CAE 463/524
Building Enclosure Design
Spring 2015

Lecture 10: March 31, 2015
Finish windows and daylighting
Energy simulation and enclosure design

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Last time

- Finished air leakage
- Windows and daylighting
  - U values
  - SHGC
  - Solar transmittance
  - Visible transmittance
- Take-home exam given
  - Due today
- Discussed final project expectations

Final project topic selection

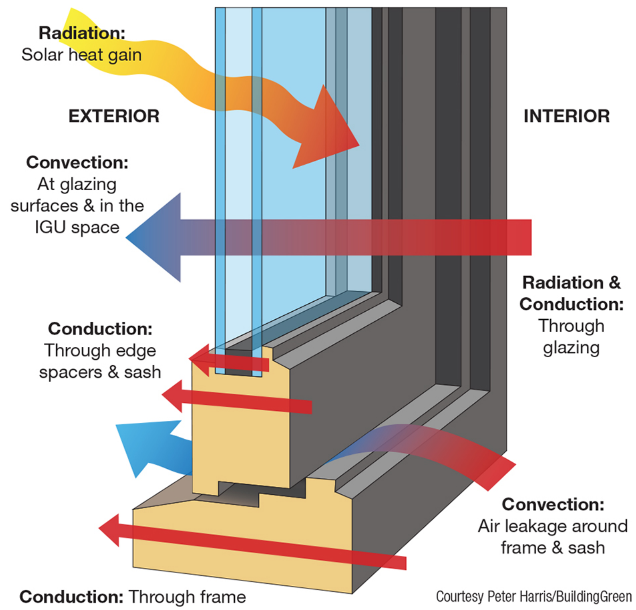
- **Email me** your topics by **Friday April 3, 2015**

Name	**Project topic**
Behrens, Maria C.	
Geoghegan, Thomas	Double skin facade
Irazabal, Carlos H.	Cool roofs
Jung, Yun Joon	
Lis, Kimberly A.	
Ng, Yin Ling	
Theisen, Whitney A.	
Carrillo Garcia, Jose	
Dorn, Lawrence E.	Electrochromic glass
Erukulla, Dilip Kumar	
Liang, Jinzhe	Double skin facade
Mullin, Elizabeth M.	Straw bale construction (or earthen materials)
Tuz, Oleg	BioSkin evaporative panel?
Chandler, Julie A.	
Chung, Allan	
Fortune, Roger G.	Brooklyn Trust building
Gadani, Dhaval S.	
Jarosz, Michelle M.	
Linn, Rebecca C.	

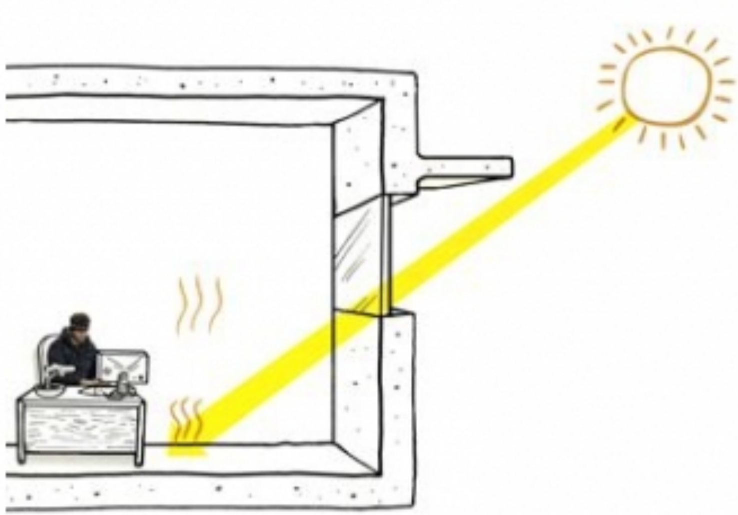
Today's objectives

- Finish windows and daylighting
- Introduce energy simulation in building enclosure design

Review of window heat transfer



$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{solar}A_{pf}SHGC$$



Some methods of achieving daylighting efficiently

- Skylights
- Light pipes and fiber optic daylighting systems
- Light shelves

- All need to be used with dimming ballasts or other advanced lighting controls to achieve savings

Skylights

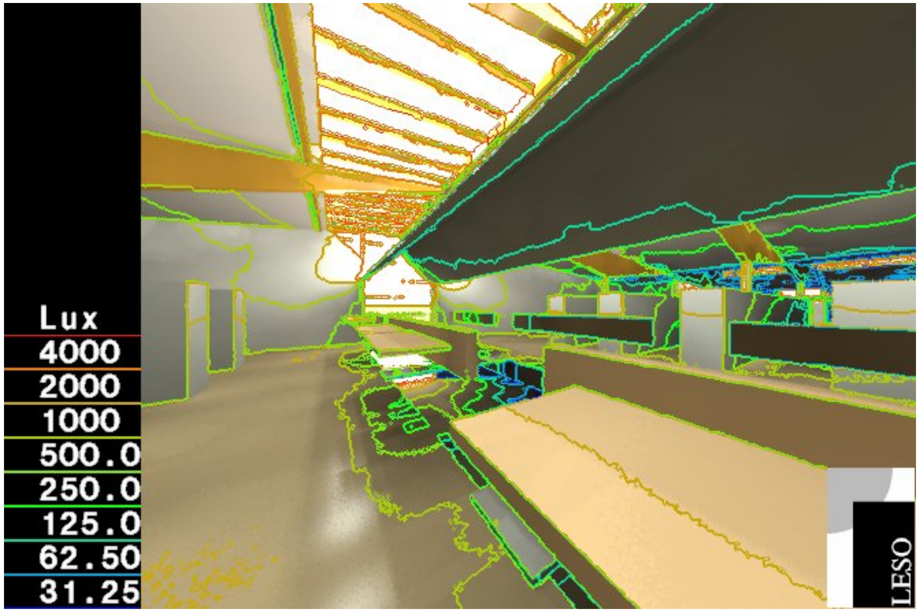
- Typically limited to low-rise structures

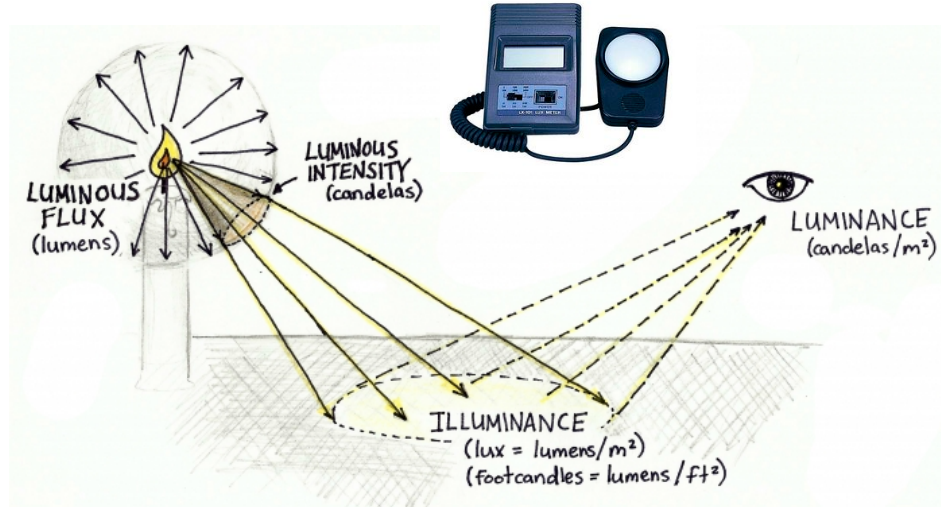
Solar tubes


Daylighting Technology
energy ENERGY STAR
Capture
Raybender® 3000 Technology
A patented daylight-capturing dome lens that:
• Redirects low-angle sunlight for maximum light capture
• Rejects overpowering midday summer sunlight
• Provides consistent daylighting throughout the day
LightTracker™ Reflector
An innovative in-dome reflector that:
• Redirects low-angle winter sunlight for maximum light capture
• Increases light input for greater light output
• Delivers unsurpassed year-round performance
Transfer
Spectralight® Infinity Tubing
Tubing made of the world's most reflective material that:
• Delivers 99.7% * specular reflectivity for maximum sunlight transfer
• Provides the purest color rendition possible so colors are truer, brighter
• Allows for run lengths over 30 feet to deliver sunlight to lower floors
Deliver
Stylish Daylight Delivery
Form and function combine for optimal daylight diffusion with:
• Solatube Decorative Fixtures
• Warming and Softening Effect Lenses
• Ventilation, dimmer and nighttime lighting options
* Specular reflectance greater than 99% with wavelength specific reflectance up to 99.7% for the visible spectrum.

Light shelves

Combining software and hardware for investigating daylighting

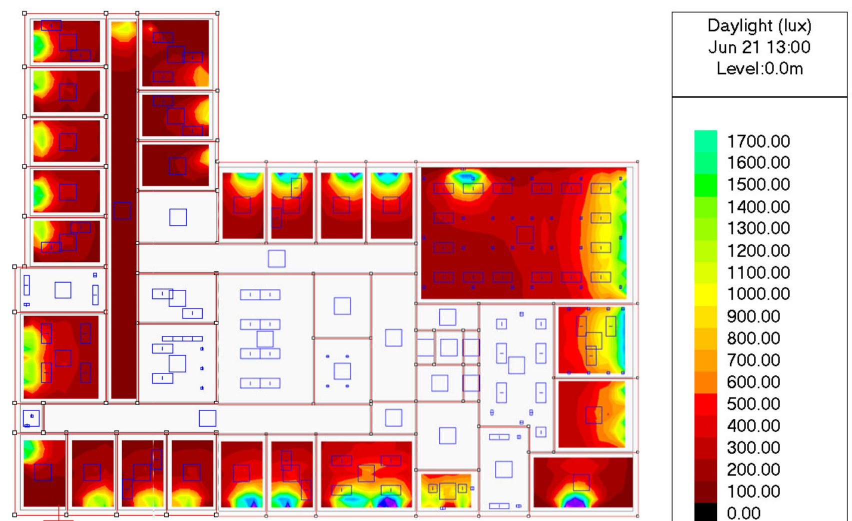




Hardware: Light sensors

Software: Radiance

http://floyd.lbl.gov/deskrad/download.htm



Designing with glass

- There are many methods used to compensate for its poor thermal properties
  - Insulated windows with double & triple glazing
  - Low E coatings
  - Low conductivity gas fills
  - Tinting
  - Reflective coatings
  - Curtains and shutters
  - Window sizing & orientation on the building
  - Shading or overhangs

