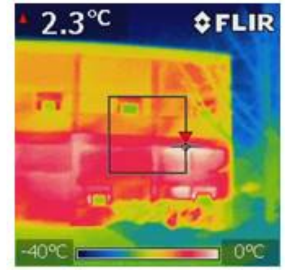
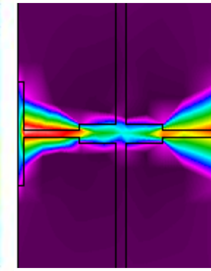
CAE 331/513
Building Science
Fall 2018





September 27, 2018
Introduction to HVAC systems

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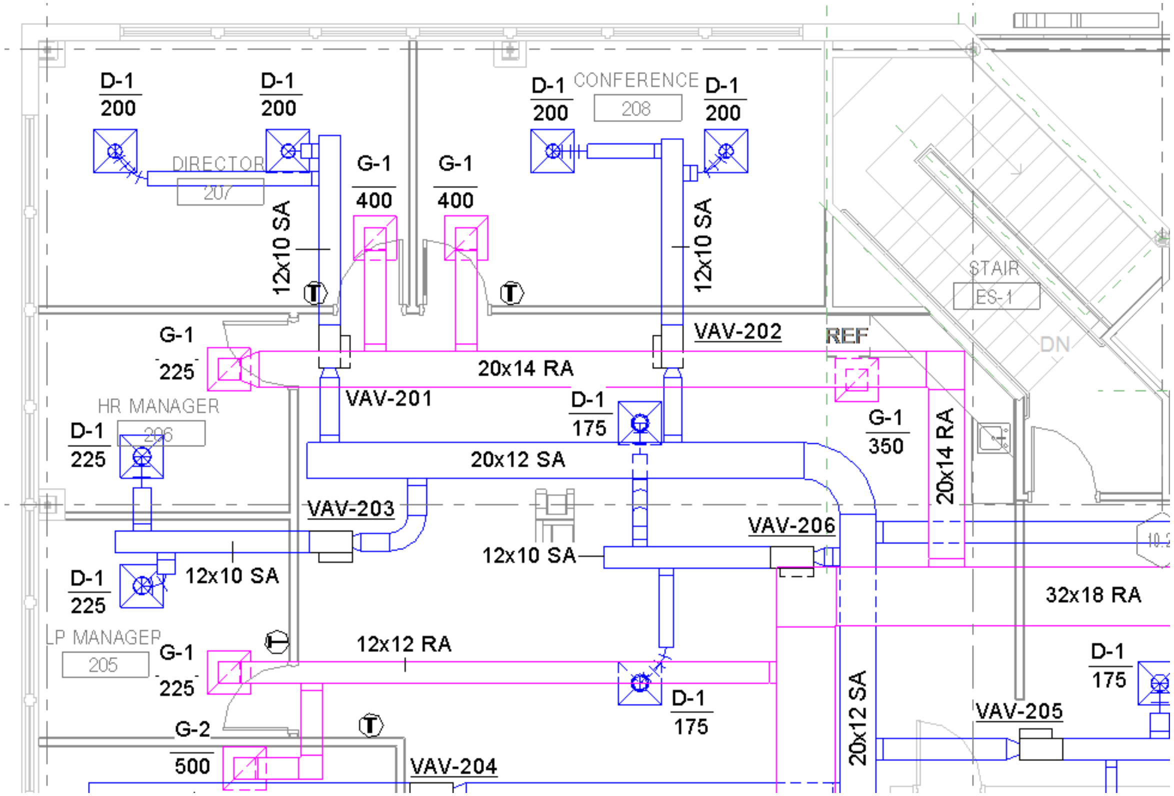
Dr. Brent Stephens, Ph.D.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
brent@iit.edu



OVERVIEW OF HVAC SYSTEMS

What do they look like and what are common processes?

Major functions of HVAC systems

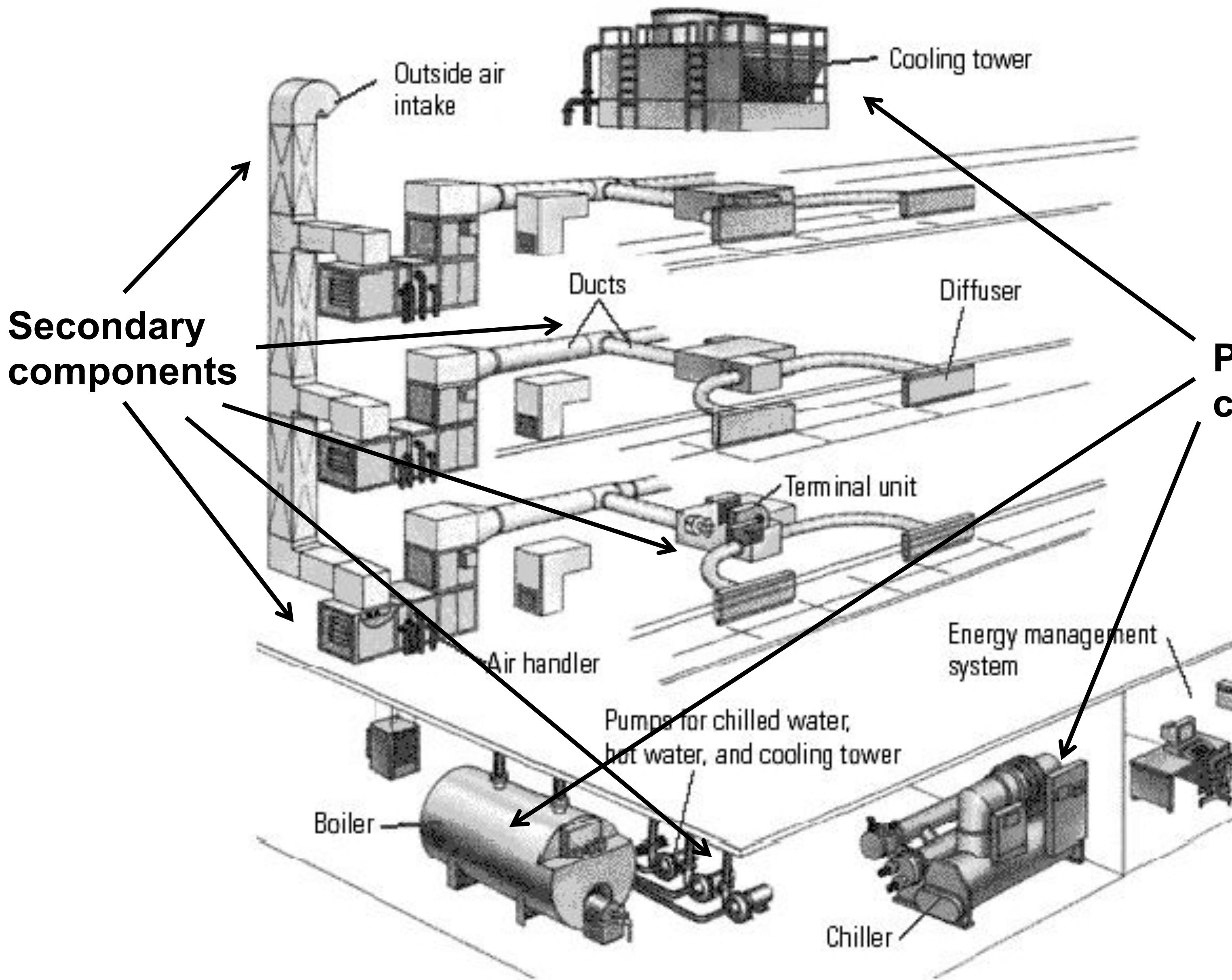
- Achieving thermal comfort
  - Cooling or heating air
  - Humidification of cold, dry air
  - Dehumidification of warm, humid air
- Providing adequate ventilation (outdoor air)
- Removing contaminants from the air (filters)

HVAC systems overview

- Primary mechanical systems
  - Vapor compression systems (i.e., chillers and condenser units)
    - Electrically driven
    - Thermally driven
  - Cooling towers
  - Evaporative coolers

- Secondary mechanical systems
  - Distribution systems (both air and water)

Typical components of an HVAC system



HVAC system design options

- We can rely on **central** HVAC systems
  - One system per building
  - May control all zones similarly or different zones differently
    - Depends on system type
- Or we can rely on **distributed** HVAC systems for every zone
  - Motels, strip malls, apartment buildings
- Need to figure out what medium we will use for heat transfer
  - Air, steam, water?
- Need to determine what capacity and efficiency we need
  - More on this in future lectures

Central vs. distributed systems

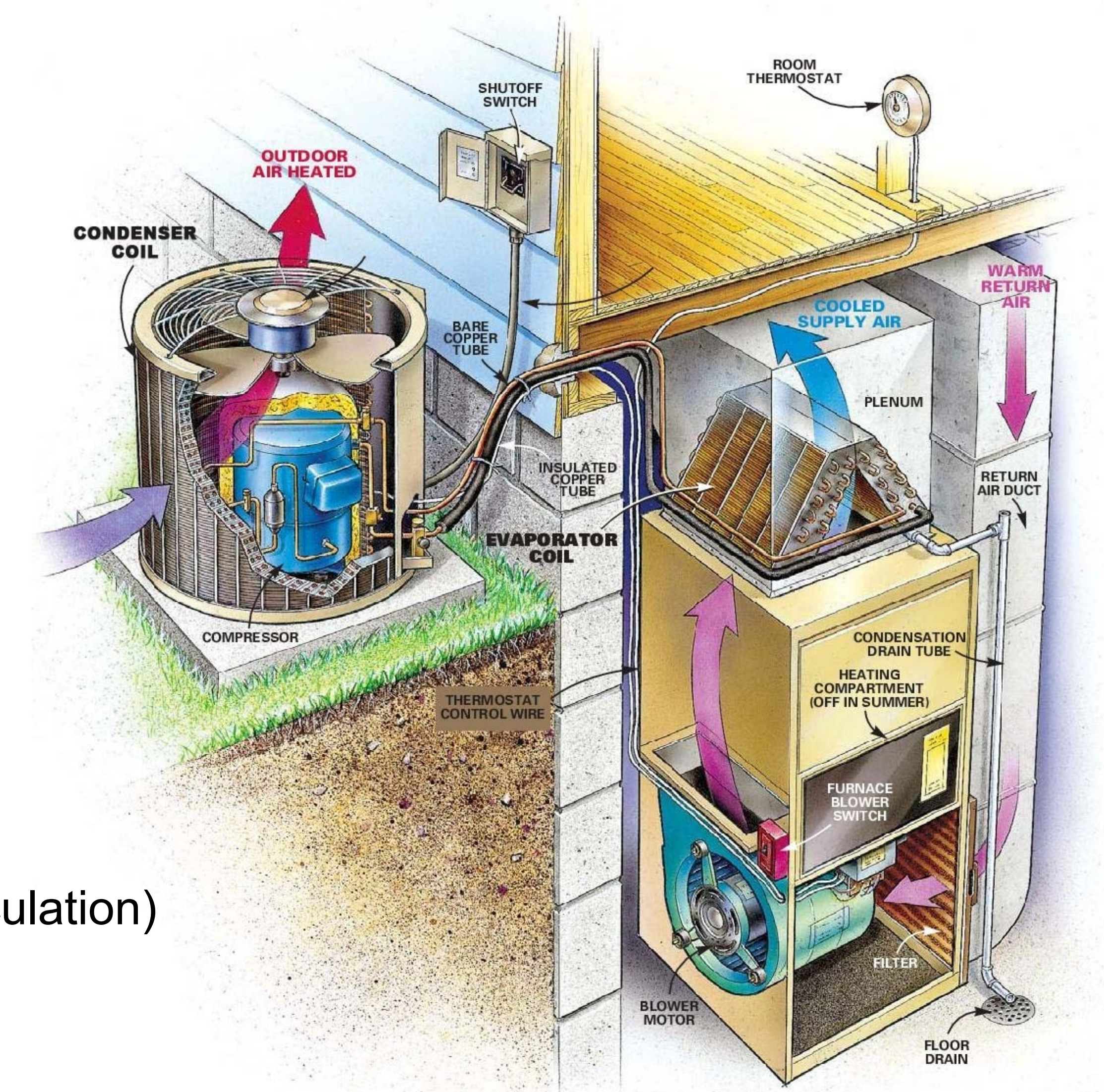
Central systems

- Large equipment has higher quality, efficiency, and durability
- Maintenance is concentrated in one place
- Noise is removed from zone
- Diversity of loads allows lower installed capacity
- Can use thermal storage solutions

Distributed systems

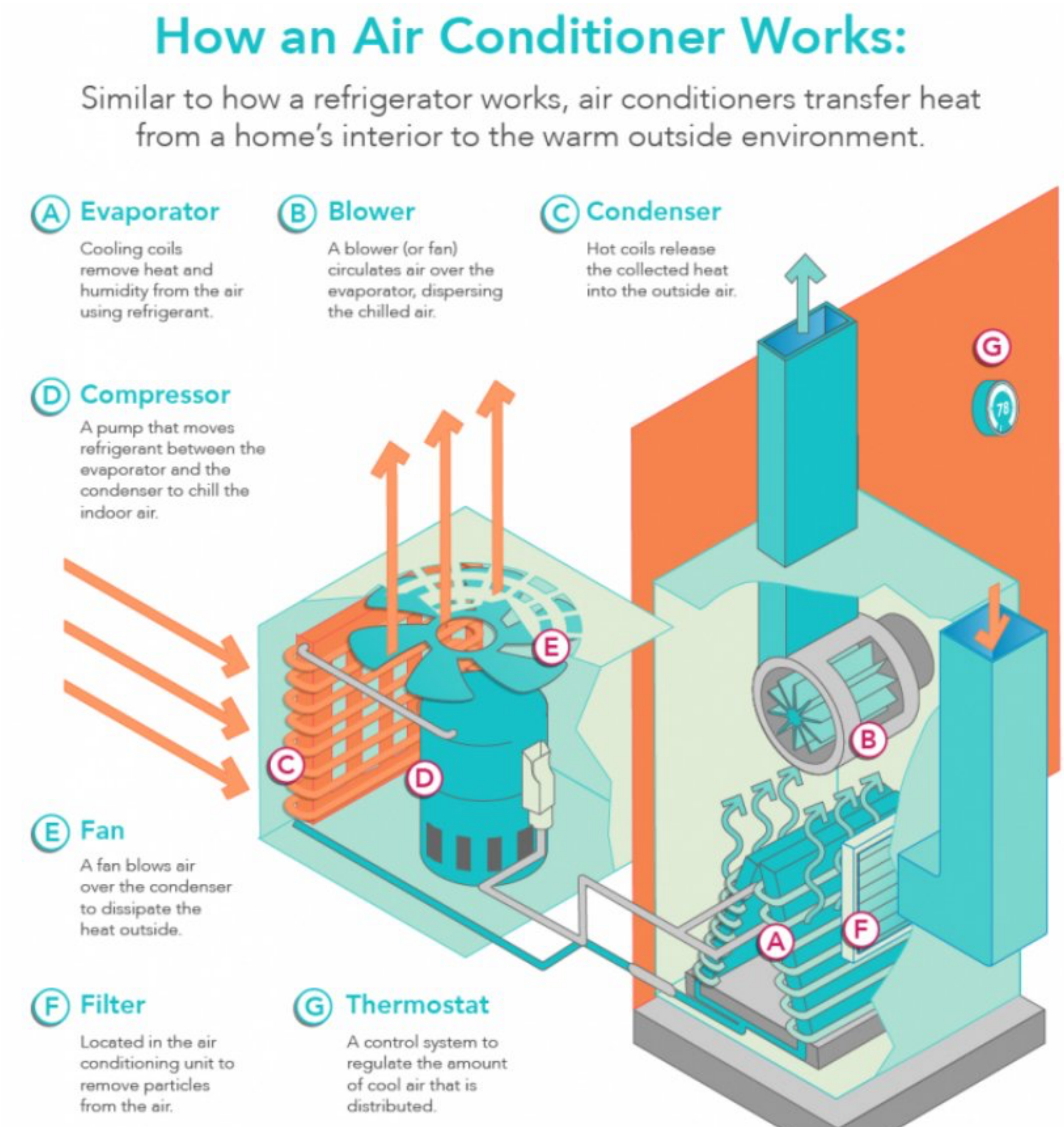
- Easy to provide zoning
- Direct control by occupants
- Easier independent scheduling for energy savings
- Generally lower capital costs and shorter lead time for equipment
- Don't need dedicated maintenance staff
- Can often install on roof (saves room in the building)

Typical central residential system

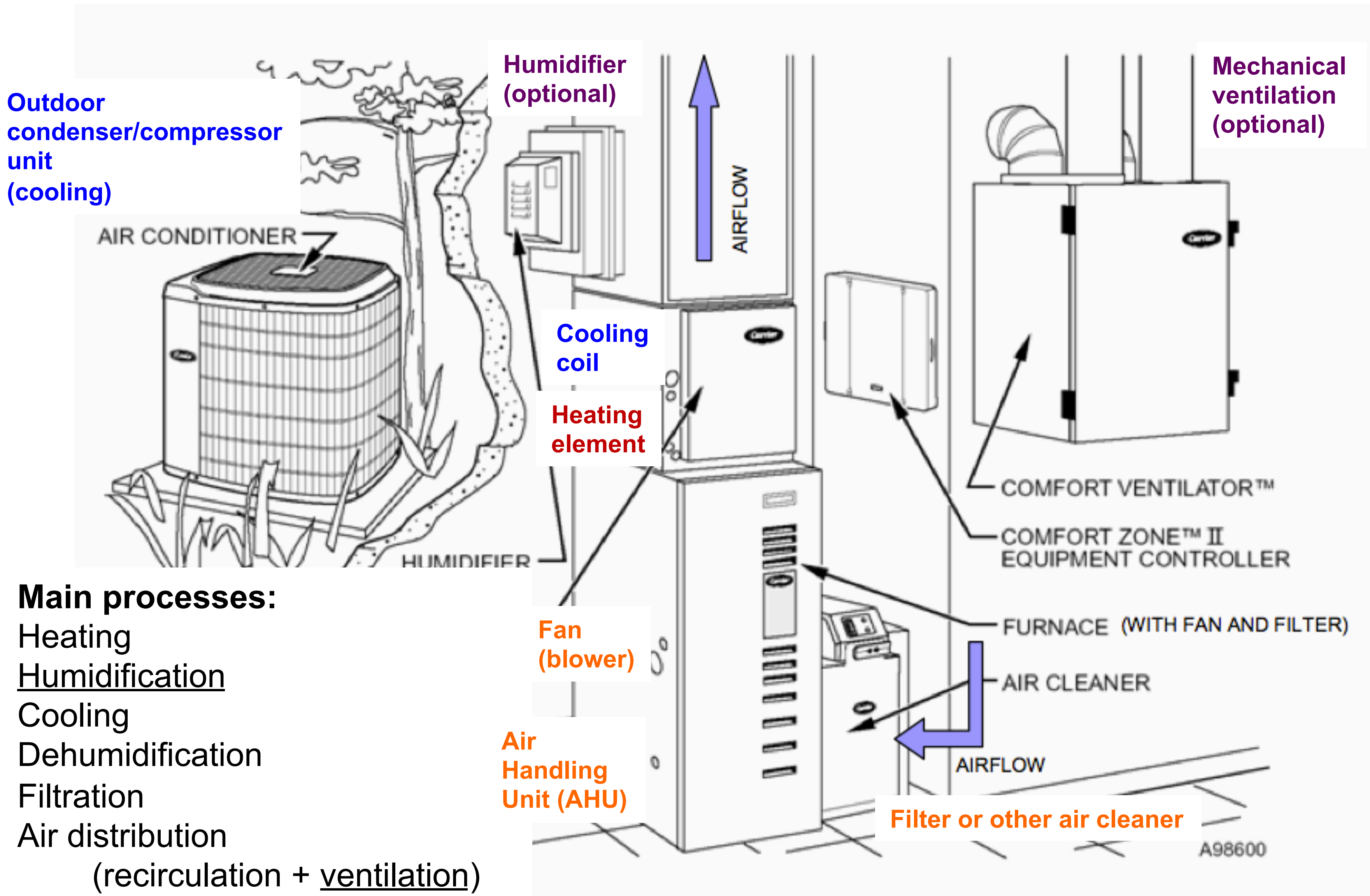


Main processes:
Heating
Cooling
Dehumidification
Filtration
Air distribution (recirculation)
On/off control

Typical central residential system



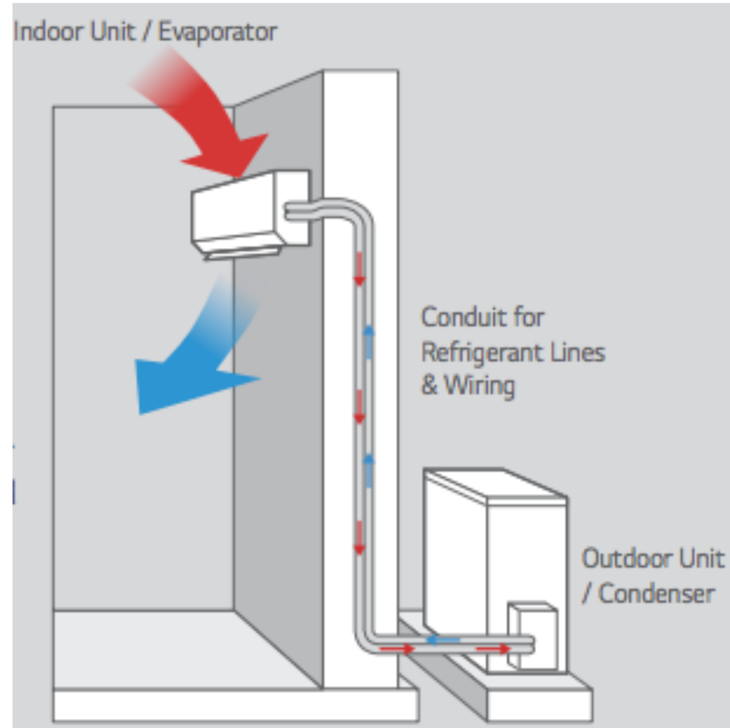
Typical central residential system w/ upgrades



