Cyber-Physical Energy Systems

LECTURE 3

PRINCIPLES OF MODELING FOR CYBER-PHYSICAL SYSTEMS

INSTRUCTOR: MADHUR BEHL

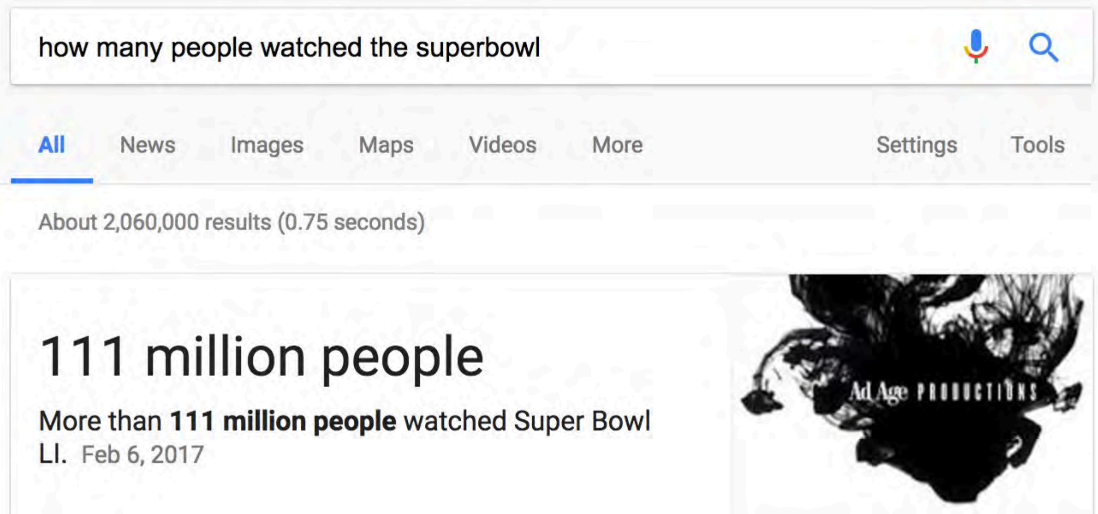


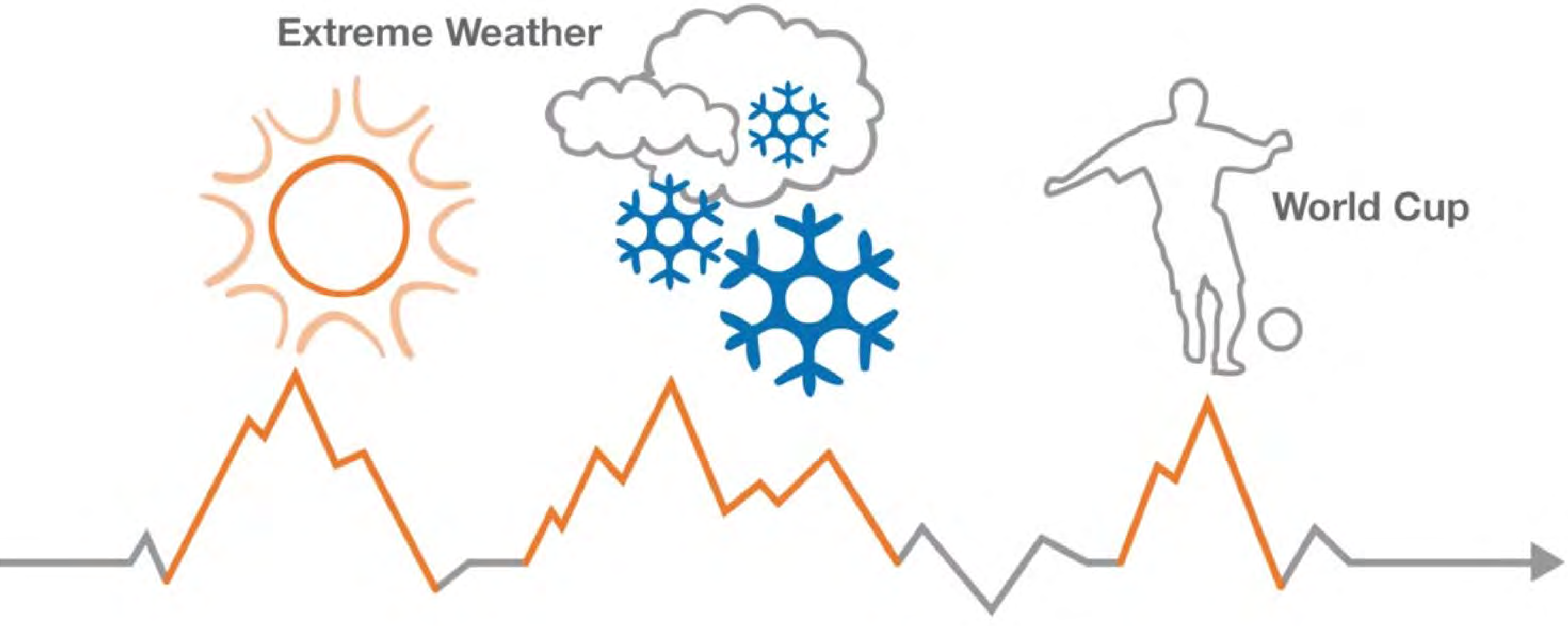





Tea Time In Britain

Peaks occur during major sporting events

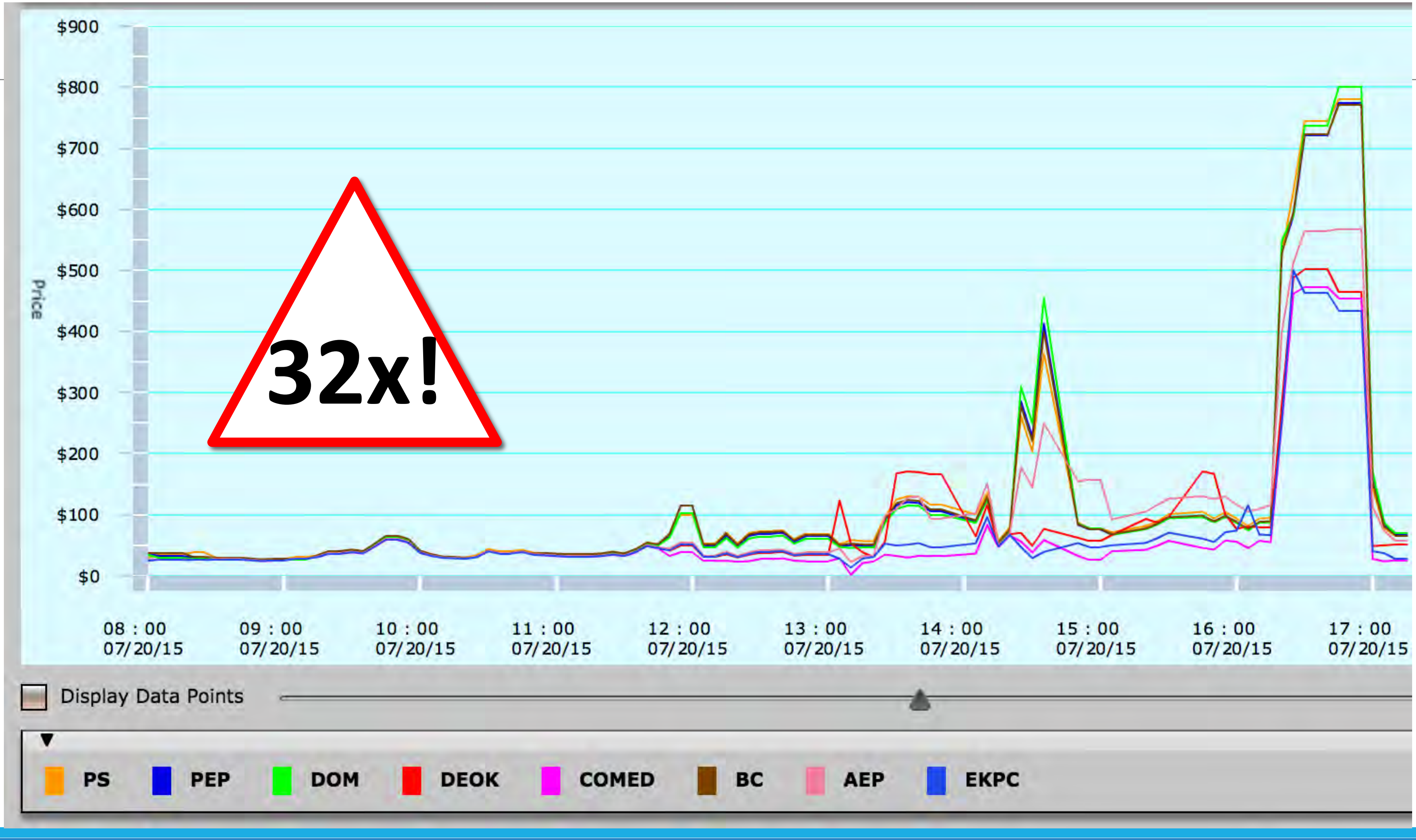



Extreme Weather
World Cup

Price Volatility: Summer peak

Nominal price: $25/MWh

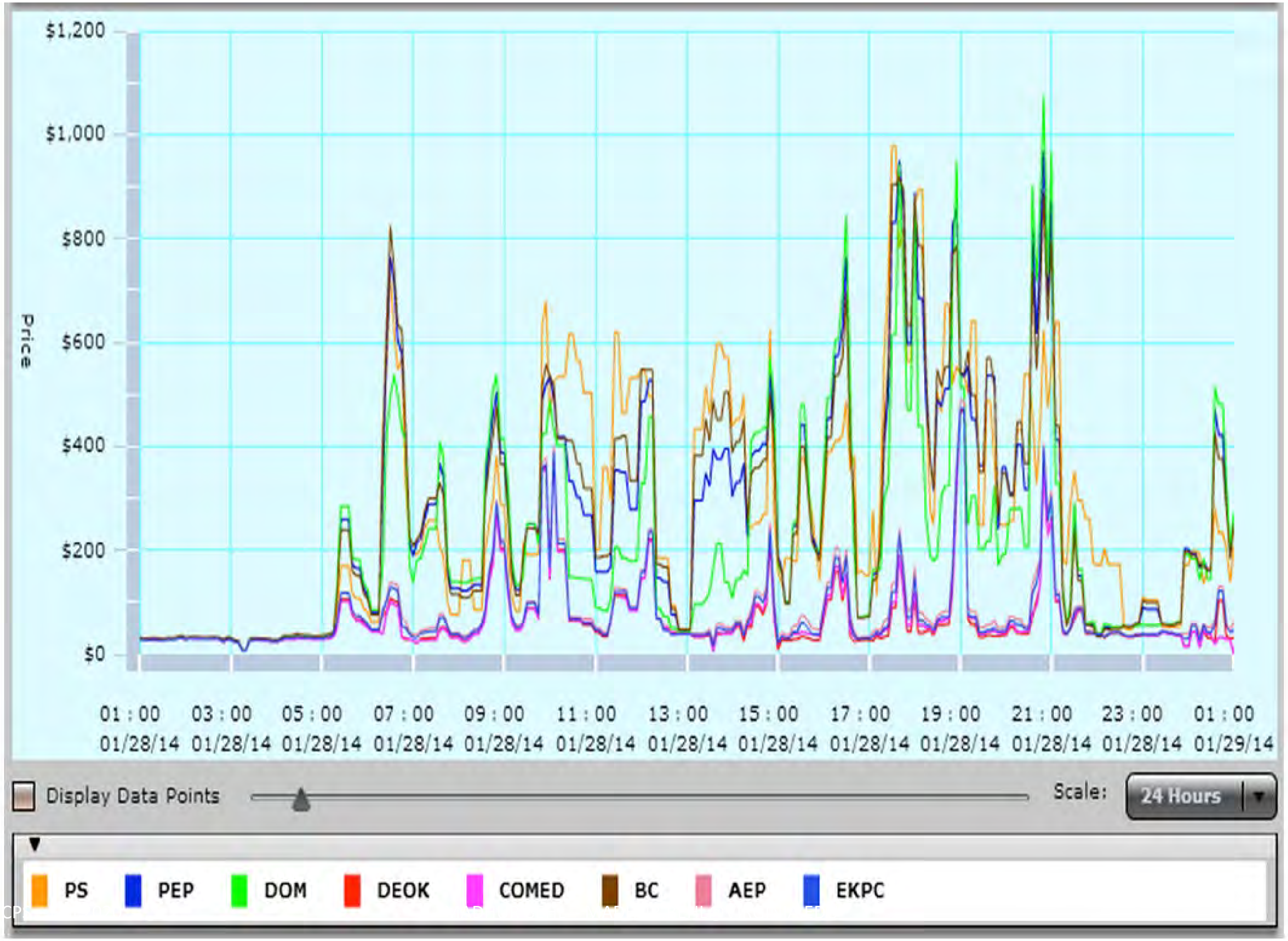
Peak Price: $800/MWh



20th, July 2015

Price volatility is the new normal

PJM (ISO) Locational Marginal Prices (LMPs) example



Peak Demand is Expensive!

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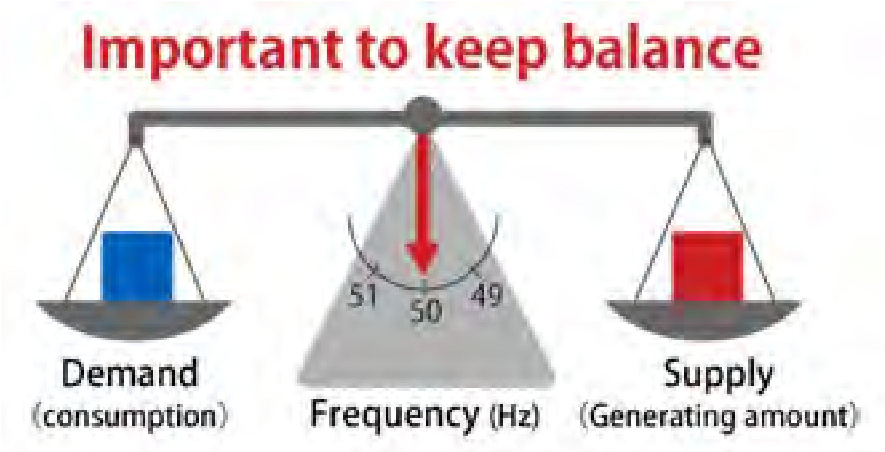
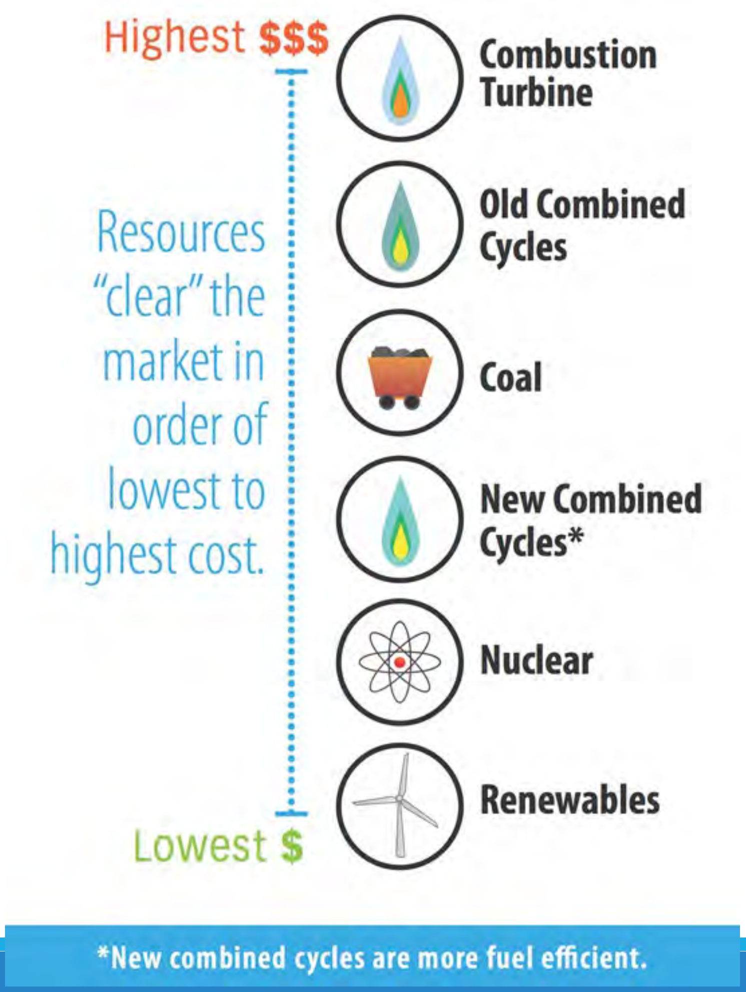
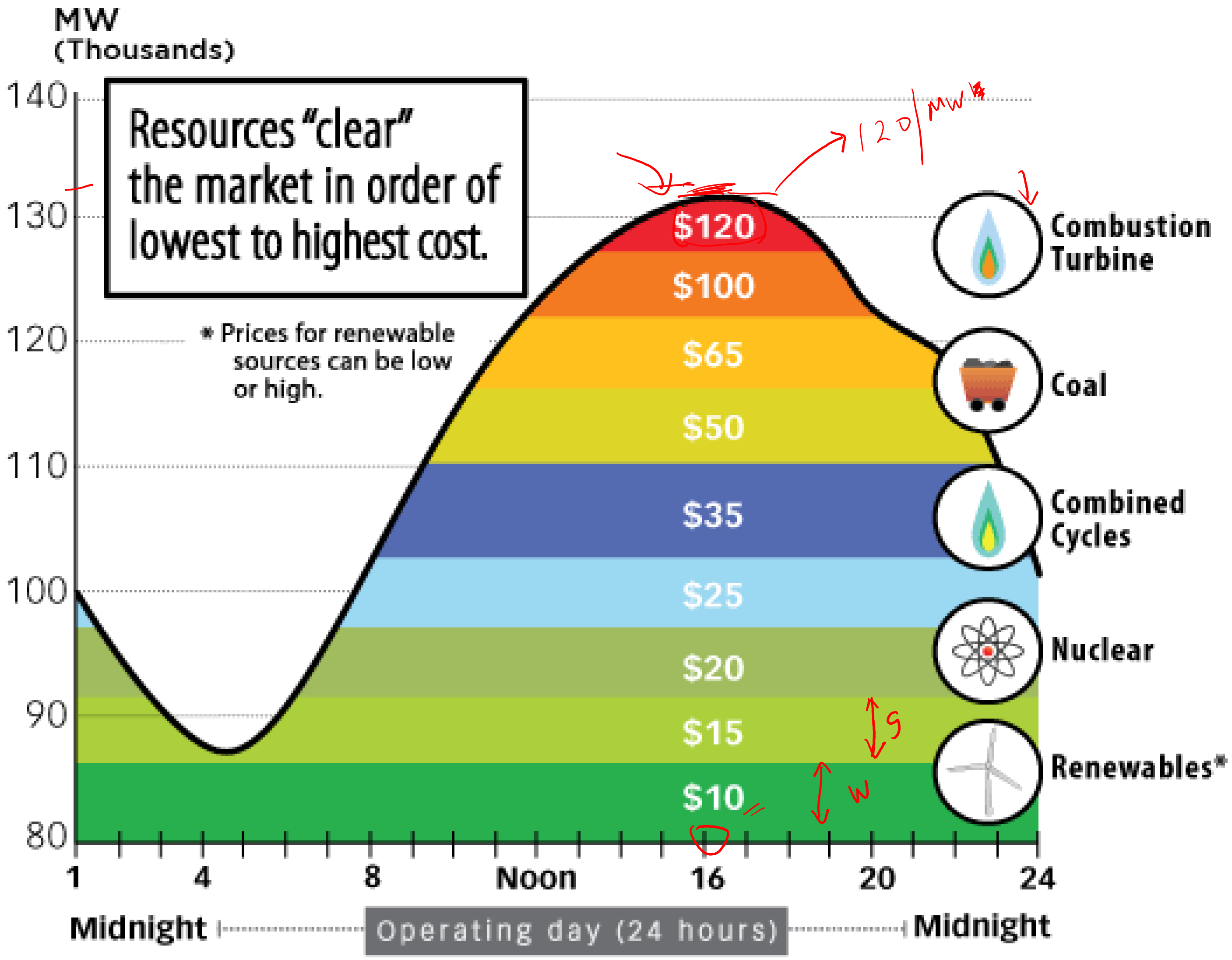
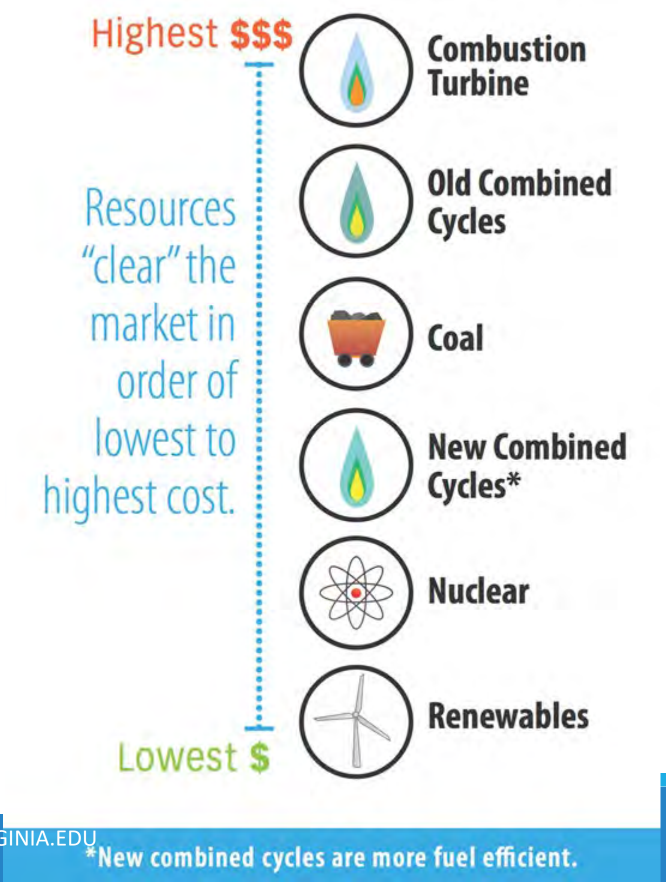