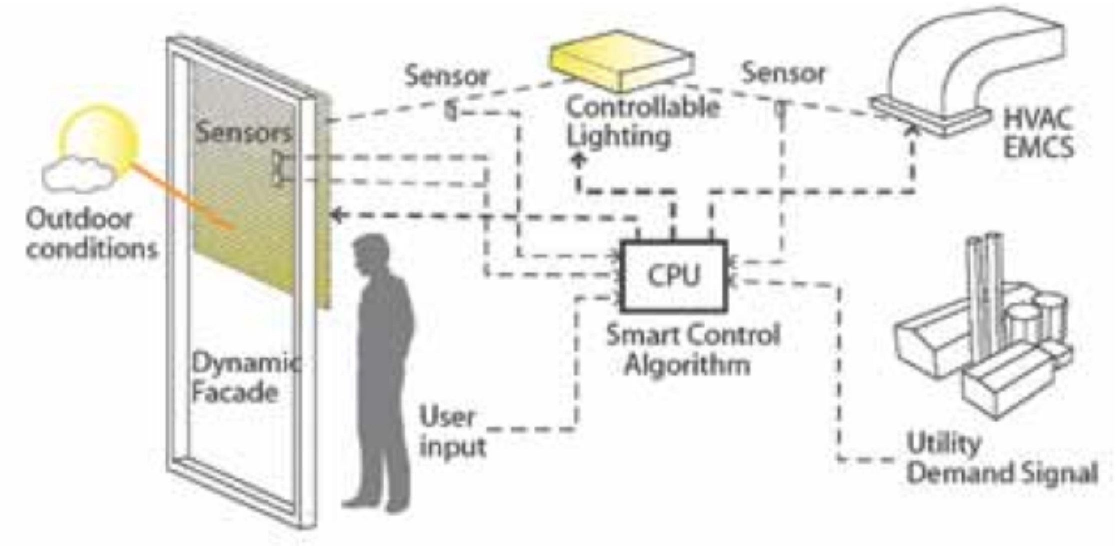
New technologies are pushing the boundaries on thermal performance of fenestration

- Building integrated photovoltaics (BIPV)
  - Photovoltaic (PV) cells provide shading and generate electricity
- Vacuum insulated windows
  - Removing air eliminates conduction and convection
    - Effective but expensive to manufacturer
- Aerogel
  - Transparent silica gel with a very low density
  - Very high insulating properties
  - Very good sound absorption properties

Designing with glass for daylighting: Controls

Systems need to be used with **dimming ballasts** or other advanced **lighting controls**

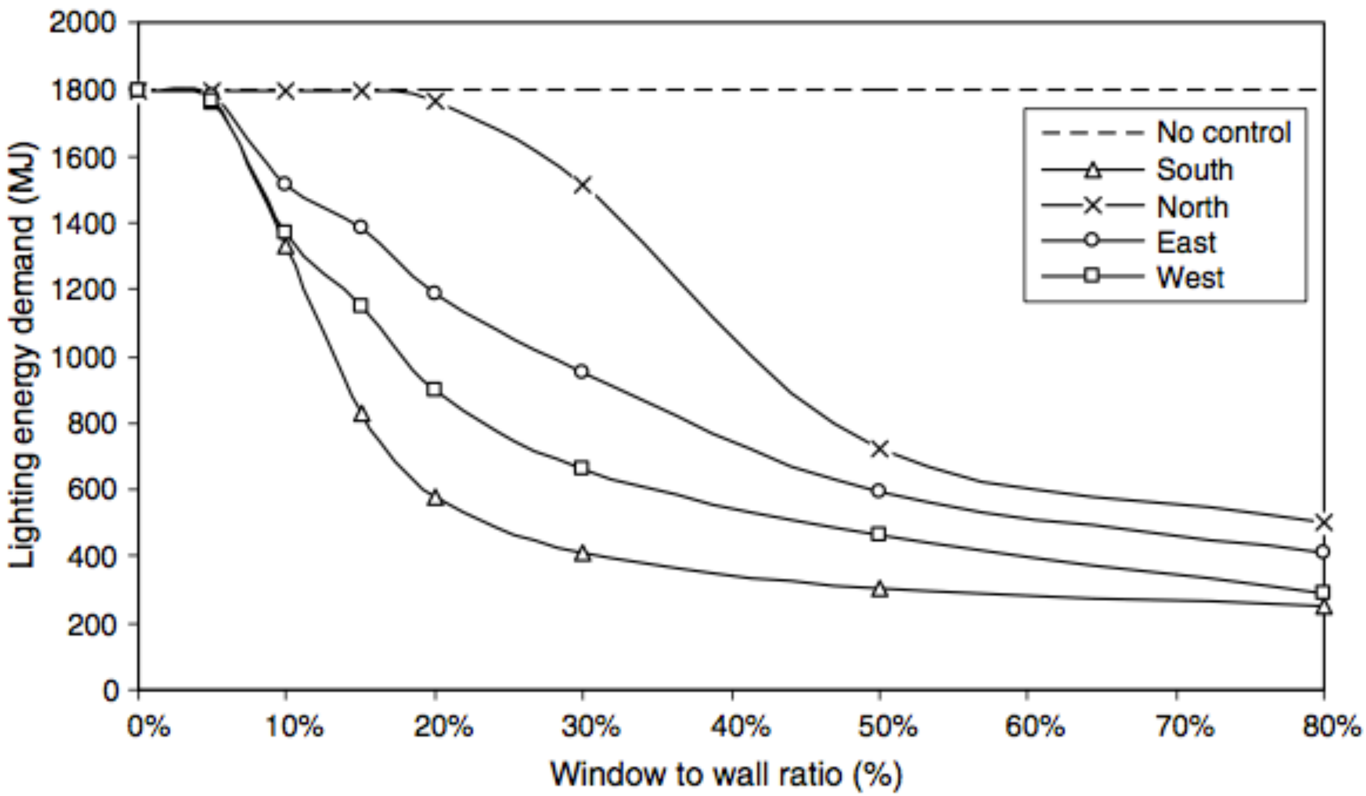
Lee and Selkowitz **2006** *Energy and Buildings*



Selkowitz **2011** *Journal of Building Enclosure Design*

Energy impacts of glazing

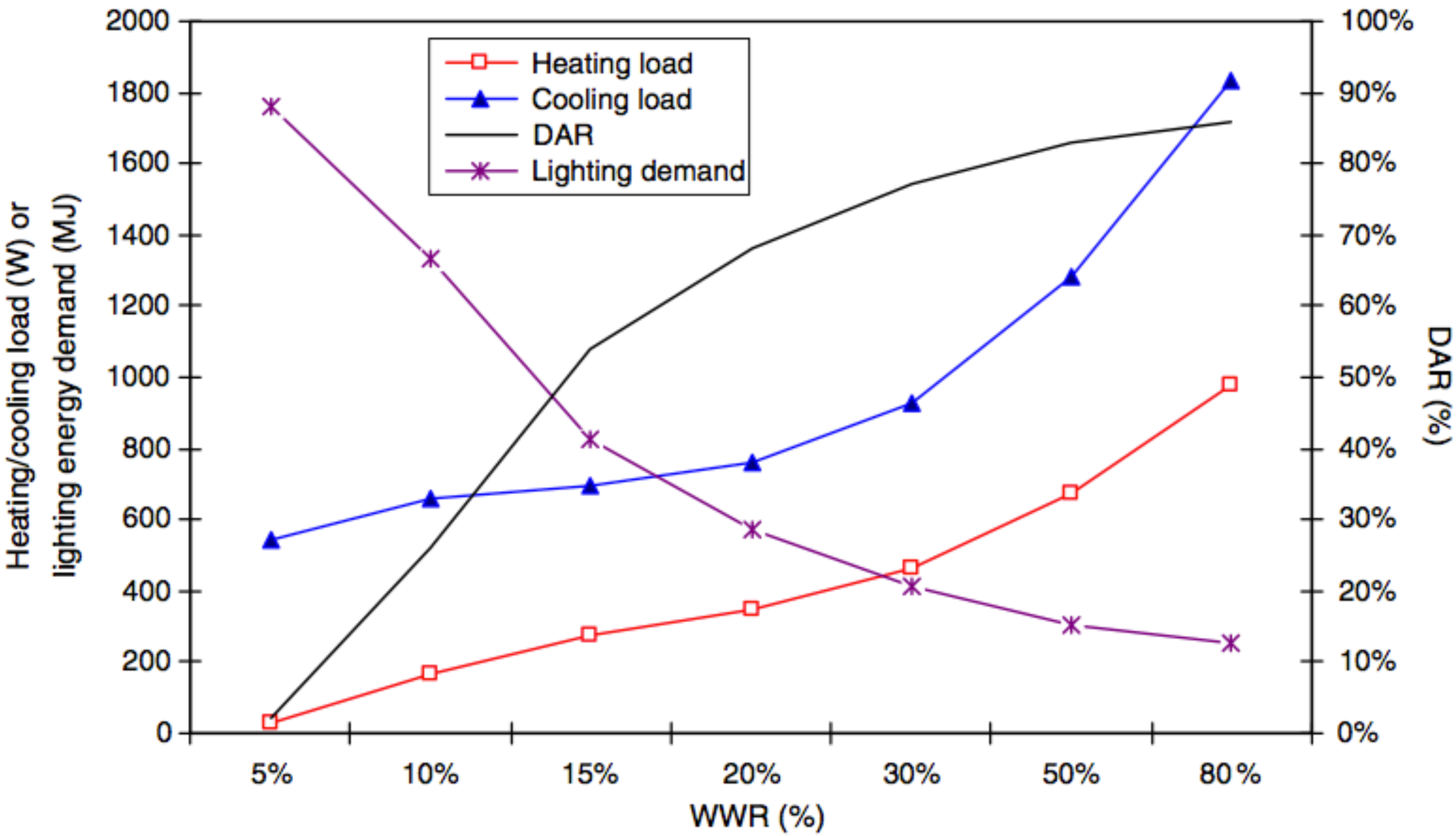
Increased daylighting can save **lighting energy** depending on WWR and orientation:



Tzempelikos and Athienitis **2007** *Solar Energy*

Energy impacts of glazing

But daylighting also affects **heating and cooling loads**…



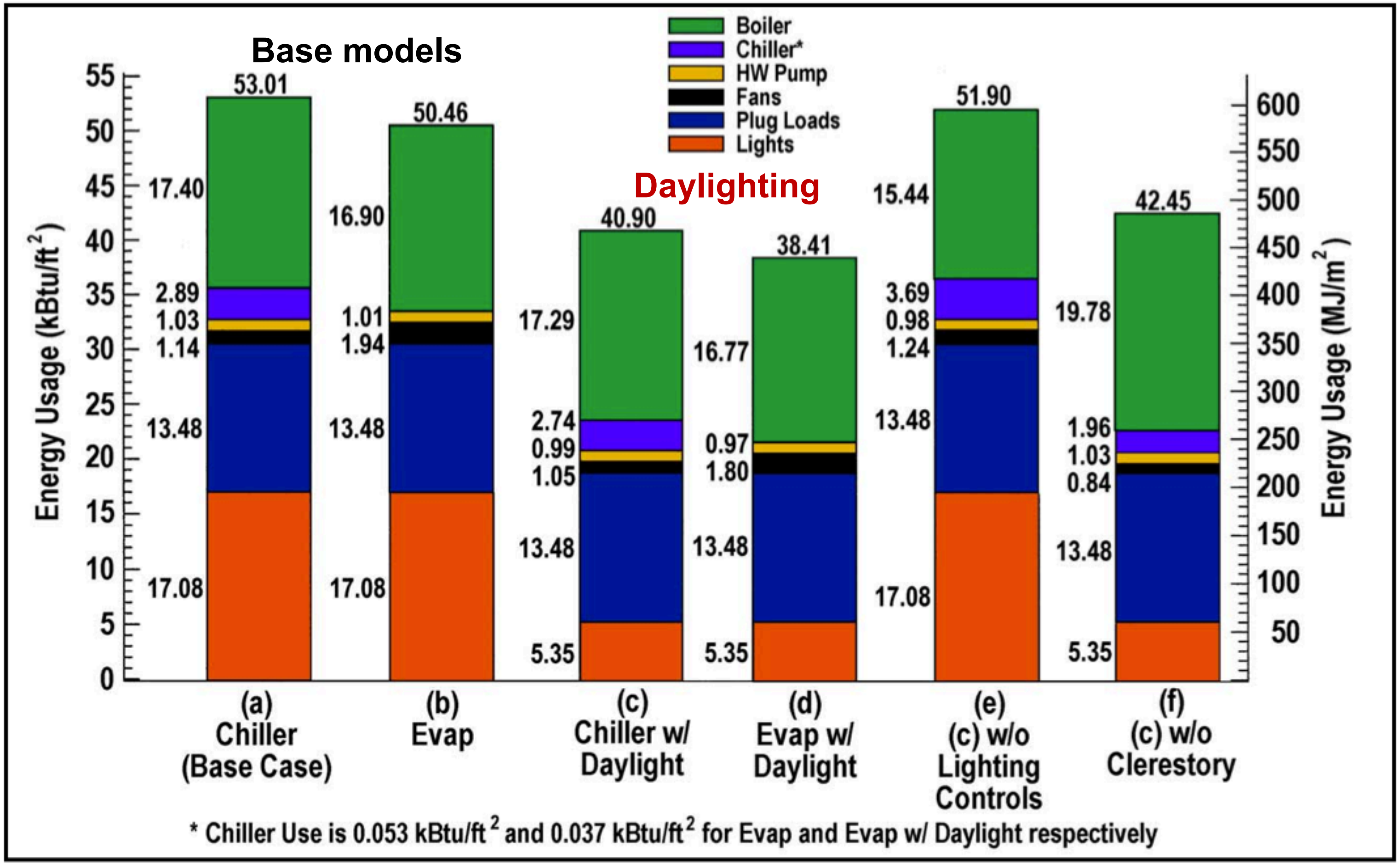
DAR = daylight availability ratio

…so how do we find the right balance?

Tzempelikos and Athienitis **2007** *Solar Energy*

Energy impacts of glazing: Energy modeling

- Example project: Energy modeling w/ daylighting in Colorado:



What about in a warmer climate?

Need to perform whole building energy modeling

McHugh et al. **1998** *ASHRAE Journal*

WHOLE BUILDING ENERGY SIMULATION

Energy simulation and enclosure design

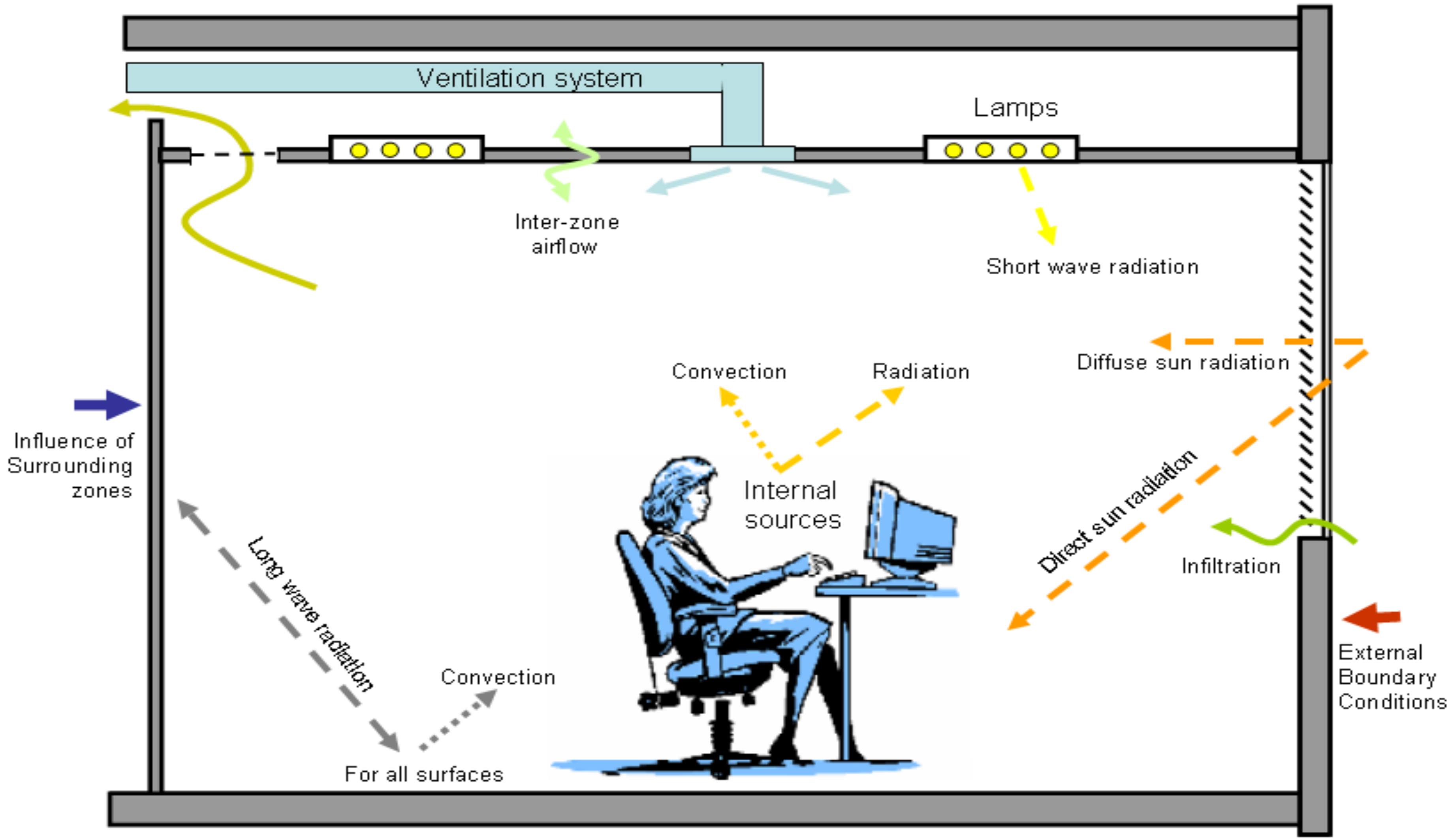
- In Building Science we discussed using sizing programs to determine peak hourly loads during heating and cooling seasons and size equipment
  - Heating loads: easy (U*A*dT)
  - Cooling loads: more complex (radiation) – CLTD, RTS, HB, etc.
    - You can influence loads and size of equipment early in the design process by specifying certain envelope characteristics

- More advanced: Whole building energy simulation programs are used to predict annual energy consumed by a building
  - Outcomes: annual BTUs, MJ, kWh, $, associated pollutant emissions
    - Typically normalized per floor area (e.g., MBTU/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

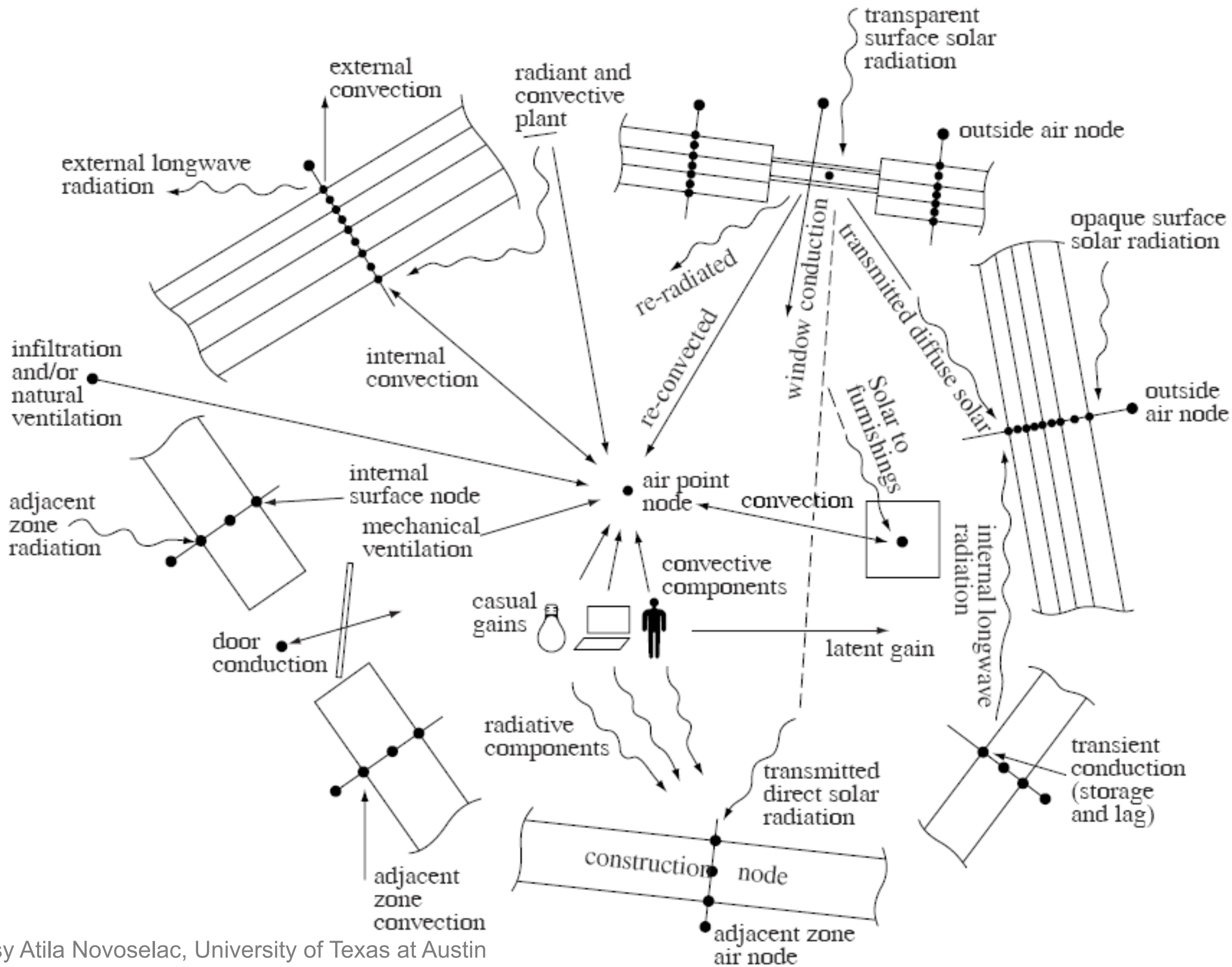
- We've covered individual **surface energy balances** before
  - Surfaces are all connected
- We can build a **system of equations** linking energy balances at a series of "nodes"
  - Each node has an equation accounting for all modes of heat transfer
- Whole building energy simulation
  - Involves linking the nodes and predicting hourly indoor air temperatures (or HVAC loads) as the primary unknown
    - 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



