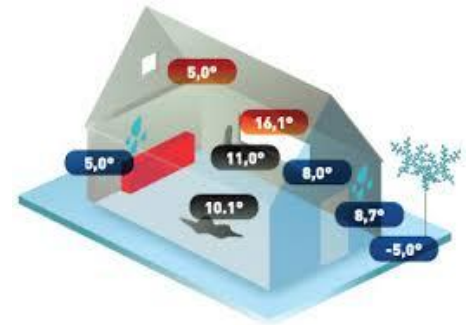
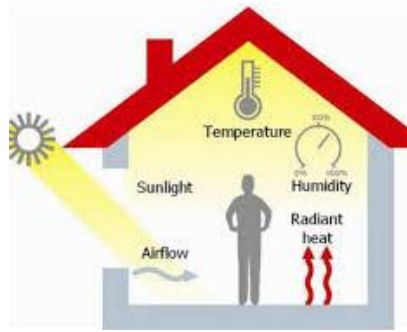


CIVIL 212

Indoor Climate

Fall 2025



Psychometrics

Heat Transfer in Buildings

18 September, 2025



Human-Oriented Built Environment Lab

Website: hobel.epfl.ch

Twitter: [@licinadusan](https://twitter.com/licinadusan)



EPFL

Assoc. Prof. Dusan Licina, Ph.D.

School of Architecture, Civil and

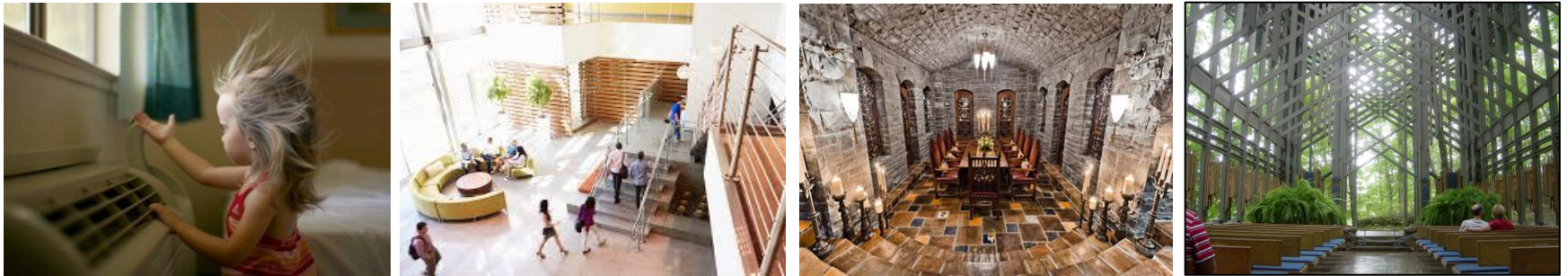
Environmental Engineering

École polytechnique fédérale de Lausanne

dusan.licina@epfl.ch

Last time we covered...

- Definitions of Indoor Environmental Quality and, more specifically, Indoor Climate



- Traditionally, we have been thinking of **Climate** as environment **outside buildings**; however, **we spend majority of our time indoors...** recall the Corsi code!

79

70

50

26

5

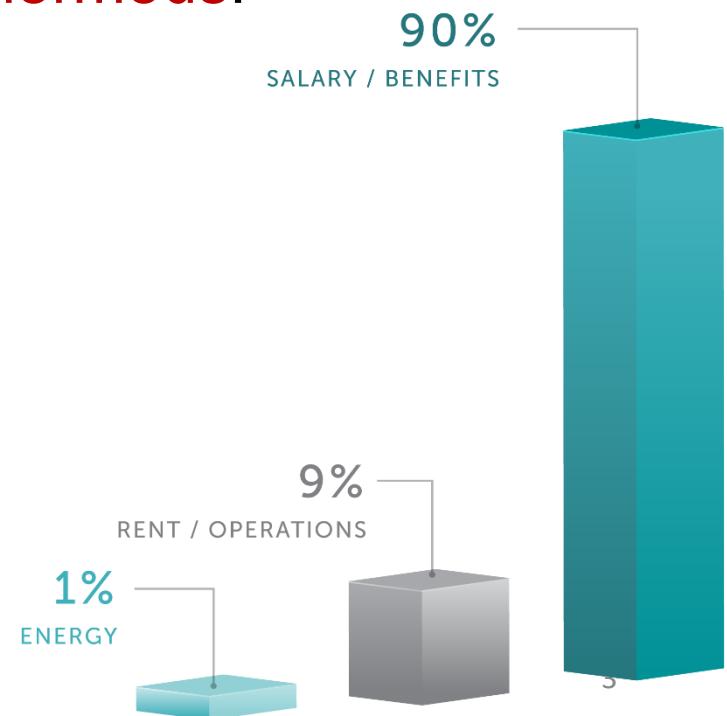
4

Last time we covered...

- What happens when you don't understand indoor climate?
 - ... you negatively influence building energy use, energy costs, greenhouse gas and other pollutant emissions, thermal comfort, indoor air quality, productivity and health

- Implications of indoor climate are **enormous!**

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



Today's objectives...

- Heat, Air and Moisture Fundamentals
- Psychometric Chart Fundamentals
 - Exercise
- Heat Transfer in Buildings

States of matter (why they matter indoors)

- **Gas (air, water vapor)**

- Molecules move freely with high kinetic energy.
- Movement (velocity) increases with temperature and pressure.
- No fixed shape or volume → air expands, fills space, and transports heat & pollutants.

- **Liquid (water, condensation)**

- Cooling or compressing a gas → molecules attracted strongly enough to form liquid.
- Flows easily (takes shape of container) but resists compression.
- Relevant indoors: condensation on windows, leaks, humidity control

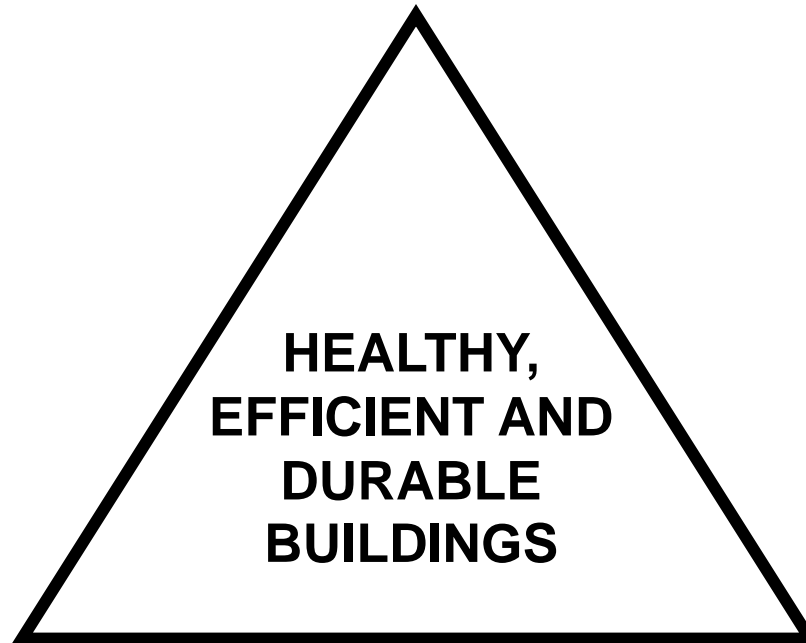
- **Solid (building materials, insulation)**

- Molecules are tightly packed with low kinetic energy.
- Strong intermolecular forces give solids a fixed shape and volume.
- Relevant indoors: insulation materials resist heat flow, surface temperatures (e.g., cold walls, floors) influence comfort, and thermal bridges affect energy use.

Heat vs. air vs. moisture – the biggest enemy?

(ENERGY, COMFORT,
sometimes also HEALTH)

HEAT



**HEALTHY,
EFFICIENT AND
DURABLE
BUILDINGS**

AIR

(ENERGY, COMFORT AND
HEALTH)

MOISTURE

(DURABILITY, HEALTH
AND ENERGY)

What is heat, really?

- **Energy** = capacity to do work (stored in systems: chemical, thermal, mechanical, etc.)
- **Heat** = energy transferred due to a temperature difference, causing either a temperature change or a phase change.
- **Temperature** \neq heat \rightarrow temperature is a measure of molecular kinetic energy
- Heat storage in a system (enthalpy):
 - **Sensible heat** \rightarrow energy stored/released with a temperature change.
 - **Latent heat** \rightarrow energy stored/released during a phase change (no change in temperature).
 - **The enthalpy** of a system represents its total heat content (sensible + latent).

Which contains more total heat energy?



Bathtub of warm water
(30 °C)

VS



Cup of boiling water
(100 °C)

Sensible Heat Equation: $Q = m \cdot c \cdot \Delta T$

m = mass [kg]

c = specific heat capacity [J/(kg·K)]

ΔT = temperature change [K]

Link to Enthalpy: $\Delta h = c \cdot \Delta T$ (h is specific enthalpy [J/kg])

So: $Q = m \cdot \Delta h$

Two faces of heat transfer

- **Sensible energy**

- Increases or decreases temperature of a material
- No phase change
- Example: Heating a room with a radiator

- **Specific heat capacity:**

- Sensible energy required to raise a unit mass of material one unit of temperature

- **Latent energy**

- Energy absorbed/released during phase change
- No temperature change while process occurs
- Example: Evaporation of sweat (cooling), condensation on a window

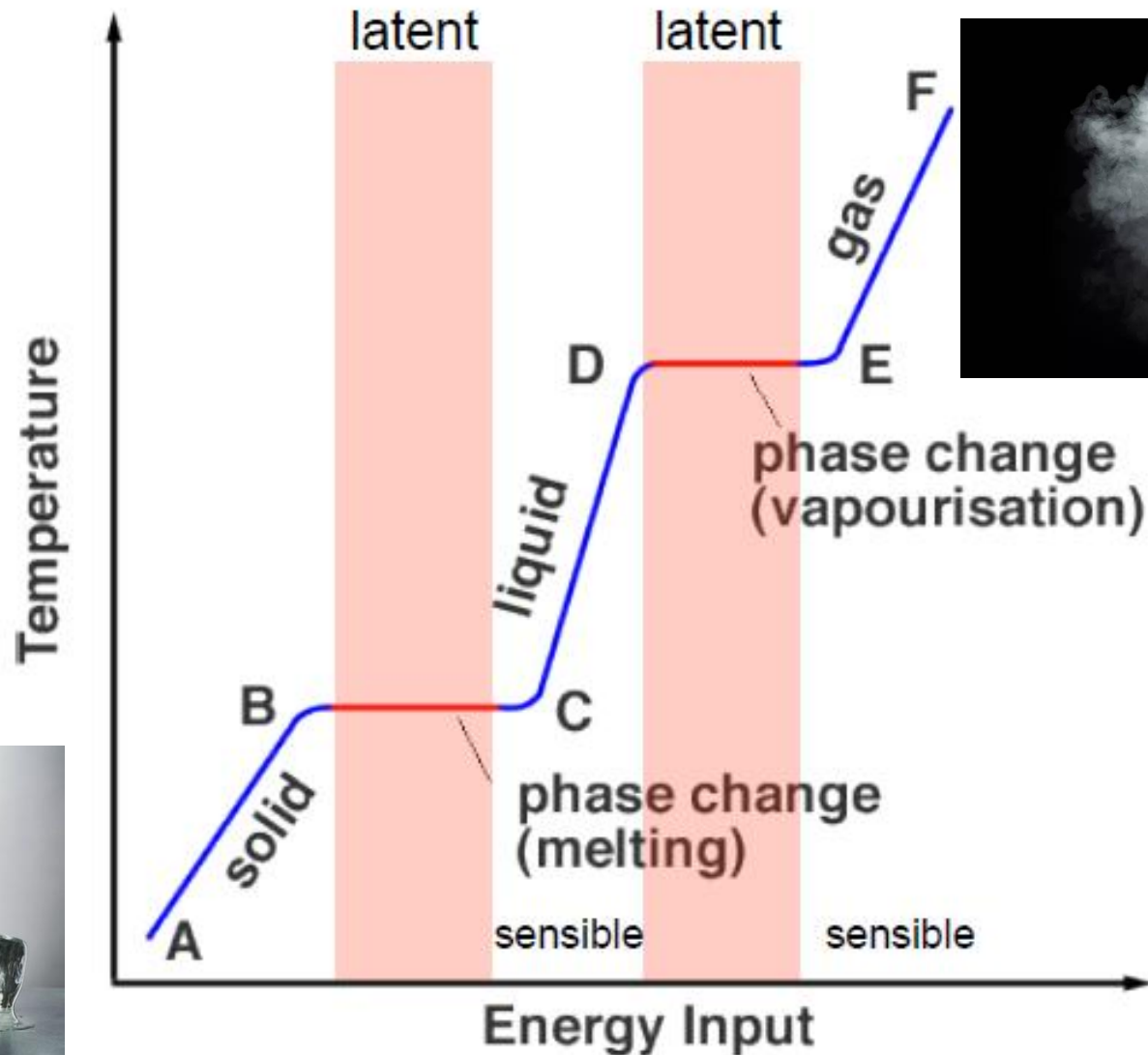


Temperature Rise



Phase Change

From ice to vapor: Why it matters?



Air – What is in clean, dry air?



