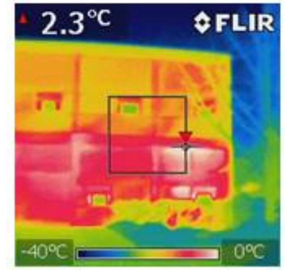
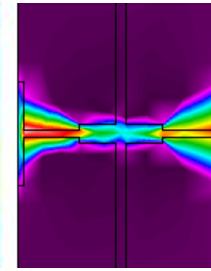
CAE 331/513
Building Science
Fall 2017





November 16, 2017
Cooling load calculations (part 1)

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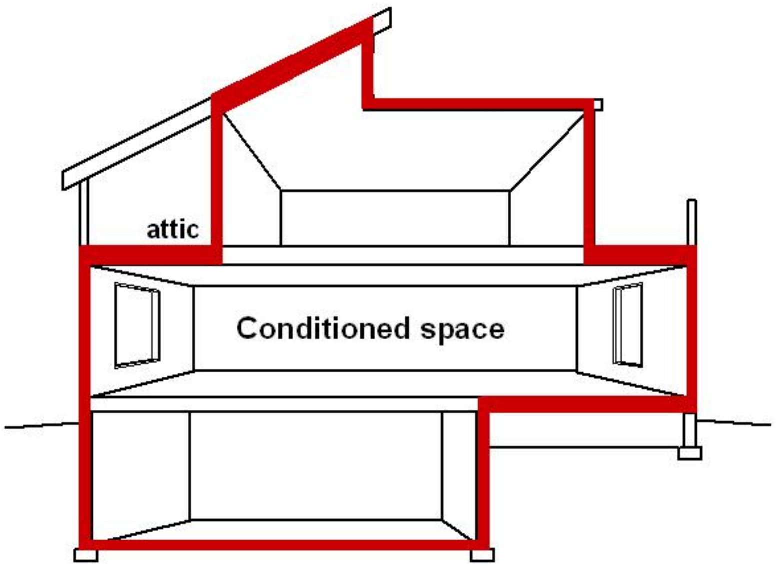
Dr. Brent Stephens, Ph.D.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
brent@iit.edu

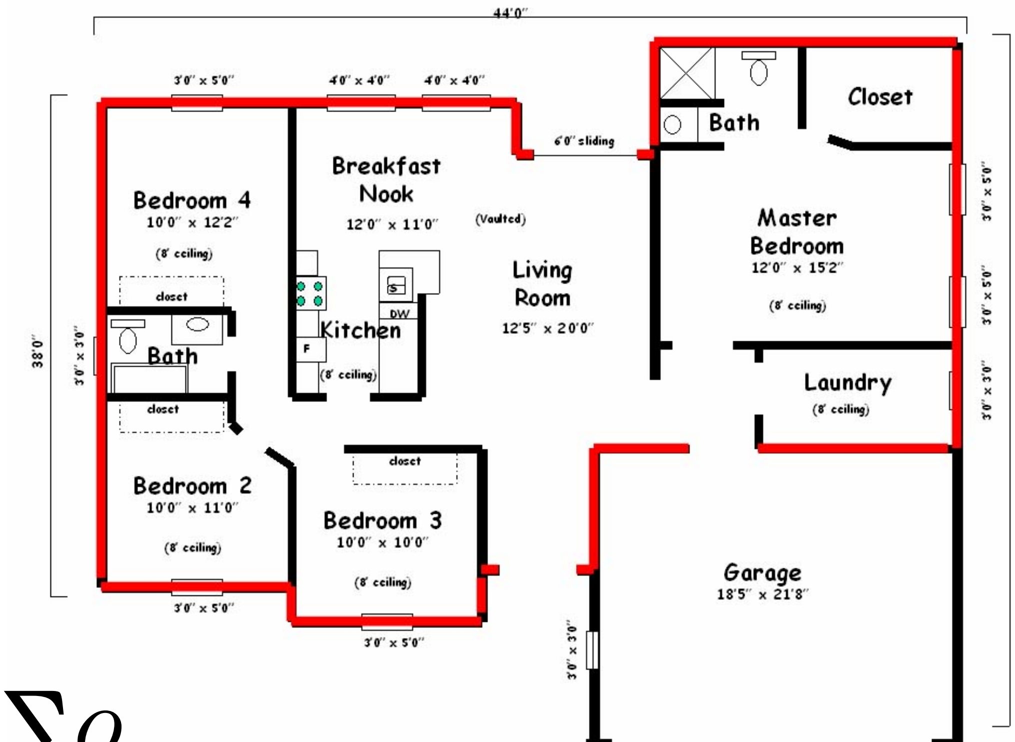
Last time

- Introduced the concept of heating and cooling load calculations
- Introduced design conditions
- Introduced heating load calculation procedures
  - Relatively simple
  - Steady-state/instantaneous
  - Envelope PLUS air exchange MINUS internal gains

Heating load calculations

- Define the building envelope, calculate transmission losses and internal gains, find design conditions, and use the steady-state equations below





$$Q_{heating\,load} = K_{total}(T_{in} - T_{out}) - \sum Q_{gains}$$

$$Q_{heating\,load} = (\sum UA + \dot{V}_{OA}\rho_{OA}C_{p,air})(T_{in} - T_{out}) - \sum Q_{gains}$$

Today's class

- Introduce cooling load calculations
  - Concepts and procedures

- On Tuesday Nov 21:
  - Introduce Trane Trace 700 software for cooling load calculations
  - You will use this on your HW 6 (in groups of 2), due Thurs Nov 30

COOLING LOADS

Cooling loads

- Cooling load calculations are more complicated than heating load calculations
- Peak cooling loads will occur during the day when solar radiation is present
  - People and equipment can also be highly variable
- Radiation varies throughout the day and the building's **thermal mass** affects the time release of this heat energy
  - Calculations must be ***dynamic*** to account for ***storage***

$$Q_{sensible\,load} =$$

$$Q_{envelope\,transmission} + Q_{air\,exchange} - Q_{solar} - Q_{people} - Q_{equipment} - Q_{lights} \pm Q_{storage}$$

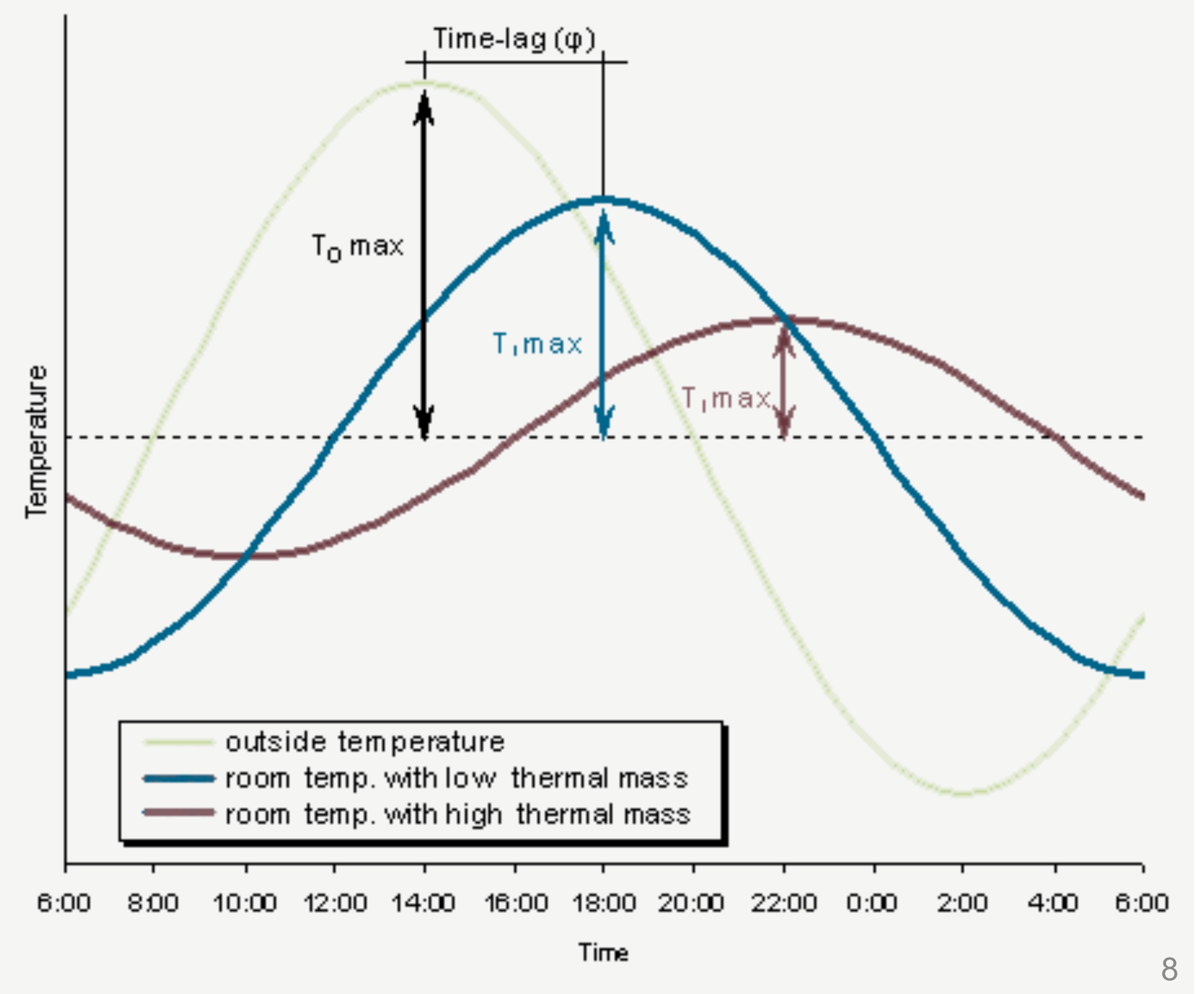
Remember:
Q is typically positive (+) when there is a heating load (cold outside)
Q is typically negative (-) when there is a cooling load (hot outside)

Dynamic response for cooling loads

- Cooling load calculations differ because gains from **radiation** do not directly heat up the air in the space
  - Only **convection** from interior surfaces contributes to an immediate temperature rise in the air space
- Radiation through windows, from interior surfaces, and from internal sources (e.g., lights) will be absorbed by other interior surfaces, and then those surfaces will eventually transfer that heat energy to the air by convection
  - But the addition of radiative heat <u>does not occur immediately</u>
- Because radiative heating is not direct, **heat storage** through **thermal mass** can create a thermal lag, which can have a large effect on cooling loads

Transient heat conduction: Accounting for heat capacity

- All materials have at least capacity to store thermal energy for extended periods of time
- This is often referred to as "thermal mass"
- Thermal mass absorbs heat gains and release them at a later time



Heat capacity, *HC*

- The **heat capacity** (*HC*) of a material is a measure of the ability of a material to store energy under a temperature diff.
  - *HC* is the product of the **density** of the material and its **specific heat capacity**, with different thickness/area/volume formulations:

$HC = \rho L C_p$	$HCA = \rho LAC_p = \rho VC_p$
[J/m^{2}K]	[J/K]

  - ρ = density [kg/m^3]
  - C_p = specific heat capacity [J/kgK]
  - L = thickness of material [m]
  - A = projected surface area of material [m^2]
  - V = volume of material [m^3]

- Heat capacity is important to thermal mass, but needs to be compared with thermal conductivity to get the whole story

Thermal diffusivity, α

- Thermal diffusivity, α, is the measure of how fast heat can travel through an object
- α is proportional to conductivity but inversely proportional to density and specific heat capacity:

$$\alpha = \frac{k}{\rho C_p} \quad [\mathrm{m^2/s}]$$

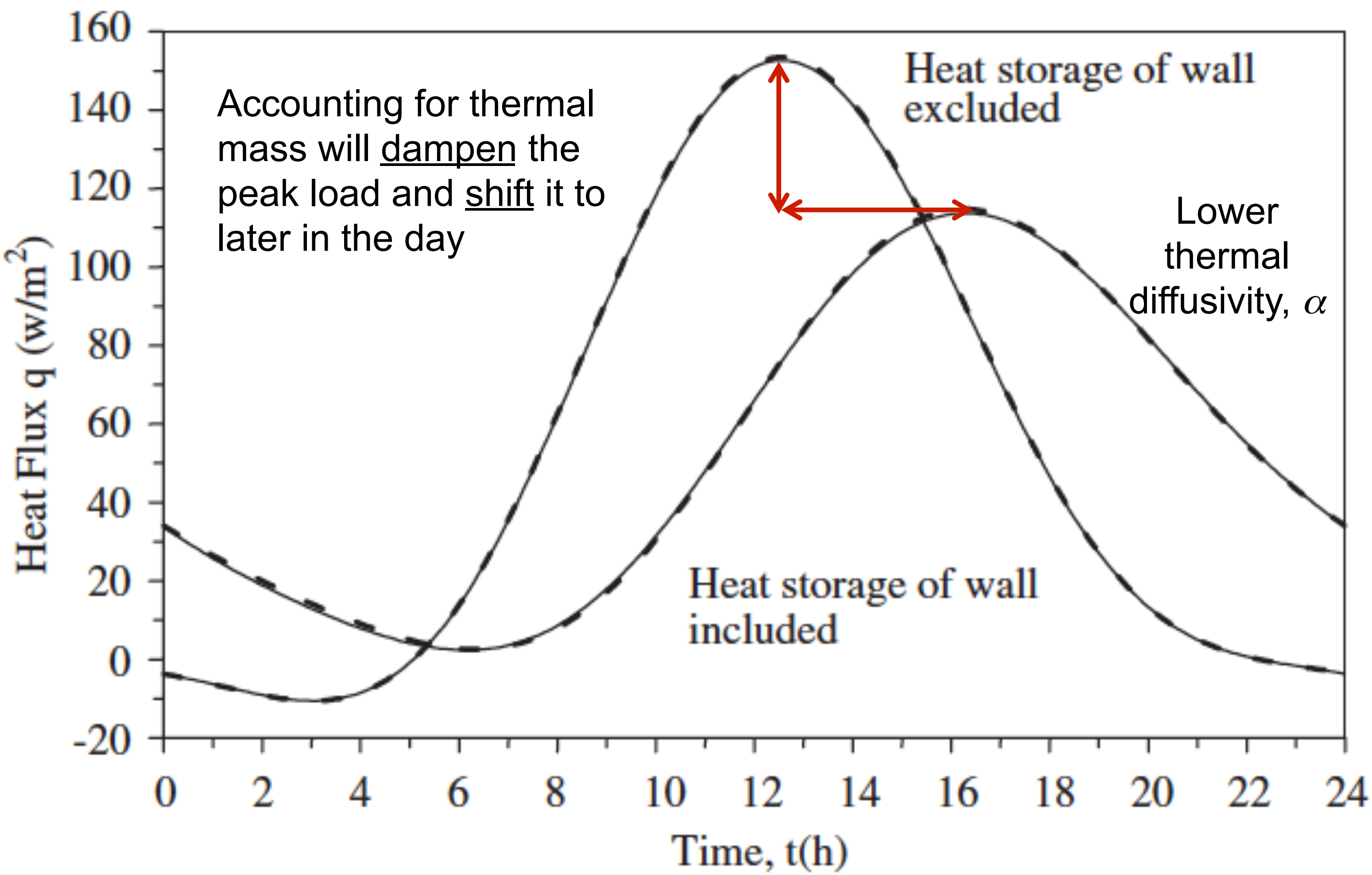
- The lower the α, the better the material is as a thermal mass (low conductivity relative to storage ability)
  - The time lag between peak internal and external temperature is related to the diffusivity of the walls
  - Steel has a high ρC_p but also a high k so it is not as good a thermal mass as concrete or brick

Thermal properties of building materials (ASHRAE)

- All three material properties can be found in the ASHRAE Handbook of Fundamentals chapter on thermal transmission data (Ch. 26 in 2013 version)
  - Thermal conductivity, density, and specific heat

Description	Density, kg/m³	Conductivity[b] (k), W/(m·K)	Conductance (C), W/(m²·K)	Resistance[c] (R) 1/k, (m·K)/W	Resistance[c] (R) For Thickness Listed (1/C), (m²·K)/W	Specific Heat, kJ/(kg·K)
Gypsum partition tile						
75 by 300 by 760 mm, solid	—	—	4.50	—	0.222	0.79
75 by 300 by 760 mm, 4 cells	—	—	4.20	—	0.238	—
100 by 300 by 760 mm, 3 cells	—	—	3.40	—	0.294	—
Concretes[o]						
Sand and gravel or stone aggregate concretes (concretes	2400	1.4-2.9	—	0.69-0.35	—	—
with more than 50% quartz or quartzite sand have	2240	1.3-2.6	—	0.77-0.39	—	0.8-1.0
conductivities in the higher end of the range)	2080	1.0-1.9	—	0.99-053	—	—
Limestone concretes	2240	1.60	—	0.62	—	—
	1920	1.14	—	0.88	—	—
	1600	0.79	—	1.26	—	—

Accounting for thermal mass impacts



Asan, H. 2006. Numerical computation of time lags an decrement factors for different building materials. *Building and Environment* 41:615-620.

