CAE 463/524
Building Enclosure Design

Spring 2016

Week 13: April 5, 2016

Energy simulation and enclosure design

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Last week

- Campus enclosure assessment presentations

- Take-home exam given
  - Due today

- Introduced final individual project expectations

Project 2: Topic selection

- **Email me** your topics by **Friday April 8, 2016**

Name	Project topic
Blat Tatay, Andrea	
Curioni, Dina P.	
Jarma, David A.	
Jordan, Taylor L.	
Kane, Benjamin M.	Double skin façades and energy
Lim, Keonho	
Mitchell, Alexander R.	
Panczak, Bianca J.	Smart glass
Rice, Lindsey E.	
Townley, Nina V.	
Ashayeri Jahan Khanemloo, Mehdi	
Babaei Sonbolabadi, Kamal	
Cueto, Patrick Kevin M.	
Del Pino Torres, Julia Del Rosario	
Faramarzi, Afshin	
Foss, Stephen M.	Smart glazing
Qiu, Luanzhizi	Green roofs
Sharghi, Ali	
Sudhakaran, Naveen	
Zhang, Xu	
Castro, Jose L.	
Dipietro, Salvatore D.	
Lee, JiWan	

Today's objectives

- Introduce energy simulation in building enclosure design
  - And applications for enclosure design

WHOLE BUILDING ENERGY SIMULATION

Energy simulation and enclosure design

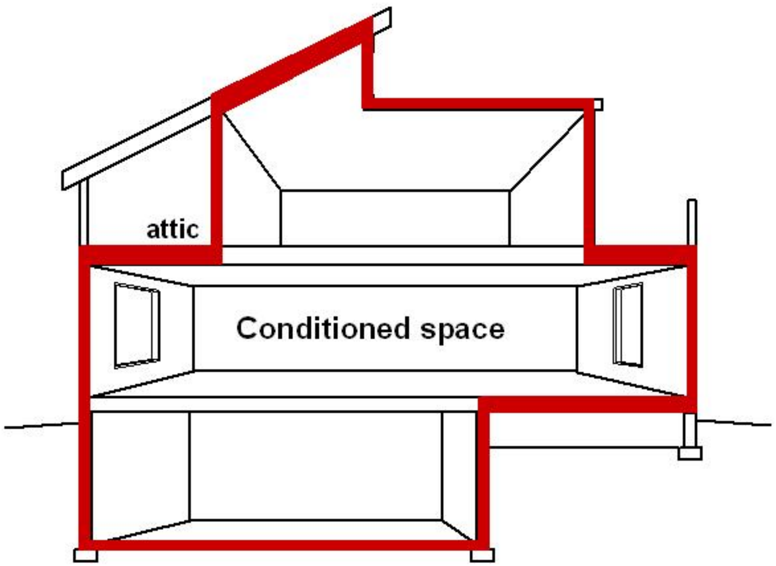
- In CAE 331/513 Building Science we discussed using sizing programs to determine peak hourly loads during heating and cooling seasons and size equipment

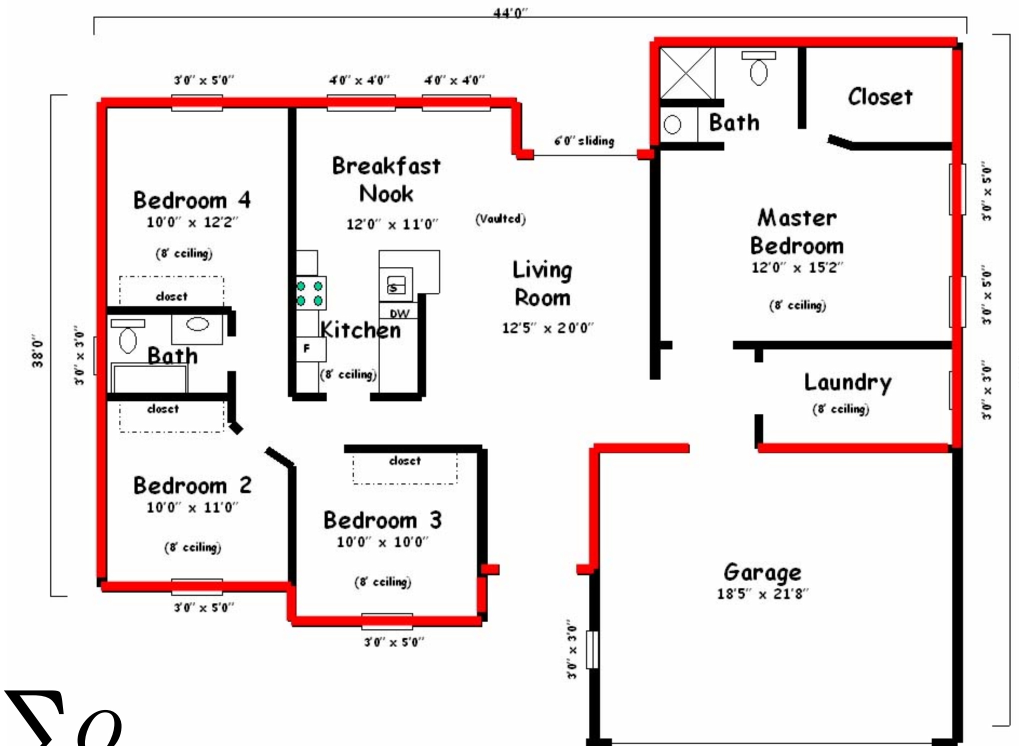
- Heating loads: easy → $Q = UA\Delta T$ method

- Cooling loads: more complex (involves radiation and storage) → CLTD, RTS, HB methods, etc.
  - You can influence loads and size of equipment early in the design process by specifying certain envelope characteristics

Heating load calculations

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





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

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

Cooling load calculations

- 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

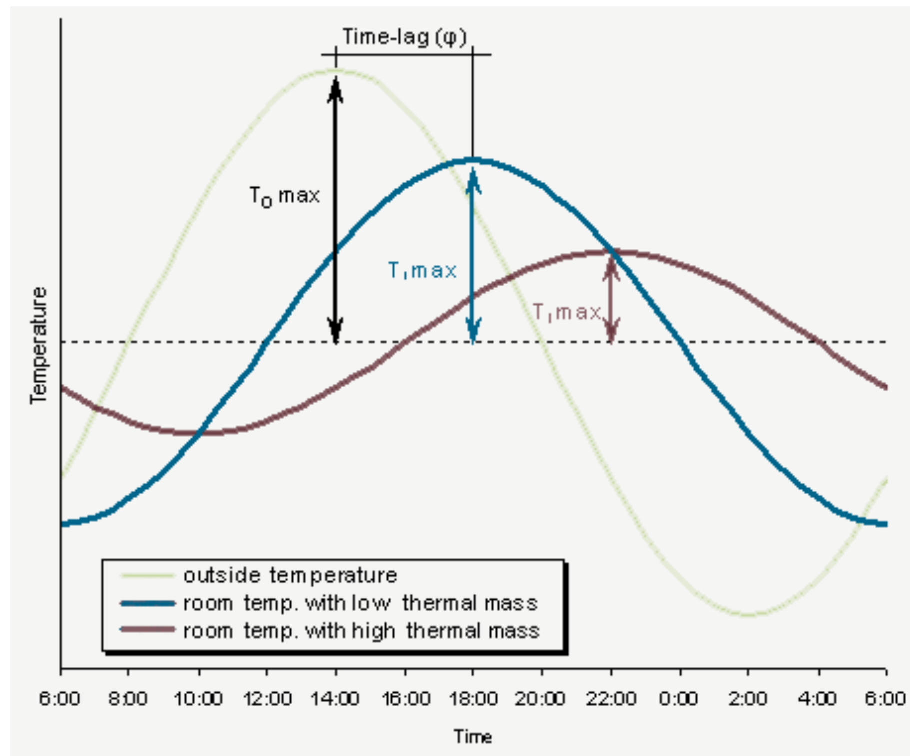
- Radiation through windows, from interior surfaces, and from internal sources (e.g., lights) will be absorbed by other interior surfaces, and then those surfaces will eventually transfer that heat energy to the air by convection
  - But the addition of radiative heat does <u>not</u> occur immediately

- 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

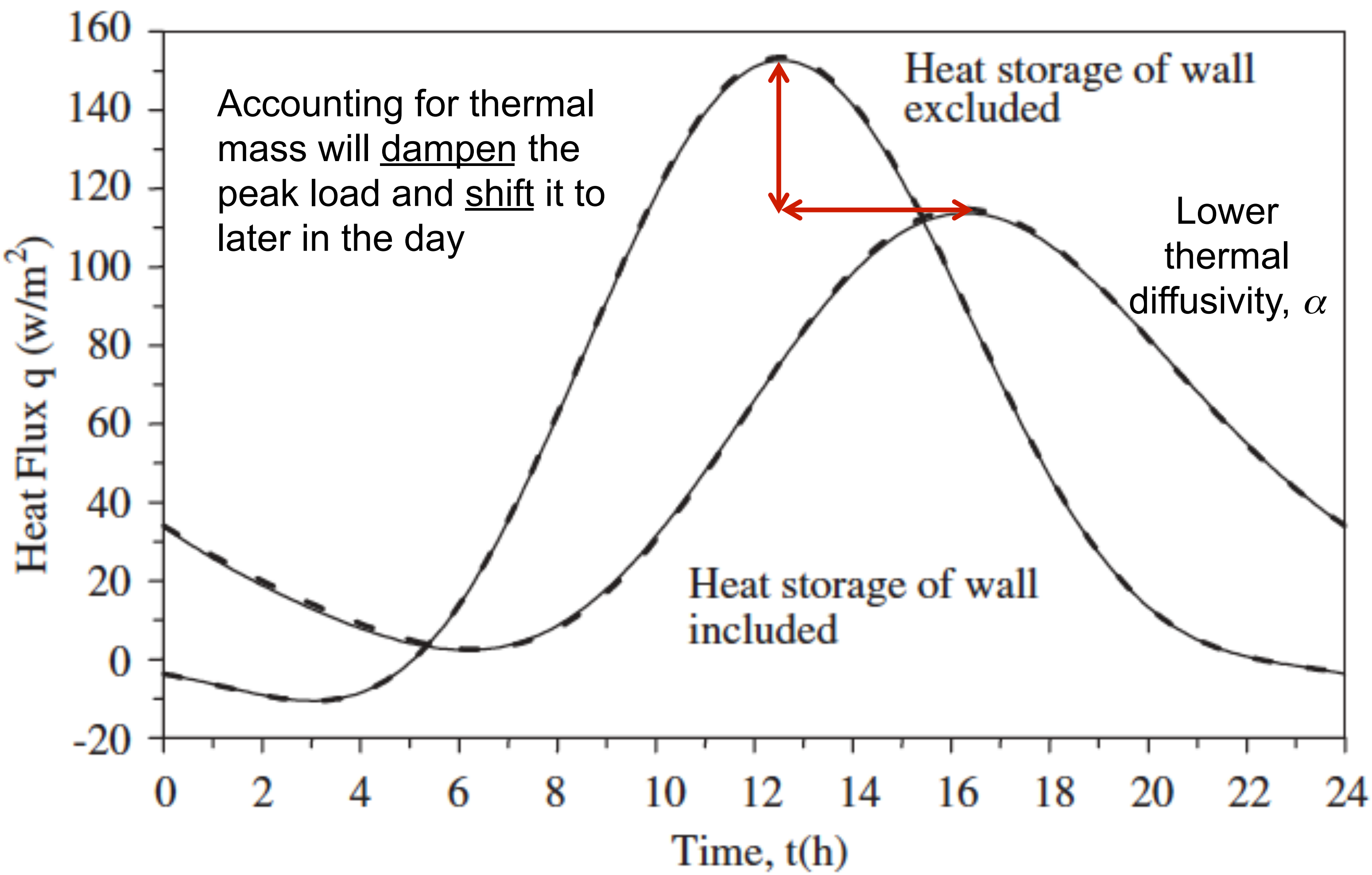
Thermal mass (more on this later)

- Thermal mass refers to materials that have the capacity to store thermal energy for extended periods of time

- Thermal mass can absorb daytime heat gains
  - Reduces peak cooling load
  - Releases heat during the night (can reduce heat load or can extend cooling load)



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 <u>systems</u> and <u>equipment</u>

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

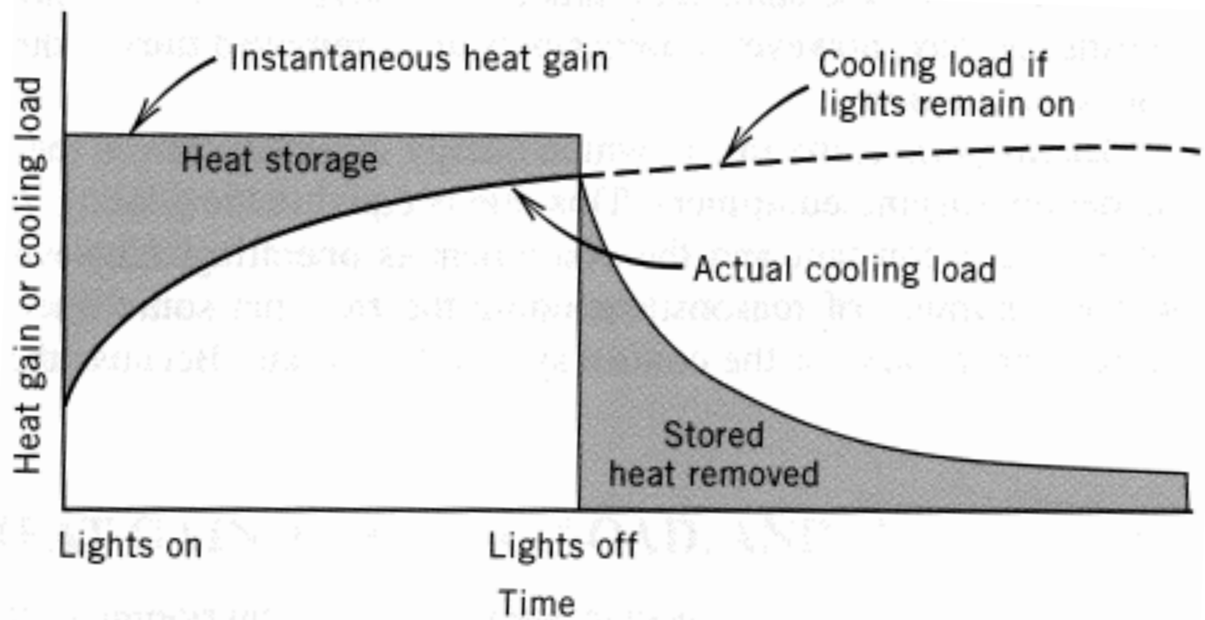


Figure 8-3 Actual cooling load from fluorescent lights.

Whole building energy simulation

- Whole building energy simulation programs are used to predict annual energy consumed by a building
- Essentially a continuation of design-day load calculation methods to the entire year
- Outcomes: annual BTUs, MJ, kWh, $, associated pollutant emissions
  - Typically normalized per floor area (e.g., kBTU/ft^2)
- You can influence annual energy consumption (and costs) early in the design process, again by specifying certain envelope characteristics

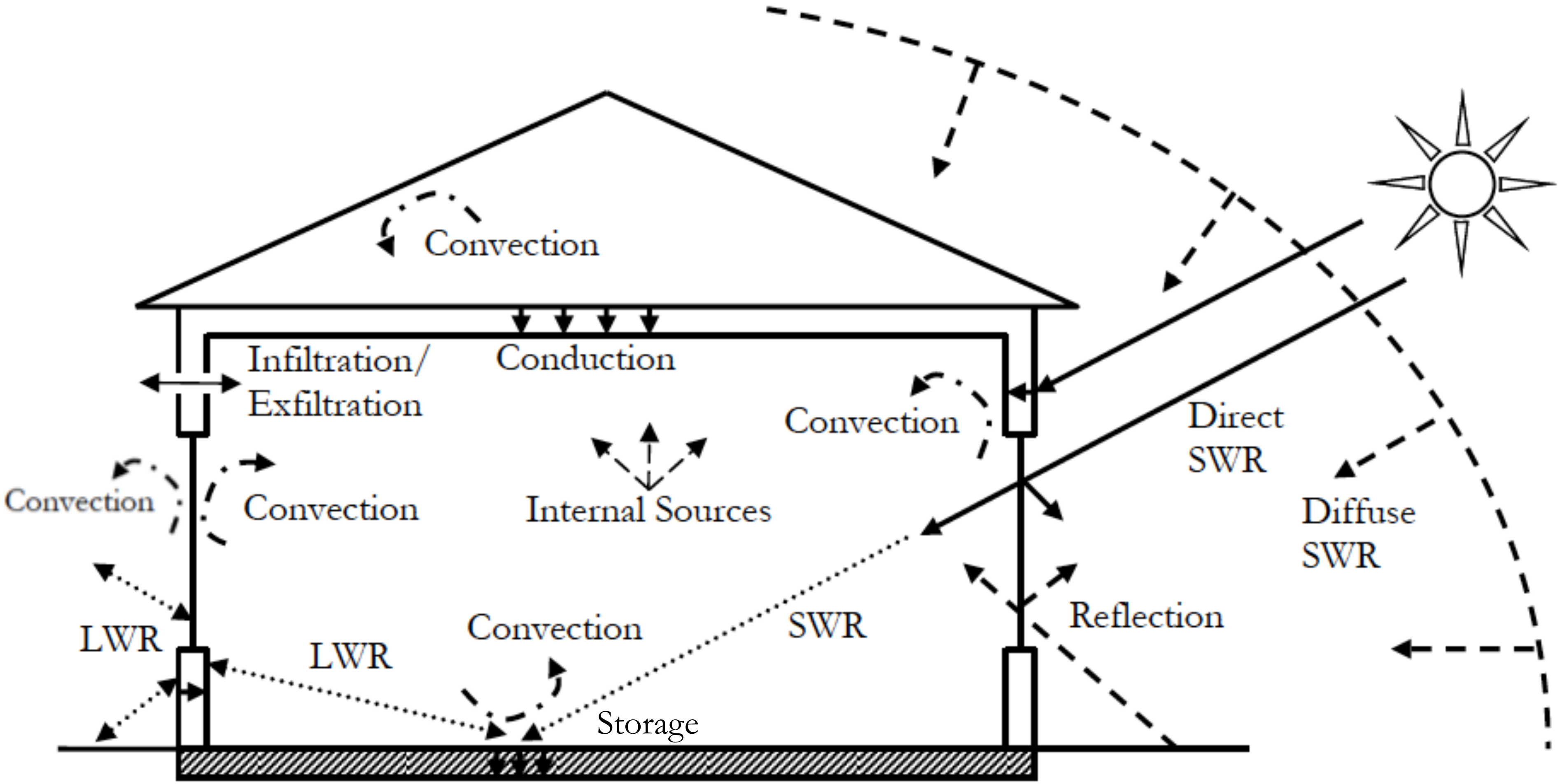
Whole building energy simulation

- We've covered individual **surface energy balances** before
  - Surfaces are all connected