Composition of the Atmosphere

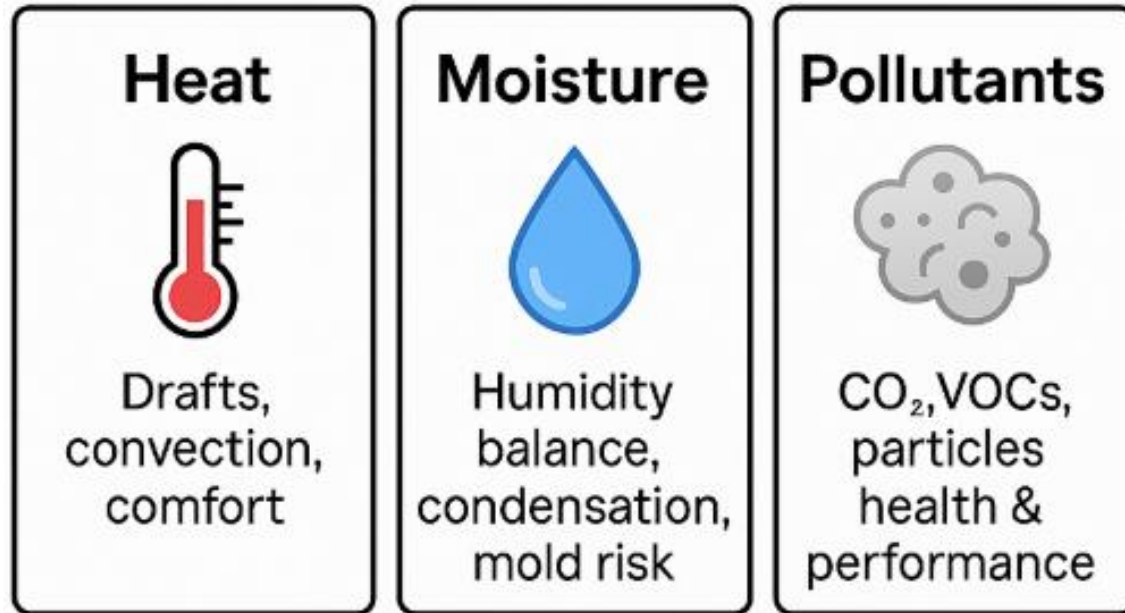
Species	MW (g/mol)	%
Nitrogen	28	78
Oxygen	32	21
Water vapor	18	<4
Argon	40	0.9
Carbon dioxide	44	0.04
Many minor species		<0.001%

- Density at standard conditions, $\rho = 1.205 \text{ kg/m}^3$
- Dynamic (absolute) viscosity, $\mu = 1.81 \times 10^{-4} \text{ g/cm/s}$
- Kinematic viscosity, $\nu = 0.15 \text{ cm}^2/\text{s}$

Does water vapor increase
or decrease air density?



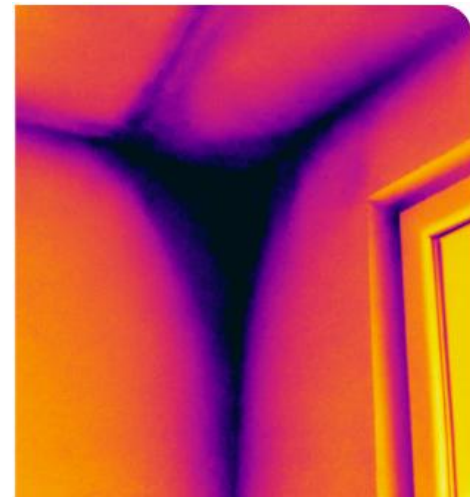
Air = Carrier of heat, moisture and pollutants



When you enter a room, what do you notice first: air temperature, air humidity, or air freshness?

Moisture: Why it matters indoors?

- Moisture transfer = movement of water in all its forms (vapor, liquid) into, through, and within buildings.
- If uncontrolled, it can:
 - ↑ Latent heating/cooling load (energy + cost impacts)
 - 🏠 Damage building materials (e.g., envelope & insulation)
 - 🍄 Create conditions for mold growth → health and material damage
- What about invisible aspects?



How moisture moves in buildings?

- **Diffusion**

- Vapor moves from high to low concentration/ vapor pressure
- Often linked to temperature differences (warm air holds more moisture → drives diffusion)
- Slow process

- **Air leakage** (convection)

- Moisture carried through building envelope cracks
- Fast process, usually dominant risk

- **Capillary action**

- Liquid water drawn through porous materials (e.g., concrete slab, gypsum board, wood in contact with damp surfaces)

- **Phase change**

- Condensation, evaporation, freezing

Need to ensure that moist air does not contact and condense on cold elements within the enclosure. **Risks:** Chemical deterioration and corrosion, Deterioration due to freezing, Mold growth, Staining/damage to interior finishes, etc.

Quick question: Moisture vs. humidity?



Moisture



Humidity

Importance of units!

- In building engineering, both SI and IP (inch-pound) units are used
 - Sorry for that!
 - IP: Typically used in USA, UK, Australia, India, Malaysia, New Zealand...
 - SI (Metric units): Used in most of the world.
- Good news!
 - Many countries are slowly transitioning towards a single system – SI
 - We will be mostly using SI units.
- What to convert IP to SI?
 - Just google “**IP to SI – ashrae**” to download free conversion tool in excel file

Important definitions: Energy

- Definition: Capacity of a system to do work
 - We use this term a lot
 - Primary units: Joules, kWh or BTU (or MMBTU = 10^6 BTU)
- Forms of energy:
 - Thermal, radiant (inc. solar), nuclear, geothermal, hydrocarbon
 - Embodied or embedded energy
 - Embedded energy is the energy required to extract resources, manufacture, and transport a product
- Energy use depends on the rate of energy use and the time/duration of operation
 - Rate of energy use = Power (Rate at which energy is produced or consumed) – don't mix these two.

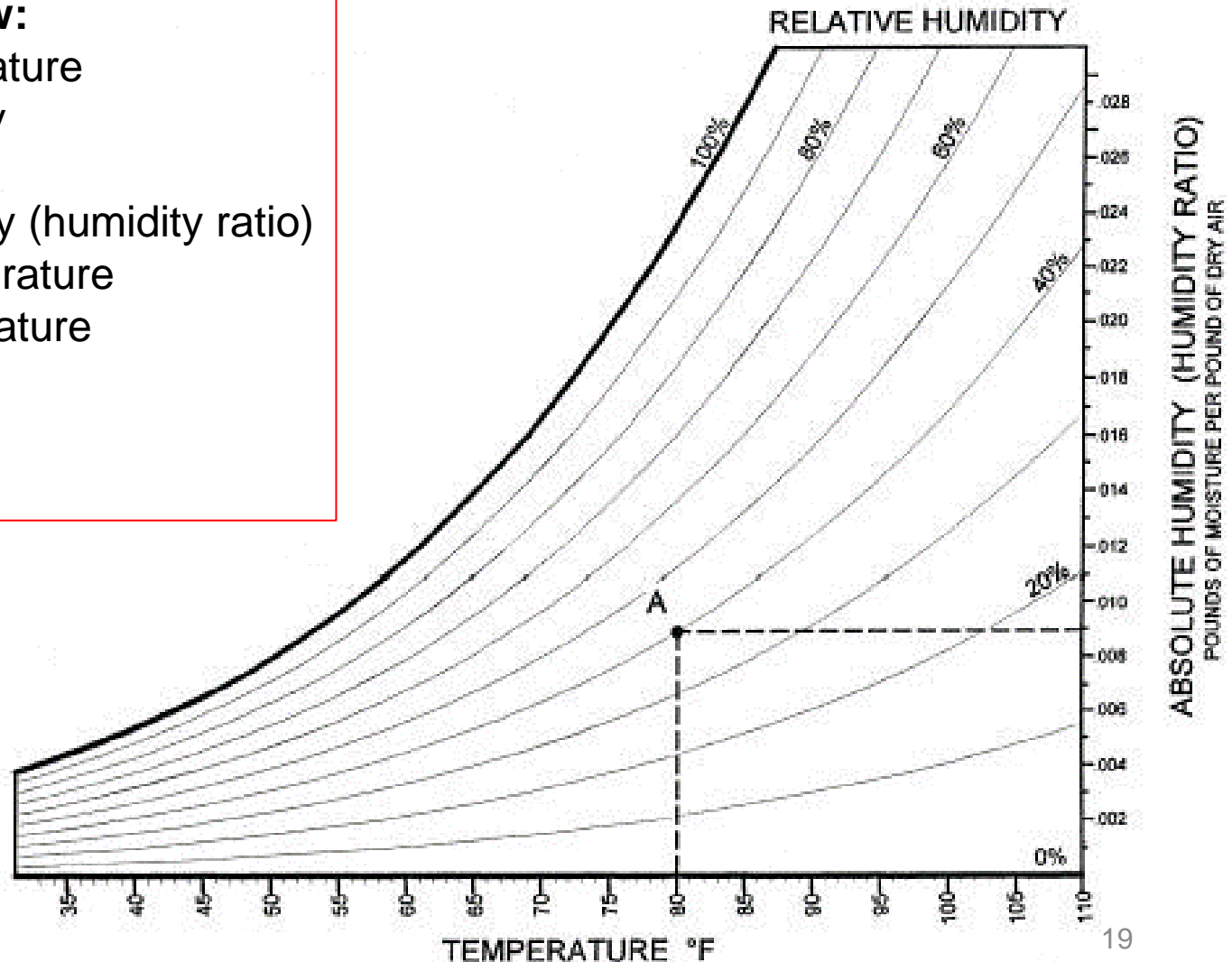
Psychrometric chart

- There are two ways to describe thermodynamic property of the air:
 - With equations and tables (tedious...)
 - Graphically using **psychrometric chart**
- Psychrometric chart
 - Two parameters are needed to define a state point
 - From a state point, we can get all other quantities
- We can do this calculation without a chart
 - Online there are many “digital” psychrometric charts available
 - You can create your own
 - Best source is ASHRAE Fundamentals (Chapter 6)

Psychrometric chart

Key terms to know:

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



Psychrometric chart: In-class exercise

- Lets take the example of typical comfortable indoor conditions:
 - Moist air at 22 °C dry-bulb temperature
 - With 50% relative humidity

Find the following:

- the humidity ratio, W
- dew point temperature, T_{dew}
- wet-bulb temperature, T_{wb}
- specific volume, v
- dry air density, ρ
- enthalpy, h



ASHRAE PSYCHROMETRIC CHART NO. 1

NORMAL TEMPERATURE

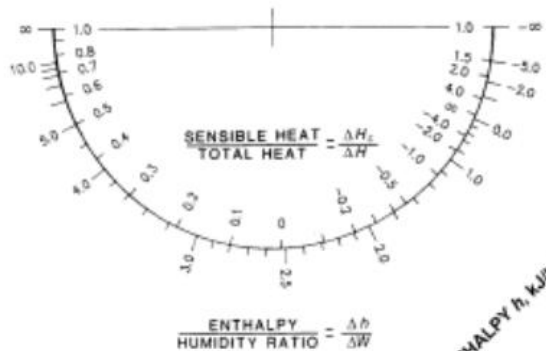
SEA LEVEL

BAROMETRIC PRESSURE:

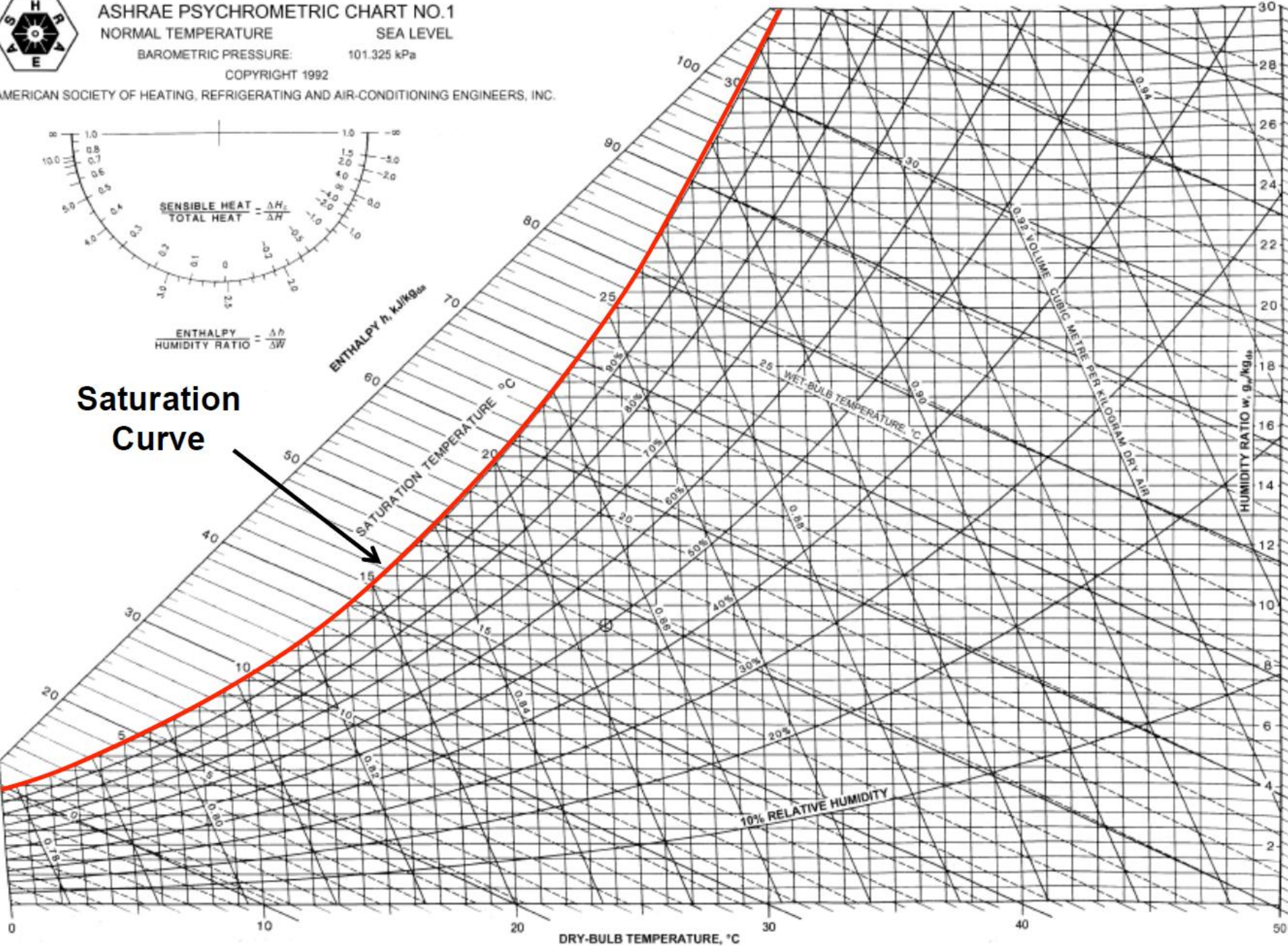
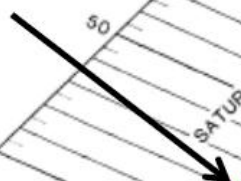
101.325 kPa

