CIVIL-407
Energy and Comfort in Buildings

Extra slides:

Quick brush-up on Energy and power units, Heat transfer in buildings, Psychrometrics

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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
    - The energy required to extract resources, manufacture, and transport a product
    - Not a focus on this course
- Energy use depends on the rate of energy use and the time/ duration of operation
  - Rate of energy use = Power

Important definitions: Power

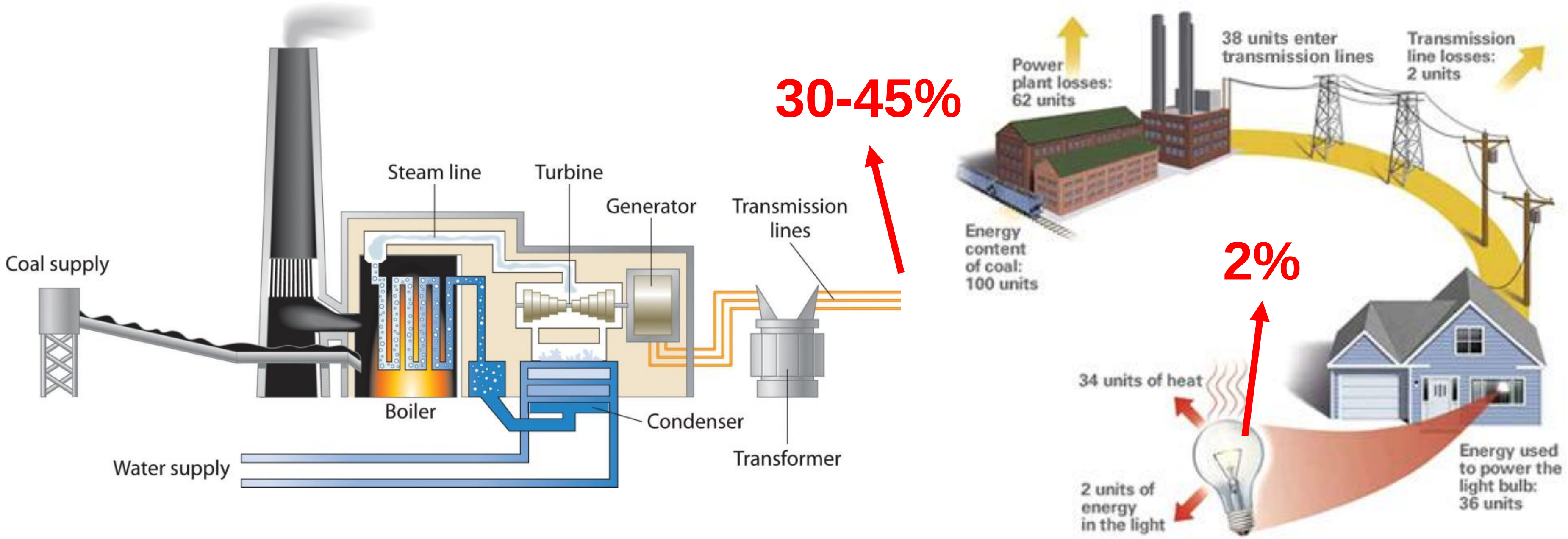
- Definition: Rate at which energy is produced or consumed
    - Unit: Energy per time
    - IP: BTU per hour (BTU/hr) or kBTU per hour (1000 BTU/hr)
    - SI: Watt (W = J/s) or kilowatt (kW = kJ/s) or megawatt (MW = MJ/s)
- Be careful not to mix
    - Many engineers tend to confuse these
- Example: What do batteries store, power or energy?
    - They store energy. The energy is released (Watt-hours) at a rate determined by the equipment's power (Watts, or amperage)

Conversion efficiency

Energy efficiency

- Energy that is utilized versus energy that is not utilized

- **Q:** What is a typical electric power plant efficiency?
- **Q:** What is the “round trip” efficiency for an incandescent light bulb?



(Source: http://www.eia.gov/tools/faqs/faq.cfm?id=107&t=3)

Importance of units!

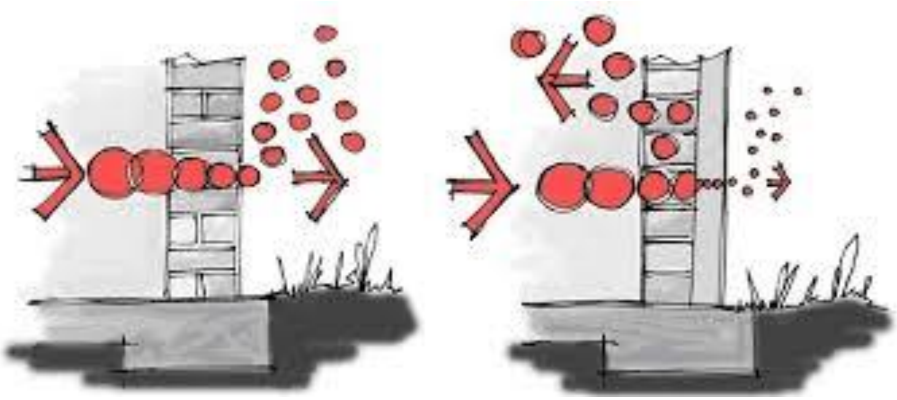
- In building engineering, both SI and IP (inch-pound) units are used
  - Sorry for that!
  - IP: Typically used in USA, UK, Australia, India, Malaysia, New Zealand…
  - SI (Metric units): Used in most of the world.

- Good news!
  - Many countries are slowly transitioning towards a single system – SI
  - We will be mostly using SI units.