Accounting for thermal mass is necessary for other types of loads as well

- Need to account for heat capacity of building materials and the fraction of radiative versus convective heat given off by systems and equipment

	Radiative, percent	Convective, percent
Fluorescent lights	50	50
People	33	67
External walls and roofs	60	40
Appliance and machines	20–80	80–20

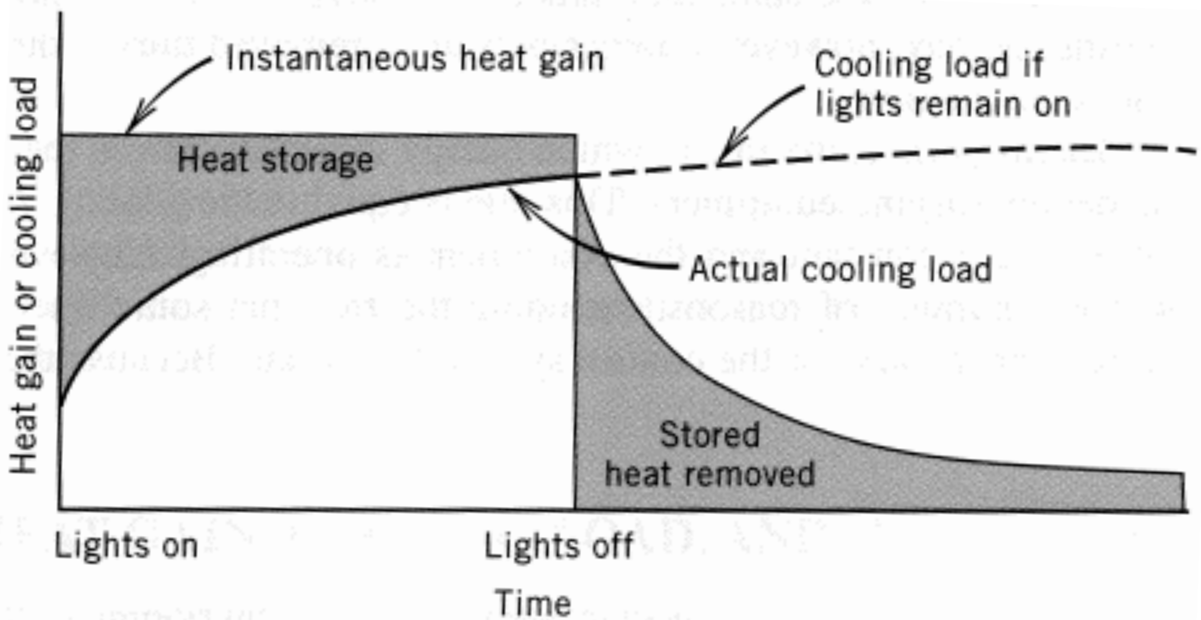


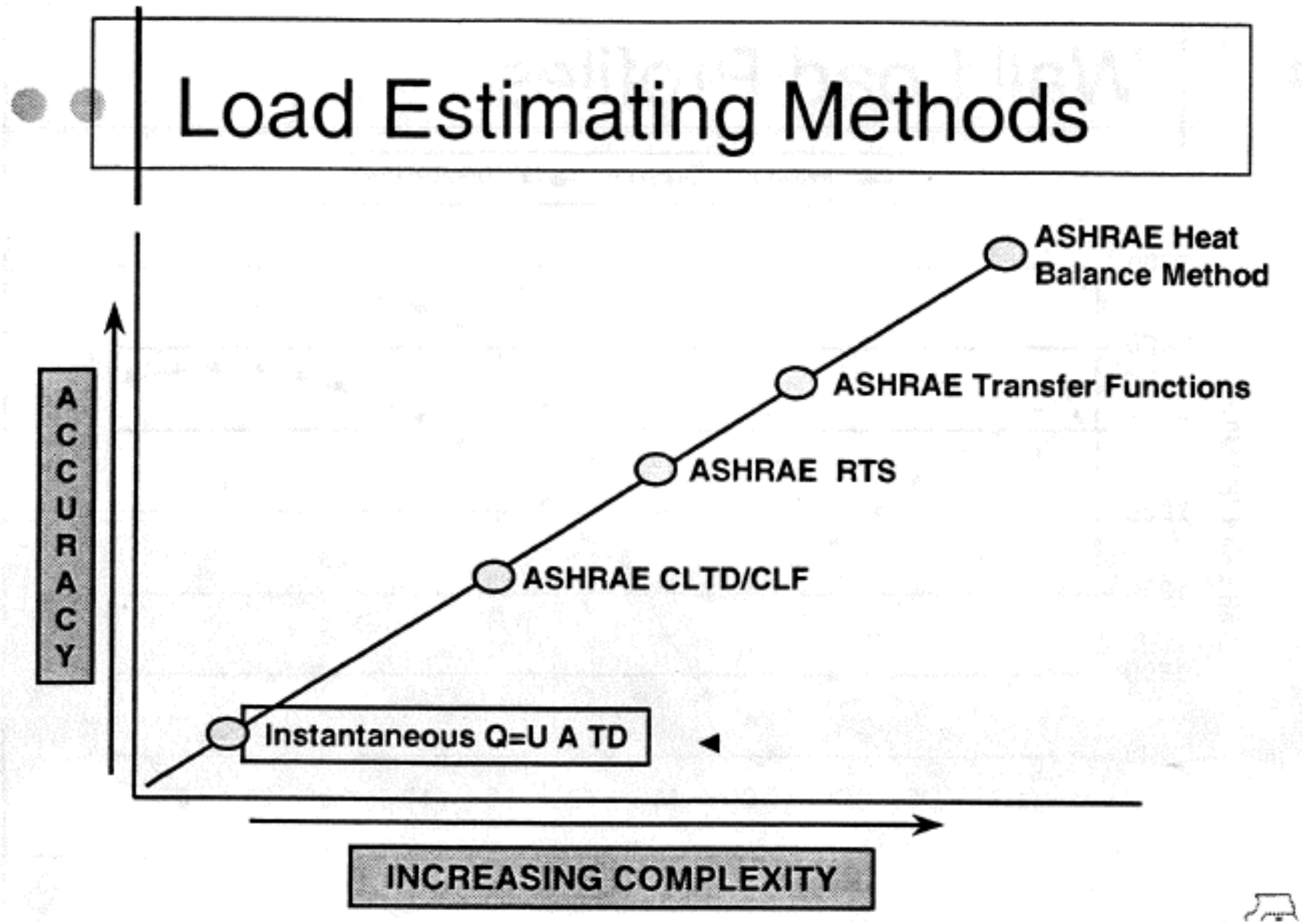
Figure 8-3 Actual cooling load from fluorescent lights.

COOLING LOAD CALCULATION METHODS

Cooling load calculation methods

- Dynamic responses & thermal mass make cooling load calculations much more complex than heating loads
- There are several methods of estimating peak cooling loads
  - They vary in complexity, accuracy, computational time, and requirements for input details
- Common cooling load calculation methods:
  - Transfer Function (TF)
  - Total Equivalent Temperature Difference (TETD)
  - Cooling Load Temperature Difference/Cooling Load Factor (CLTD/CLF)
  - Radiant Time-Series Method (RTSM)
  - Heat Balance Method (HBM)
- They all rely on spreadsheets and/or computer programs

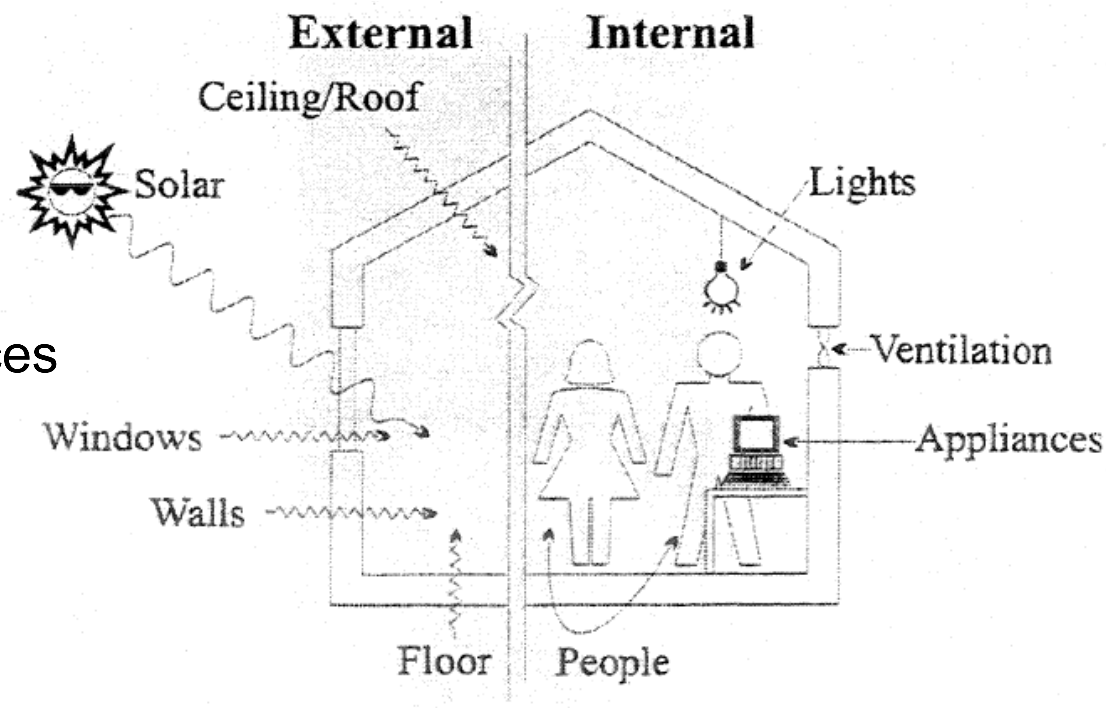
Cooling load calculation methods



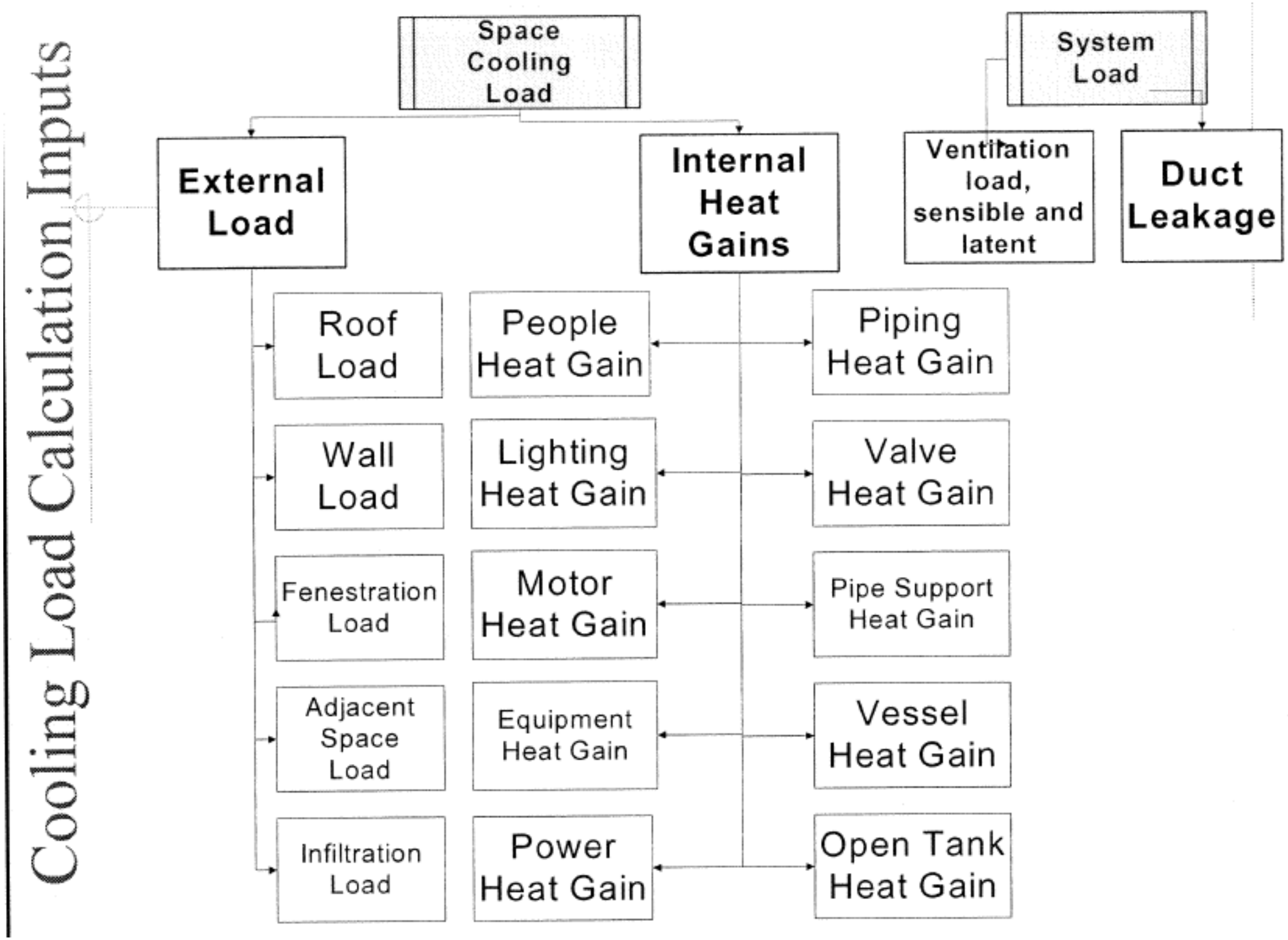
Components of cooling loads

- External loads
  - Heat gain from exterior roofs, walls, floors,
  - Solar heat gain transmitted through fenestration
  - Conductive heat gain through fenestration
  - Ventilation/infiltration of outdoor air