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Saturation Curve





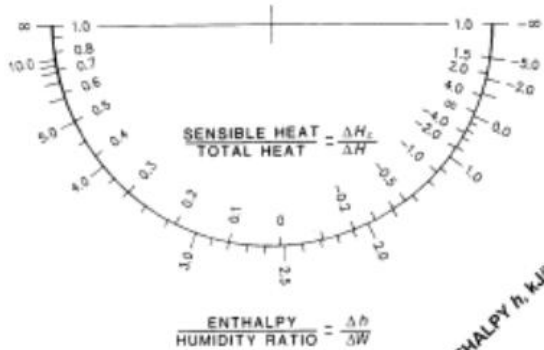
ASHRAE PSYCHROMETRIC CHART NO.1

NORMAL TEMPERATURE SEA LEVEL

BAROMETRIC PRESSURE: 101.325 kPa

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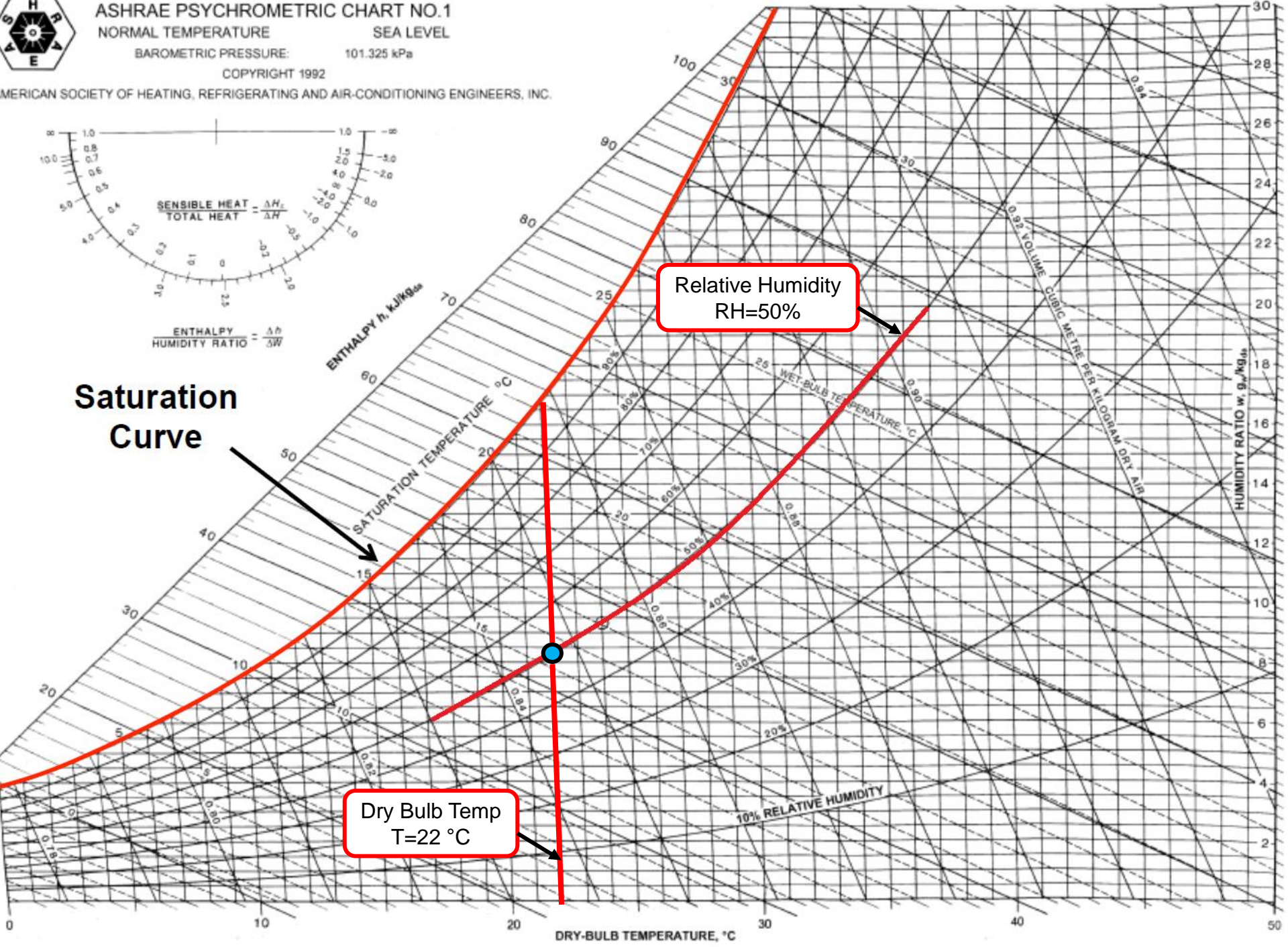
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Saturation Curve

Relative Humidity
RH=50%

Dry Bulb Temp
T=22 °C





ASHRAE PSYCHROMETRIC CHART NO.1

NORMAL TEMPERATURE

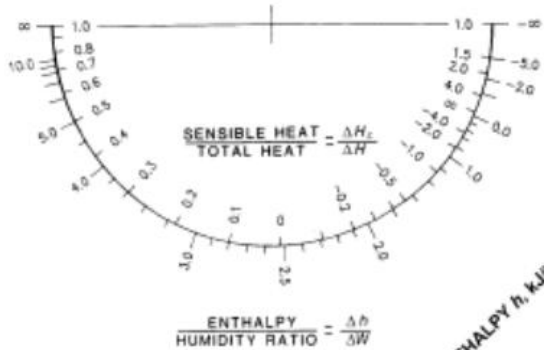
SEA LEVEL

BAROMETRIC PRESSURE:

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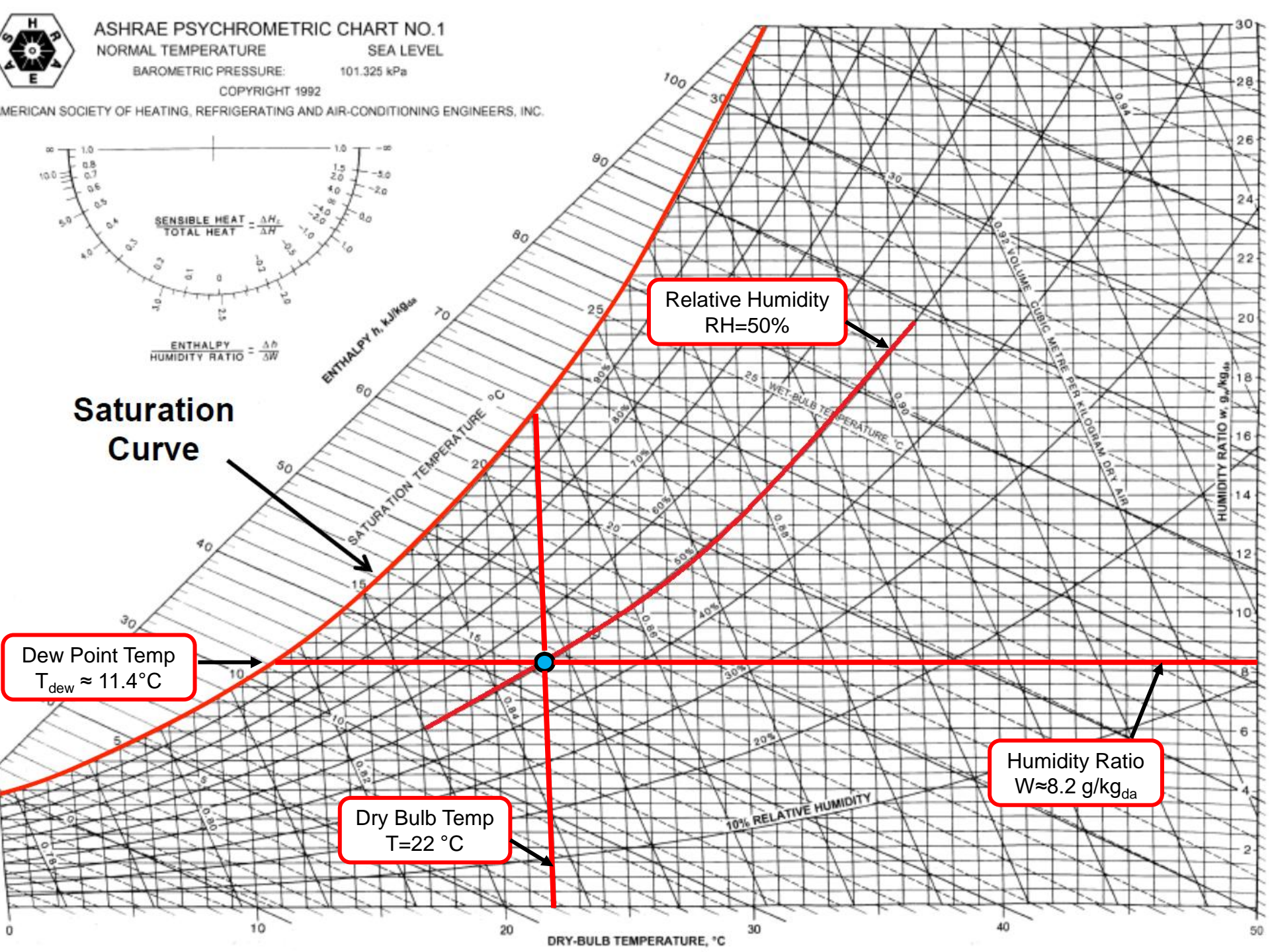
Saturation Curve

Dew Point Temp
 $T_{\text{dew}} \approx 11.4^\circ\text{C}$

Dry Bulb Temp
 $T = 22^\circ\text{C}$

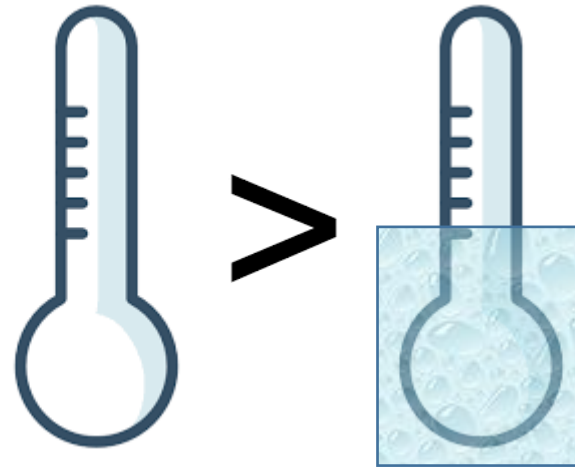
Relative Humidity
 $\text{RH} = 50\%$

Humidity Ratio
 $W \approx 8.2 \text{ g/kg}_{\text{da}}$



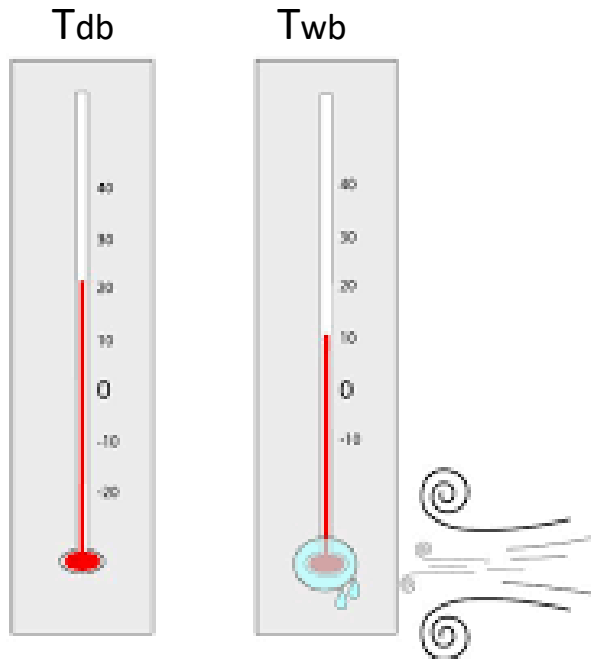
Which T do you expect to be higher?

- dry-bulb temperature, T_{db}
- wet-bulb temperature, T_{wb}



- Wet-bulb T is lower than dry-bulb T:
 - Evaporating moisture removes heat from thermometer bulb
 - Wet-bulb temperature is the theoretical minimum temperature which may be achieved by purely evaporative cooling of a wetted surface
 - The higher the humidity
 - Smaller difference between wet-bulb and dry-bulb temperature

A note of T_{db} vs T_{wb}



- T_{wb} is the lowest temperature that can be reached using the evaporation of water only
- Logic behind: T_{wb} is measured by a standard thermometer located under the shade, but with its bulb wrapped in a cotton wick whose bottom is submerged in a container of water. Exposing the wick to wind causes the water to evaporate. Evaporation processes causes the bulb to cool down. A value representing the wet-bulb temperature is then obtained in the thermometer.

- When air is below the saturation level, that is, when the relative humidity is below 100%, T_{wb} is always lower than T_{db} . The evaporation is reduced when the air contains more water vapor. For relative humidity of 100, $T_{wb}=T_{db}$
- The difference T_{db} and T_{wb} is an indication of the potential of evaporative cooling systems. The human body uses this principle (evaporative cooling) through perspiration. That's why high humidity will cause discomfort for human body.