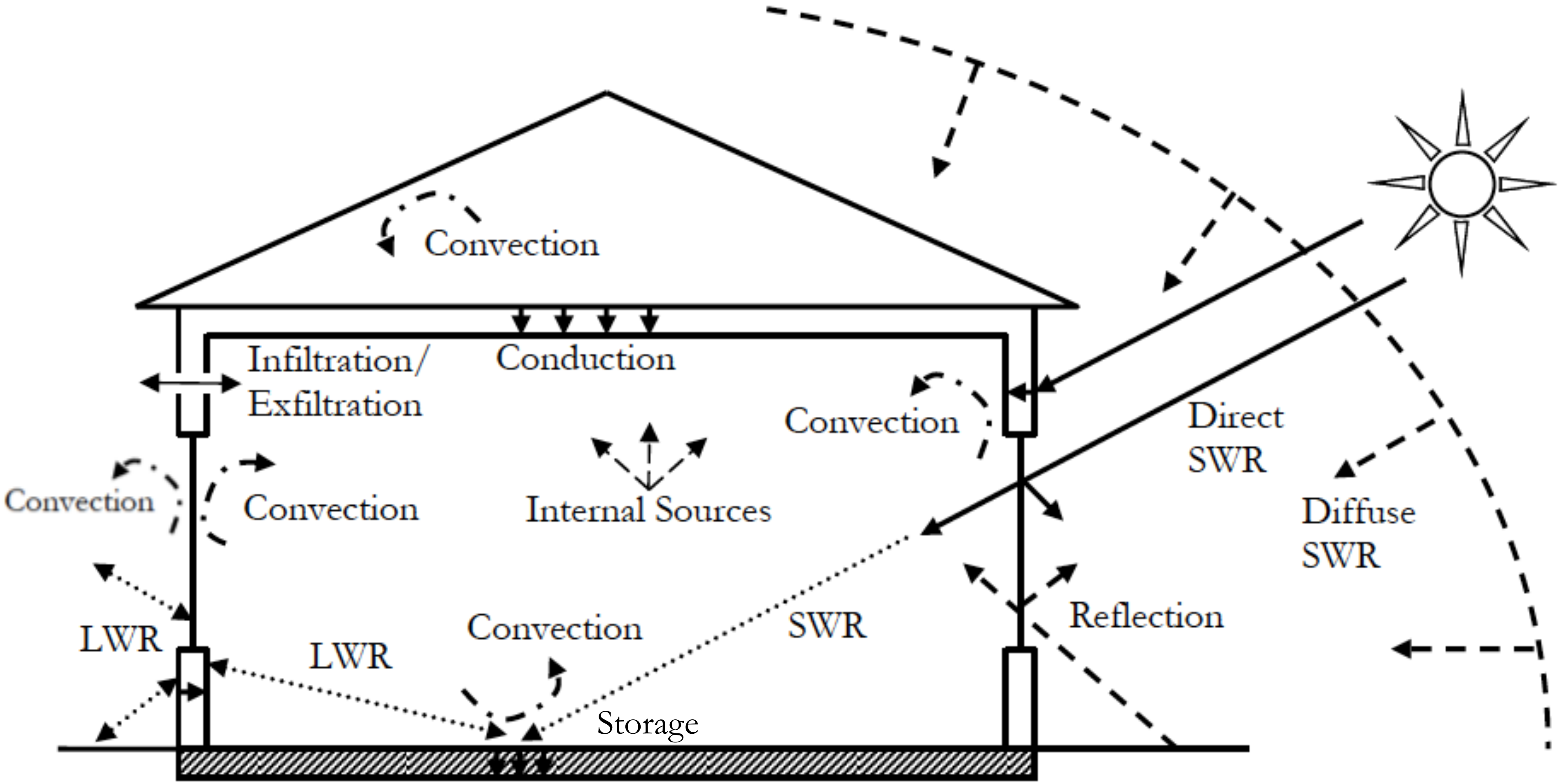
Slide courtesy Atila Novoselac, University of Texas at Austin

Whole building energy simulation



Slide courtesy Atila Novoselac, University of Texas at Austin

Building enclosures and heat transfer, visualized



Heat transfer in building science: Summary

Conduction

$$q = \frac{k}{L}\left(T_{surf,1} - T_{surf,2}\right)$$

$$\frac{k}{L} = U = \frac{1}{R}$$

$$R_{total} = \frac{1}{U_{total}}$$

$$R_{total} = R_1 + R_2 + R_3 + \ldots$$

For thermal bridges and combined elements:

$$U_{total} = \frac{A_1}{A_{total}} U_1 + \frac{A_2}{A_{total}} U_2 + \ldots$$

Convection

$$q_{conv} = h_{conv}\left(T_{fluid} - T_{surf}\right)$$

$$R_{conv} = \frac{1}{h_{conv}}$$

Radiation

Long-wave

$$q_{1\to 2} = \frac{\sigma\left(T^4_{surf,1} - T^4_{surf,2}\right)}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{A_1}{A_2}\frac{1-\varepsilon_2}{\varepsilon_2} + \frac{1}{F_{12}}}$$

$$q_{rad,1\to 2} = h_{rad}\left(T_{surf,1} - T_{surf,2}\right)$$

$$h_{rad} = \frac{4\sigma T^3_{avg}}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad R_{rad} = \frac{1}{h_{rad}}$$

Or more simply: $q_{1\to 2} = \varepsilon_{surf}\sigma F_{12}\left(T^4_{surf,1} - T^4_{surf,2}\right)$

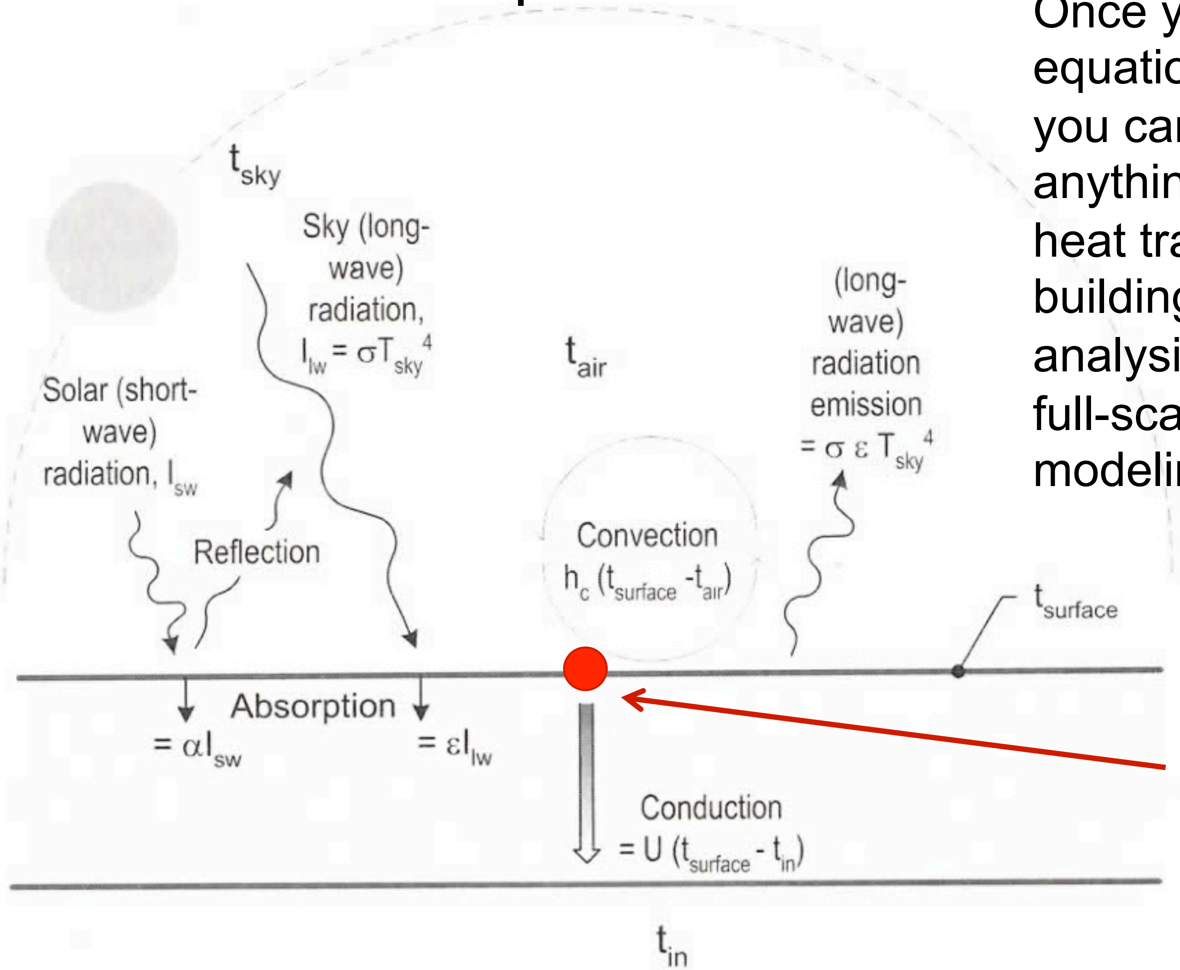
Solar radiation: (opaque surface) $q_{solar} = \alpha I_{solar}$

Transmitted solar radiation: (transparent surface) $q_{solar} = \tau I_{solar}$

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



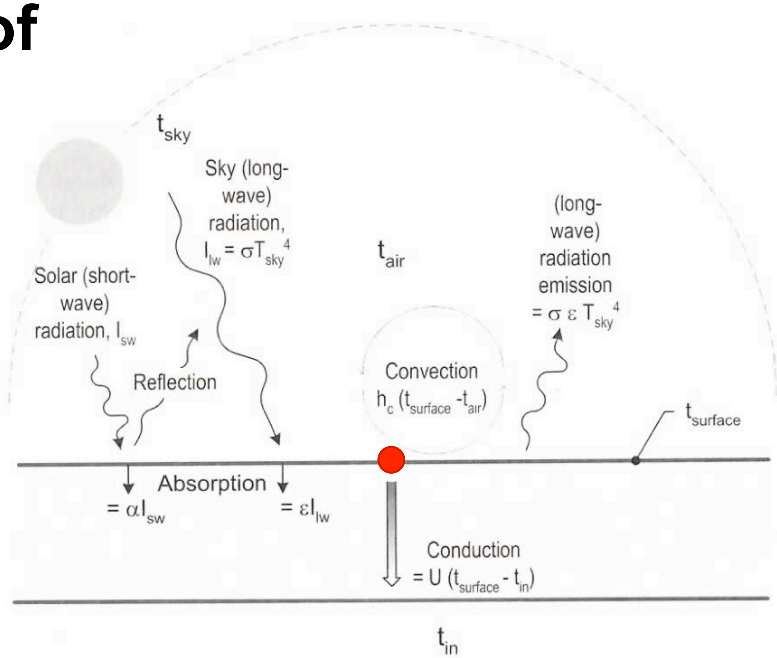
Steady-state energy balance at this exterior surface:
What enters must also leave (no storage)