Main processes:

Heating
<u>Humidification</u>
Cooling
Dehumidification
Filtration
Air distribution
(recirculation + <u>ventilation</u>)
On/off control (or <u>variable control</u>)

Modern ductless residential system (“mini-split”)



Cooling: Refrigeration systems

- **Refrigeration** is the process of extracting heat from a lower temperature heat source, substance, or cooling medium, and transferring it to a higher temperature heat sink
  - Refrigeration maintains the temperature of the heat source below that of its surroundings while transferring the extracted heat, and any required energy input, to a heat sink (such as atmospheric air or surface or ground water)

- A **refrigeration system** is a combination of components and equipment connected in a sequential order to produce the refrigeration effect

Types of refrigeration systems

- **Vapor compression systems** (most commonly used)
  - Compressors activate the refrigerant by compressing it to a higher pressure and higher temperature after it has produced its refrigeration effect (high P, high T)
  - The compressed refrigerant transfers its heat energy to the sink (e.g., ambient air) and then is condensed into a liquid
  - The liquid refrigerant is then throttled (i.e., expands) to a low pressure, low temperature vapor (low P, low T) to produce the refrigerating effect during evaporation
  - The refrigeration cycle then repeats itself

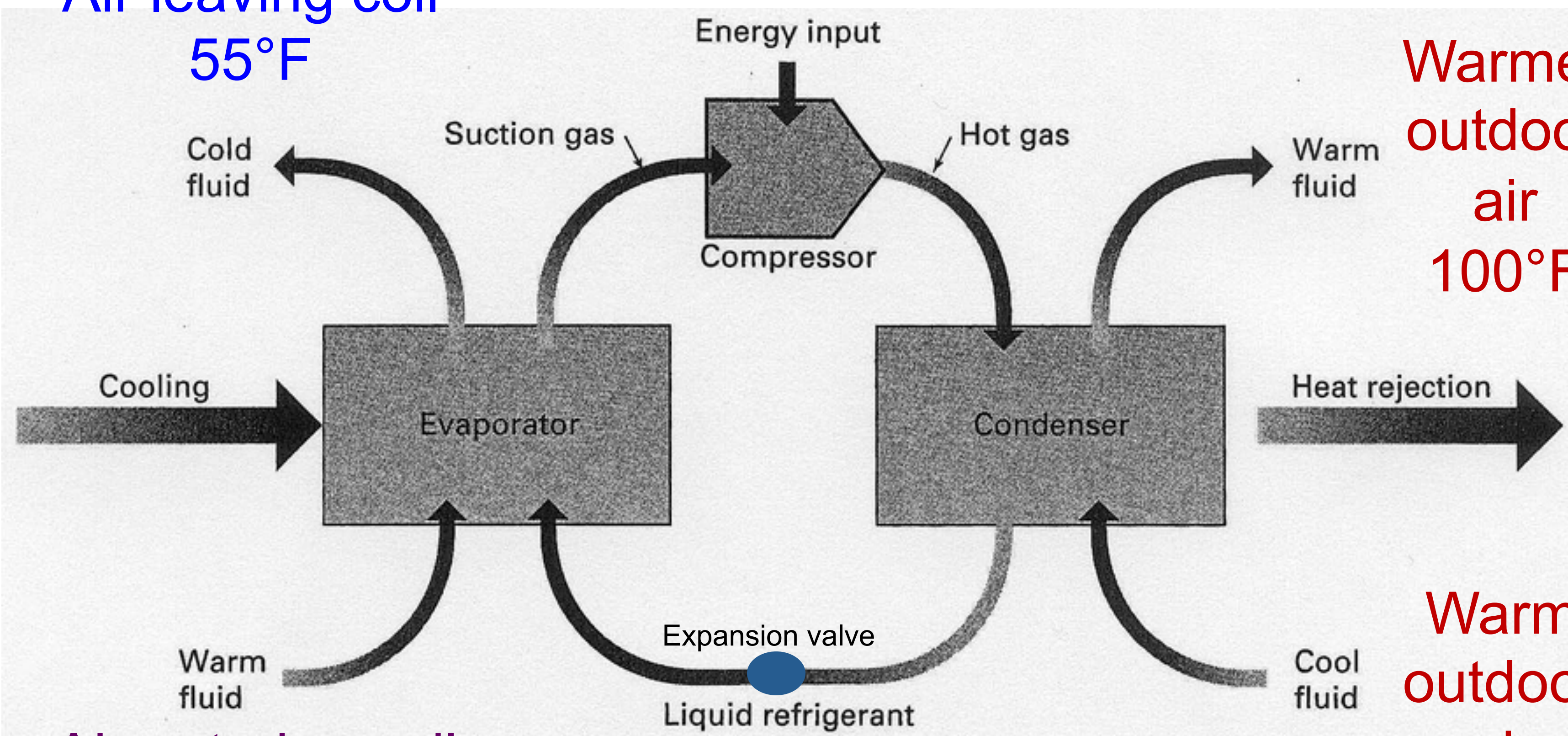
Fundamentals of vapor compression systems

https://www.youtube.com/watch?v=2wZb6HgIDE0

Typical vapor compression cycle: Air-conditioning unit

Air leaving coil
55°F

Warmer outdoor air
100°F

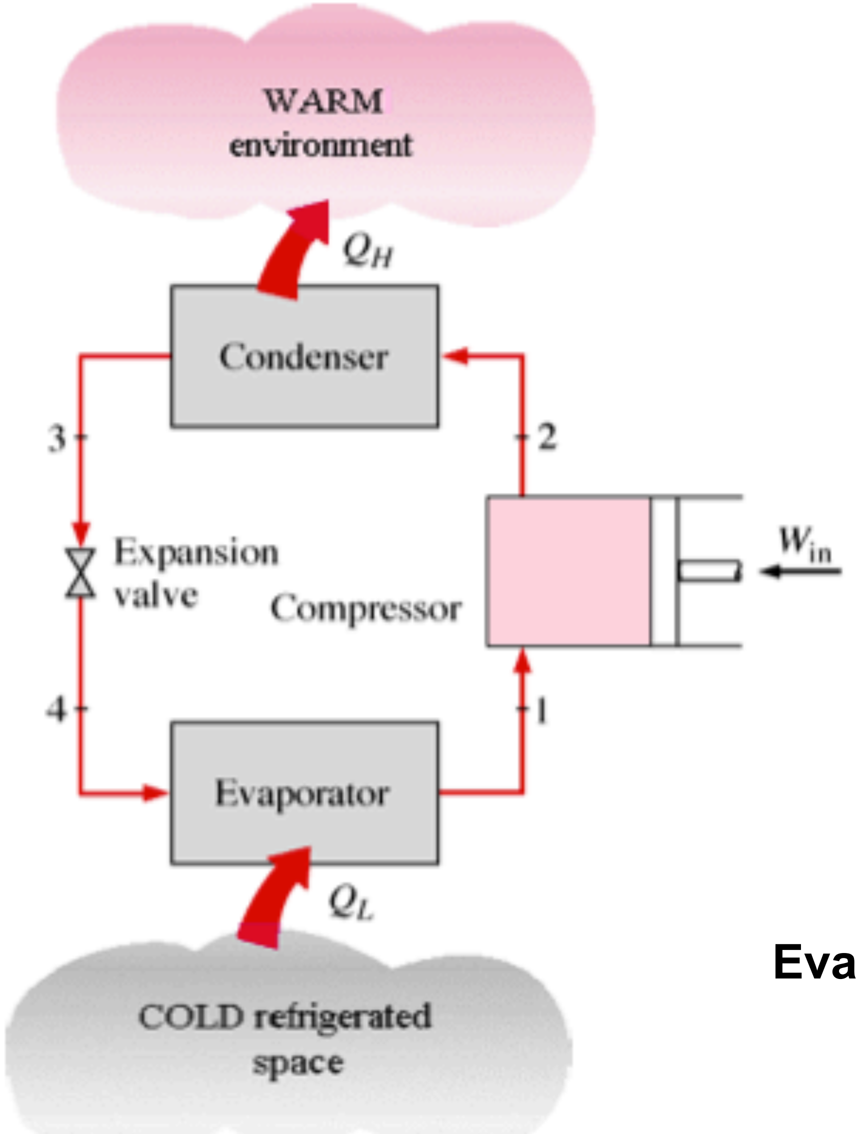


Warm outdoor air
90°F

Air entering coil
75°F

Changing refrigerant T and P

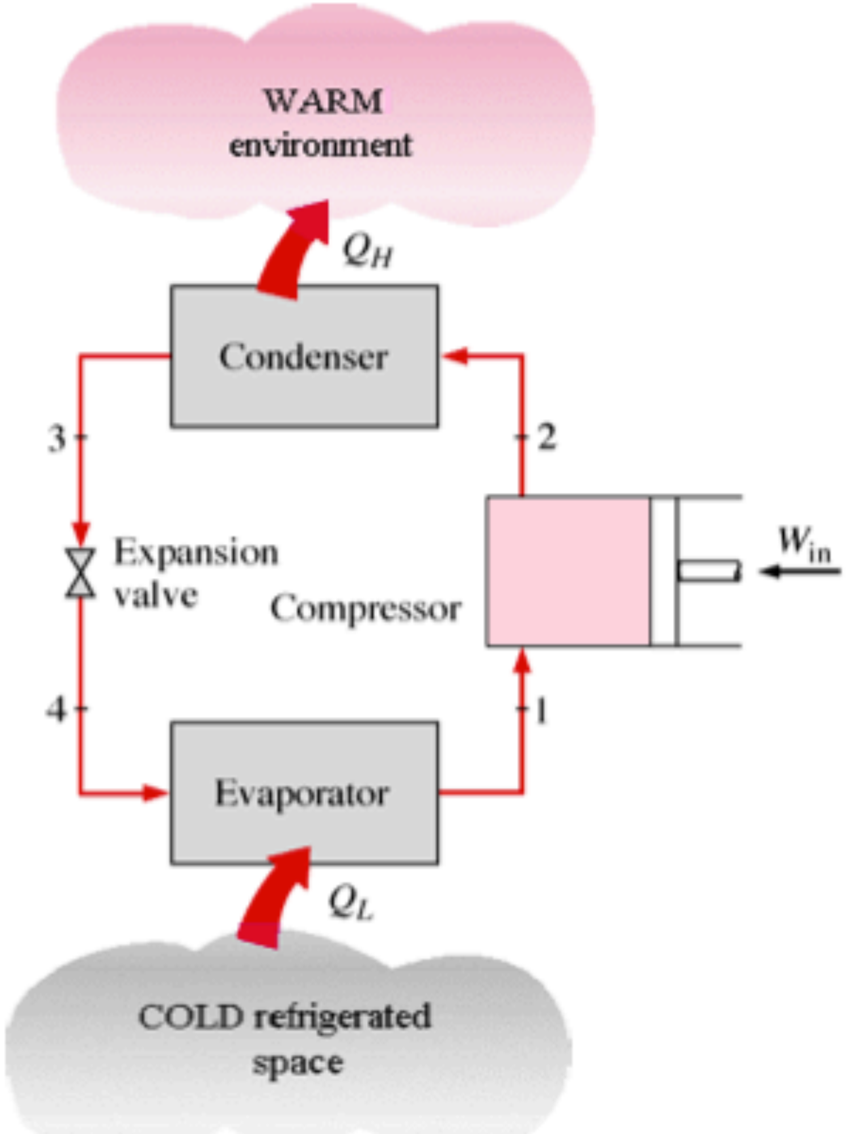
Ideal single-stage vapor compression cycle



Expansion valve
(creates the high P restriction)

Evaporator coil

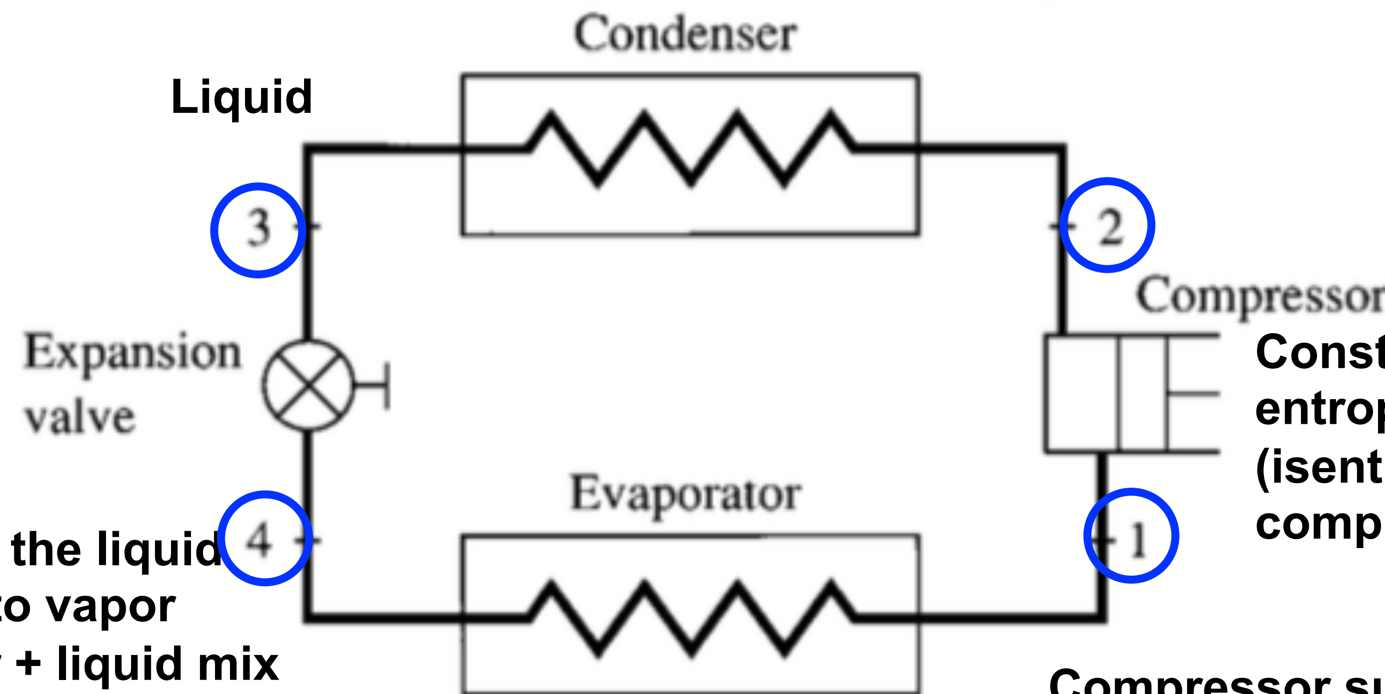
Ideal single-stage vapor compression cycle



Ideal single-stage vapor compression cycle

Latent heat of condensation
(rejected to heat sink)

Liquid



Constant
entropy
(isentropic)
compression

Some of the liquid
flashes to vapor
- Vapor + liquid mix

Rest of liquid
evaporates at
evaporating
temperature

Compressor suction
- "suction pressure"

Question: What is the COP?

A. Congressional Observer Publications
B. California Offset Printers
C. Coefficient of Performance ←
D. Slang for a police officer

$$COP = \frac{\text{Provided cooling energy [W or BTU/hr]}}{\text{Used electric energy [W or BTU/hr]}}$$

Equivalent to the efficiency of an air-conditioning unit

Joke courtesy of Jeff Siegel, University of Toronto

What is the efficiency of a typical residential AC unit?

A. 10%
B. 50%
C. 80%
D. 100%
E. 300% ←

What do we need to know about cooling systems?

Equipment selection example:

A load calculation determines you need 1.2 tons of water cooling

1 ton = 12000 Btu/hr
1.2 tons = 14,400 Btu/hr

You would choose a 1.35 ton capacity unit

<u>1.35 ton is accurate for:</u>
115°F air condenser temp
and
50°F of leaving water temperature

SPECIFICATIONS	IK-	.25A	.33A	.5A	.75A	1A	1.5A	2A	2W	3W	3A	4A
COMPRESSOR	Capacity[2]	.25	.32	.41	.70	.98	1.35	2	2	3	3	4
	HP each	.25	.33	.50	.75	1	1.5	2	2	3	3	4
	Type[3]	H	H	H	H	H	H	H	H	H	H	H

Notes: 1. Full load amps must be used for sizing disconnects and supply wiring. 2. Tons of capacity at 12,000 BTU/ton @ 50°F LWT @ 105°F condensing temperature for water-cooled units and 115°F for air-cooled units. Capacities may be +/- 5% as reserved by the compressor manufacturer. Capacity multipliers are 50°F - 1.00; 40°F -.80; 30°F - .60; 20°F - .40. The minimum recommended operating temperature when no glycol is used is 48°F. 3. H - hermetic compressor used on this model. 4. Consult factory for 50hz operation. 5. Approximate unit weight crated for shipment.

AC capacity and efficiency changes with outdoor T, indoor T/RH, and airflow rates

Table 4. Example Manufacturer EPT (Subset of Data Displayed)

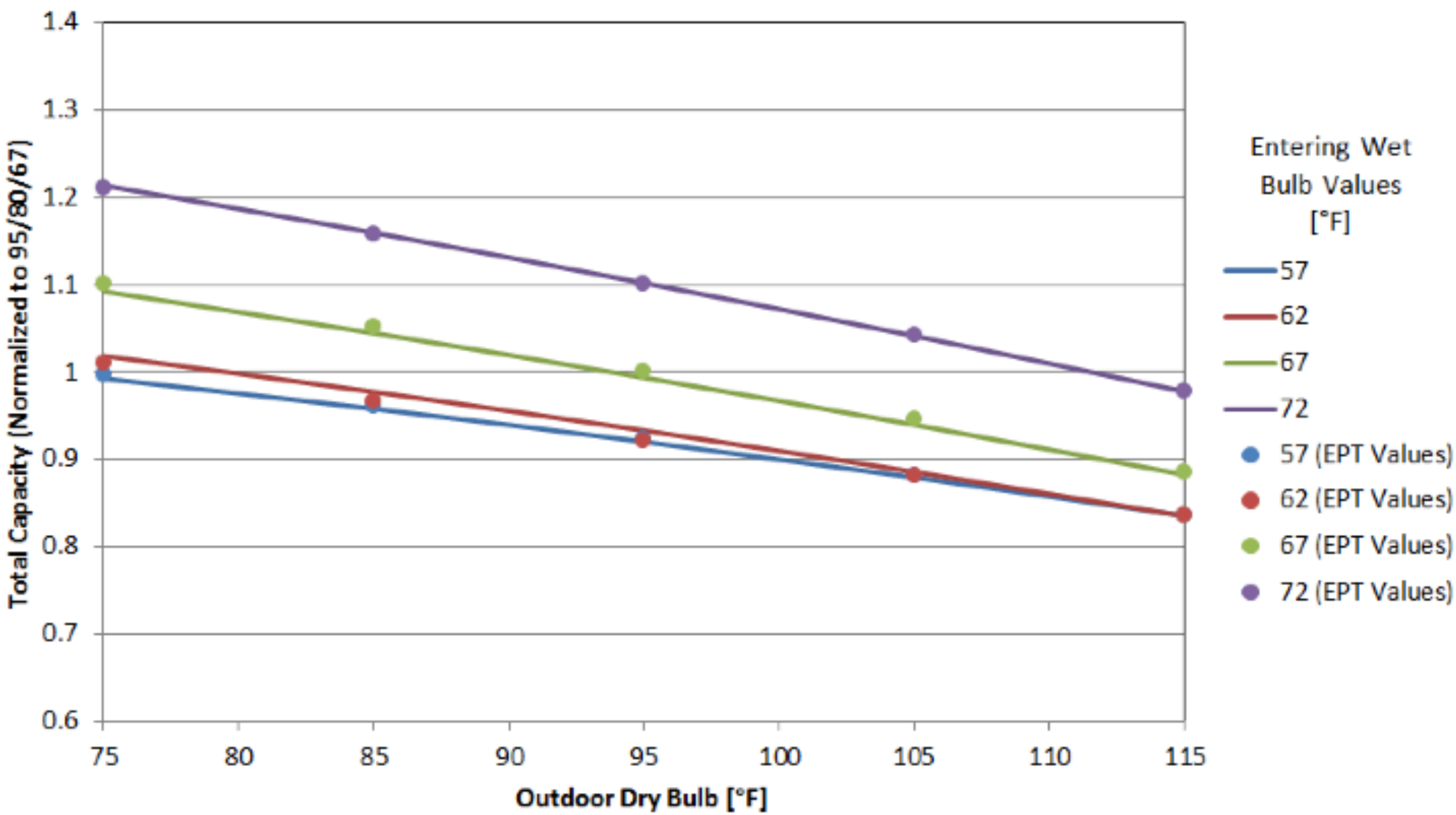
Evaporator Air		Condenser Air °F (°C)								
		75 (23.9)			95 (35)			105 (40.6)		
cfm	EWB °F (°C)	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[1,2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]
875	72 (22)	34.32	17.27	1.96	31.24	16.13	2.44	29.59	15.54	2.71
	67 (19)	31.45	21.21	1.96	28.59	20.05	2.43	27.04	19.44	2.71
	63 (17)	29.35	20.58	1.96	26.66	19.40	2.43	25.19	18.78	2.70
	62 (17)	28.82	25.13	1.95	26.24	23.94	2.43	24.86	23.29	2.70
	57 (14)	28.00	28.00	1.95	25.89	25.89	2.43	24.74	24.74	2.70
1000	72 (22)	34.88	18.05	2.01	31.66	16.90	2.48	29.96	16.30	2.76
	67 (19)	31.98	22.49	2.01	29.00	21.31	2.48	27.40	20.68	2.75
	63 (17)	29.88	21.78	2.00	27.07	20.58	2.48	25.55	19.95	2.75
	62 (17)	29.44	26.90	2.00	26.81	26.81	2.48	25.62	25.62	2.75
	57 (14)	29.10	29.10	2.00	26.85	26.85	2.48	25.62	25.62	2.75
1125	72 (22)	35.27	18.78	2.06	17.61	17.61	2.53	30.22	17.07	2.81
	67 (19)	32.36	23.68	2.05	22.50	22.50	2.53	27.66	21.88	2.80
	63 (17)	30.25	22.90	2.05	21.70	21.70	2.52	25.82	21.07	2.80
	62 (17)	30.02	28.49	2.05	27.62	27.62	2.52	26.32	26.32	2.80
	57 (14)	29.99	29.99	2.05	27.62	27.62	2.52	26.32	26.32	2.80

[1] Total and sensible capacities are net capacities. Blower motor heat has been subtracted.