ASHRAE PSYCHROMETRIC CHART NO.1

NORMAL TEMPERATURE

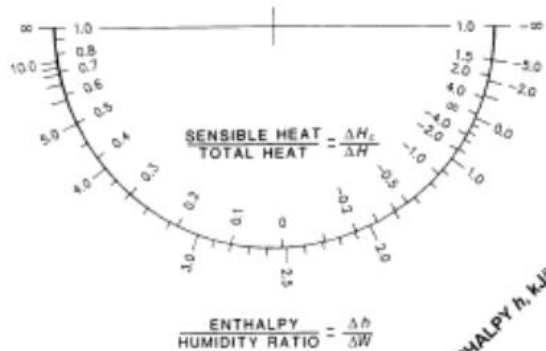
SEA LEVEL

BAROMETRIC PRESSURE:

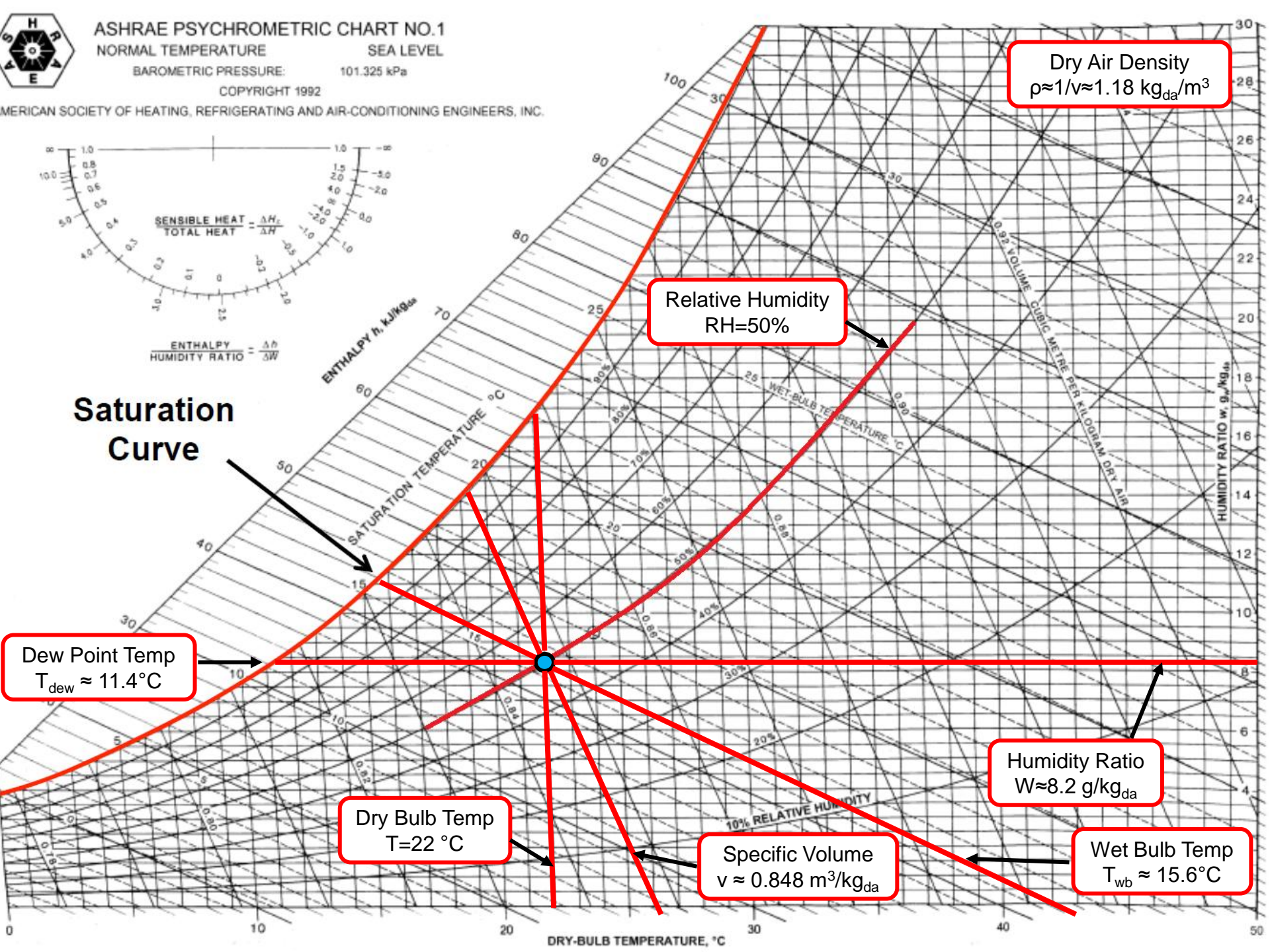
101.325 kPa

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Saturation Curve



Dry Air Density
 $\rho \approx 1/v \approx 1.18 \text{ kg}_{da}/\text{m}^3$

Relative Humidity
RH=50%

Dew Point Temp
 $T_{dew} \approx 11.4^\circ\text{C}$

Dry Bulb Temp
 $T = 22^\circ\text{C}$

Specific Volume
 $v \approx 0.848 \text{ m}^3/\text{kg}_{da}$

Humidity Ratio
 $W \approx 8.2 \text{ g/kg}_{da}$

Wet Bulb Temp
 $T_{wb} \approx 15.6^\circ\text{C}$



ASHRAE PSYCHROMETRIC CHART NO.1

NORMAL TEMPERATURE

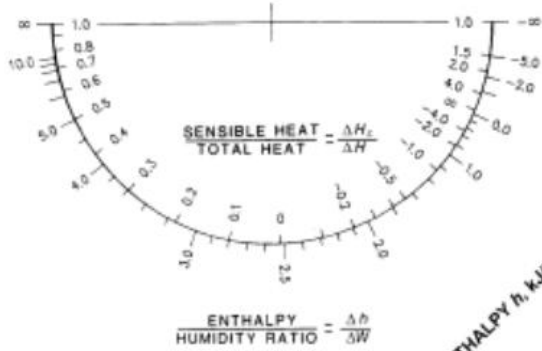
SEA LEVEL

BAROMETRIC PRESSURE:

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Saturation Curve

Enthalpy $h \approx 44 \text{ kJ/kg}_{da}$

Dew Point Temp $T_{dew} \approx 11.4^\circ\text{C}$

Dry Bulb Temp $T = 22^\circ\text{C}$

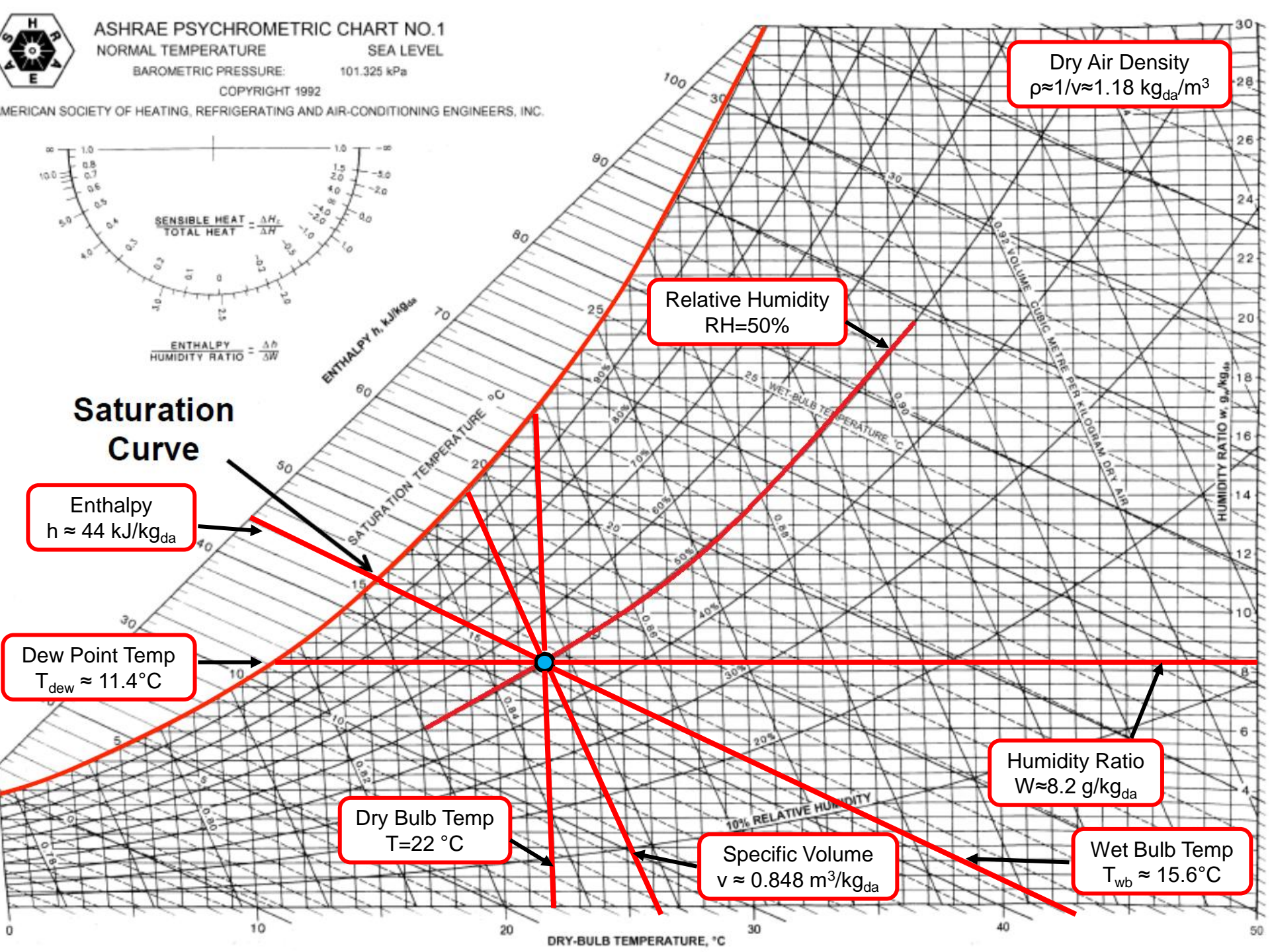
Specific Volume $v \approx 0.848 \text{ m}^3/\text{kg}_{da}$

Humidity Ratio $W \approx 8.2 \text{ g/kg}_{da}$

Wet Bulb Temp $T_{wb} \approx 15.6^\circ\text{C}$

Relative Humidity $RH=50\%$

Dry Air Density $\rho \approx 1/v \approx 1.18 \text{ kg}_{da}/\text{m}^3$



Enthalpy, h [J/kg] & Humidity ratio, W [g/kg_{da}]

- **Enthalpy** (from Psychrometric chart) =
 - Total energy in air [J/kg, BTU/lb]: Sensible + latent
 - Very valuable for calculations
- Recall: **Sensible** – Energy associated with temperature change
- **Latent** – Energy associated with moisture change (often more important than sensible)

$$h = 1.006t + W(2501 + 1.86t)$$



$$W = 0.62198 \frac{p_w}{p - p_w}$$

Humidity ratio, W :

- Mass of water vapor/divided by mass of dry air
- Hard to measure directly

(p – total pressure; p_w – vapor pressure)

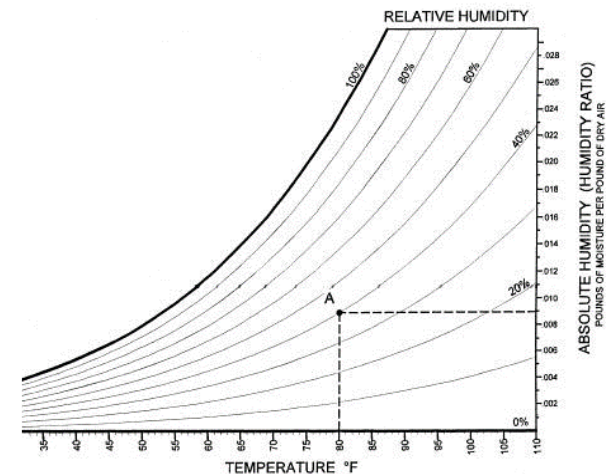
Psychrometric chart: In-class exercise

- **Given:** Moist air at 30 °C dry-bulb temperature, and dew point temperature at 15 °C.
- **Find:** the humidity ratio, wet-bulb temperature, specific volume, relative humidity, enthalpy

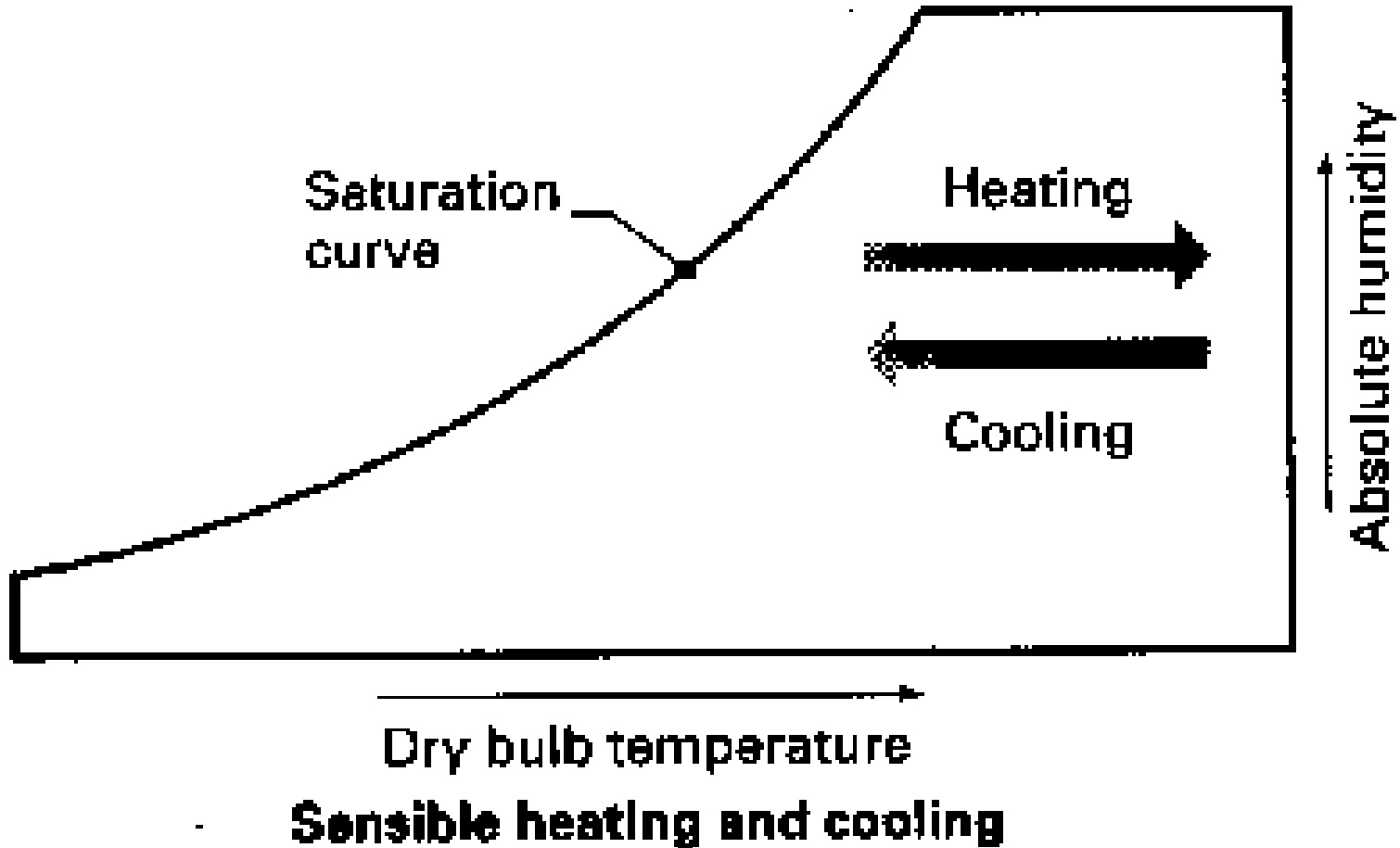
You can download the chart here:

<https://www.ashrae.org/File%20Library/Technical%20Resources/Bookstore/UP3/SI-1.pdf>