- Internal loads
  - People
  - Electric lights
  - Equipment and appliances

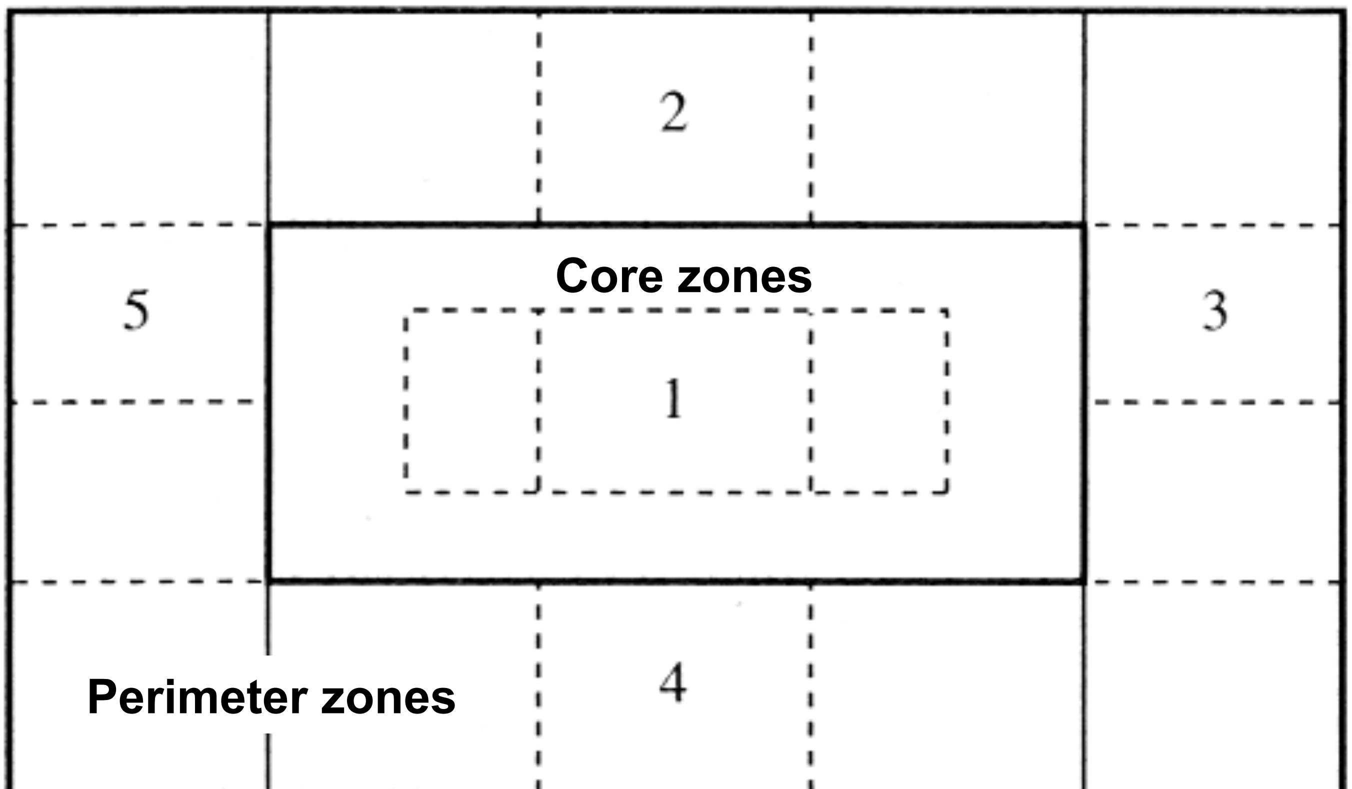


Inputs for all cooling load calculations

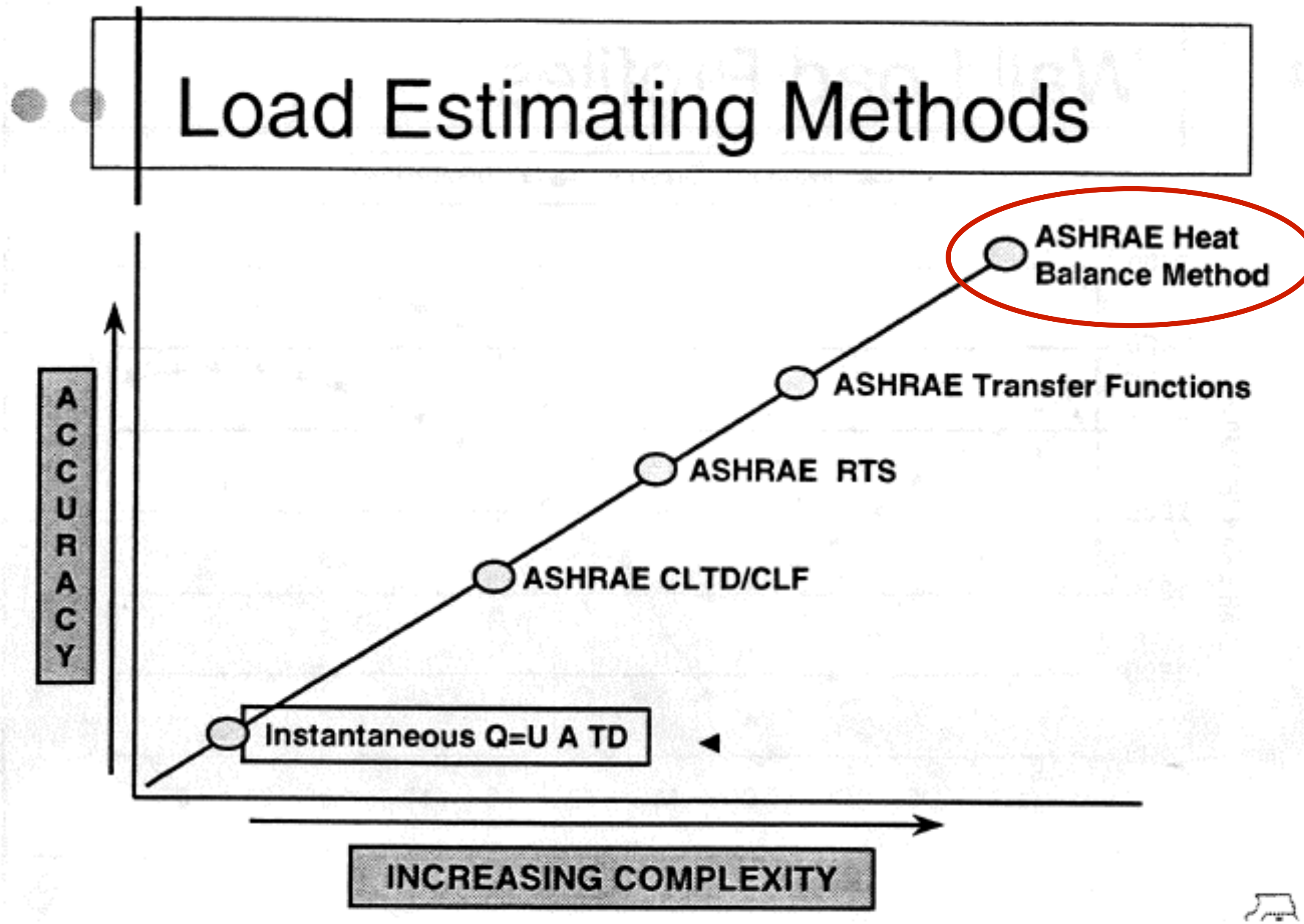


Zoning

Cooling load calculations (and heating load calculations) can be done room-by-room or zone-by-zone, and summed up for the whole building



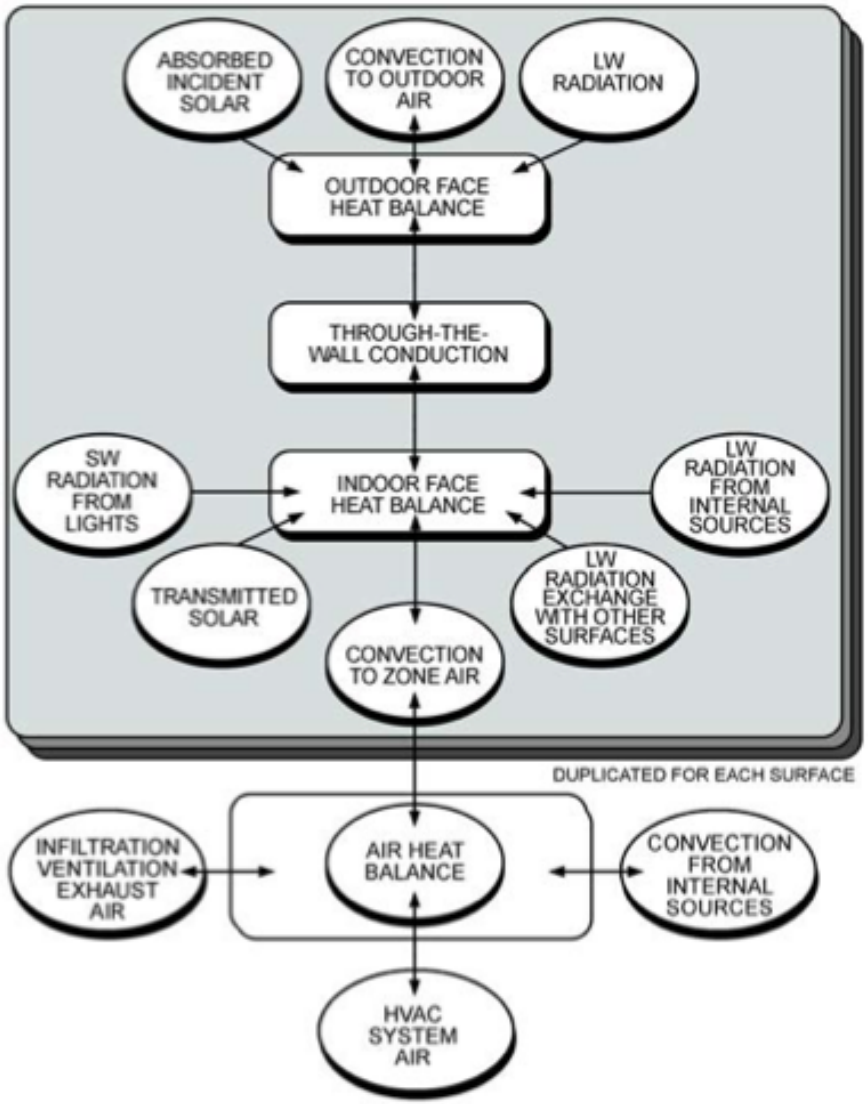
Cooling load calculation methods



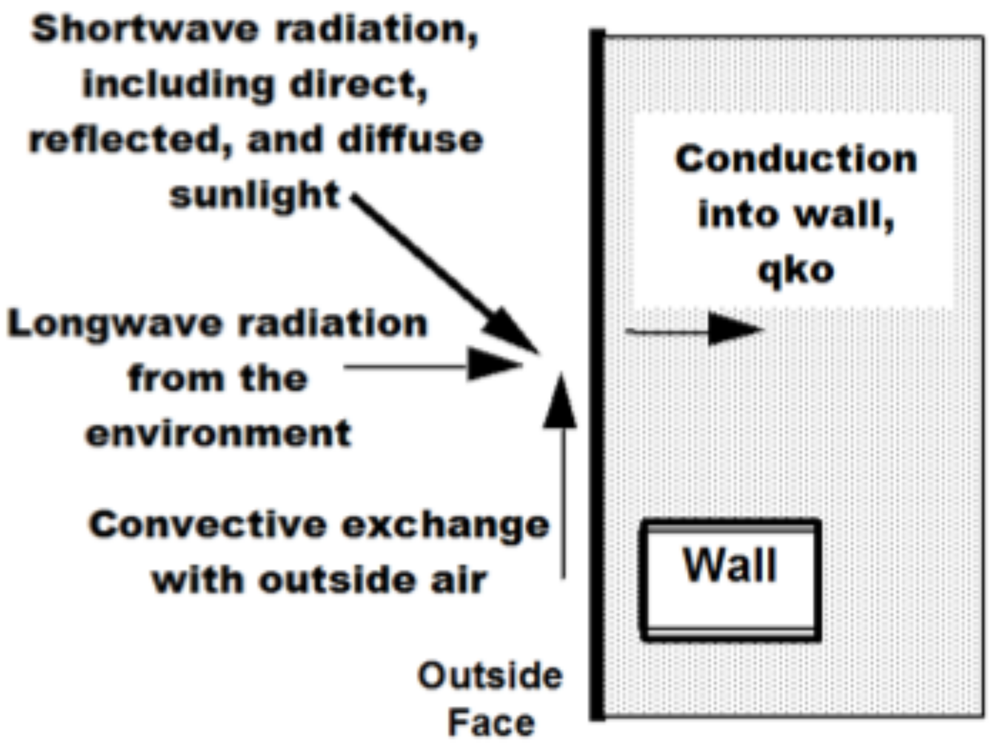
Heat balance method (HBM)

- HBM is based on the law of conservation of energy
  - A set of energy balance equations for an enclosed space is solved simultaneously for unknown surface and air temperatures
- Consists of three important energy balance equations:
  - Heat balance on exterior surfaces
  - Heat balance on interior surfaces
  - Heat balance on indoor air
    - The energy balance is based on the fundamental heat transfer equations we already know
- Calculations are initiated by hourly outdoor weather data
  - Design day meteorological data (or full year, e.g., TMY3)
- It is more fundamentally linked than other approaches
  - Makes fewer assumptions than the other methods
    - But is more complex to solve
  - HBM provides the basis for modern energy simulation programs

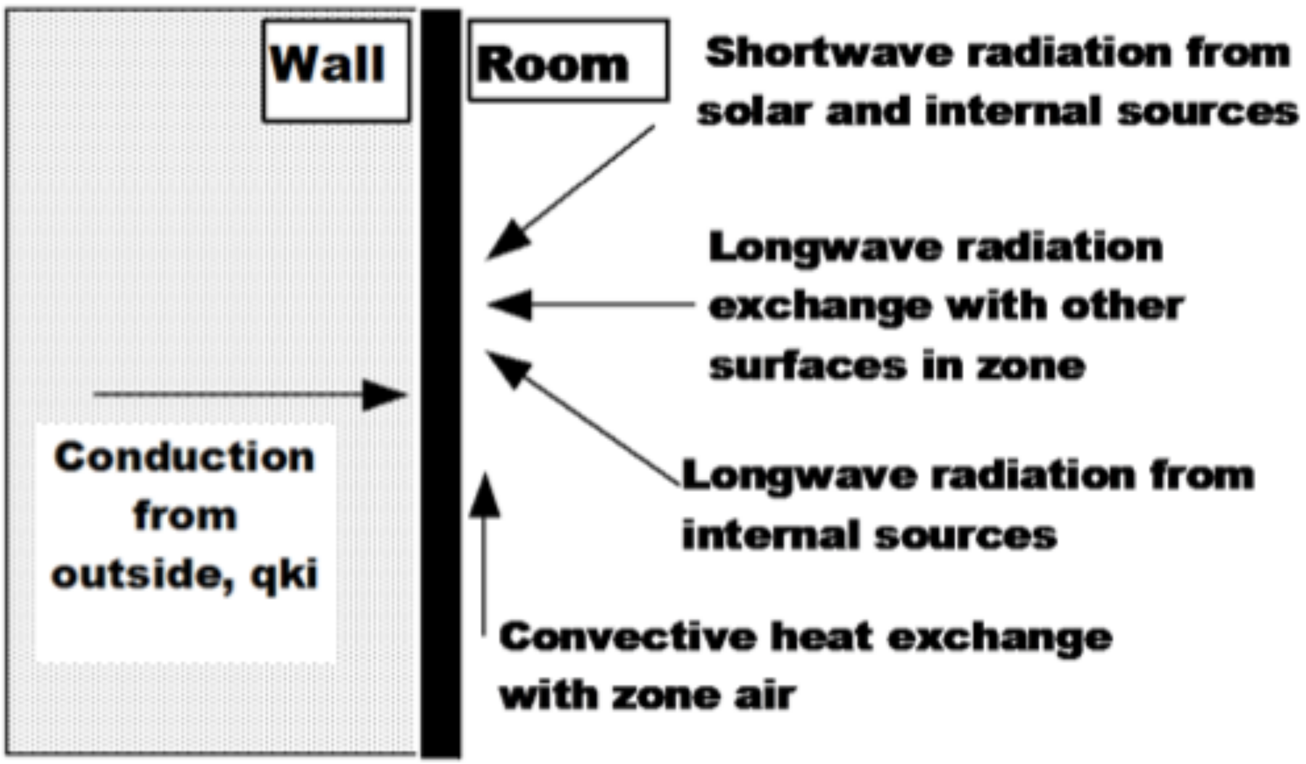
Heat balance method (HBM)