- How to convert IP to SI?
  - Just google "IP to SI – ashrae" to download free conversion tool in excel file

Heat transfer in buildings

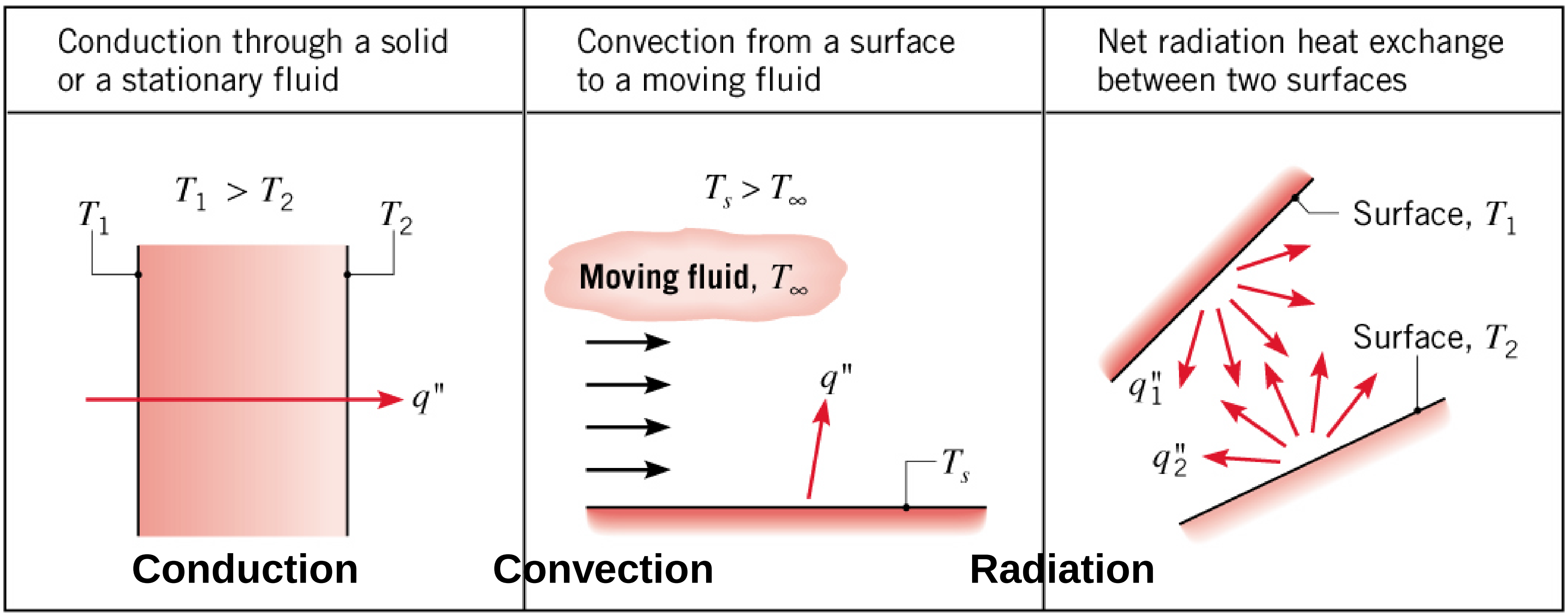
- Transfer of thermal energy between objects with different T
- Knowing heat transfer is important because:
  - We can select and size HVAC equipment to provide indoor comfort
  - Estimate building energy use and operating costs
  - Understand trade-offs in energy efficient design



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

Three dominant modes of heat transfer

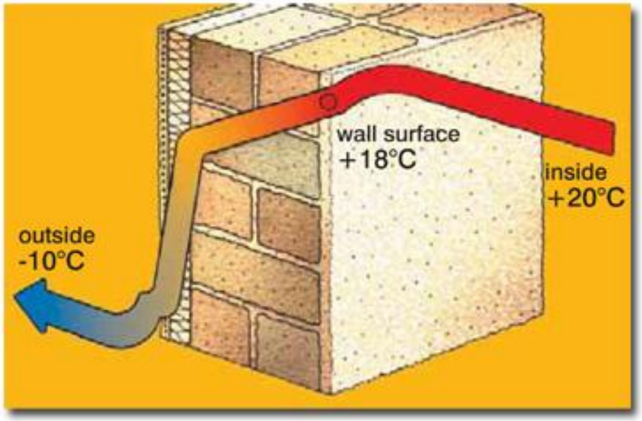
- Conduction: transfer of heat resulting from intermolecular transfer of kinetic energy in solids liquids and gases
- Convection: transfer of heat resulting from larger-scale fluid motion (can be in liquid or in gas)
- Radiation: transfer of heat by means of electromagnetic waves