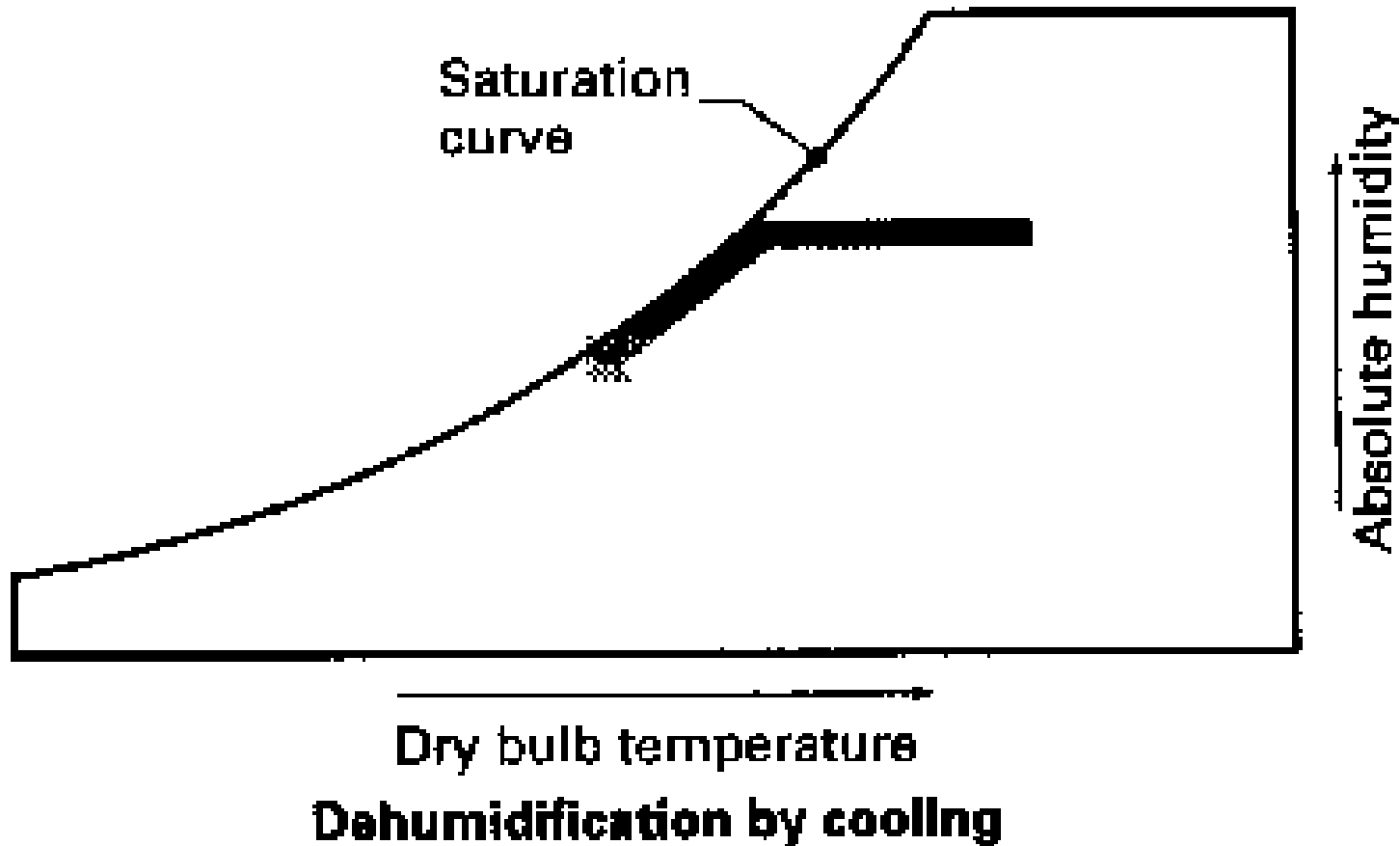
Solutions:



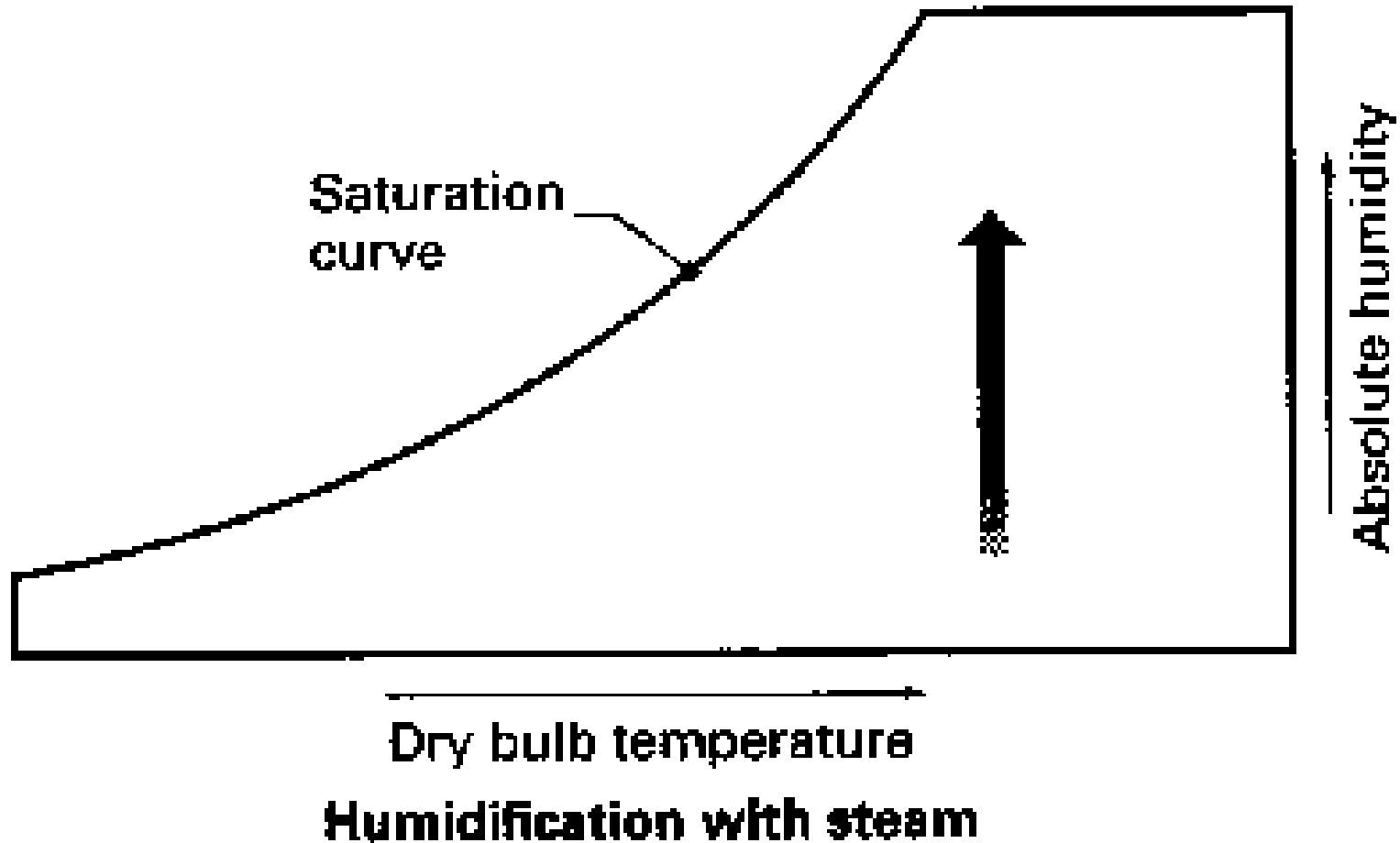
Processes useful for indoor climate



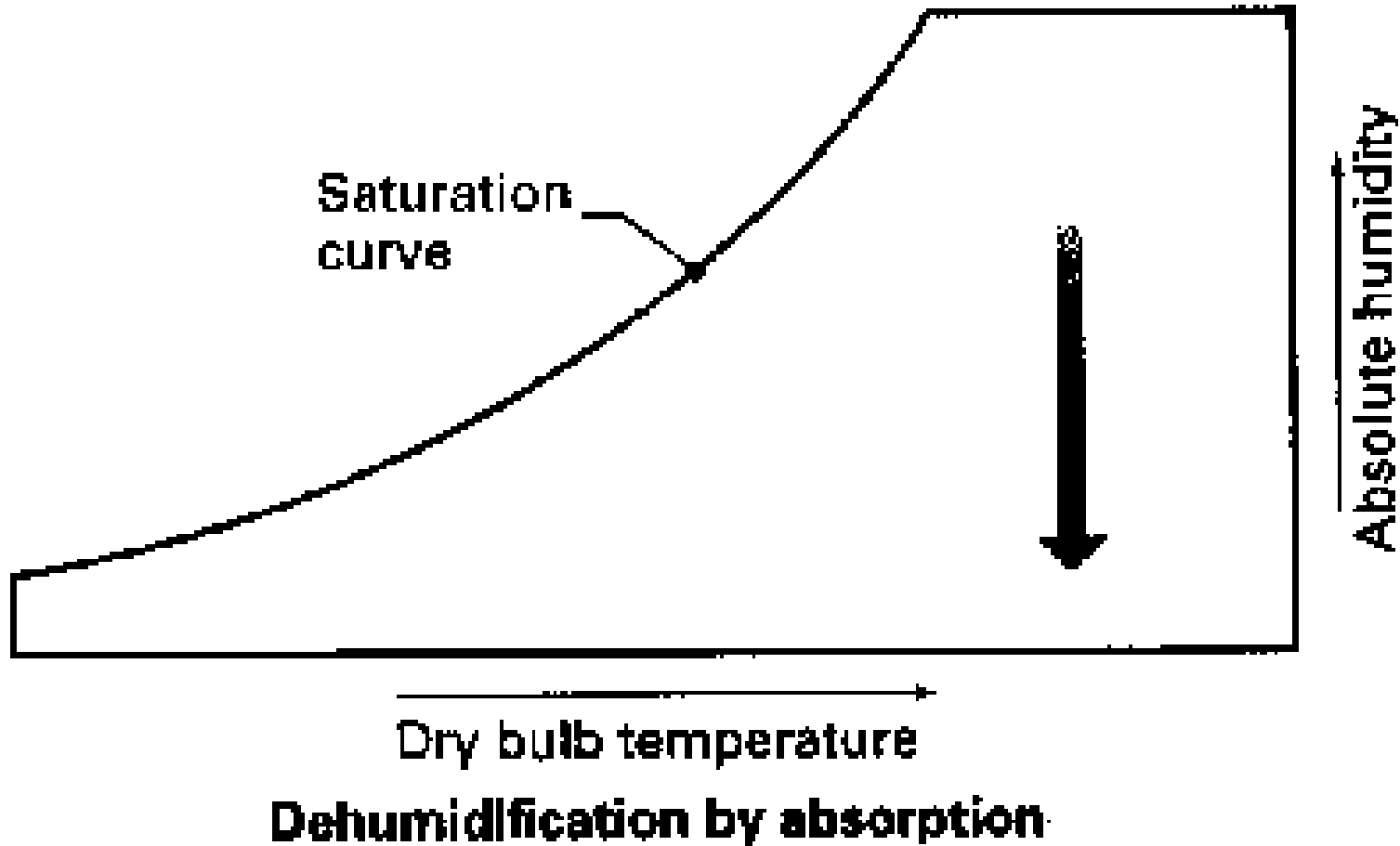
Processes useful for indoor climate



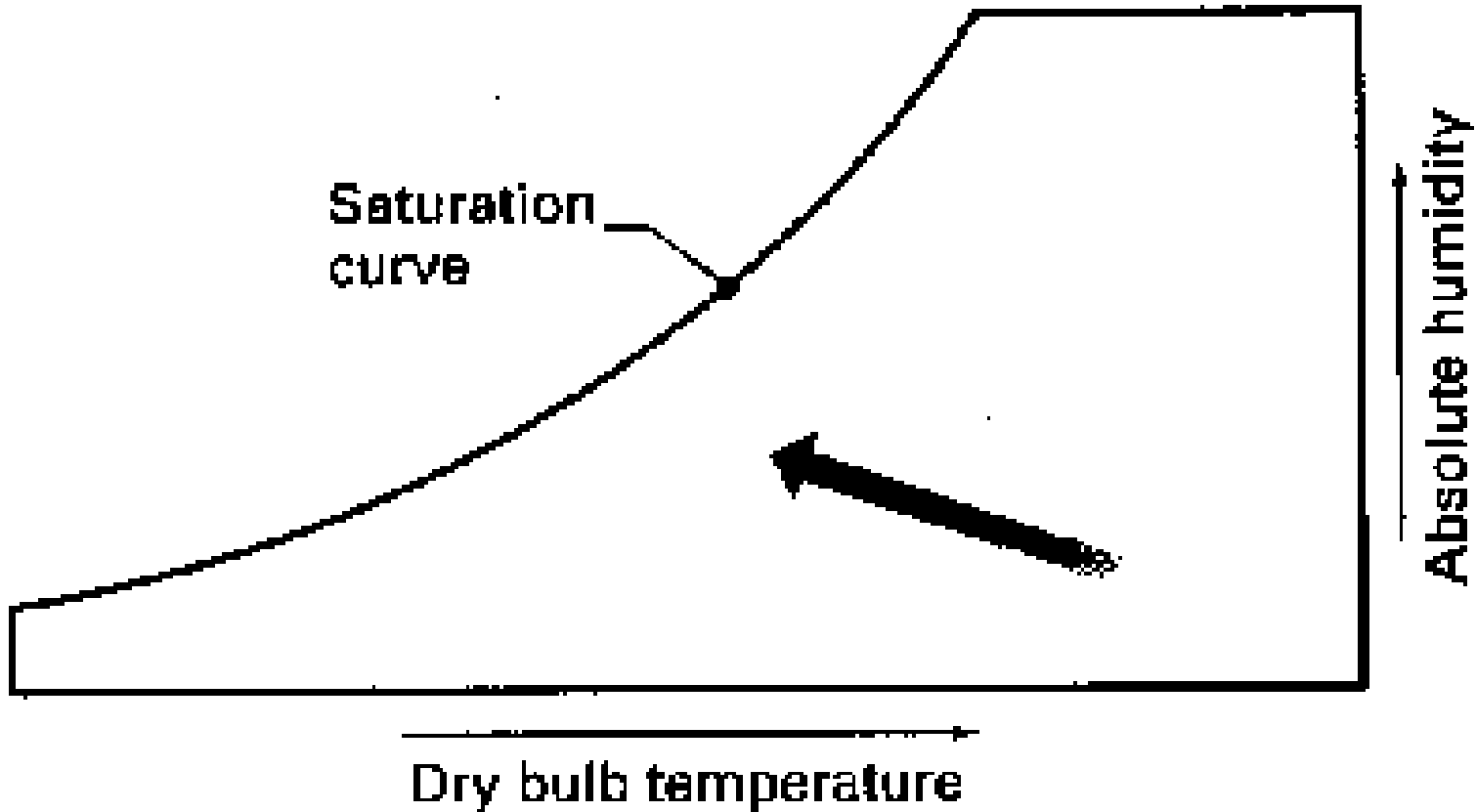
Processes useful for indoor climate



Processes useful for indoor climate



Processes useful for indoor climate



Humidification by evaporative cooling

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?