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

Surface energy balance: Bringing all the modes together

- Exterior surface example: **Roof**

$$\sum q = 0$$



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

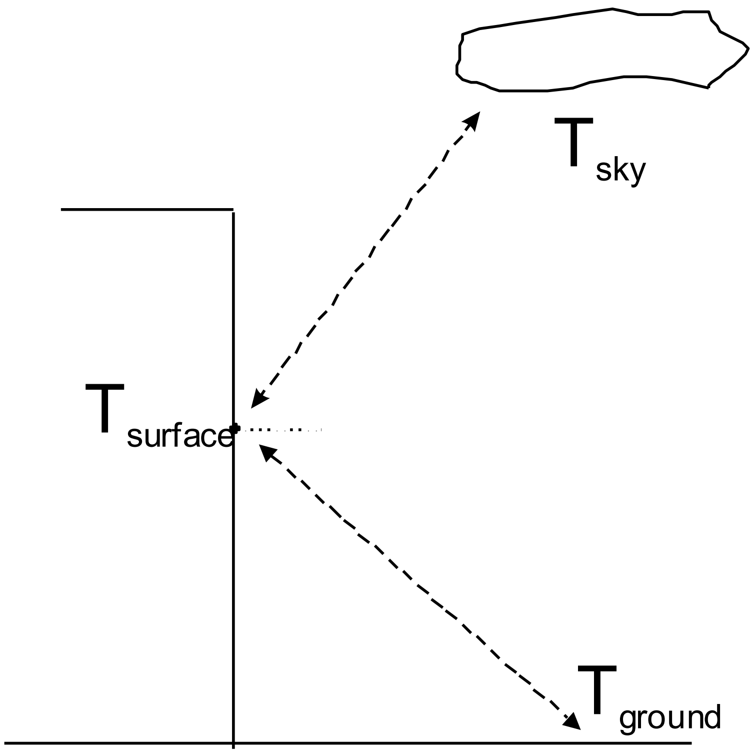
At steady state, net energy balance is zero

- Because of T^4 term, often requires iteration

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

Typical view factors, F_{1-2}

- Some typical view factors from surfaces to ground or sky

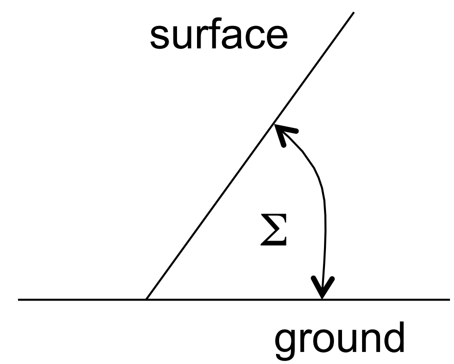


View ("shape") factors for:

Vertical surfaces:
- To sky ($F_{surface-sky}$) 0.5
- To ground ($F_{surface-ground}$) 0.5

Horizontal surfaces:
- To sky ($F_{surface-sky}$) 1
- To ground ($F_{surface-ground}$) 0

3) Tilted surfaces
- To sky $(1+\cos\Sigma)/2$
- To ground $(1-\cos\Sigma)/2$



Typically assume:

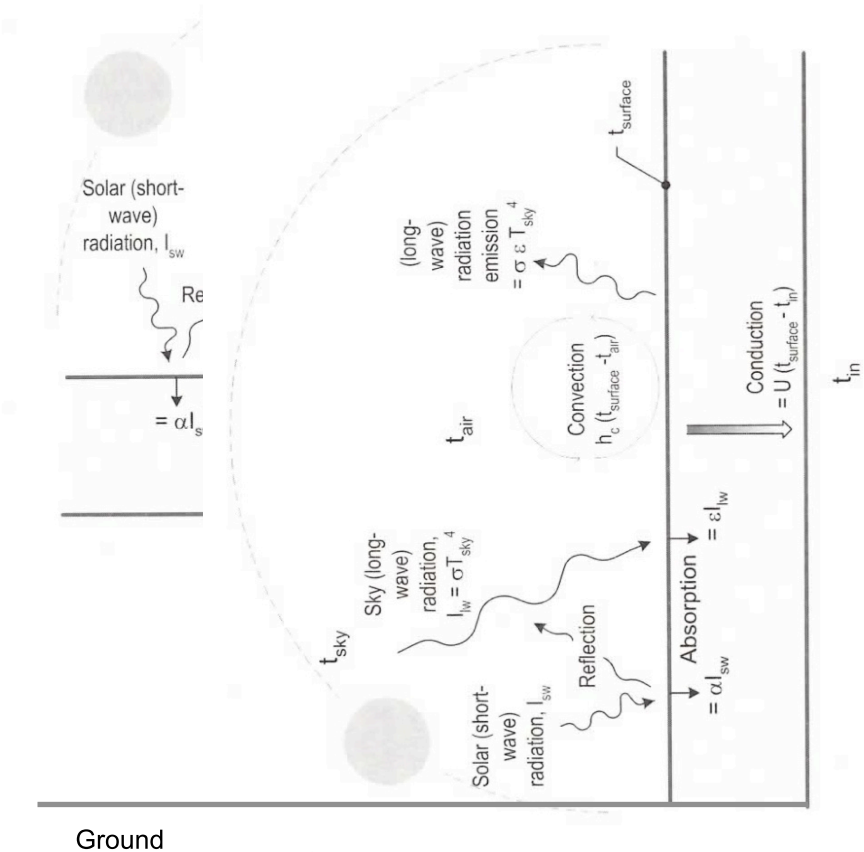
$$T_{ground} = T_{air}$$

*Note that other surrounding buildings complicate view factors, but their net temperature differences probably aren't that different so long-wave radiation can be negligible

Surface energy balance: Bringing all the modes together

- Similarly, for a vertical surface:

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

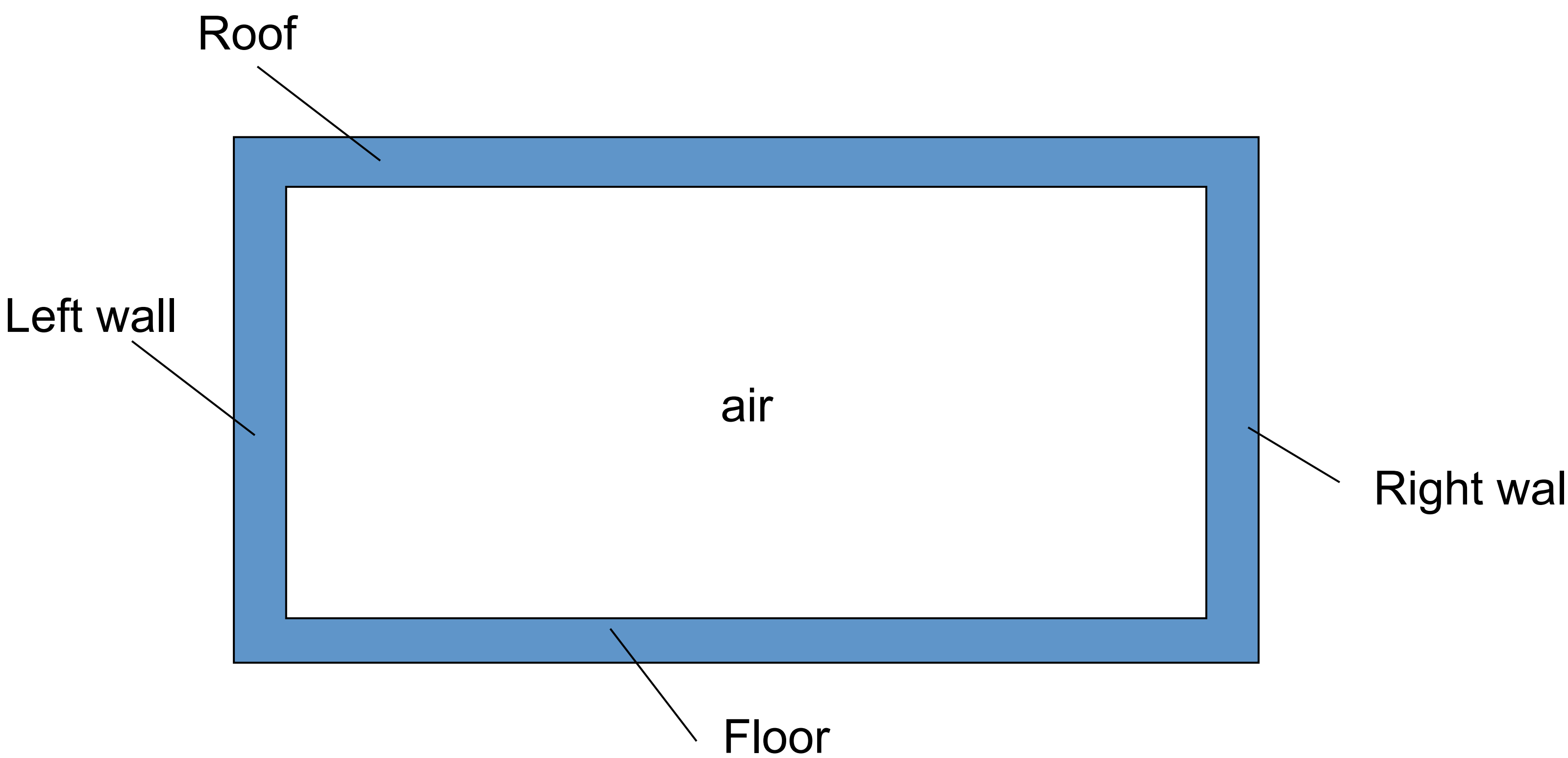


$$\alpha I_{solar}$$
$$+\varepsilon_{surface} \sigma F_{sky} (T_{sky}^4 - T_{surface}^4)$$
$$+\varepsilon_{surface} \sigma F_{ground} (T_{ground}^4 - T_{surface}^4)$$
$$+h_{conv} (T_{air} - T_{surface})$$
$$-U (T_{surface} - T_{surface,interior}) = 0$$

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 numeric methods or discrete 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