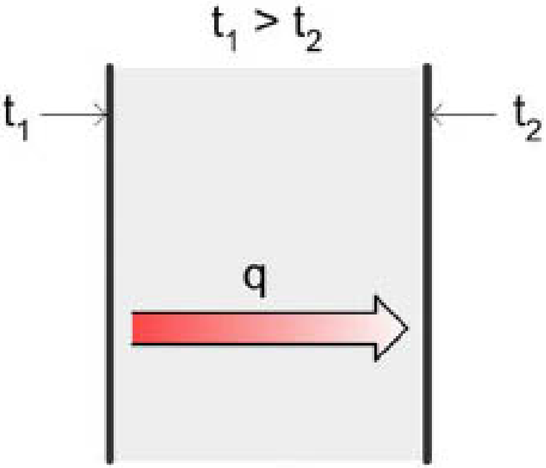


Heat transfer: Conduction

- 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

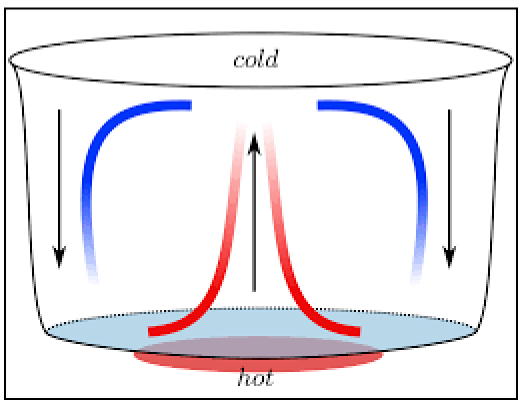


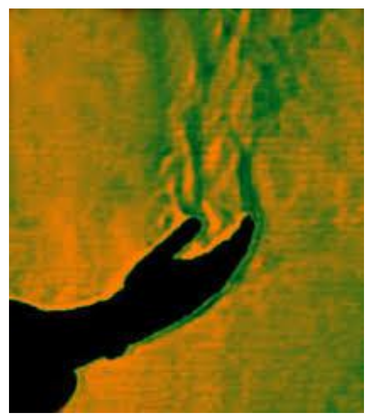
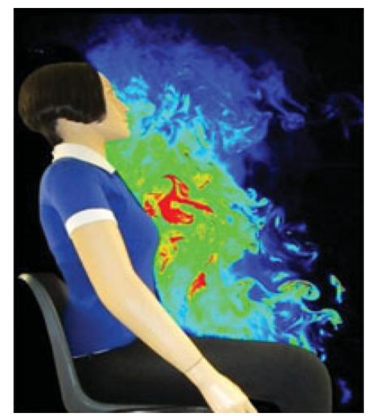
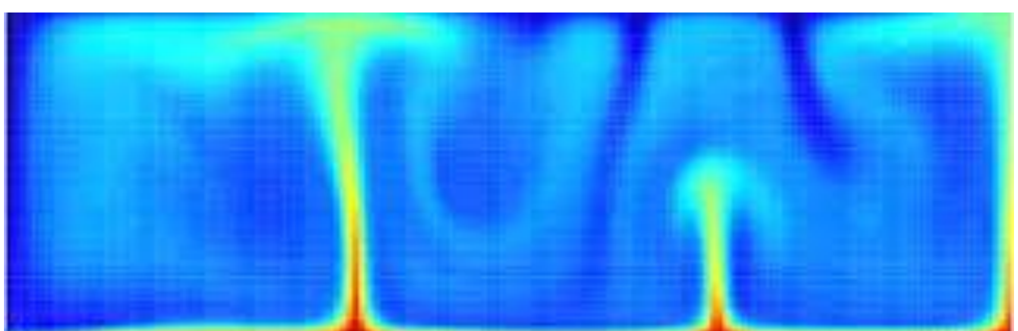
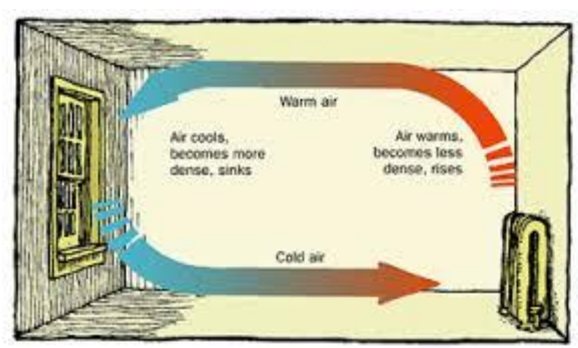


(Source: Images from Google)

Heat transfer: Convection

- 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

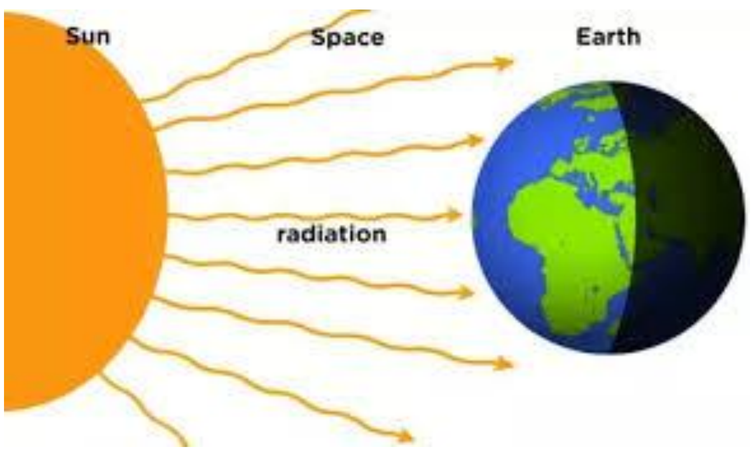


(Sources: Images from Google; Licina et al. 2015 Sci Tech Built Environ)

Heat transfer: Radiation

- Electromagnetic wave exchange between 2 surfaces at different temperatures
- It must be absorbed my 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.



(Source: Images from Google)

Definitions and terminologies

- **Heat flux** (q”, W/m^2) –
  rate of *thermal energy transfer* per *unit area from* or *to* a surface
- **Thermal conductivity** (k or λ, W/m*K) –
  amount of heat than can be conducted during 1 second through 1 m^2 of a **homogeneous** (non-porous materials) layer of material subjected to a gradient in temperature of 1 K/m.
- **Thermal Transmittance** (U-value, W/m^2K) –
  heat transfer coefficient, an indicator of the efficiency to prevent heat conduction
- **Thermal Resistance** (R-value, m^2K/W) –
  the capacity of a material to resist heat flow. The higher the R-value, the greater the insulating power of a material.