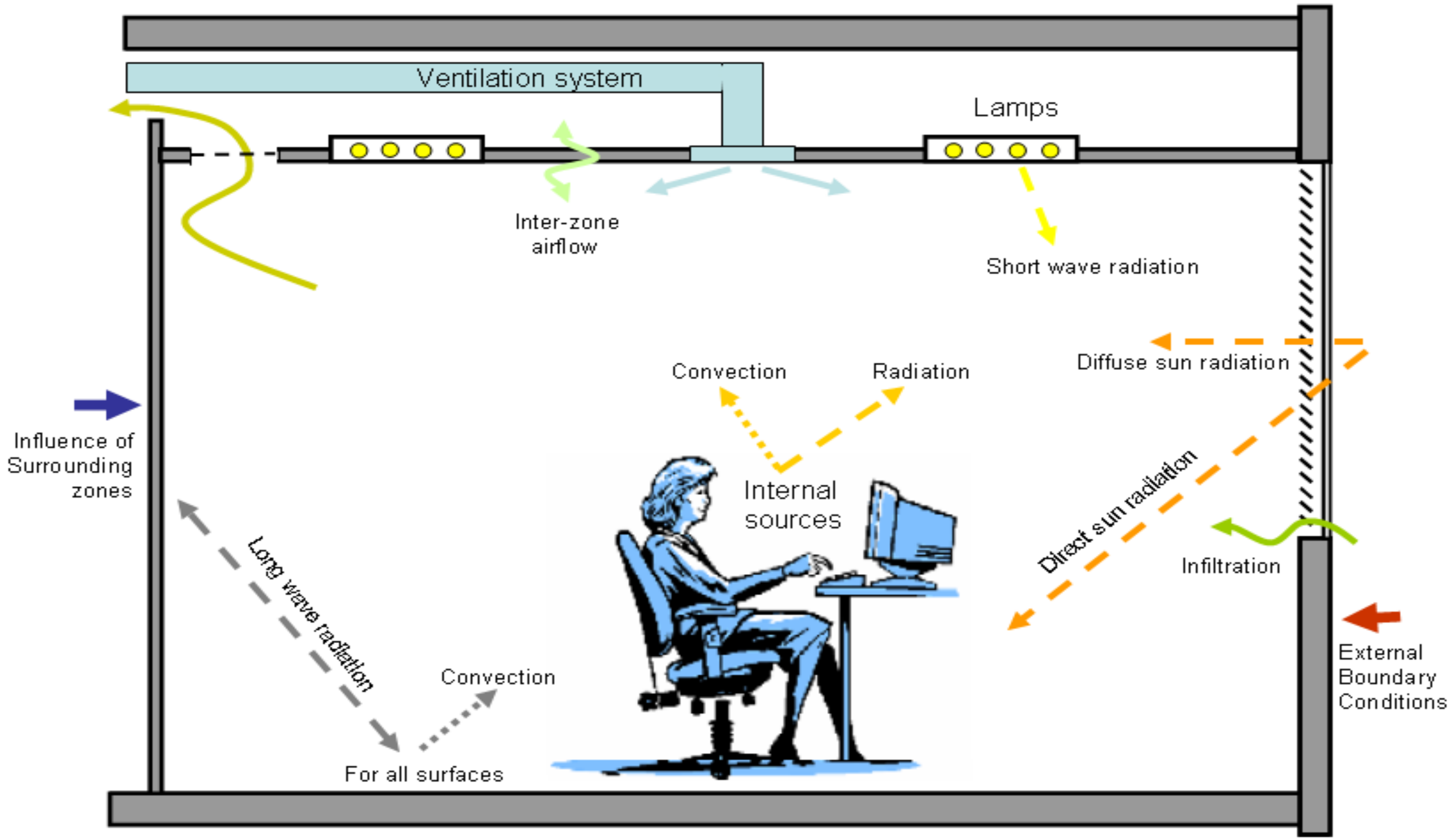
- We can build a **system of equations** linking energy balances at a series of "nodes"
  - Each node has an equation accounting for all modes of heat transfer

- Whole building energy simulation
  - Involves linking the nodes and predicting hourly indoor air temperatures (or HVAC loads) as the primary unknown(s)
    - Include HVAC system capacity and efficiency to get HVAC energy
  - Also includes interior heat gains
    - People, lights, equipment, etc.
    - Direct power draw + indirect heat gains

Whole building energy simulation

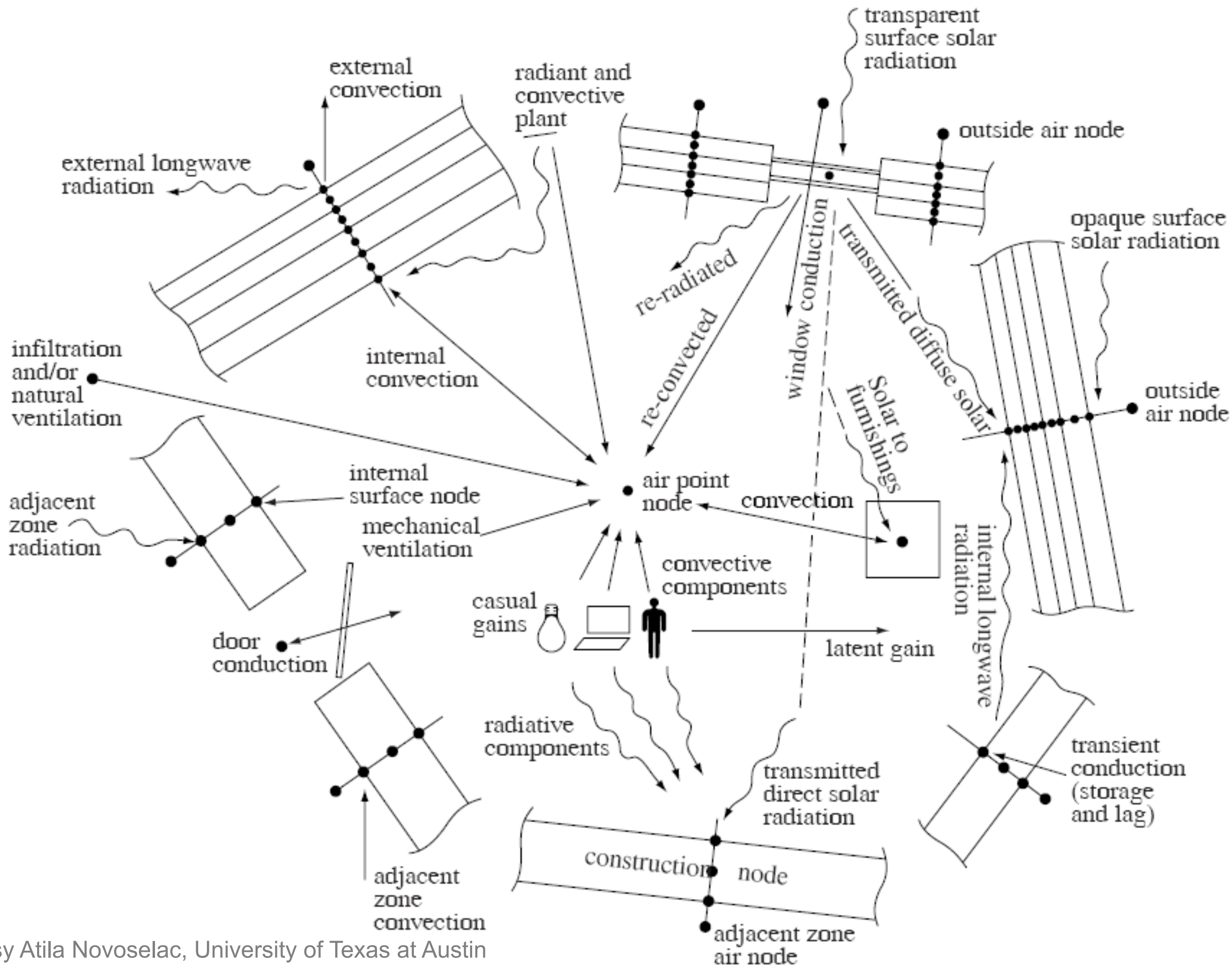


Whole building energy simulation



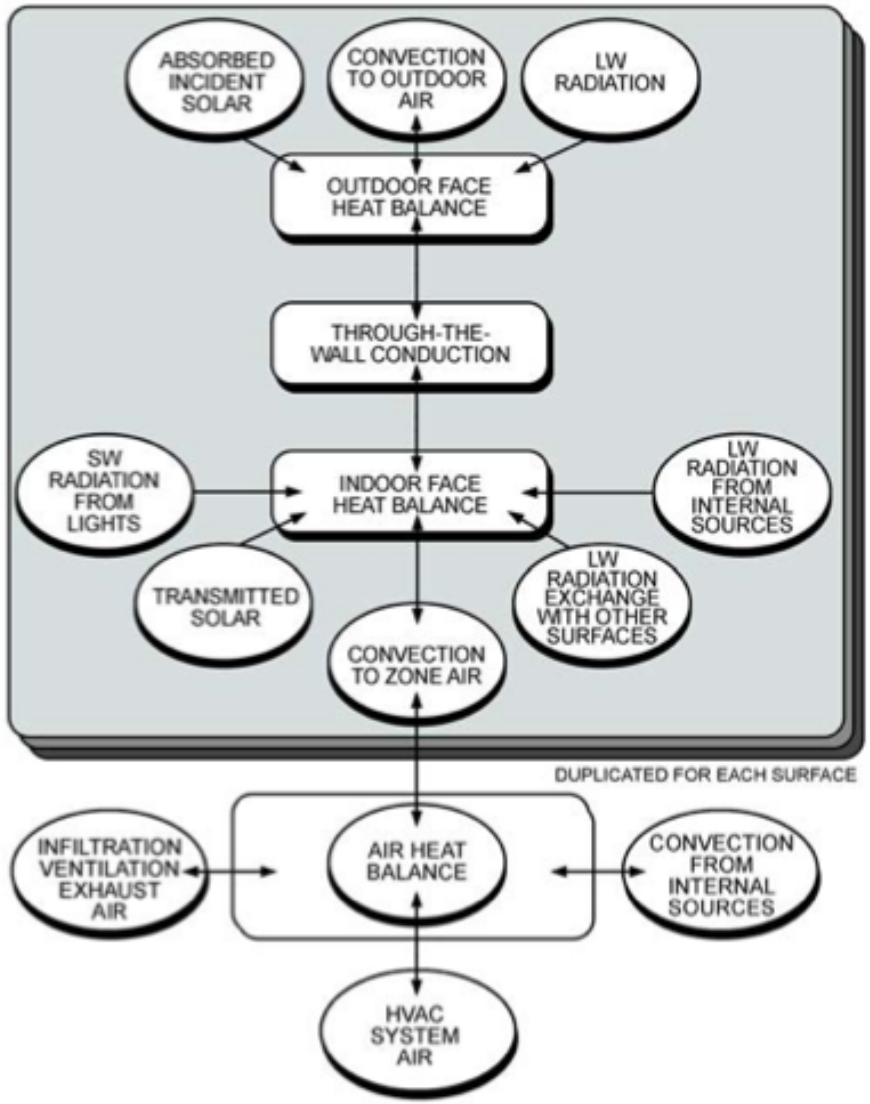
Slide courtesy Atila Novoselac, University of Texas at Austin

Whole building energy simulation



Slide courtesy Atila Novoselac, University of Texas at Austin

Whole building energy simulation

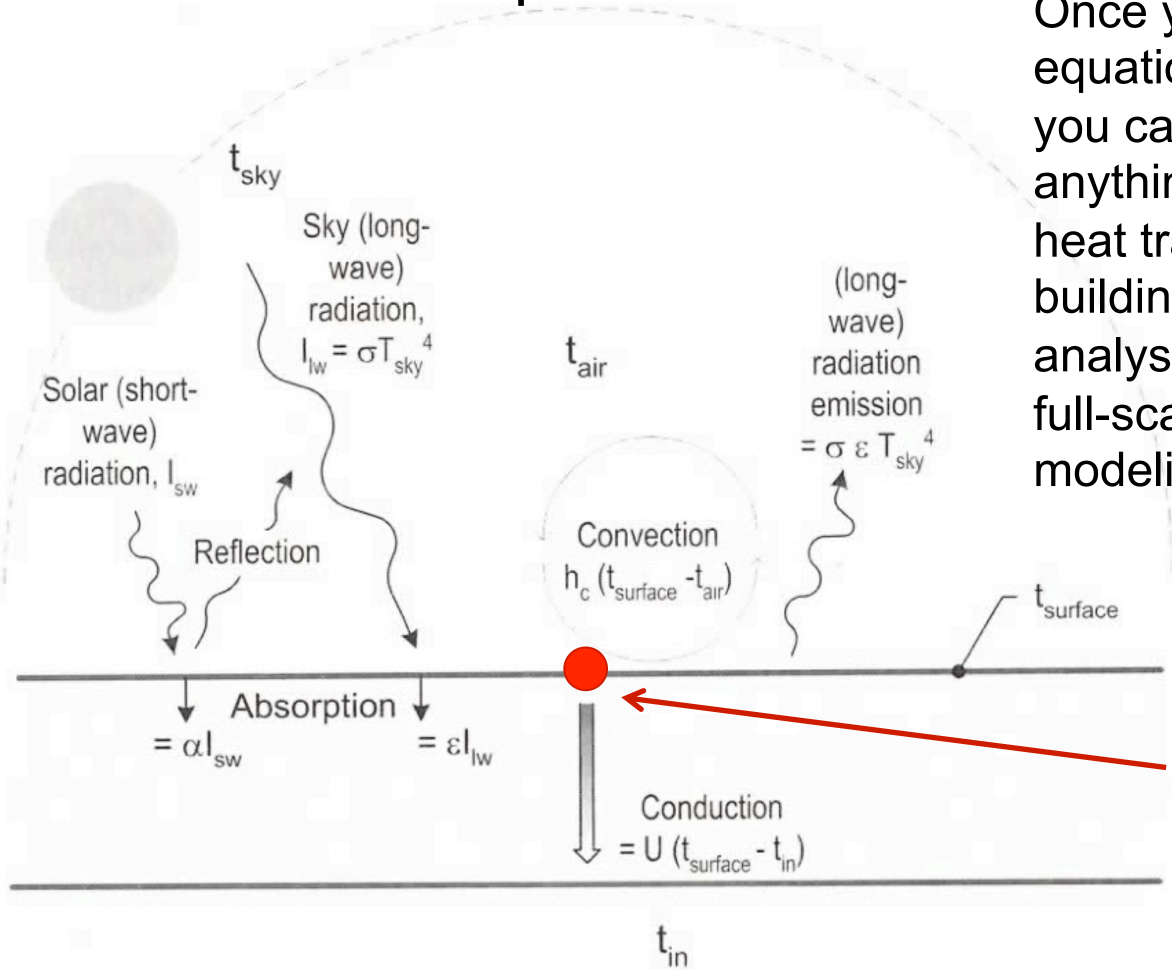


An extension of the Heat Balance Method (HBM)

Surface energy balance: Bringing all the modes together

- 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



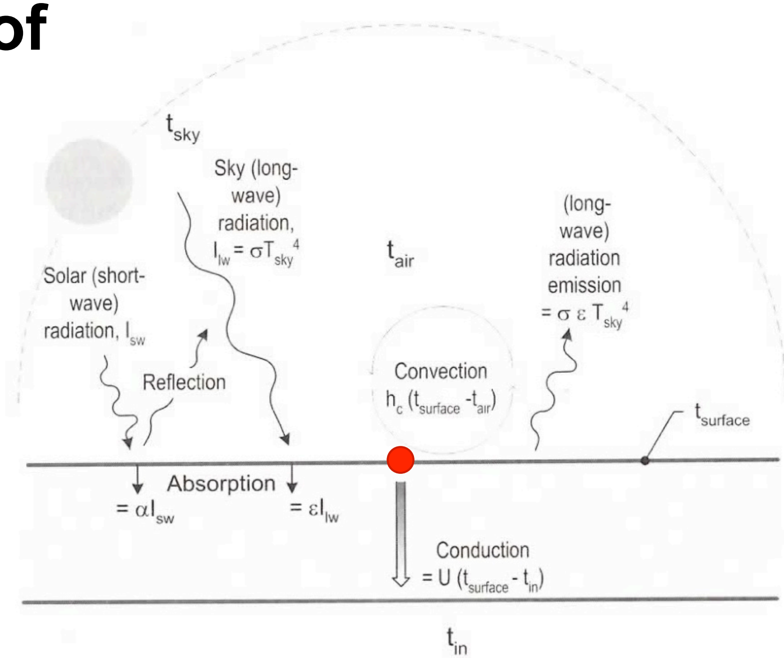
Steady-state energy balance at this exterior surface: What enters must also leave (no storage)

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

Surface energy balance: Bringing all the modes together

- Exterior surface example: **Roof**

$$\boxed{\sum q = 0}$$



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

At steady state, net energy balance is zero

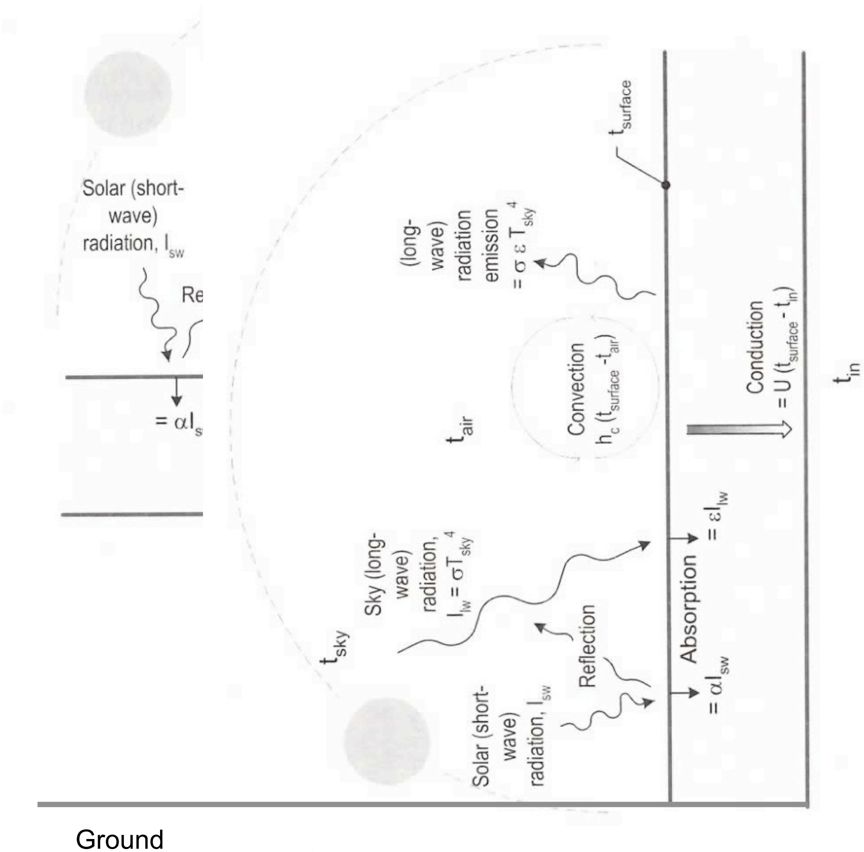
- Because of T^4 term, often requires iteration

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

Surface energy balance: Bringing all the modes together

- Similarly, for a vertical surface:

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

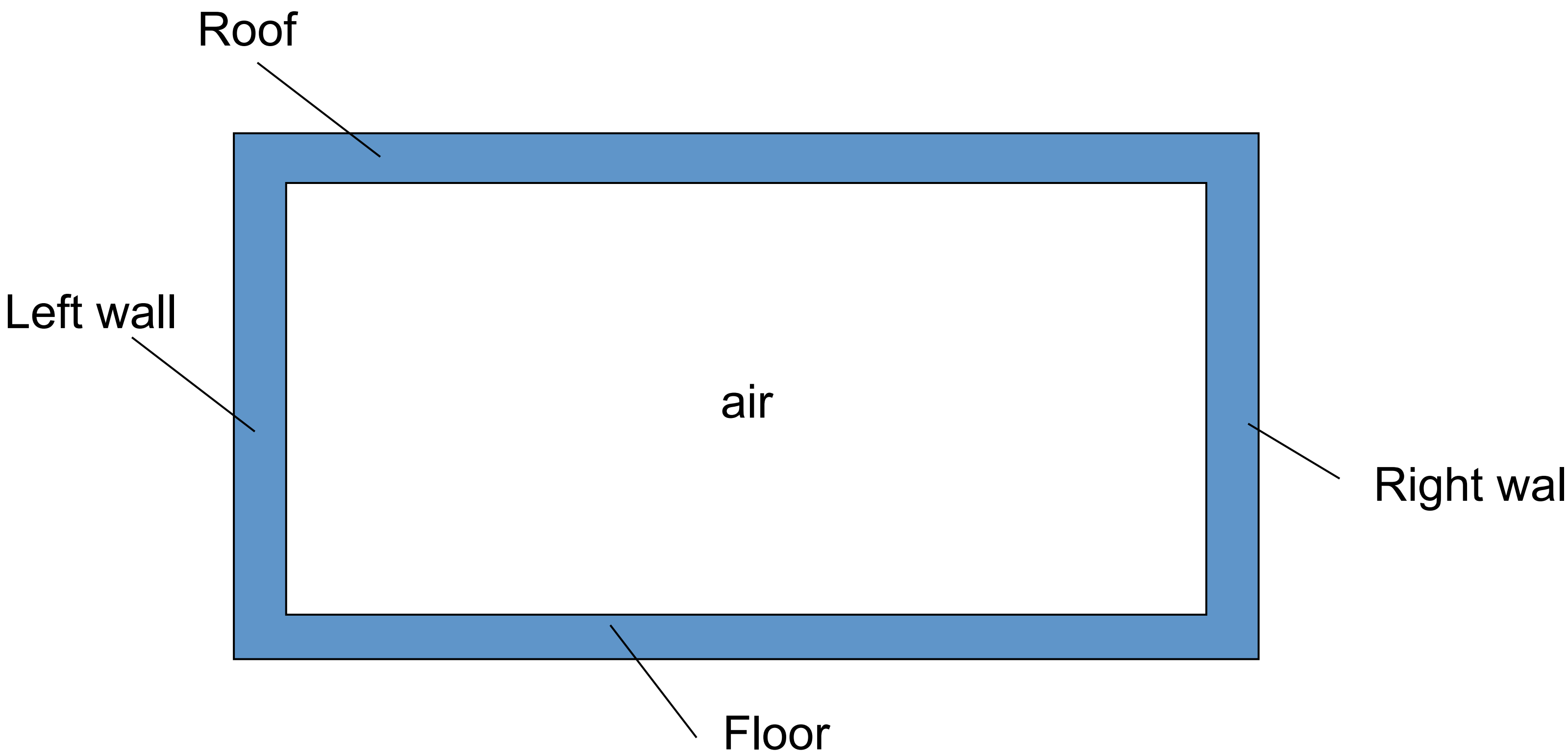


$$\alpha I_{solar}$$
$$+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surface}^4)$$
$$+\varepsilon_{surface}\sigma F_{ground}(T_{ground}^4 - T_{surface}^4)$$
$$+h_{conv}(T_{air} - T_{surface})$$
$$-U(T_{surface} - T_{surface,interior}) = 0$$