Heat balance method (HBM): Outside surface heat balance

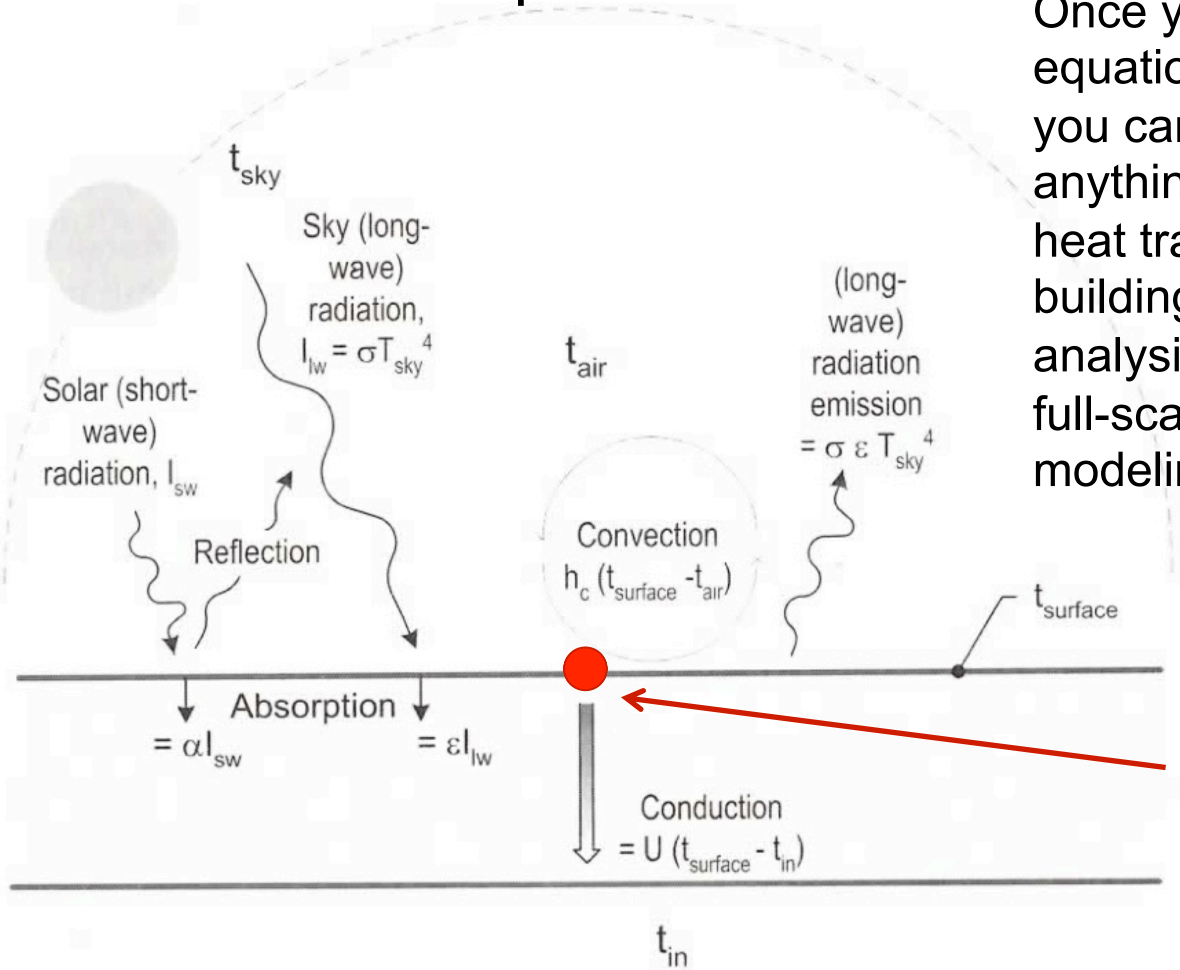


Heat balance method (HBM): Inside surface heat balance



HBM: Surface energy balance

- Exterior surface example: roof



Once you have this equation described, you can do just about anything regarding heat transfer in building enclosure analysis, leading into full-scale energy modeling

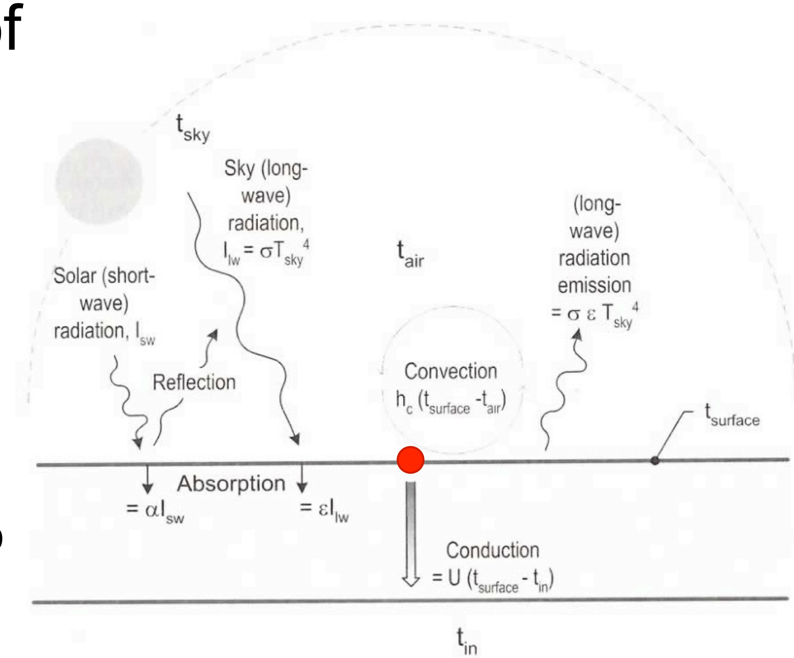
Steady-state energy balance at this exterior surface:
What enters must also leave (no storage)

$$q_{solar} + q_{longwaveradiation} + q_{convection} - q_{conduction} = 0$$

HBM: Surface energy balance

- Exterior surface example: roof

$$\sum q = 0$$



We can use this equation to estimate indoor and outdoor surface temperatures

At steady state, net energy balance is zero

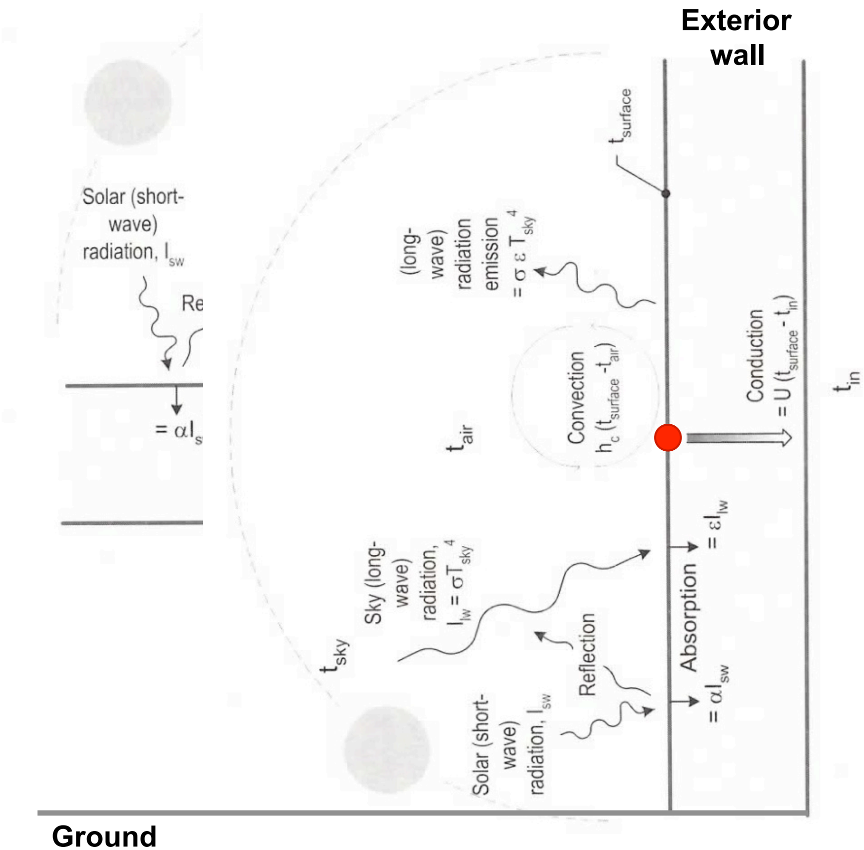
- Because of T^4 term, often requires iteration

Solar gain	αI_{solar}	$q_{sw,solar}$
Surface-sky radiation	$+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surf}^4)$	$+q_{lw,surface-sky}$
Convection on external wall	$+h_{conv}(T_{air} - T_{surface})$	$+q_{convection}$
Conduction through wall	$-U(T_{surface} - T_{surface,interior}) = 0$	$-q_{conduction} = 0$

HBM: Surface energy balance

- Similarly, for a vertical surface:

$$q_{solar} + q_{lwr} + q_{conv} - q_{cond} = 0$$



$$\alpha I_{solar}$$
$$+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surface,ext}^4)$$
$$+\varepsilon_{surface}\sigma F_{ground}(T_{ground}^4 - T_{surface,ext}^4)$$
$$+h_{conv}(T_{air} - T_{surface,ext})$$
$$-U(T_{surface,ext} - T_{surface,int}) = 0$$

HBM: Combining surface energy balances

- For an example room like this, you would setup a system of equations where the temperature at each node (either a surface or within a material) is unknown
  - 12 material nodes + 1 indoor air node

Heat Xfer @ external surfaces:
Radiation and convection

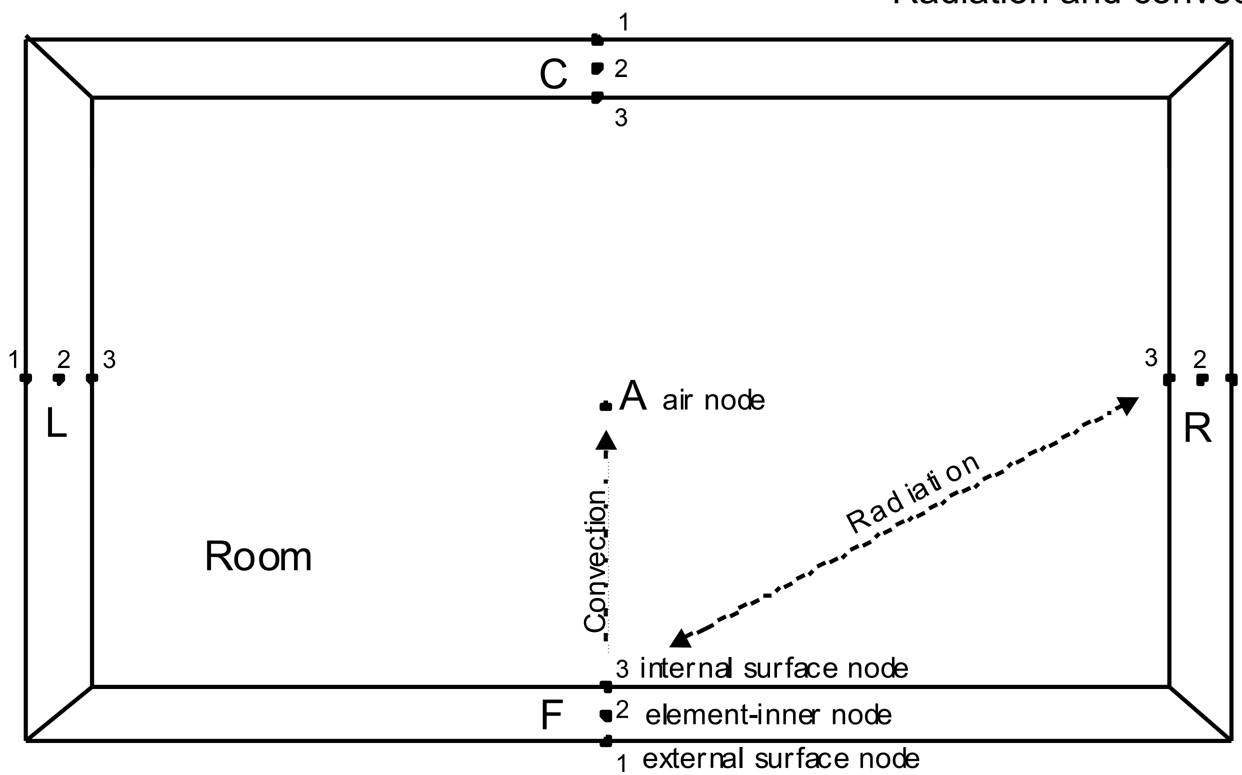
At surface nodes:

$$\sum q = 0$$

At nodes inside materials:

$$mc_p \frac{dT}{dt} = \sum q_{at\ boundaries}$$

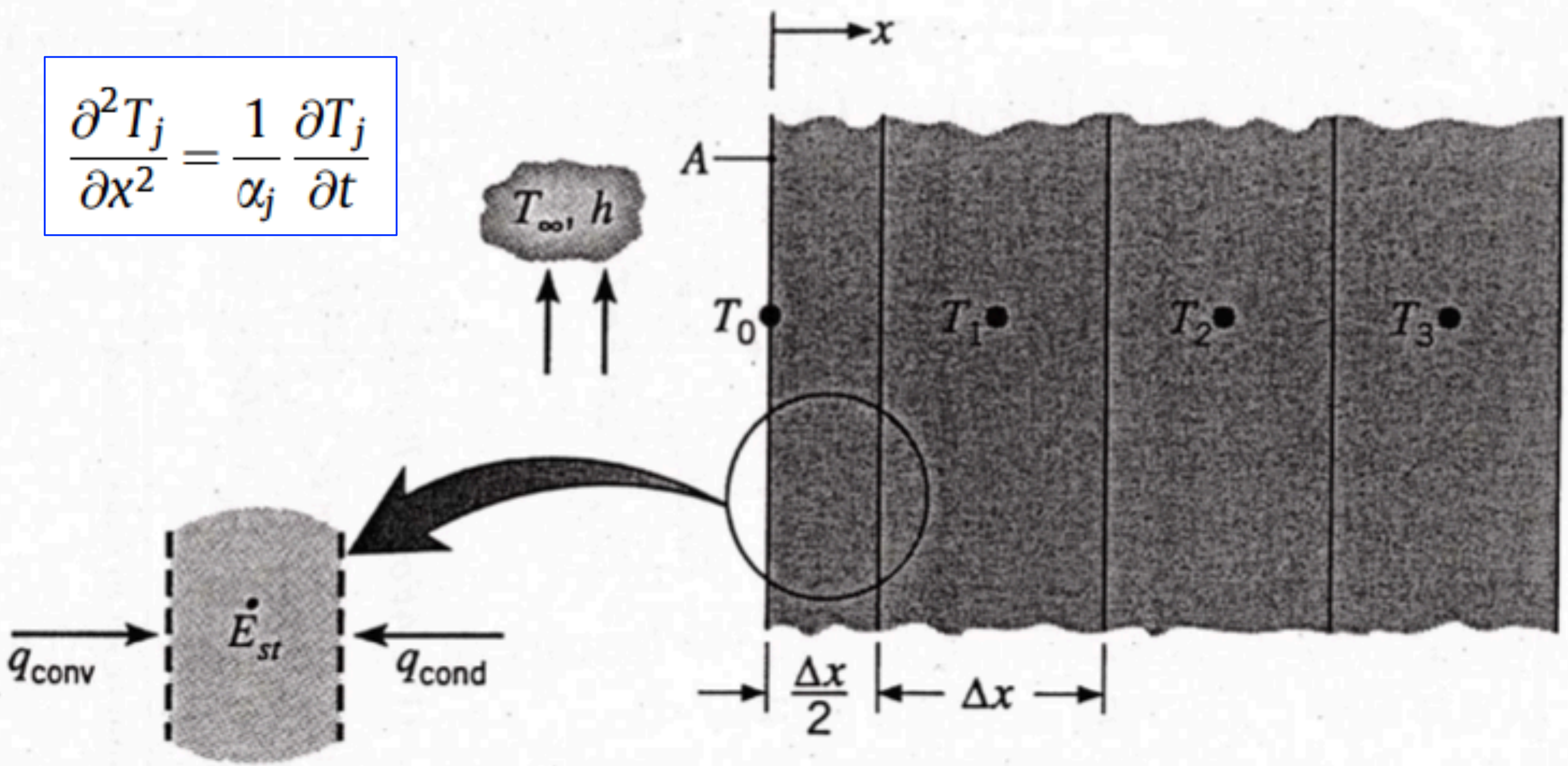
Based on density and heat capacity of material…