Psychrometric chart

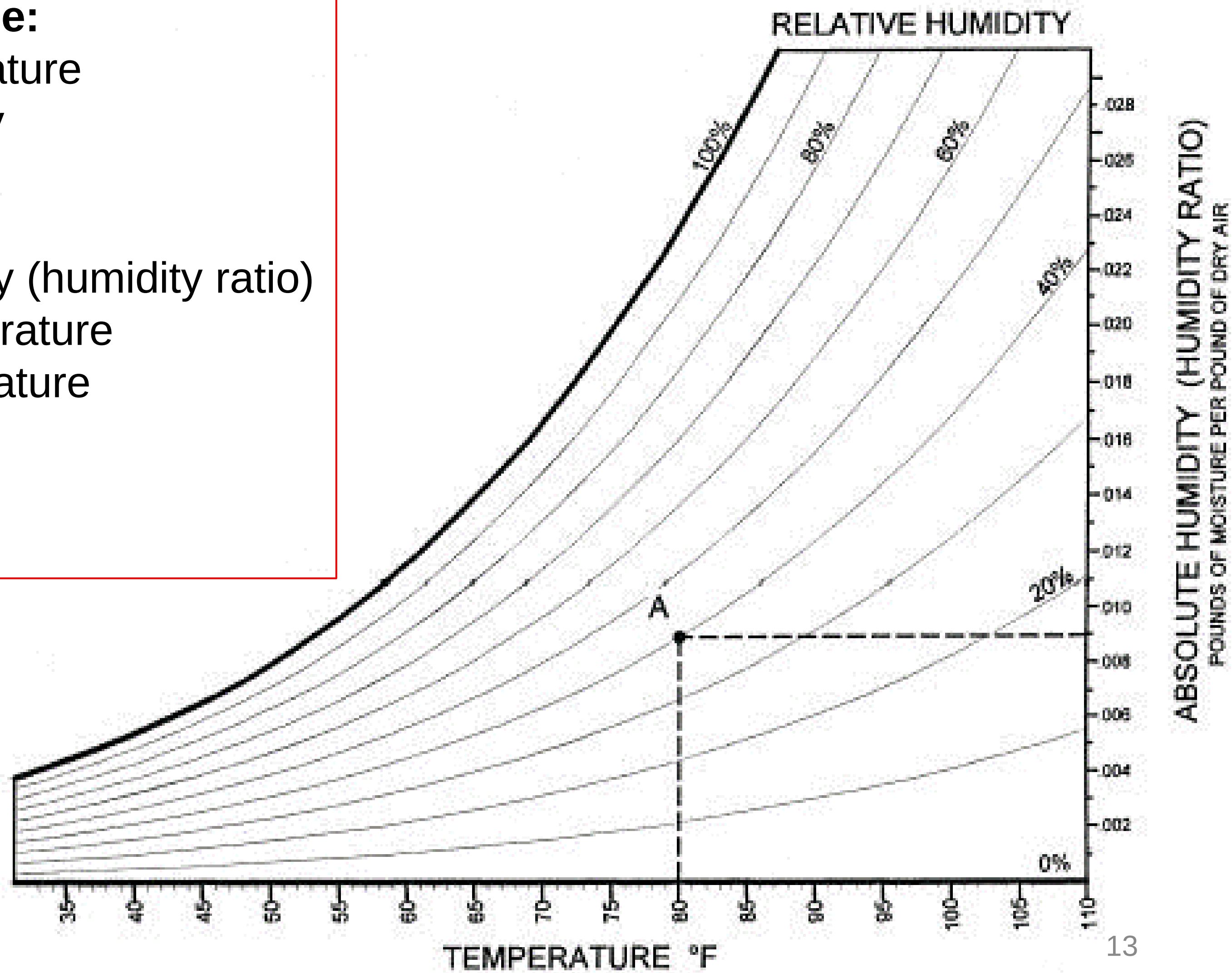
- There are two ways to describe thermodynamic property of the air:
  - With equations and tables (tedious…)
  - Graphically using psychrometric chart

- Psychometric 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 (I have uploaded one on Moodle)
  - You can create your own
  - Best resource is ASHRAE Fundamentals (Chapter 6)