Whole building energy modeling steps

- Define the domain
- Analyze the most important phenomena and define the most important elements
- Discretize the elements and define connections
- Write the energy and mass balance equations
  - Include any assumptions for indoor sources
- Solve the equations
  - Use numerical methods or analytical solutions
  - Time-varying analysis over an entire year
- Present the results
  - kWh electricity; BTU or MJ of other fuels
  - Hourly, daily, monthly, yearly

Simplest ‘box’ model



Elements are connected by:

1) Convection – air node
2) Radiation – surface nodes

Slide courtesy Atila Novoselac, University of Texas at Austin

Bringing all modes (and nodes) together

- 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

At surface nodes:

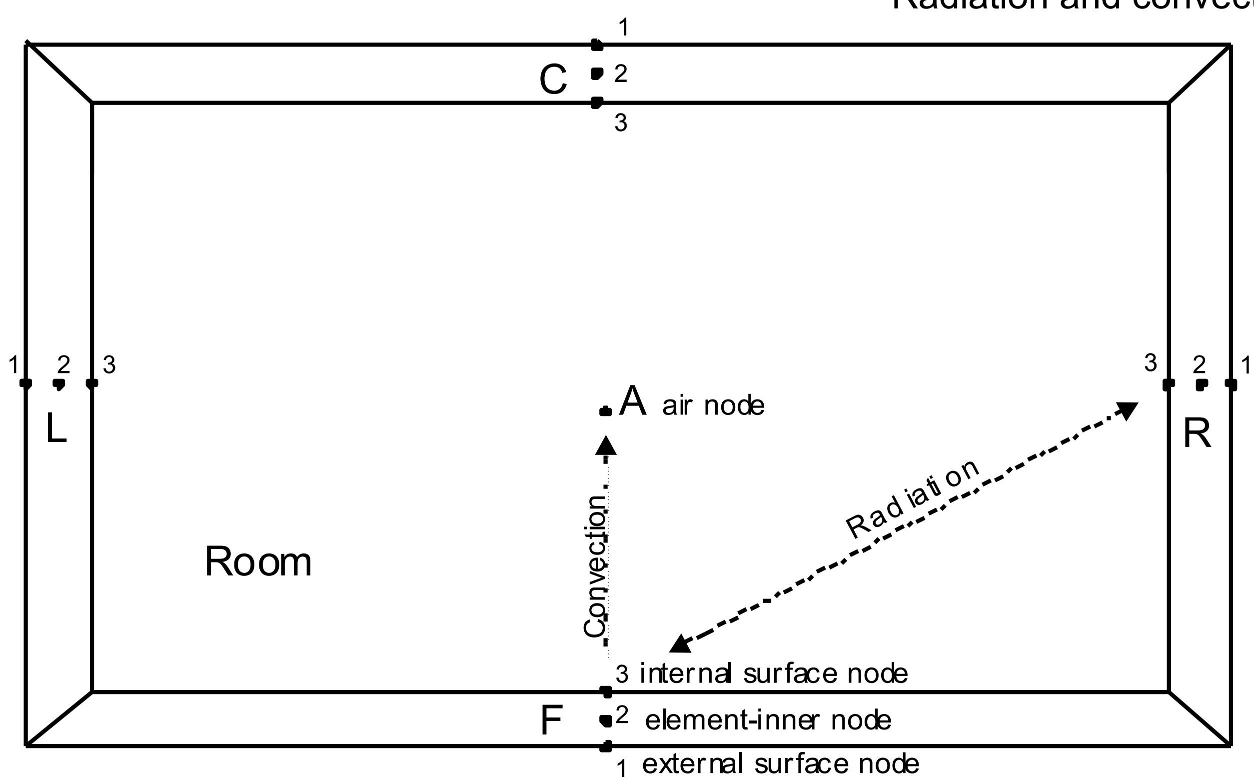
$$\sum q = 0$$

At nodes inside materials:

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

Based on density and heat capacity of material

Heat Xfer @ external surfaces: Radiation and convection

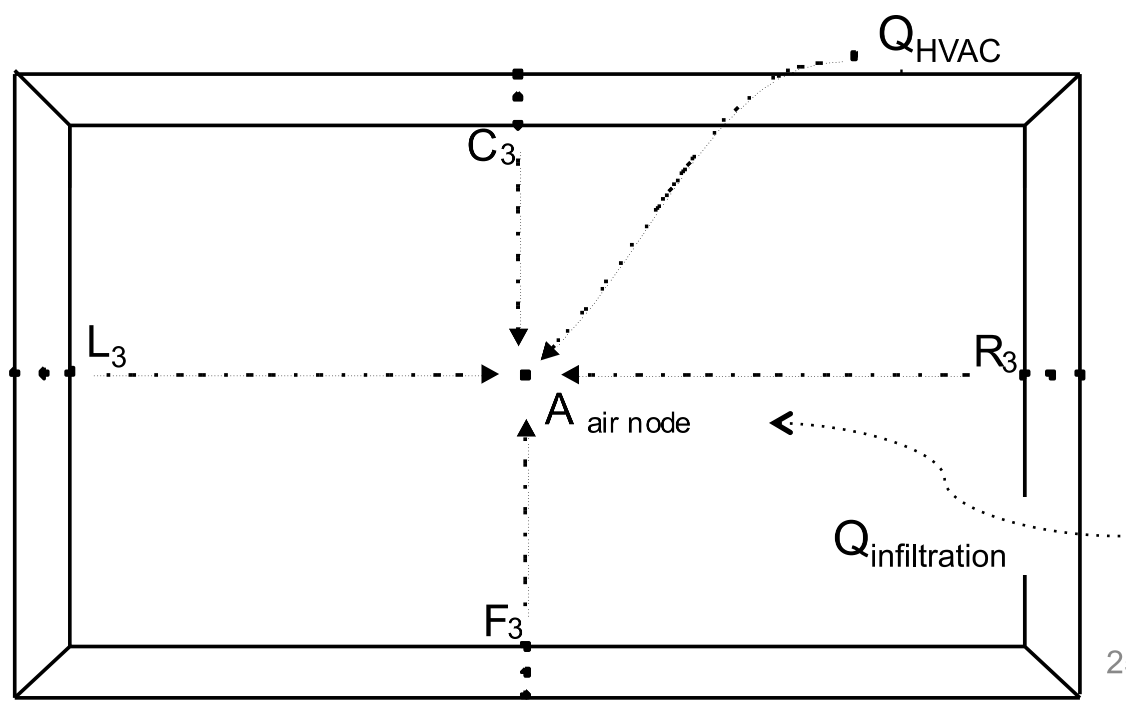


Unsteady energy balance for air node

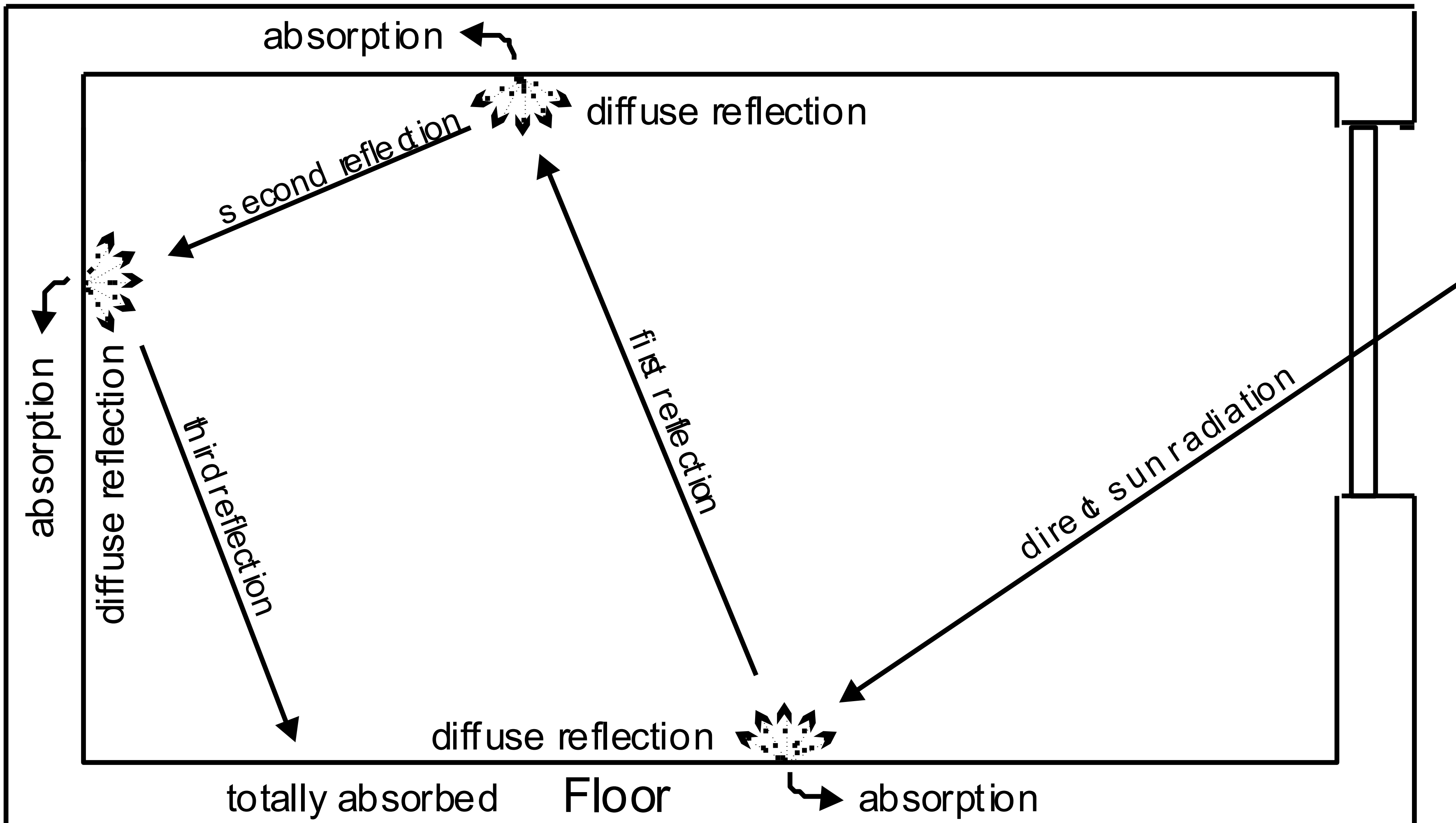
- To get the impact on indoor air temperature (and close the system of equations)
  - Write an energy balance on the indoor air node
  - Air impacted directly only by convection (bulk and surface)

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

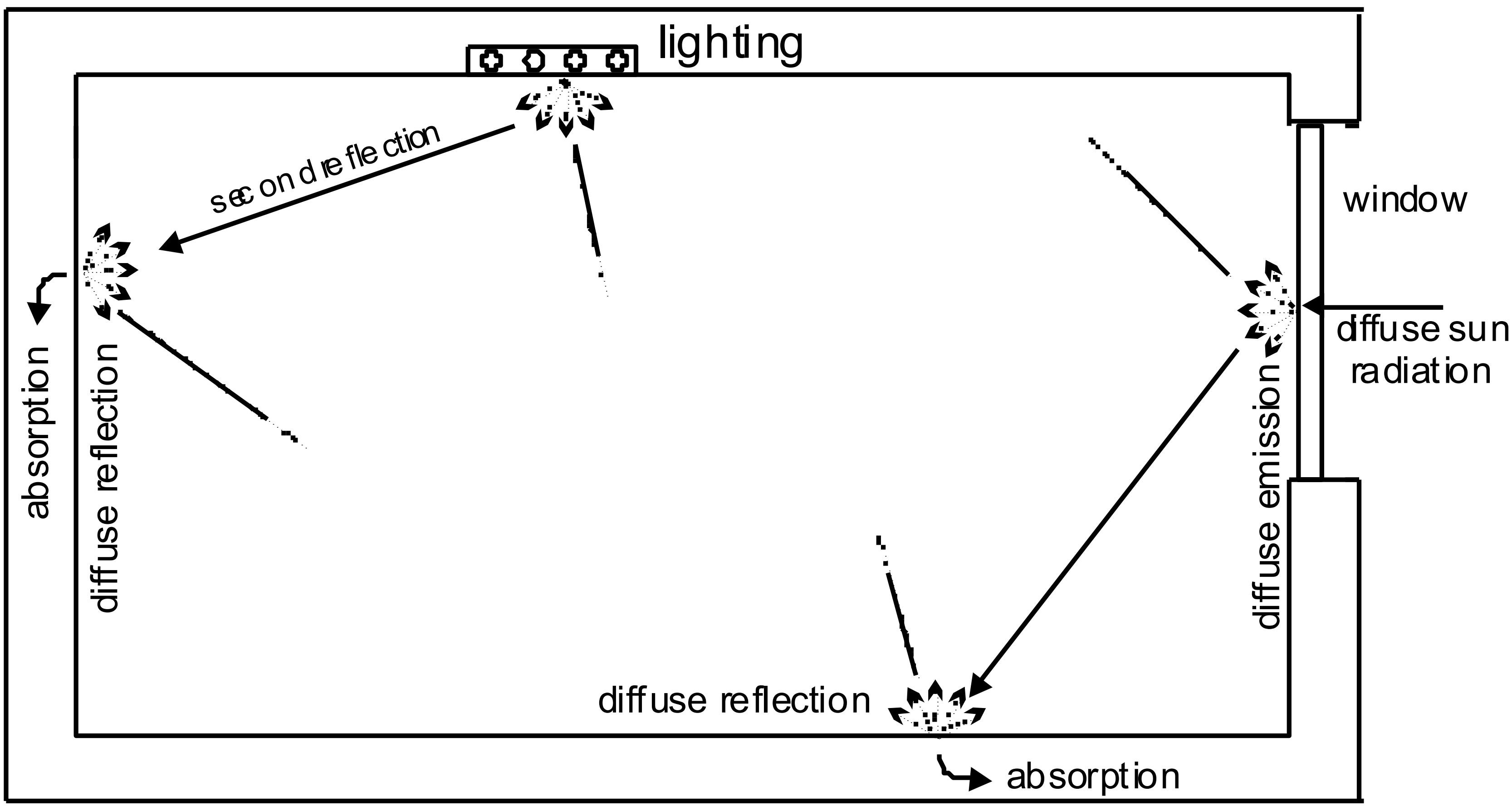
In plain English:
The change in indoor air temperature is equal to the sum of convection from each interior surface plus outdoor air delivery (by infiltration or dedicated outdoor air supply), plus the bulk convective heat transfer delivered by the HVAC system