[2] Sensible capacities shown are based on 80°F (27°C) entering air at the indoor coil. For sensible capacities at other than 80°F (27°C), deduct 835 Btu/h (245 W) per 1000 cfm (480 L/S) of indoor coil air for each degree below 80°F (27°C), or add 835 Btu/h (245 W) per 1000 cfm (480 L/s) of indoor coil air per degree above 80°F (27°C).

[3] System kilowatt is the total of indoor and outdoor unit kilowatts.

AC capacity and efficiency changes with outdoor T, indoor T/RH, and airflow rates



EER and SEER

- EER = Energy Efficiency Ratio
  - Same as COP but in mixed units: (Btu/hr)/W
  - Example from previous page:

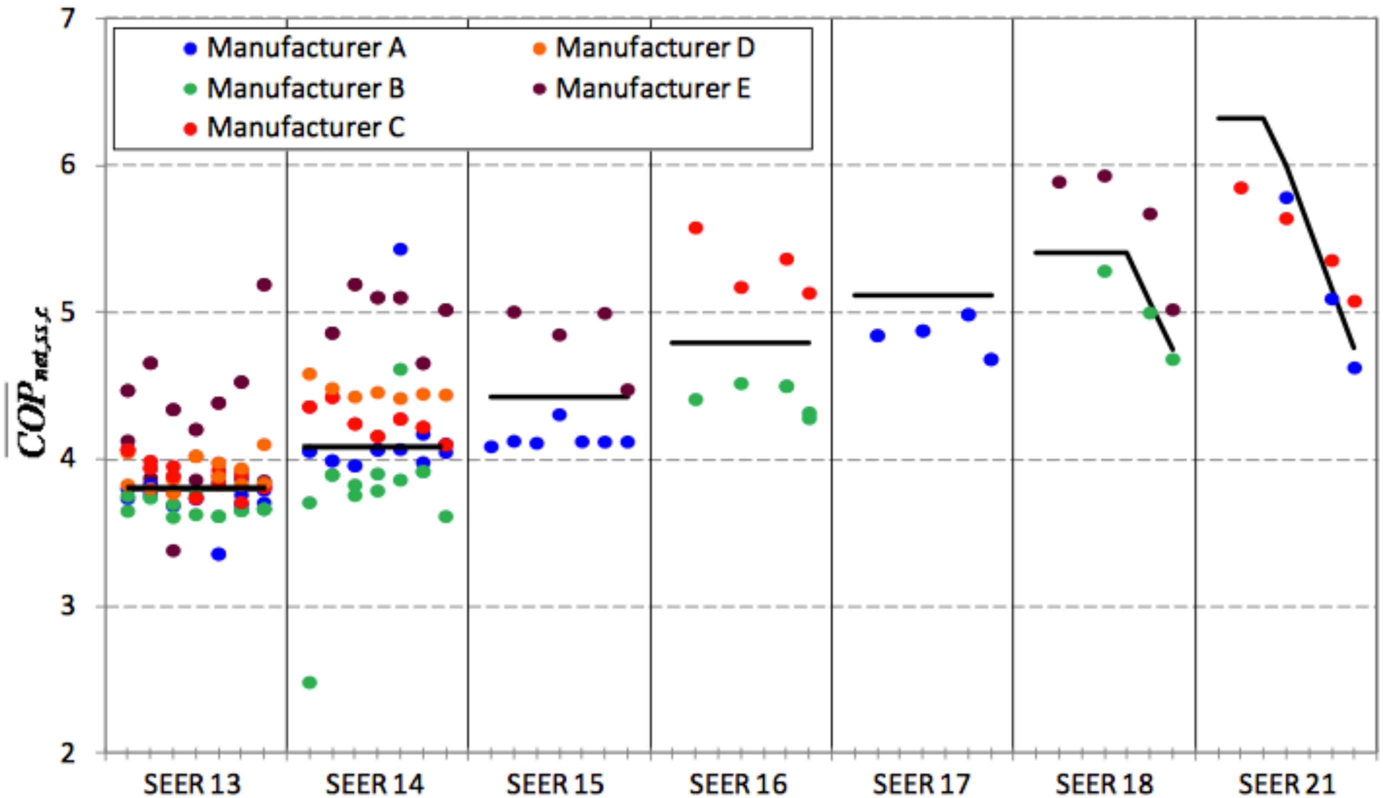
$$COP = \frac{8.5\ [\text{kW}]}{2.48\ [\text{kW}]} = 3.43 \qquad EER = \frac{29.0\ [\text{kBtu/hr}]}{2.48\ [\text{kW}]} = 11.7$$

$$EER = COP \times 3.41$$

- SEER = Seasonal Energy Efficiency Ratio, units: [Btu/Wh]
  - Cooling output during a typical cooling season divided by the total electric energy input during the same period
  - Represents expected performance over a range of conditions

$$EER \approx -0.02 \times SEER^2 + 1.12 \times SEER$$

EER and SEER



- AC units must be 14 SEER (or 12.2 EER) beginning on January 1, 2015 if installed in southeastern region of the US

Using COP to estimate power draw and energy consumption

- If you know the cooling load and you know the COP, you can estimate the instantaneous electric power draw required to meet the load:

$$\mathrm{P}_{elec} = \frac{Q_{cooling,load}}{COP}$$

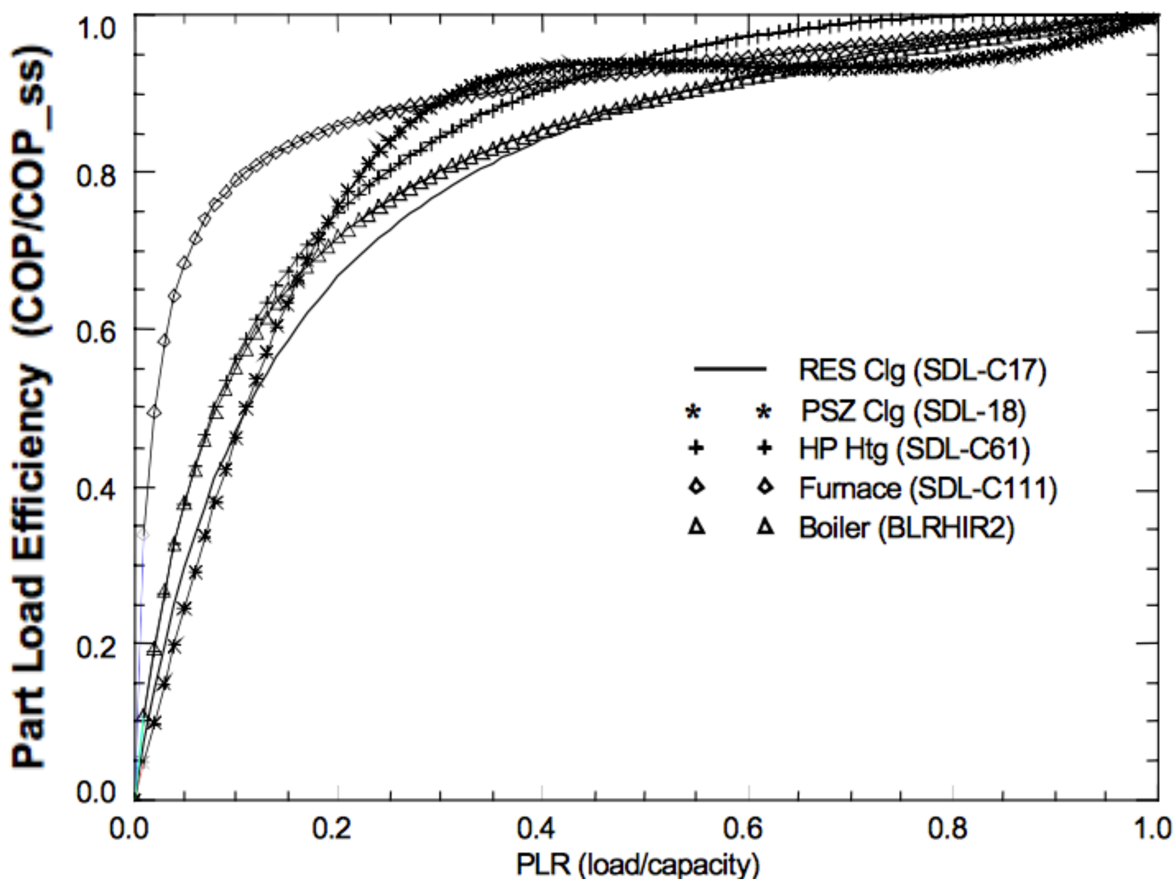
- If you multiply by the number of hours and sum over a period of operating time, you can estimate energy consumption:

$$E = \sum \mathrm{P}_{elec}\, \Delta t$$

- You can also split data into bins if COP/EER changes with varying conditions

Part-load ratio (PLR)

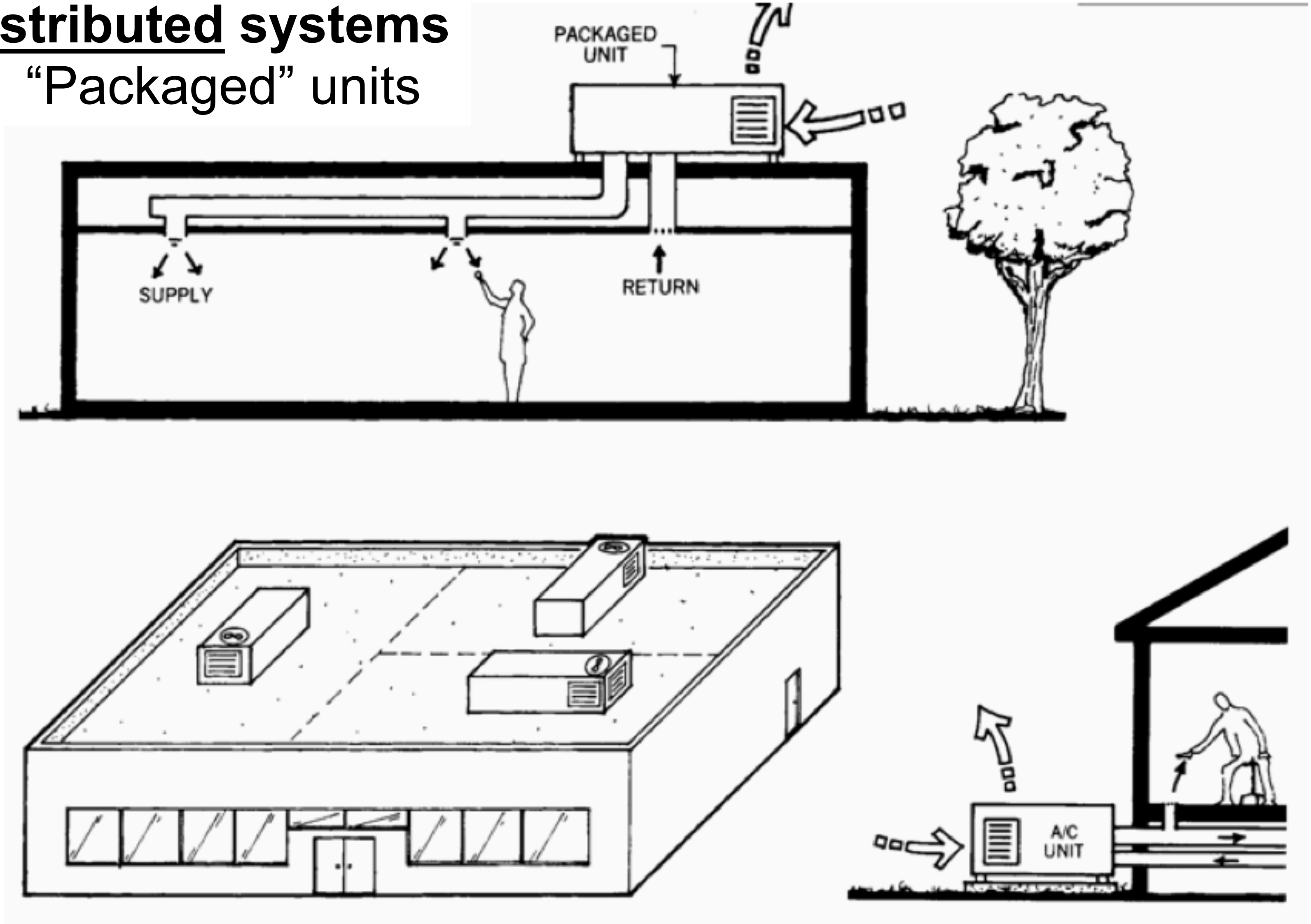
- Many systems operate at their highest efficiency (highest COP) at design load conditions
  - Maximum load
- But systems don't always operate at peak load conditions
  - "Part-load" conditions are common
- The "part-load ratio" quantifies COP at part-load conditions



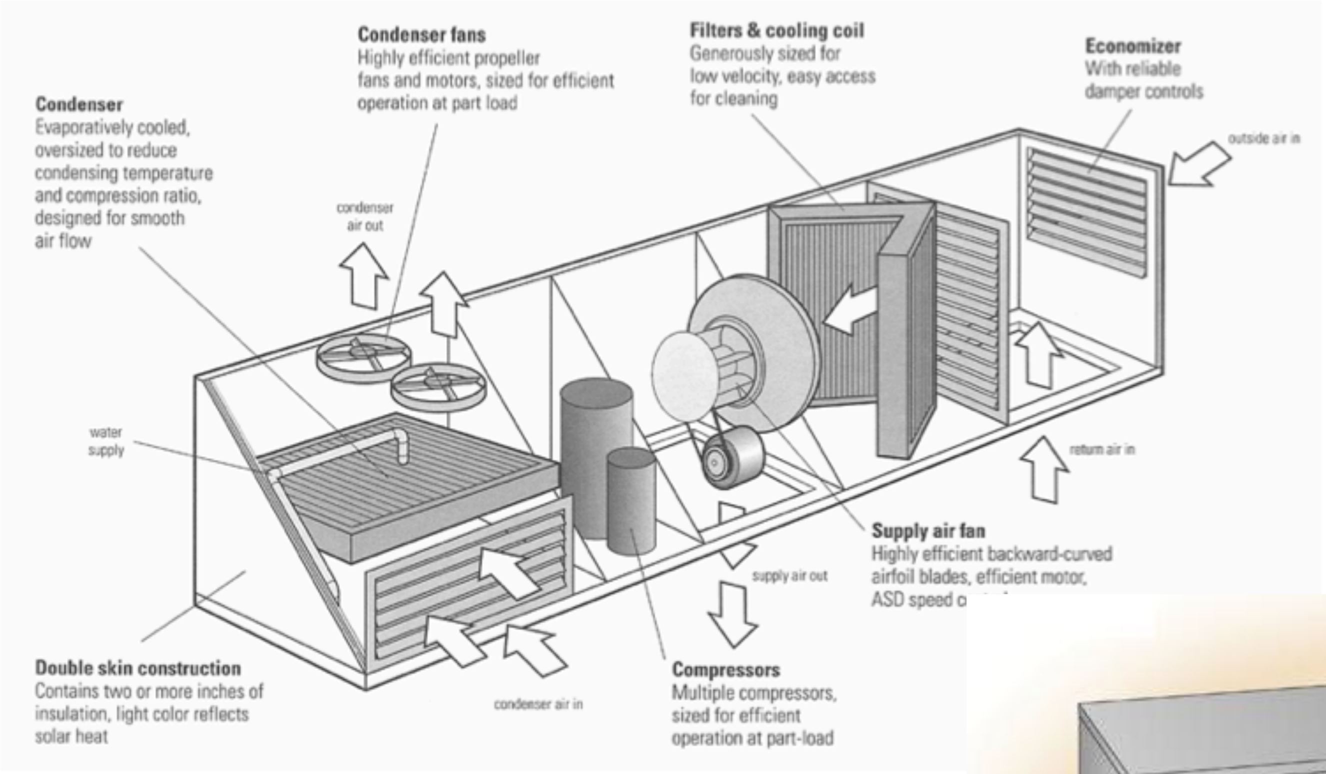
Typical large distributed commercial systems