Psychrometric chart

Key terms to revise:
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

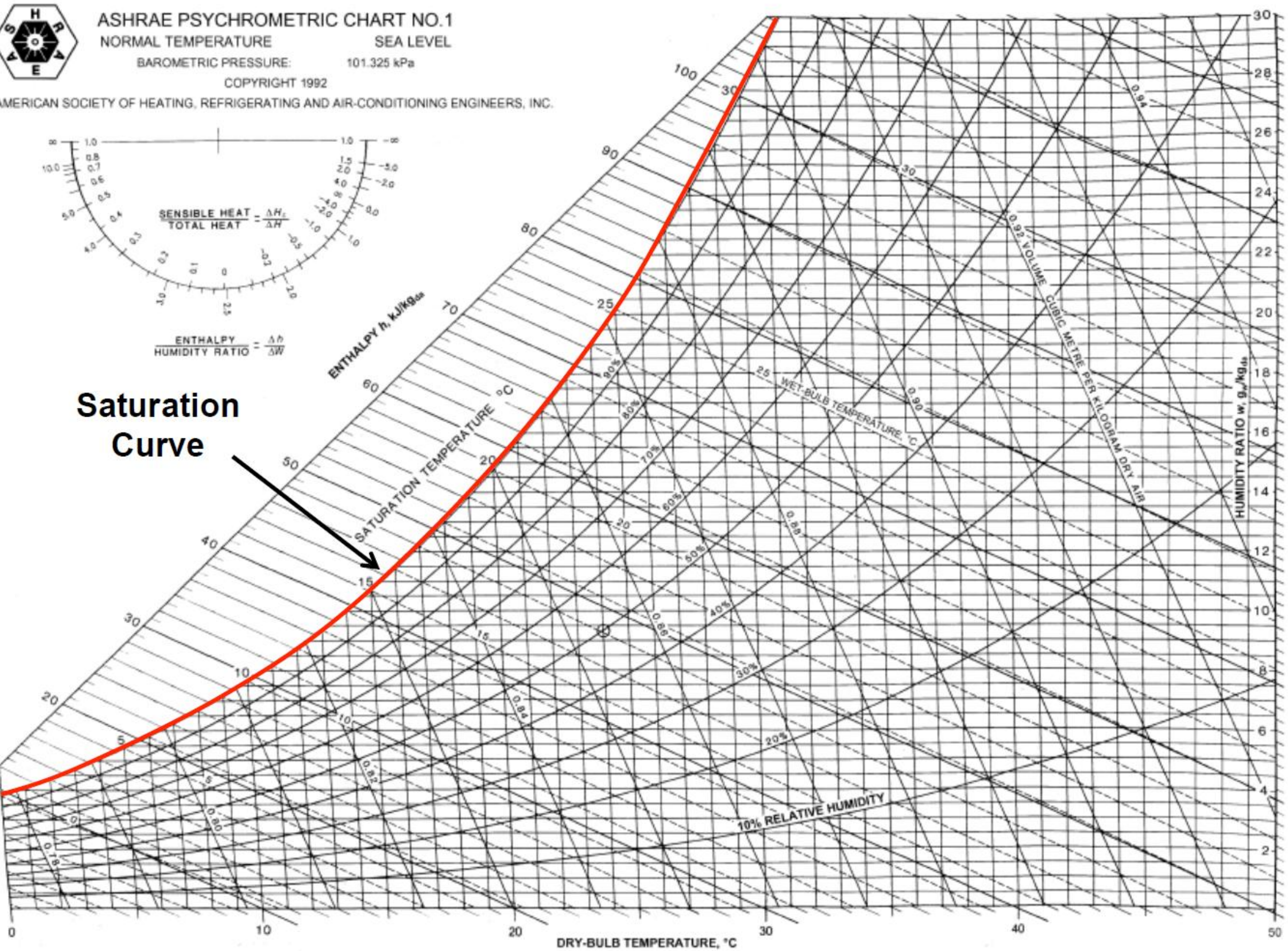


Psychrometric chart: Detailed example

- Lets take the example of typical comfortable indoor conditions:
  - Moist air at 22 ºC 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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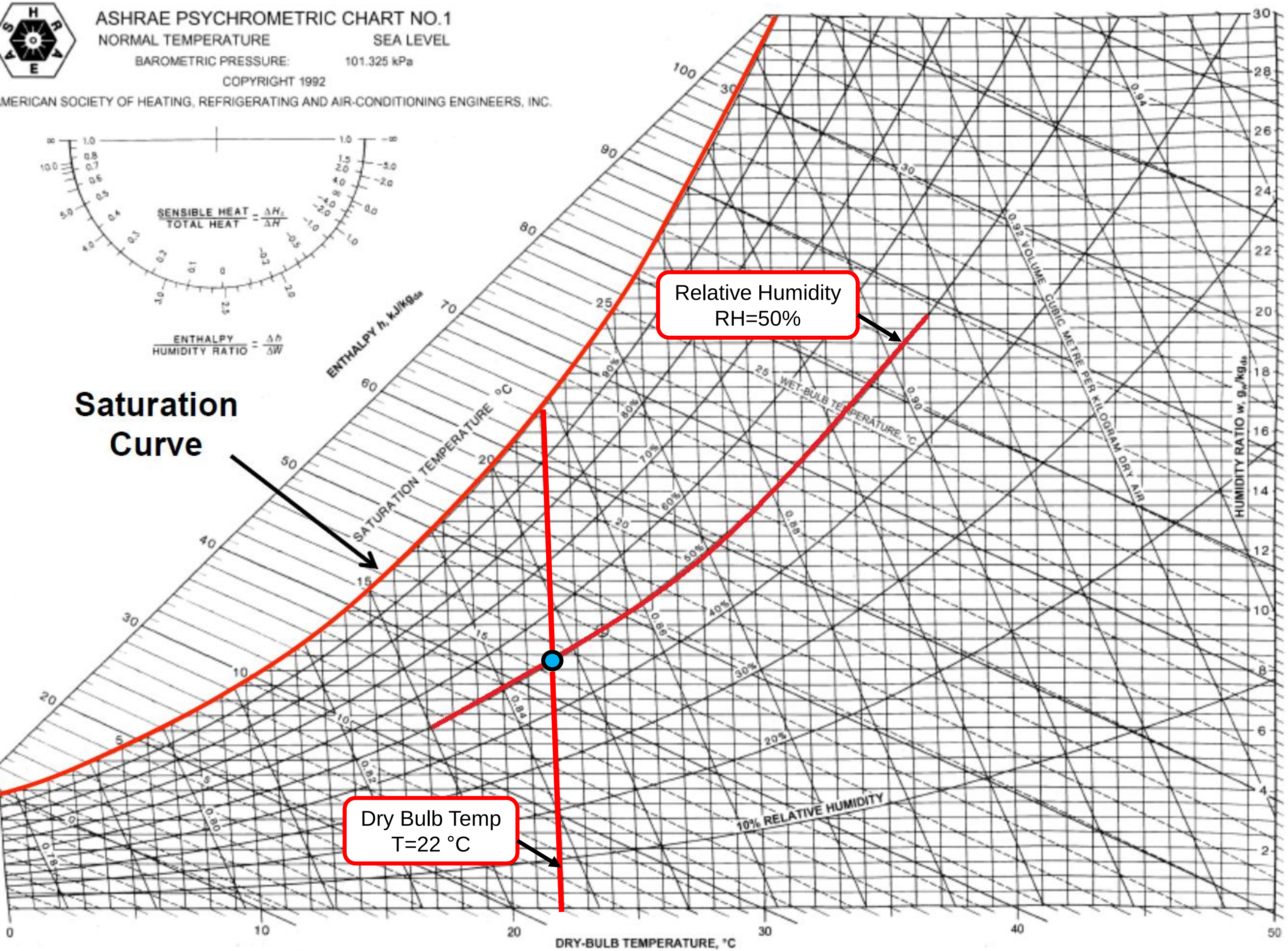
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kgda
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
0.92 VOLUME CUBIC METRE PER KILOGRAM DRY AIR
HUMIDITY RATIO w, gw/kgda