Heat Xfer @ external surfaces:
Radiation and convection

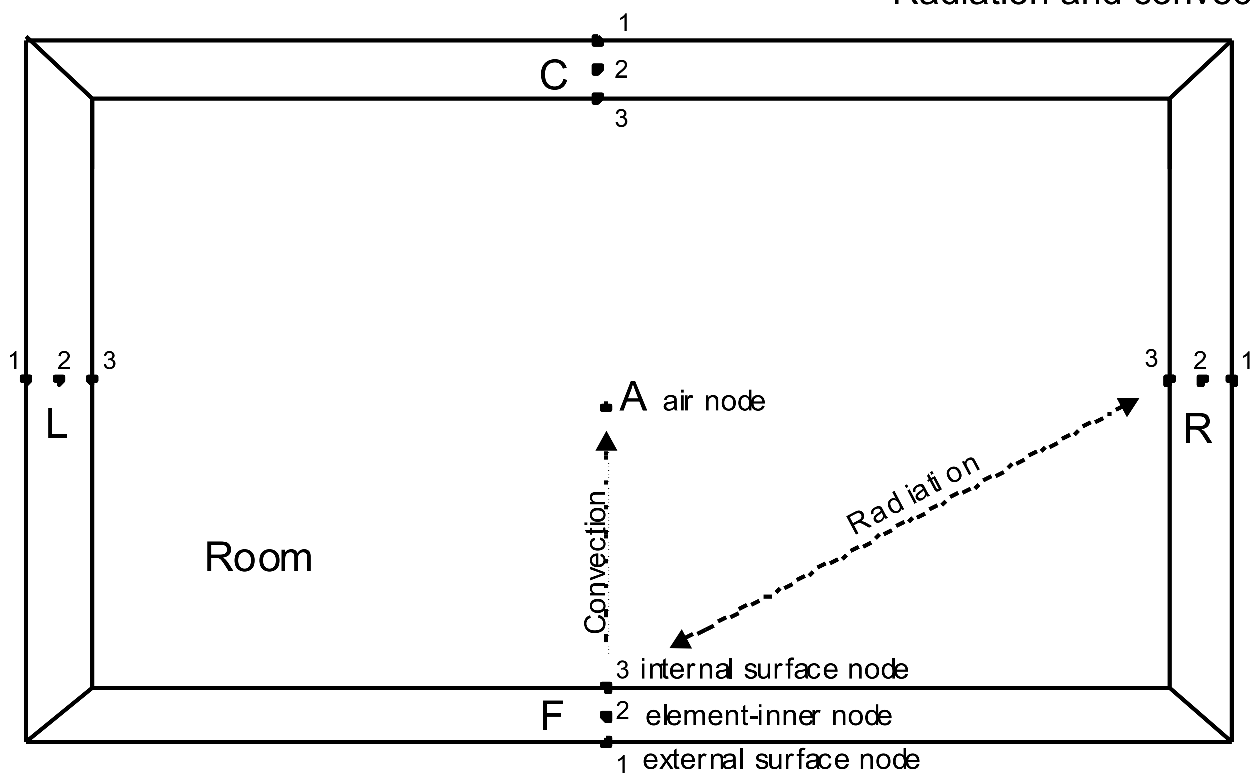
At surface nodes:

$$\sum q = 0$$

At nodes inside materials:

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

Based on density and heat capacity of material

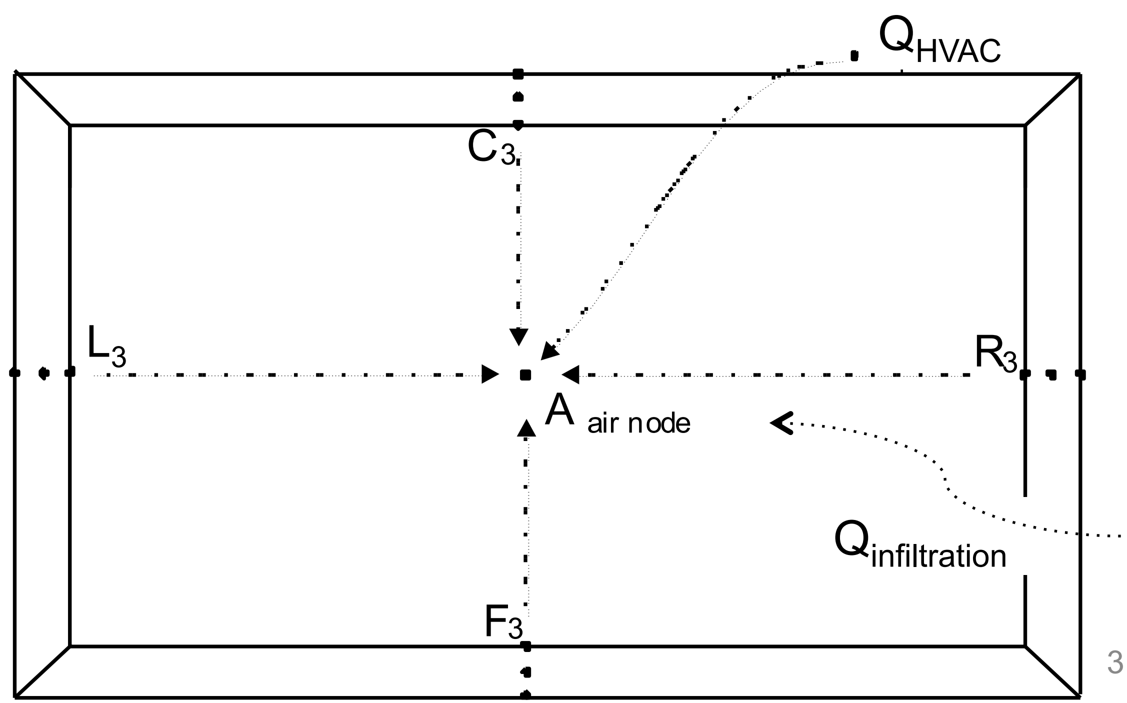


Unsteady energy balance for air node

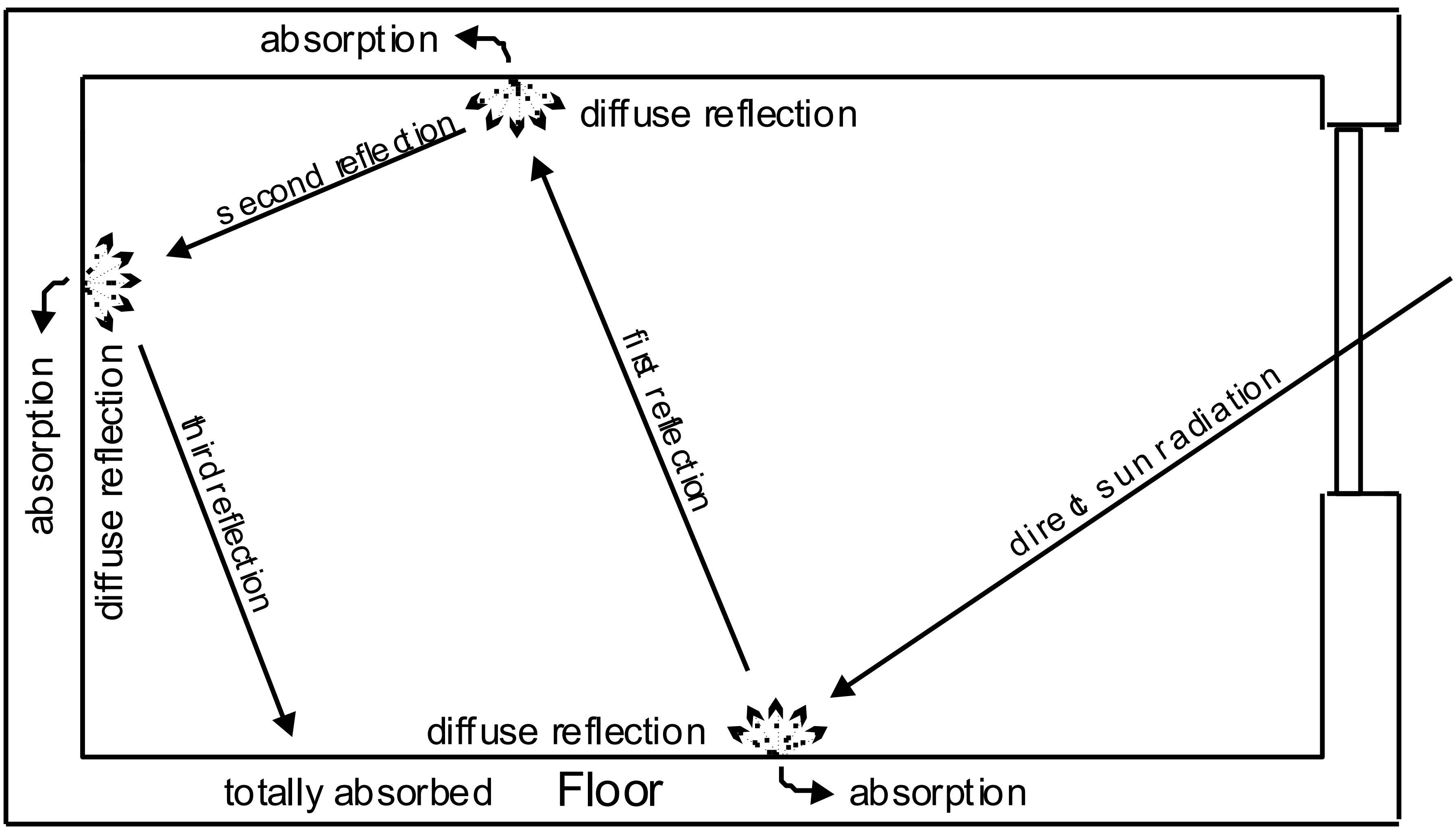
- To get the impact on indoor air temperature (and close the system of equations)
  - Write an energy balance on the indoor air node
  - Air impacted directly only by convection (bulk and surface)

