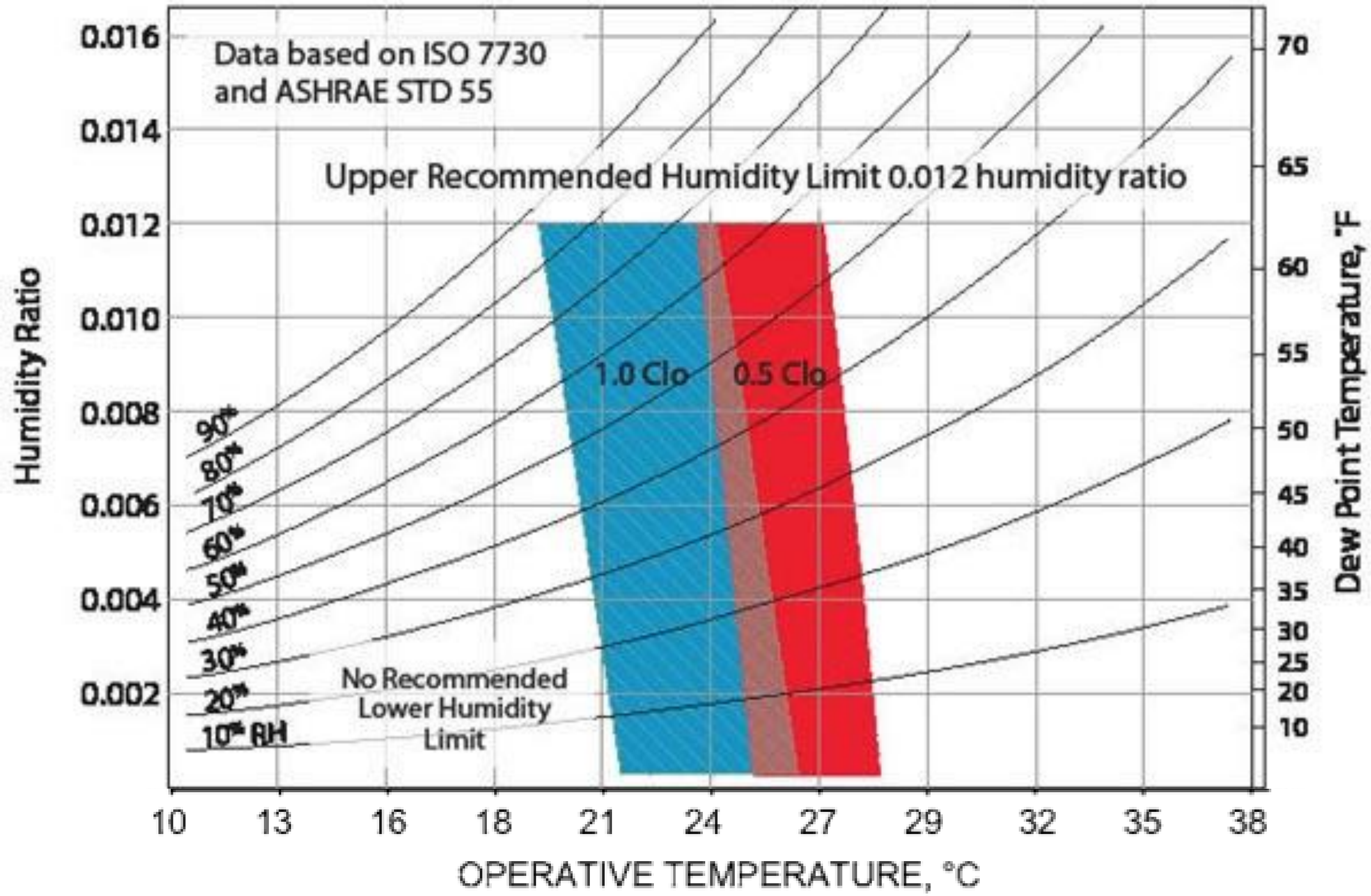
Clothing level (Clo)