Peak Demand is Expensive!

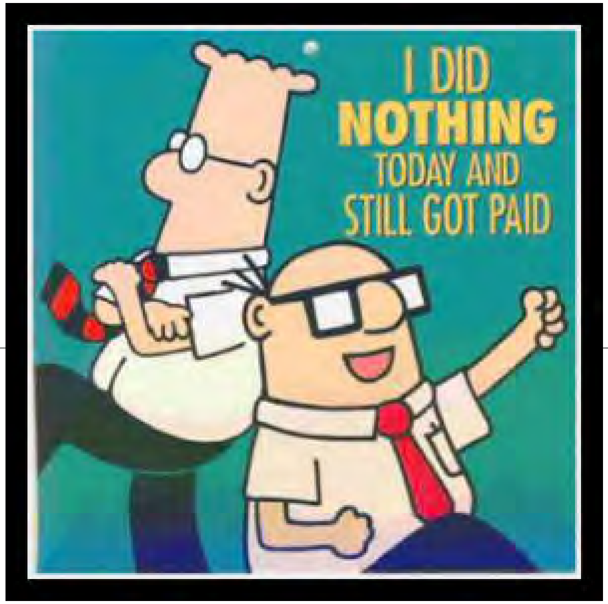




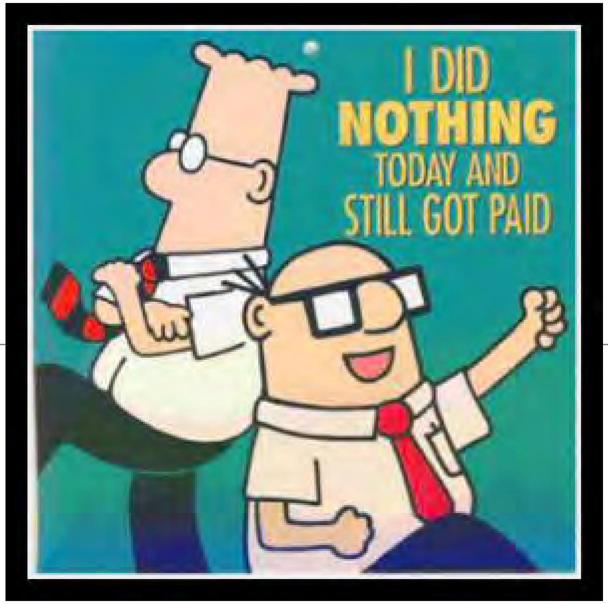
"All kilowatts are not created equally"

Demand Response

- Reliable
- Clean
- Cost-Effective



Imagine getting paid for doing nothing



~~Imagine getting paid for doing nothing~~

Greetings to you my friend,

I know this will come to you as a surprise because you do not know me.
I am John Alison I work in Central Bank of Nigeria packaging and courier department.

I got your contact among others from a search on the internet and I was inspired to seek your co-operation. I want you to help me clear this consignment that is already in the Europe which I shipped through our CBN accredited courier agent. The content of the package is $20.000.000.00 all in $100 bills, but the courier company does not know that the consignment contains money.

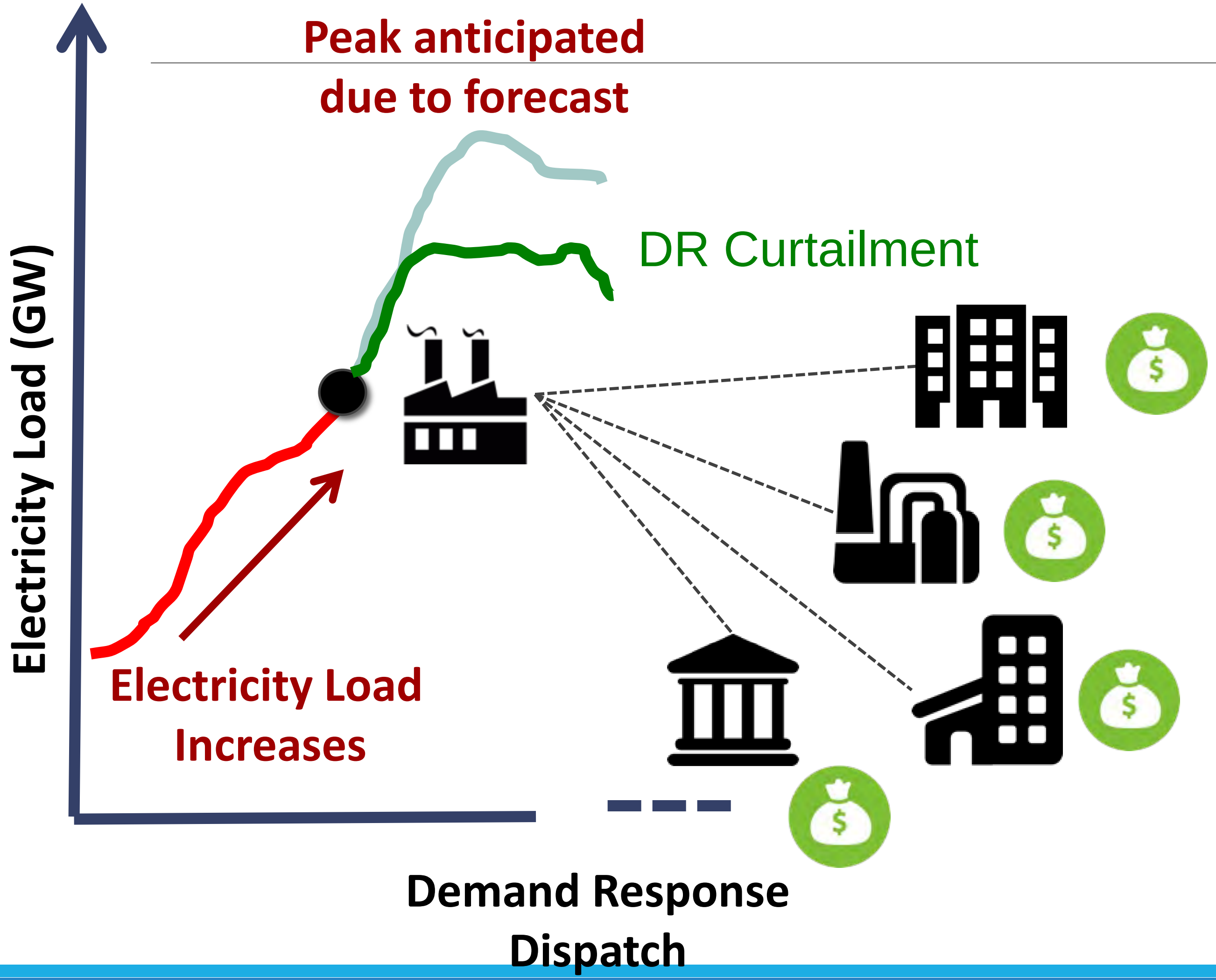
All I want you to do for me now is to give me your mailing address, your private phone and fax number, and I believe that at the end of the day you will have 50% and 50% will be for me. My identity must not be revealed to anybody.

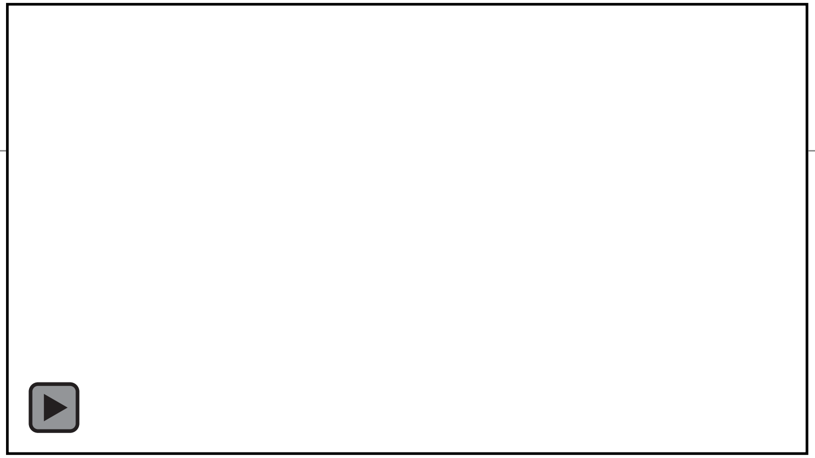
If this arrangement is okay by you, you can call

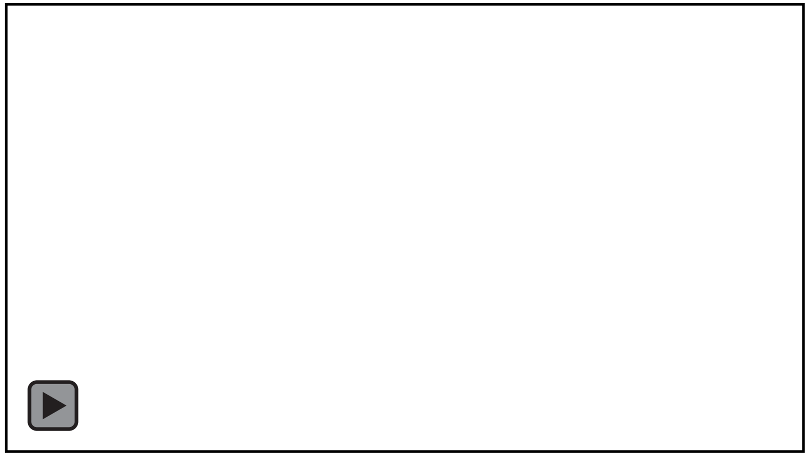
Phone: +234 8028776685
Email:john_alison444@yahoo.com

Imagine getting paid, or otherwise compensated, for not using electricity during peak hours!