Distributed systems

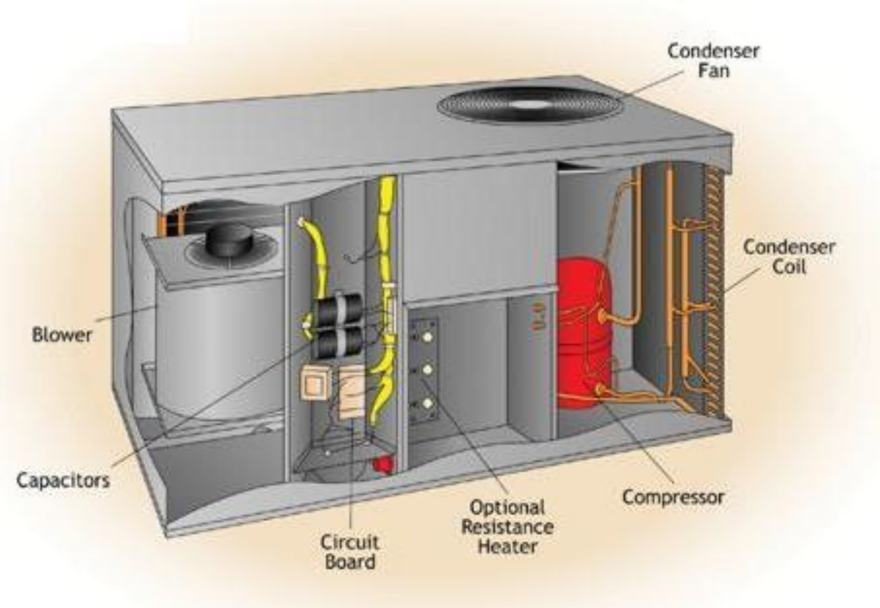
"Packaged" units



Typical large distributed commercial systems



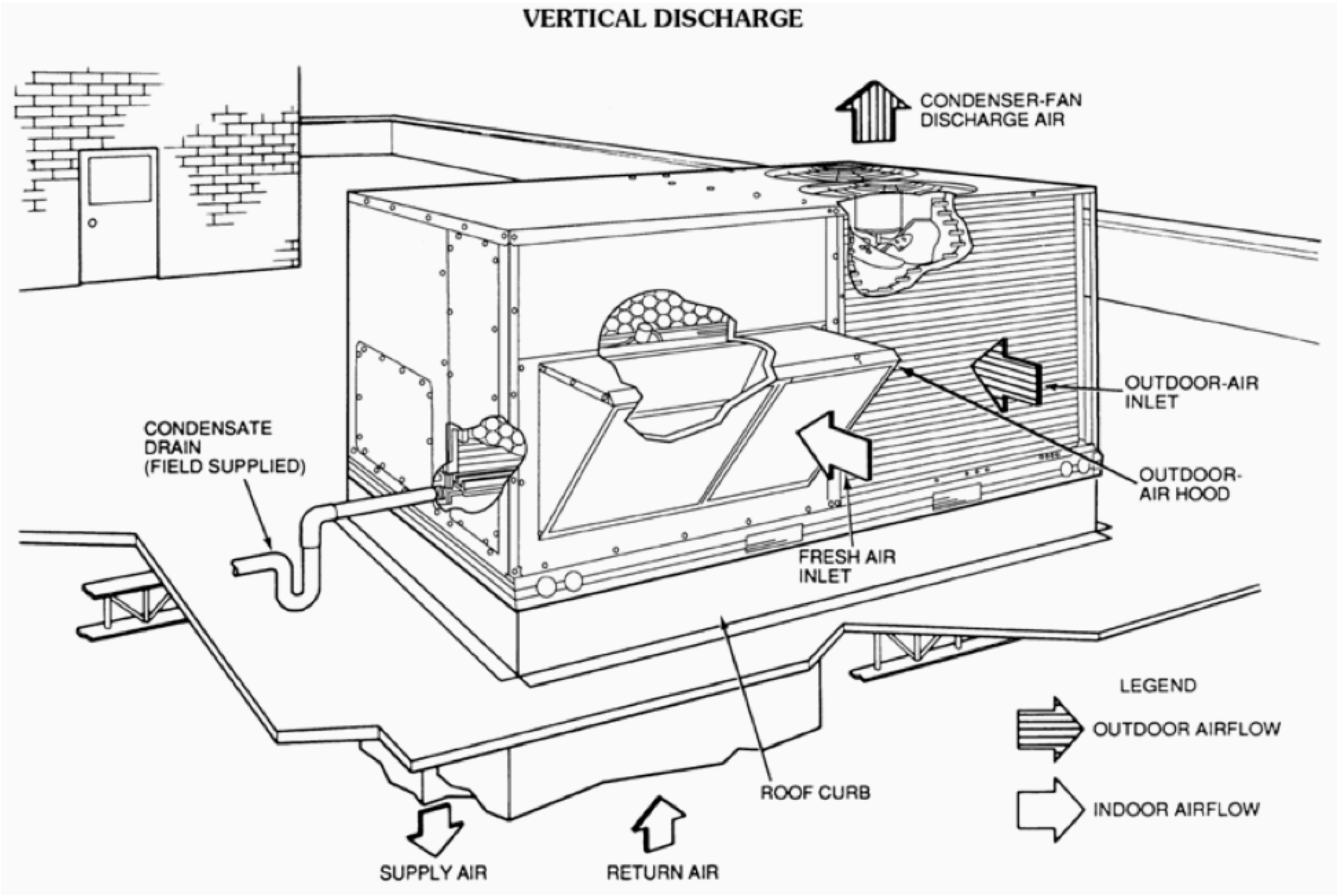
Packaged systems



Typical large distributed commercial systems

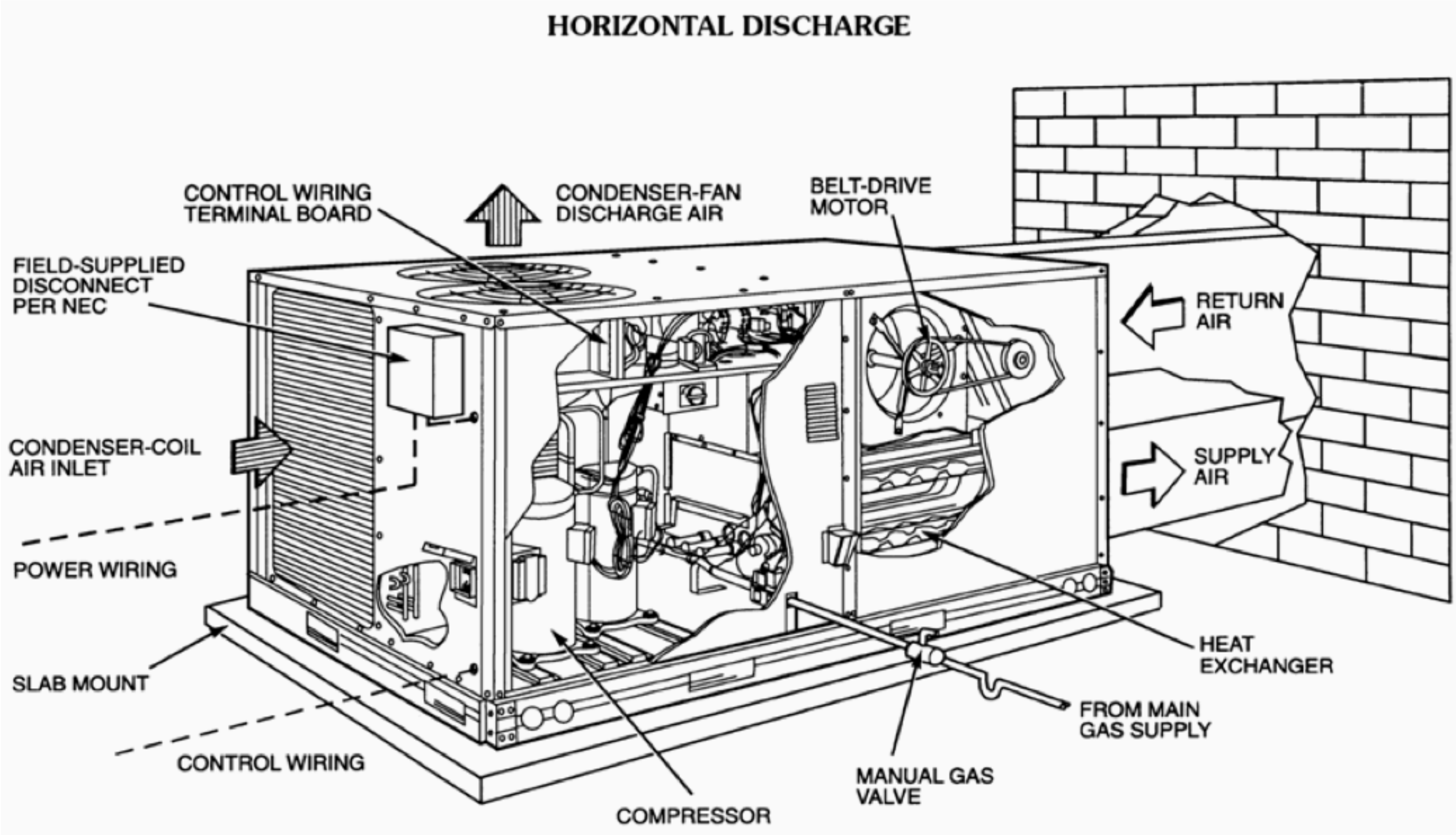
Typical large distributed commercial systems

Packaged roof-top units (RTUs)



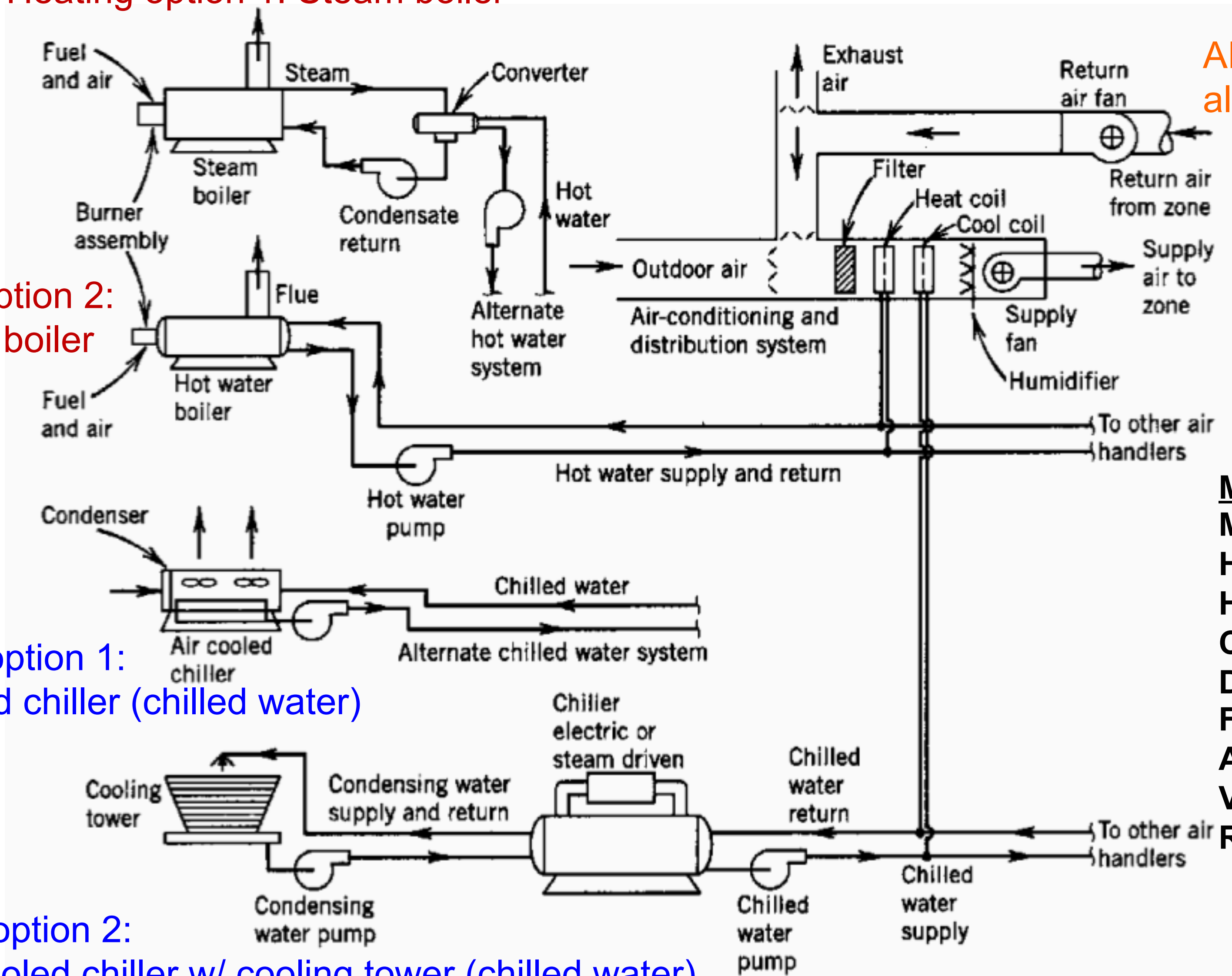
Typical large distributed commercial systems

Packaged slab installations



Typical large central commercial systems

Heating option 1: Steam boiler



AHU serves all rooms

Heating option 2: Hot water boiler

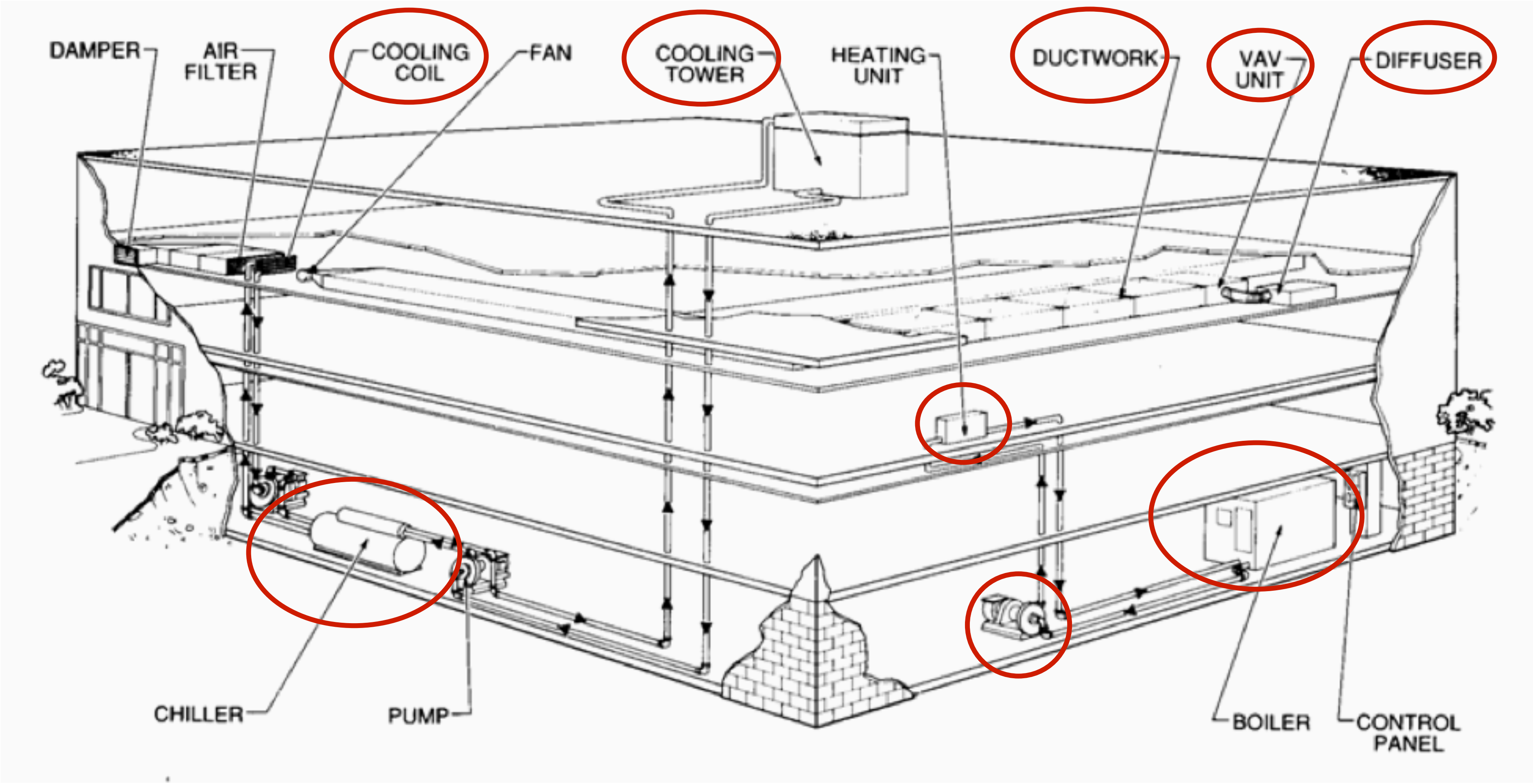
Cooling option 1: Air cooled chiller (chilled water)

Cooling option 2: Water cooled chiller w/ cooling tower (chilled water)

Main processes:
Mixing
Heating
Humidification
Cooling
Dehumidification
Filtration
Air distribution
Ventilation
Recirculation

Typical large central commercial systems

Heating and cooling distribution done separately:



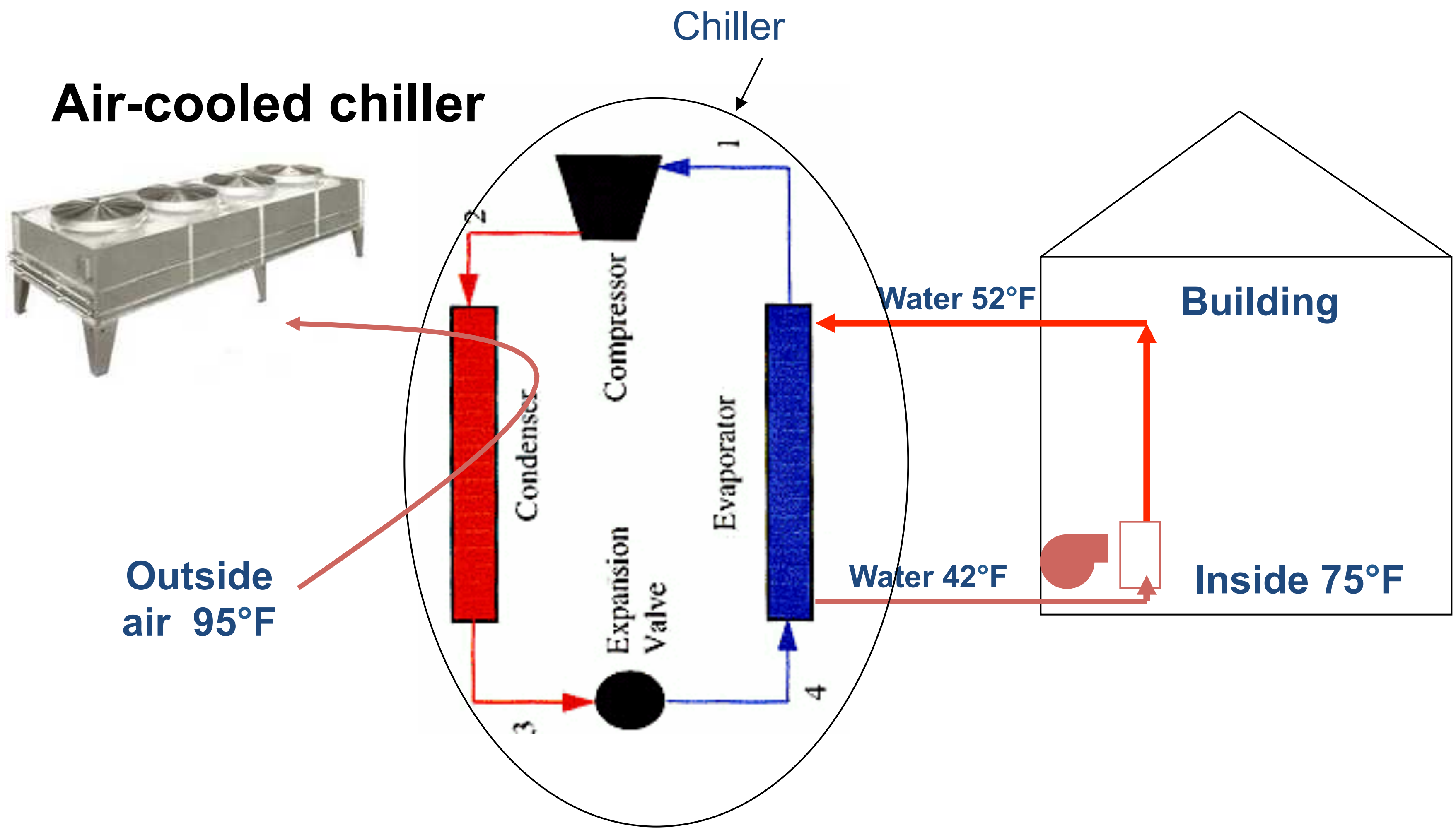
Typical large central commercial system components

Air cooled chiller
Smaller capacity

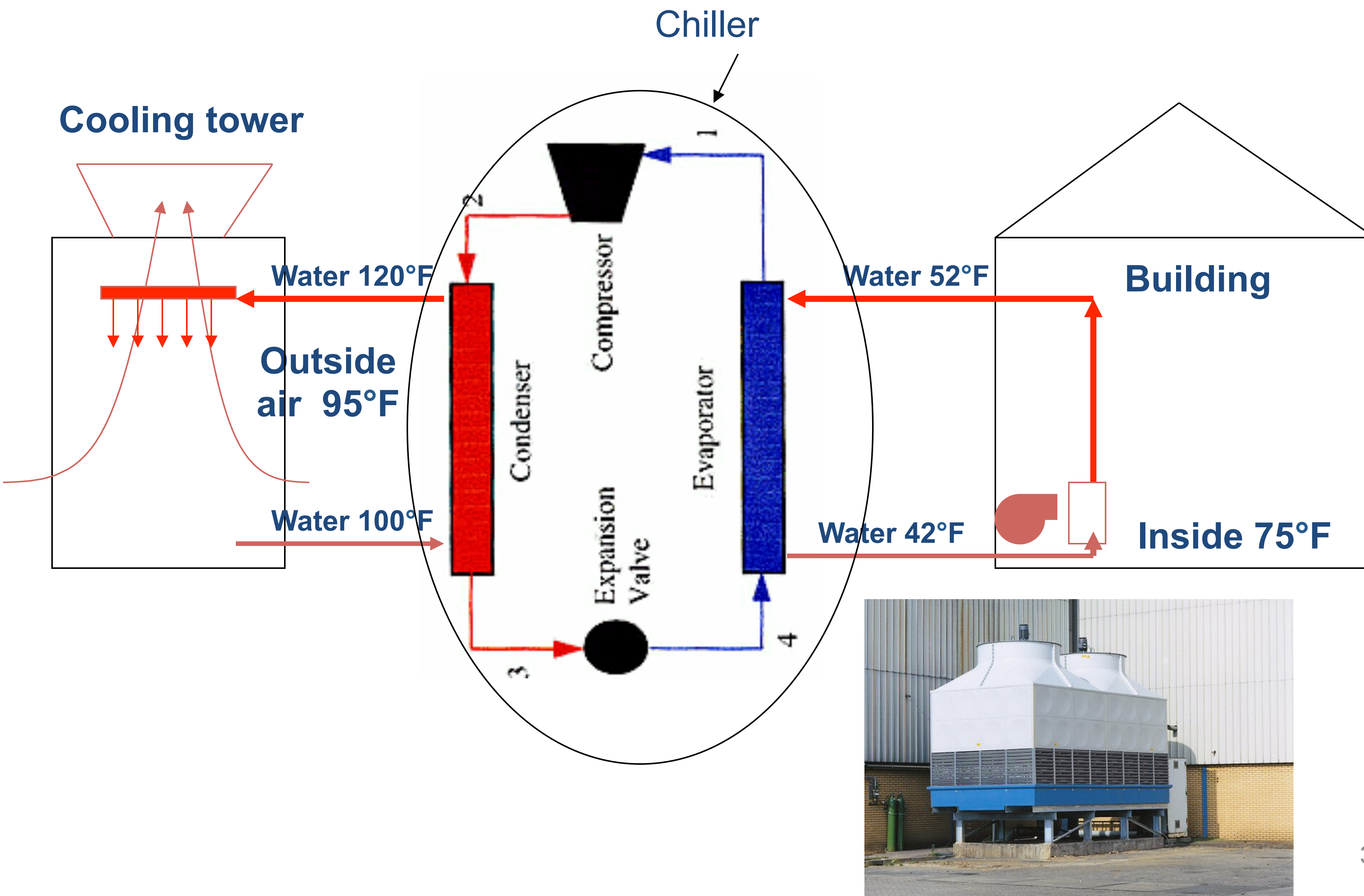
Water-cooled chiller
(w/ cooling tower – larger capacity & more efficient)

Air-cooled chillers

- Chillers use vapor compression or absorption systems to produce chilled water for cooling spaces



Water-cooled chillers (i.e., “cooling tower”)



Heating systems

- Heating systems are relatively straightforward
  - They add energy to heat a medium (e.g., air or water)

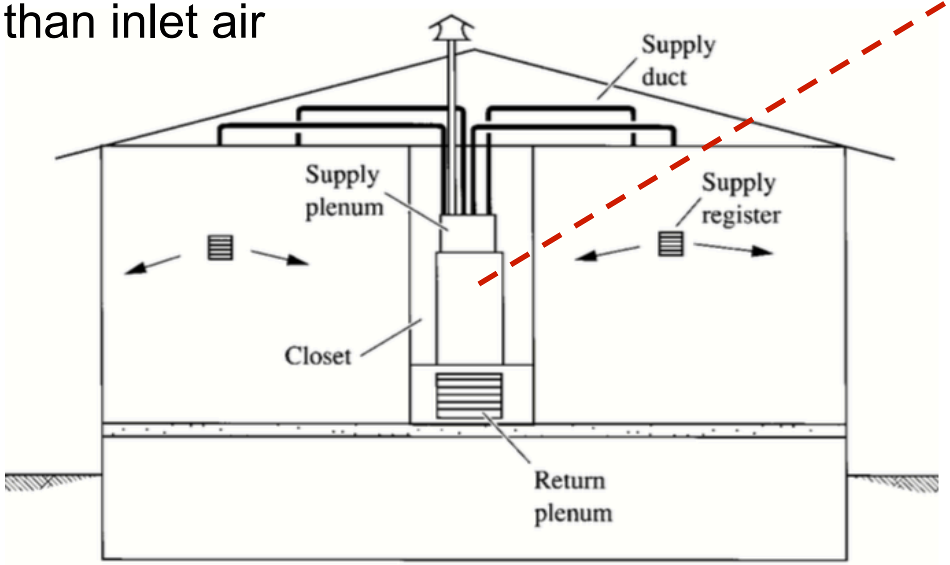
- Heating systems vary by building type:

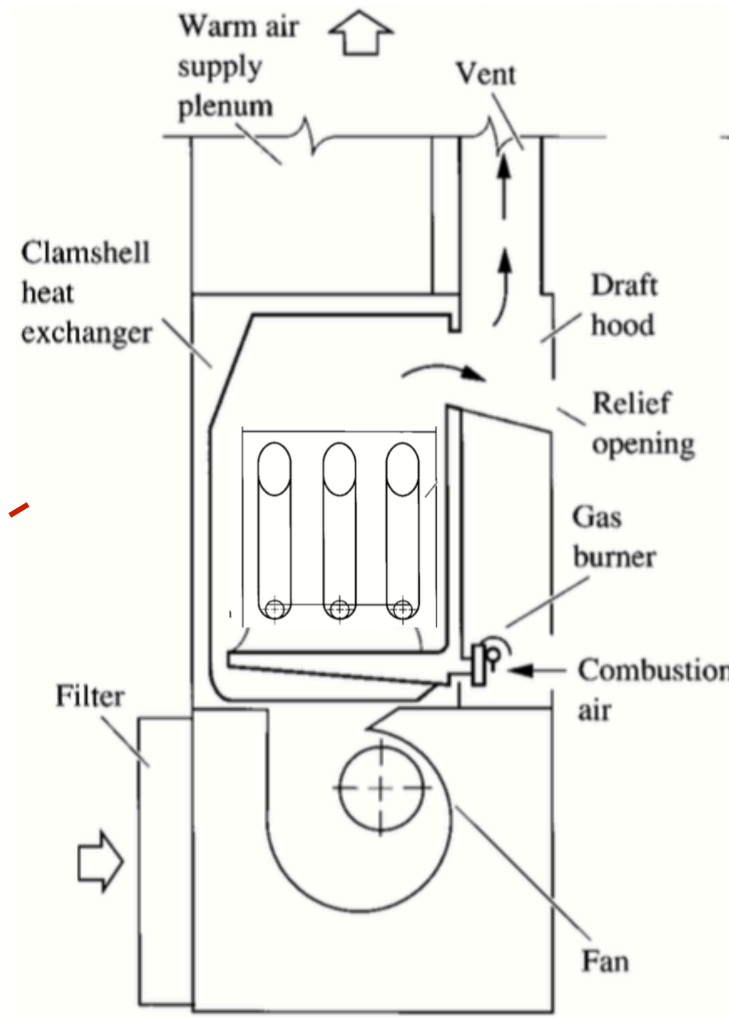
	Commercial, percent	Residential, percent
Heating systems using boilers	28	33
Warm air furnaces and packaged heating units	24	37
Heat pumps	10	30
Individual space heaters including electric, gas, and radiant heaters	28	
District heating	10	

Heating systems: Warm air furnaces

Warm air furnace

- Gas or oil is directly fired (combustion) to heat air passing through a heat exchanger (or air is directly heated by electric resistance elements)
- Most common fuel: Natural gas
  - Capacities up to 175,000 BTU/hr are typical
  - Exit air is typically 50-80°F (28-45°C) higher than inlet air





Wang Chapter 8

Heating systems: Warm air furnaces

- **Thermal efficiency, E_t**
  - Ratio of energy output of the fluid (air or water) to the fuel energy input

$$E_t = \frac{100\,(\text{fluid energy output})}{\text{fuel energy input}}$$

- **Annual fuel utilization efficiency, AFUE**
  - Ratio of *annual* energy output of the fluid (air or water) to the *annual* fuel energy input (accounts for non-heating season pilot losses)

$$\text{AFUE} = \frac{100\,(\text{annual output energy})}{\text{annual input energy}}$$

Construction characteristics	AFUE, percent
Natural vent	
Pilot ignition	64.5
Intermittent ignition	69
Intermittent ignition + venting damp	78
Power vent	
Noncondensing	81.5
Condensing	92.5

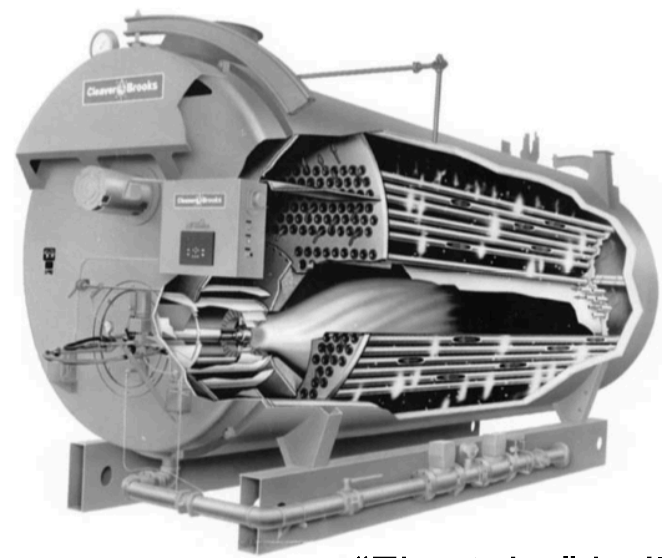
Heating systems: Hot water boilers

Hot water boiler

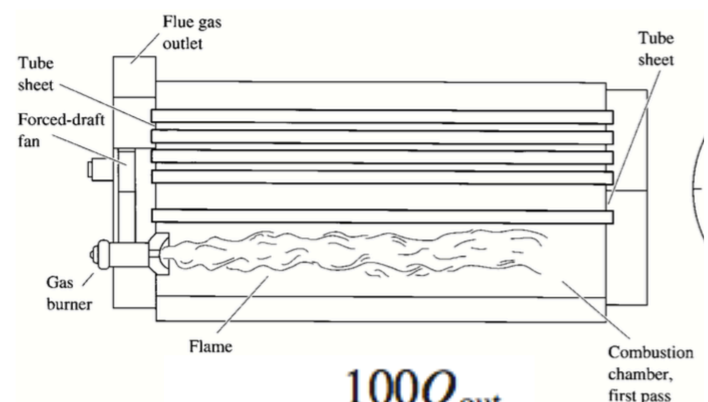
- Enclosed pressure vessel in which water is heated to a required temperature and pressure without evaporation
- Most common fuel: Natural gas
  - Capacities up to 50,000 kBTU/hr are typical

Gas-fired boilers	71 percent
Oil-fired boilers	15 percent
Electric boilers	11 percent
Others	2 percent

- Low pressure boilers
  - Working pressure up to 160 psig (1.1 MPa)
  - Working temperature up to 250°F (121°C)
    - Common for low temperature water (e.g., single buildings)
- High pressure boilers
  - Higher temperature and higher pressure (e.g., 300-400°F (150-205°C)
    - Common for large building complexes and campuses

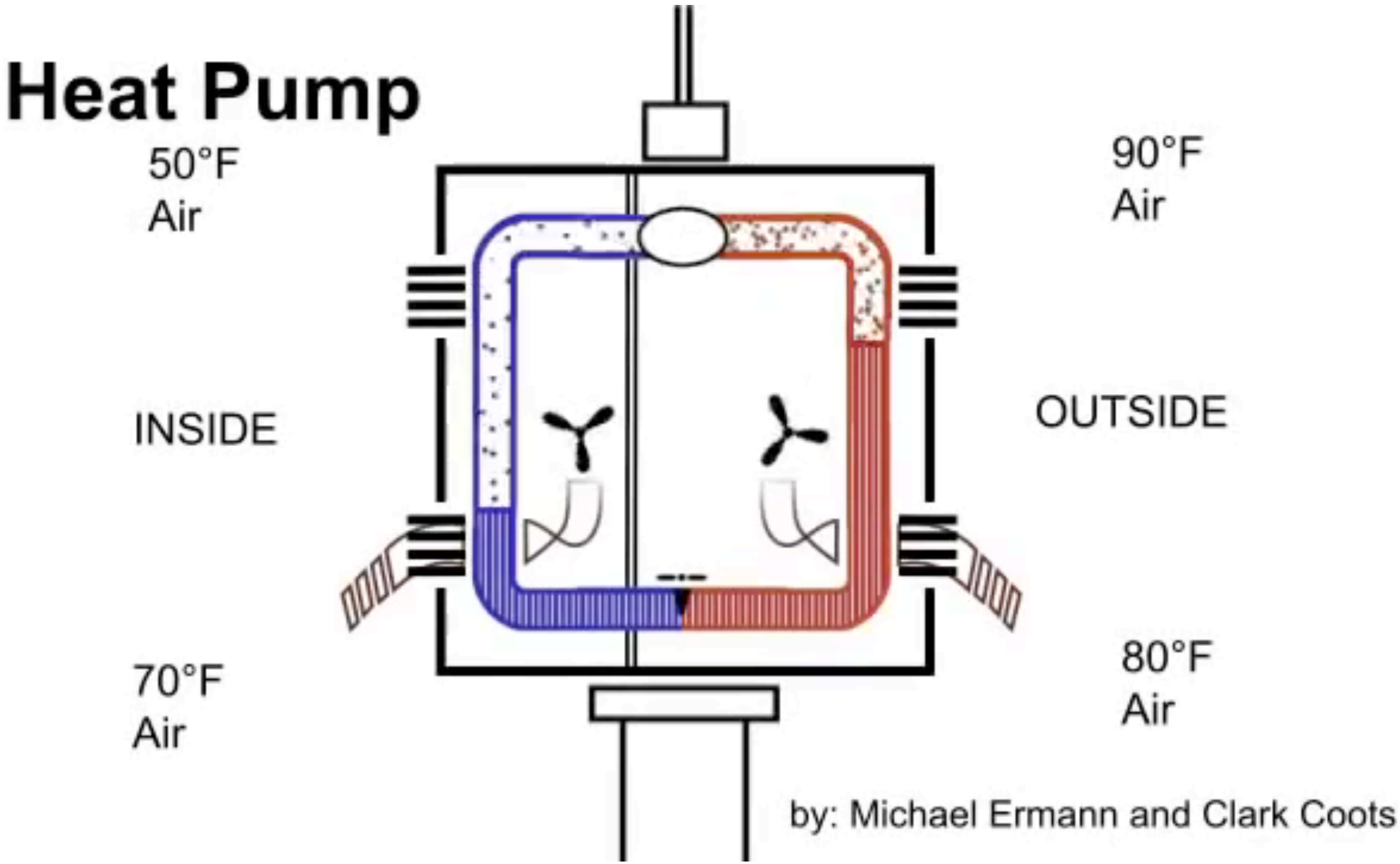


"Fire-tube" boiler



$$E_c = \frac{100Q_{\text{out}}}{Q_{\text{fuel}}}$$

Heat pumps

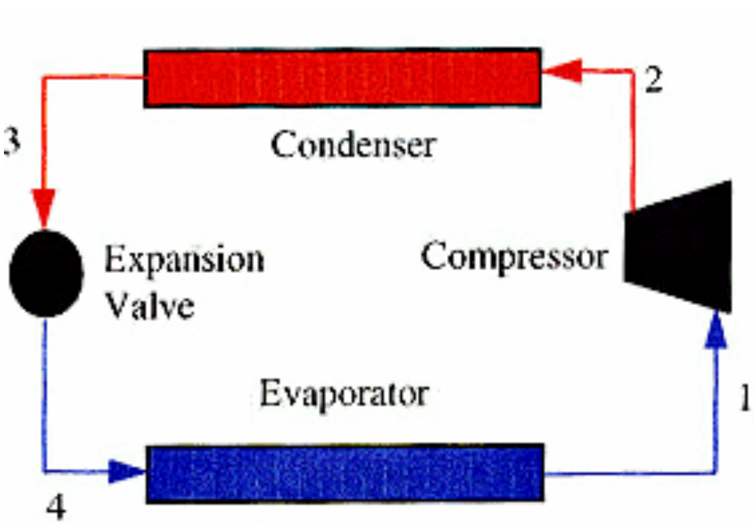


https://www.youtube.com/watch?v=NyNeh7wPQQk

Heat pumps

Cooling

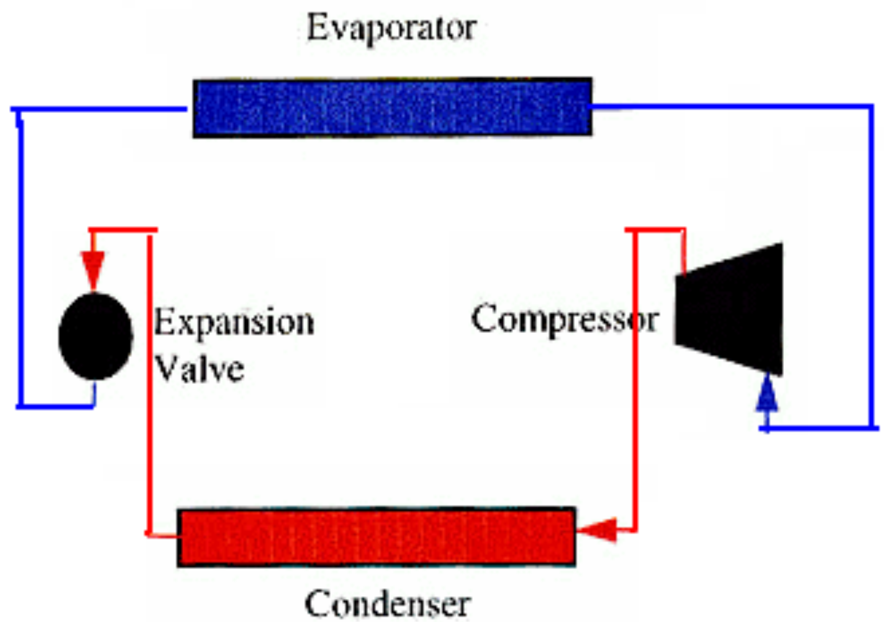
Outside 95°F



Inside 75°F

Heating

Outside 45°F

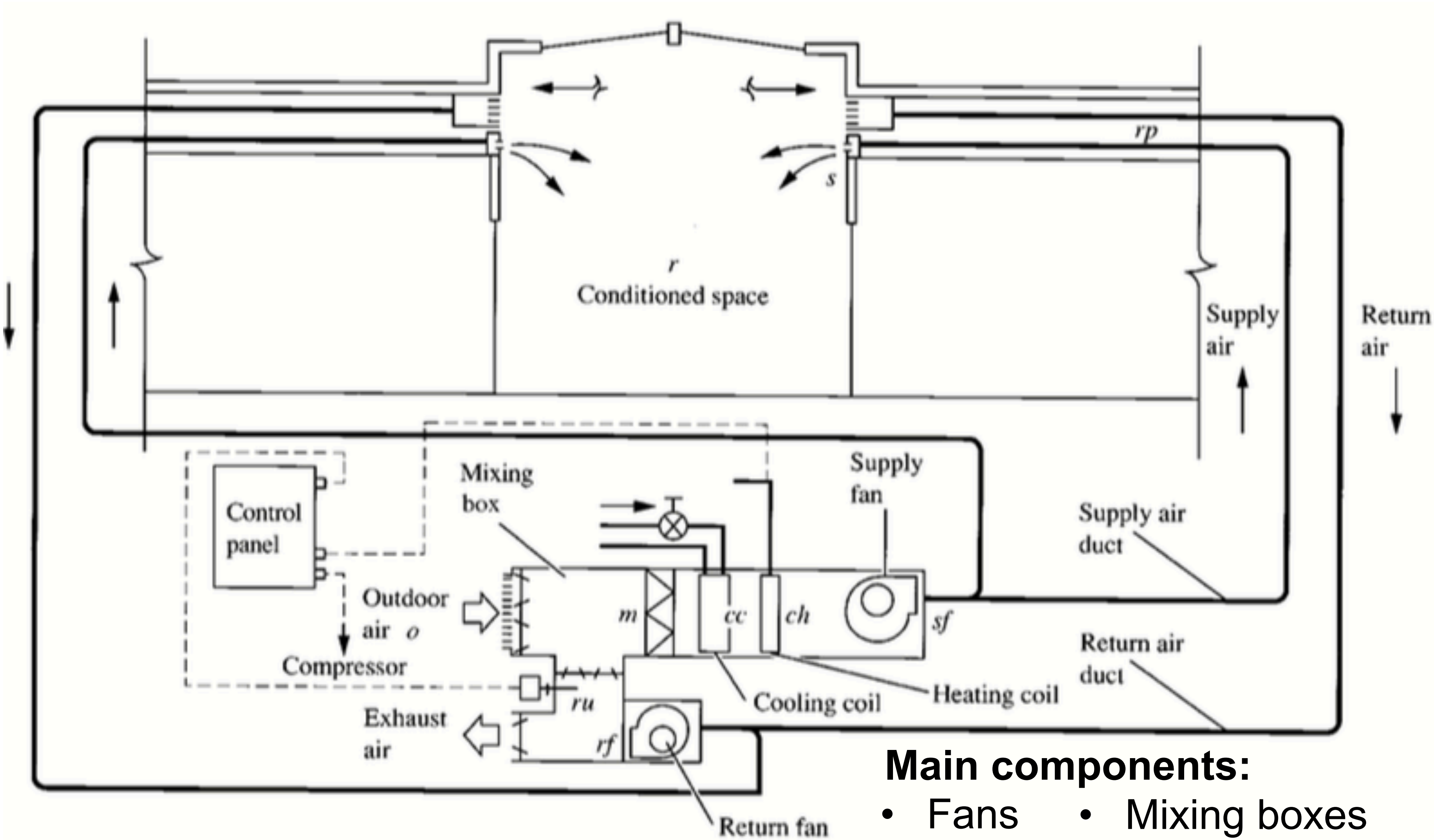


Inside 75°F

Air-conditioner run in reverse

AIR DISTRIBUTION SYSTEMS

Typical central commercial air distribution system



Main components:

- Fans
- Coils
- Filters
- Mixing boxes
- Ducts
- Diffusers

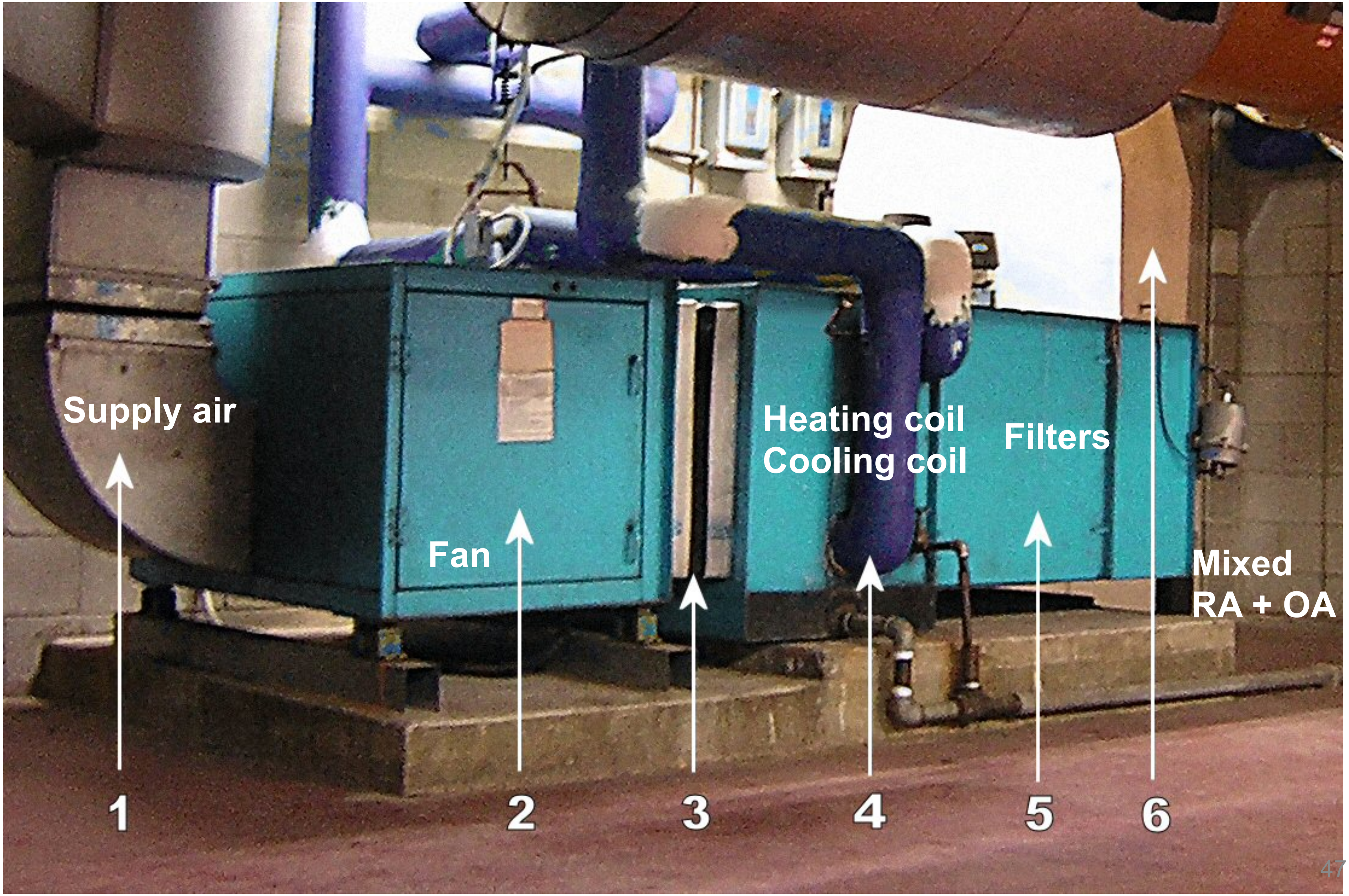
Typical central commercial air handling unit (AHU)

Air Handling Unit (AHU)

Mixing box
(OA + RA)

Heating coil
Cooling coil

Typical central commercial air handling unit (AHU)



Typical large central commercial AHU components

Fan (or "blower")

Variable frequency drives (VFDs)