0.9 – 1.3 Clo

0.7 – 0.8 Clo

0.1 – 0.4 Clo

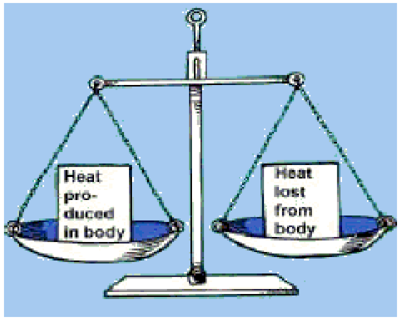
Clo value and comfort zones



Thermal comfort: Criterias

- Body's thermal neutrality (based on T, RH, v, MRT, MET and Clo) is a necessary, but not sufficient condition for thermal comfort
- Local thermal discomfort due to radiant asymmetry, vertical temperature gradient, warm or cold floors, or draught may cause unacceptable thermal conditions

- **To evaluate thermal comfort, it is necessary to combine both:**



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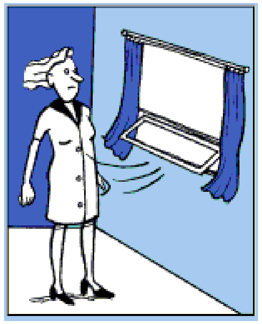
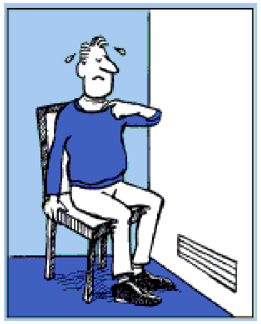


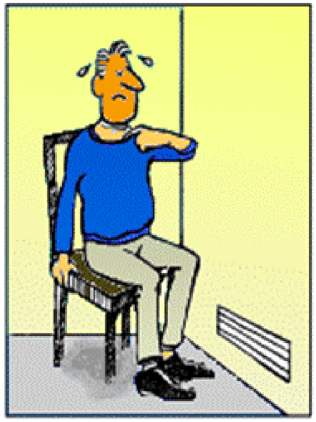


Criteria for local thermal discomfort (LTD)

- The thermal comfort 2nd condition: Absence of LTD
- Estimated number of dissatisfied occupants due to LTD ~10%
- Not included in determining average operative temperature