Modeling thermal mass: Transient (unsteady) conduction

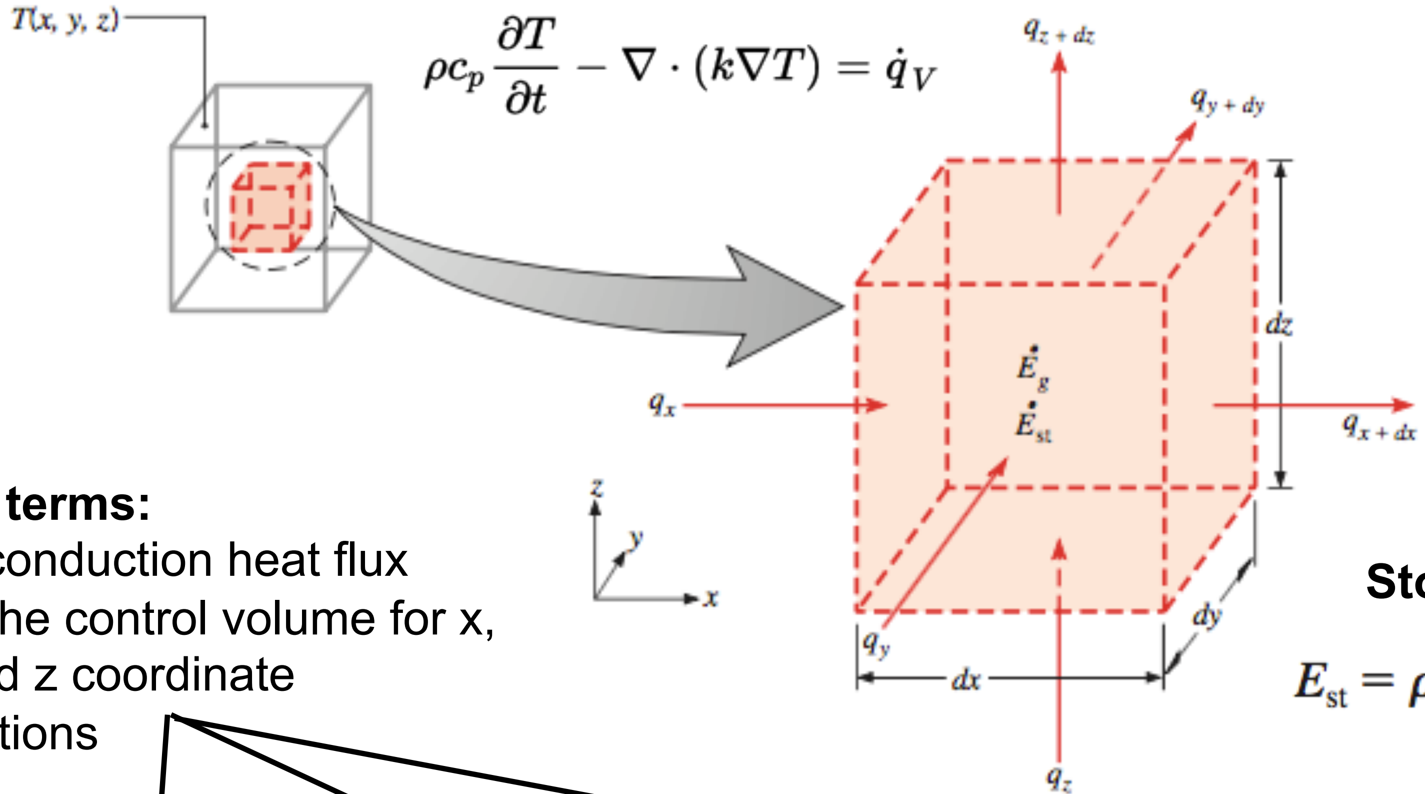
- Divide material assembly into multiple nodes

$$\frac{\partial^2 T_j}{\partial x^2} = \frac{1}{\alpha_j}\frac{\partial T_j}{\partial t}$$



Modeling thermal mass: Transient (unsteady) conduction

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = \dot{q}_V$$



Flux terms:
Net conduction heat flux into the control volume for x, y, and z coordinate directions

Storage term:

$$E_{st} = \rho c_p \frac{\partial T}{\partial t} dx\, dy\, dz$$

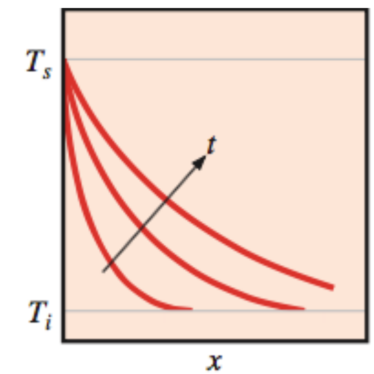
$$\frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) + q = \rho c_p \frac{\partial T}{\partial t}$$

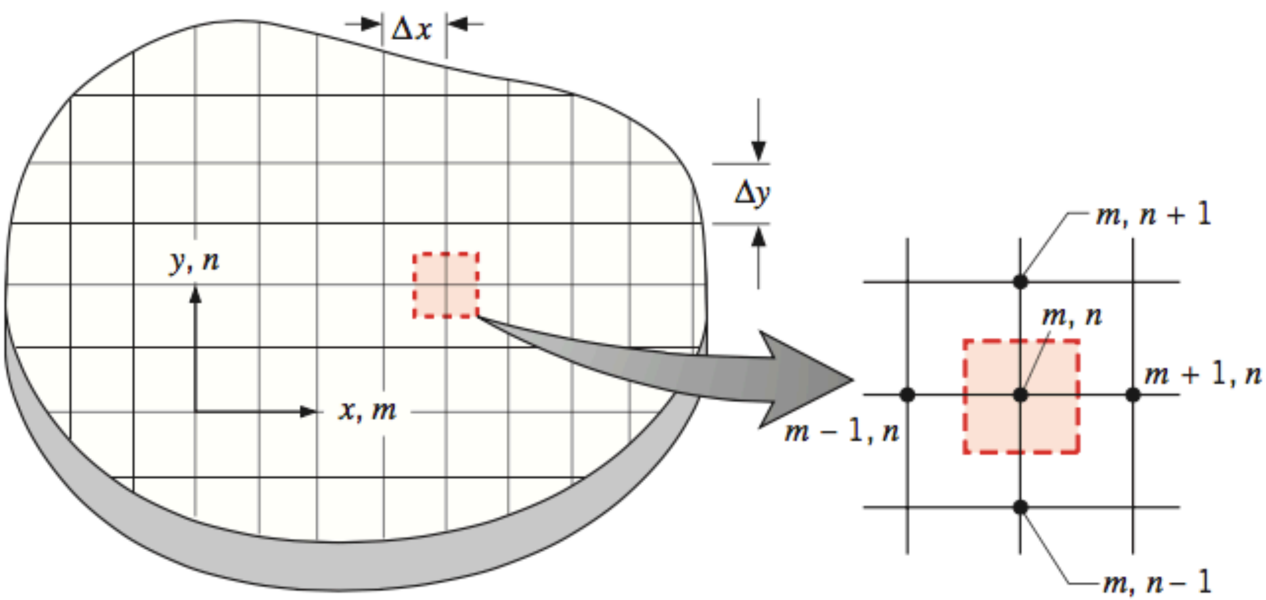
Heat energy source term:
Usually ignored

Solutions to the transient heat conduction equation

- **Analytical solutions:**
  - Case specific
  - Simple geometries and boundary conditions
  - Mathematically more complicated
- **Numerical solutions:**
  - Finite-difference methods (explicit and implicit)

$$\frac{T(x,t) - T_s}{T_i - T_s} = \operatorname{erf}\left(\frac{x}{2\sqrt{\alpha t}}\right)$$





$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}$$

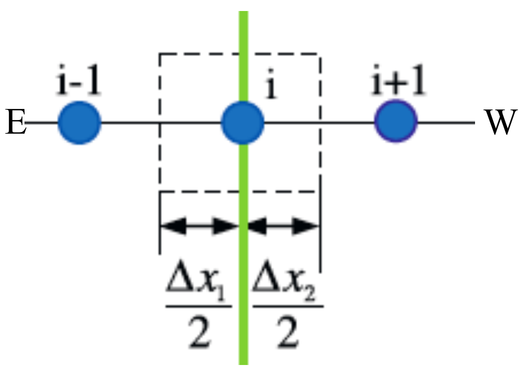
$$\left.\frac{\partial T}{\partial x}\right|_{m-1/2,n} = \frac{T_{m,n} - T_{m-1,n}}{\Delta x}$$

$$\left.\frac{\partial T}{\partial x}\right|_{m+1/2,n} = \frac{T_{m+1,n} - T_{m,n}}{\Delta x}$$

Transient conduction: Example numerical approach

- Conduction finite difference solution (**implicit**)

$$C_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \frac{1}{2}\left[\left(k_W \frac{\left(T_{i+1}^{j+1} - T_i^{j+1}\right)}{\Delta x} + k_E \frac{\left(T_{i-1}^{j+1} - T_i^{j+1}\right)}{\Delta x}\right) + \left(k_W \frac{\left(T_{i+1}^{j} - T_i^{j}\right)}{\Delta x} + k_E \frac{\left(T_{i-1}^{j} - T_i^{j}\right)}{\Delta x}\right)\right] \quad (36)$$



Where:
T = node temperature
Subscripts:
i = node being modeled
i+1 = adjacent node to interior of construction
i-1 = adjacent node to exterior of construction
j+1 = new time step
j = previous time step
Δt = calculation time step
Δx = finite difference layer thickness (always less than construction layer thickness)
C_p = specific heat of material
k_W = thermal conductivity for interface between i node and i+1 node
k_E = thermal conductivity for interface between i node and i-1 node
ρ = density of material

Selecting grid size:

$$\left(Fo = \alpha \Delta t / \Delta x^2\right) < 0.5$$

Implicit = temperatures are evaluated at time j+1 as a function of temperatures at time j

Modeling thermal mass: Transient (unsteady) conduction

- Conduction and thermal mass together can also be modeled using a **lumped capacitance** approach in 1-dimension:

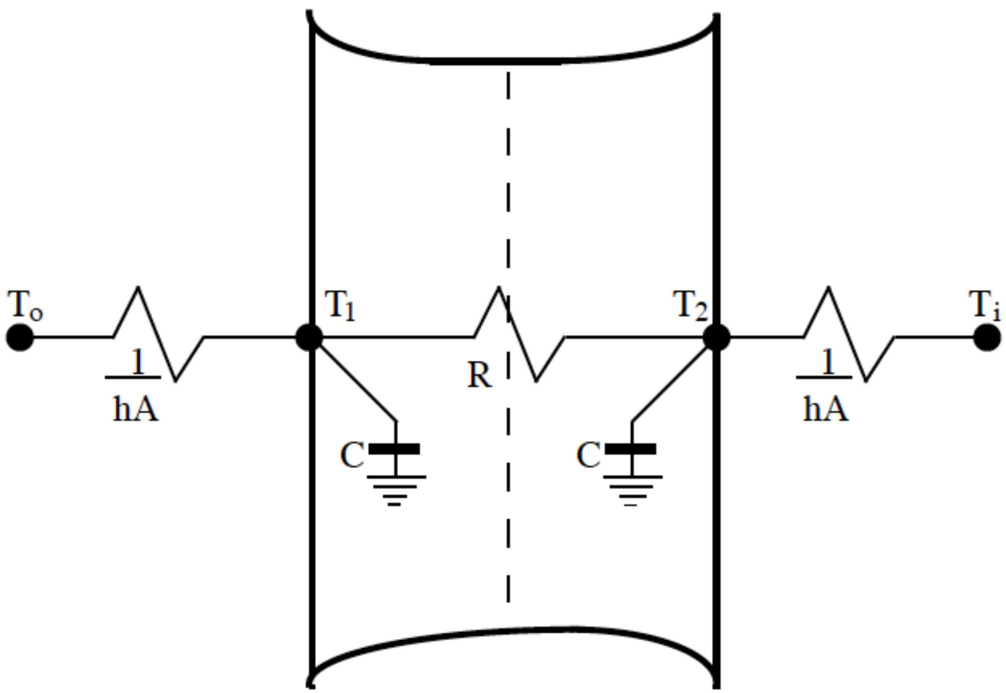


Figure 9. Two Node State Space Example.

$$C\frac{dT_1}{dt} = hA(T_o - T_1) + \frac{T_2 - T_1}{R}$$

$$C\frac{dT_2}{dt} = hA(T_i - T_2) + \frac{T_1 - T_2}{R}$$

where:

$$R = \frac{\ell}{kA},$$

$$C = \frac{\rho c_p \ell A}{2}$$

Lumped capacitance model

- Wall example: Exterior surface balance at T_1 changes

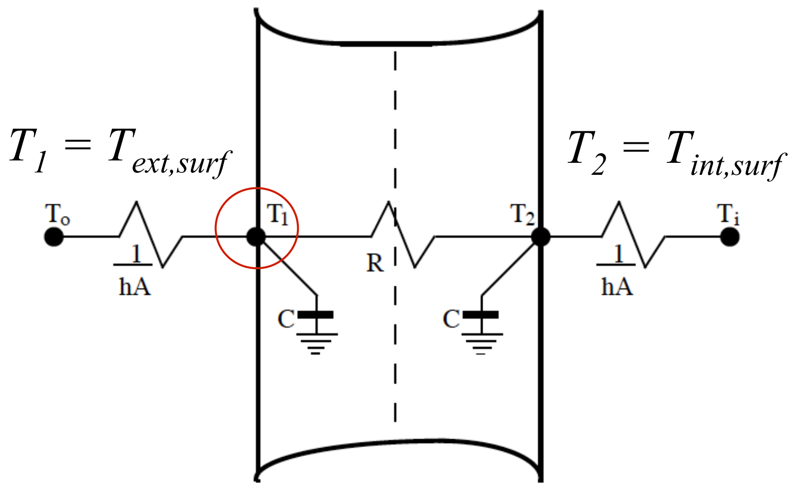


Figure 9. Two Node State Space Example.

From:

$$q_{sw,solar} + q_{lw,surface-sky} + q_{lw,surface-ground} + q_{convection} - q_{conduction} = 0$$

To:

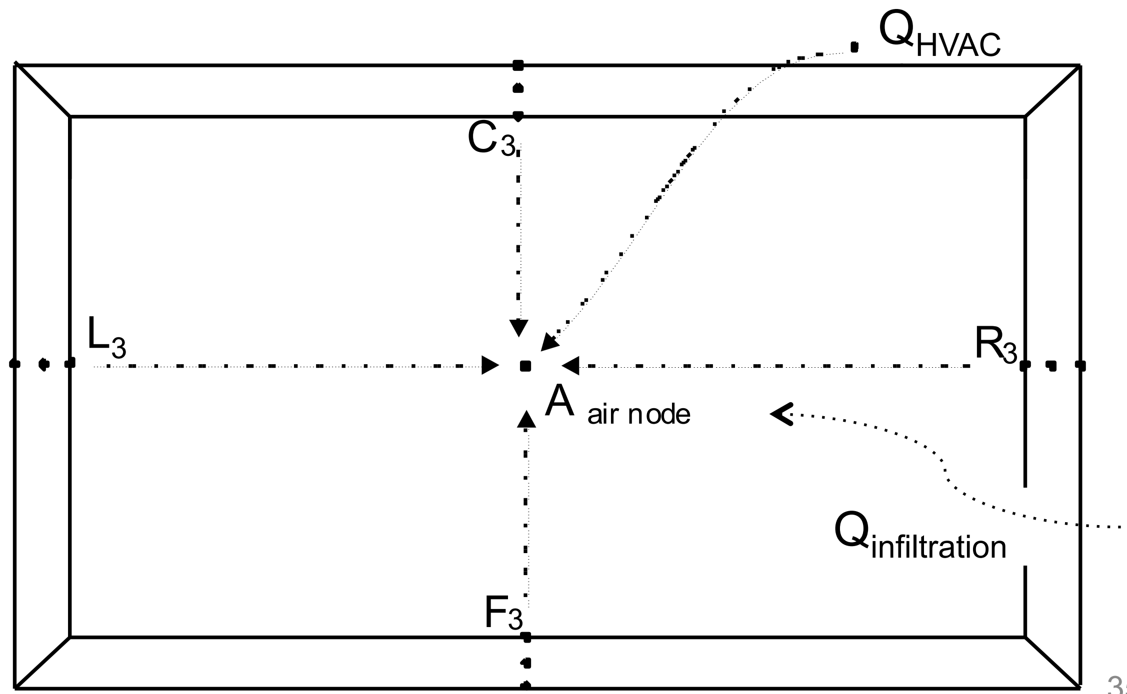
$$q_{sw,solar} + q_{lw,surface-sky} + q_{lw,surface-ground} + q_{convection} - q_{conduction} = \rho C_p \frac{L}{2} \frac{dT}{dt}$$

HBM: Indoor air energy balance

- To get the impact on indoor air temperature (and close the system of equations)
  - Write an energy balance on the indoor air node
  - Air impacted directly only by convection (bulk and/or surface)

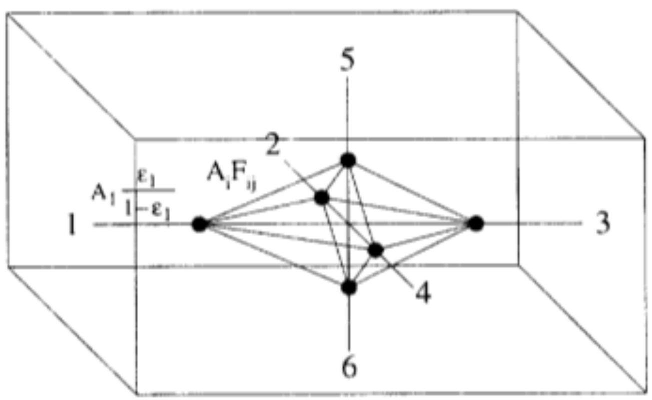
$$(V_{room}\rho_{air}c_{p,air})\frac{dT_{air,in}}{dt} = \sum_{i=1}^{n} h_i A_i \left(T_{i,surf} - T_{air,in}\right) + \dot{m}c_p\left(T_{out} - T_{air,in}\right) + Q_{HVAC}$$