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C
Saturation Curve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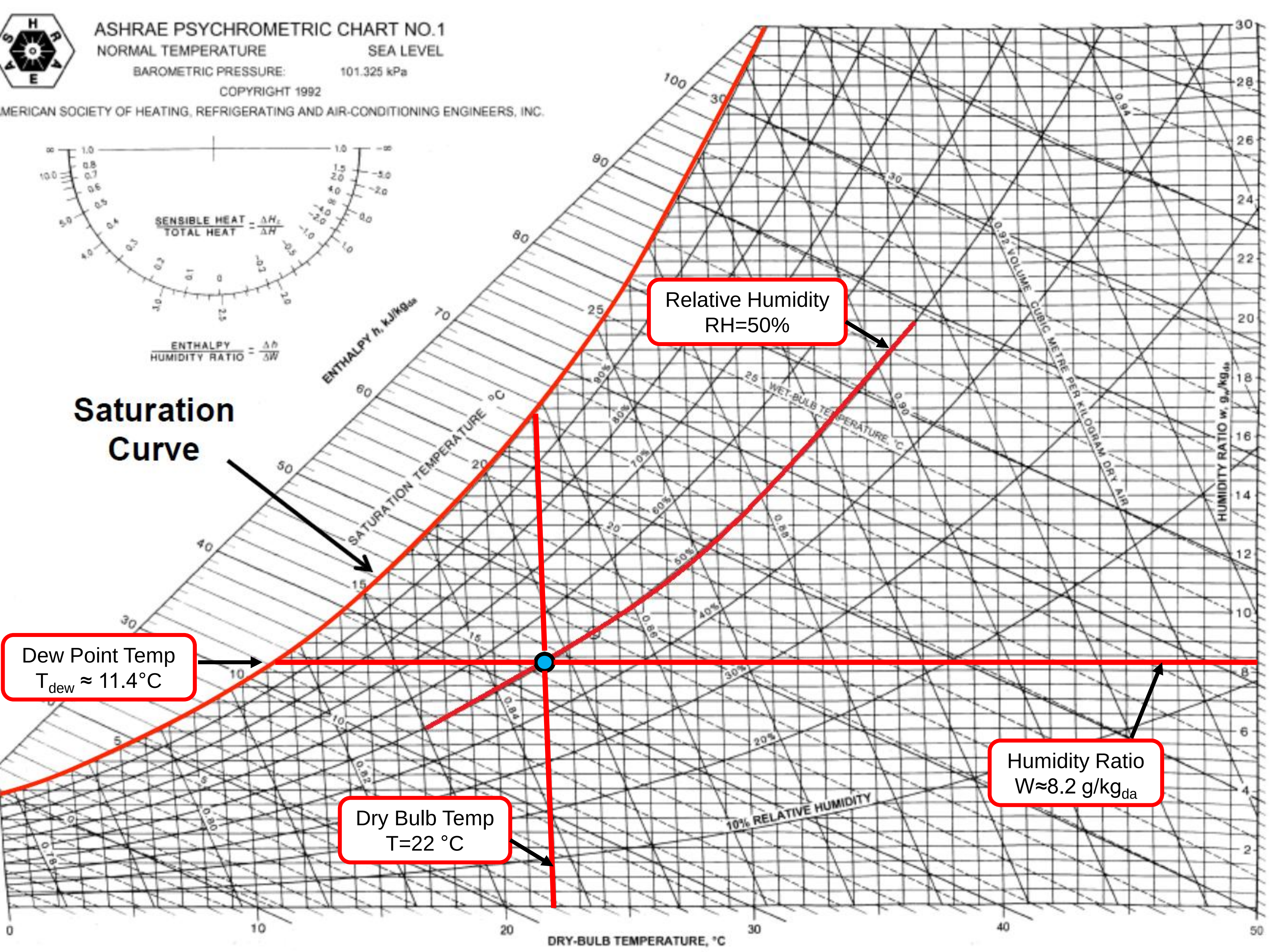
HUMIDITY RATIO w, g/kg
DRY-BULB TEMPERATURE, °C
Saturation Curve
Relative Humidity
RH=50%
Dry Bulb Temp
T=22 °C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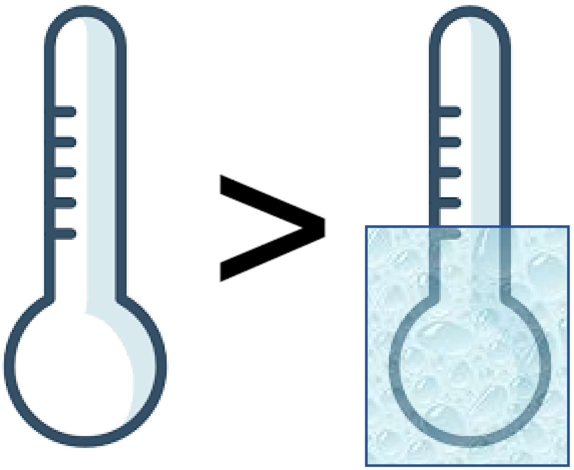
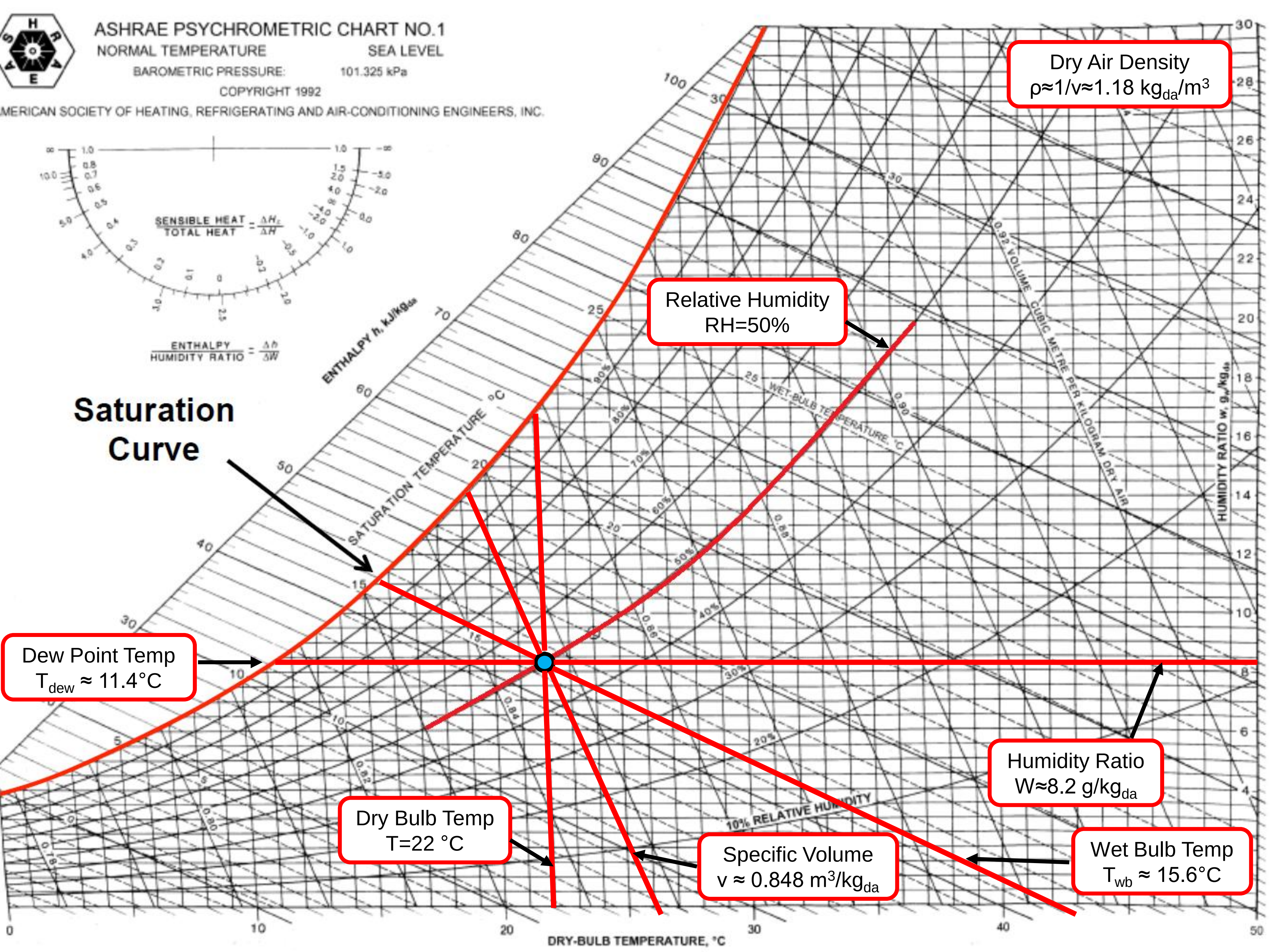
HUMIDITY RATIO w, g w/kg da
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C
Saturation Curve
Relative Humidity RH=50%
Dew Point Temp T dew ≈ 11.4°C
Humidity Ratio W≈8.2 g/kg da
Dry Bulb Temp T=22 °C