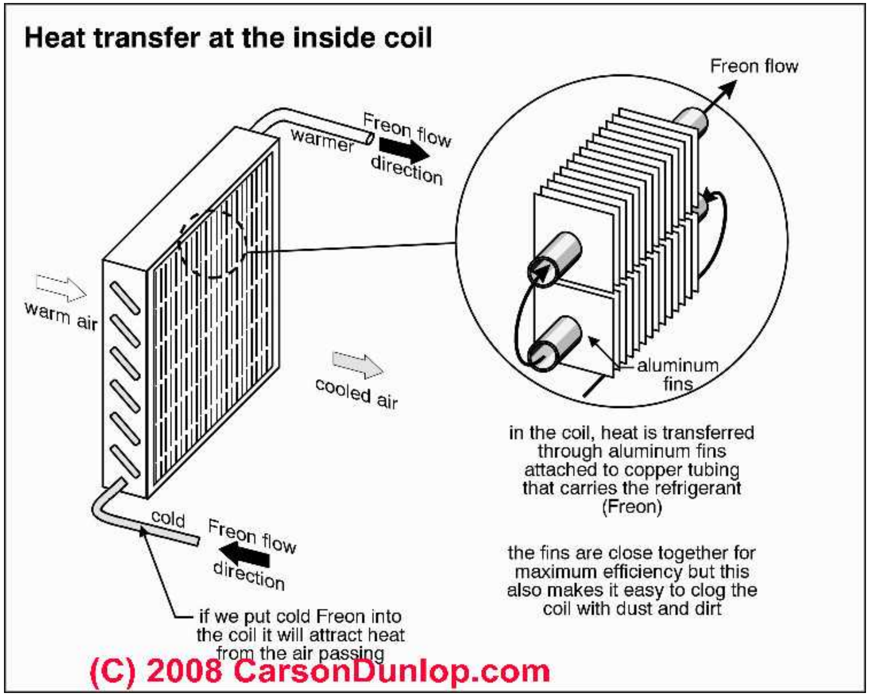
Typical large central commercial AHU components

Mixing box

Dampers

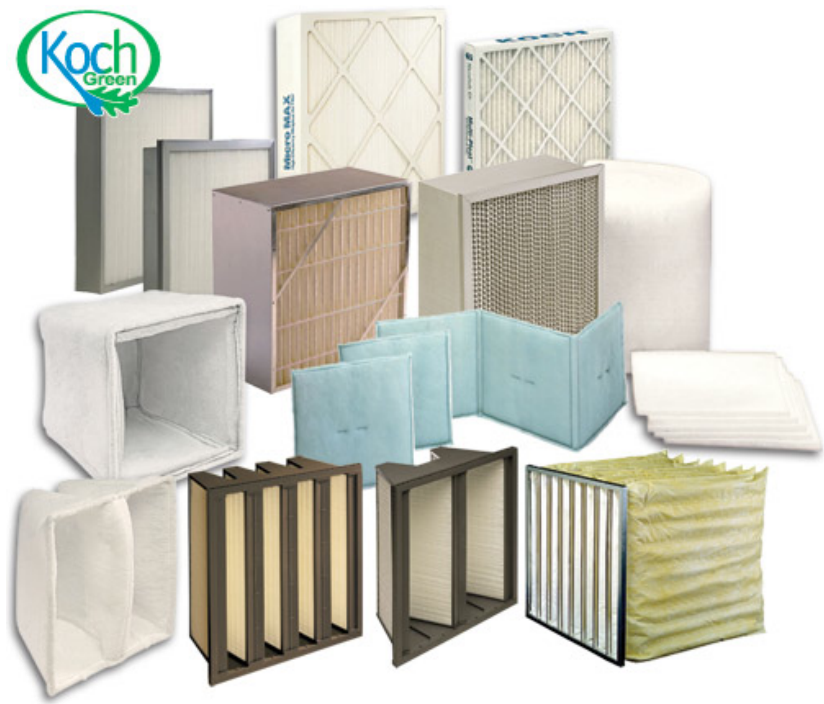
Typical large central commercial AHU components

Heating and cooling coils



Typical large central commercial AHU components

Filter bank



Typical large central commercial AHU components

Filter bank

Typical large central commercial systems

Center for Care and Discovery
University of Chicago Medicine

Typical large central commercial systems

Typical large central commercial systems

Typical large central commercial systems

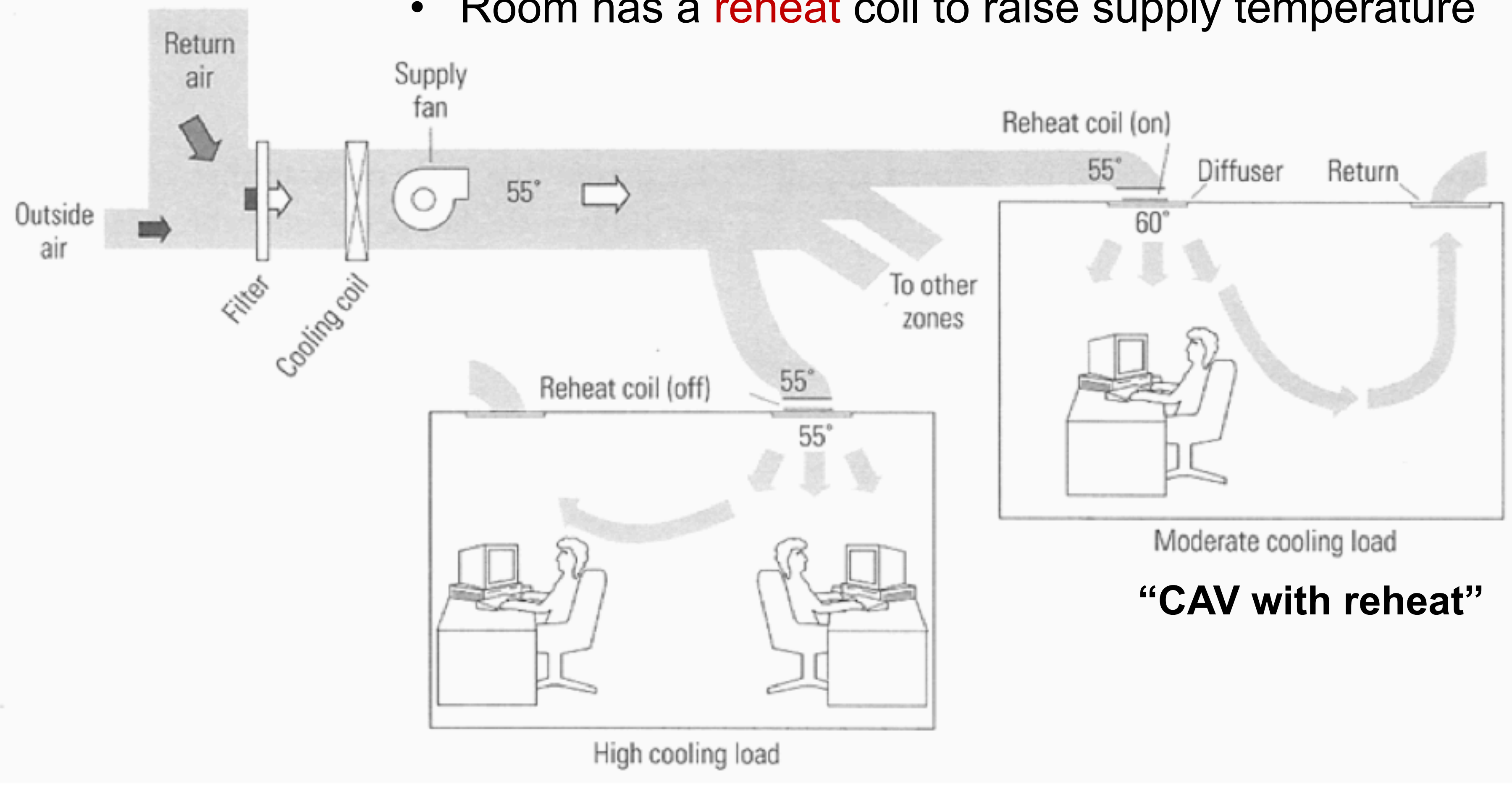
Common commercial air distribution systems

- Constant air volume (**CAV**)
- Variable air volume (**VAV**)
- Dual duct (**DD**)
- Multizone (**MZ**)

Typical constant air volume (CAV) system

Constant airflow rate and temperature to each room

- Cold air delivered to room
- Room has a reheat coil to raise supply temperature



"CAV with reheat"

Typical constant air volume (CAV) system

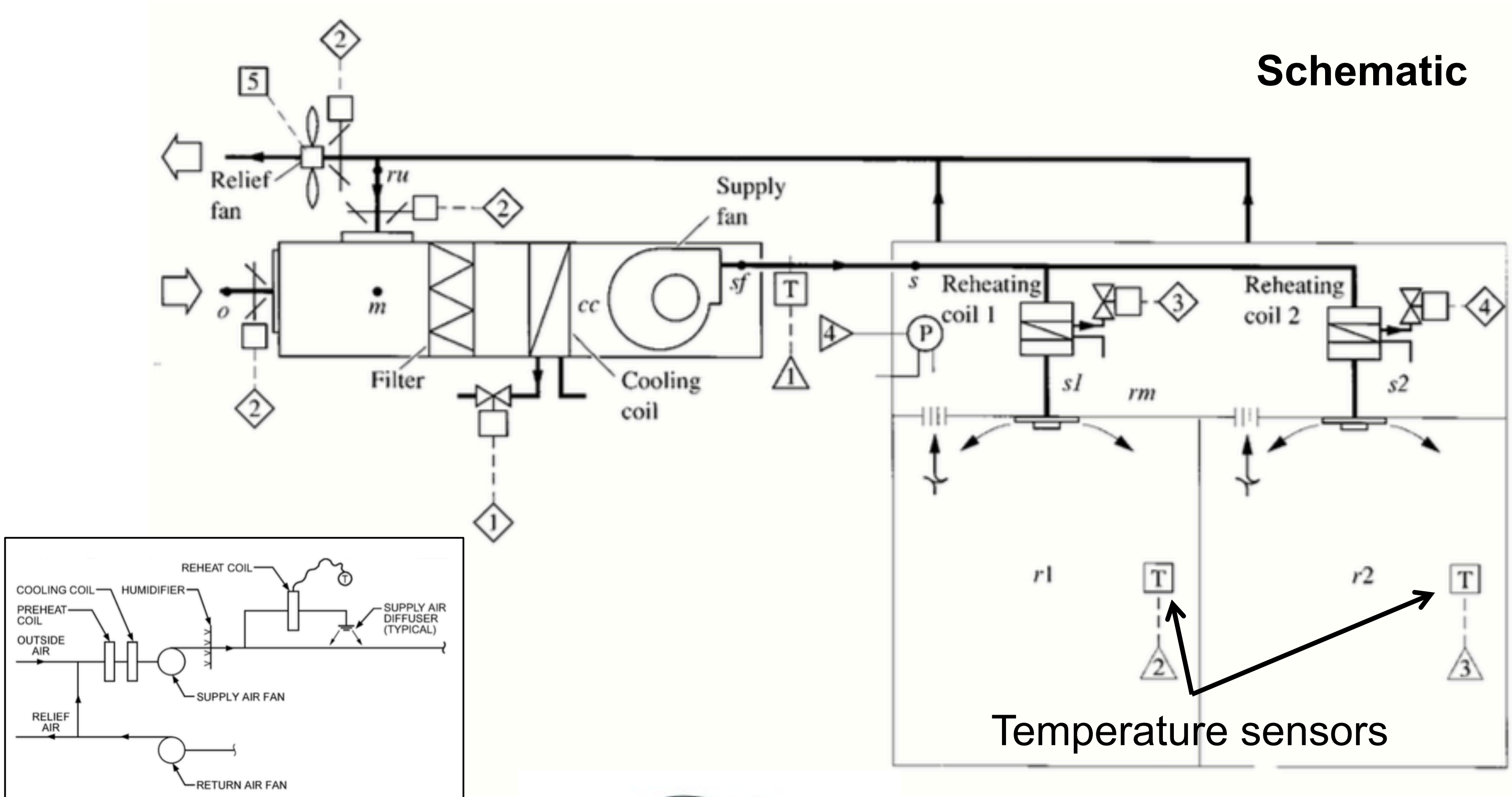


Fig. 9 Constant-Volume System with Reheat

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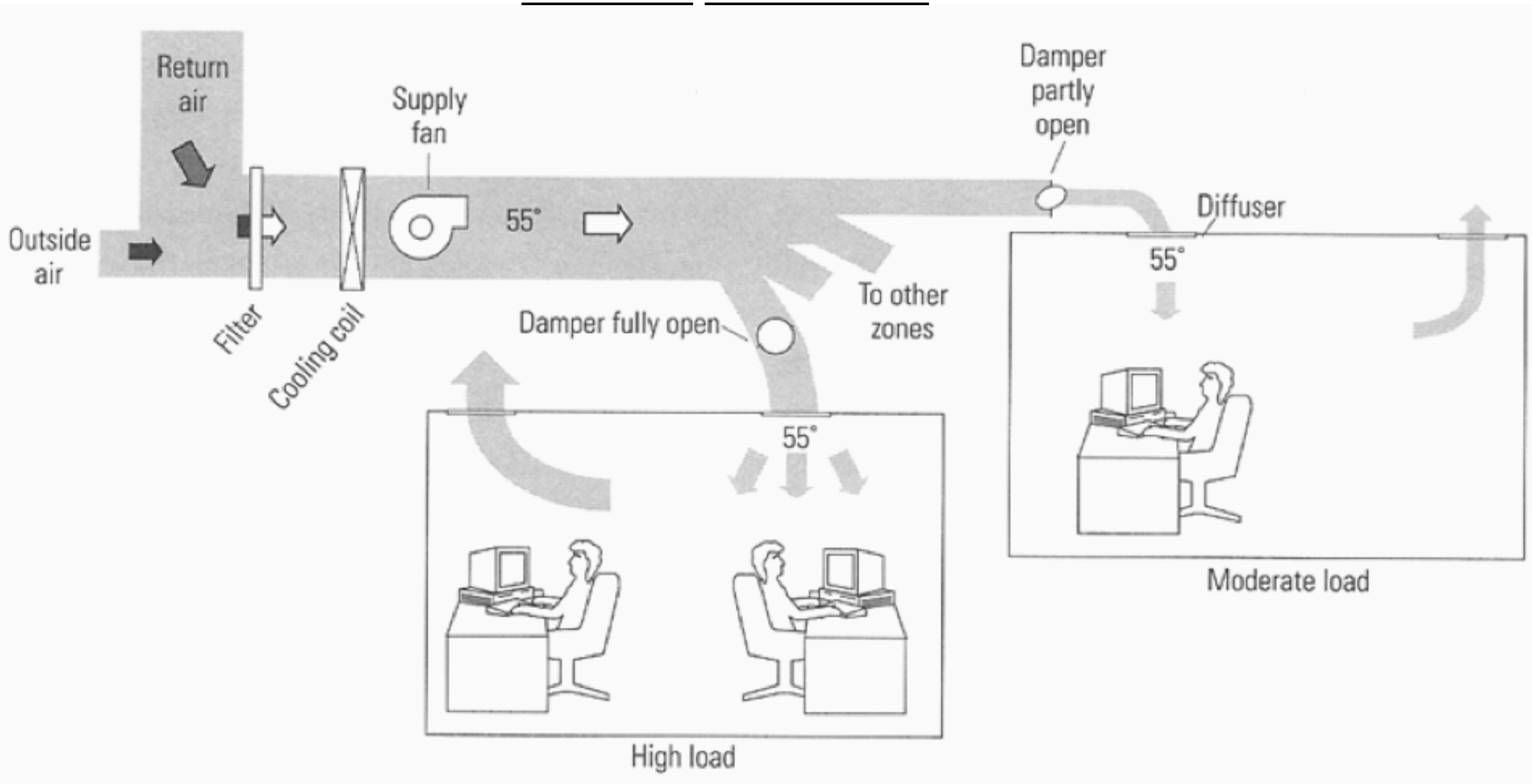
Typical variable air volume (VAV) system

Same temperature air delivered to each room

- <u>Different</u> <u>airflow rate</u> delivered to each room



Typical variable air volume (VAV) system

Same temperature air delivered to each room

- <u>Different</u> <u>airflow rate</u> delivered to each room

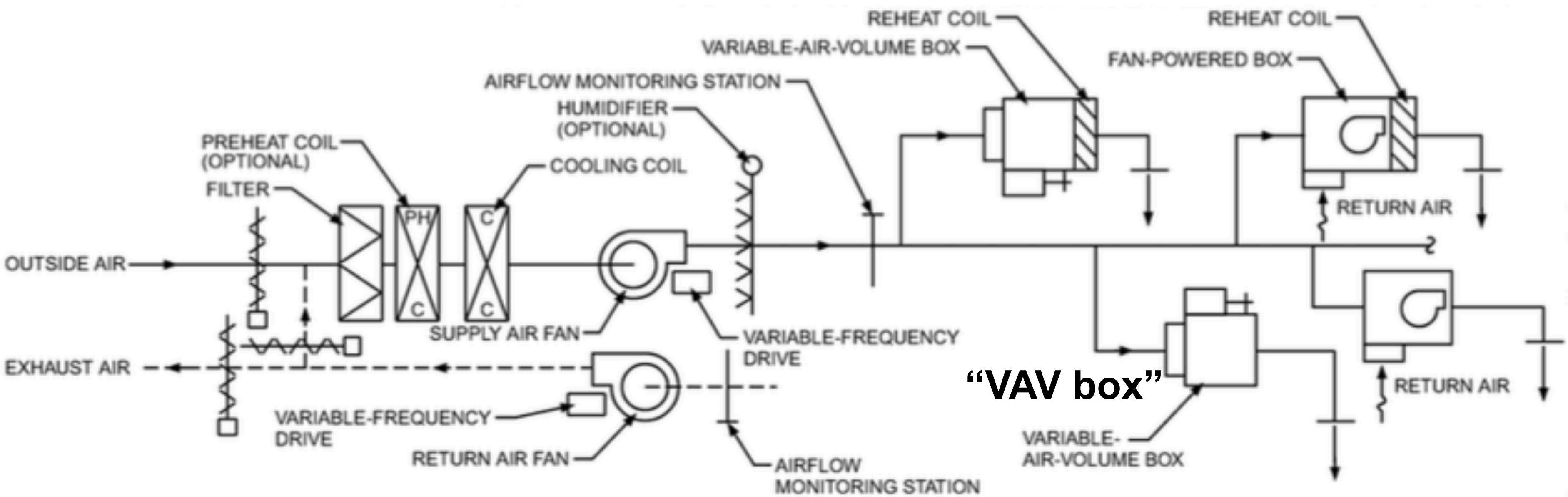
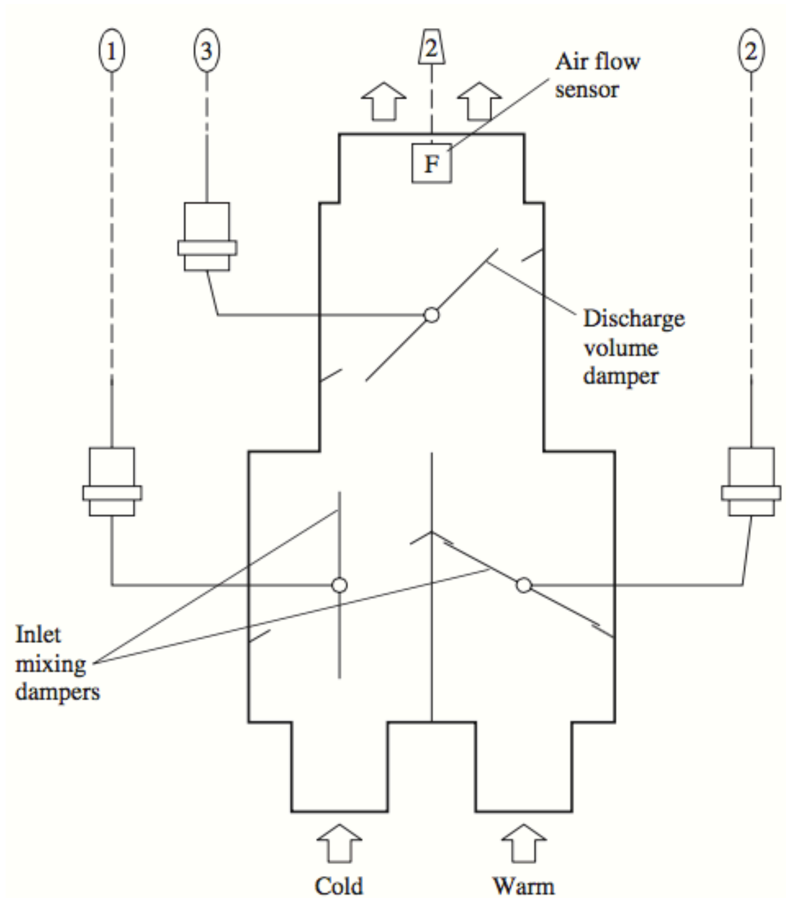
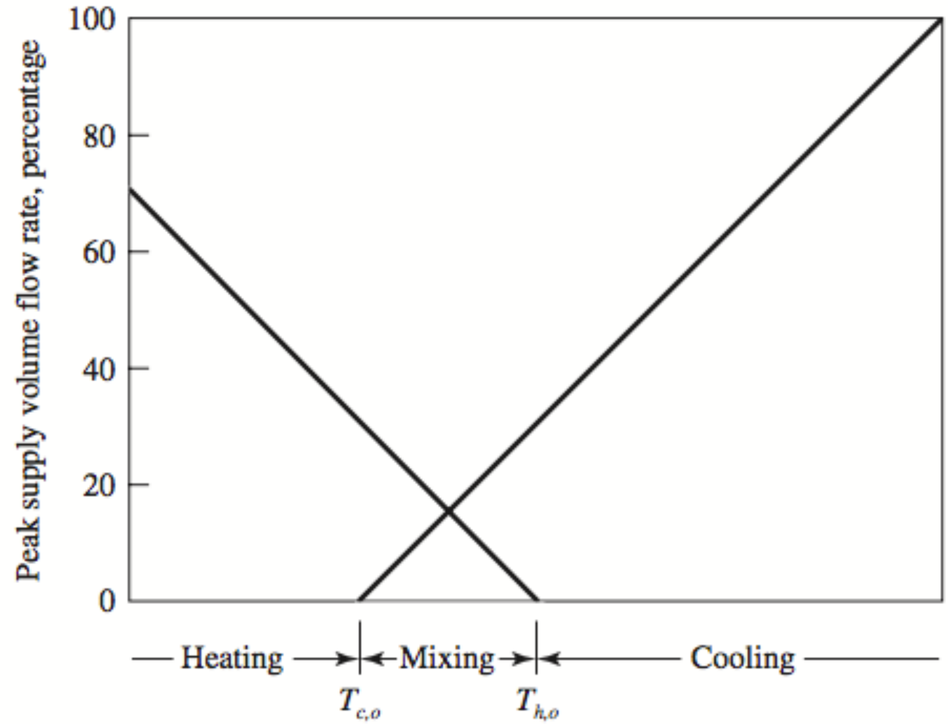