Adding a window: Direct solar radiation

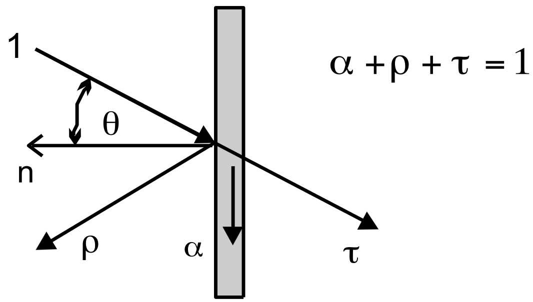


Adding a window: Diffuse solar radiation

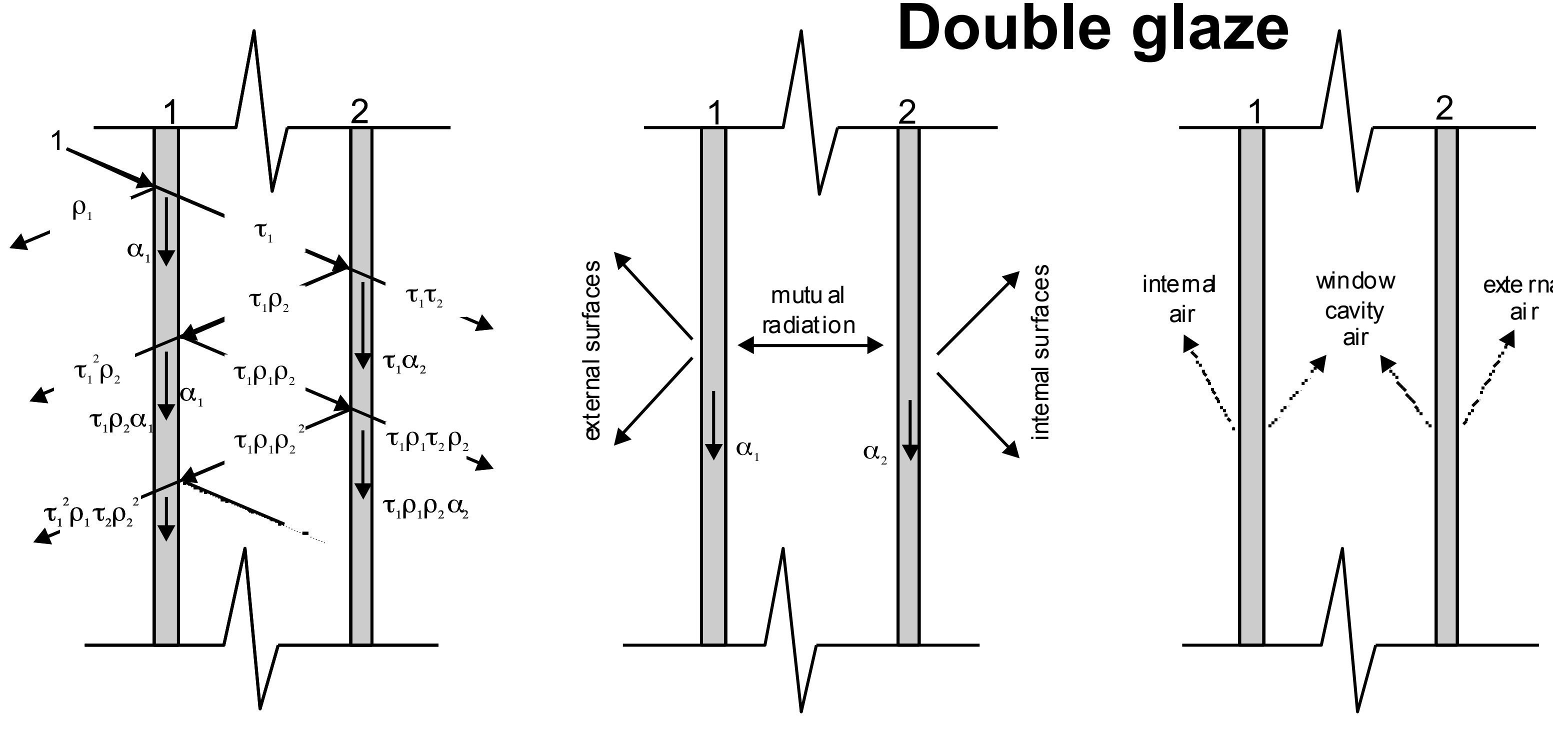


Heat transfer in windows

Single glaze



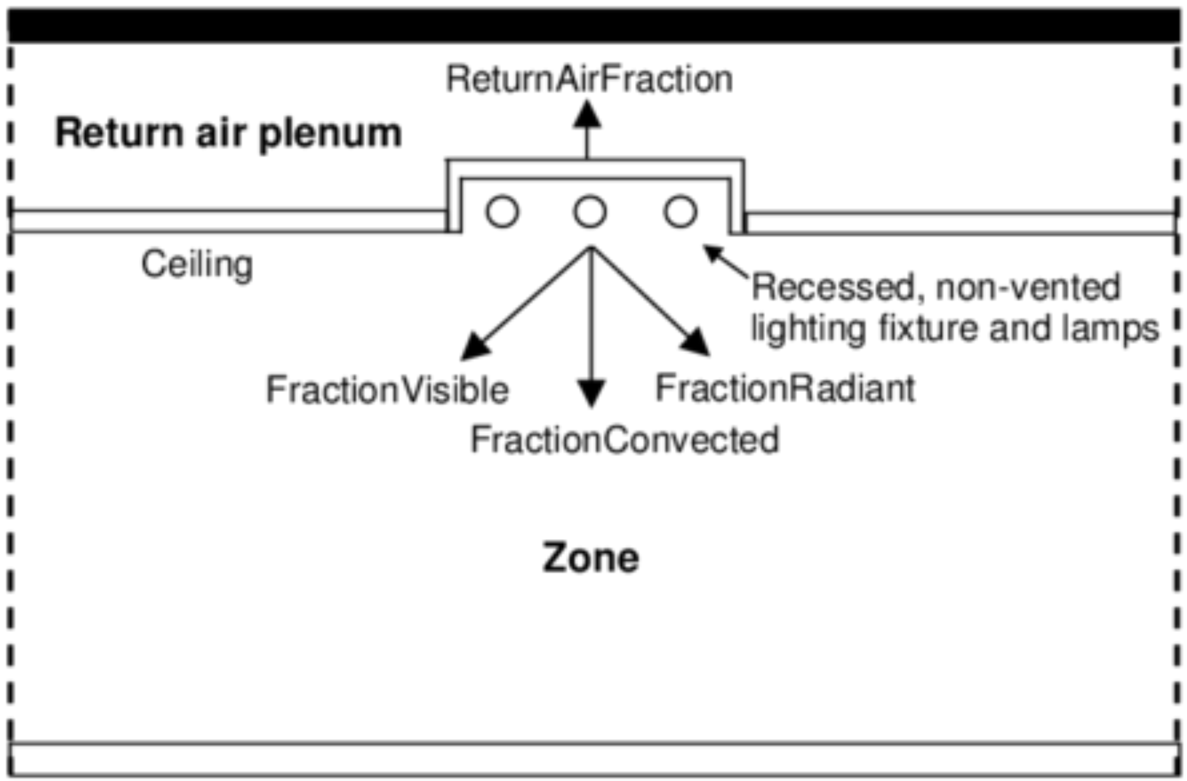
Double glaze



a) Short-wave radiation b) Long-wave radiation c) Convection

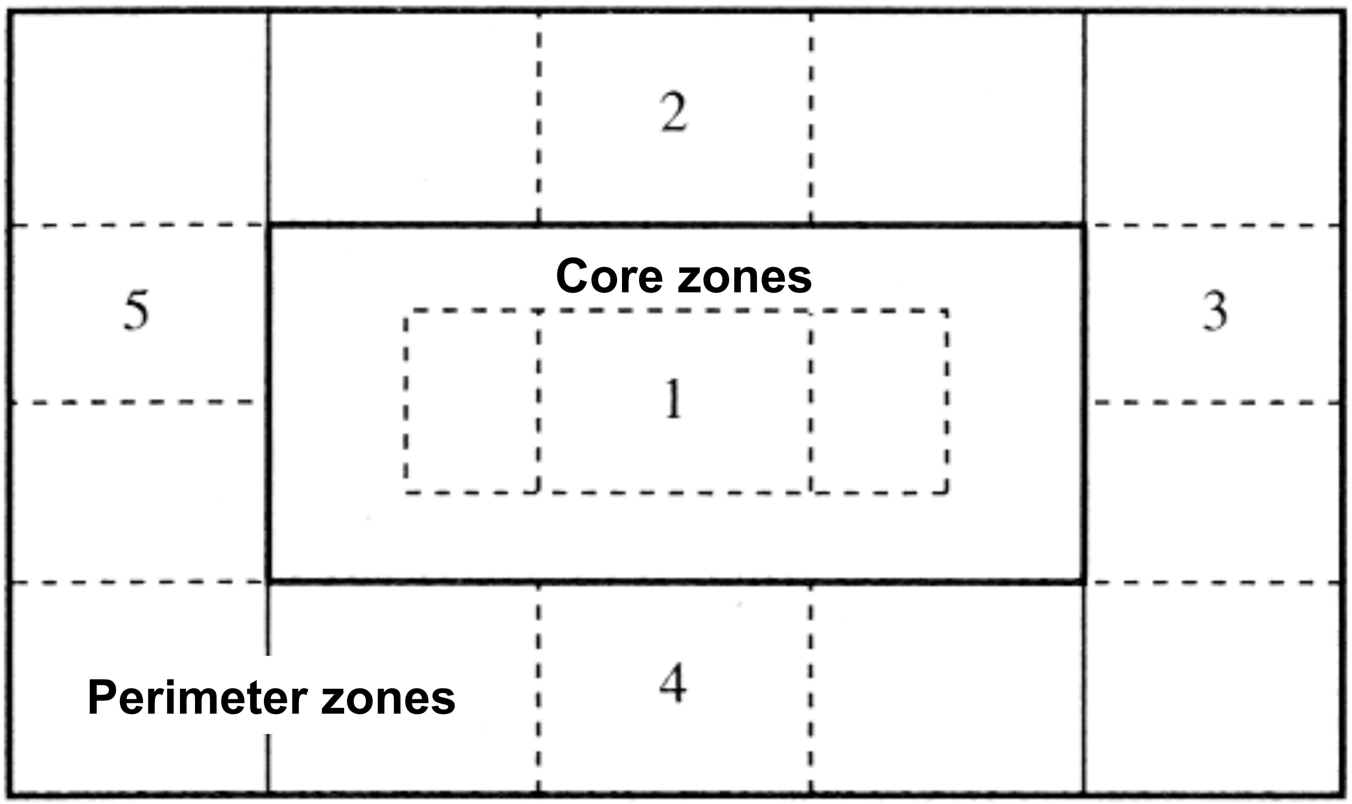
Internal heat sources (e.g., lighting)

- Sources of both convective and radiative heat flux

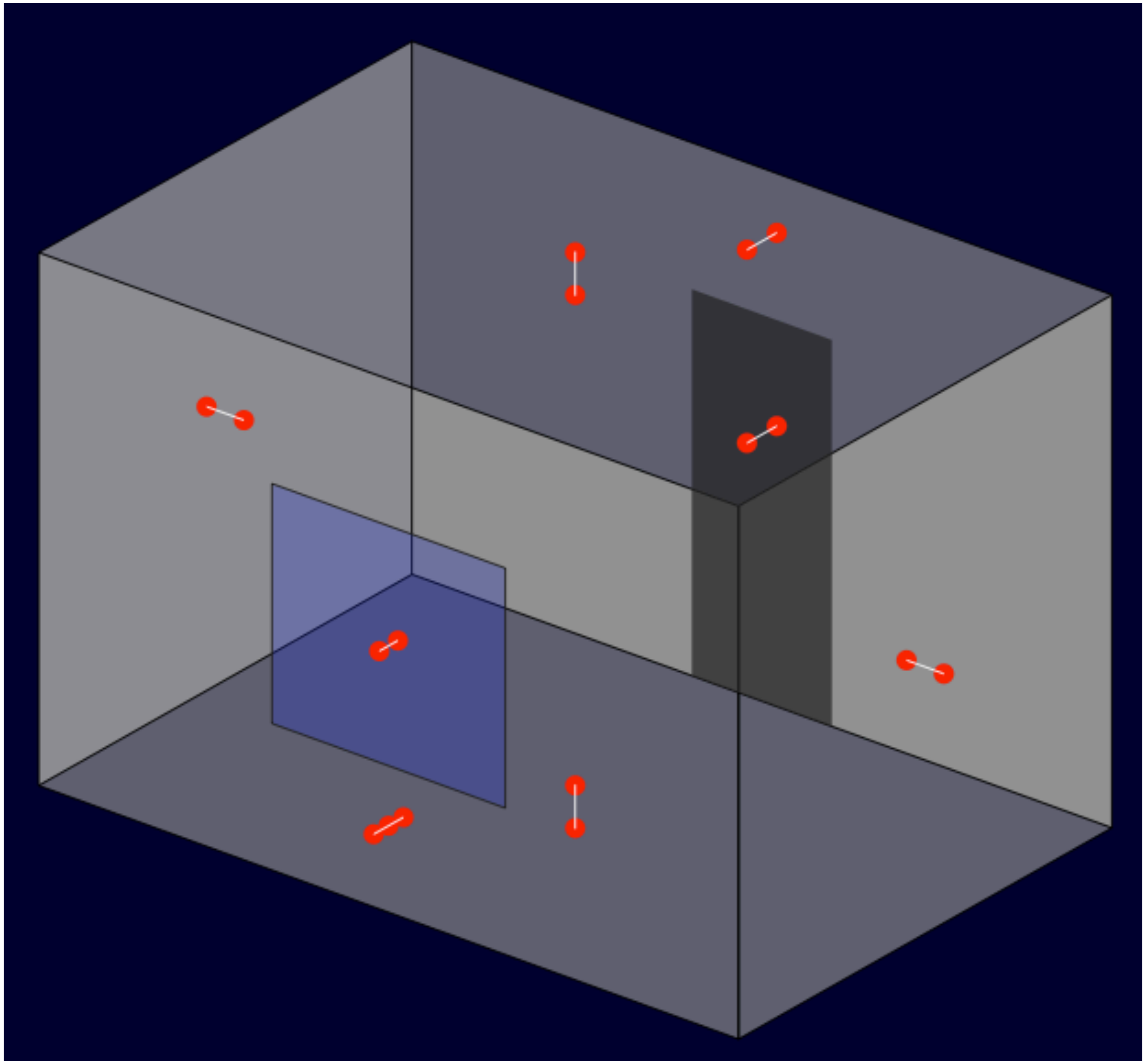


Zoning

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

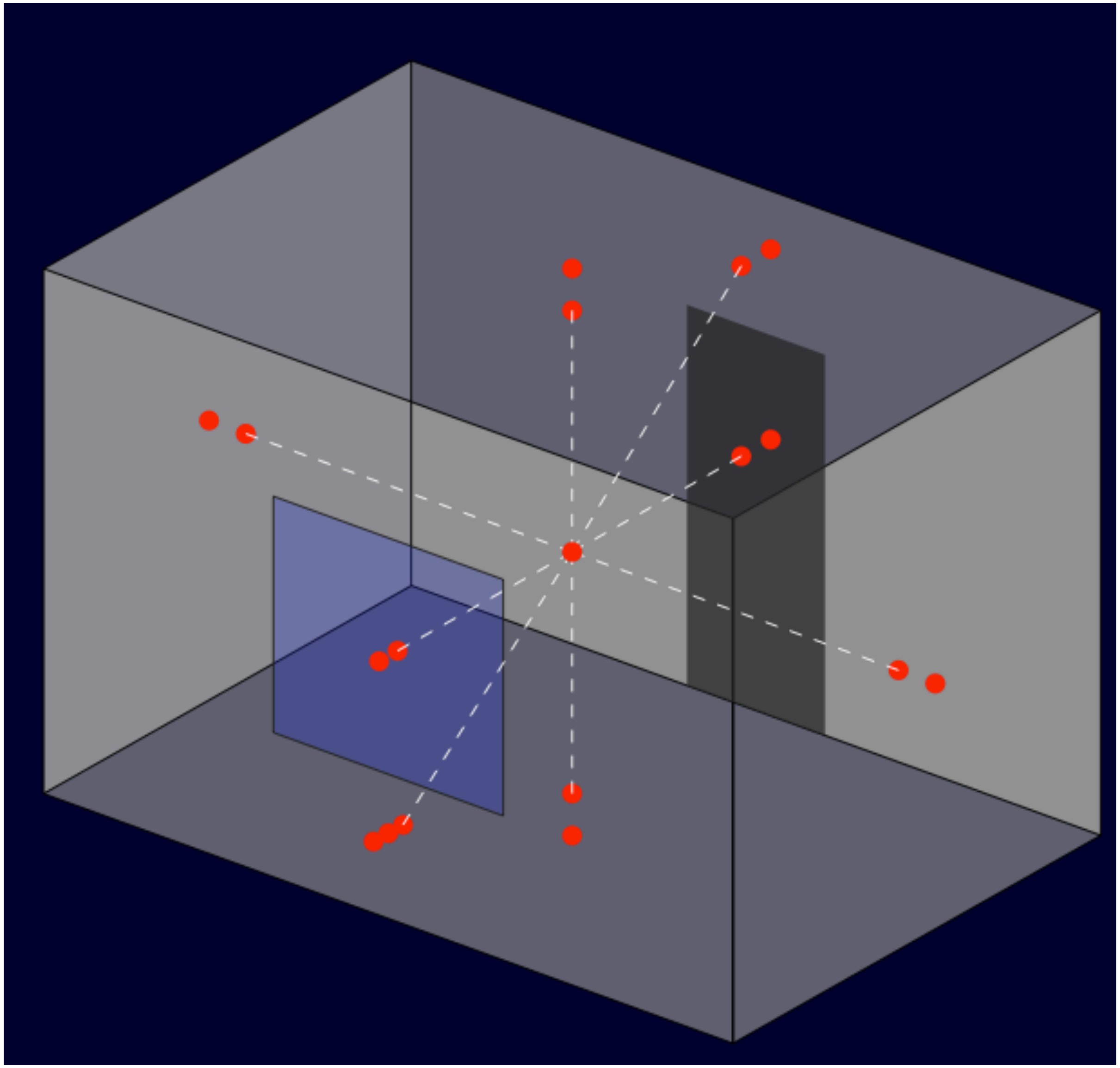


Simplest ‘box’ model: Conduction elements



http://www.ibpsa.us/pub/simbuild2008/presentations/SB08-PPT-IS06-Augenbroe.pdf

Simplest 'box' model: Interior convection elements



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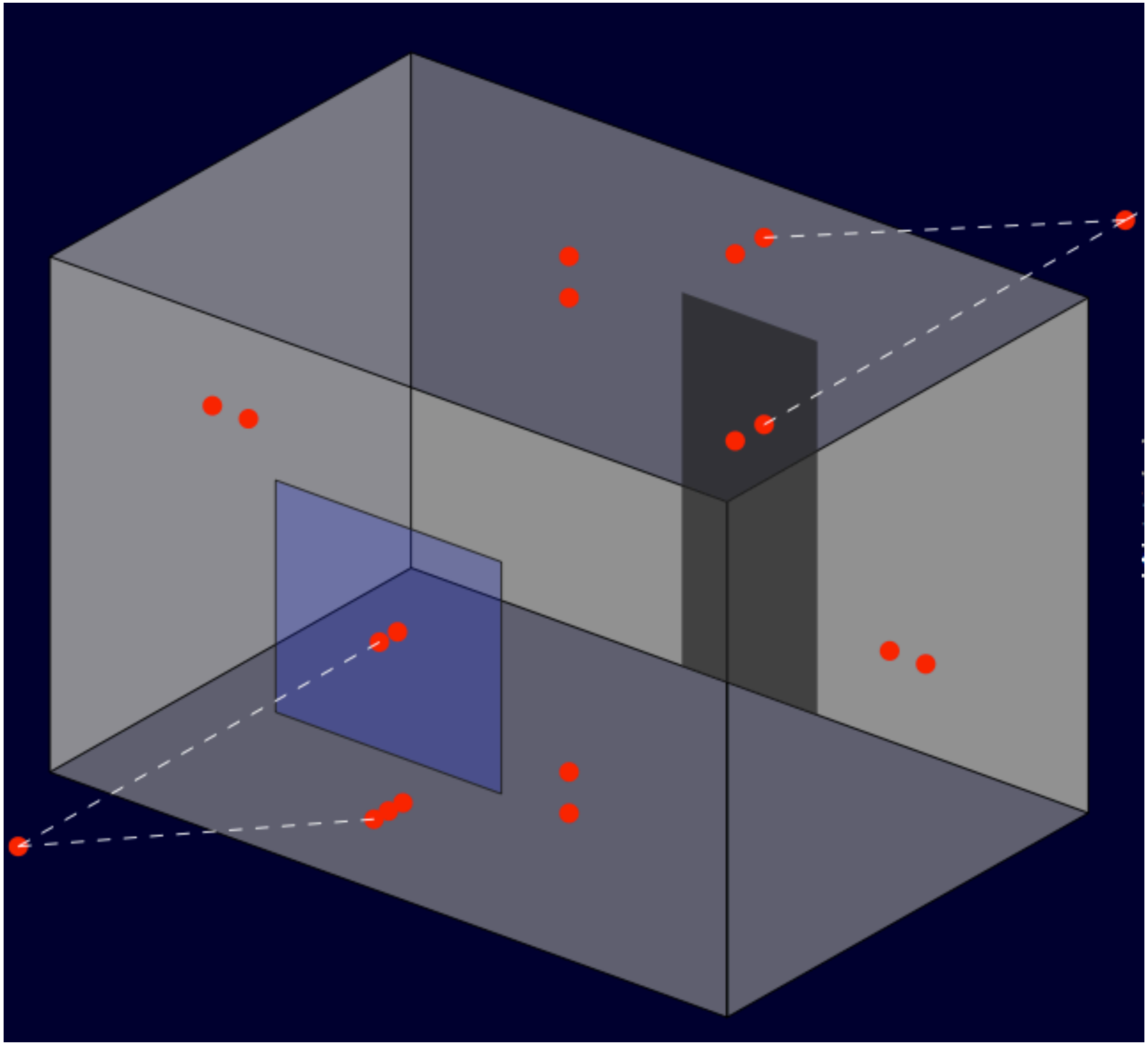
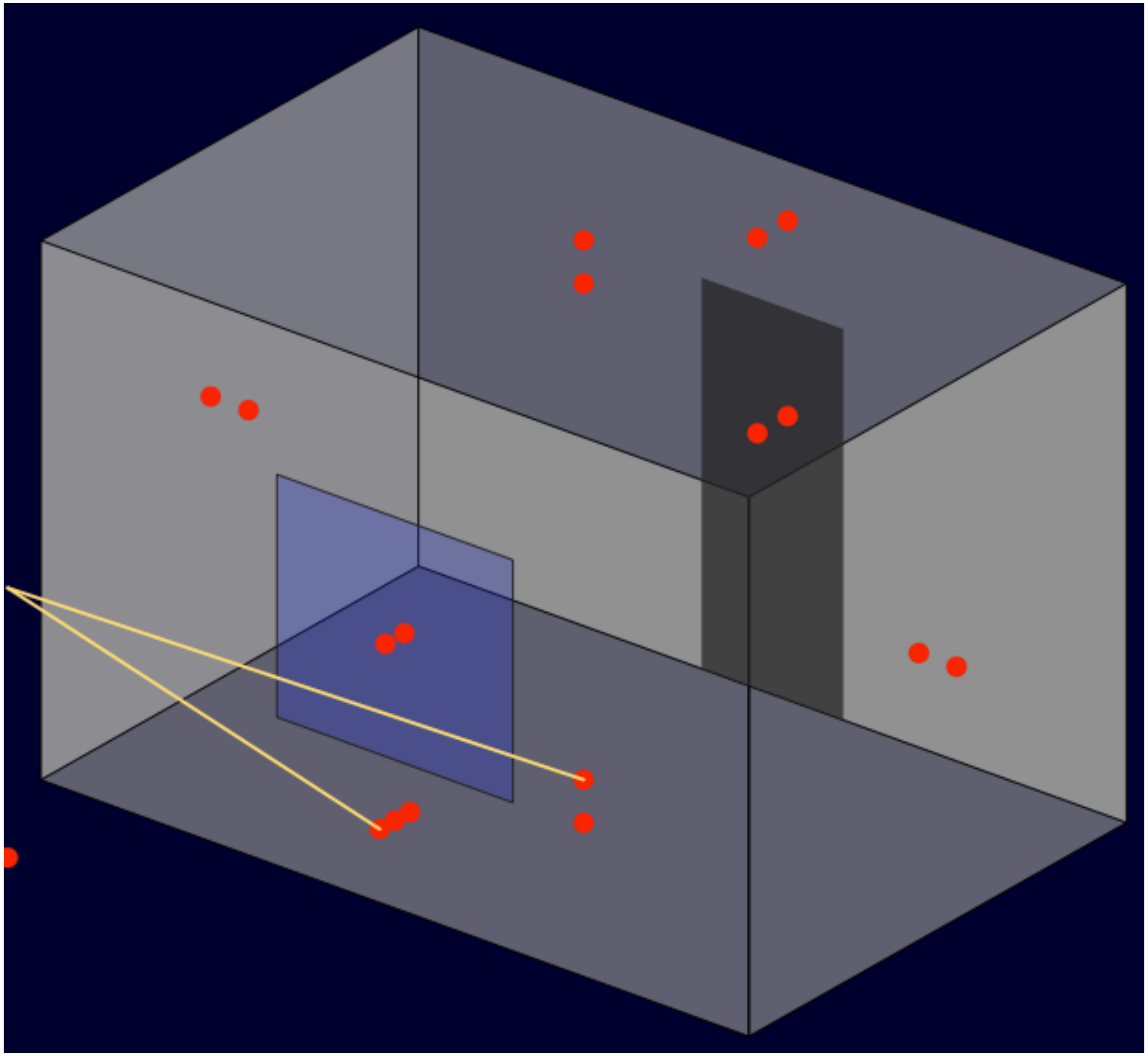
Simplest ‘box’ model: Exterior convection elements



http://www.ibpsa.us/pub/simbuild2008/presentations/SB08-PPT-IS06-Augenbroe.pdf

Simplest ‘box’ model: Solar (direct + diffuse)