Which T do you expect to be higher?

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



- Web-bulb T is lower than dry-bulb T:
  - Evaporating moisture removes heat from thermometer bulb
  - Wet-bulb temperature is the 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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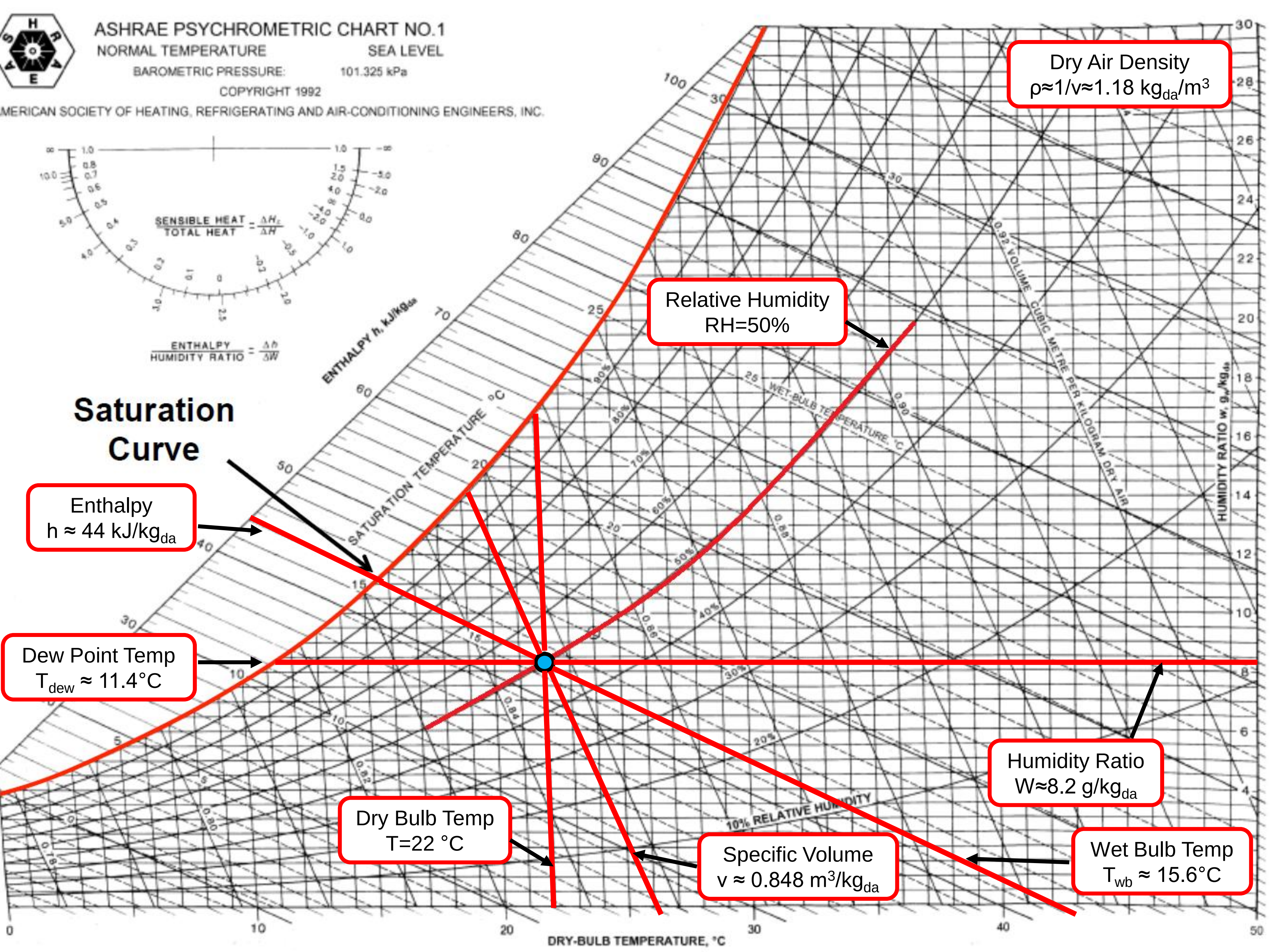
10% RELATIVE HUMIDITY
HUMIDITY RATIO W, g w/kg da
DRY-BULB TEMPERATURE, °C
Saturation Curve
Dry Air Density
ρ≈1/v≈1.18 kg da/m3
Relative Humidity
RH=50%
Dew Point Temp
T dew ≈ 11.4°C
Humidity Ratio
W≈8.2 g/kg da
Dry Bulb Temp
T=22 °C
Specific Volume
v ≈ 0.848 m3/kg da
Wet Bulb Temp
T wb ≈ 15.6°C