Radiant temperature asymmetry

Draught rate

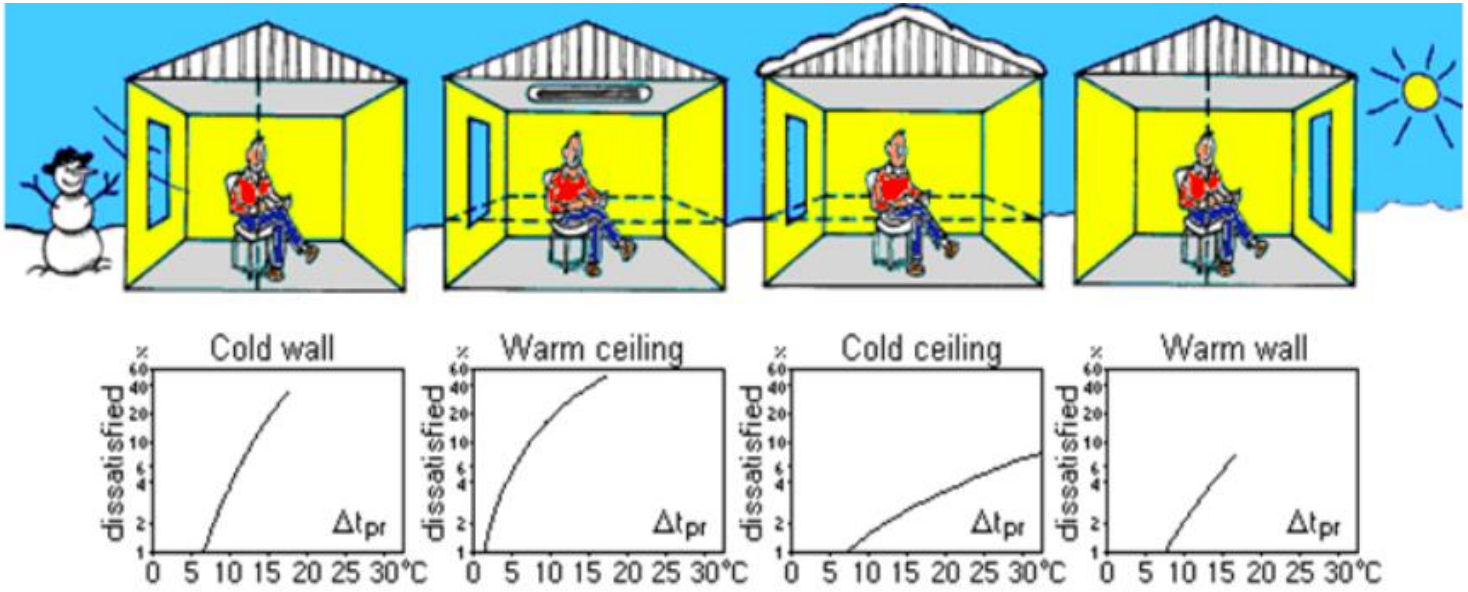


Vertical air temperature difference

Floor surface temperature

LTD: Radiant asymmetry

Definition: The difference in the two half-room temperatures. The thermal radiation field about the body may be non-uniform due to hot and cold surfaces and direct sunlight. This asymmetry may cause local discomfort and reduce the thermal acceptability of the space