Assumptions:

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



You can download the chart here:

<https://www.ashrae.org/File%20Library/Technical%20Resources/Bookstore/UP3/SI-1.pdf>

Psychrometric chart: Homework #2

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

Dry bulb temp $^{\circ}\text{C}$	Wet bulb temp $^{\circ}\text{C}$	Specific enthalpy kJ/kg	Specific volume m^3/kg	% saturation	Moisture content kg/kg
40°C	-	-	-	-	0.01
40°C	20°C	-	-	-	-
40°C	-	-	-	30%	-
15°C	-	-	0.82	-	-
25°C	15°C	-	-	-	-
30°C	-	30	-	-	-
50°C	-	120	-	-	-

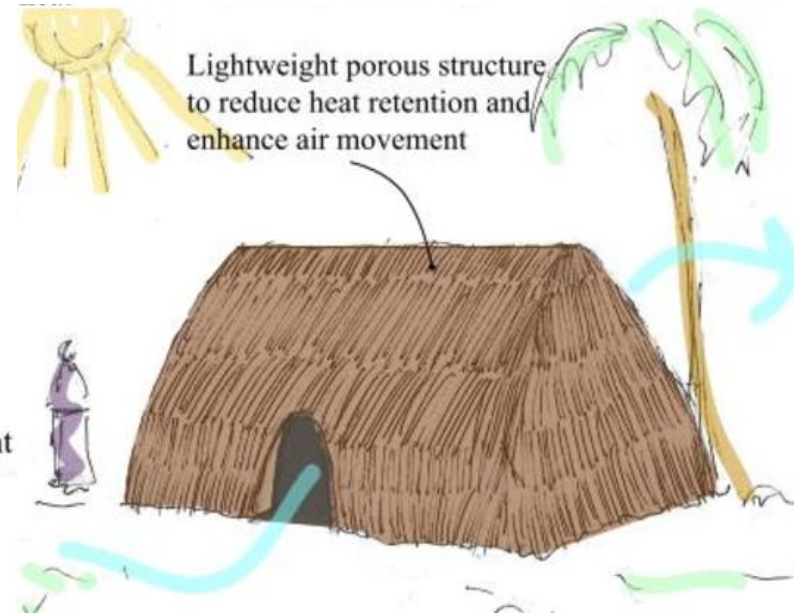
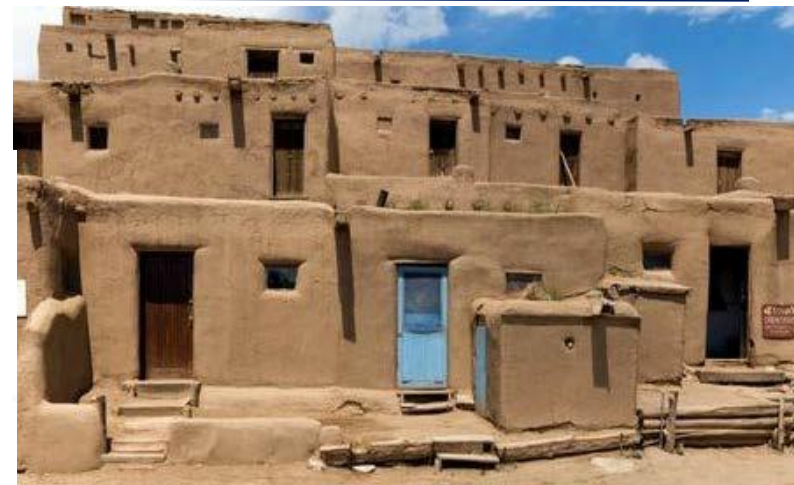
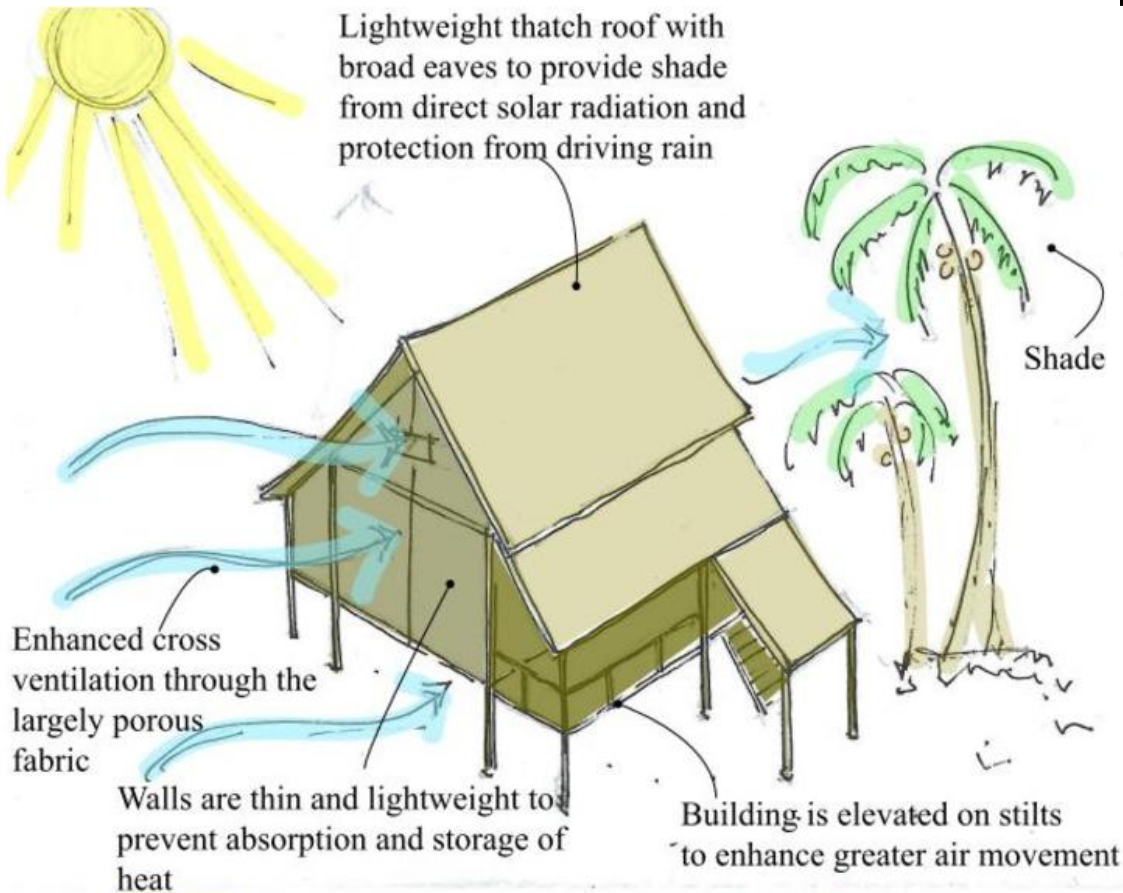
You can download the chart here:

<https://www.ashrae.org/File%20Library/Technical%20Resources/Bookstore/UP3/SI-1.pdf>

Any questions?



Climate-responsive architecture



Evolution of buildings

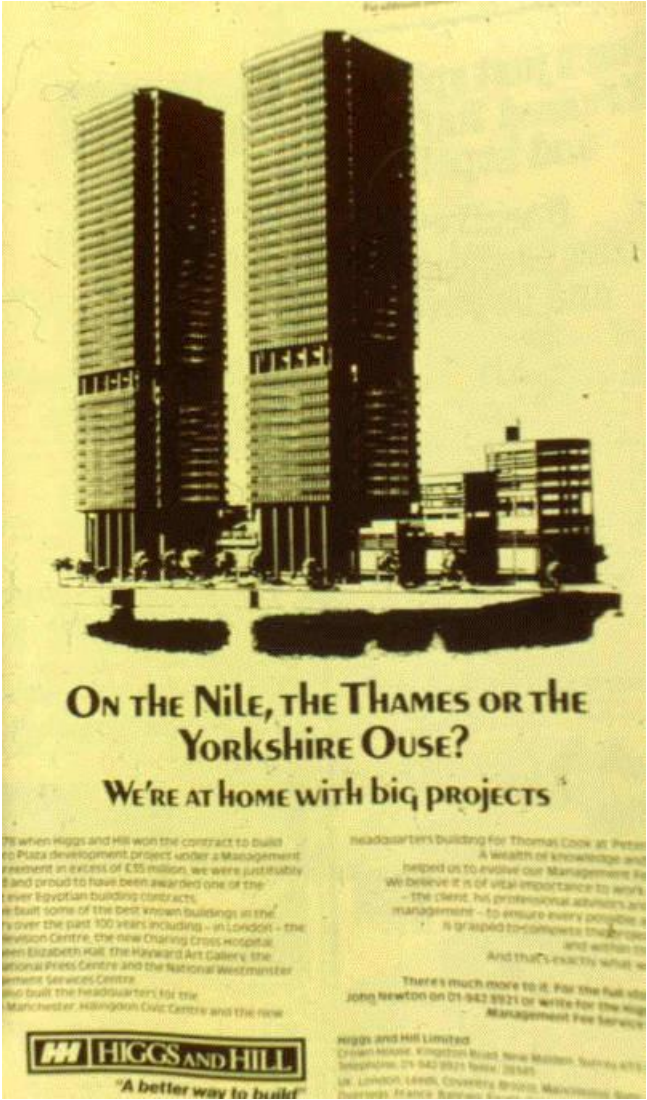


Climate (envelope)
dominated



Internal-load
dominated

Evolution of big skyscrapers



**ON THE NILE, THE THAMES OR THE YORKSHIRE OUSE?
WE'RE AT HOME WITH BIG PROJECTS**

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We have built some of the best known buildings in the world over the past 100 years including - in London - the National Exhibition Centre, the new Charing Cross Hospital, the new Elizabeth Hall, the Hayward Art Gallery, the National Pirelli Centre and the National Westminster Bank Services Centre.

We have also built the headquarters for the Manchester, Millington Cup Centre and the new headquarters building for Thomas Cook at Peterborough.

A wealth of knowledge and experience helped us to evolve our Management Agreement - the client, his professional advisers and management - to ensure every possible advantage is applied to complete the project and within the agreed budget.

And that's exactly what we do.

There's much more to it. For the full story contact **John Newton** on 01-942 9921 or write for the Management Fee Service.

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International Offices: Birmingham, London, Manchester, New Malden, Peterborough, Reading, Southampton, Warwick, Westbury, Wokingham



(Sources: Carrier advertisement, Flickr.com)

What are implications of climate-ignorant design?

The New York Times

A New, Deadly Risk for Cities in Summer: Power Failures During Heat Waves

The author of a new study said the combination of blackouts and extreme heat “may be the deadliest climate-related event we can imagine.”

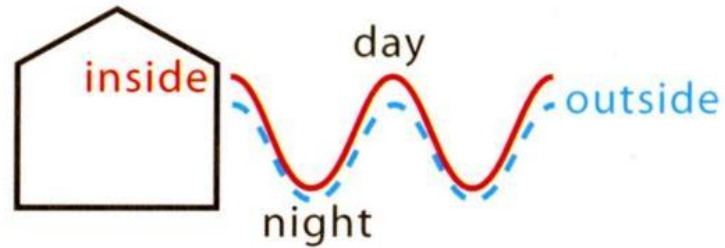


(Source: StockCake)

Impact of thermal mass on indoor climate

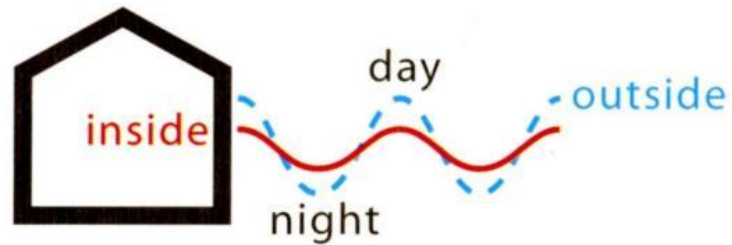
A Tent climate

Temperature follows the outdoor climate



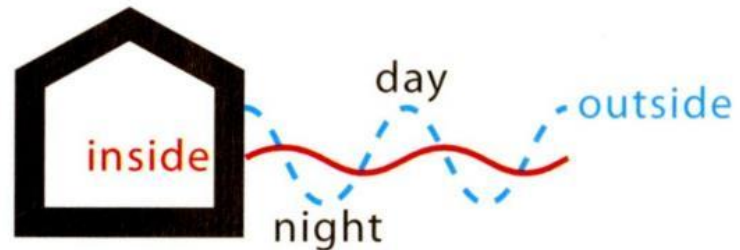
B Cabin climate

Quickly warm and cold



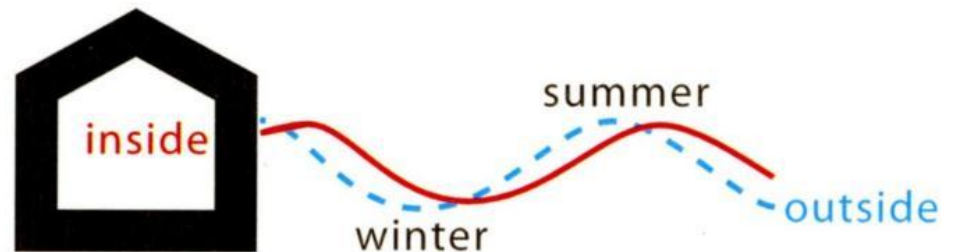
C Stone house climate

Phase offset variation across the day



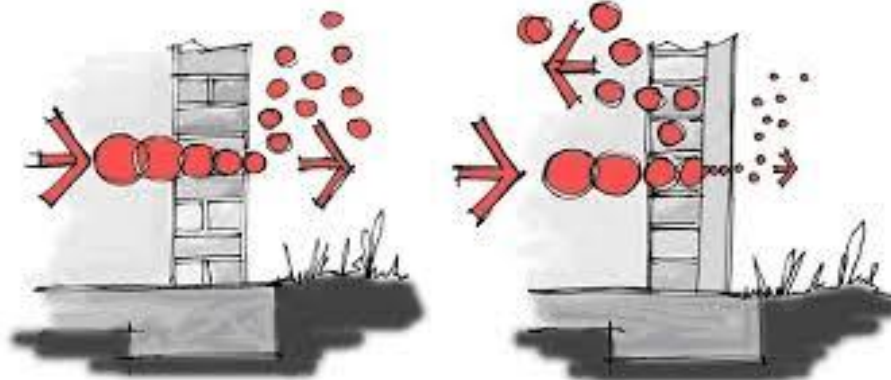
D Cave climate

Phase offset variation across the year



Heat transfer in buildings

- Transfer of thermal energy between objects with different T
- Knowing heat transfer is important because:
 - We can select and size HVAC equipment to provide indoor comfort
 - Estimate building energy use and operating costs
 - Understand trade-offs in energy efficient design



- **SIA 380/1**: Swiss standard for heat balances in the building

A few basic notes before we start...