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VOLUME CUBIC METRE PER KILOGRAM DRY AIR
HUMIDITY RATIO w, g/kg da
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C
Saturation Curve
Dry Air Density ρ≈1/v≈1.18 kg_da/m³
Relative Humidity RH=50%
Enthalpy h ≈ 44 kJ/kg_da
Dew Point Temp T_dew ≈ 11.4°C
Humidity Ratio W≈8.2 g/kg_da
Dry Bulb Temp T=22 °C
Specific Volume v ≈ 0.848 m³/kg_da
Wet Bulb Temp T_wb ≈ 15.6°C

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
- 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: DIY exercise #1

- Lets take an example of hot indoor conditions
  - Moist air at 30 ºC dry-bulb temperature
  - Dew point temperature at 15 ºC

Find the following:

- the humidity ratio, W
- wet-bulb temperature, T_{wb}
- specific volume, v
- relative humidity, RH
- enthalpy, h

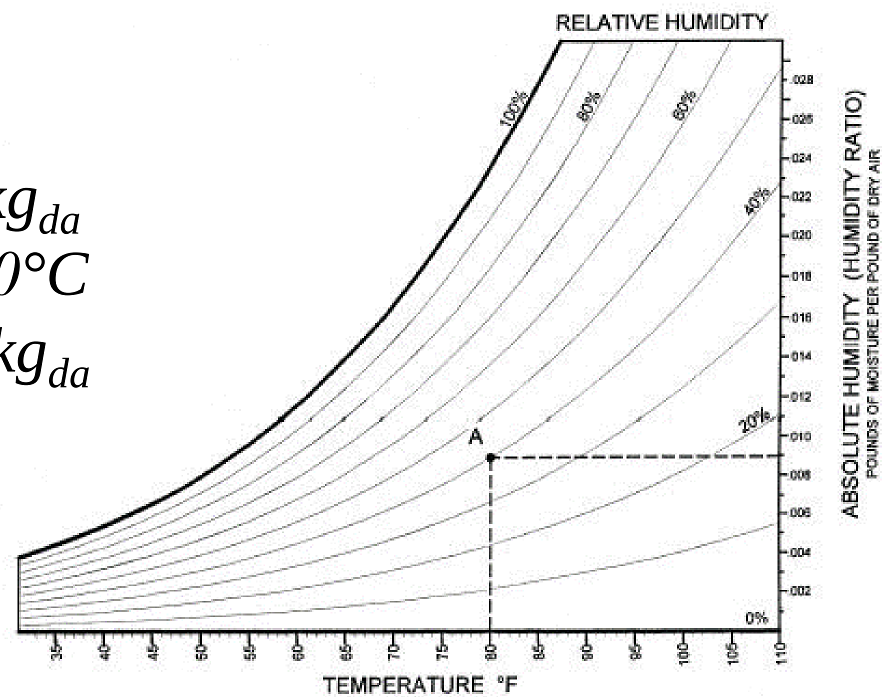
You can download the chart here or from Moodle:
https://www.ashrae.org/File%20Library/Technical%20Resources/Bookstore/UP3/SI-1.pdf

Psychrometric chart: Solutions

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

Solutions:

- the humidity ratio, $W \approx 10.7\ g/kg_{da}$
- wet-bulb temperature, $T_{wb} \approx 20°C$
- specific volume, $v \approx 0.875\ m^3/kg_{da}$
- relative humidity, RH $\approx 40\%$
- enthalpy, $h \approx 58\ kJ/kg_{da}$



Psychrometric chart: DIY exercise #2

- 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 °C
- relative humidity, RH = 80%

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

Psychrometric chart: Solution

- 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 °C
- relative humidity, RH = 80%

Solution:

- Air will condense on windows when the outside air temperature is below 23 °C

Processes useful for this course