Fig. 10 Variable-Air-Volume System with Reheat and Induction and Fan-Powered Devices

Typical variable air volume (VAV) system





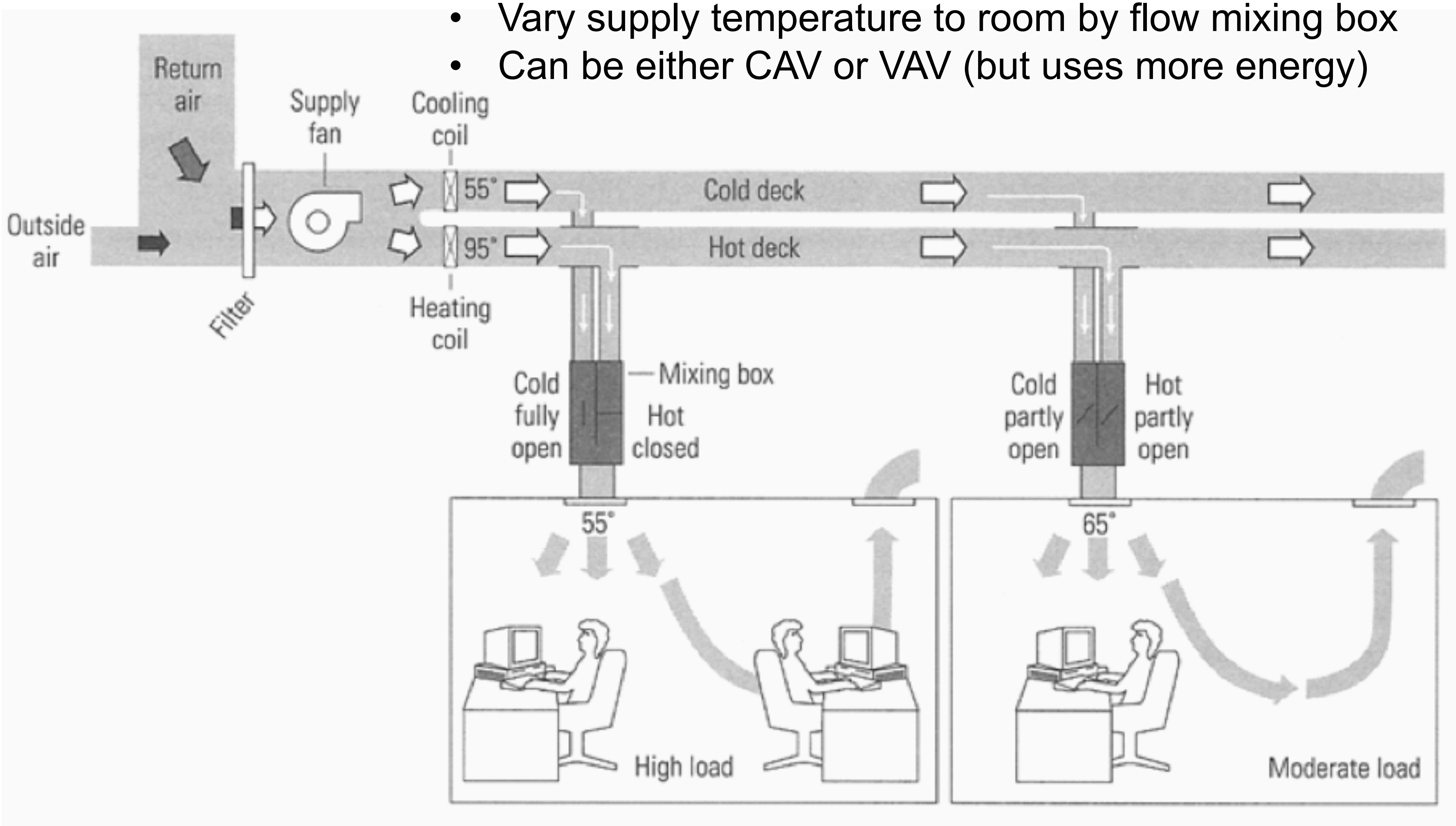
VAV box: A zone-level flow control device

- Damper with an automatic actuator

Typical dual duct (DD) system (older systems)

1 hot deck and 1 cold deck

- Vary supply temperature to room by flow mixing box
- Can be either CAV or VAV (but uses more energy)



Typical dual duct (DD) system (older systems)

1 hot deck and 1 cold deck
- Vary supply temperature to room by flow mixing box
- Can be either CAV or VAV (but uses more energy)

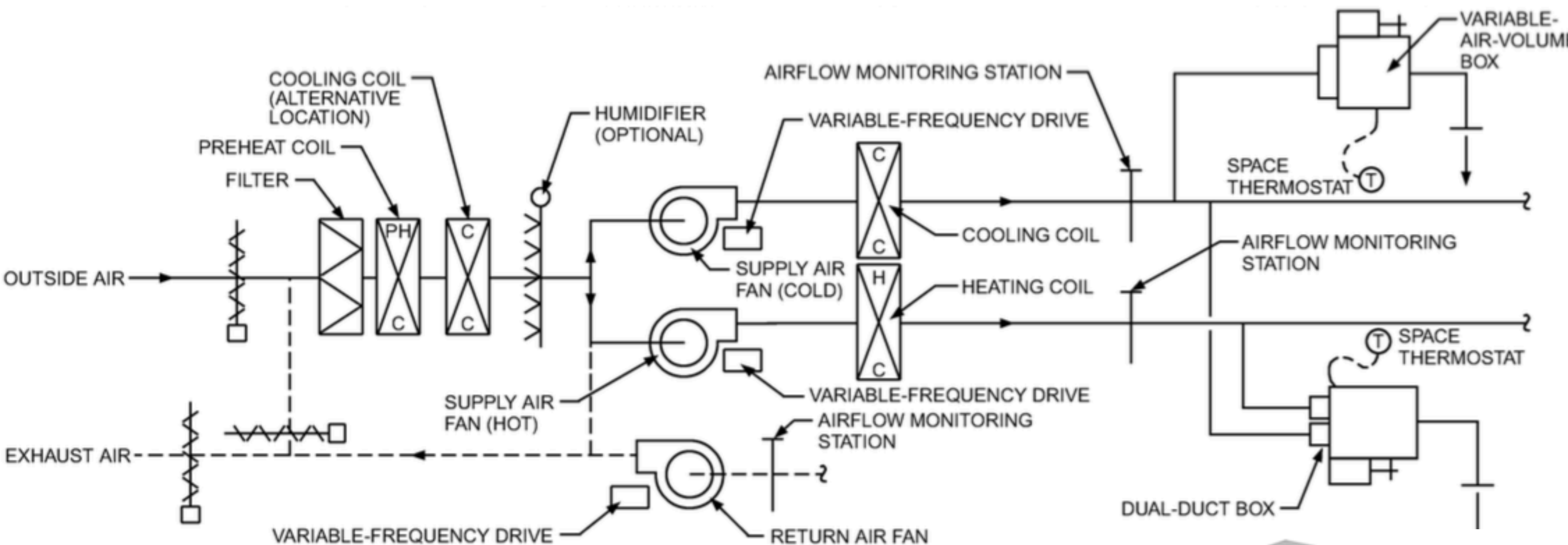
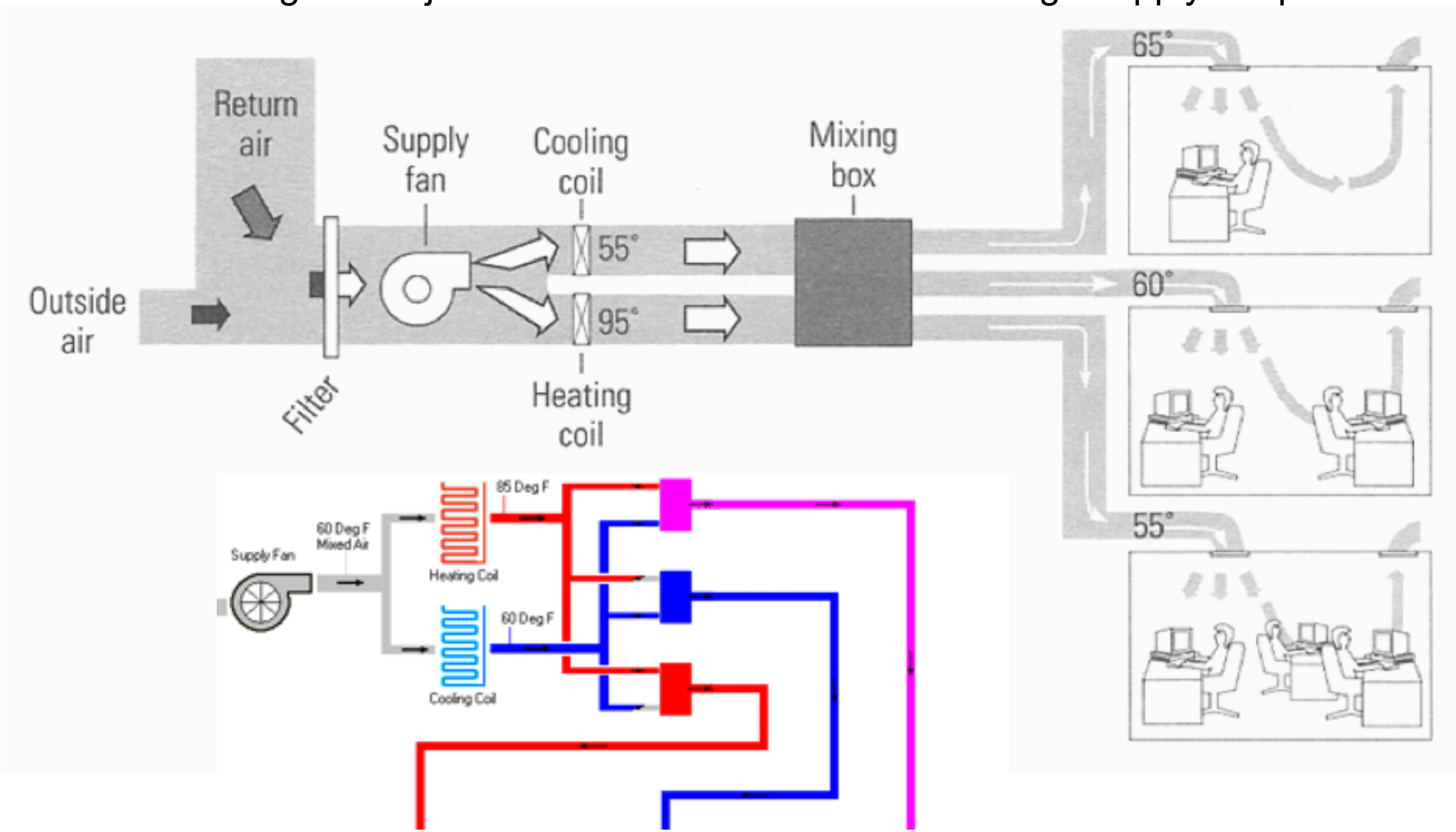


Fig. 12 Dual-Fan, Dual-Duct System

Typical multi-zone (MZ) system

Same airflow rate to each room

- Mixing box adjusts mixture of hot and cold to change supply temperature



Typical multi-zone (MZ) system

Same airflow rate to each room

- Mixing box adjusts mixture of hot and cold to change supply temperature

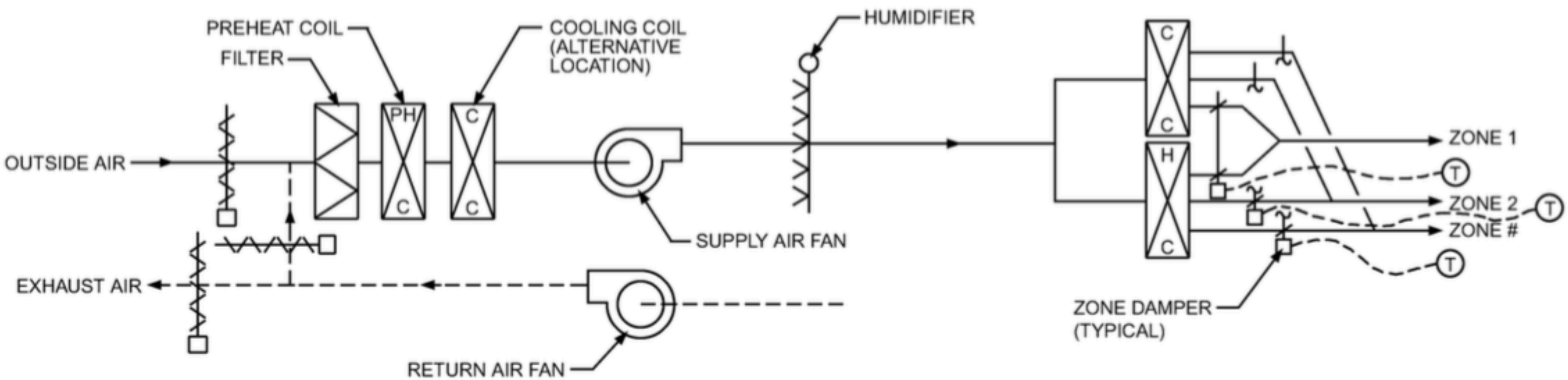
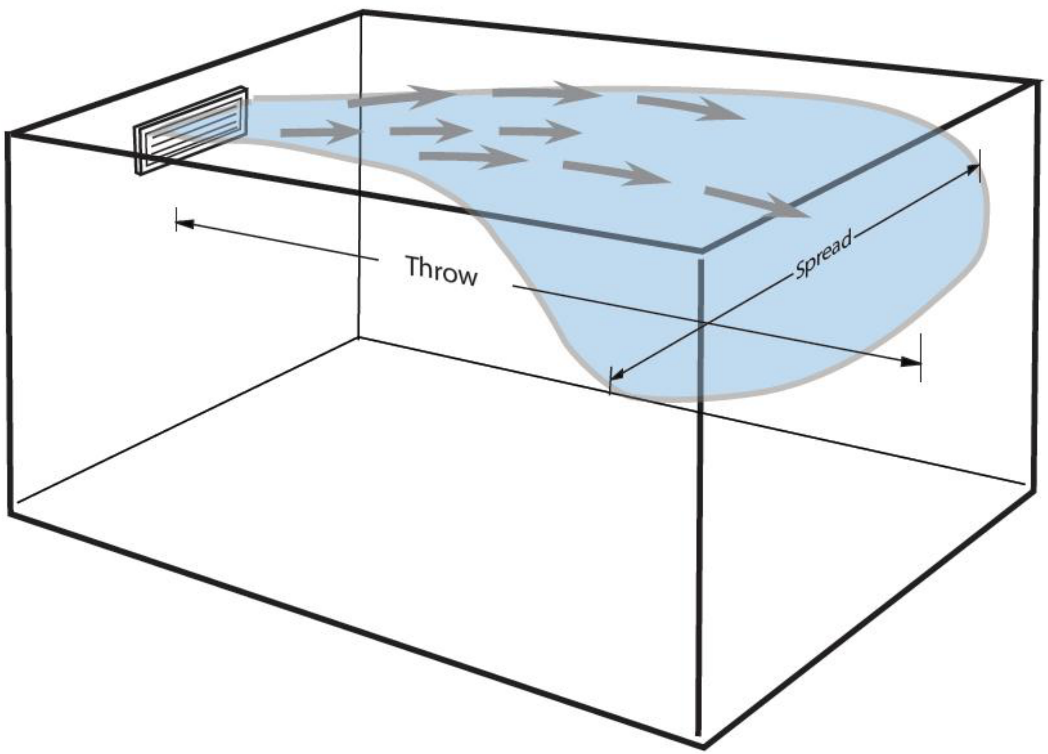
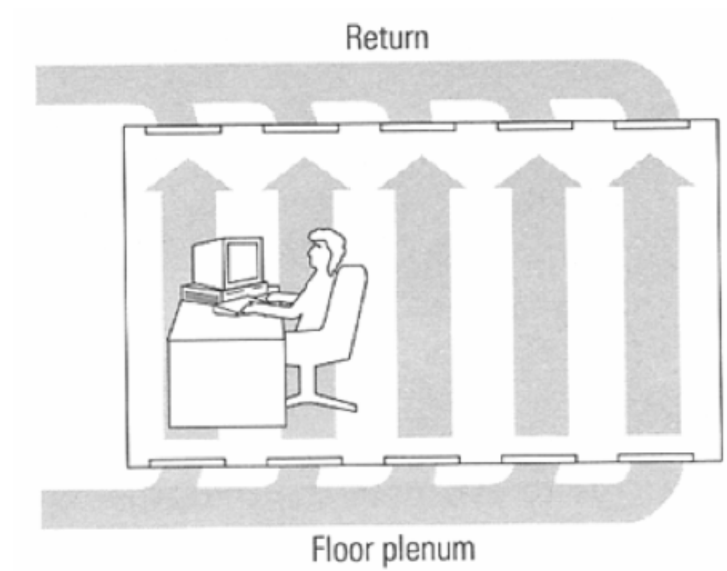


Fig. 13 Multizone System

Air supply and diffusers

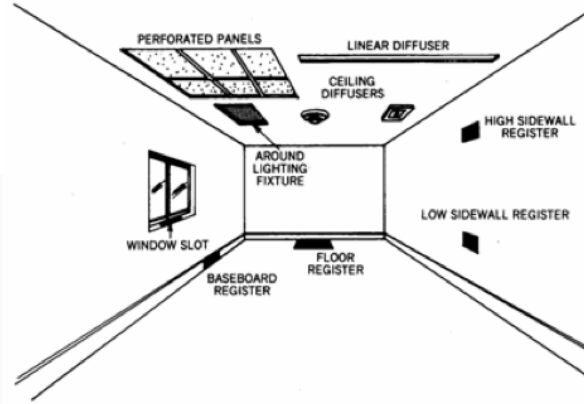
- Mixed versus displacement ventilation
- Diffuser selection