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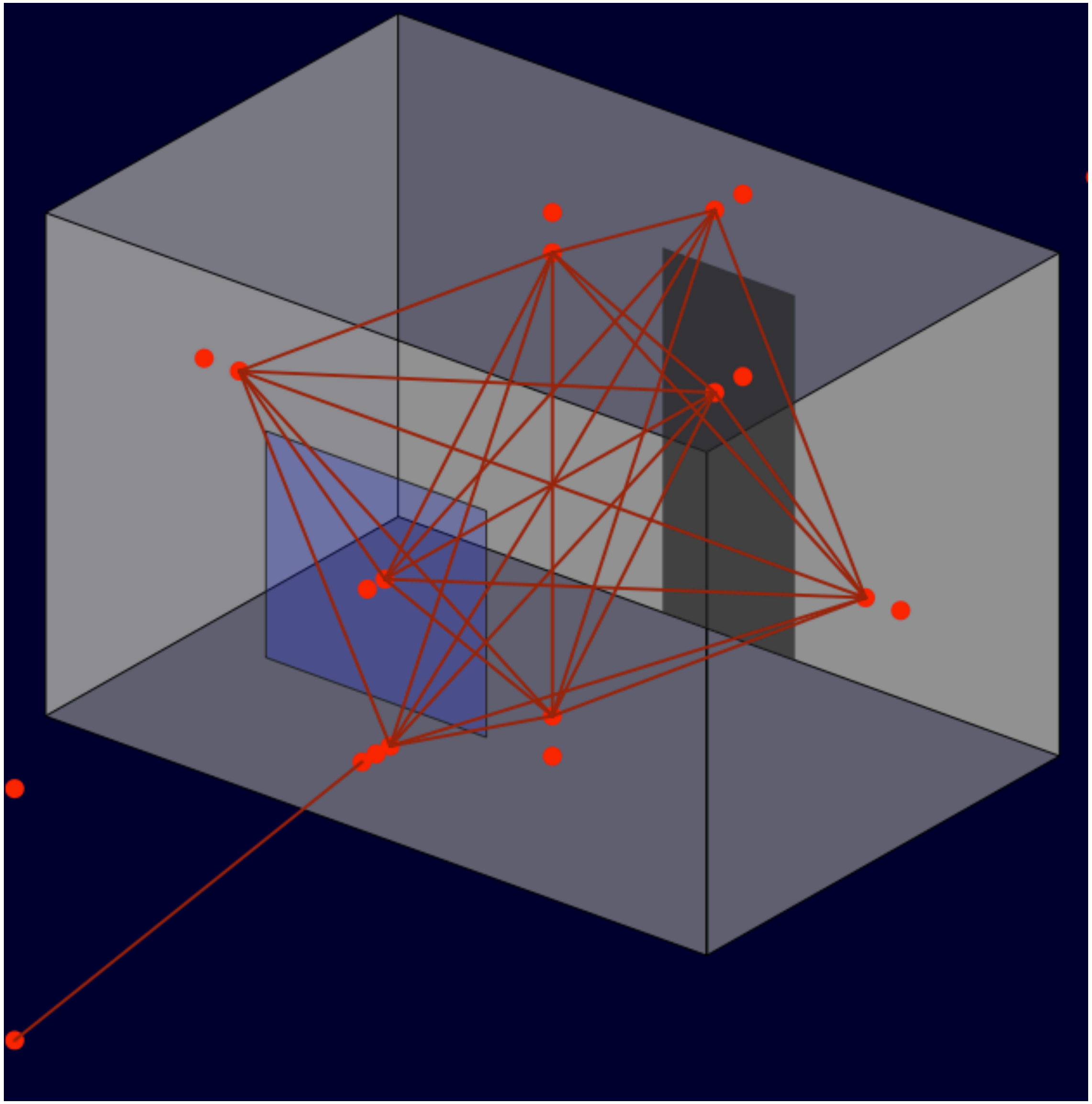
Simplest 'box' model: Long wave radiation elements



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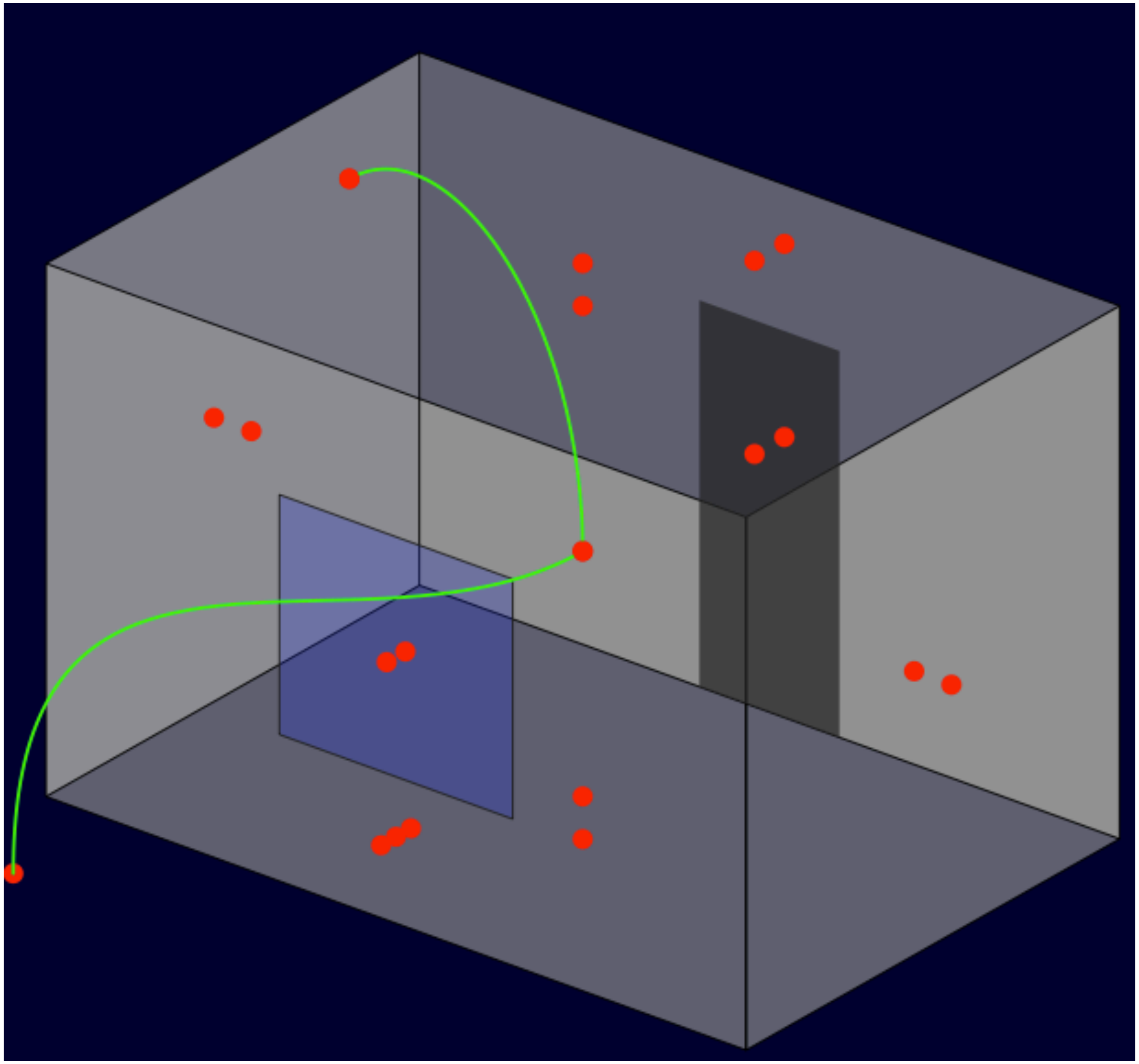
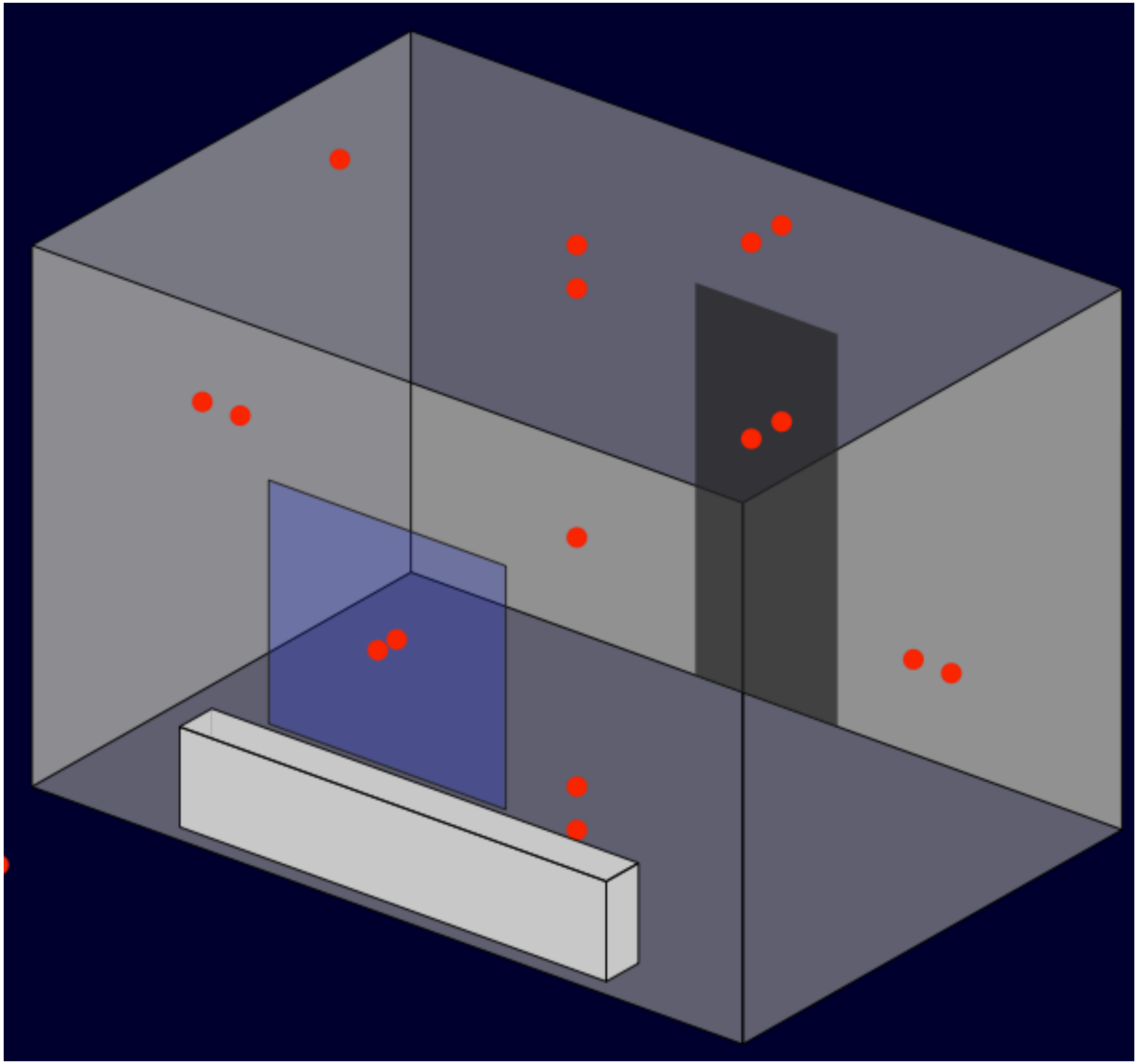
Simplest ‘box’ model: Ventilation/infiltration elements



http://www.ibpsa.us/pub/simbuild2008/presentations/SB08-PPT-IS06-Augenbroe.pdf

Simplest ‘box’ model: Internal mass (e.g., furniture)



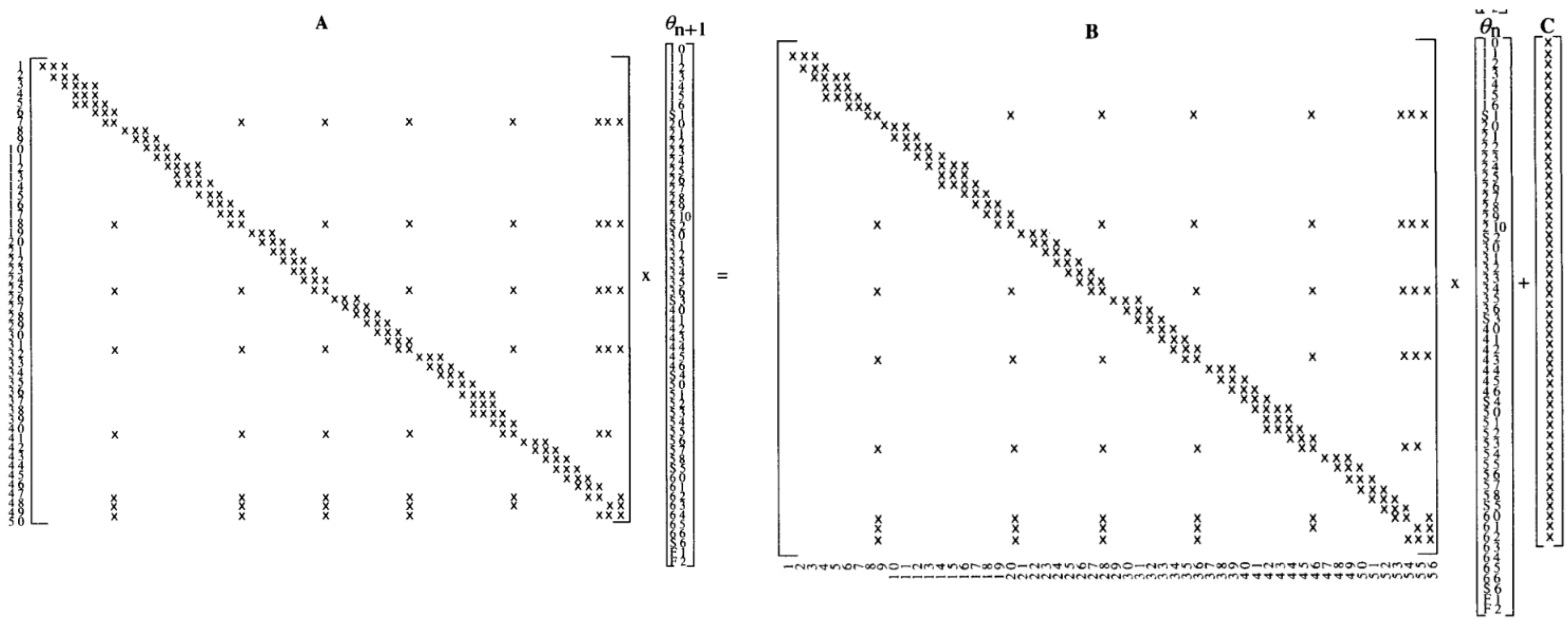
http://www.ibpsa.us/pub/simbuild2008/presentations/SB08-PPT-IS06-Augenbroe.pdf

Solving the system of equations

In matrix notation, the system of equations can be expressed as

$$\mathbf{A}\theta_{n+1} = \mathbf{B}\theta_n + \mathbf{C} = \mathbf{Z} \tag{4.1}$$

where **A** is a sparse matrix of future time-row coefficients of the nodal temperature or heat injection terms of the conservation equations, **B** the corresponding matrix established at the present time-row, **C** a column matrix of known boundary excitations relating to the present and future time-rows, θ a column matrix of nodal temperatures and heat injections, $n+1$ refers to the future time-row, n the present time-row, and **Z** is a column matrix. Initial conditions are given by $\theta(0) = \theta_0$.



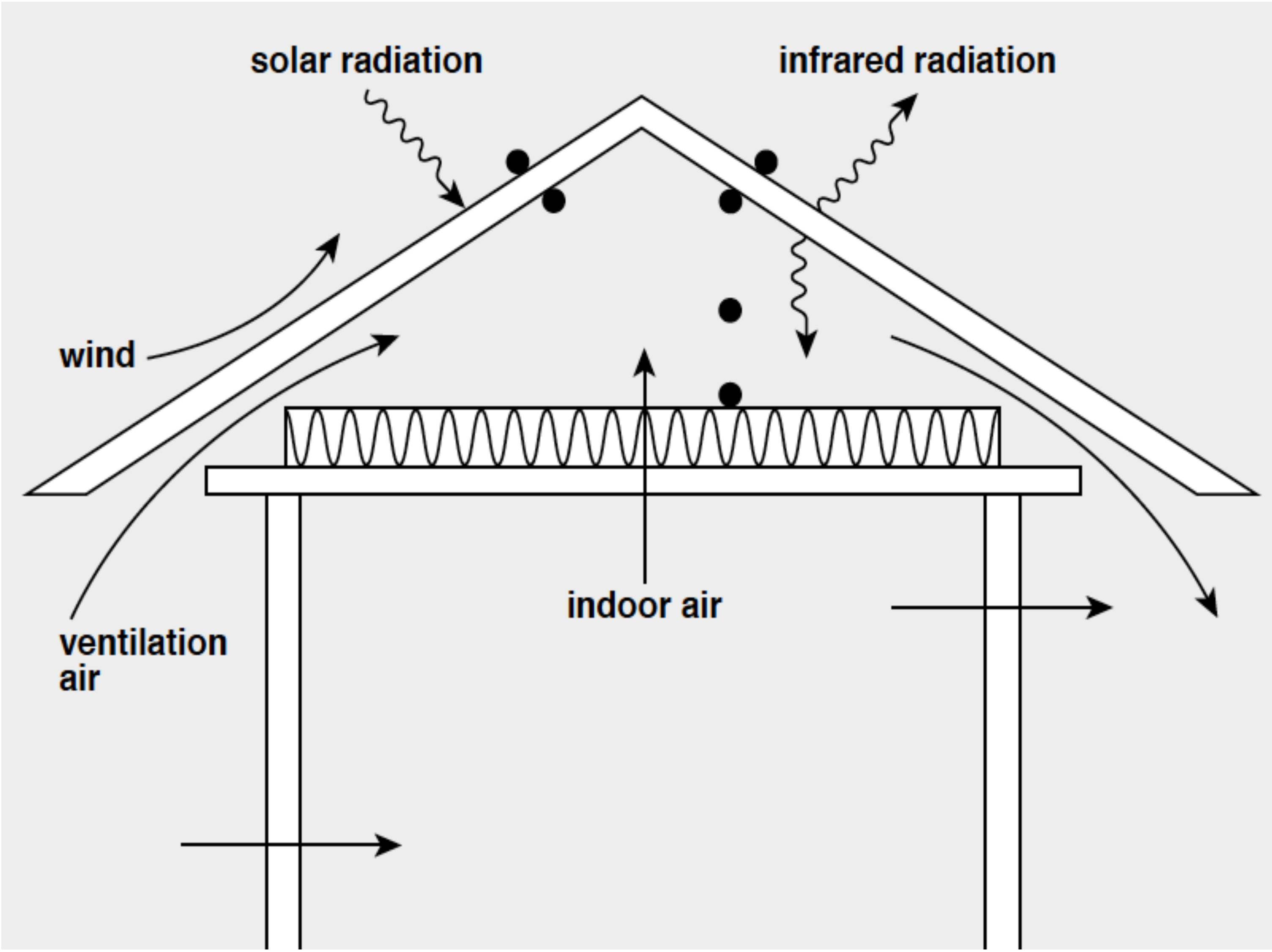
Clarke 2001 *Energy Simulation in Building Design*

Important input parameters for energy simulation

- Conduction (and storage) solution method
  - Finite difference (explicit, implicit)
  - Response functions techniques
- Time steps
  - Too short and calculations take forever
  - Too long and solutions diverge
- Meteorological data (TMY, AMY)
  - Temperature, wind speed, solar radiation, cloud cover
- Radiation and convection models
  - Internal and external
- Windows and shading
- Air infiltration models
- Conduction to the ground
- HVAC system and control models

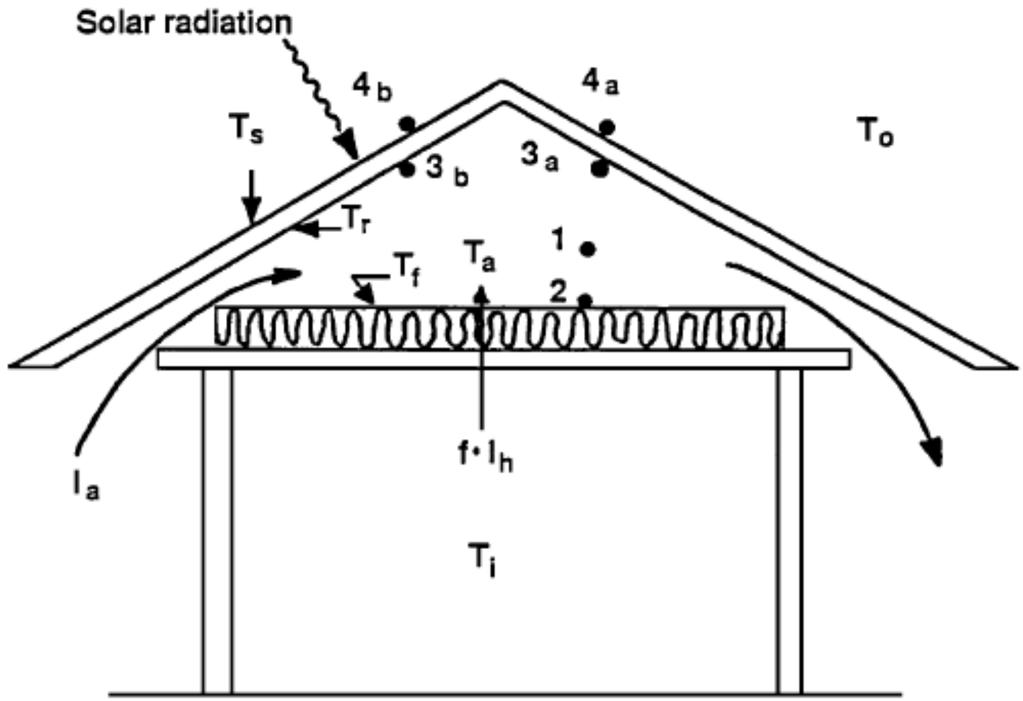
BUILDING ENERGY SIMULATION EXAMPLE: ATTIC HEAT TRANSFER

Attic simulation example



TenWolde, Anton. 1997. FPL roof temperature and moisture model: Description and verification. Res. Pap. FPL–RP–561. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 48 p.