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

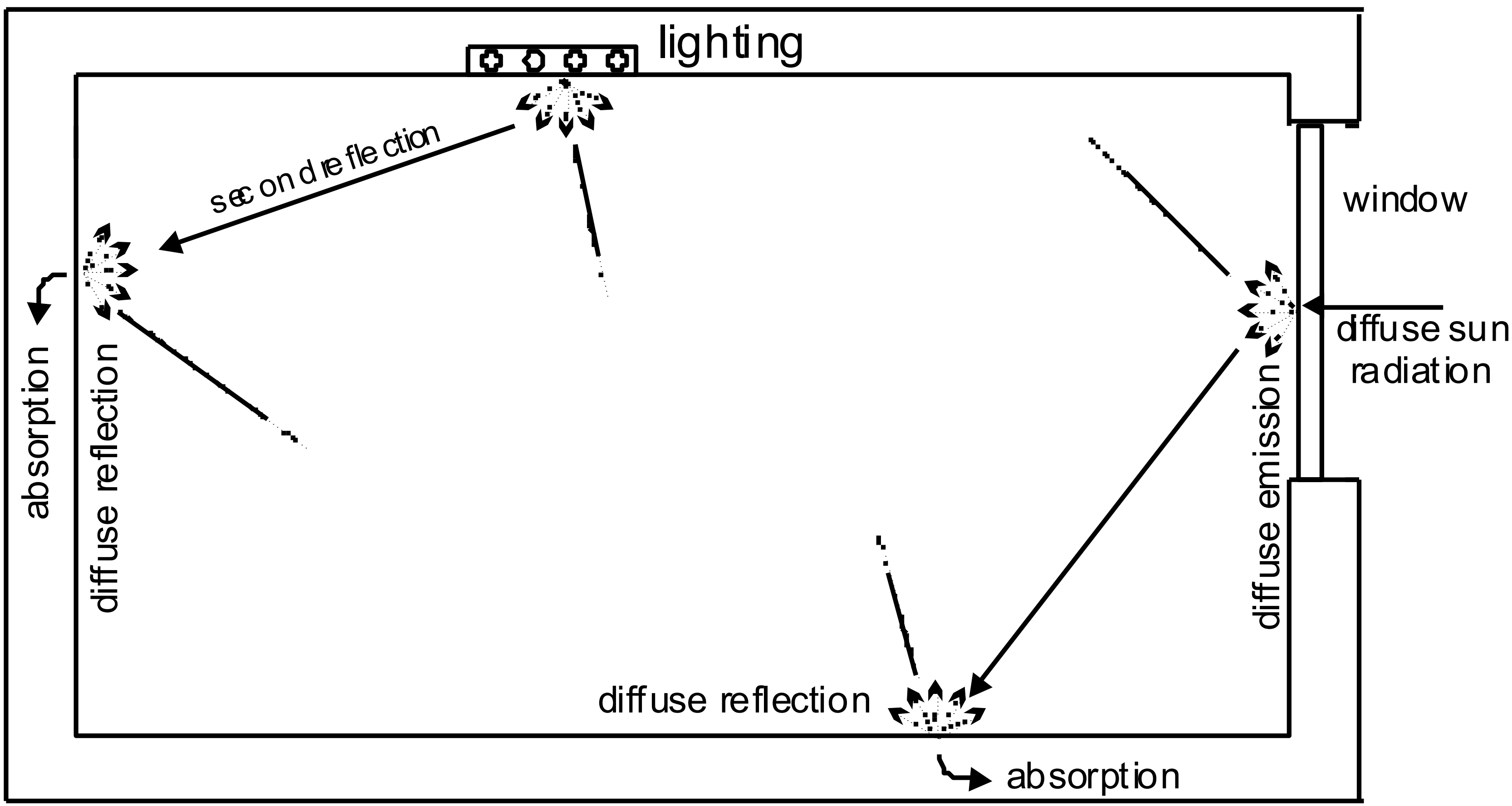
In plain English:
The change in indoor air temperature is equal to the sum of convection from each interior surface plus outdoor air delivery (by infiltration or dedicated outdoor air supply), plus the bulk convective heat transfer delivered by the HVAC system