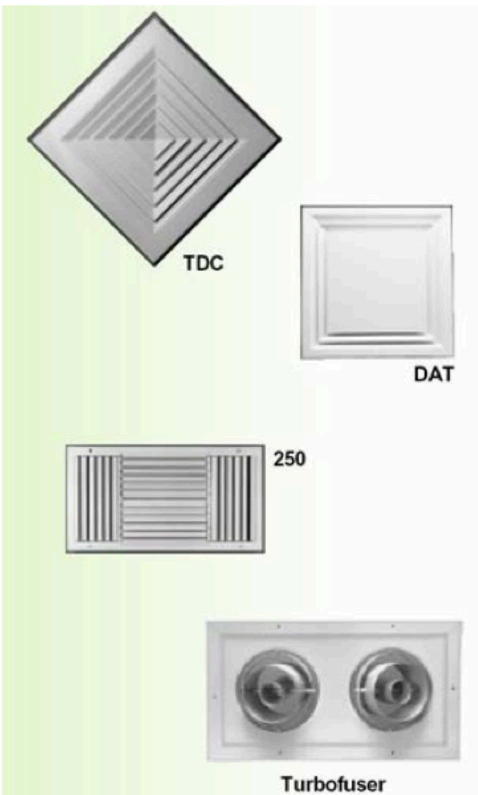


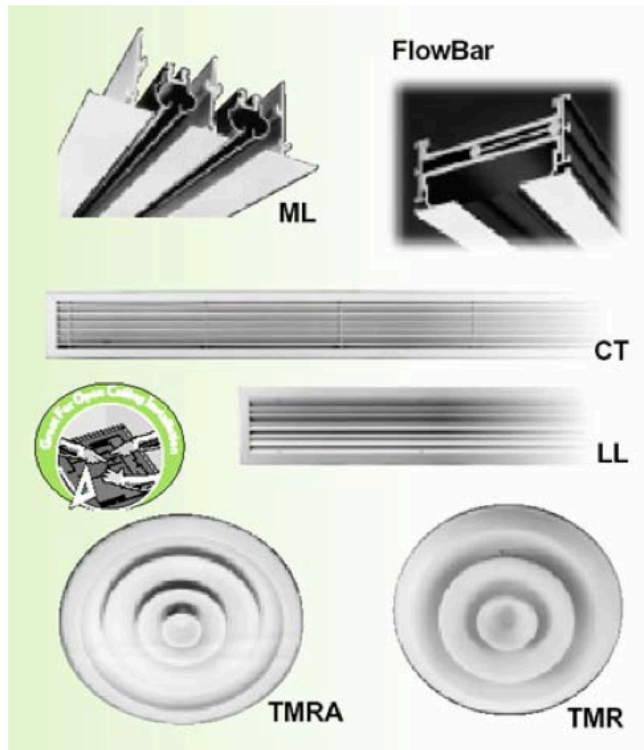


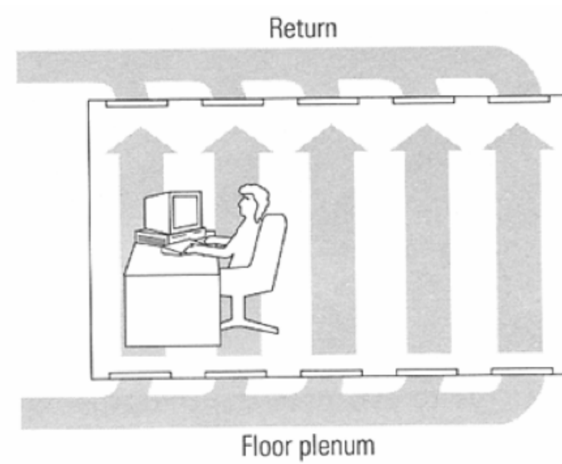
Air supply and diffusers

- Mixed versus displacement ventilation
- Diffuser selection









Air + water systems

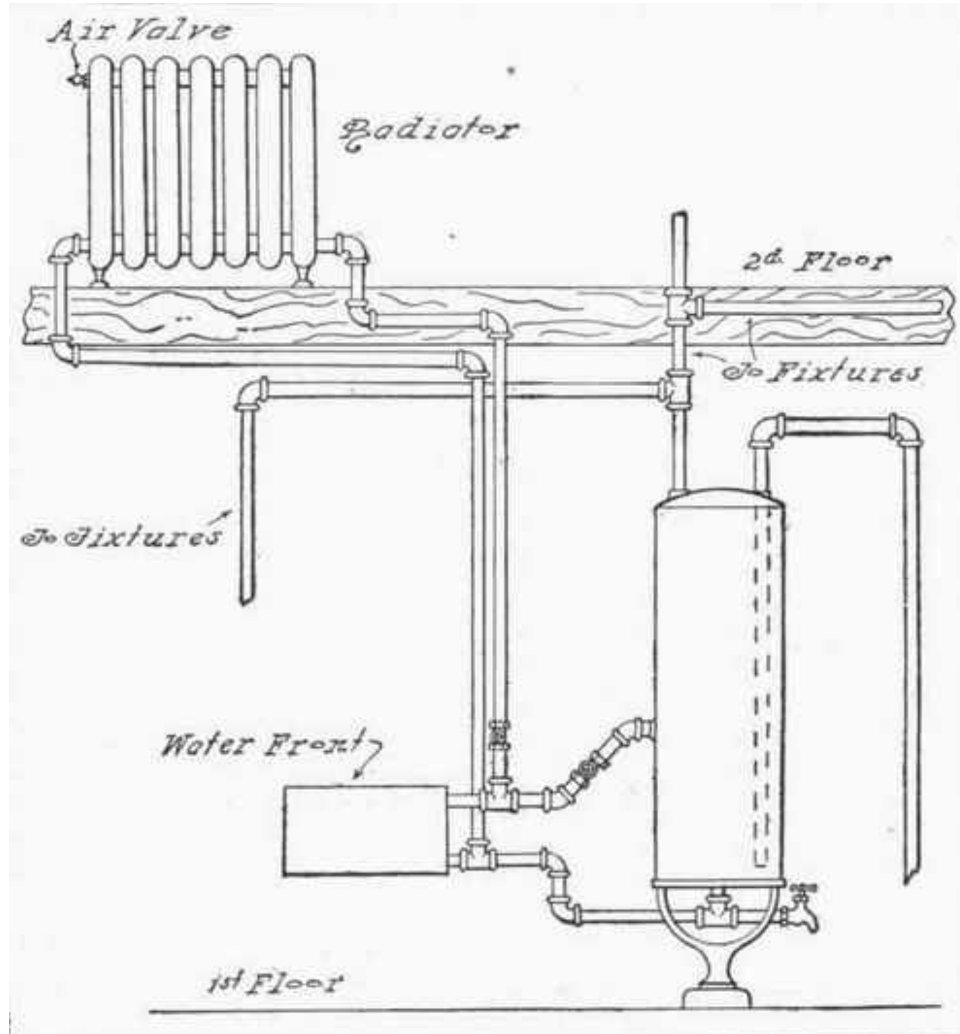
- Many commercial buildings use a combination of conditioned air and zone water coils

- Ventilation requires air movement

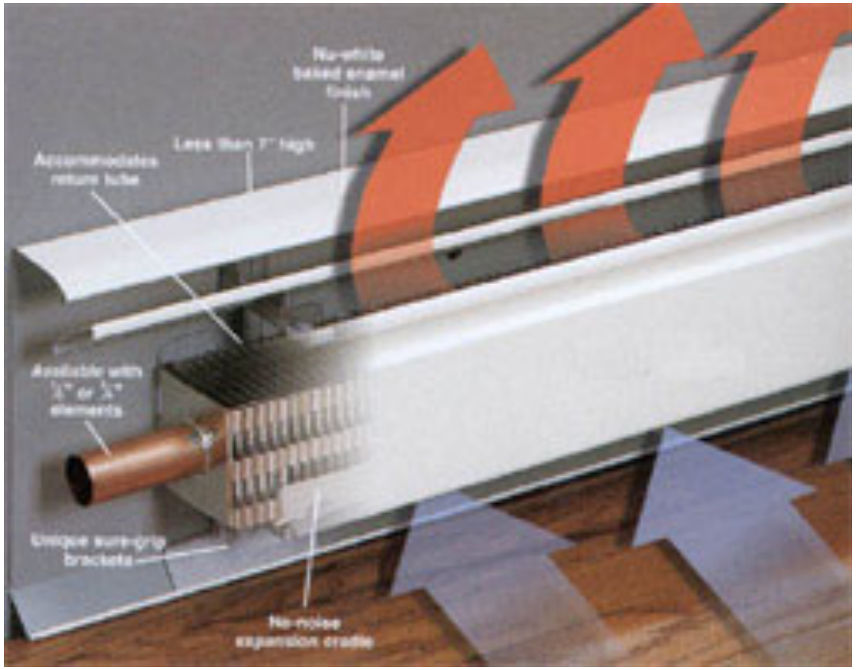
- But zone heating and cooling loads can be met with coils
  - We mostly use fan coils now
  - We previously mostly used radiators (like in Alumni Hall)

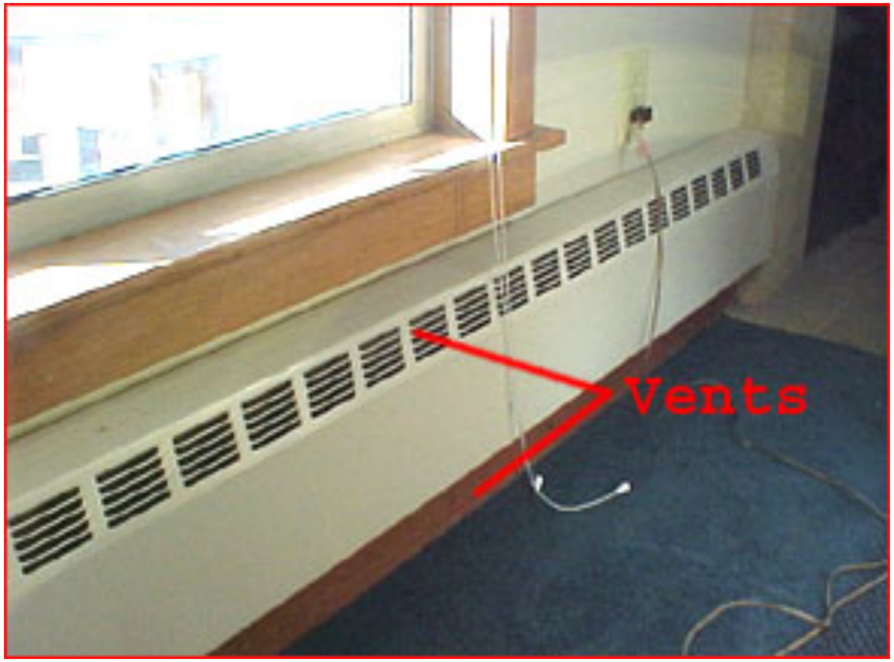
Radiator systems (for heating)

What modes of heat transfer are involved?



Water-based baseboard systems (heating)





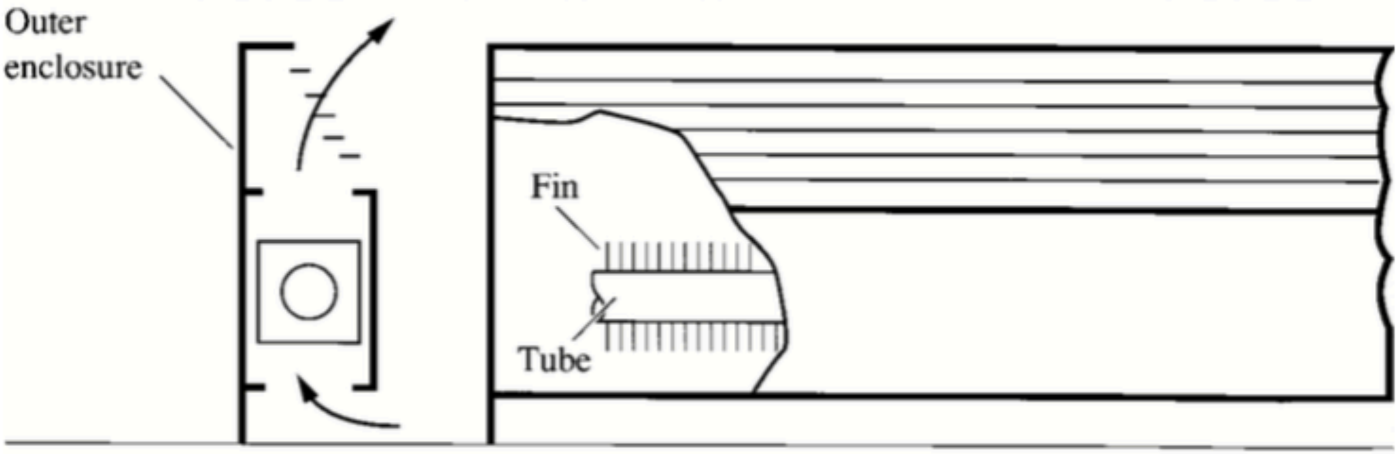


FIGURE 8.8 Baseboard finned-tube heater.

Water-based baseboard systems (heating)

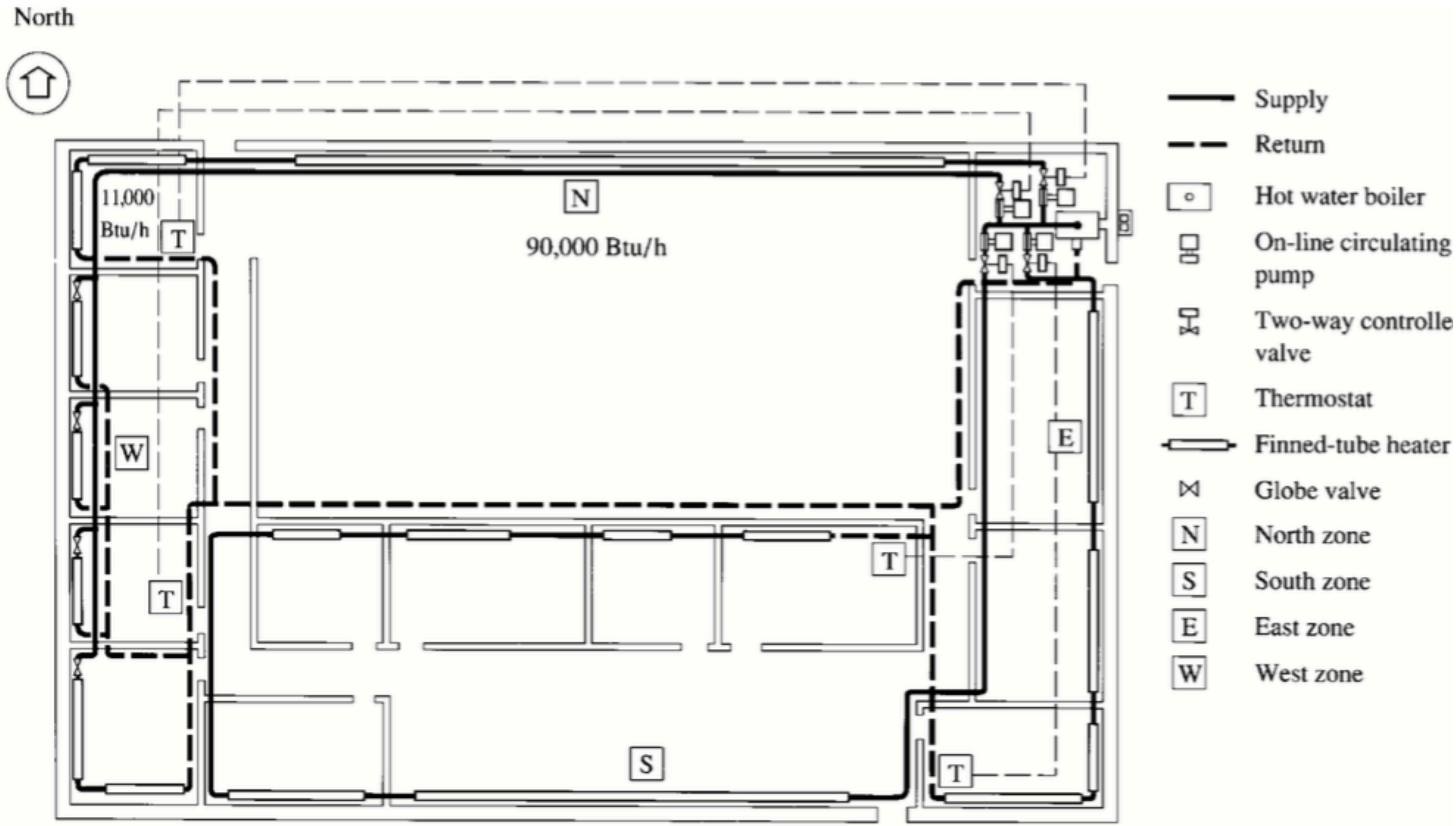
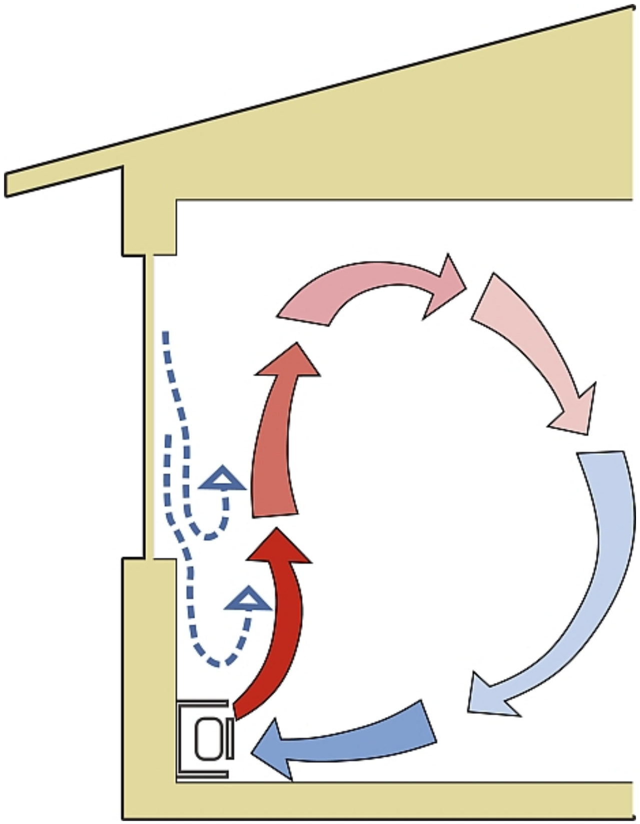
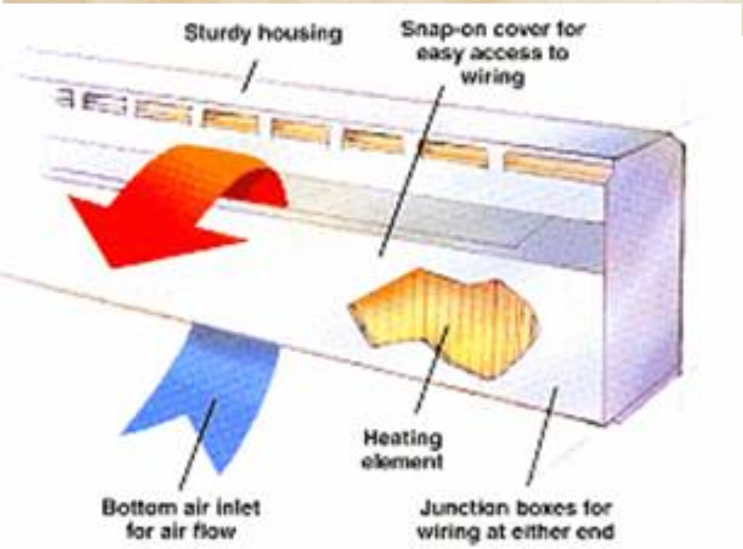


FIGURE 8.7 A two-pipe individual-loop low-temperature hot water heating system for a factory.

Electric baseboard systems (for heating)





Fan coils: Modern radiator replacement w/ fan

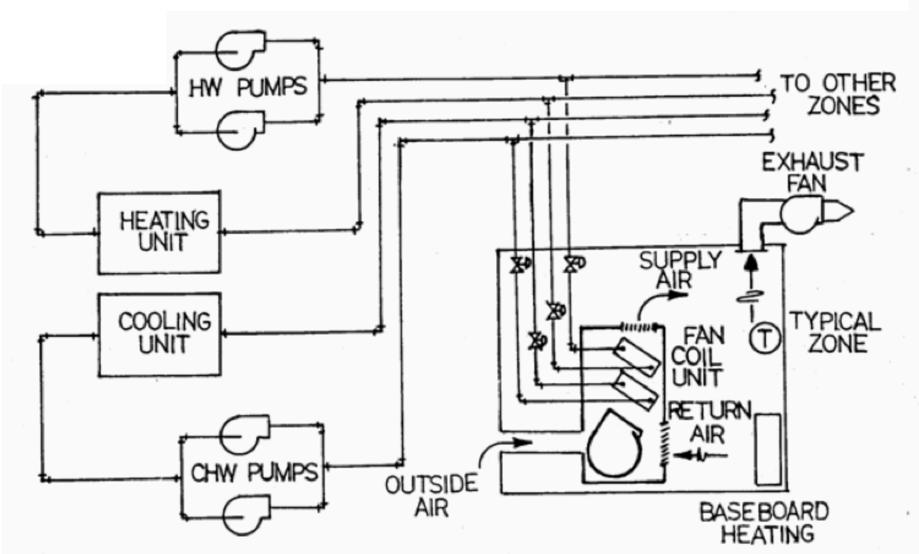
Combines air and water

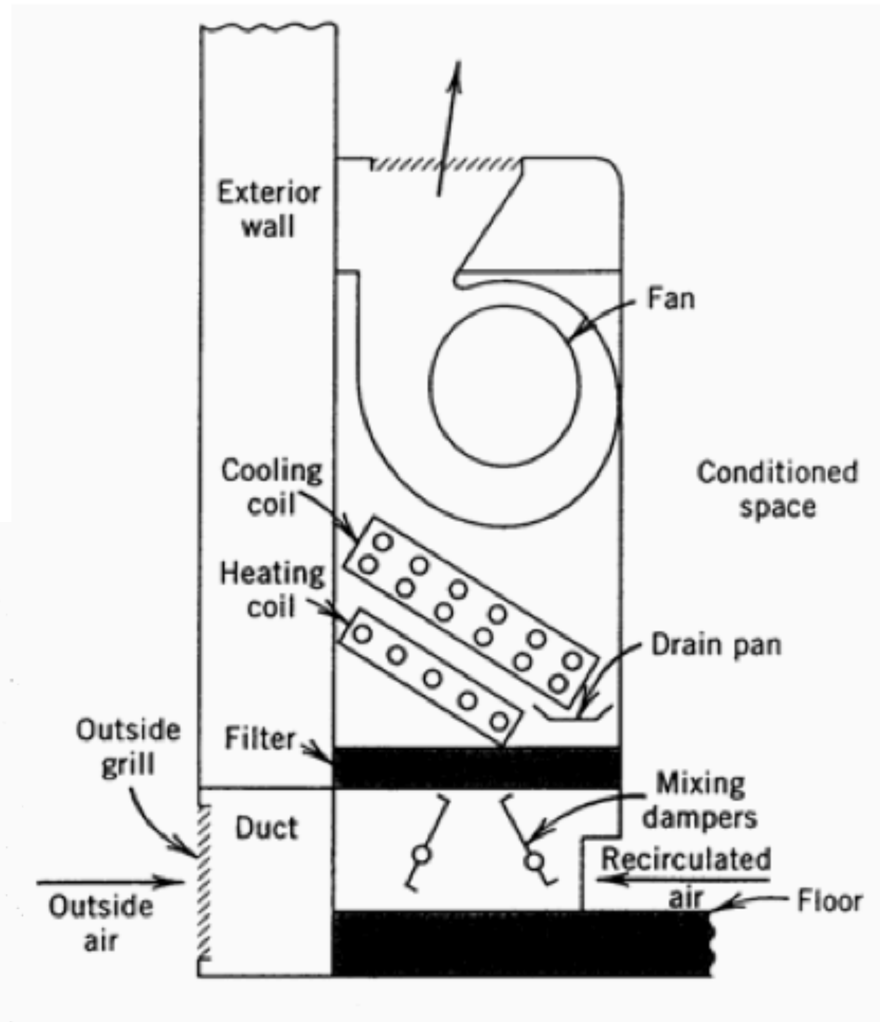
Wall installation

Overhead/ceiling installation

Fan coils: Modern radiator replacement w/ fan

- One or two coils (H or C)
- Thermostat controls water flow
- Ventilation is met with conditioned or unconditioned outdoor air





Other: Chilled beams and radiant panels

Chilled beams

Radiant panels

Next time

- Introduce Psychrometrics
  - The science and engineering of air/vapor mixtures