Attic heat transfer



● Nodes for heat balance

T_a, T_i, T_f, T_o, T_r, T_s Temperatures of attic, indoor air, attic floor outside air, underside of roof, surface of roof

f Fraction of air entering attic

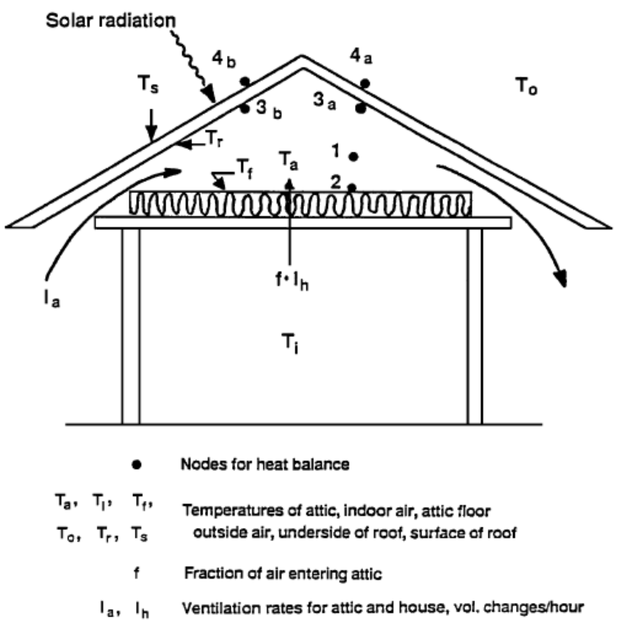
I_a, I_h Ventilation rates for attic and house, vol. changes/hour

TenWolde, Anton. 1997. FPL roof temperature and moisture model: Description and verification. Res. Pap. FPL–RP–561. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 48 p.

Attic heat transfer

Attic Air—The heat balance for the attic air (node 1) is given by

$$A_c h_f (T_f - T_a) + f I_h V_h \rho C_p (T_i - T_a)$$
$$= \frac{A_r}{2} h_{r,1}(T_a - T_{r,1}) + \frac{A_r}{2} h_{r,2}(T_a - T_{r,2}) + \frac{A_{es}}{R_{es}}(T_a - T_o)$$
$$+ I_a \rho C_p V_a (T_a - T_o)$$



where

- A_c, A_r, A_{es} = surface areas of ceiling, total roof area, and combined area of soffit and end walls (ft^2)
- C_p = specific heat of air (Btu/lb·°F)
- f = fraction of house exfiltration that transfers into attic
- h_f, $h_{r,n}$ = convective heat transfer coefficients at attic floor and underside of roof (surface n), respectively (Btu/h·ft^2·°F)
- I_h = house exfiltration rate (h^{-1})
- I_a = attic ventilation rate, i.e., outdoor air entering attic (h^{-1})
- $R_{e,s}$ = average thermal resistance of end walls and eaves (h·ft^2·°F/Btu)
- T_a = attic air temperature (°R)
- T_f = temperature of attic floor surface (°R)
- T_i = indoor air temperature (°R)
- T_o = outdoor air temperature (°R)
- $T_{r,1}$ = temperature of roof sheathing underside a (°R)
- $T_{r,2}$ = temperature of roof sheathing underside b (°R)
- V_a = volume of attic space (ft^3)
- V_h = volume of house (ft^3)
- ρ = density of air (lb/ft^3)

TenWolde, Anton. 1997. FPL roof temperature and moisture model: Description and verification. Res. Pap. FPL–RP–561. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 48 p.

Attic heat transfer

Attic Floor—The heat balance for the attic floor (node 2) is

$$\frac{T_\mathrm{i} - T_\mathrm{f}}{R_\mathrm{c}} = h_\mathrm{f}(T_\mathrm{f} - T_\mathrm{a}) + \frac{F_1}{2}(T_\mathrm{f} - T_{\mathrm{r},1}) + \frac{F_2}{2}(T_\mathrm{f} - T_{\mathrm{r},2}) \qquad (3)$$

where

R_c = thermal resistance of attic floor (ceiling) (h·ft^2·°F/Btu)

F_1, F_2 = radiative heat transfer coefficients between attic floor and undersides of roof (Btu/h·ft^2·°F), with the following definition:

$$F_n = \frac{\sigma}{(1/\varepsilon_\mathrm{f}) + (1/\varepsilon_\mathrm{r}) - 1}(T_\mathrm{f}^2 + T_{\mathrm{r},n}^2)(T_\mathrm{f} + T_{\mathrm{r},n}) \quad n = 1,2$$

where

ε_f = emissivity of attic floor surface (assumed to be 0.9)

ε_r = emissivity of roof sheathing surface (underside, assumed to be 0.9)

σ = Stefan–Boltzman constant (Btu/h·ft^2·°R^4)

TenWolde, Anton. 1997. FPL roof temperature and moisture model: Description and verification. Res. Pap. FPL–RP–561. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 48 p.

Attic heat transfer

Sheathing—The heat balance at the underside of sheathing (nodes 3a and 3b) is

$$\frac{T_{r,n} - T_{s,n}}{R_r} = h_r(T_a - T_{r,n}) + \frac{A_c}{A_r}F_n(T_f - T_{r,n}) + \frac{2}{A_r}L_h W_{r,n} \quad n = 1,2 \tag{5}$$

where

L_h = latent heat of vaporization (1,050 Btu/lb)
R_r = thermal resistance of roof (h·ft^2·°F/Btu)
$T_{s,n}$ = temperature of outside roof surface (°R)
$W_{r,n}$ = rate of moisture adsorption into sheathing (lb/h)

TenWolde, Anton. 1997. FPL roof temperature and moisture model: Description and verification. Res. Pap. FPL–RP–561. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 48 p.

Attic heat transfer

The heat balance at the top surface of sheathing (nodes 4a and 4b) is

$$\frac{T_{s,n} - T_{r,n}}{R_r} = \alpha I_n + (h_{o,n} + h_{IR})(T_o - T_{s,n}) - L_{IR} \qquad n = 1,2 \qquad (6)$$

where

h_{IR}, L_{IR} = adjustments for infrared radiation exchange with sky (see Eqs. (7), (8), and (9))

$h_{o,n}$ = convective heat transfer coefficient at exterior roof surface n (Btu/h·ft^2·°F)

I_n = total solar radiation incident on roof surface (Btu/h·ft^2)

α = solar absorptance

TenWolde, Anton. 1997. FPL roof temperature and moisture model: Description and verification. Res. Pap. FPL–RP–561. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 48 p.

Attic heat transfer

$$h_{IR} = 4\varepsilon_s \sigma T_o^3 \qquad (7)$$

$$L_{IR} = \varepsilon_s \sigma T_o^4 (1 - \varepsilon_{IR}) \qquad (8)$$

where

ε_s = emissivity of roof shingles (assumed to be 0.9)

ε_{IR} = sky emissivity with clouds

The sky emissivity is calculated with equations from Martin and Berdahl (1984). The emissivity for a clear sky is

$$\varepsilon_0 = 0.711 + 0.56 \frac{T_d}{100} + 0.73 \left(\frac{T_d}{100} \right)^2 + 0.013 \cos \left(\frac{2\pi t}{24} \right) \qquad (9)$$

where

ε_0 = emissivity of clear sky

T_d = outdoor dew point temperature (°C)

t = time (h)

and the emissivity of the sky with clouds is

$$\varepsilon_{IR} = \varepsilon_0 + 0.784C(1 - \varepsilon_0) \qquad (10)$$

where C = total cloud cover as recorded by National Climatic Center (Asheville, NC). Values of C range from 0 to 10.

TenWolde, Anton. 1997. FPL roof temperature and moisture model: Description and verification. Res. Pap. FPL–RP–561. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 48 p.

Attic heat transfer

Sheathing surface temperature: Measured vs. modeled

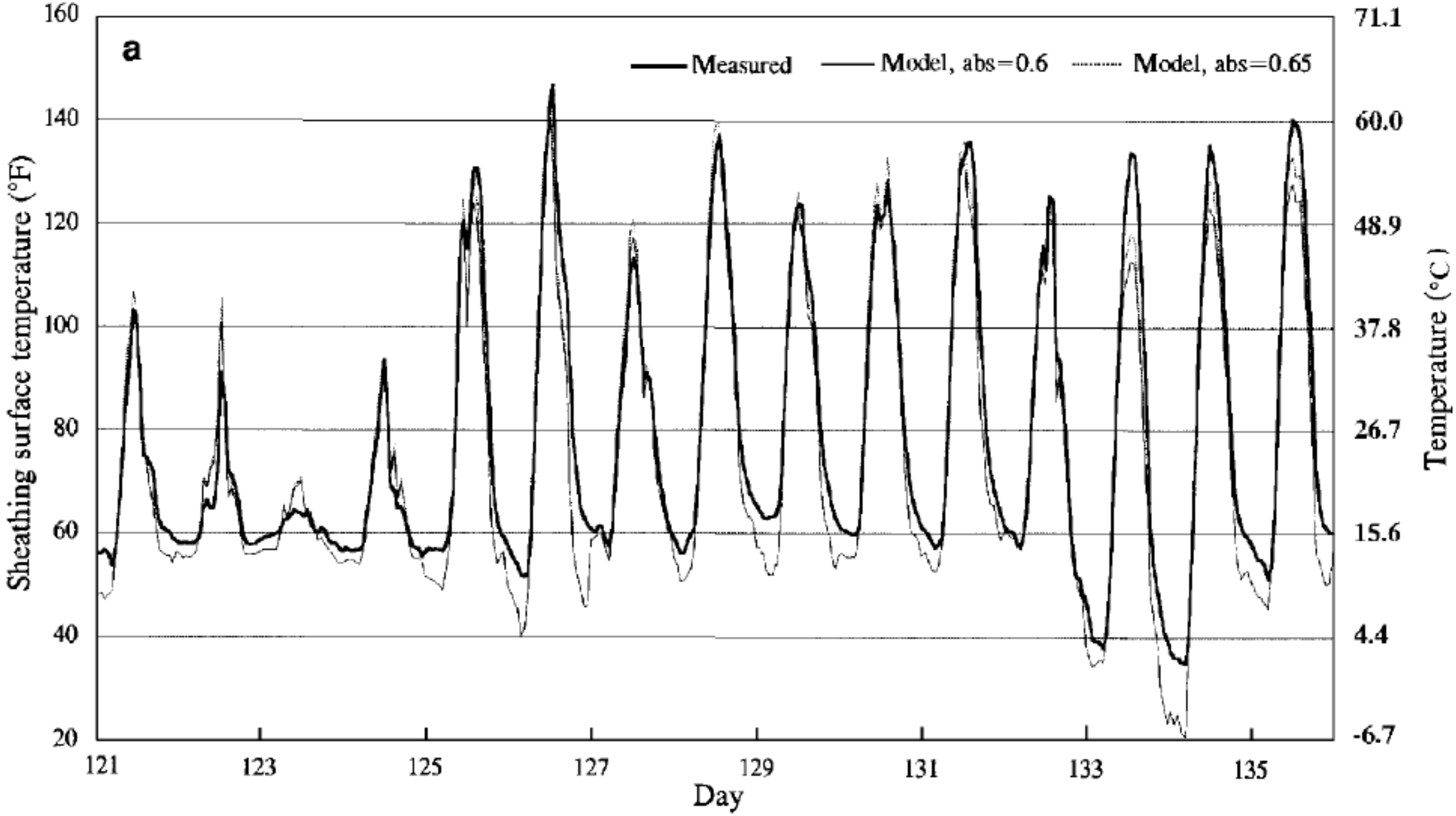


Figure 4—Exterior sheathing surface temperature, bay 2, May 1–15, 1993.

Attic heat transfer

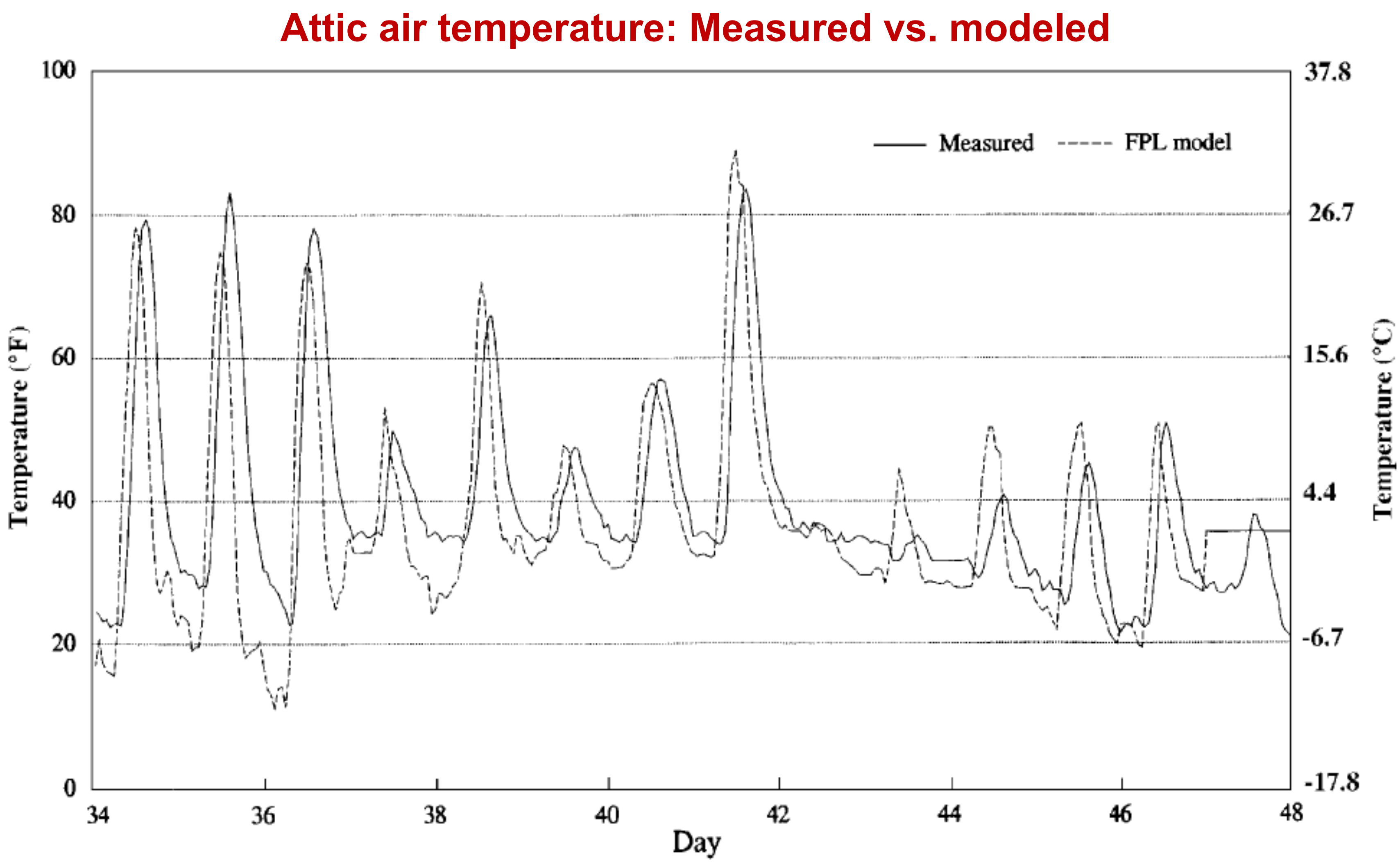


Figure 5—Attic air temperature, bay 2, February 3–16, 1993; absorptance = 0.65.

Attic heat transfer summary

- Attic temperature is important
  - HVAC equipment is often located in attics
  - Impacts conduction across ceiling into interior space

- Ways to reduce attic temperatures?
  - Increase convective heat transfer
    - Attic ventilation

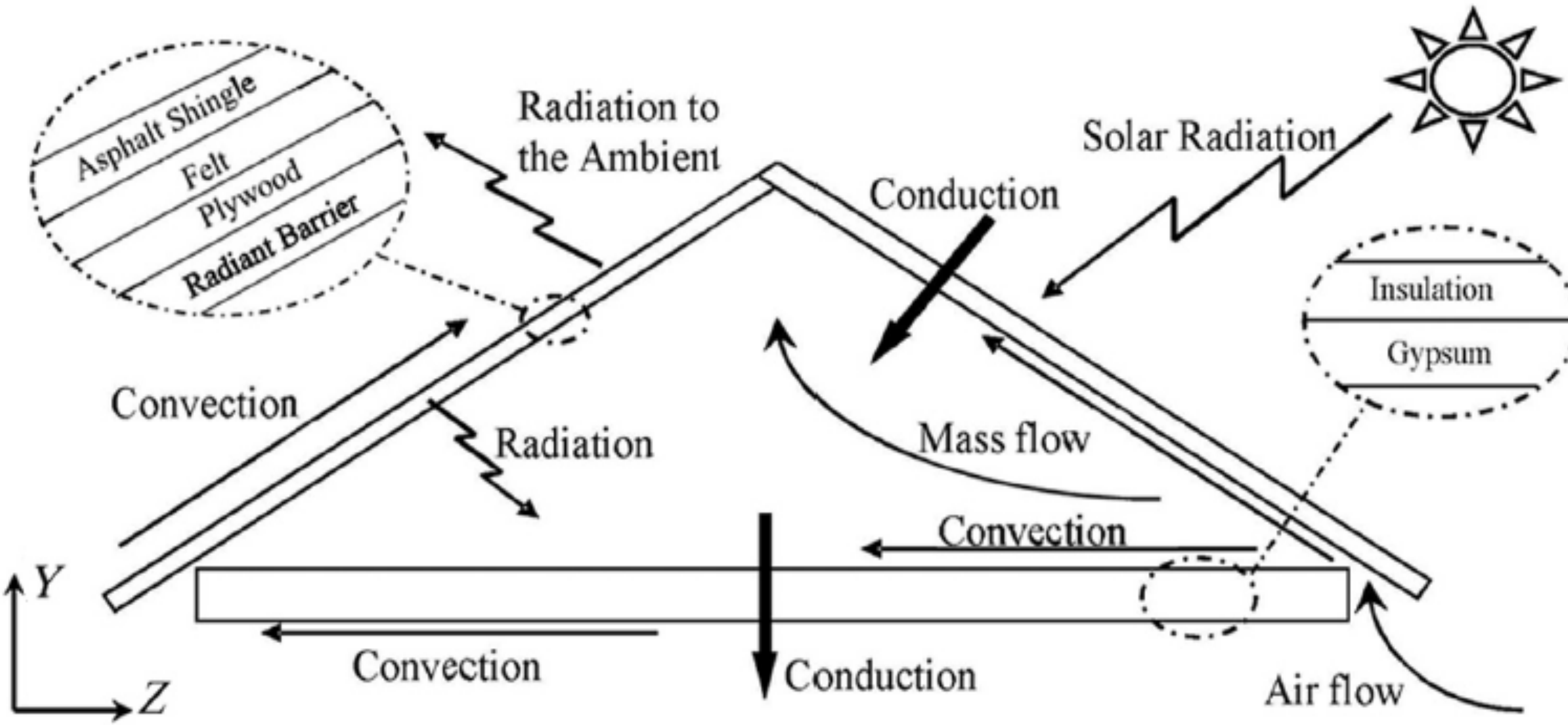
  - Reduce exterior roof surface temperature
    - ‘Cool roof’ low absorptivity materials on the exterior

  - Reduce attic floor surface and underside sheathing temperatures
    - Low-emissivity materials inside attic
      - Attic floor or underside of sheathing
    - Radiant barriers

Radiant barriers

- Radiant barriers typically have LW emissivity less than ~0.1
  - Approximately 90% of materials have emissivity of 0.9
- Inhibits heat flow through radiation only
  - Doesn't directly impact convection or conduction

Modeling the impacts of radiant barriers



Asadi et al., 2012. Performance evaluation of an attic radiant barrier system using three dimensional transient finite element method. *Journal of Building Physics*.