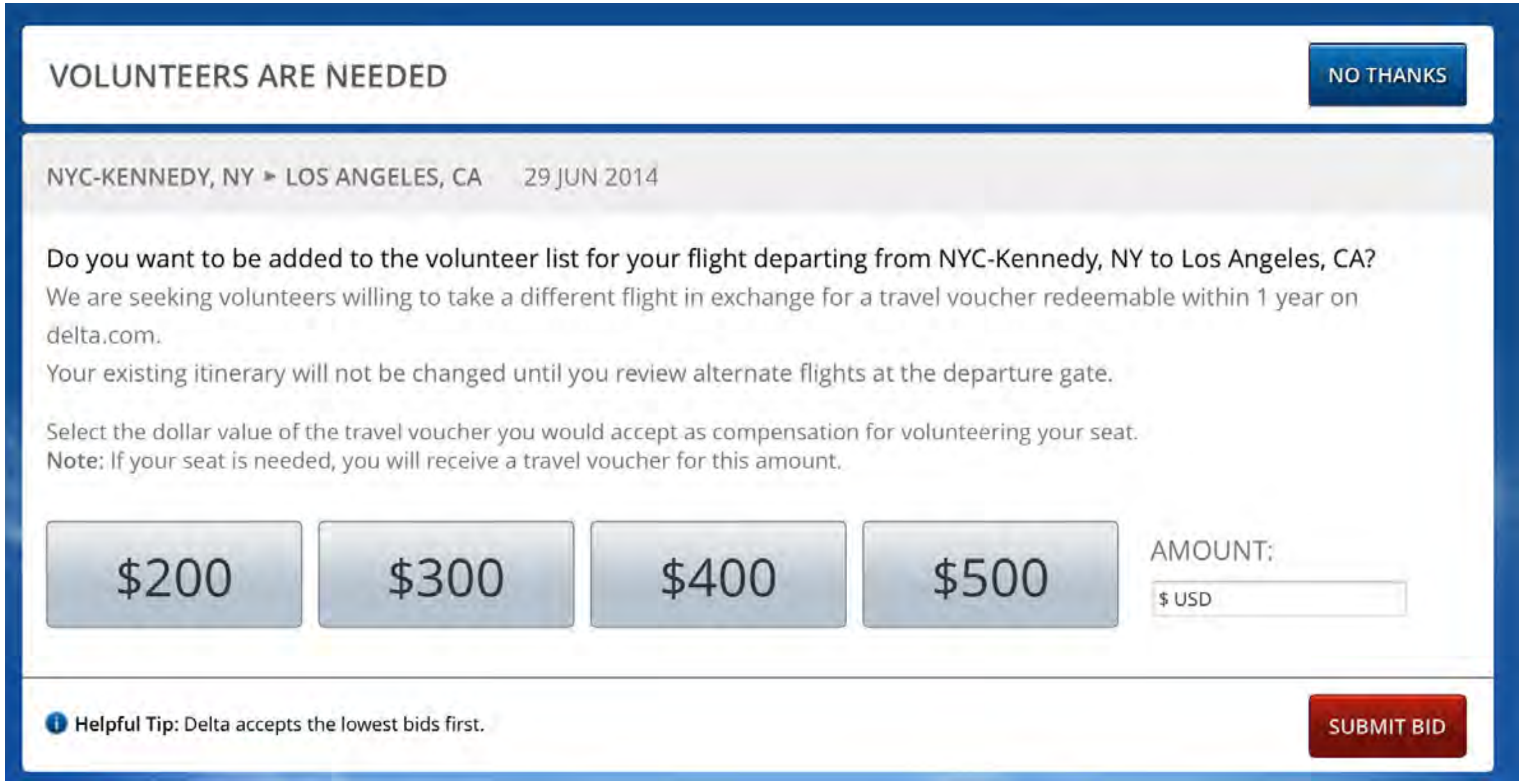
A Demand Response Event





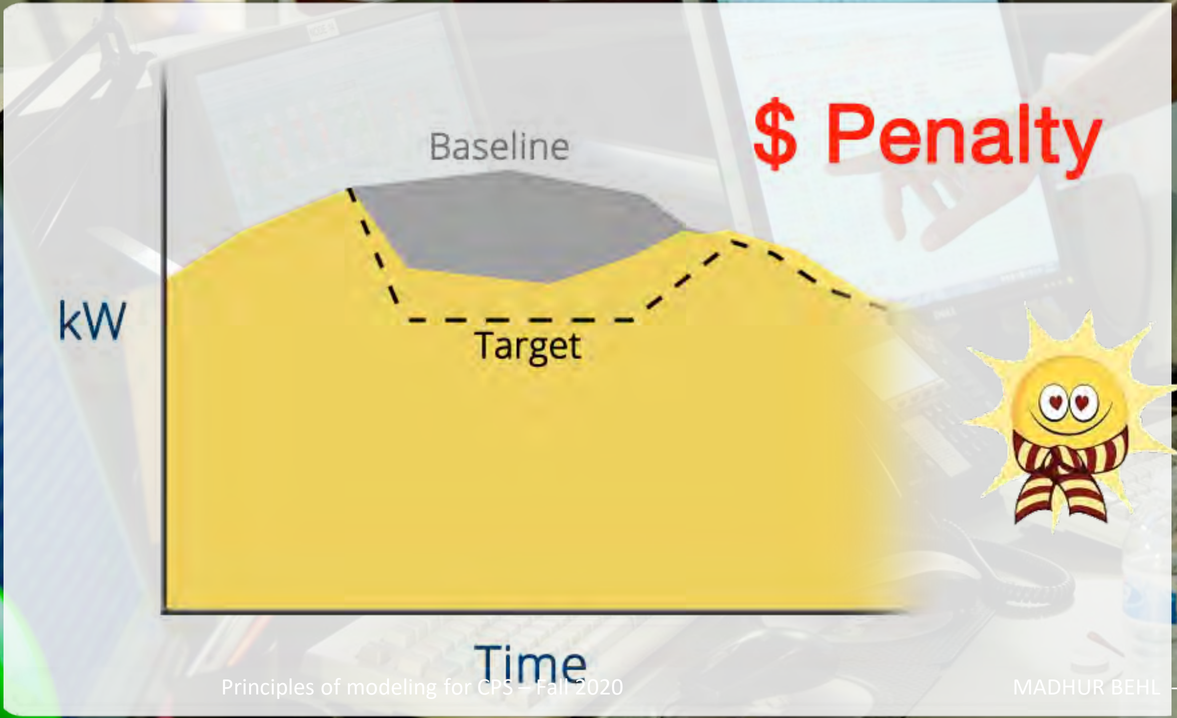


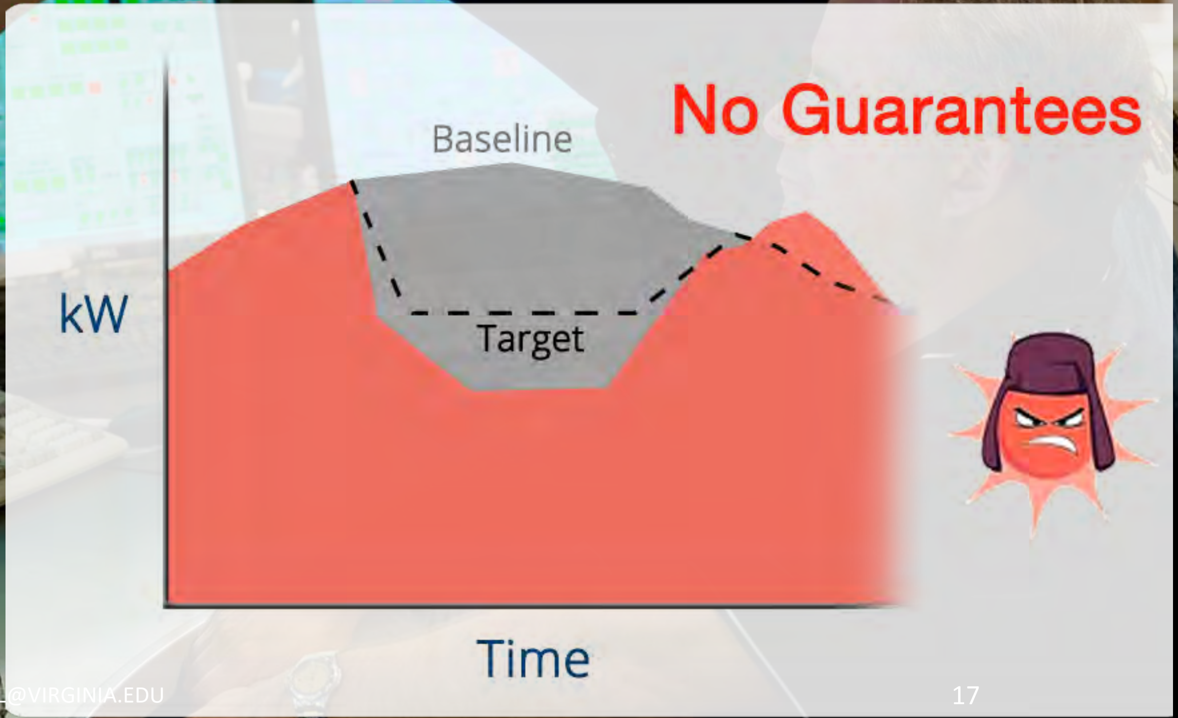
Demand Response – Looks familiar



Fixed Strategy 1
Fixed Strategy 2
Fixed Strategy 3

Fixed Strategy 4
Fixed Strategy 5





Q) If you don't know what's going to happen when you change a set-point. How do you even know the change is worth making ?

Q) What is the best change that you can make right now ?

Model-based predictive control (MPC)

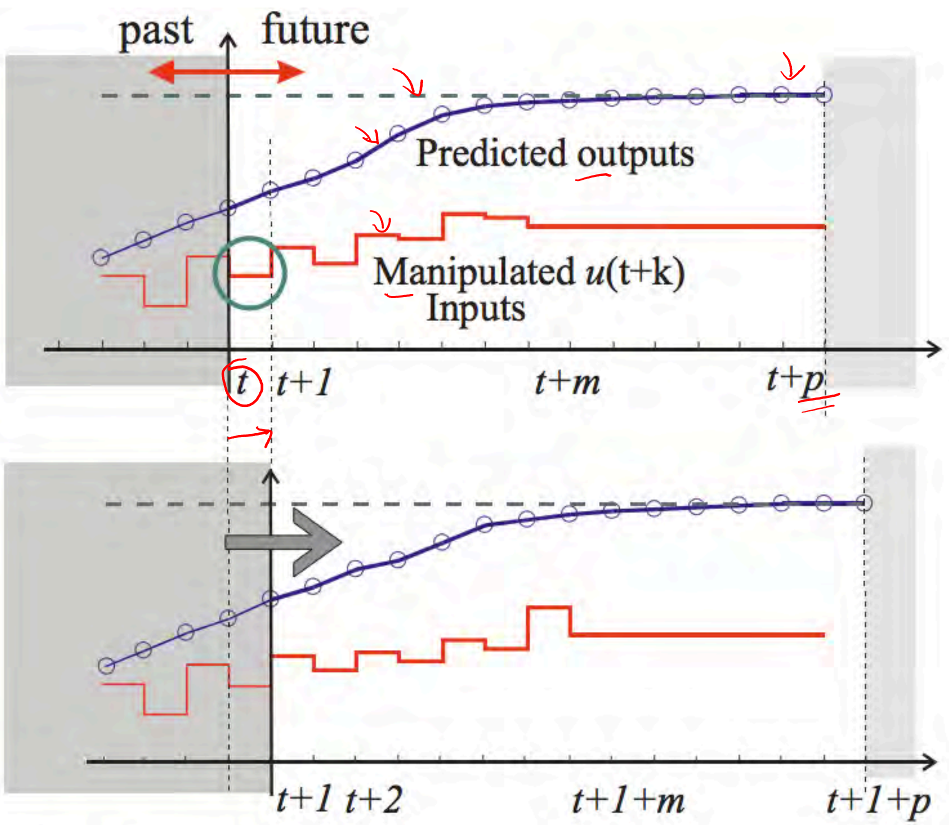
What kind of models ?

The control problem in buildings

Integrated control of:

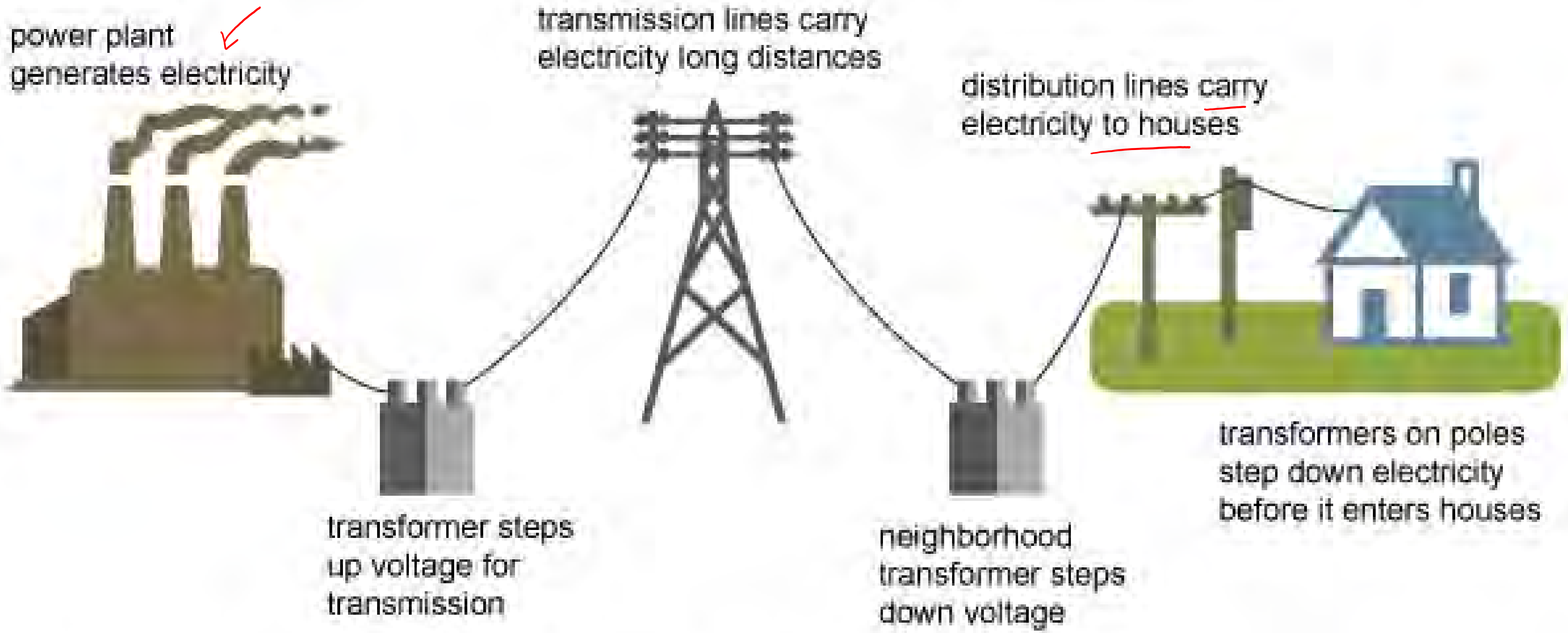
- Heating
- Cooling
- Ventilation
- Lighting
- Blinds

Model Predictive Control (MPC)



- Determine state $x(t)$
- Determine optimal sequence of inputs over horizon
- Implement first input $u(t)$
- Wait for next sampling time; $t := t + 1$

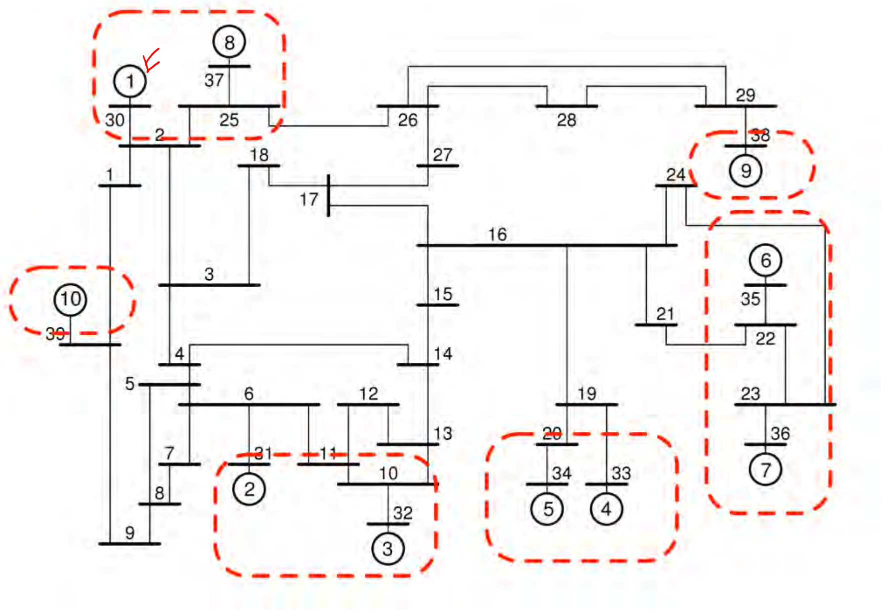
Generation, Transmission, Distribution: Supply-side



Source: Adapted from National Energy Education Development Project (public domain)

Modeling the grid dynamics ?

Modeling the grid dynamics ? Not in this course.



IEEE 39 New England Power Grid Model

- 39 transmission buses
- 10 generators

$$\textbf{linearized dynamics:} \quad \dot{x}(t) = A\,x(t) + B_1\,d(t) + B_2\,u(t)$$

$$\textbf{objective function:} \quad J = \lim_{t \to \infty} \mathcal{E}\left(\theta^T(t)\,Q_\theta\,\theta(t) + \dot{\theta}^T(t)\,Q_{\dot{\theta}}\,\dot{\theta}(t) + u^T(t)\,R\,u(t) + \gamma \sum_{i,j} w_{ij}\,|F_{ij}|\right)$$

$$\textbf{memoryless controller:} \quad u = -F\,x(t)$$

Electricity consumption Buildings: Demand-side

Commercial, Industrial & Institutional (C/I/I)

Residential

Why Buildings ?

40% — Portion of global energy use

70% — Portion of electricity consumption in the United States

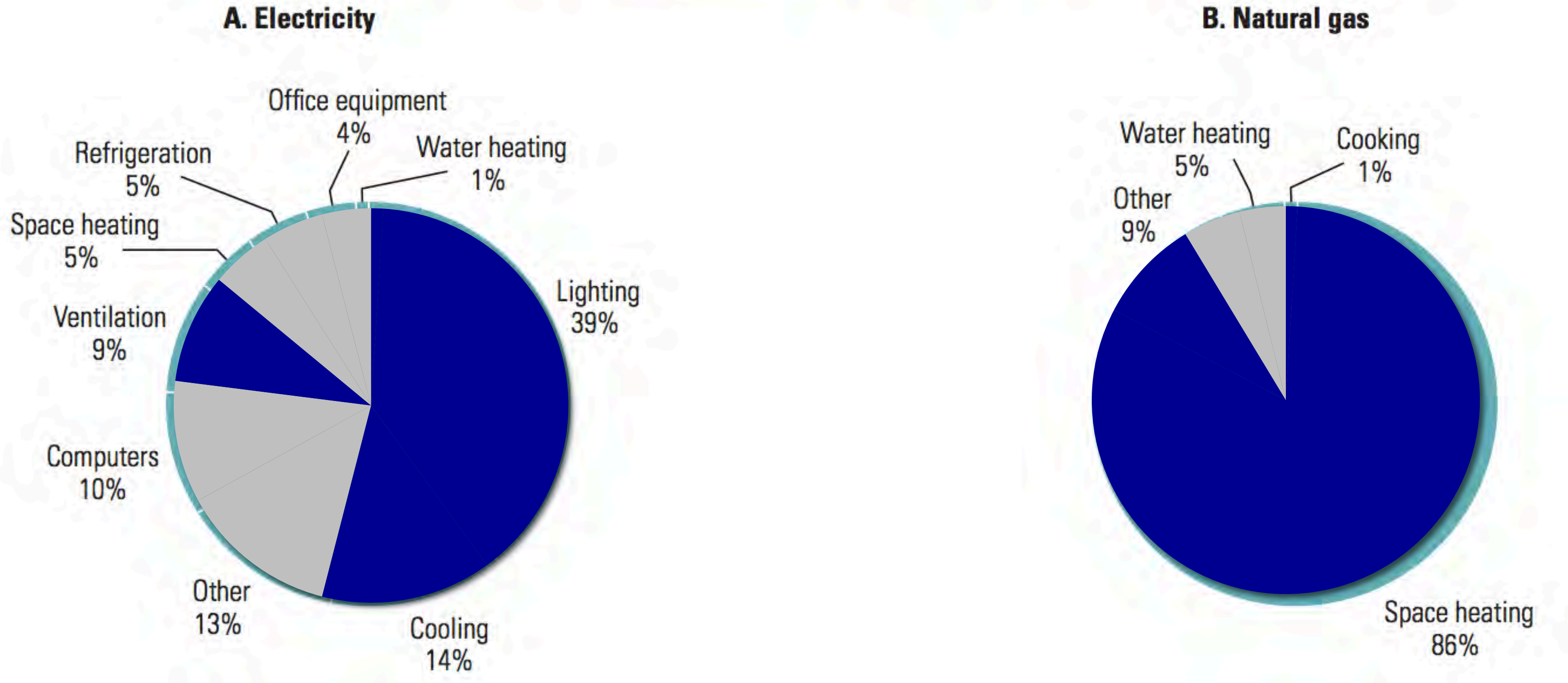
1/3 — Portion of global total CO_2 emissions

62% | **Electricity use due to cooling, lighting and ventilation**

Portion of natural gas use dedicated to space heating | **86%**

FIGURE 1: Office buildings energy consumption by end use in the U.S.

Data from the U.S. Energy Information Administration show that cooling, lighting, and ventilation account for 62 percent of electricity use (A), and space heating dominates natural gas use at 86 percent (B).

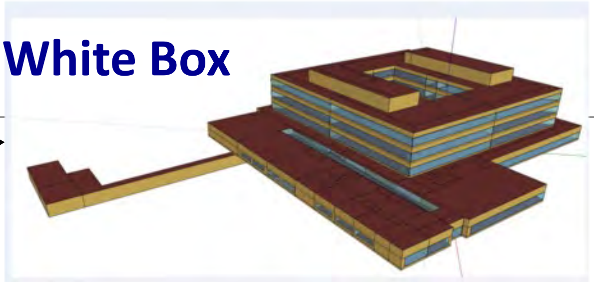


Note: Insufficient data were available for electric consumption of Cooking equipment; sum may not total 100% due to rounding.

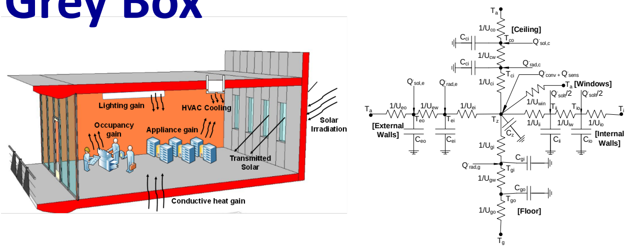
© E Source; data from the U.S. Energy Information Administration

How are building models obtained today ?