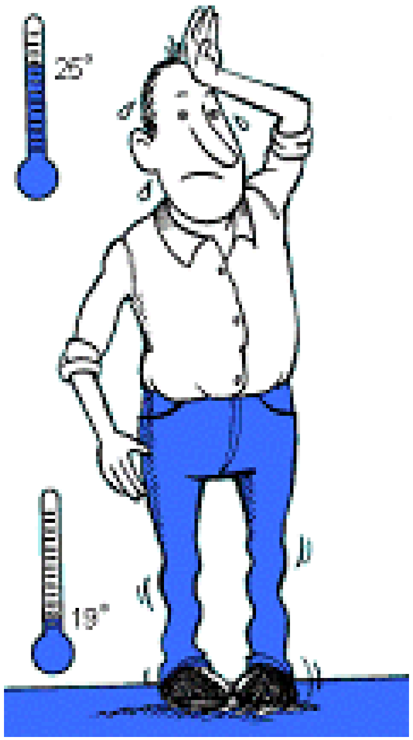


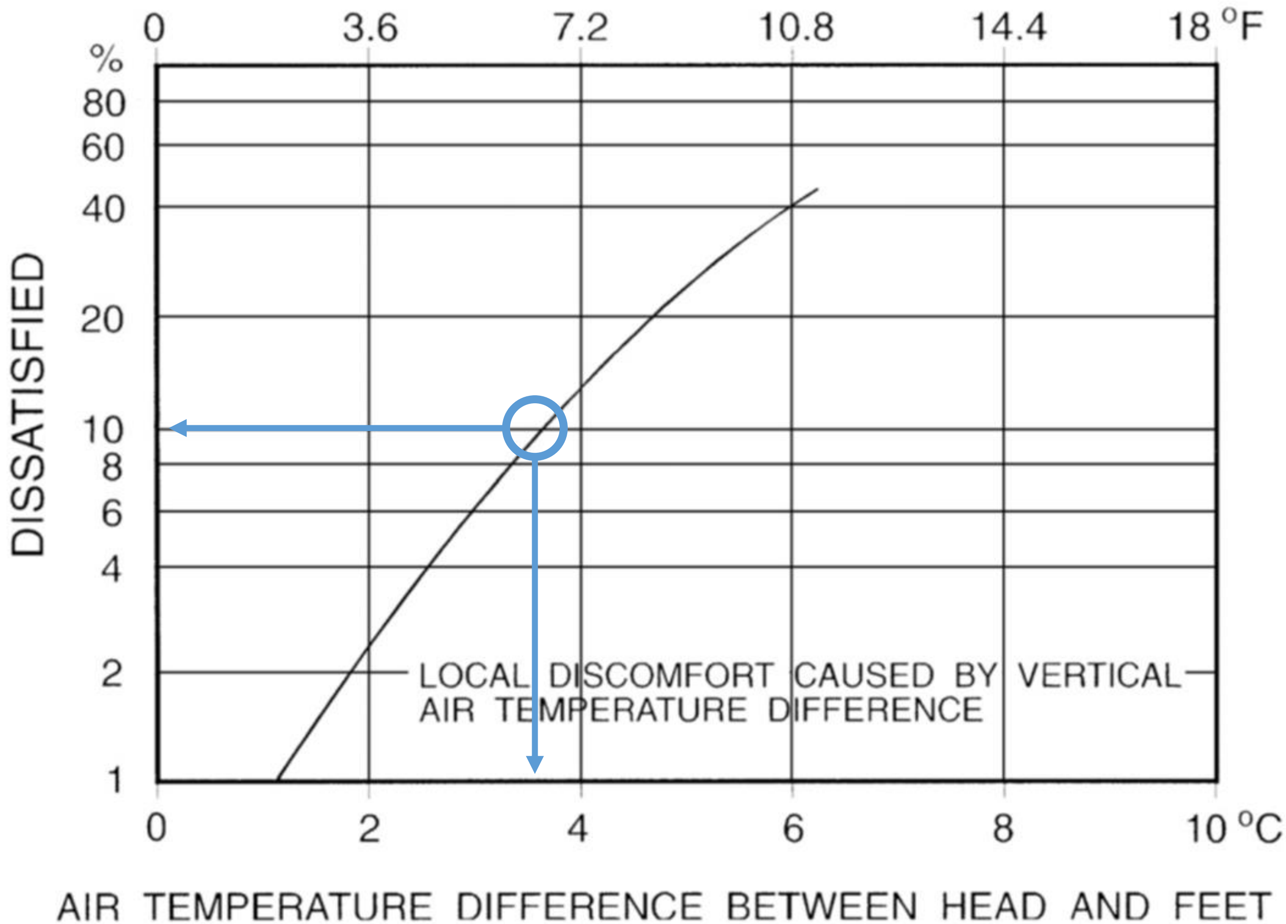
Cold surfaces: Glazing, bad insulation of the outside wall
Radiant chilled ceiling

Hot surfaces: Sunny glazing, ceiling and/or heated floor, radiant issues of heat (lamps, heating, etc.)