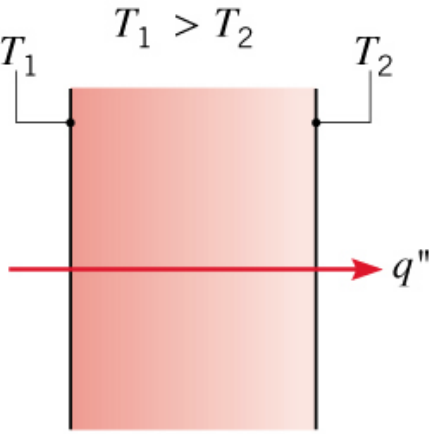
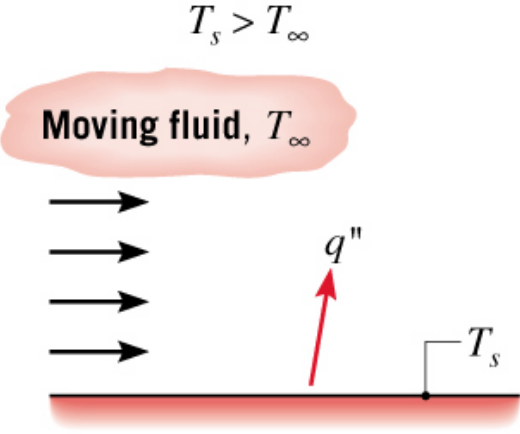
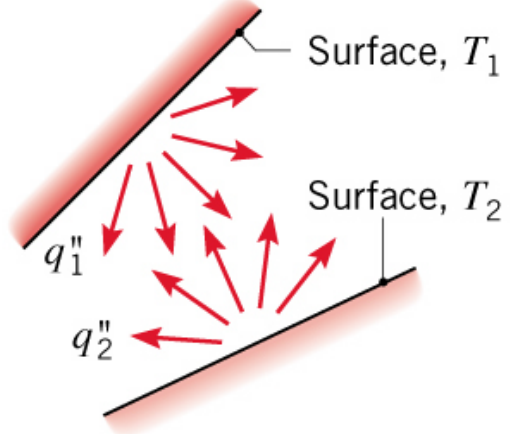
- Heat flow can be transient or steady-state
 - Transient (temperature & heat flow vary w/ time)
 - Steady-state (temperature & heat flow don't vary w/ time)
 - Choice depends on what problem you're investigating
- Heat flow occurs in 1, 2, and 3-dimensions
 - In almost all real situations, heat flow occurs in 3-D
 - 1-D is often acceptable from a practical standpoint

And one more thing: Units of heat transfer

- We denote the total rate of heat energy transfer by the symbol Q
 - It is a rate of energy transfer (i.e., a power)
 - So the units are W (J/s) or Btu/h (1 W = 3.41 Btu/h)
- We denote the rate of heat transfer per unit area by the symbol q
 - By definition $q = Q/A$, where A is the area through which the heat is moving
 - The units of q are W/m² [or Btu/(h·ft²)]
 - Using q instead of Q makes it easier to compare the thermal properties of assemblies without regard to the actual size of them

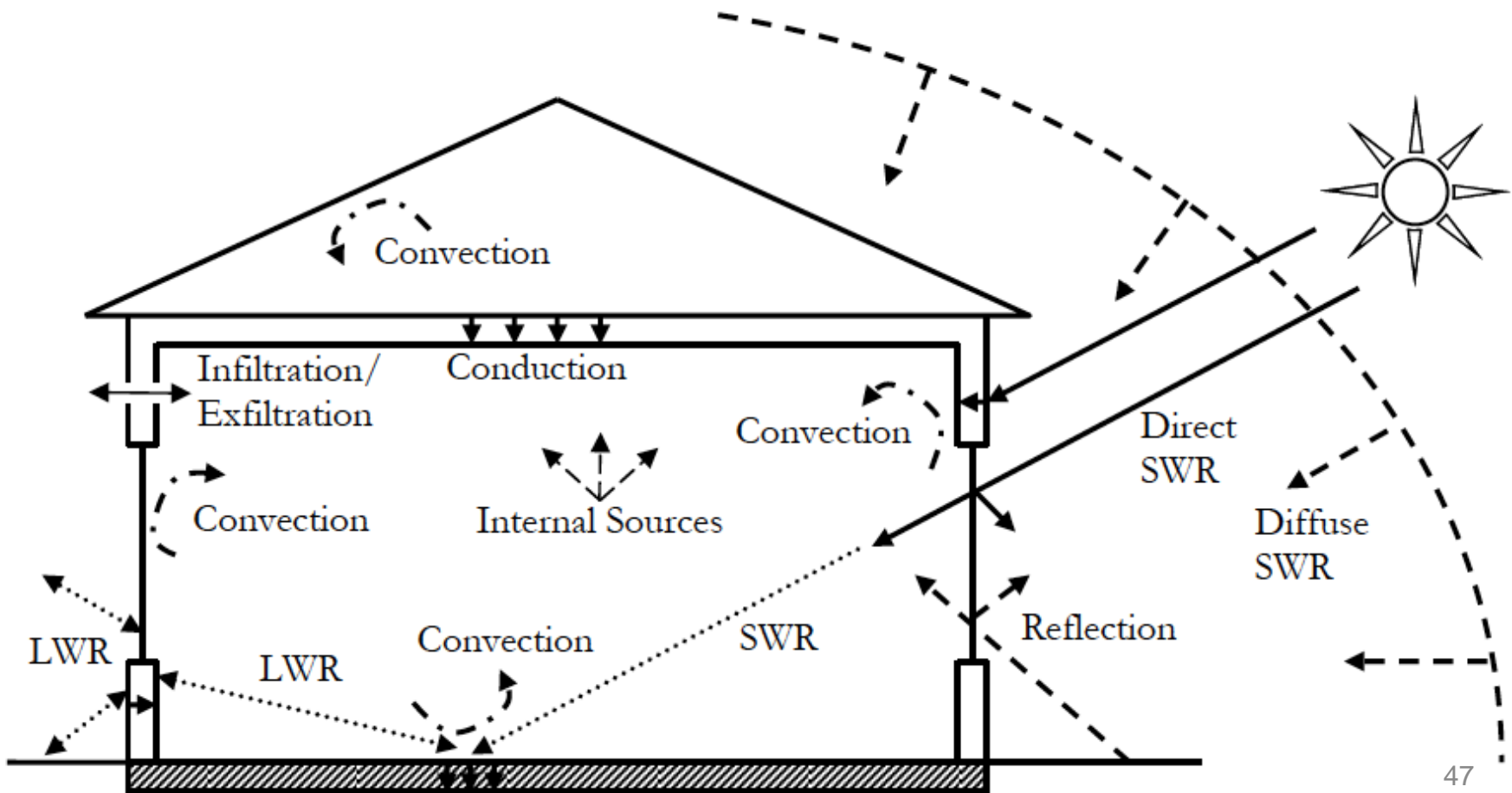
Three dominant modes of heat transfer

- **Conduction:** transfer of heat resulting from intermolecular transfer of kinetic energy in solids liquids and gases
- **Convection:** transfer of heat resulting from larger-scale fluid motion (can be in liquid or in gas)
- **Radiation:** transfer of heat by means of electromagnetic waves

Conduction through a solid or a stationary fluid	Convection from a surface to a moving fluid	Net radiation heat exchange between two surfaces
 <p>Conduction</p>	 <p>Convection</p>	 <p>Radiation</p>

In reality: combined heat transfer modes

Each heat transfer mode is present in every building → different consequences for comfort, health, and energy.

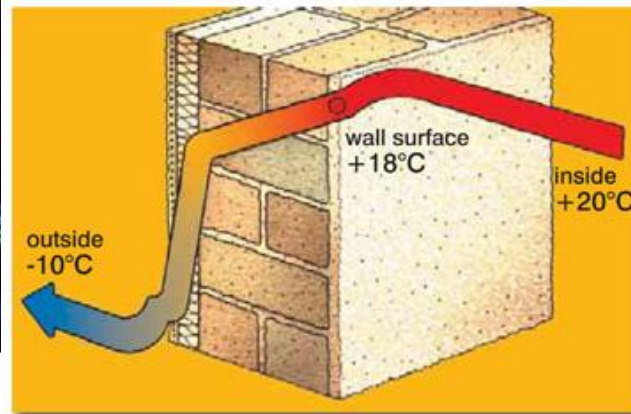


Heat transfer: Conduction

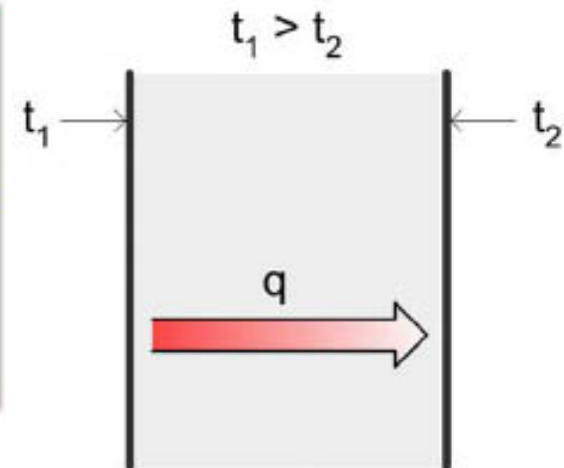
- Conductive heat transfer is heat transfer through direct molecular contact. It is basically the transfer of thermal momentum between atoms or molecules and follows Fourier's Law
 - Similar to electrical conduction in solid objects
- Occurs in the direction from high to low temperature
- Example: Heat gain through opaque walls in summer



IR image of conductive losses in home



(Source: Images from Google)



Heat transfer: Conduction

- Conduction follows Fourier's Law

"The time rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient, through which heat flows."

$$q = -k \cdot \nabla T = -k \left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z} \right)$$

heat flux per
unit area [W/m²]

thermal conductivity
[W/m·K]

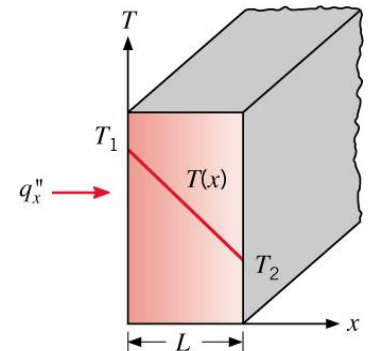
- For 1-D problems, this becomes: $q = -k \frac{\partial T}{\partial x} \quad \left[\frac{W}{m^2} \right]$

- To get total heat flow, Q [W], simply multiply q [W/m²] by A [m²]:

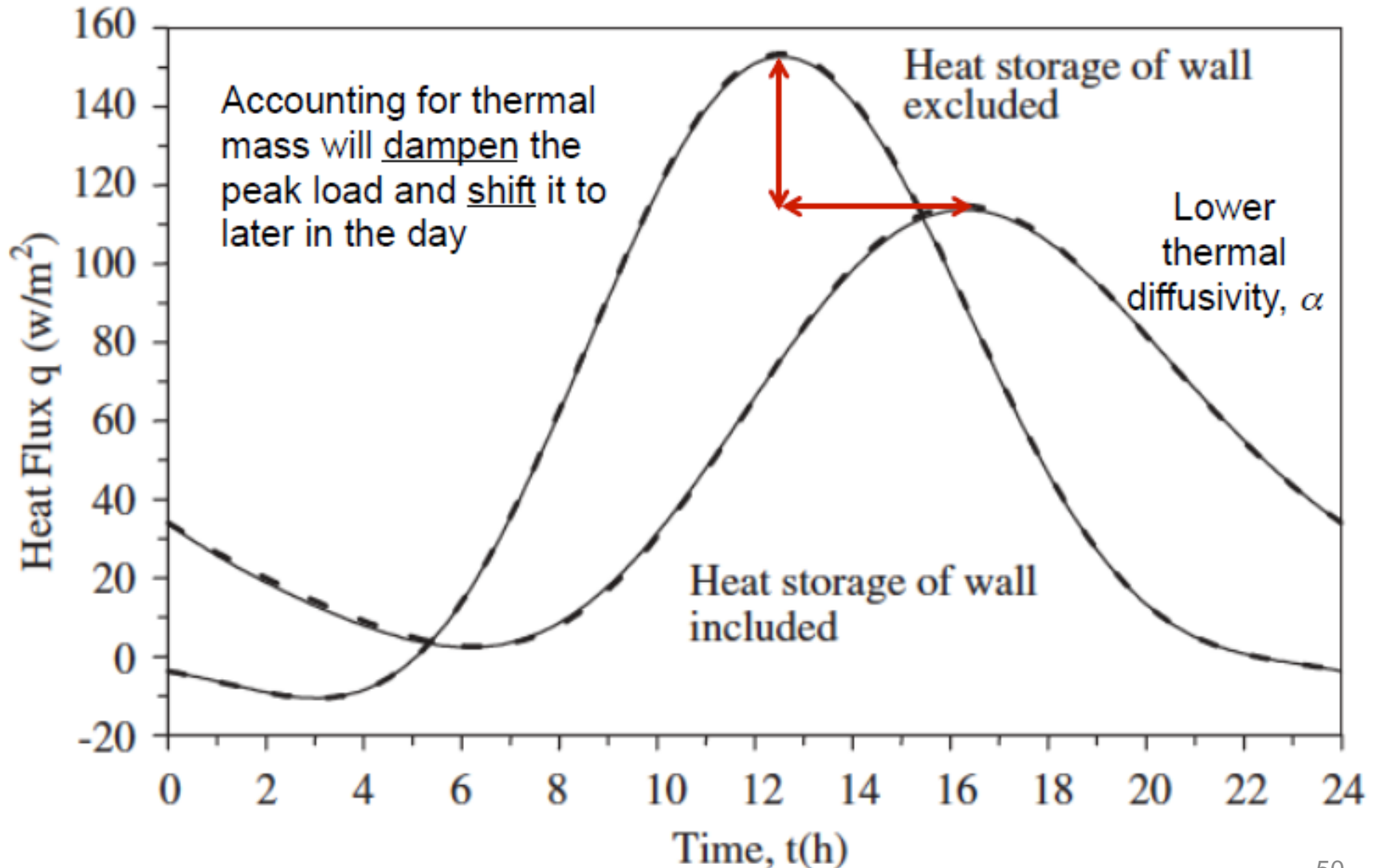
$$Q = q \cdot A = A \cdot \frac{k}{L} (T_1 - T_2)$$

Note 1: Here T1 and T2 are the surface temperatures but keep in mind that heat will always flow from high to low temperature.