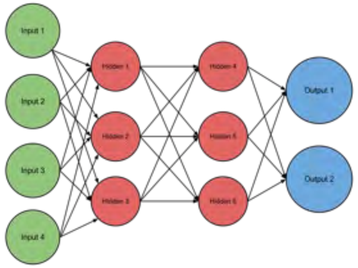
White Box



Grey Box

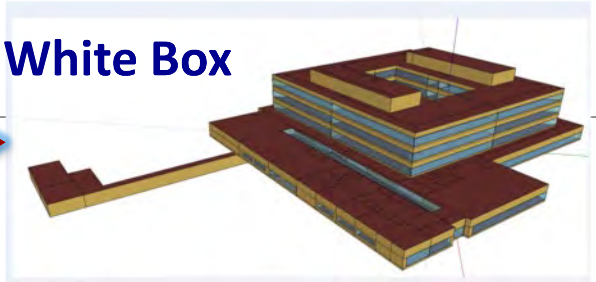


Black Box

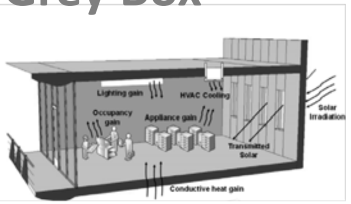


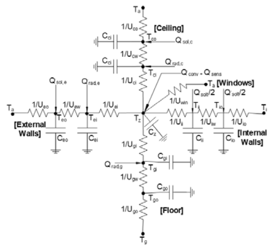
How are building models obtained today ?

White Box

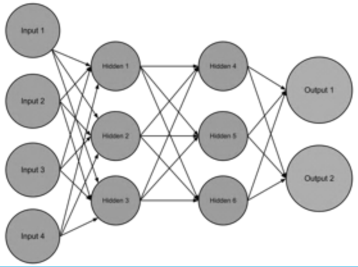


Grey Box



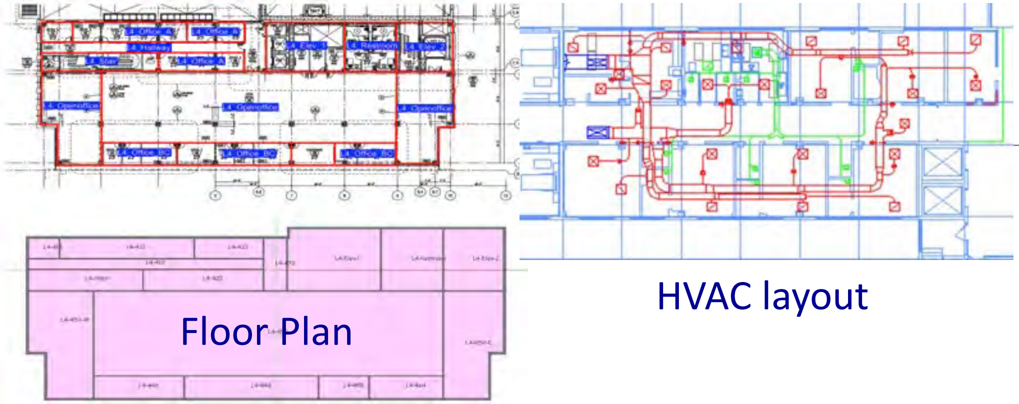


Black Box



White-Box Modeling

Not always available

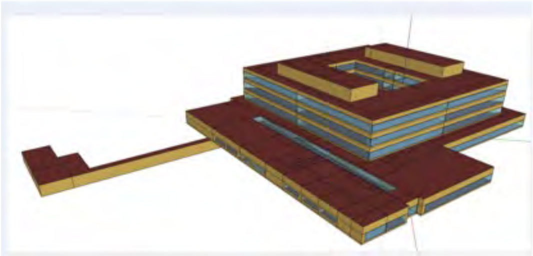


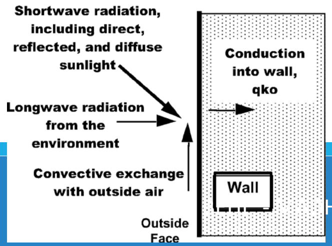
Model Tuning
Data
Sensor retrofits

Set parameters
Floor by floor
Zone by zone
Wall by wall
Layer by layer
Equipment by equipment
Transfer geometry

Guess nominal parameter values

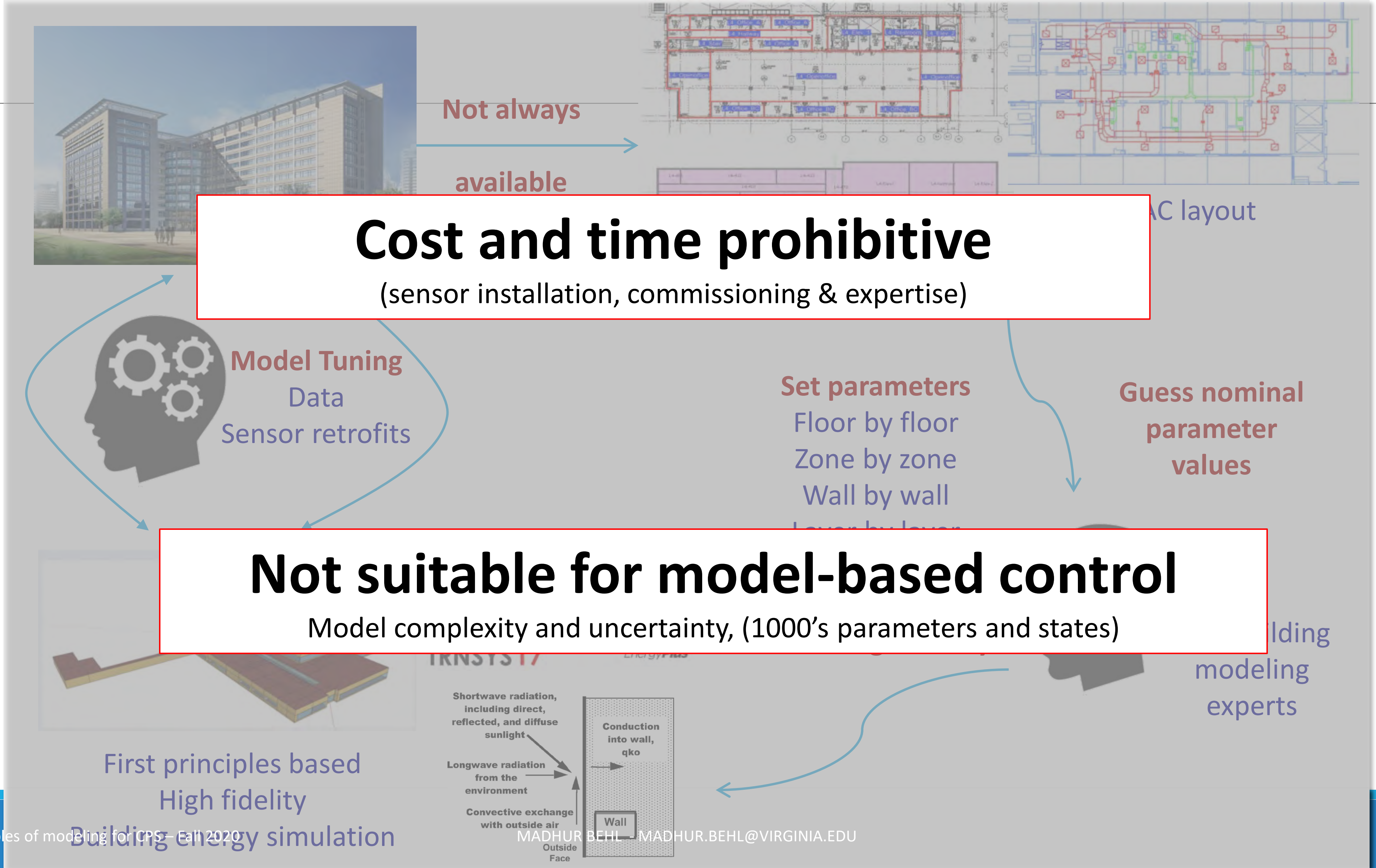
Hire building modeling experts





First principles based building energy simulation

White-Box Modeling



Cost and time prohibitive

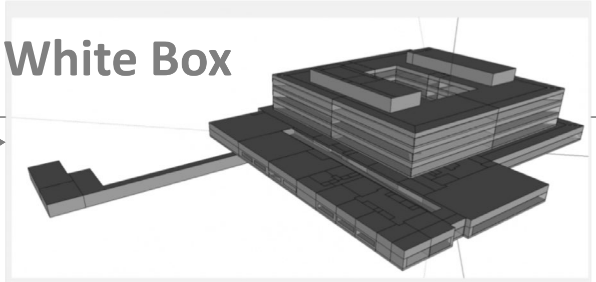
(sensor installation, commissioning & expertise)

Not suitable for model-based control

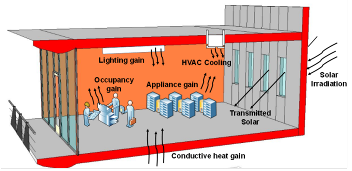
Model complexity and uncertainty, (1000’s parameters and states)

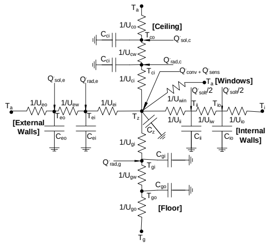
How are building models obtained today ?

White Box

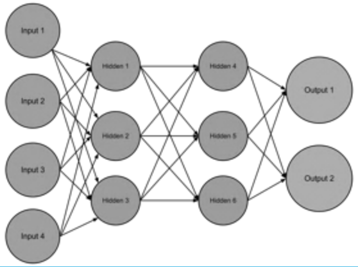


Grey Box



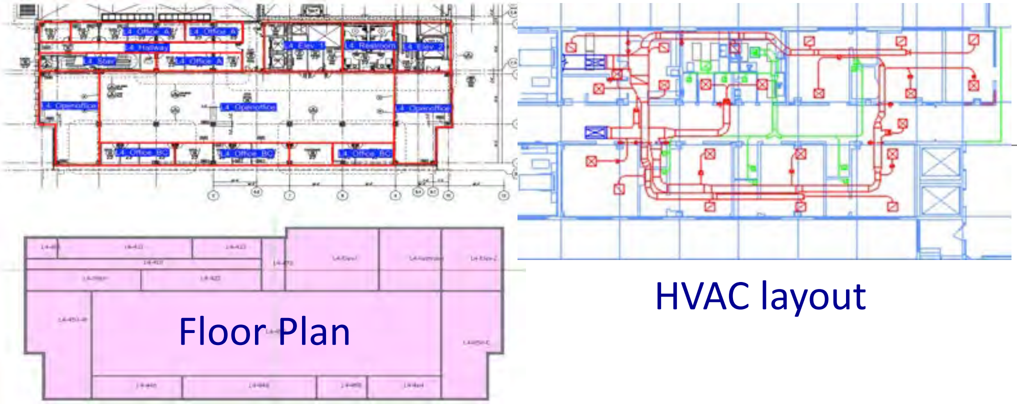


Black Box



Grey-Box [Inverse] Modeling

Not always available



Parameter Estimation
Data
Sensor retrofits

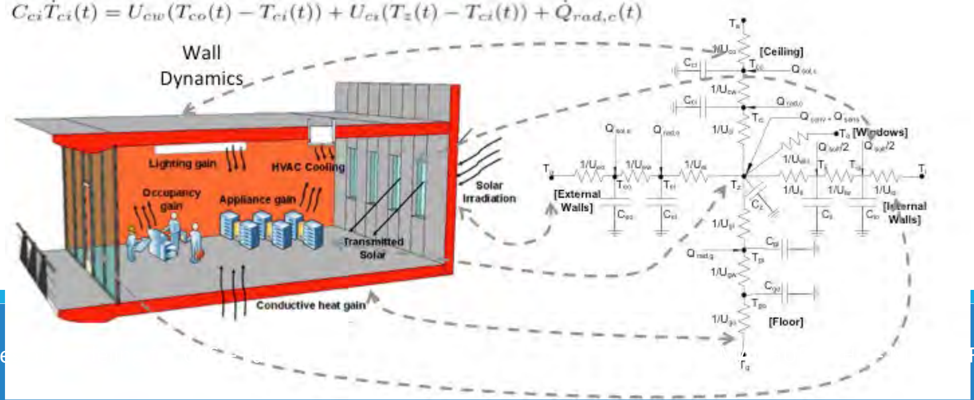
Set parameters
Floor by floor
Zone by zone
~~Wall by wall~~
~~Layer by layer~~
Equipment by equipment
Transfer geometry

Guess nominal parameter values

Hire building modeling experts

Lumped Parameter 'RC' model

$$C_{co}\dot{T}_{co}(t) = U_{co}(T_a(t) - T_{co}(t)) + U_{cw}(T_{ci}(t) - T_{co}(t)) + \dot{Q}_{sol,c}(t)$$
$$C_{ci}\dot{T}_{ci}(t) = U_{cw}(T_{co}(t) - T_{ci}(t)) + U_{ci}(T_z(t) - T_{ci}(t)) + \dot{Q}_{rad,c}(t)$$



Grey-Box Modeling: 'RC' networks

Discrete-Time State Space Model:

(parameterized by θ)

$$x(k+1) = \hat{A}_\theta x(k) + \hat{B}_\theta u(k)$$
$$y(k) = \hat{C}_\theta x(k) + \hat{D}_\theta u(k)$$

States (**All node temperatures**):

$x = [T_{eo}, T_{ei}, T_{co}, T_{ci}, T_{go}, T_{gi}, T_{io}, T_{ii}, T_z]^T$

Inputs (**Disturbances and Control**):

$u = [T_a, T_g, T_i, Q_{sole}, Q_{solc}, Q_{rade}, Q_{radc}, Q_{radg}, Q_{solt}, Q_{conv}, \mathbf{Q_{sens}}]^T$

Parameter Estimation:

Least Squares Error

$$\theta^* = \underset{\theta_l \leq \theta \leq \theta_u}{\arg\min} \sum_{k=1}^{N} (T_{z_m}(k) - T_{z_\theta}(k))^2$$

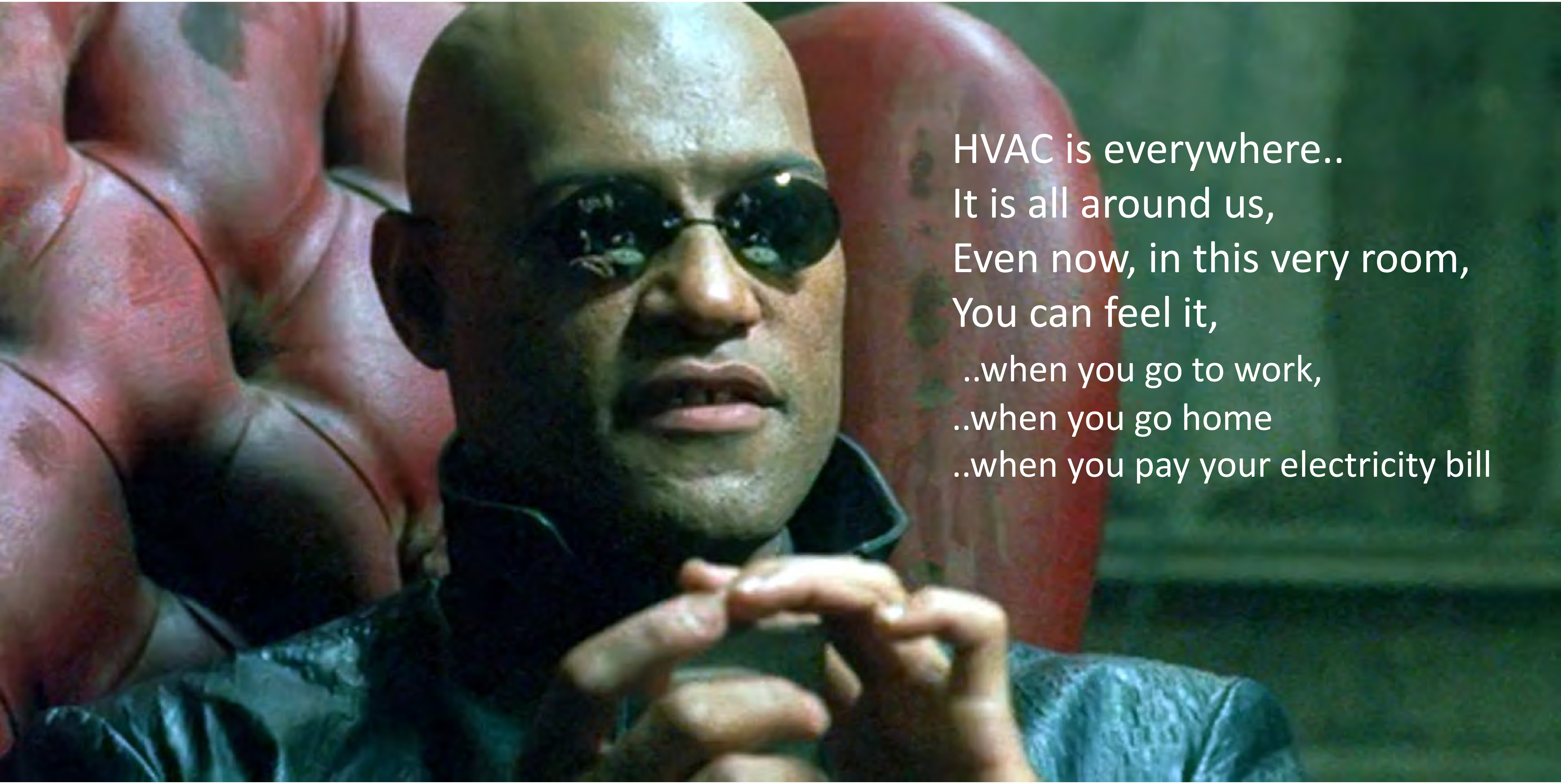
$$\text{subject to } \theta_l \leq \theta \leq \theta_u$$

LIST OF PARAMETERS

$U_{\star o}$	convection coefficient between the wall and outside air
$U_{\star w}$	conduction coefficient of the wall
$U_{\star i}$	convection coefficient between the wall and zone air
U_{win}	conduction coefficient of the window
$C_{\star\star}$	thermal capacitance of the wall
C_z	thermal capacity of zone z_i

g: floor; e: external wall; c: ceiling; i: internal wall

Heating, Ventilation, & Air Conditioning


HVAC is everywhere..
It is all around us,
Even now, in this very room,
You can feel it,
..when you go to work,
..when you go home
..when you pay your electricity bill

Its all about comfort..