Modeling the impacts of radiant barriers

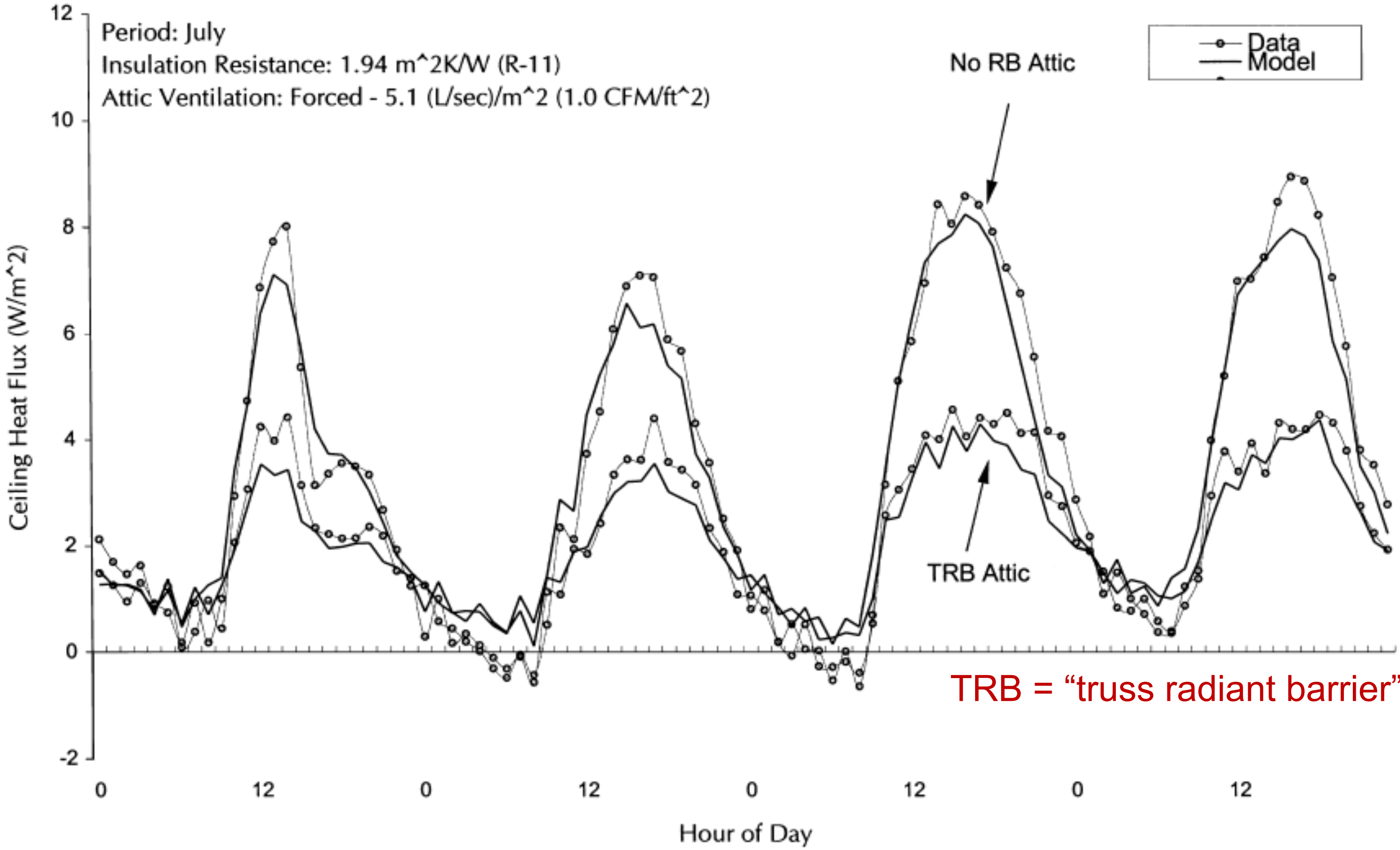


Fig. 6. Ceiling heat fluxes (TRB case, insulation resistance: 1.94 m^2 K/W, *R*-11; with attic airflow rate: 5.1 l/s/m^2, 1.0 CFM/ft^2).

Medina, M. 2000. On the performance of radiant barriers in combination with different attic insulation levels. *Energy and Buildings* 33:31-40.

Modeling the impacts of radiant barriers

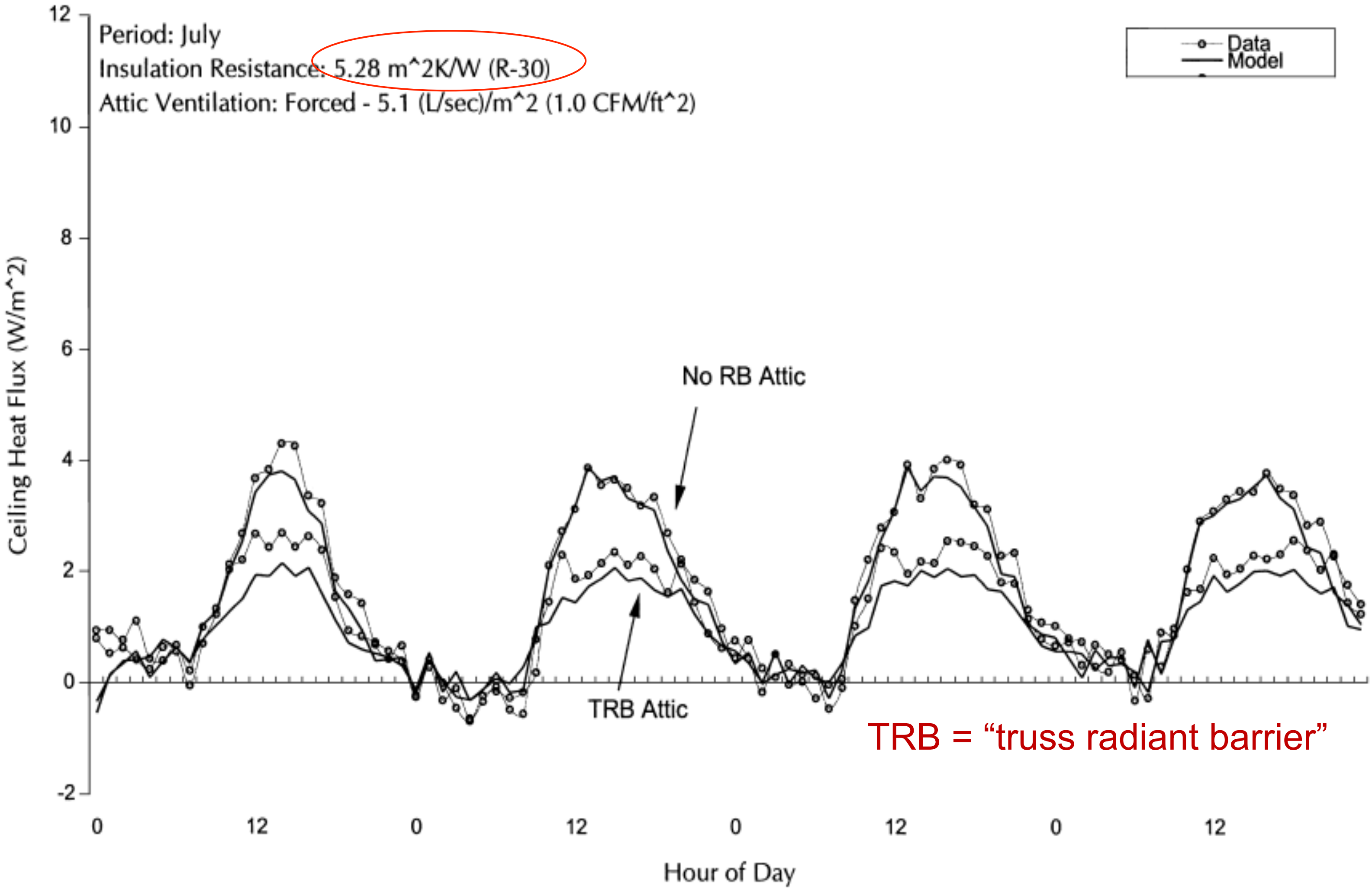
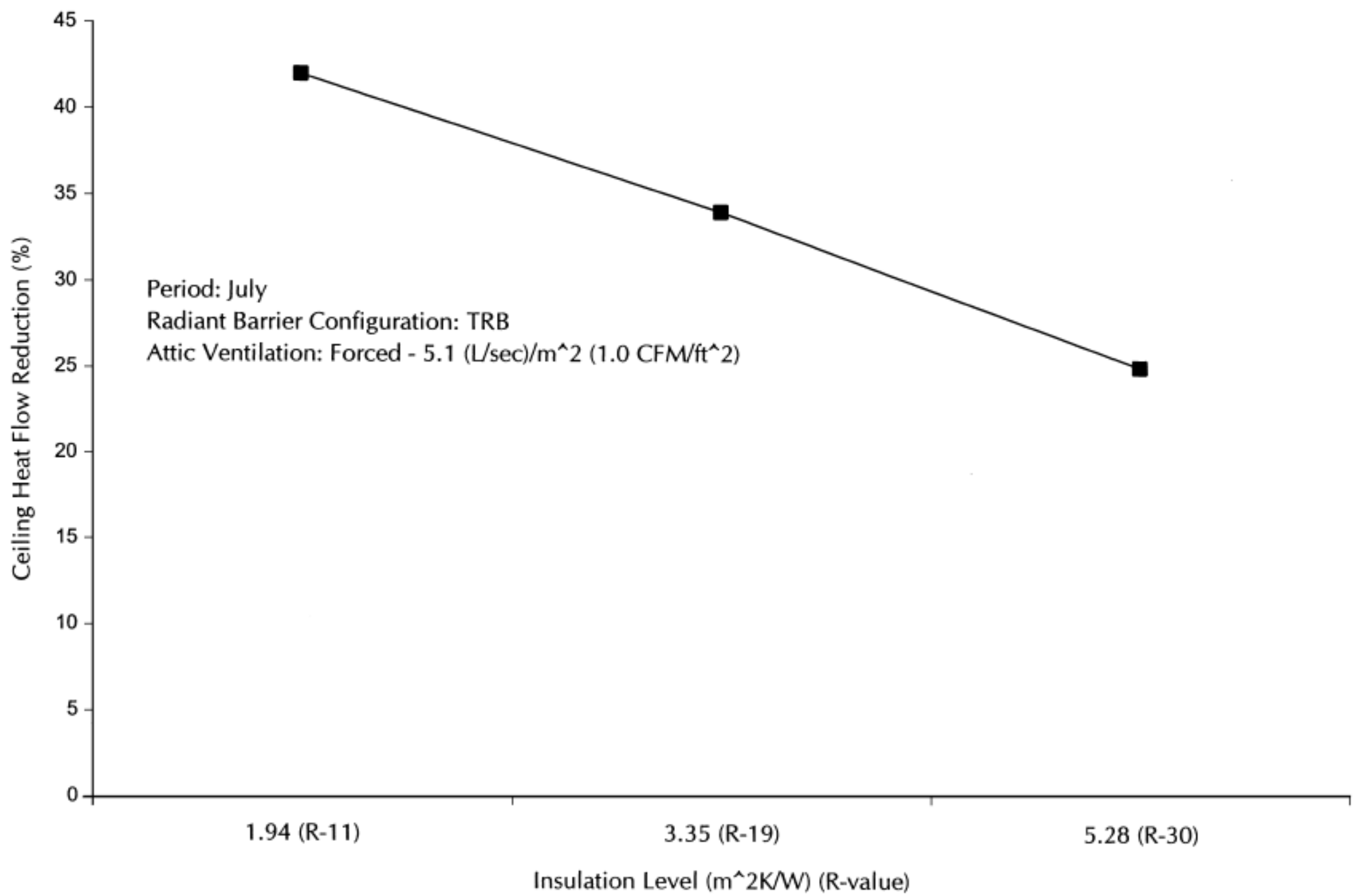


Fig. 7. Ceiling heat fluxes (TRB case, insulation resistance: 5.28 m^2 K/W, *R*-30; with attic airflow rate: 5.1 l/s/m^2, 1.0 CFM/ft^2).

Medina, M. 2000. On the performance of radiant barriers in combination with different attic insulation levels. *Energy and Buildings* 33:31-40.

Modeling the impacts of radiant barriers

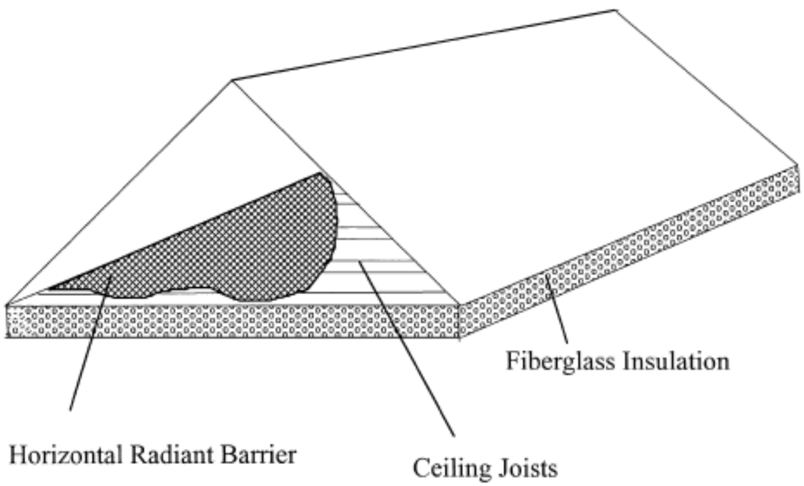
- Radiant barriers have less of an impact on well-insulated roofs

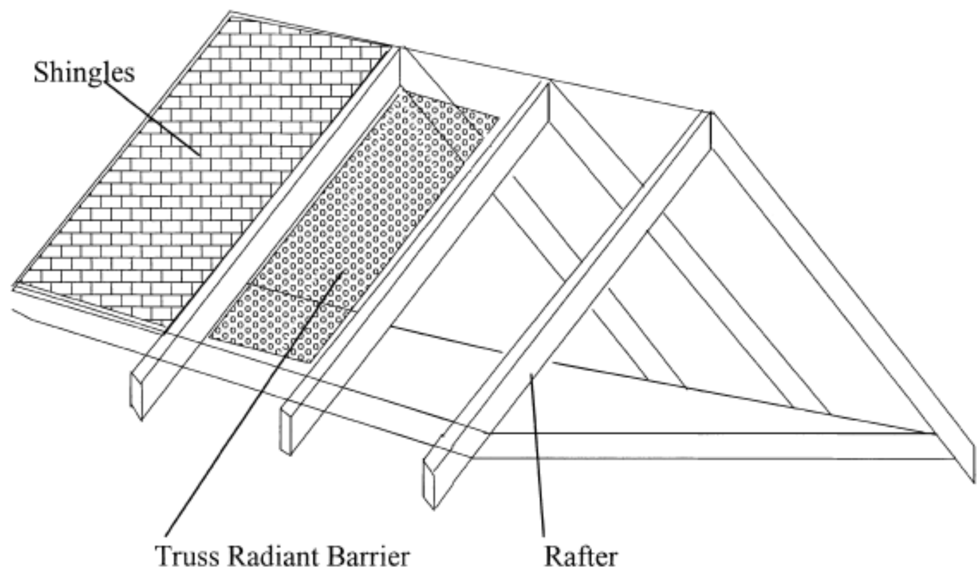


Medina, M. 2000. On the performance of radiant barriers in combination with different attic insulation levels. *Energy and Buildings* 33:31-40.

Modeling the impacts of radiant barriers

- Should we install radiant barriers on attic floors or underside of roof sheathing?





Medina, M. 2000. On the performance of radiant barriers in combination with different attic insulation levels. *Energy and Buildings* 33:31-40.

Modeling the impacts of radiant barriers

- Should we install radiant barriers on attic floors or underside of roof sheathing?

Doesn't much matter from physics standpoint
- May matter in terms of dust collection and performance over time

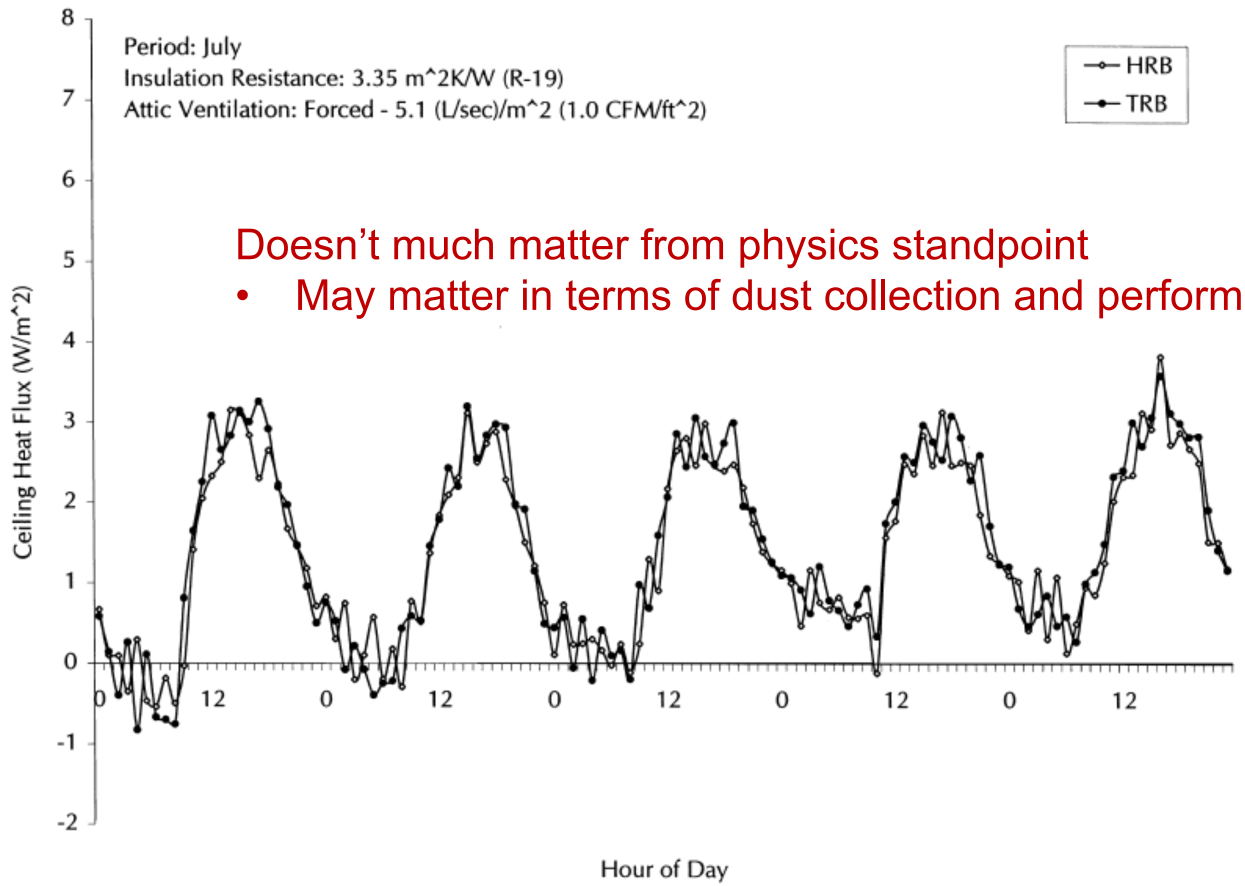


Fig. 9. Comparison between HRB and TRB configurations — experimental (insulation resistance: 3.35 m^2 K/W, *R*-19; with airflow rate: 5.1 l/s/m^2, 1.0 CFM/ft^2).