*Note 2: k/L represents **U value**, which is thermal conductance [W/m²K]*

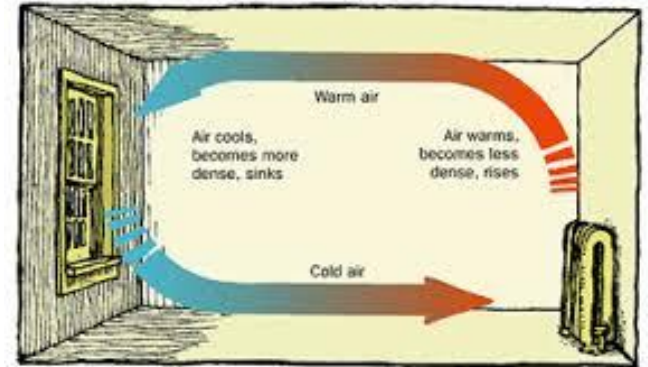
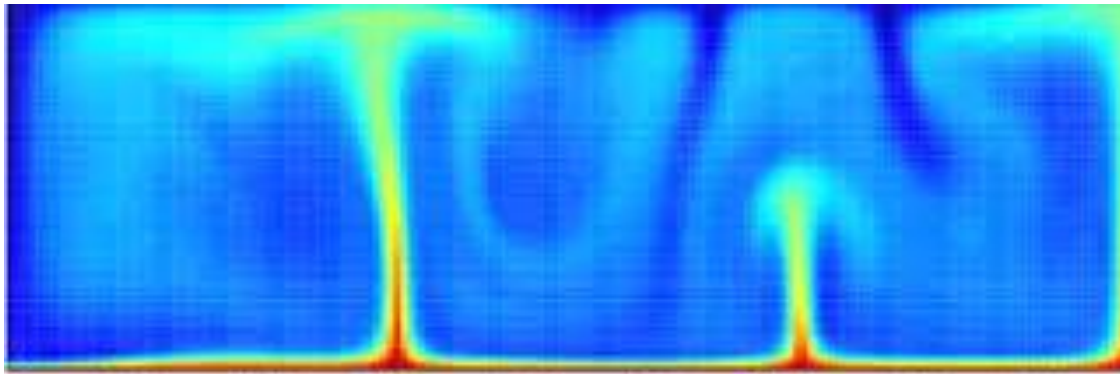


Accounting for the impact of thermal mass



Heat transfer: Convection

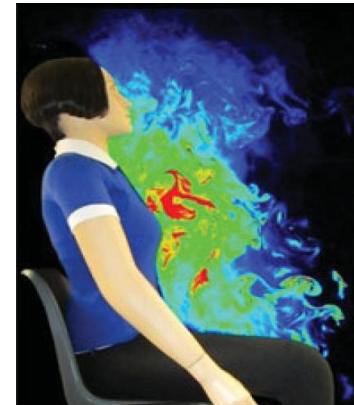
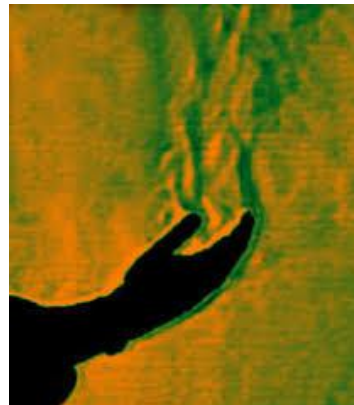
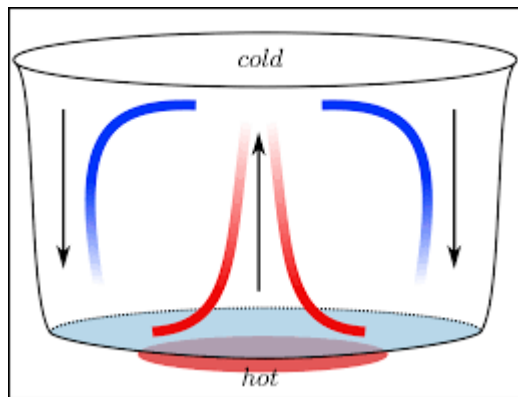
- Result of larger-scale motions of a fluid, either liquid or gas
- Increases with the higher velocity of fluid flow
- Also increases with higher temperature difference
- Example: Using a fan to cold down person's skin and remove heat

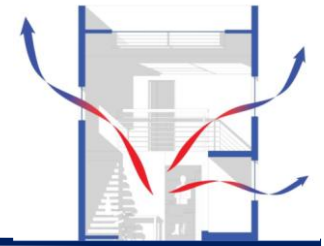


Heat transfer: Convection

Two main types of convective heat transfer in buildings:

- “**Advection**” (or bulk convection)
 - The transport of heat between fluids by fluid flow (e.g. air or water)
 - Example: Ventilation air supply cools down the room air
- What we most refer to as “**convection**”
 - Convective heat transfer between a surface and a fluid
 - Example: heat transfer from the human skin to surrounding air





Advection (bulk convection)

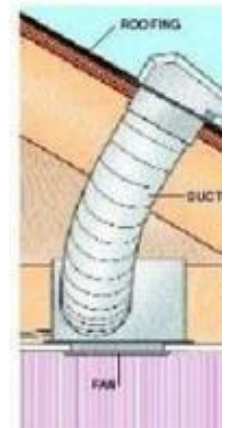
- It's more direct compared to convection between surfaces and fluids
- Air has the capacity to store heat, so air flowing into or out of a control volume (building) also carry heat with it

$$Q_{bulk} = \dot{m} C_p \Delta T \quad [W] = \left[\frac{kg}{s} \cdot \frac{J}{kg \cdot K} \cdot K \right]$$

Mass flow rate of fluid (kg/s) specific heat capacity of fluid [J/(kgK)]

• Do-it-yourself:

- If it's 22 °C inside the apartment and 5 °C outside, what is the rate of heat loss via advection (bulk convection) during this condition?
 - Assume that mechanical fan which you have in the bathroom operates at an airflow rate of 170 m³/h.



Solution to the previous problem

- If it's 22 °C inside the apartment and 5 °C outside, what is the rate of heat loss via advection (bulk convection) during this condition?
 - Assume that mechanical fan which you have in the bathroom operates at an airflow rate of 170 m³/h.

$$Q_{bulk} = \dot{m}c_p\Delta T \quad [W] = \left[\frac{kg}{s} \cdot \frac{J}{kg \cdot K} \cdot K \right]$$

Mass flow rate of fluid (kg/s) specific heat capacity of fluid [J/(kgK)]

$c_p =$ specific heat of air (1.006 kJ/kg K)

$\rho =$ density of air (1.202 kg/m³)

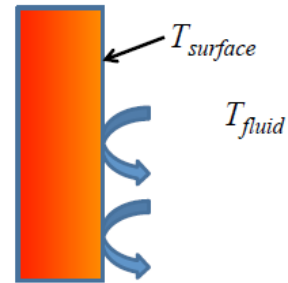
$\Delta T =$ temperature difference (°C or K)

$$\dot{m} = 170 \frac{m^3}{h} \cdot 1.202 \frac{kg}{m^3} = 204.34 \frac{kg}{h} = 0.0567 \frac{kg}{s}$$

$$Q_{bulk} = \dot{m}c_p\Delta T = 0.0567 \frac{kg}{s} \cdot 1.006 \frac{kJ}{kg K} \cdot 17K = 0.97 \frac{kJ}{s} \approx 1kW$$

Convection (between a surface and a fluid)

- When a fluid comes in contact with a surface at a different temperature
- We use a heat transfer coefficient, h_{conv} , to relate the rate of heat transfer to the difference between the solid surface temperature, $T_{surface}$, and the temperature of the fluid far from the surface, T_{fluid}



$$q_{conv} = h_{conv}(T_{fluid} - T_{surface}) \quad \left[\frac{W}{m^2} \right]$$

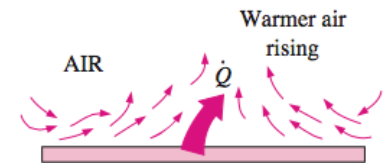
convective heat transfer coefficient $[W/(m^2 \cdot K)]$ fluid temperature far enough not to be affected by $T_{surface}$

- To get Q , simply multiply by surface area, A

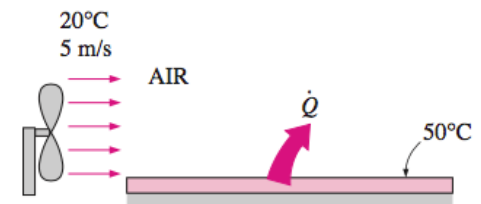
$$Q_{conv} = h_{conv} \cdot A(T_{fluid} - T_{surface}) \quad [W]$$

Two types of surface/fluid convection

- **Natural (or free) convection:** Results from density differences in the fluid caused by contact with the surface to or from which the heat transfer occurs
 - **Buoyancy** is the main driver (temperature dependent density differences)
 - Example: The circulation of air in a room caused by the presence of a solar-warmed window or wall (without a mechanical system) is a manifestation of natural/free convection

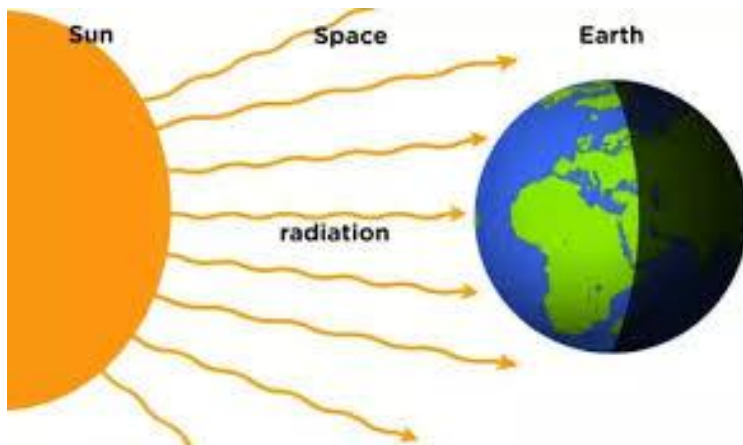


- **Forced convection:** Results from a force external to the problem (other than gravity or other body forces) moves a fluid past a warmer or cooler surface
 - Usually much higher velocities and more random and chaotic flow
 - Driven by mechanical forces (e.g. fans and wind)
 - Example: Heat transfer between cooling coils and an air stream



Heat transfer: Radiation

- Electromagnetic wave exchange between 2 surfaces at different temperatures
- It must be absorbed by the surface to produce internal energy
- Example: Short wave radiation from the Sun to the Earth, and long wave radiation from the Earth to the atmosphere.



Heat transfer: Radiation

- All objects above absolute zero radiate electromagnetic energy according to:

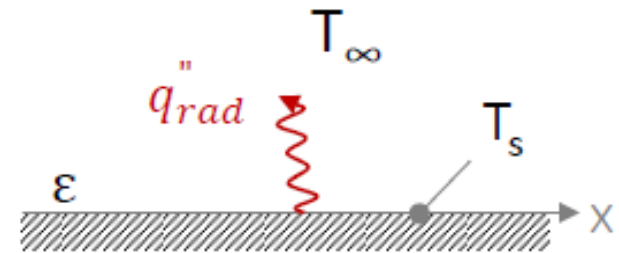
$$q_{rad} = \varepsilon \cdot \sigma \cdot T^4$$

where ε is emissivity, σ is Stefan-Boltzmann constant = 5.670×10^{-8} [W/m²·K⁴], and T is absolute temperature in Kelvin

- General surface-to-air radiation:

$$q_{rad} = \frac{Q_{rad}}{A} = \varepsilon \cdot \sigma \cdot (T_{surface}^4 - T_{\infty}^4)$$

Emissivity (ε) represents effectiveness of the surface in emitting energy as *thermal (infrared) radiation*, can have a value from 0 (shiny mirror) to 1 (blackbody). Real surfaces emit less radiation than ideal “black” ones. For most common building materials (e.g. brick, concrete, wood), emissivity is around 0.9.



Surface	Emittance 50-100 °F
A small hole in a large box, sphere, furnace, or enclosure	0.97 to 0.99
Black nonmetallic surfaces such as asphalt, carbon, slate, paint, paper	0.90 to 0.98
Red brick and tile, concrete and stone, rusty steel and iron, dark paints (red, brown, green, etc.)	0.85 to 0.95
Yellow and buff brick and stone, firebrick, fire clay	0.85 to 0.95
White or light-cream brick, tile, paint or paper, plaster, whitewash	0.85 to 0.95
Window glass	0.90 to 0.95
Bright aluminum paint; gilt or bronze paint	0.40 to 0.60
Dull brass, copper, or aluminum; galvanized steel; polished iron	0.20 to 0.30
Polished brass, copper, monel metal	0.02 to 0.05
Highly polished aluminum, tin plate, nickel, chromium	0.02 to 0.04

Quick: Which heat transfer mode dominates?



Any questions?



Next time...

- Course assignment overview
- Human thermal comfort:
 - Thermal comfort fundamentals
 - Human body heat balance
 - Factors affecting thermal comfort
 - Quiz time



(Source: NY Times)