Temperature	*68°F (20°C) and 75°F (25°C)*
Humidity	*30% relative humidity (RH) and 60% RH*
Pressure	*A slightly positive pressure to reduce outside air infiltration.*
Ventilation	*Rooms typically have several complete air changes per hour*

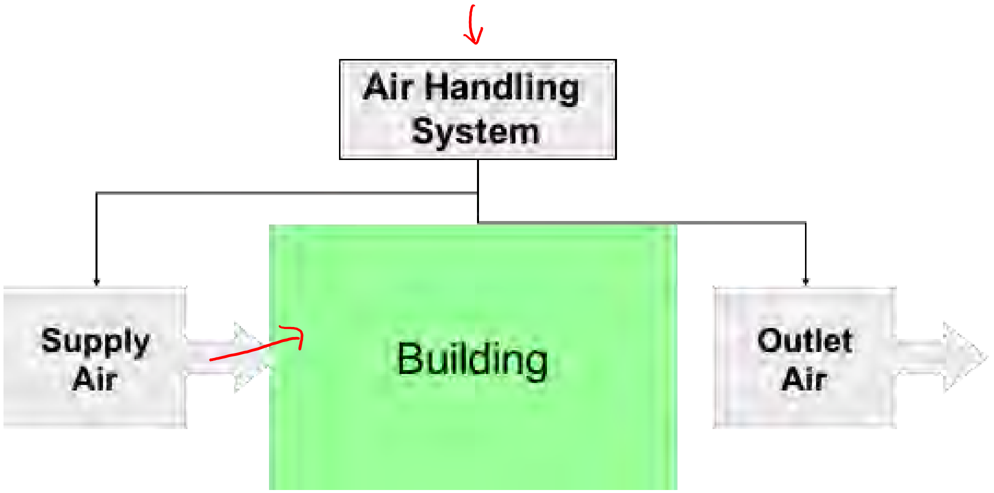
Components of HVAC System

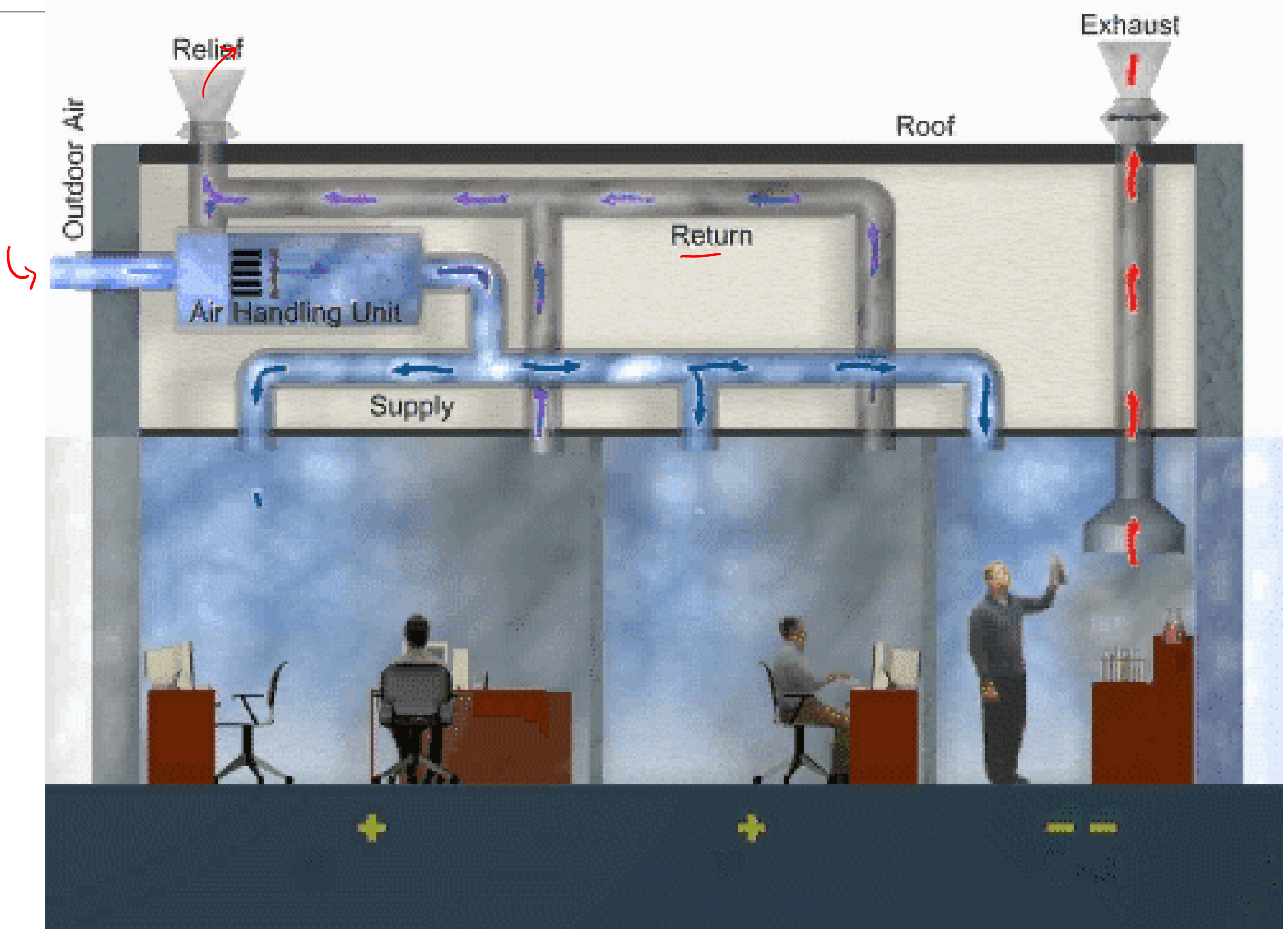
5 system loops..

The Five System Loops

- Airside
- Heat rejection
- Chilled water
- Controls
- Refrigeration

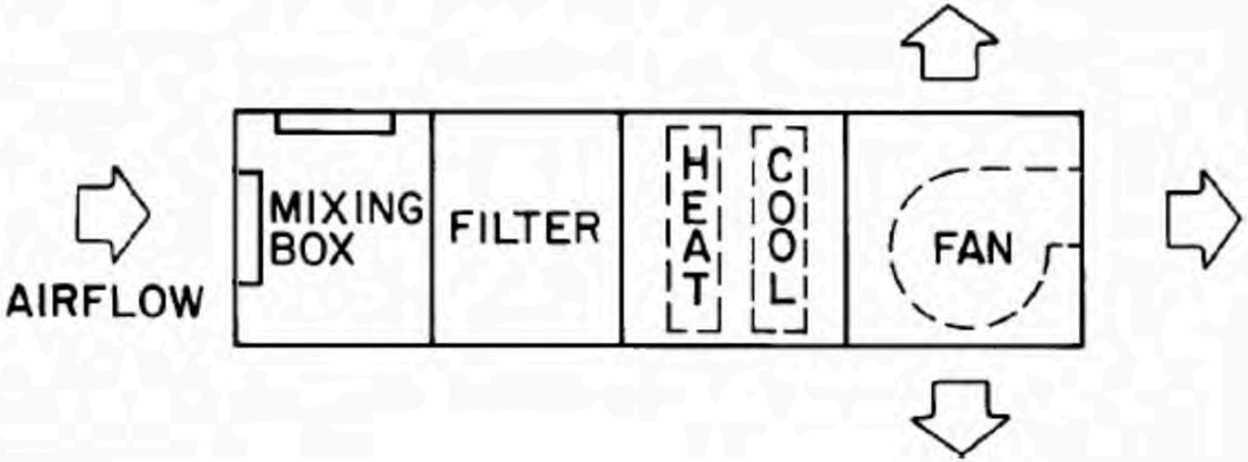
Air handling systems



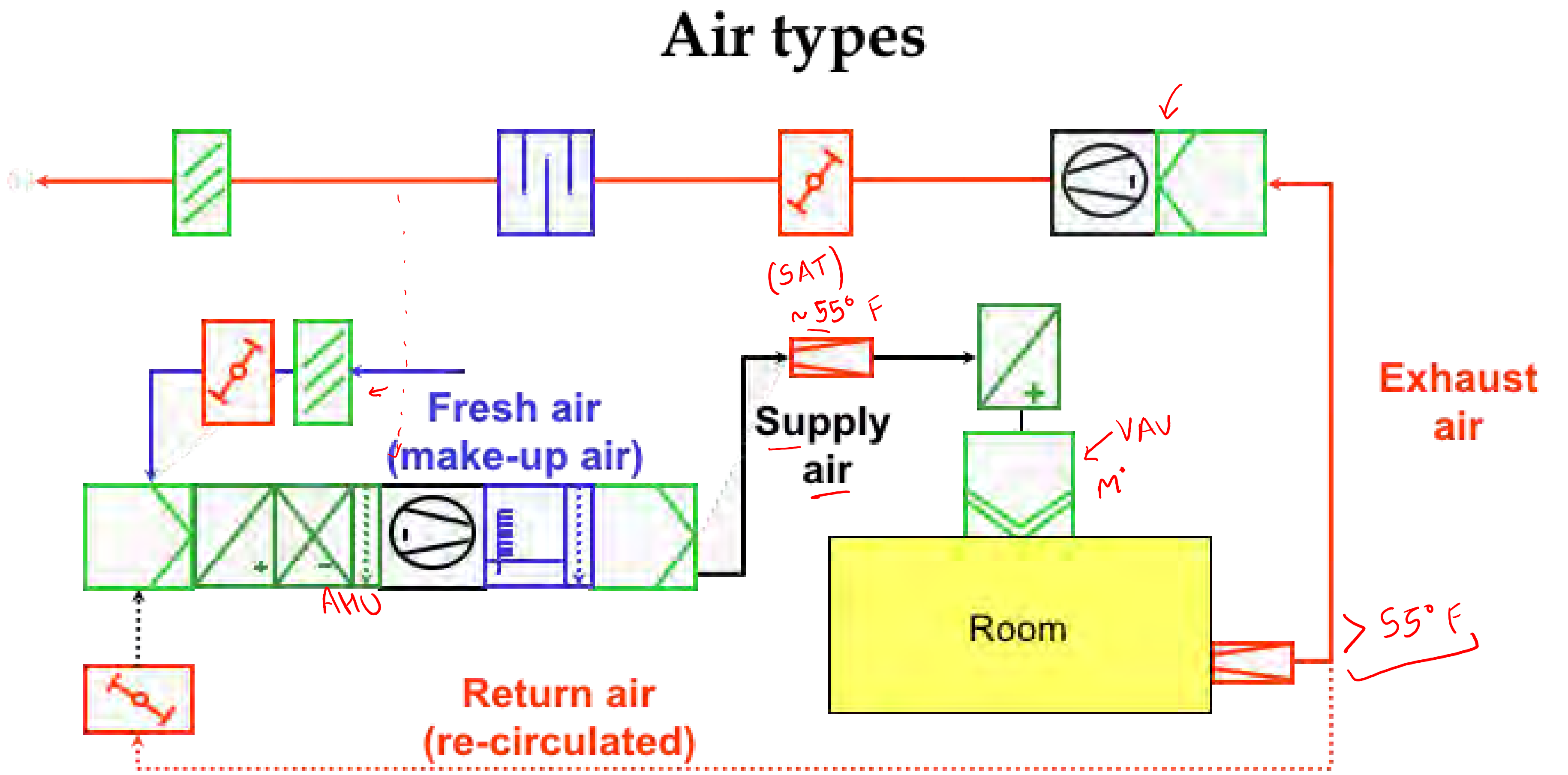


Air handling systems

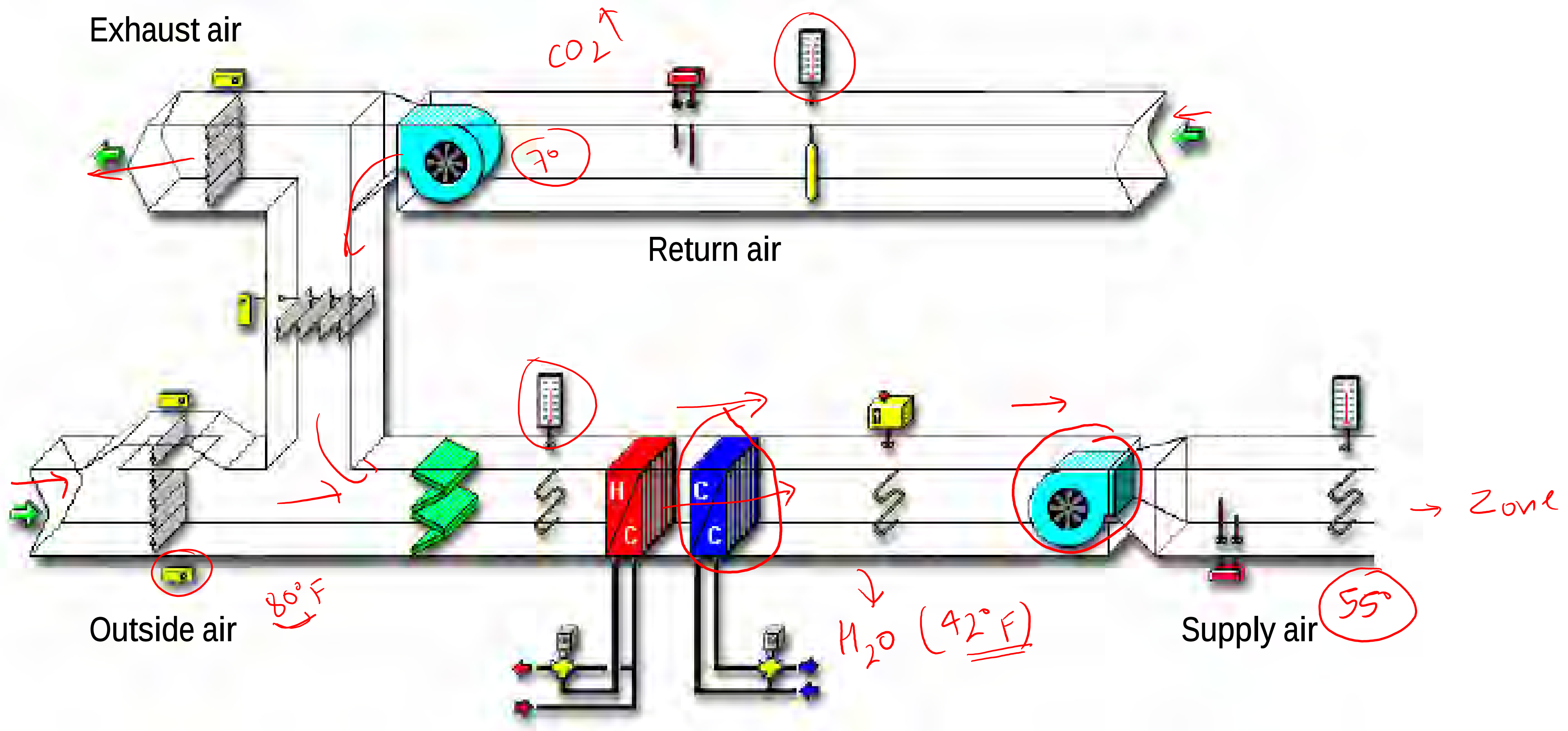
- Delivers air to zones
- Heats and cools air
- Often integrates ventilation