LTD: Vertical air temperature difference

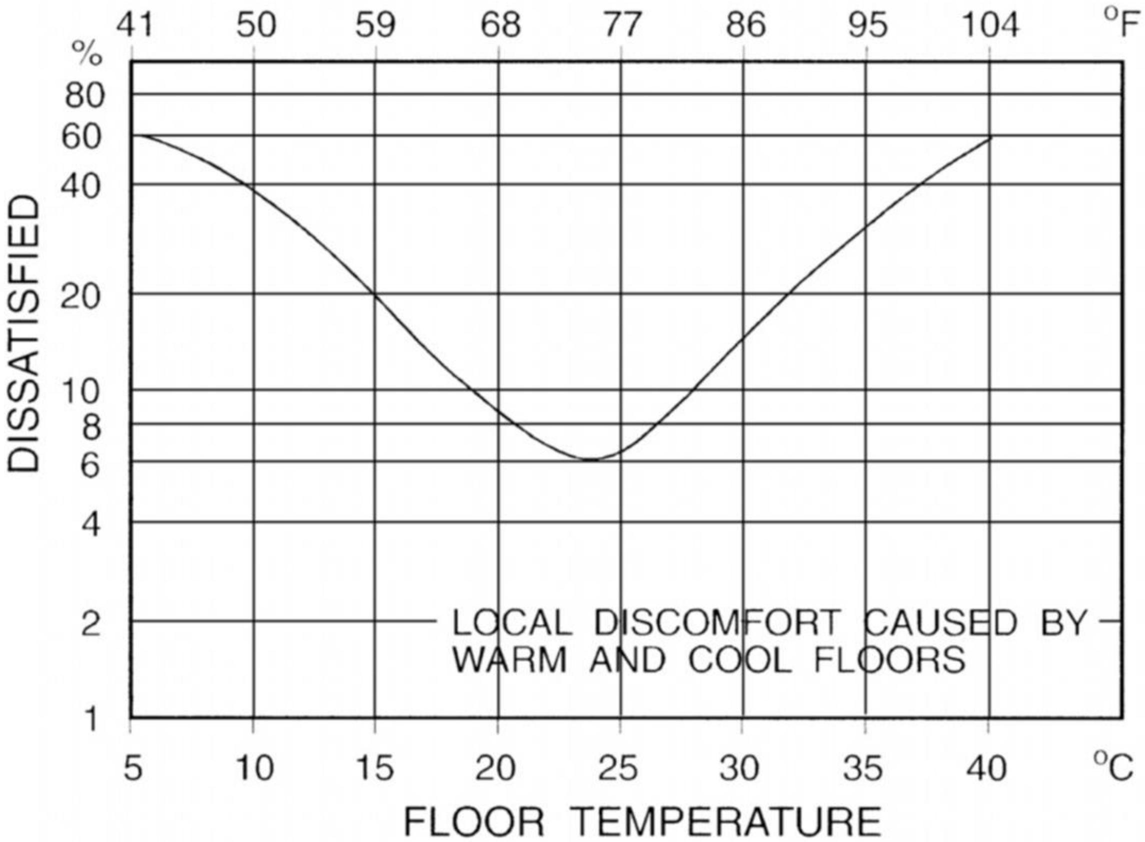
Definition: Thermal stratification that results in the air temperature at the head level being warmer than that at the ankle level may cause thermal discomfort. Thermal stratification in the opposite direction is rare





LTD: Floor surface temperature

Definition: Occupants may feel uncomfortable due to contact with floor surfaces that are too warm or too cool. The temperature of the floor, rather than the material of the floor covering, is the most important factor for foot thermal comfort while wearing shoes.



LTD: Draught rate

Definition: Unwanted movement of air that causes excessive local cooling. Draft sensation depends on air velocity, air turbulence, air temperature, activity, and clothing. It is the most frequent cause of complains in thermal comfort studies

$$DR = (34 - T_{op})\left(V_{m,a} - 0.05\right)^{0.62}\left(0.37V_{m,a} * Tu + 3.14\right)$$

Operative temparture (°C)   Average air spead (m/s)   Turbulence intensity (%)

CONDITION 1:
Occupants have no control,
Clo < 0.7, Met < 1.3, operative temperature <22.5°C.
Maximum permissible air speed provided by the HVAC cannot exceed **0.15 m/s**

CONDITION 2:
Occupants given a control over their thermal environment.
Maximum permissible air speed can go up to **1.2 m/s**

Q1. What is the usually accepted definition of thermal comfort ?

Q2. What types of individual differences exist among people in perception of thermal comfort?

Q3. As the indoor air temperature increase, the latent heat loss from a human body increases or decreases?

Q4. Which of the following is not a main variable that influences thermal comfort?

a) Dry bulb temperature
b) Noise level
c) Activity
d) Air movement

Q5. What are the two key personal variables that influence thermal comfort?

Q6. Operative temperature is derived from?

Q7. A person experience air temperature of 25 °C, MRT of 21 °C, and air speed of 0.12 m/s. What is the operative temperature?

Q8. What is the approximate Clo value of a man wearing a business suit?

Q9. What are the two important criteria for thermal comfort?

Q10. List at least three causes of local thermal discomfort?

Next time…

Human thermal comfort assessment:
- Actual thermal comfort
- Models (PMV + Adaptive)

Exercise
Standards requirements
Quiz time