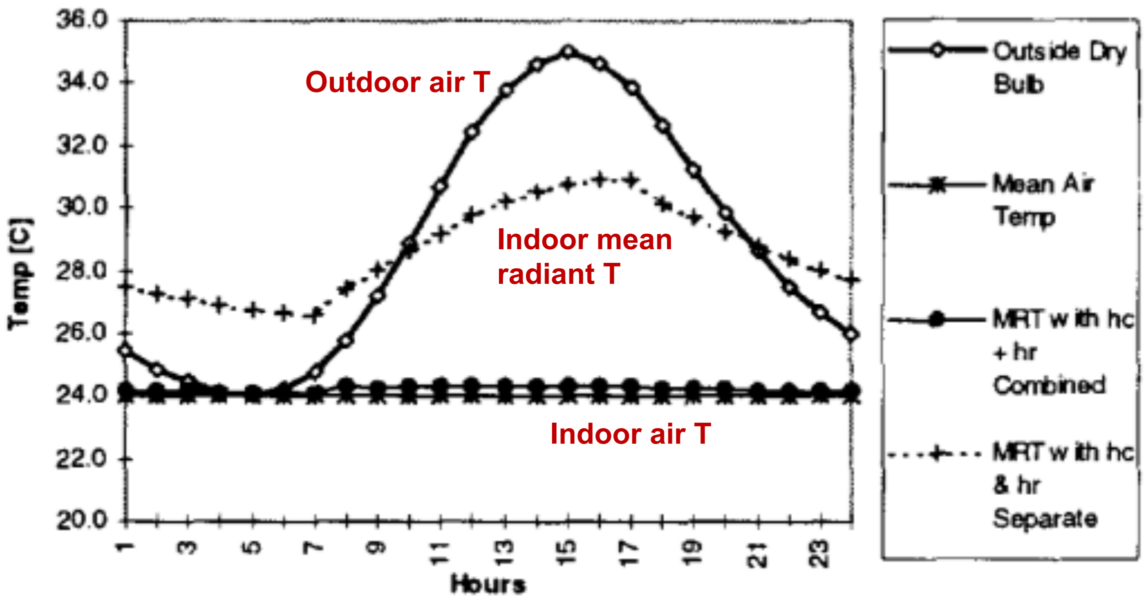
In plain English:
The change in indoor air temperature is equal to the sum of convection from each interior surface plus outdoor air delivery (by infiltration or dedicated outdoor air supply), plus the bulk convective heat transfer delivered by the HVAC system



Using HBM to calculate peak loads

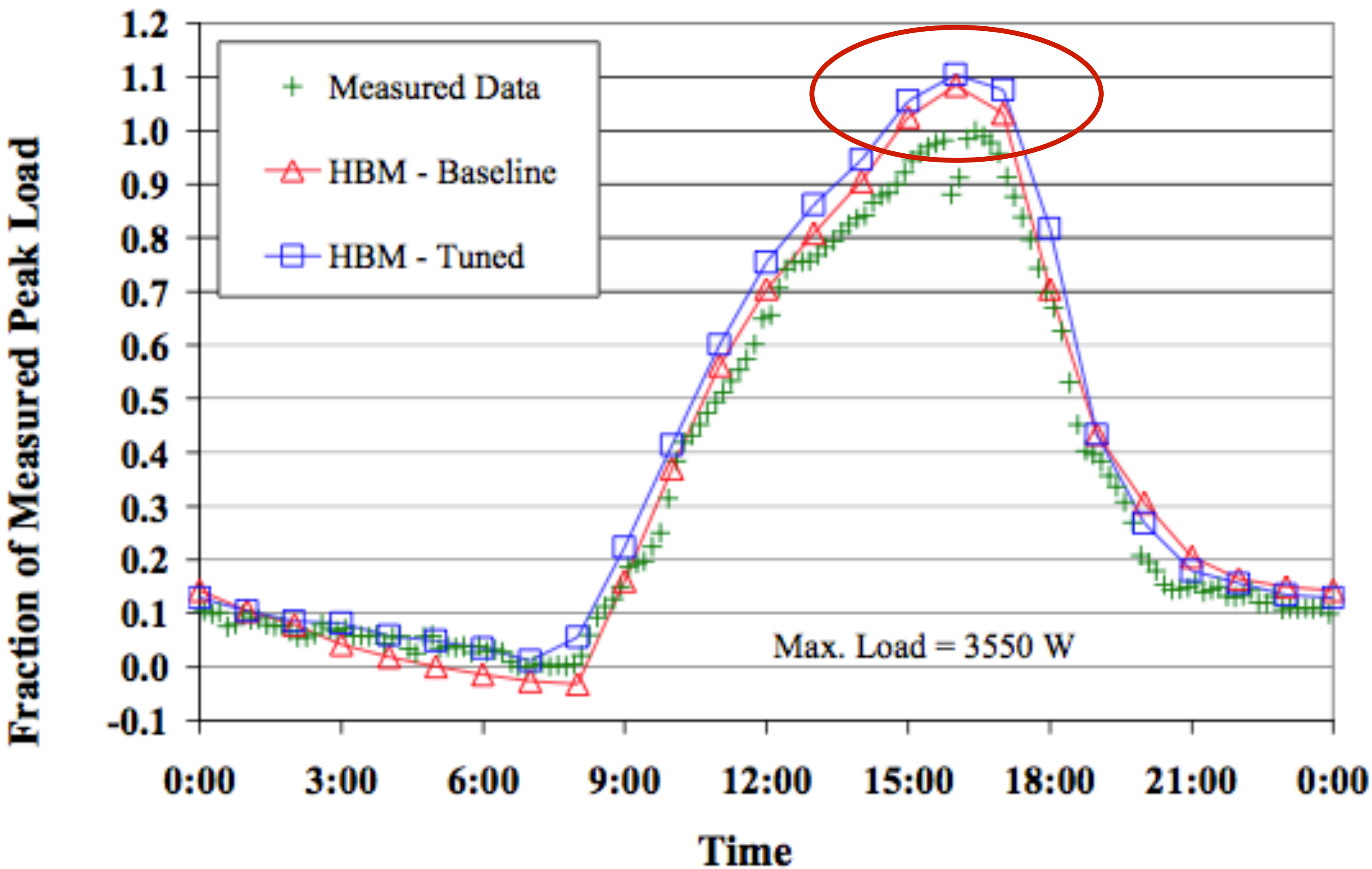
- Tracking indoor and outdoor temperatures for a simple space:





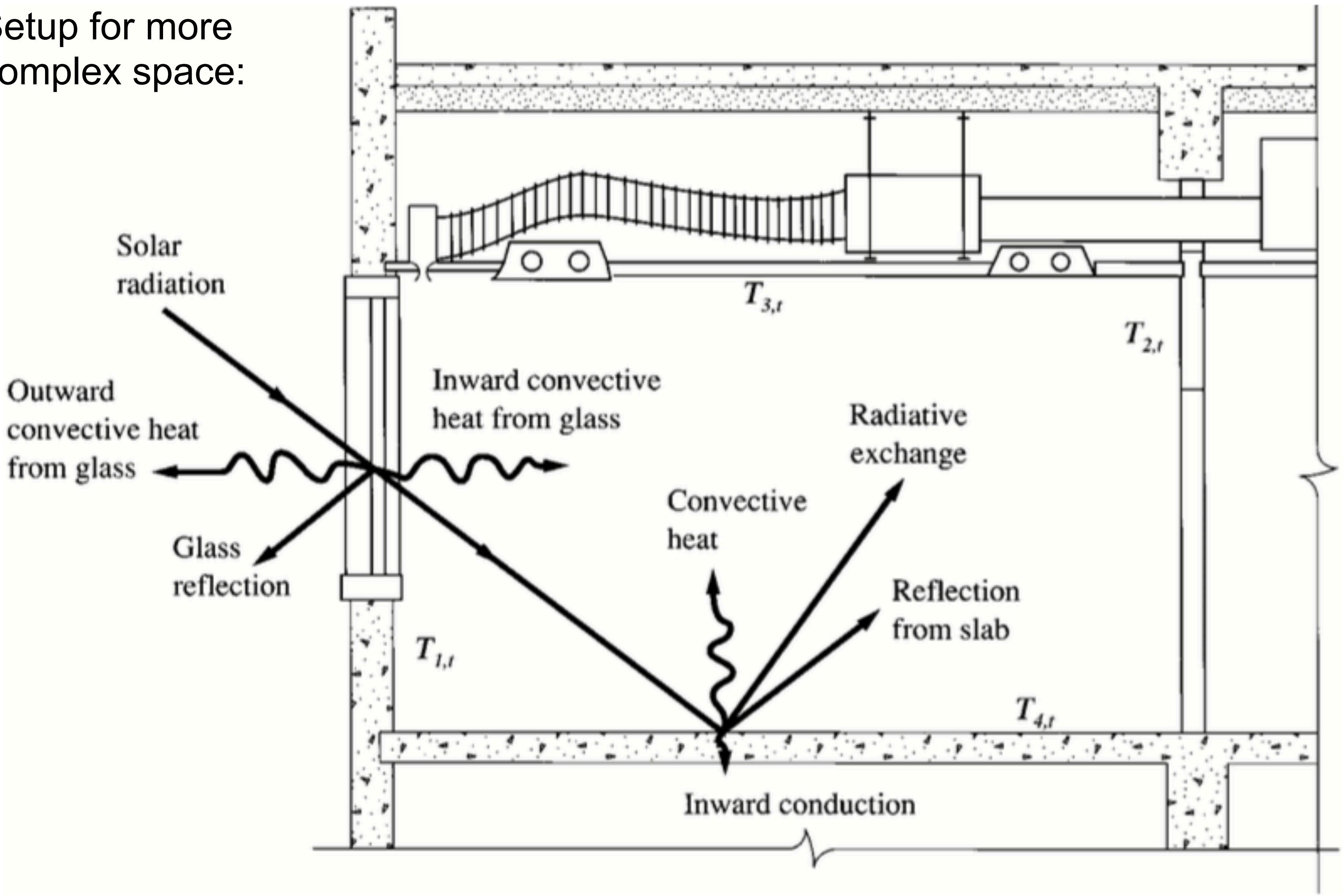
Using HBM to calculate peak loads

- Tracking the cooling load for a simple space:

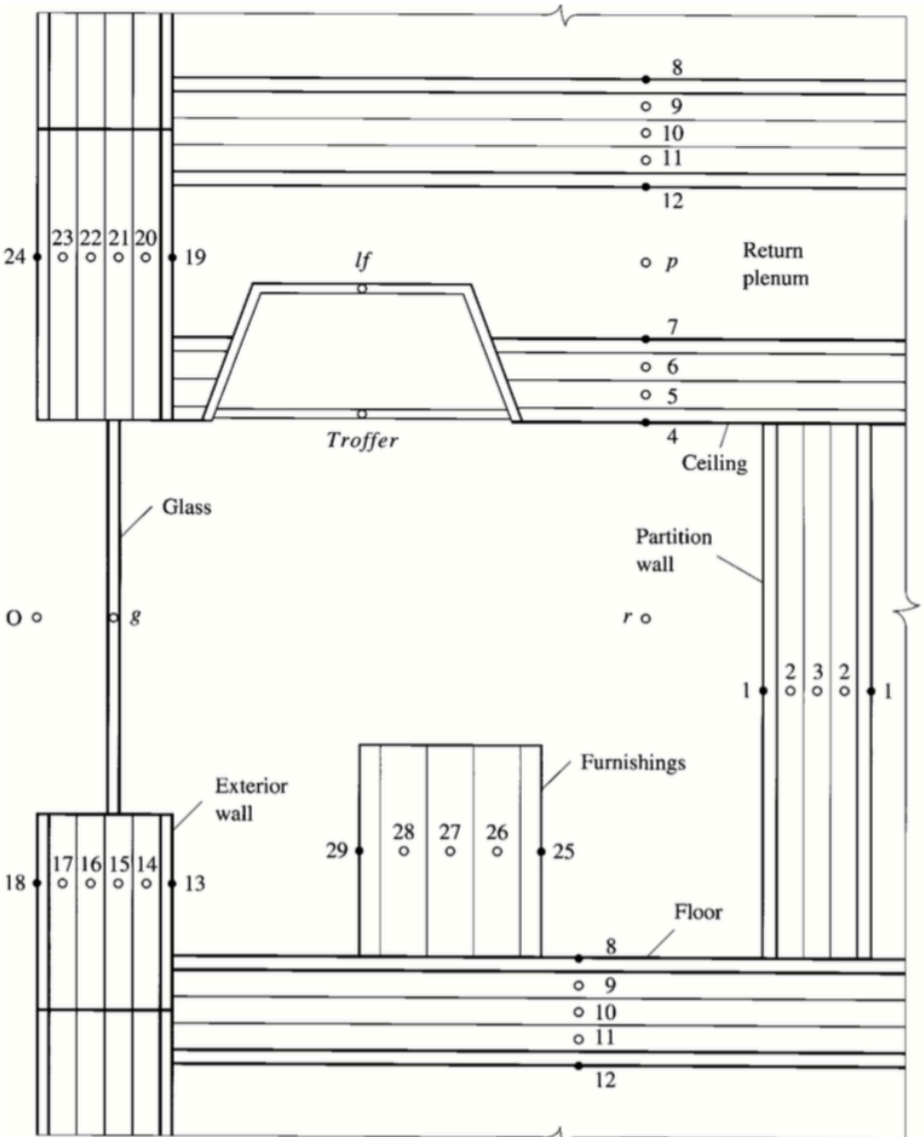


Using HBM to calculate peak loads

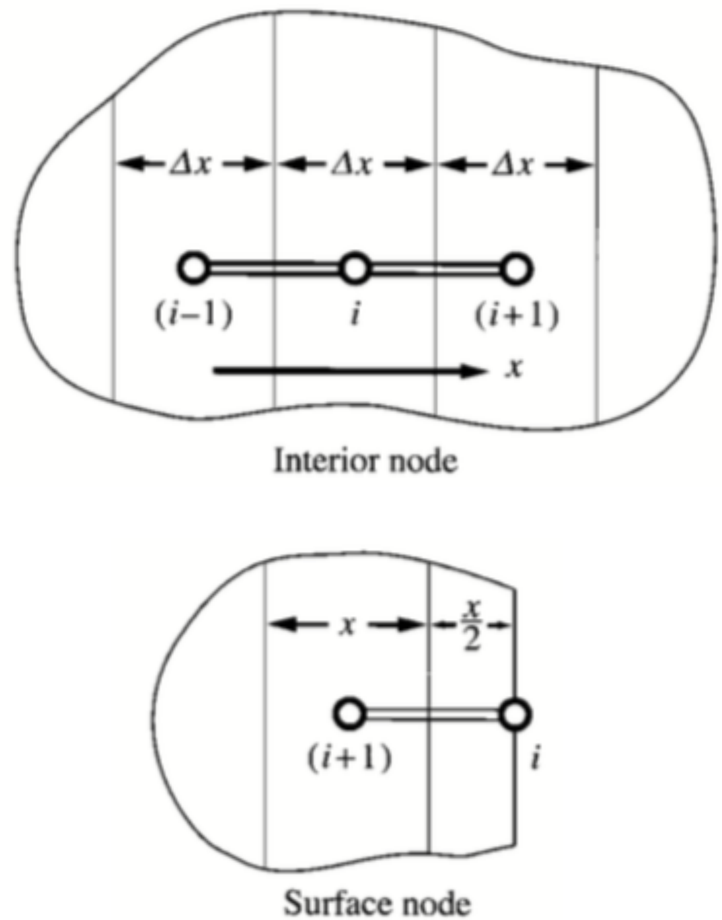
Setup for more complex space:



Using HBM to calculate peak loads: Complex



Setup for more complex space:



Notes on estimating cooling loads

- Frequently, a cooling load must be calculated before every parameter in the conditioned space can be properly or completely defined
  - An example is a cooling load estimate for a new building with many floors of un-leased spaces where detailed partition requirements, furnishings, lighting selection and layout cannot be predefined
  - Potential tenant modifications once the building is occupied also must be considered