Air handling system

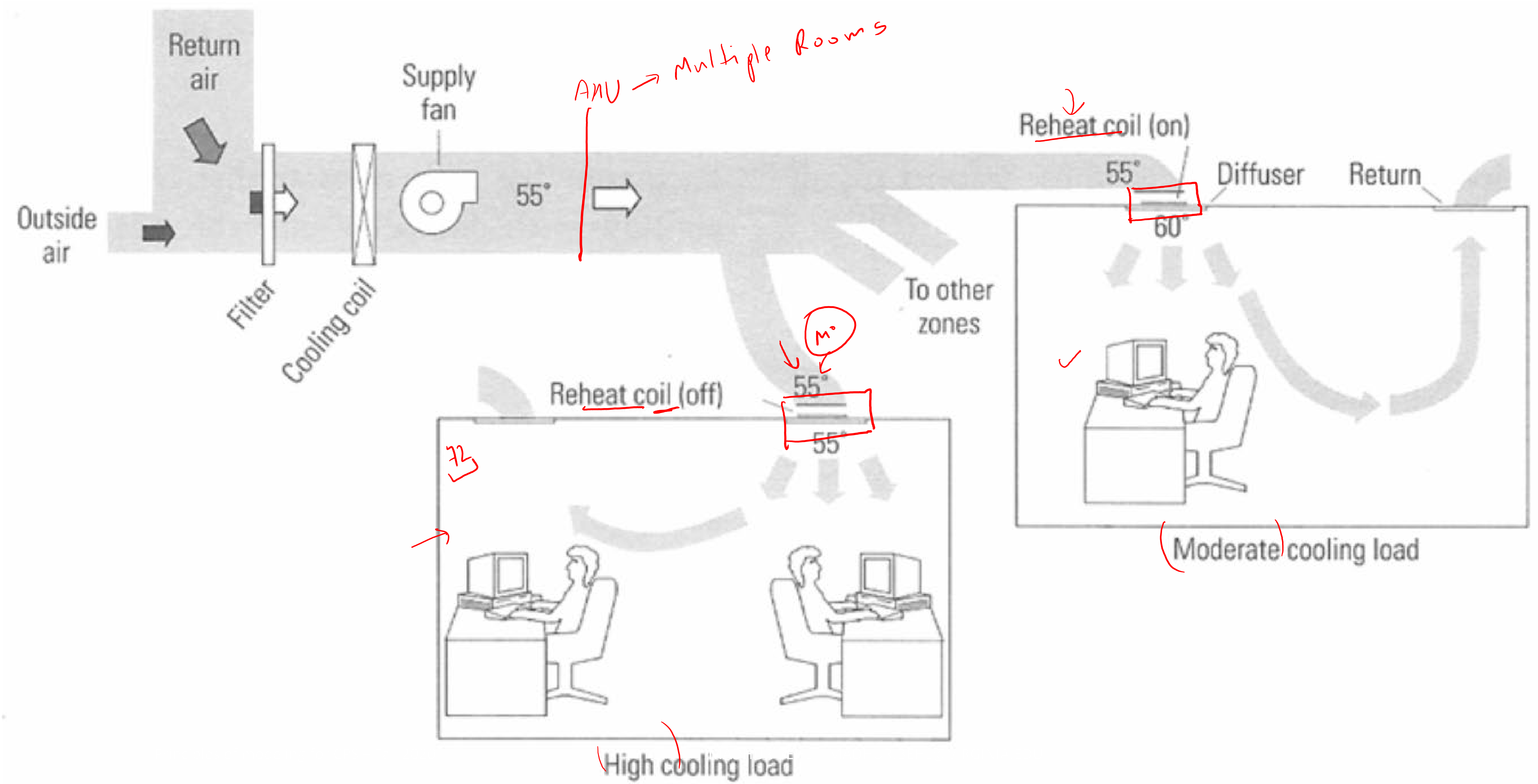


Air handling unit

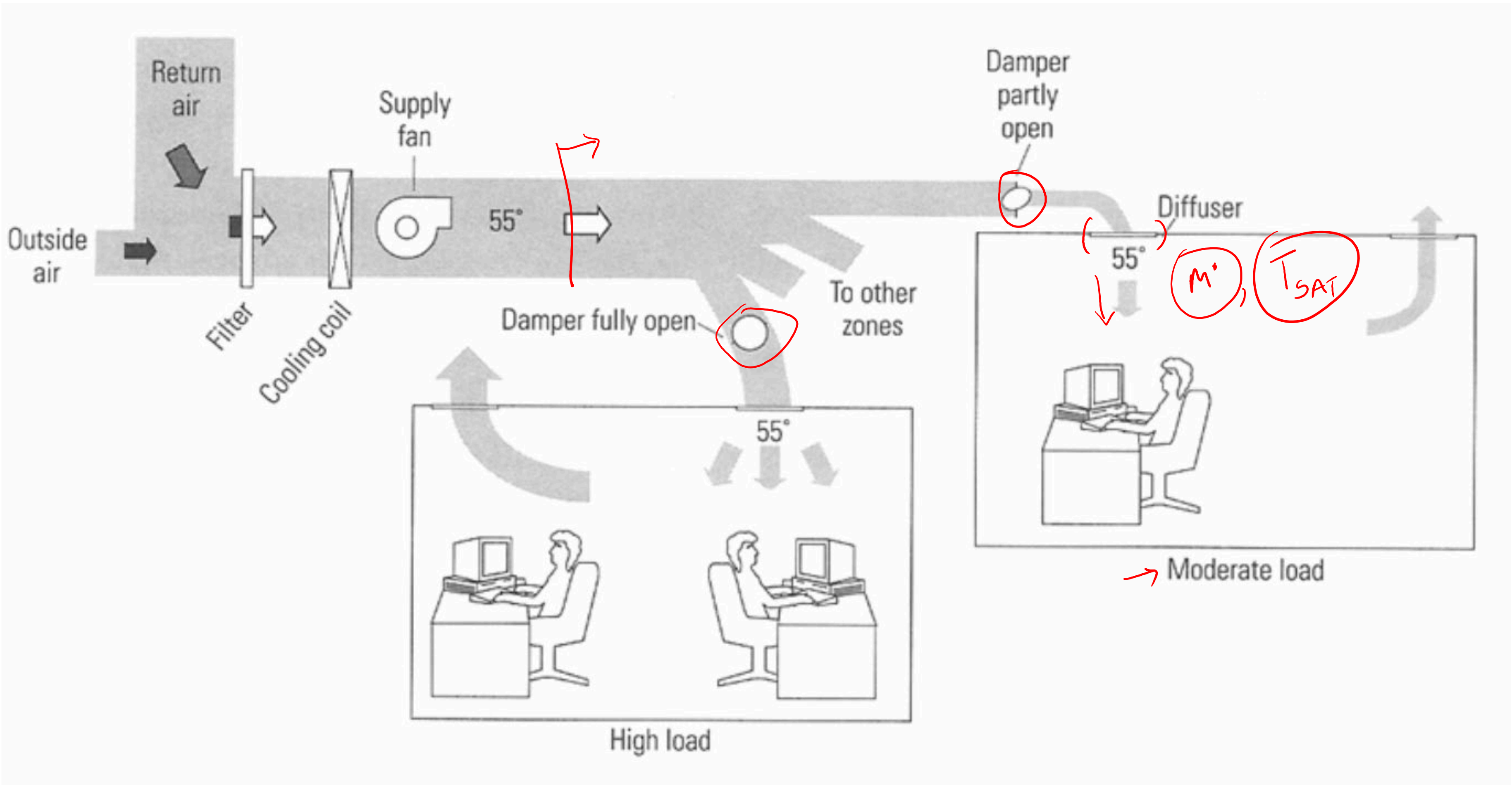


Air handling unit

Air terminals: Constant Air Volume (CAV)



Air terminals: Variable Air Volume (VAV)



IF temperature too high

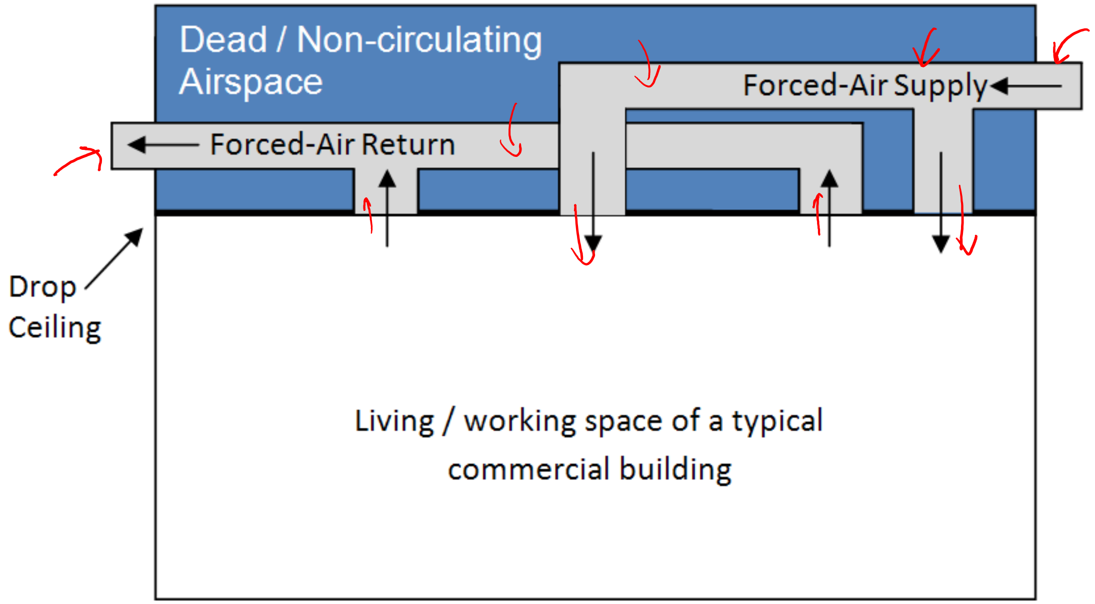
First reduce reheat till fully closed
Then increase air volume

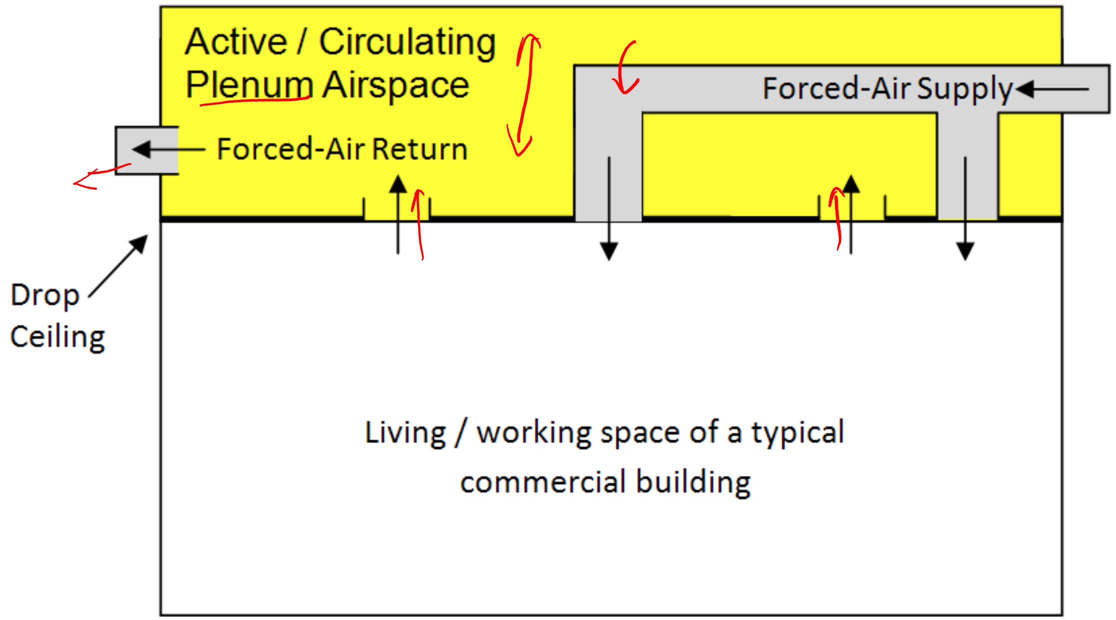
IF temperature too low

First reduce air volume till minimum
Then start reheat

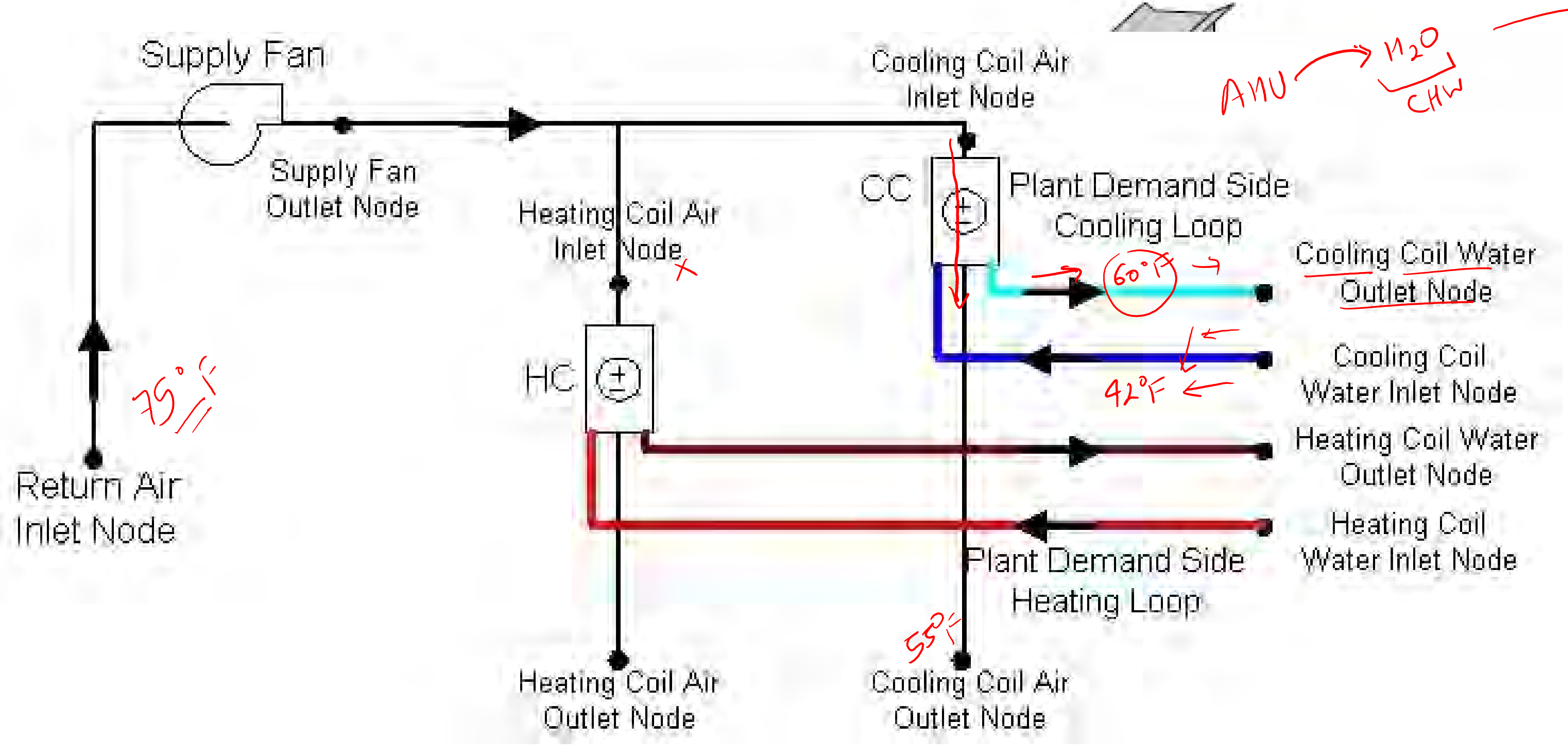
Ceiling plenum return

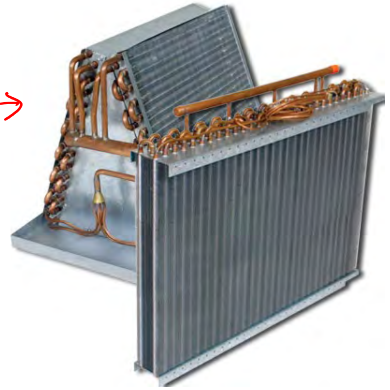
The plenum is the space between the ceiling and the roof, or floor, above.



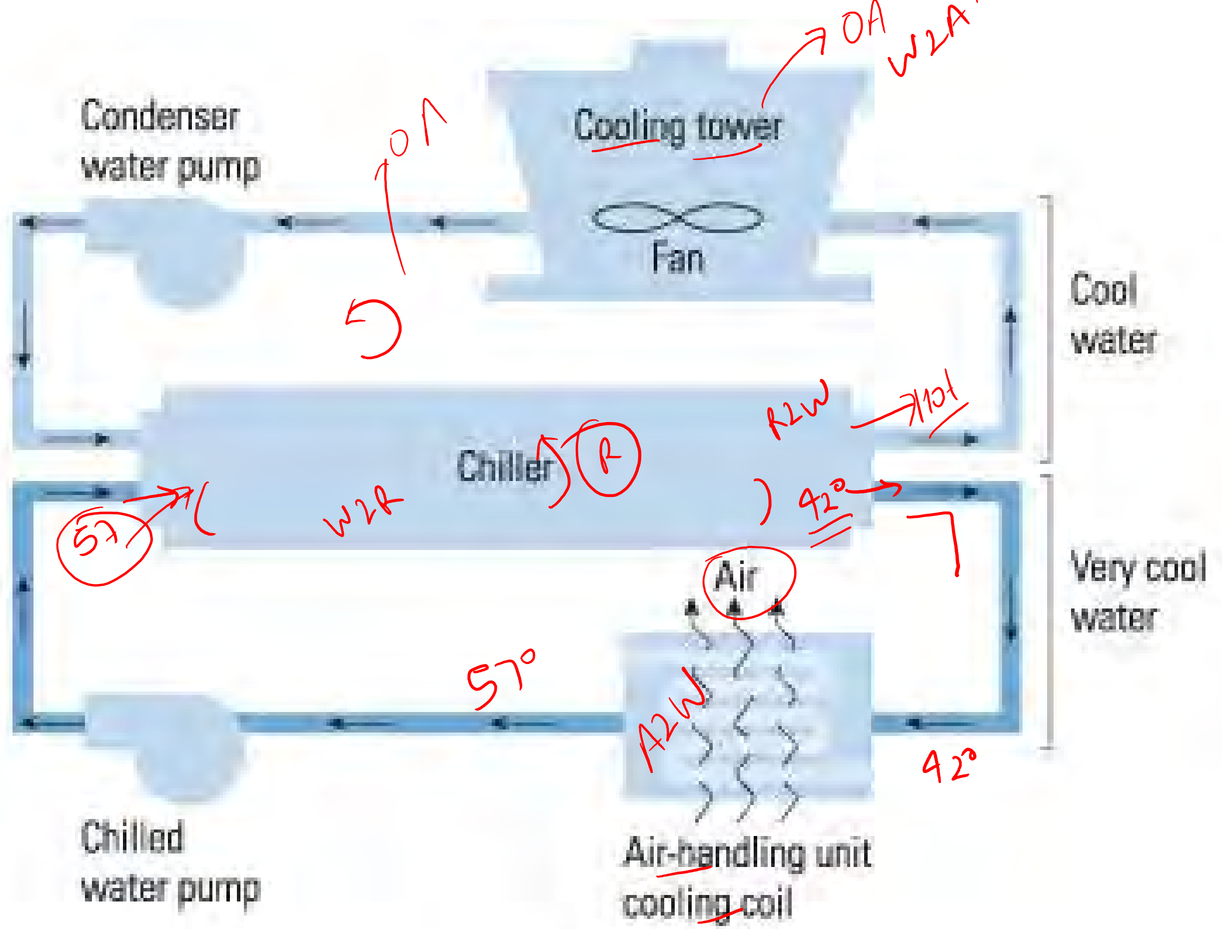


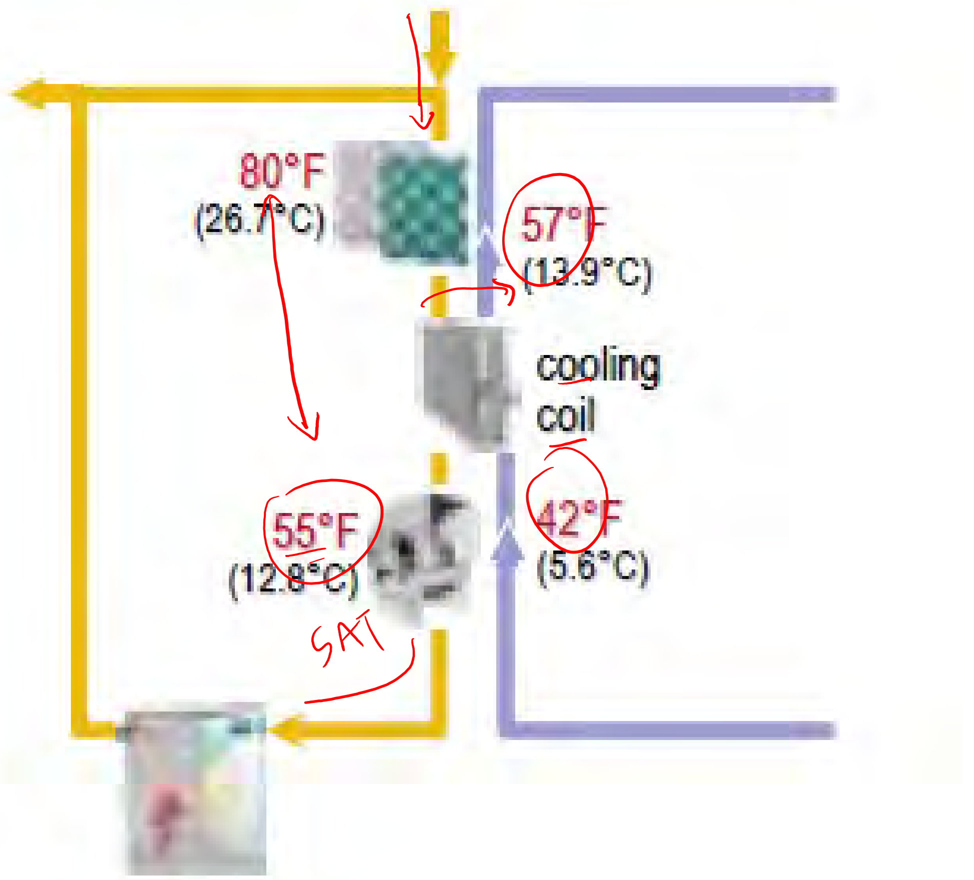
Air-Water interface- Heat exchanger.