Medina, M. 2000. On the performance of radiant barriers in combination with different attic insulation levels. *Energy and Buildings* 33:31-40.

Roof and attic heat transfer simulation summary

- Roof surfaces can be extremely hot
  - Several energy and material longevity impacts
  - We can alter materials in design to reduce roof temperatures
- Attic air can also be very warm
  - Also has energy and comfort impacts
  - We now know what governs attic air temperatures
  - We know radiant barriers can help
    - Particularly if you have a poorly insulated roof
    - Better off just insulating roof if you can
- For both of these, we can use thermal modeling approaches in the design phase

WHOLE BUILDING ENERGY SIMULATION (BES) PROGRAMS

Energy simulation (BES) programs

- A wide variety of programs exists
  - http://apps1.eere.energy.gov/buildings/tools_directory/subjects_sub.cfm
  - Different levels of functions, user interfaces, and pricing
  - Some have very good GUIs with less functionality
    - Some have the exact opposite
- Most commonly used BES programs:
  - eQUEST (DOE2 engine; free; easy GUI)
  - ESPr (free; difficult to use; research grade)
  - TRNSYS (modular; requires extensive inputs; expensive)
  - TRACE 700 (from Trane; HVAC focus; expensive)
  - EnergyGauge USA (residential only; user-friendly; cheap)
  - EnergyPlus (free; excellent capabilities; modular; difficult to use)
    - Ease of use is improving with DesignBuilder USA, OpenStudio (free), and Simergy (free)
  - IES-VE (expensive; free educational; many capabilities; easy to use)

Building energy simulation (BES) programs

An Architect's Guide to
INTEGRATING
ENERGY MODELING
IN THE DESIGN PROCESS

THE AMERICAN INSTITUTE OF ARCHITECTS

MODELING TOOL	CALCULATION ENGINE	GRAPHIC INTERFACE FOR FRONT-END INPUT	GRAPHIC RESULTS PROVIDED	APPROPRIATE FOR EARLY DESIGN PHASE	APPROVED FOR CODE COMPLIANCE MODELING	FREEWARE
COMFEN (RESFEN – residential)	EnergyPlus	Yes	Yes	Yes	No	Yes
DesignBuilder	EnergyPlus	Yes	Limited	Yes	Yes	No
Ecotect	CIBSE Admittance Method	Yes	Yes	Yes	No	No
EMIT1.2	None (spread-sheet)	No	Not specifically, (but s/s capability)	Yes	No	Yes
EnergyPro	DOE-2.1E	No	No(auto-generates compliance report)	No	Yes (easiest to use)	No
eQUEST®	DOE-2.2	Yes	No	Must be far enough along to input HVAC	Yes (most popular)	Yes
Green Building Studio / Vasari	DOE-2.2	Yes	Yes	Yes	No	No
Hourly Analysis Program (HAP)	Transfer Function Method	Limited	No	No	Yes	No
IES Virtual Environment	Apache	Yes	Yes	Gaia + Toolkit Yes Pro requires input of HVAC	Yes	No
OpenStudio	EnergyPlus	Yes (similar to SketchUp)	Yes	Must be far enough along to input HVAC	Yes	Yes
Sefaira Concept	Sefaira	Yes	Yes	Yes	No	No
Simergy	EnergyPlus	Yes	Limited	Not yet	Yes	Yes
TAS	TAS	Yes	Yes	Yes	Yes	No
TRACE® 700	TRACE	No	Limited	Must be far enough along to input HVAC	Yes	No
TRNSYS	TRNSYS	Yes	No	No	No	No

Example engineering calculations for BES program

Outside Surface Heat Balance

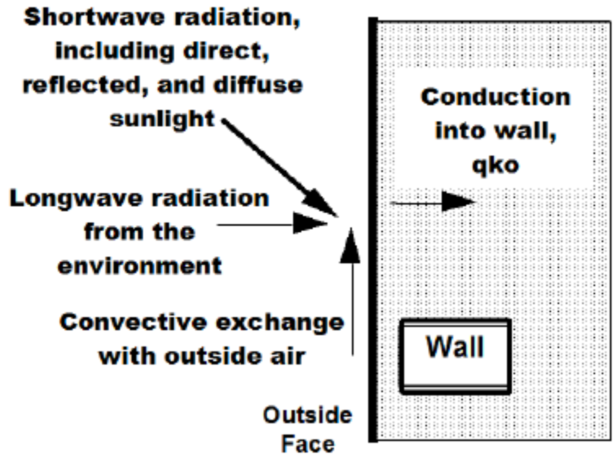


Figure 17. Outside Heat Balance Control Volume Diagram

The heat balance on the outside face is:

$$q''_{\alpha sol} + q''_{LWR} + q''_{conv} - q''_{ko} = 0 \qquad (64)$$

where:

$q''_{\alpha sol}$ = Absorbed direct and diffuse solar (short wavelength) radiation heat flux.

q''_{LWR} = Net long wavelength (thermal) radiation flux exchange with the air and surroundings.

q''_{conv} = Convective flux exchange with outside air.

q''_{ko} = Conduction heat flux (q/A) into the wall.

- We know how to model all of these elements now
- Programs differ in how they select inputs, particularly heat transfer coefficients…

EnergyPlus Engineering Reference, 2012

Example engineering calculations for BES program

Simple Combined

The simple algorithm uses surface roughness and local surface windspeed to calculate the exterior heat transfer coefficient (key:SimpleCombined). The basic equation used is:

$$h = D + EV_z + FV_z^2 \tag{82}$$

where

h = heat transfer coefficient

V_z = local wind speed calculated at the height above ground of the surface centroid

D, E, F = material roughness coefficients

The roughness correlation is taken from Figure 1, Page 22.4, ASHRAE Handbook of Fundamentals (ASHRAE 1989). The roughness coefficients are shown in the following table:

Table 6. Roughness Coefficients D, E, and F.

Roughness Index	D	E	F	Example Material
1 (Very Rough)	11.58	5.894	0.0	Stucco
2 (Rough)	12.49	4.065	0.028	Brick
3 (Medium Rough)	10.79	4.192	0.0	Concrete
4 (Medium Smooth)	8.23	4.0	-0.057	Clear pine
5 (Smooth)	10.22	3.1	0.0	Smooth Plaster
6 (Very Smooth)	8.23	3.33	-0.036	Glass

EnergyPlus Engineering Reference, 2012

Example engineering calculations for BES program

Inside Heat Balance

The heart of the heat balance method is the internal heat balance involving the inside faces of the zone surfaces. This heat balance is generally modeled with four coupled heat transfer components: 1) conduction through the building element, 2) convection to the air, 3) short wave radiation absorption and reflectance and 4) longwave radiant interchange. The incident short wave radiation is from the solar radiation entering the zone through windows and emittance from internal sources such as lights. The longwave radiation interchange includes the absorption and emittance of low temperature radiation sources, such as all other zone surfaces, equipment, and people.

The heat balance on the inside face can be written as follows:

$$q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{ki} + q''_{sol} + q''_{conv} = 0 \qquad (92)$$

where:

q''_{LWX} = Net longwave radiant exchange flux between zone surfaces.

q''_{SW} = Net short wave radiation flux to surface from lights.

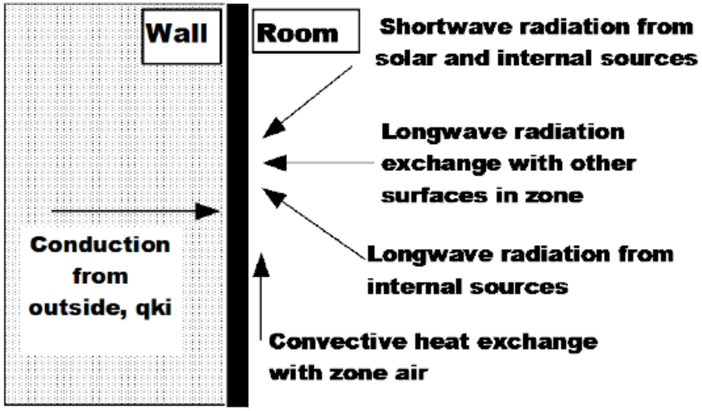
q''_{LWS} = Longwave radiation flux from equipment in zone.

q''_{ki} = Conduction flux through the wall.

q''_{sol} = Transmitted solar radiation flux absorbed at surface.

q''_{conv} = Convective heat flux to zone air.

Each of these heat balance components is introduced briefly below.



EnergyPlus Engineering Reference, 2012

Example engineering calculations for BES program

- Choice of interior convection coefficients is complicated
  - Still a topic of ongoing research
  - Remember: Forced vs. laminar? Orientation? Cold or hot surface?

- Different equations for different surfaces
  - Simple buoyancy
    - Vertical walls, tilted surfaces, windows, etc.
  - In-floor heating or in-ceiling cooling
    - Vertical walls, heated floors, chilled ceilings, windows
  - Forced flow near diffusers
    - Ceiling diffusers, floor diffusers, near heated or cooled windows
  - Central mechanical fan circulation
    - Walls, horizontal flow

- EnergyPlus documentation has a great review of all of these

EnergyPlus Engineering Reference, 2012

Example engineering calculations for BES program

- These programs rely on the same equations we've been using

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p \left(T_{zi} - T_z\right) + \dot{m}_{\inf} C_p \left(T_\infty - T_z\right) + \dot{Q}_{sys}$$

where:

$\sum_{i=1}^{N_{sl}} \dot{Q}_i$ = sum of the convective internal loads

$\sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right)$ = convective heat transfer from the zone surfaces

$\dot{m}_{\inf} C_p \left(T_\infty - T_z\right)$ = heat transfer due to infiltration of outside air

$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p \left(T_{zi} - T_z\right)$ = heat transfer due to interzone air mixing

$\dot{Q}_{sys}$ = air systems output

$C_z \frac{dT_z}{dt}$ = energy stored in zone air

$C_z = \rho_{air} C_p C_T$

ρ_{air} = zone air density

C_p = zone air specific heat

EnergyPlus Engineering Reference, 2012

Example engineering calculations for BES program

- Rearrange to solve for instantaneous HVAC system capacity:

$$-\dot{Q}_{sys} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p \left(T_{zi} - T_z\right) + \dot{m}_{\inf} C_p \left(T_\infty - T_z\right)$$

- Instantaneous HVAC sensible capacity also equals:

$$\dot{Q}_{sys} = \dot{m}_{sys} C_p \left(T_{\sup} - T_z\right)$$

- Once you have Q_{sys} at each time step, you can calculate the energy required to deliver that rate of bulk heat transfer by knowing the efficiency/COP of your equipment

$$COP = \frac{Q_{sys}}{P_{sys}} \longrightarrow P_{sys} = \frac{Q_{sys}}{COP}$$

EnergyPlus Engineering Reference, 2012

Example engineering calculations for BES program

- Discretizing for time t versus time $t - \delta t$:

$$C_z \frac{T_z^t - T_z^{t-\delta t}}{dt} + T_z^t \left(\sum_{i=1}^{N_{surfaces}} h_i A_i + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p + \dot{m}_{\inf} C_p + \dot{m}_{sys} C_p \right) =$$

$$\sum_{i=1}^{N_{sl}} \dot{Q}_i^t + \dot{m}_{sys} C_p T_{\text{supply}}^t + \left(\sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p T_{zi} + \dot{m}_{\inf} C_p T_\infty \right)^{t-\delta t}$$

- If there is any thermal mass at any element, link to surface T:

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

Discretized conduction

BES programs vary in how they treat conduction and thermal mass

EnergyPlus Engineering Reference, 2012

Example engineering calculations for BES program

- Or use a lumped capacitance model (more detail next lecture):

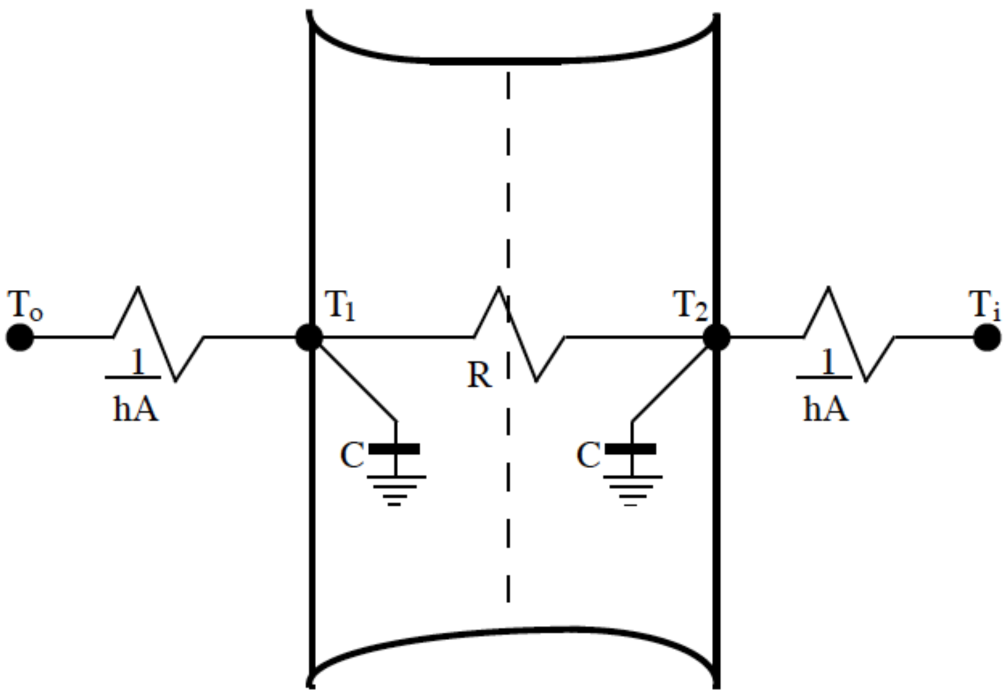


Figure 9. Two Node State Space Example.

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

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

where:

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

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

BES programs vary in how they treat conduction and thermal mass

Lumped capacitance model for conduction

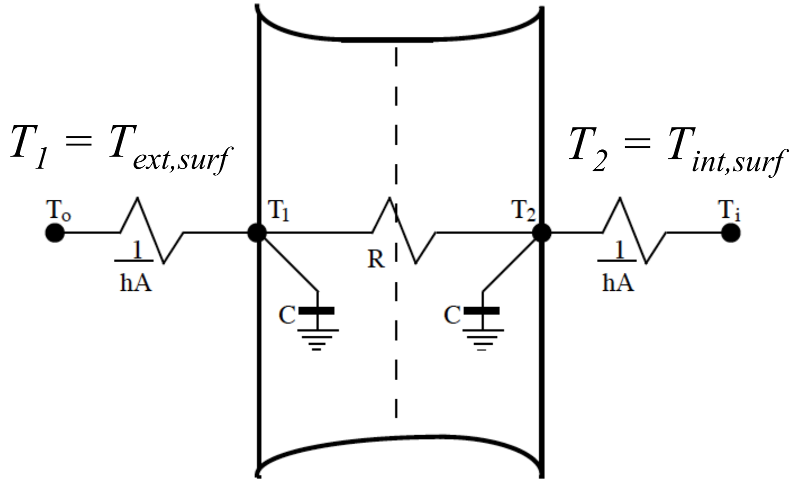


Figure 9. Two Node State Space Example.

Steady state surface energy balance…

$$\alpha I_{solar} + \varepsilon_1 \sigma F_{sky}(T_{sky}^4 - T_1^4) + \varepsilon_1 \sigma F_{air}(T_{air}^4 - T_1^4) + \varepsilon_1 \sigma F_{ground}(T_{ground}^4 - T_1^4) + h_{conv}(T_{air} - T_1) - U(T_1 - T_2) = 0$$

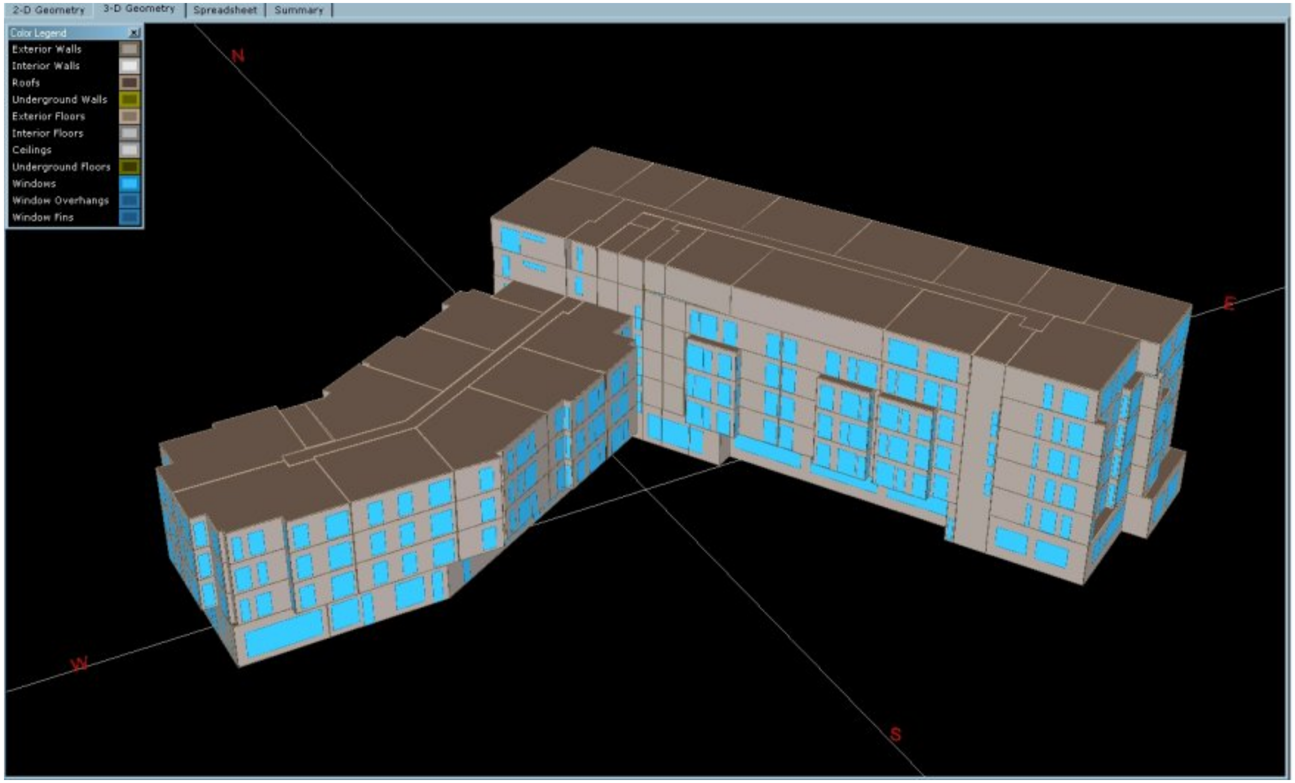
…becomes a time-varying surface energy balance:

$$\alpha I_{solar} + \varepsilon_1 \sigma F_{sky}(T_{sky}^4 - T_1^4) + \varepsilon_1 \sigma F_{air}(T_{air}^4 - T_1^4) + \varepsilon_1 \sigma F_{ground}(T_{ground}^4 - T_1^4) + h_{conv}(T_{air} - T_1) - U(T_1 - T_2) = \frac{\rho C_p}{\Delta t} \frac{L}{2}(T_1^n - T_1^{n-1})$$

BES programs vary in how they treat conduction and thermal mass

Demonstration of eQUEST

- eQUEST demonstration
  - Launch program



http://www.buildingenergyexperts.com/wp-content/uploads/2010/08/Equest.jpg

HW #4

- HW #4 involves modeling a commercial building in eQUEST
  - And making changes to the enclosure
  - Assigned today, due April 12
- http://www.doe2.com/equest/
- Current version: 3.65 (released March 2014)