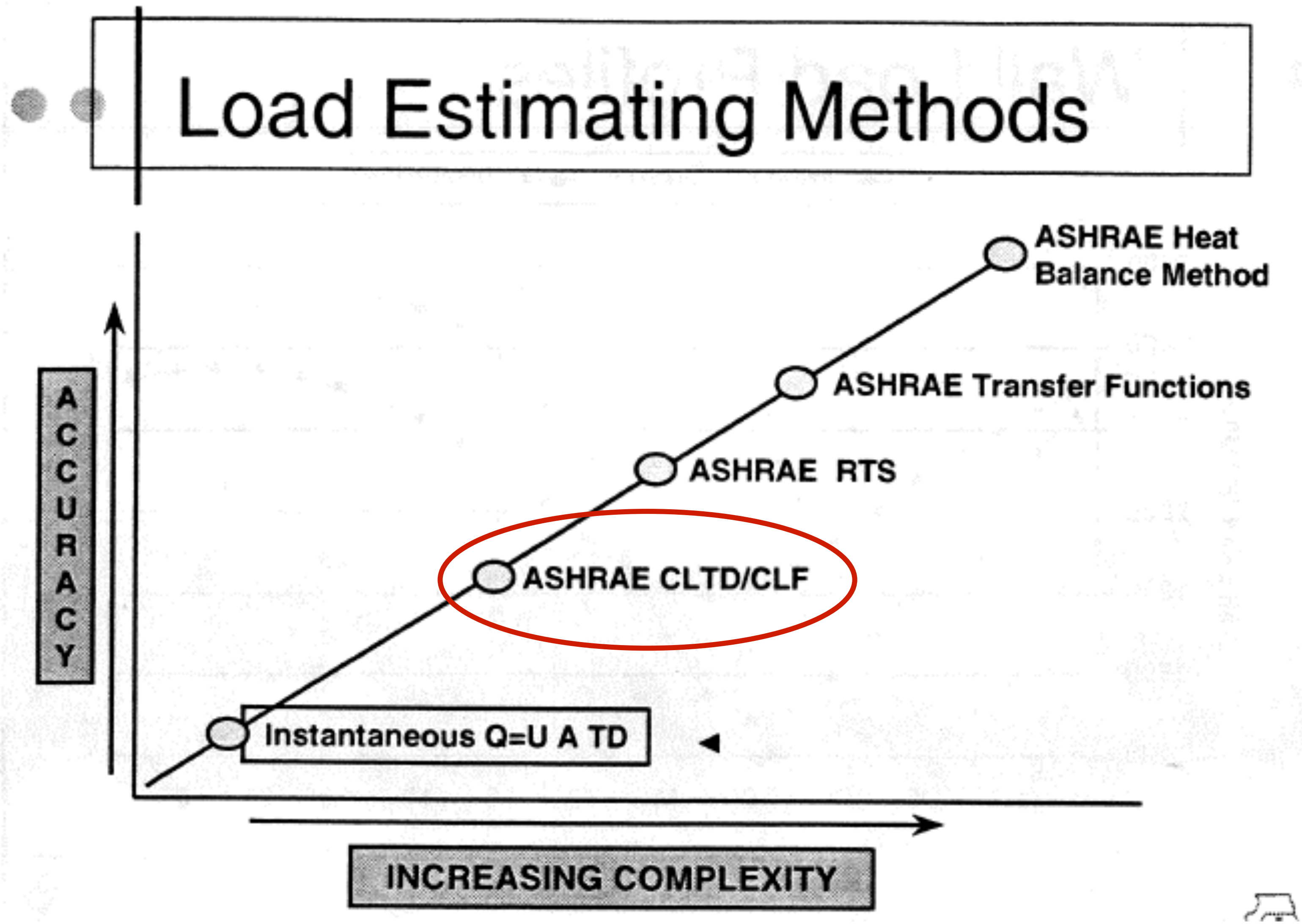
- The total load estimating process requires some engineering judgment that includes a thorough understanding of heat balance fundamentals

Issues with oversizing

- Since getting an accurate cooling load estimate can be difficult (or even impossible at an early design stage) some engineers design conservatively and deliberately oversize systems

- Oversizing a system is problematic because
  - Oversized systems are less efficient, harder to control, and noisier than properly sized systems
  - Oversized systems tend to duty cycle (turn on and off) which reduces reliability and increases maintenance costs
  - Oversized systems take up more space and cost more

Cooling load calculation methods



Simpler method: The ASHRAE CLTD/CLF method

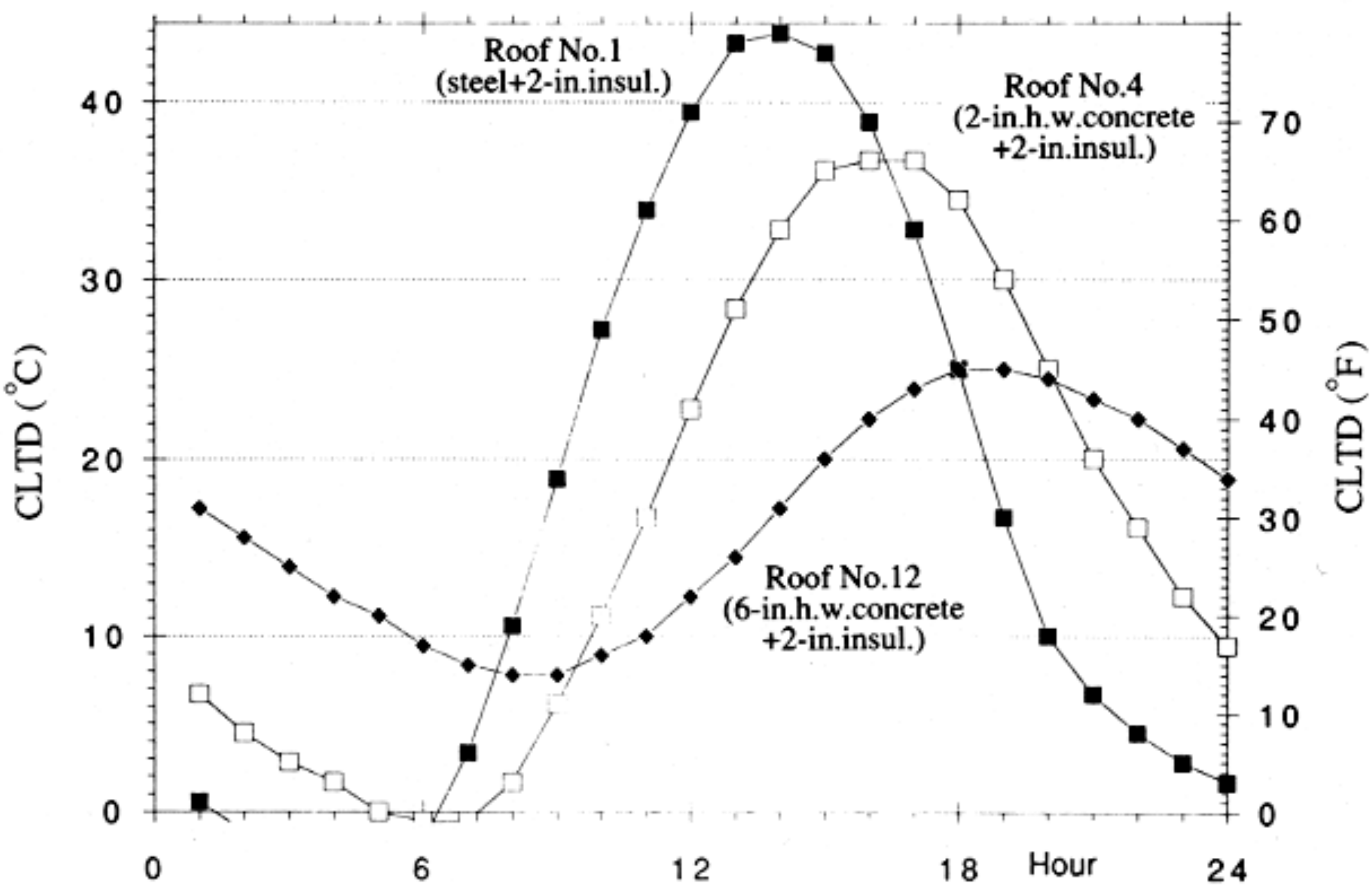
- One method of accounting for periodic responses for conduction and radiation (simpler than others) is the CLTD/CLF method (it's a mouthful)

- CLTD = cooling load temperature difference [K]
  - The temperature difference that gives the same cooling load when multiplied by UA for a given assembly
  - Calculate these "effective ΔT" values for typical constructions and typical temperature patterns
    - Then adjust the conductive load accordingly

Instead of: $$Q_{cooling,conduction} = UA(T_{out} - T_{in})$$

You use: $$Q_{cooling,conduction} = UA(CLTD_t)$$ at hour t

CLTD for typical roof materials

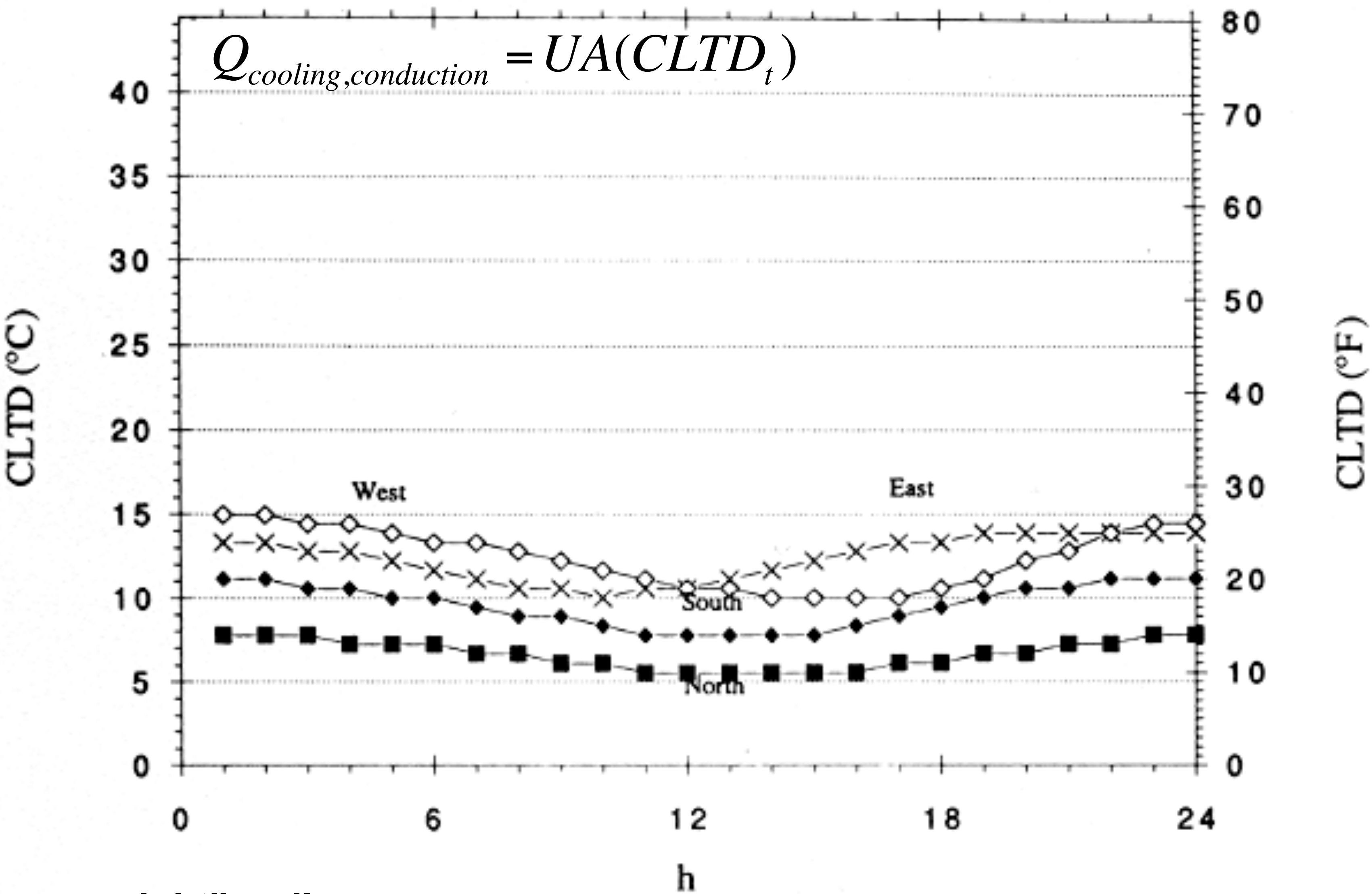


$$Q_{cooling,conduction} = UA(CLTD_t)$$

h

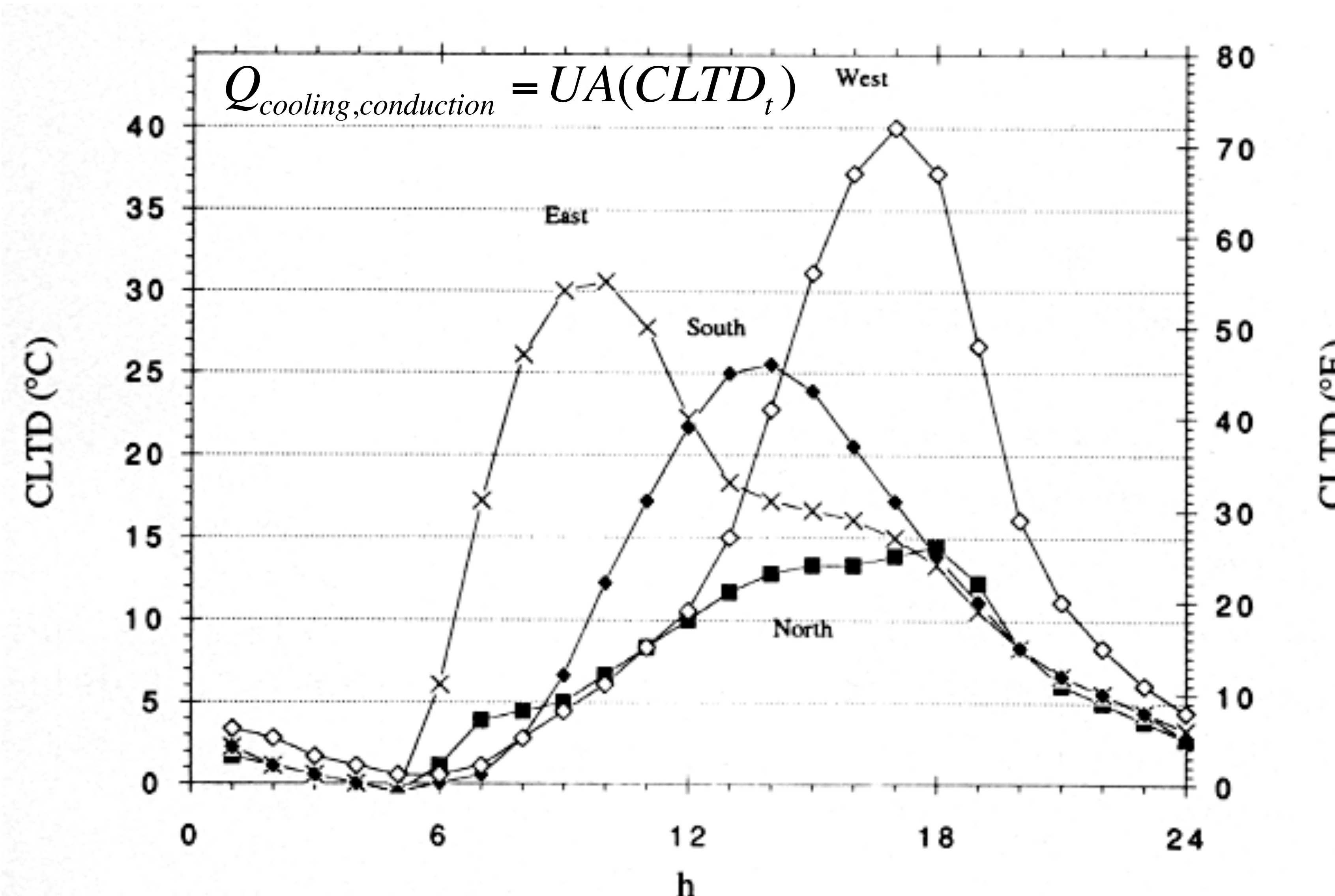
CLTD for typical “heavy” or “massive” walls