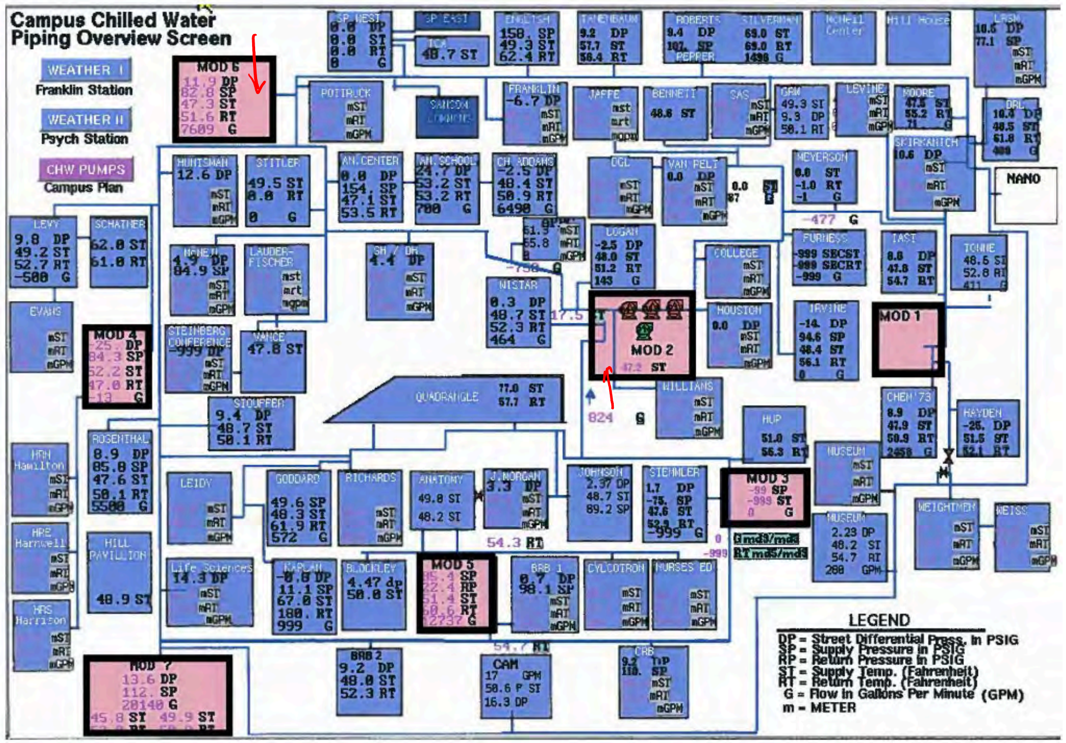


Chilled water loop



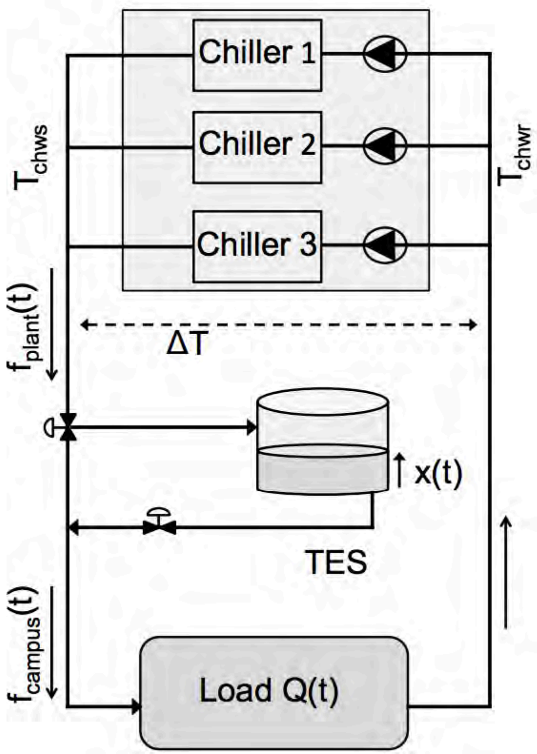


Chiller plants

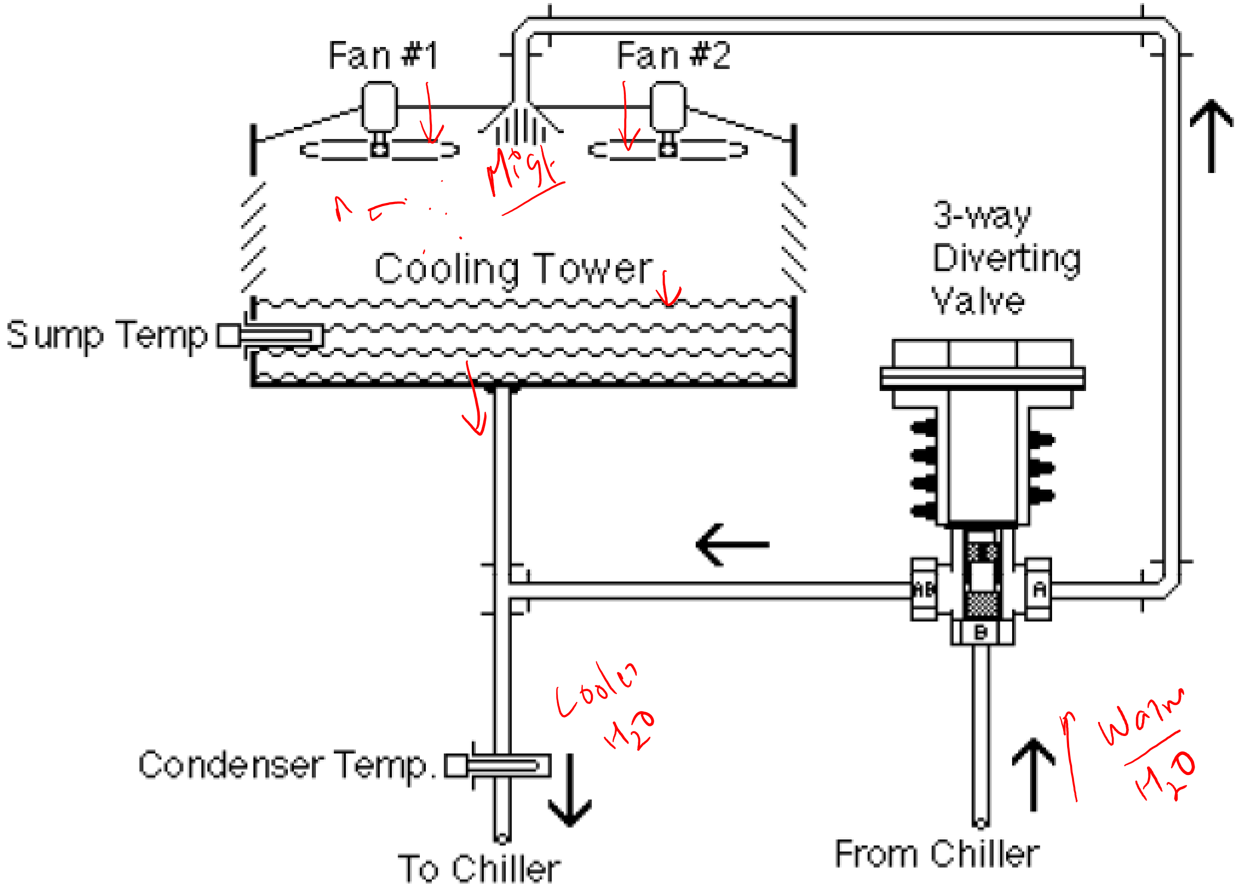


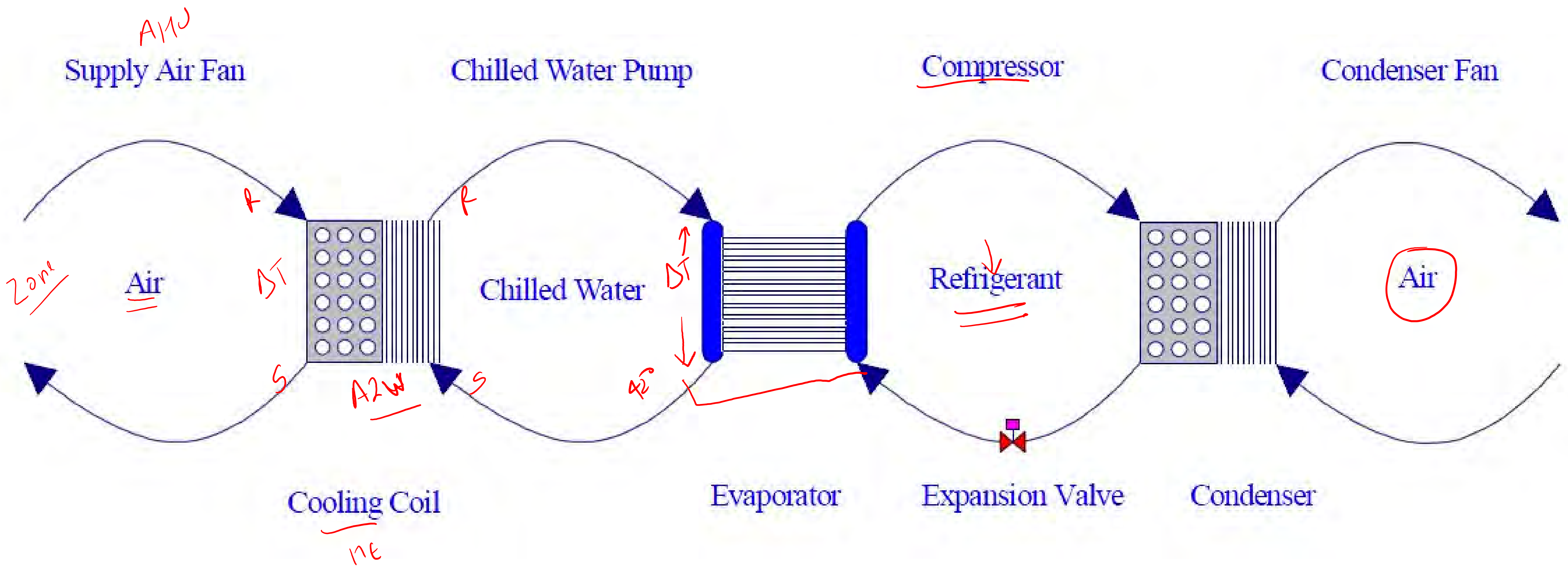
4 million gallons of water at 42 degree Fahrenheit

26 MW peak load

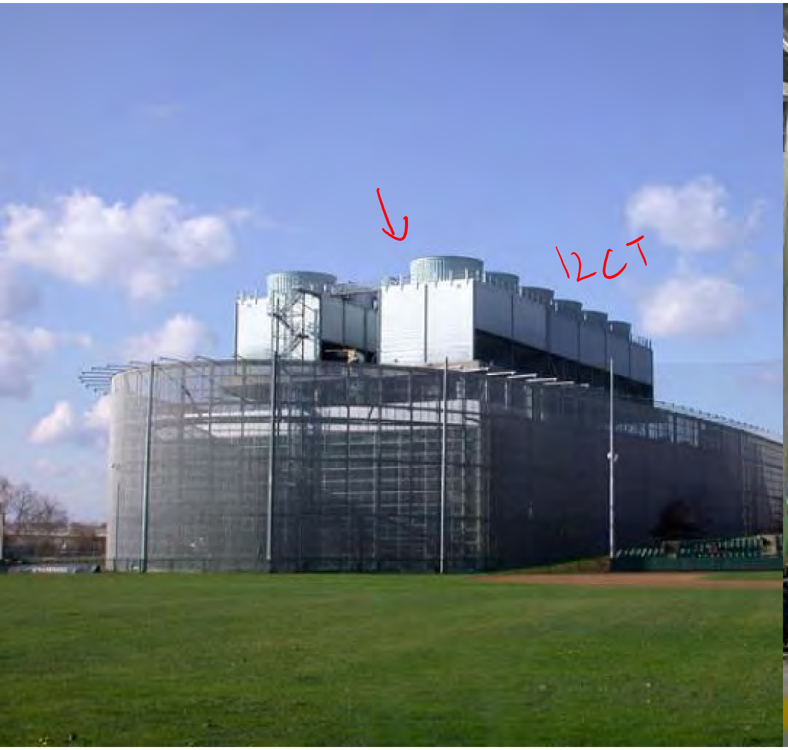


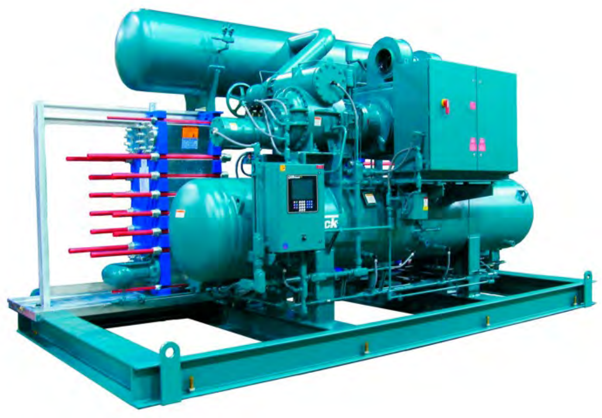
Cooling towers




AHU
Supply Air Fan
Chilled Water Pump
Compressor
Condenser Fan
Zone
Air
Chilled Water
Refrigerant
Air
Cooling Coil
Evaporator
Expansion Valve
Condenser