$$Q_{cooling,conduction} = UA(CLTD_t)$$



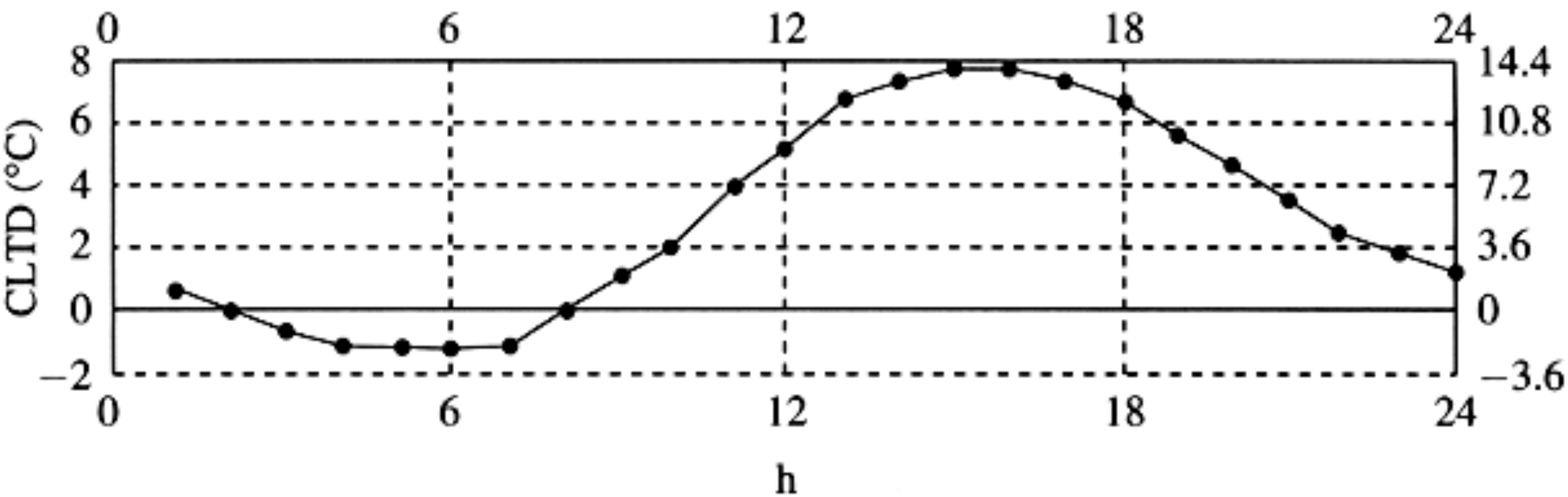
“Heavyweight” walls

CLTD for typical "lightweight" walls



"Lightweight" walls

CLTD for typical glazing



$$Q_{cooling,conduction} = UA(CLTD_t)$$

ASHRAE CLTD/CLF method

- CLF = cooling load factor [dimensionless]
  - Yields the cooling load at hour *t* as a function of maximum daily load
    - Also calculated for common construction materials
    - Just look values up in tables

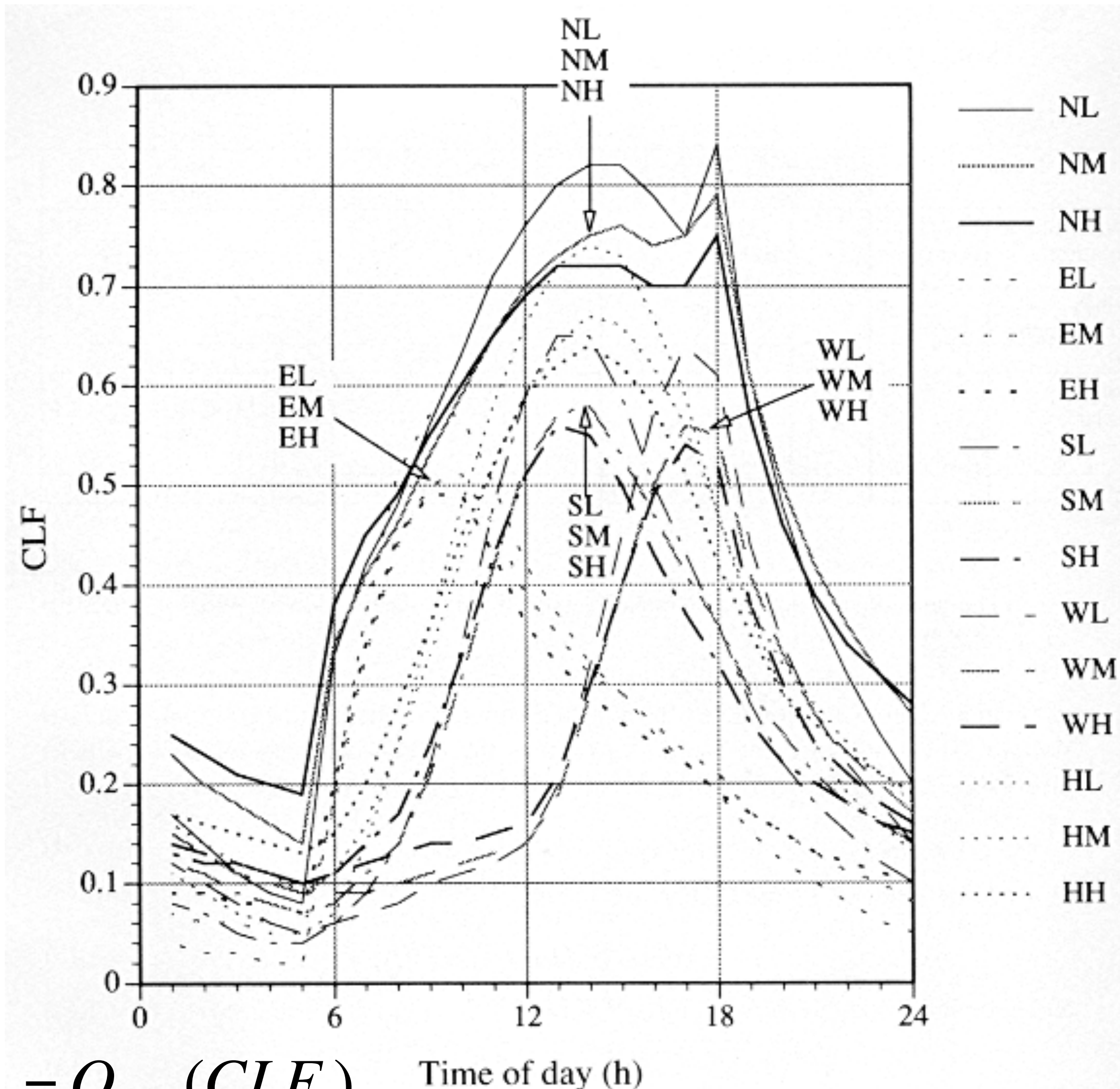
Instead of: $$Q_{solar} = \alpha I_{solar} A$$

You use: $$Q_{cooling,radiation,t} = Q_{\max}(CLF_t)$$ at hour t

CLF for typical glazing

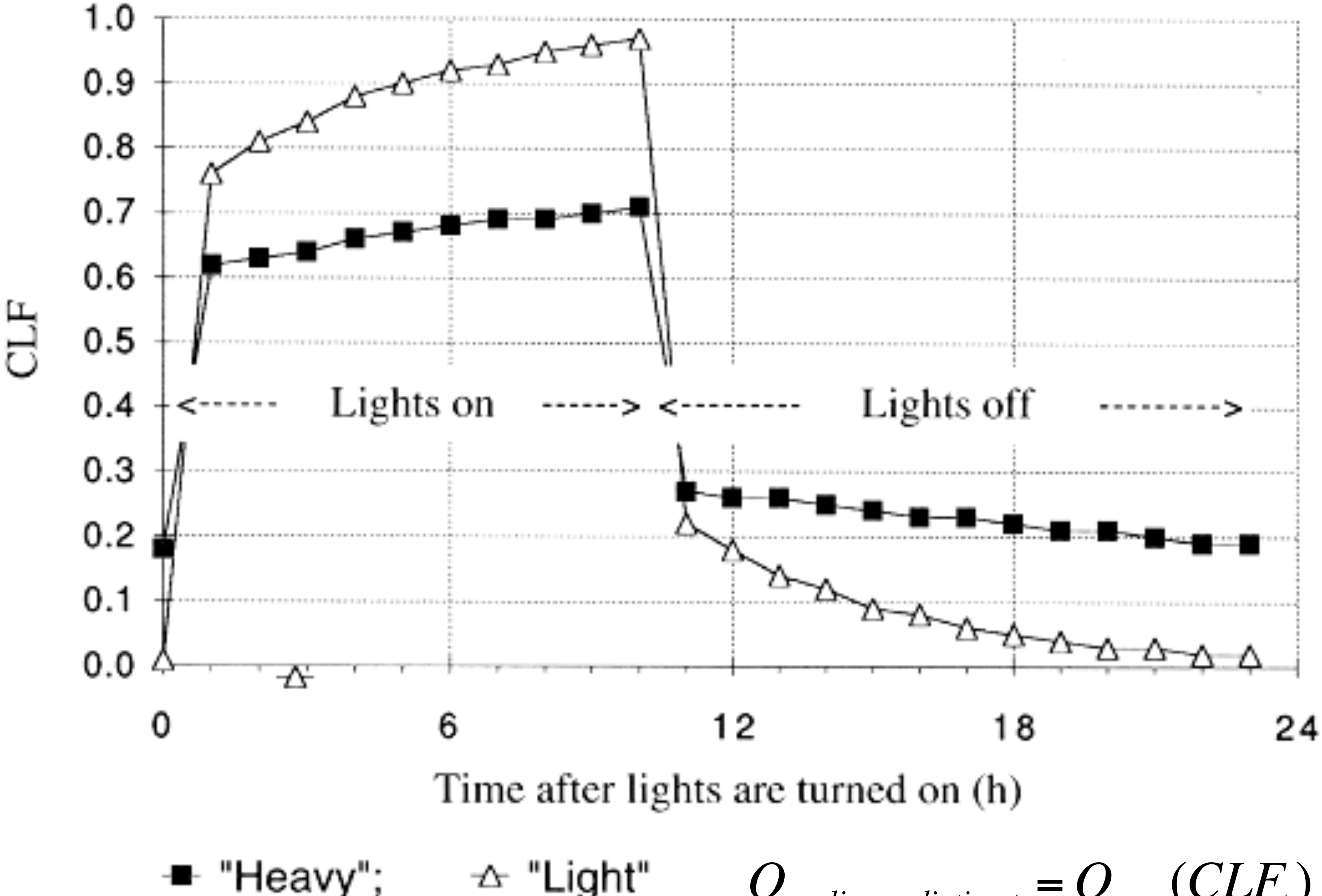
L = light
M = medium
H = heavy

N = north
E = east
W = west
S = south



$$Q_{cooling,radiation,t} = Q_{\max}(CLF_t)$$

CLF for typical internal gains



$$Q_{cooling,radiation,t} = Q_{\max}(CLF_t)$$

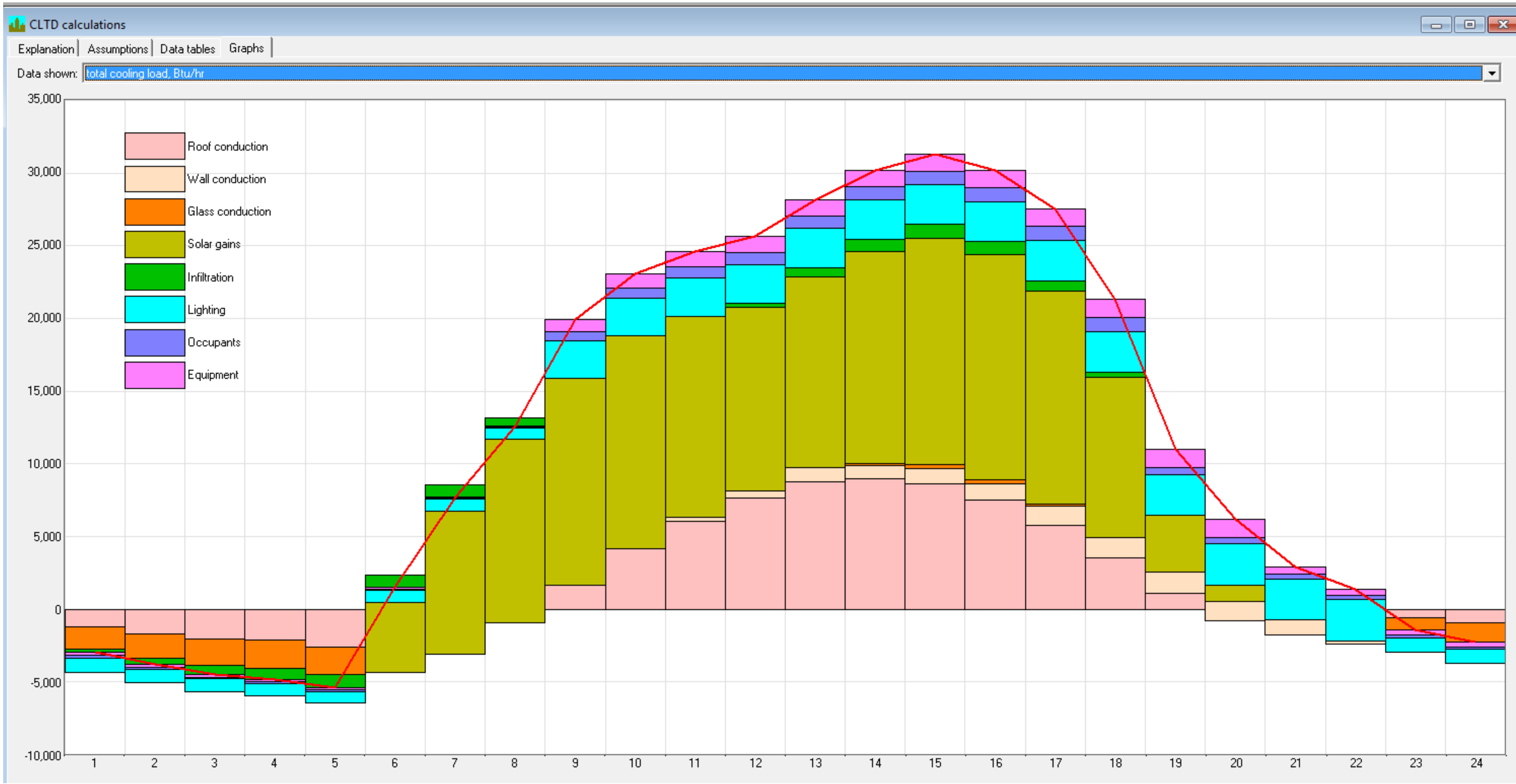
Finding peak cooling load with CLTD/CLF method

- To find the peak cooling load you would need to take into account the magnitude of all individual loads around a peak time period (typically within about 3 hours)
- Typically late afternoon or early evening
- Use a spreadsheet tool
- For a full example, see older versions of the ASHRAE Handbook of Fundamentals
  - http://www.tagengineering.ca/wp-content/uploads/2015/01/1997-Fundamentals_28.pdf

ASHRAE CLTD/CLF method

Sensible loads					hour t			hour t		
					3p	4p	5p			
Component and orientation	Construction type		U	A	$CLTD_t$			$\dot{Q}_t=U\times A\times CLTD_t$		
Walls										
Roof										
Glazing conduction										
Glazing solar		A	SC	$SHGF_{max}$	CLF_t			$\dot{Q}_t=A\times SC\times SHGF_{max}\times CLF_t$		
Air exchange		V	$\dot{V}$	T_i	T_o			$\dot{Q}=\rho\times c_p\times\dot{V}\times(T_o-T_i)$ (instantaneous)		
Internal partitions			U	A	ΔT across partition			$\dot{Q}=U\times A\times\Delta T$ (instantaneous)		
Ceiling										
Floor										
Sides										
Ducts										
Internal gains		number	gain /unit	$\dot{Q}$	CLF_t			$\dot{Q}_t=\dot{Q}\times CLF_t$		
Appliances										
Fans										
Lights										
Motors										
People										
TOTAL SENSIBLE										

CLTD/CLF method applied



Software tools for load calculations

- These are not done by hand, sometimes by spreadsheet
  - Many use ACCA Manual J
- Most use computer programs
- Big list of programs:
  - http://apps1.eere.energy.gov/buildings/tools_directory/subjects.cfm/pagename=subjects/pagename_menu=whole_building_analysis/pagename_submenu=load_calculation

Cooling load calculation methods