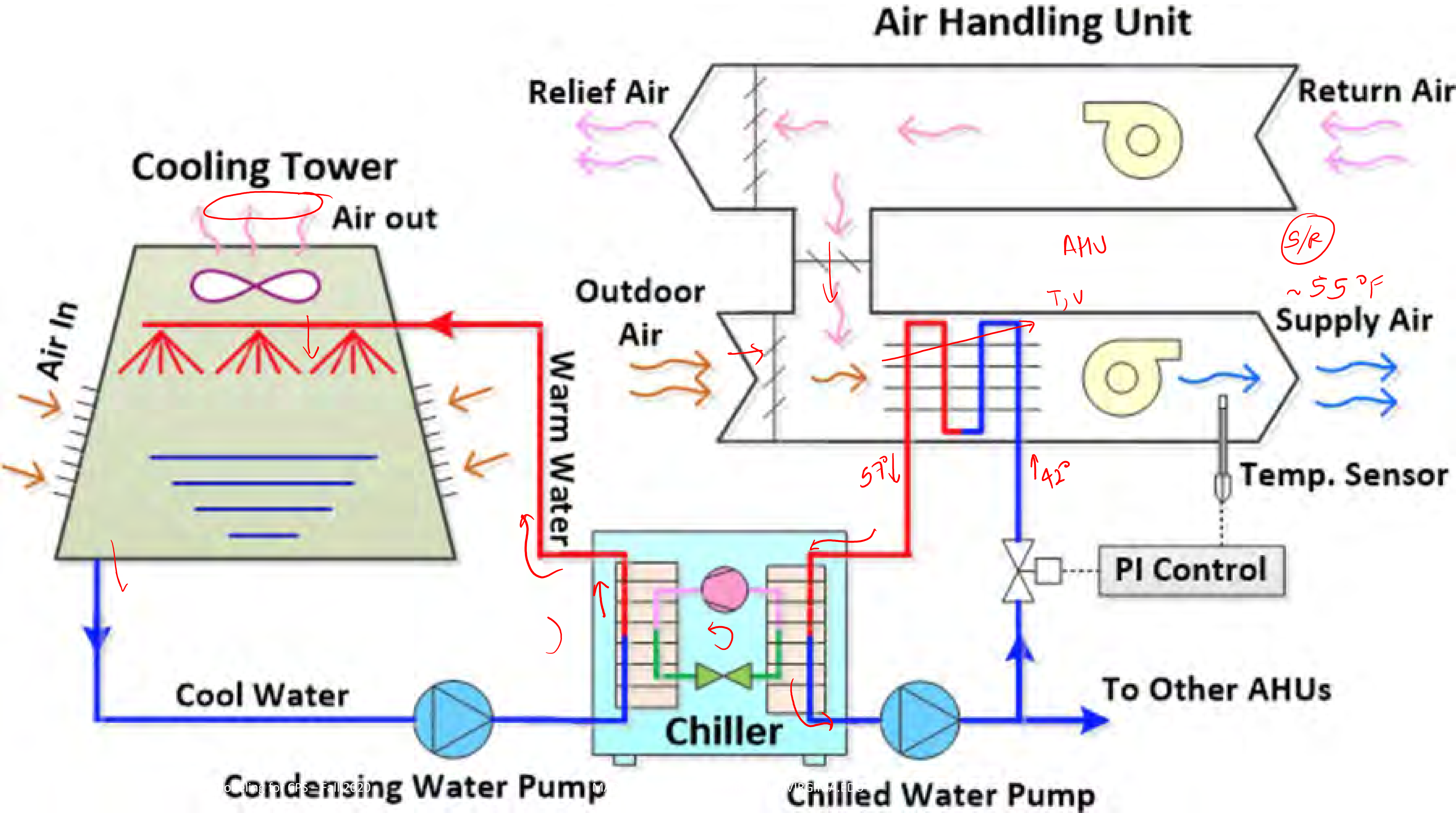
Chiller plants





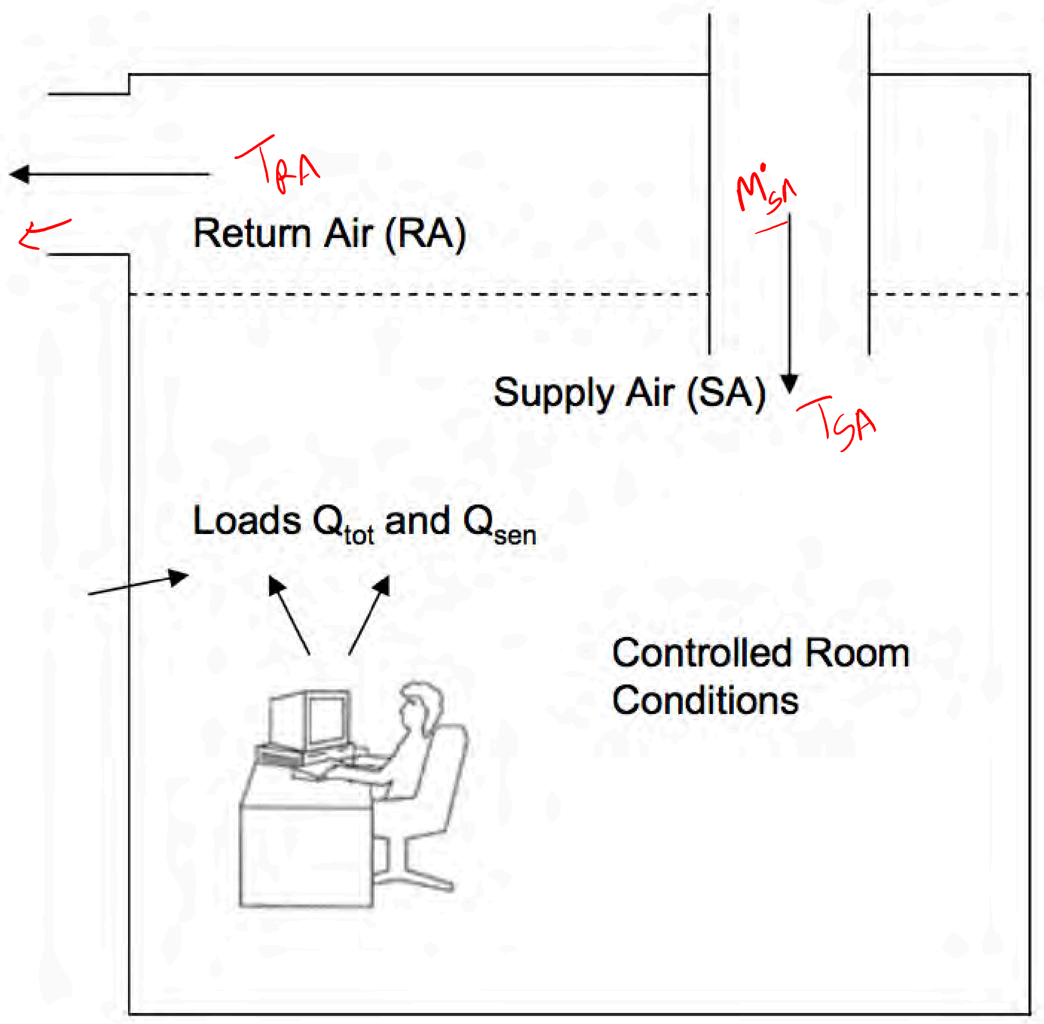
Just chilling as a grad student…


my biggest fans...



Air Handling Unit
Relief Air
Return Air
Cooling Tower
Air out
Air In
Outdoor Air
Supply Air
Warm Water
Temp. Sensor
PI Control
Chiller
Cool Water
To Other AHUs
Condensing Water Pump
Chilled Water Pump
AHU
S/R
~55°F
T, V
57°
42°

Meeting zone loads



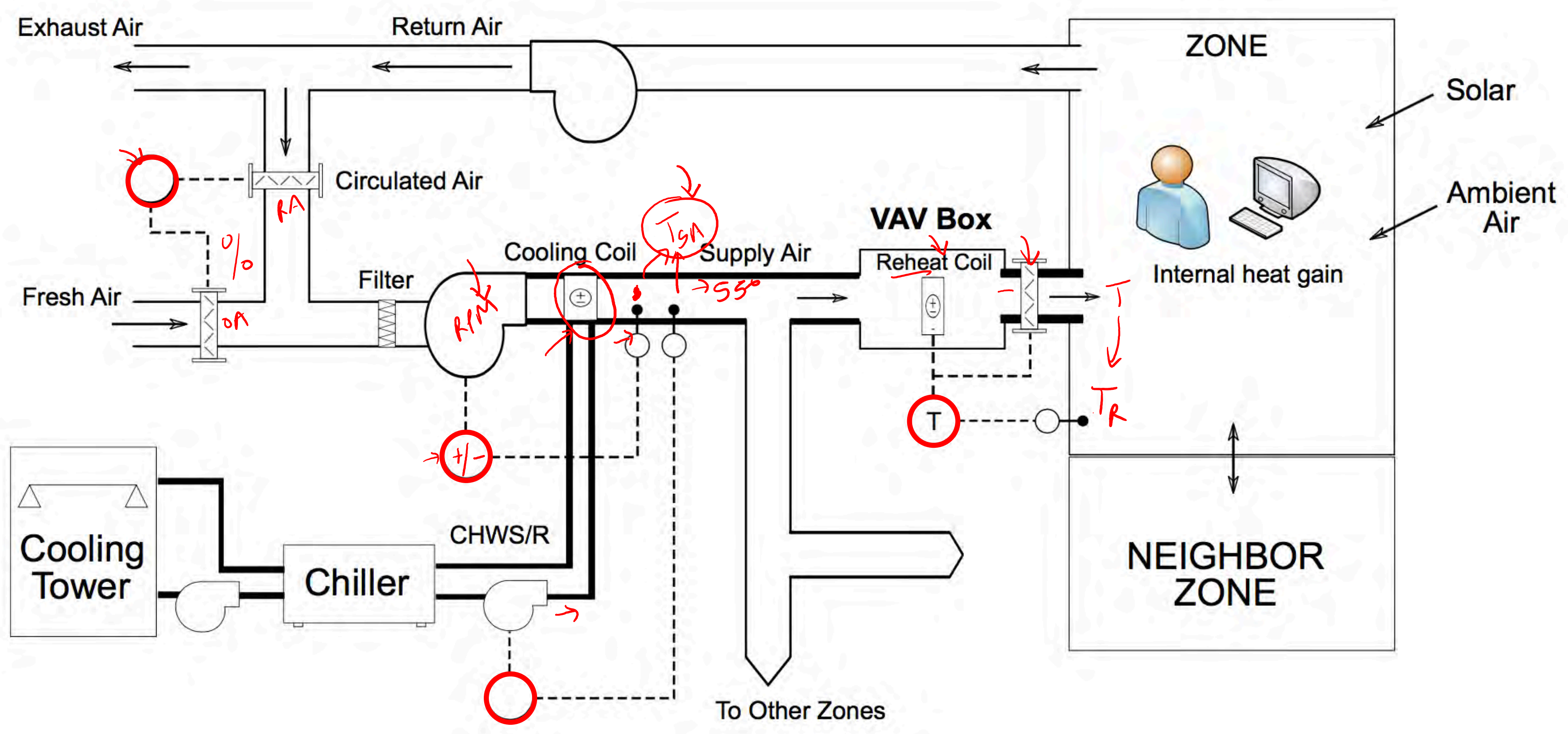
$$Q_{tot} = \dot{m}_{SA}(h_{RA} - h_{SA})$$

$$Q_{sen} = \dot{m}_{SA}c_p(T_{RA} - T_{SA})$$

Given controlled room air temperature, can control airflow or supply temperature to meet changing sensible loads

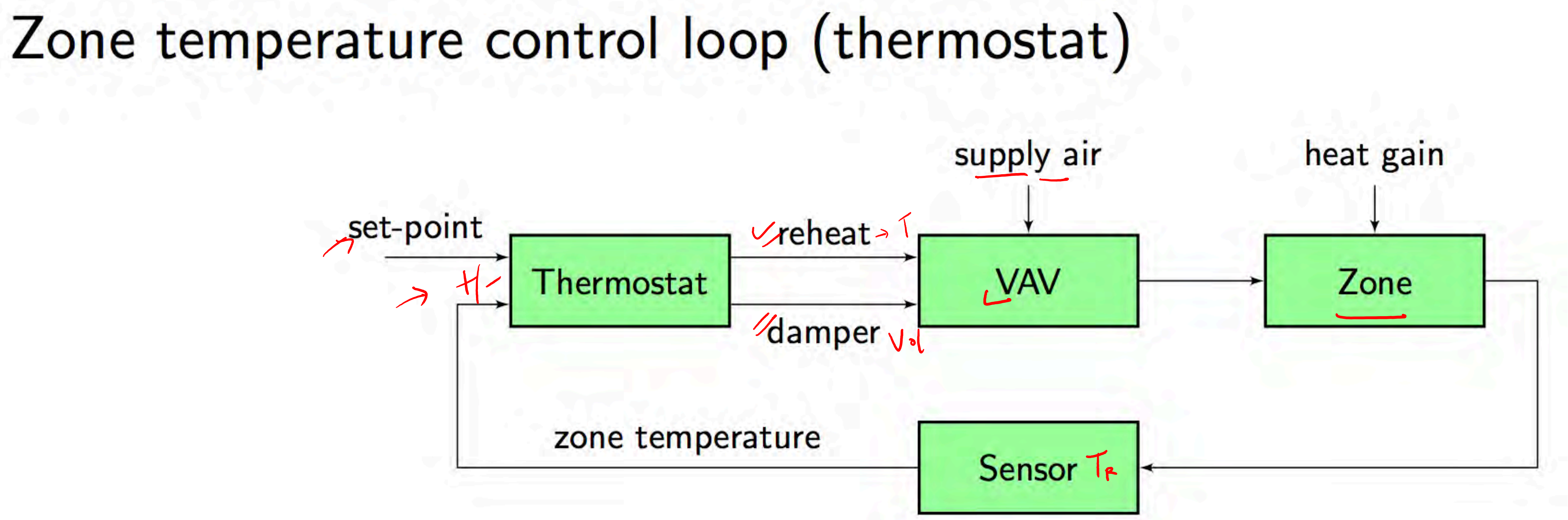
Control loops

VAV System:



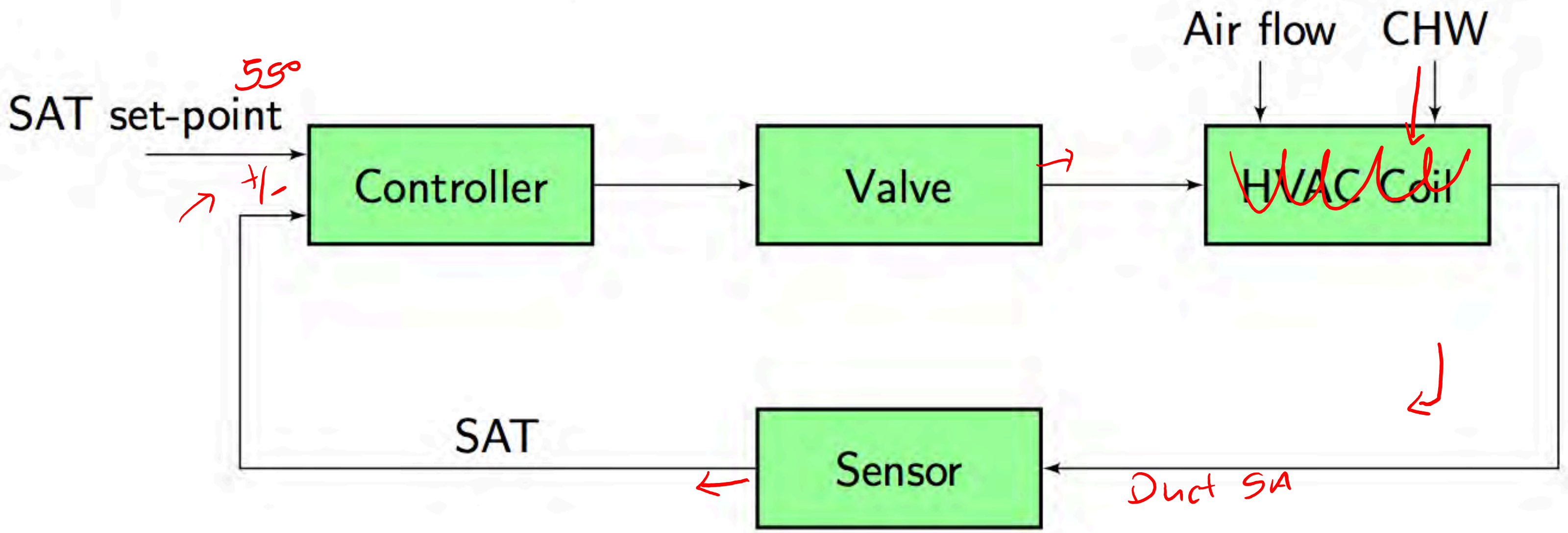
- Local control loops: thermostats, supply air controllers, etc.
- Supervisory control: set-points and modes for local control loops.

Local control loops



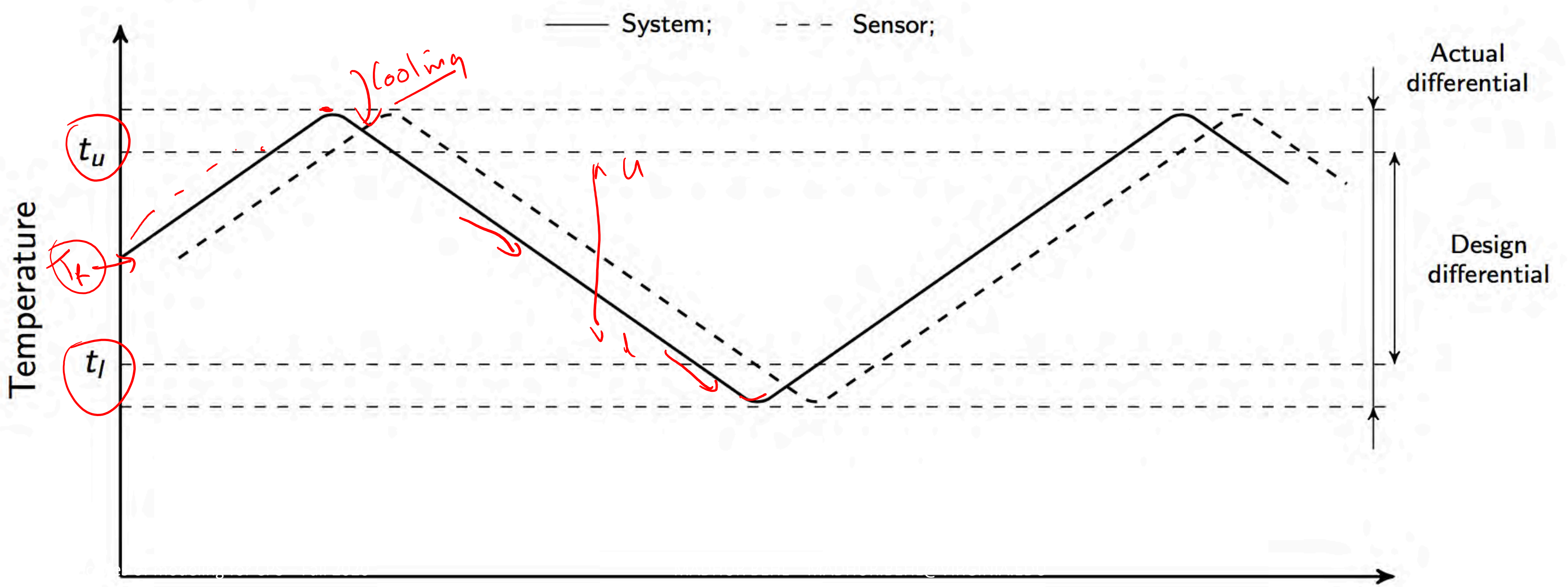
Local control loops

Supply Air Temperature (SAT) control loop



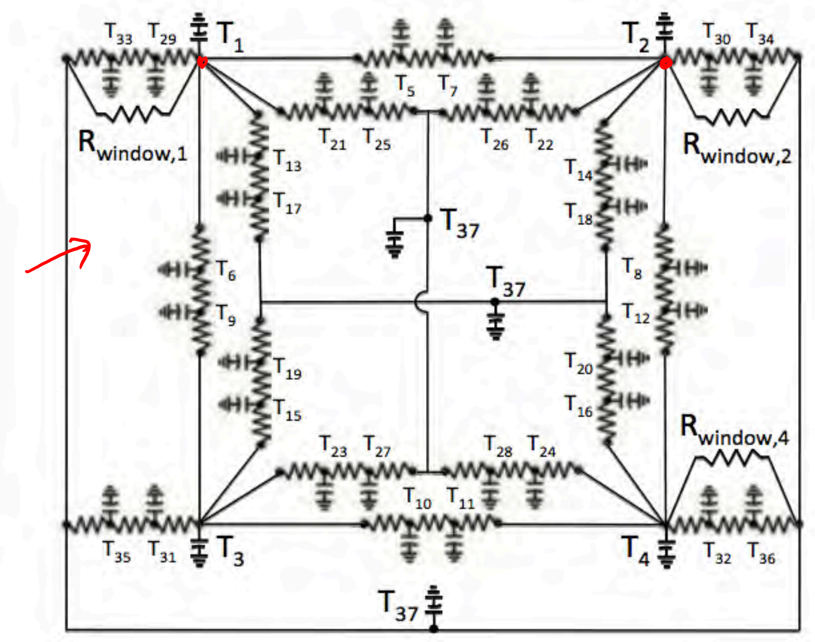
Simplest and common control is **on/off** control.

- Upper threshold t_u, lower threshold t_l, differential $= t_u - t_l$.
- Switch **off** when $t \geq t_u$ and **on** when $t \leq t_l$.
- Time lag may cause larger operating differential.
- Suitable for thermostats (slow dynamics) but not for supply-air fan control.



Next lecture..

Creating a dynamical system model of a zone.



Source: [Deng et al., 2010]

→ Thermal RC Model

$\equiv \dot{x} = Ax + Bu$