Adding a window: Direct solar radiation

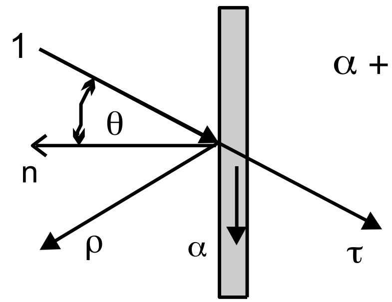


Adding a window: Diffuse solar radiation



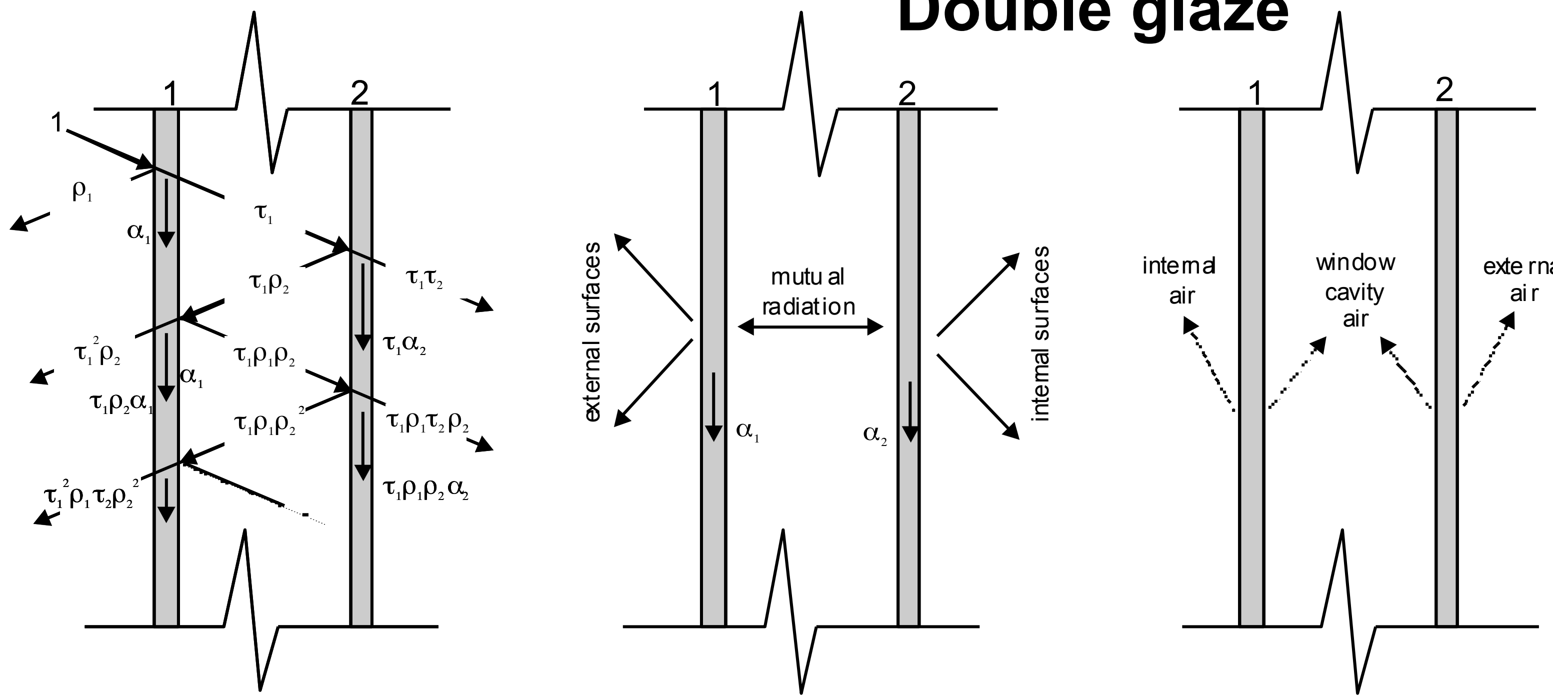
Heat transfer in windows

Single glaze



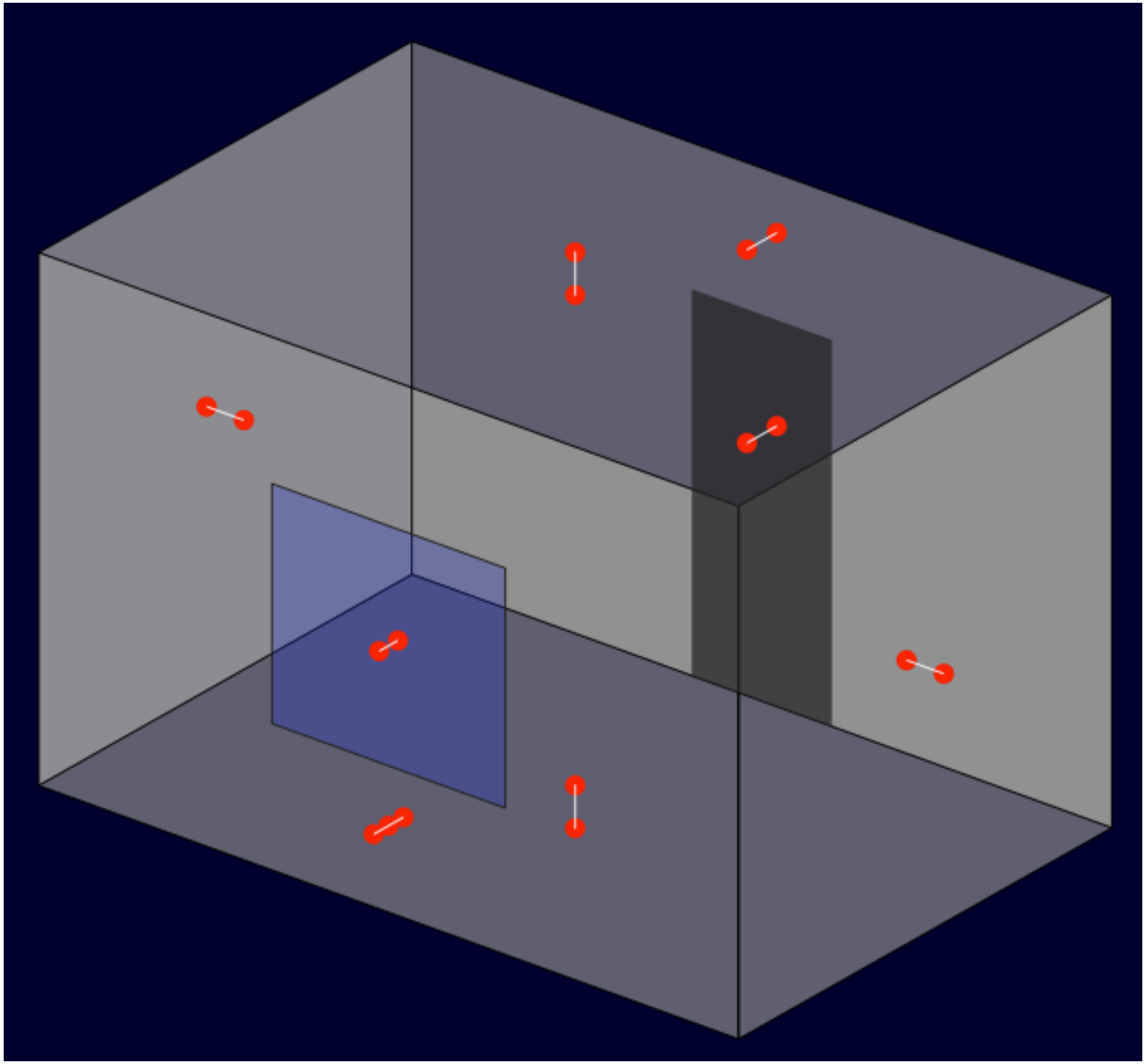
$$\alpha + \rho + \tau = 1$$

Double glaze



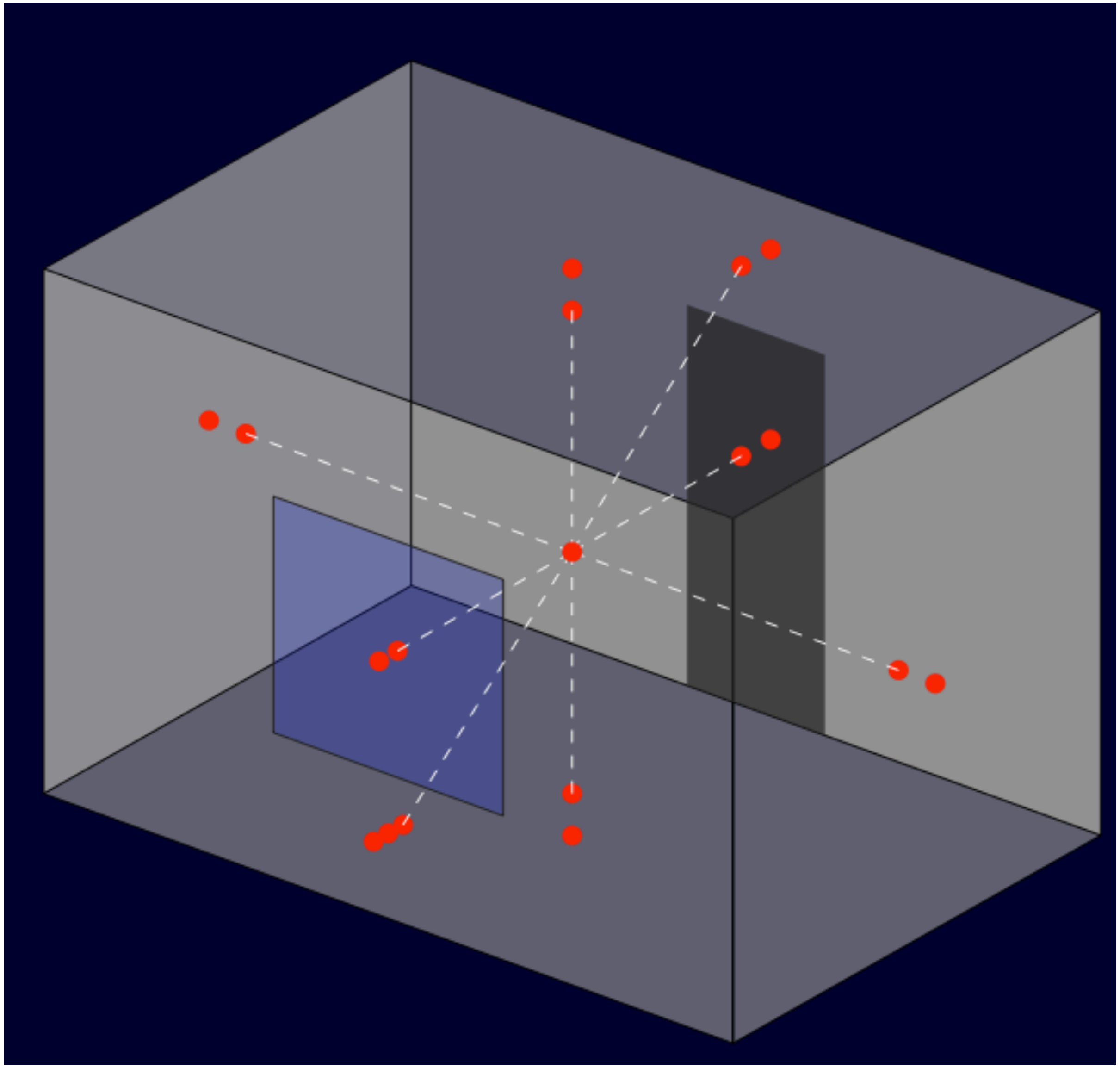
a) Short-wave radiation b) Long-wave radiation c) Convection

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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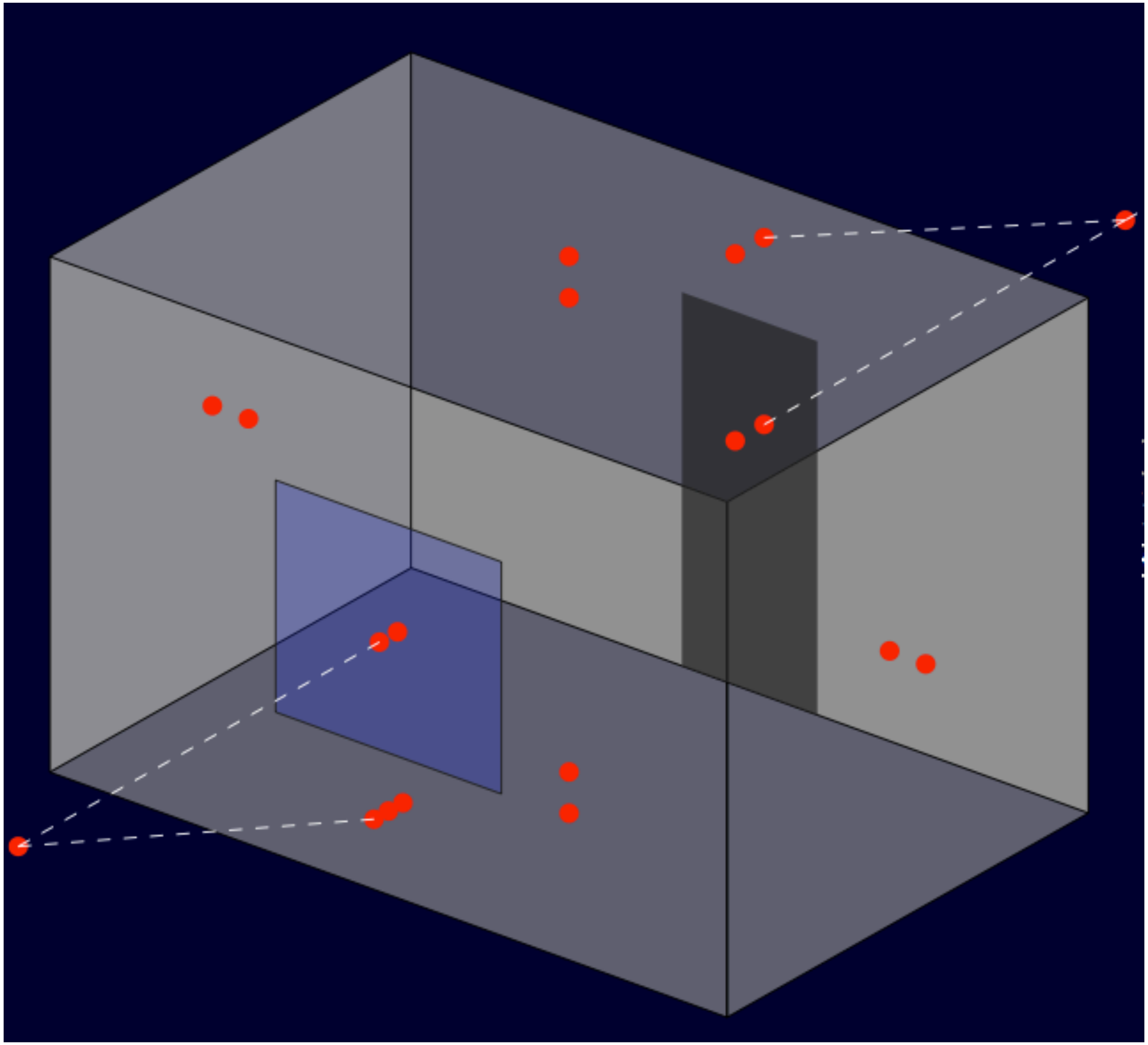
Simplest 'box' model: Exterior convection elements



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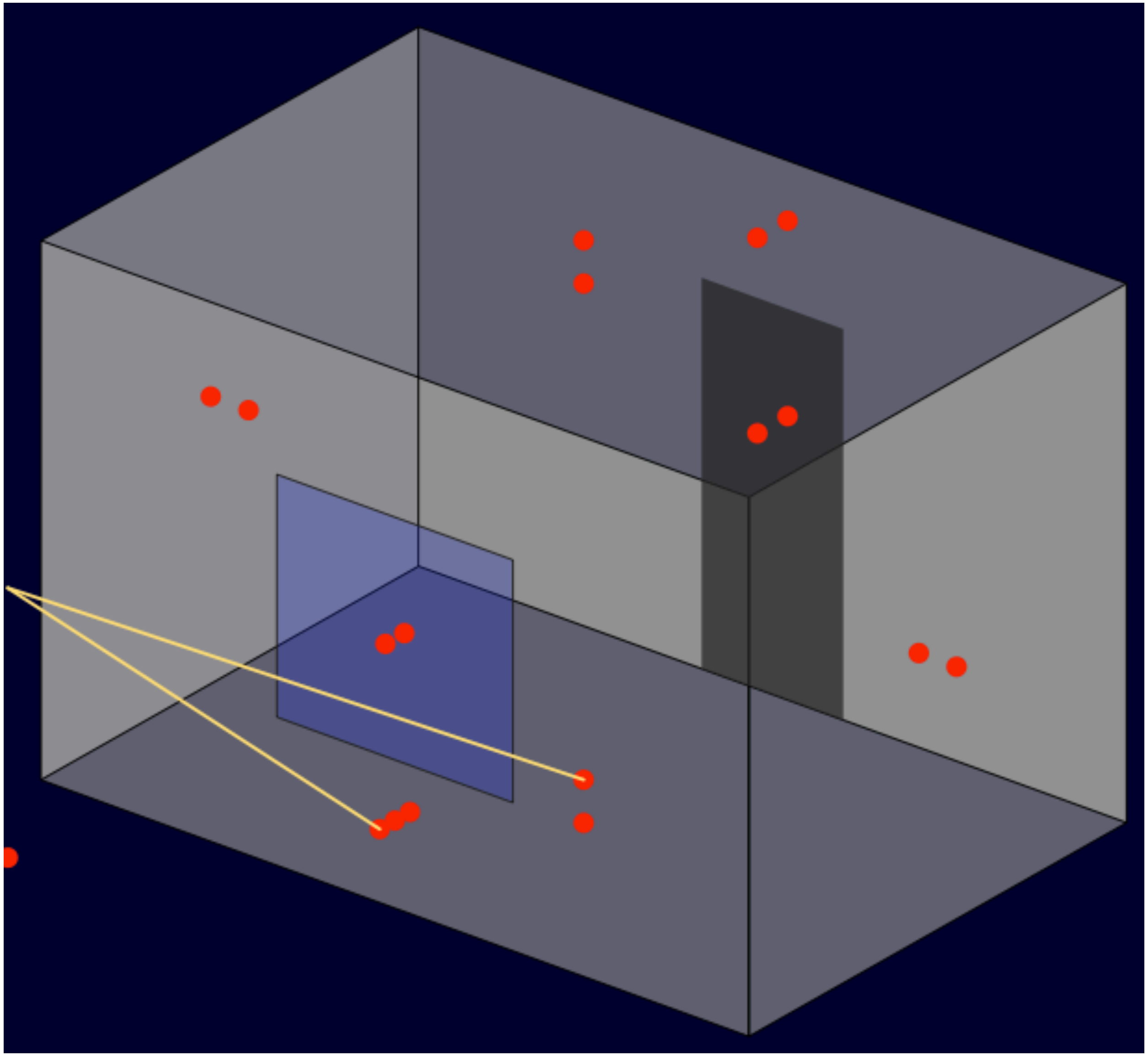
Simplest ‘box’ model: Solar (direct + diffuse)



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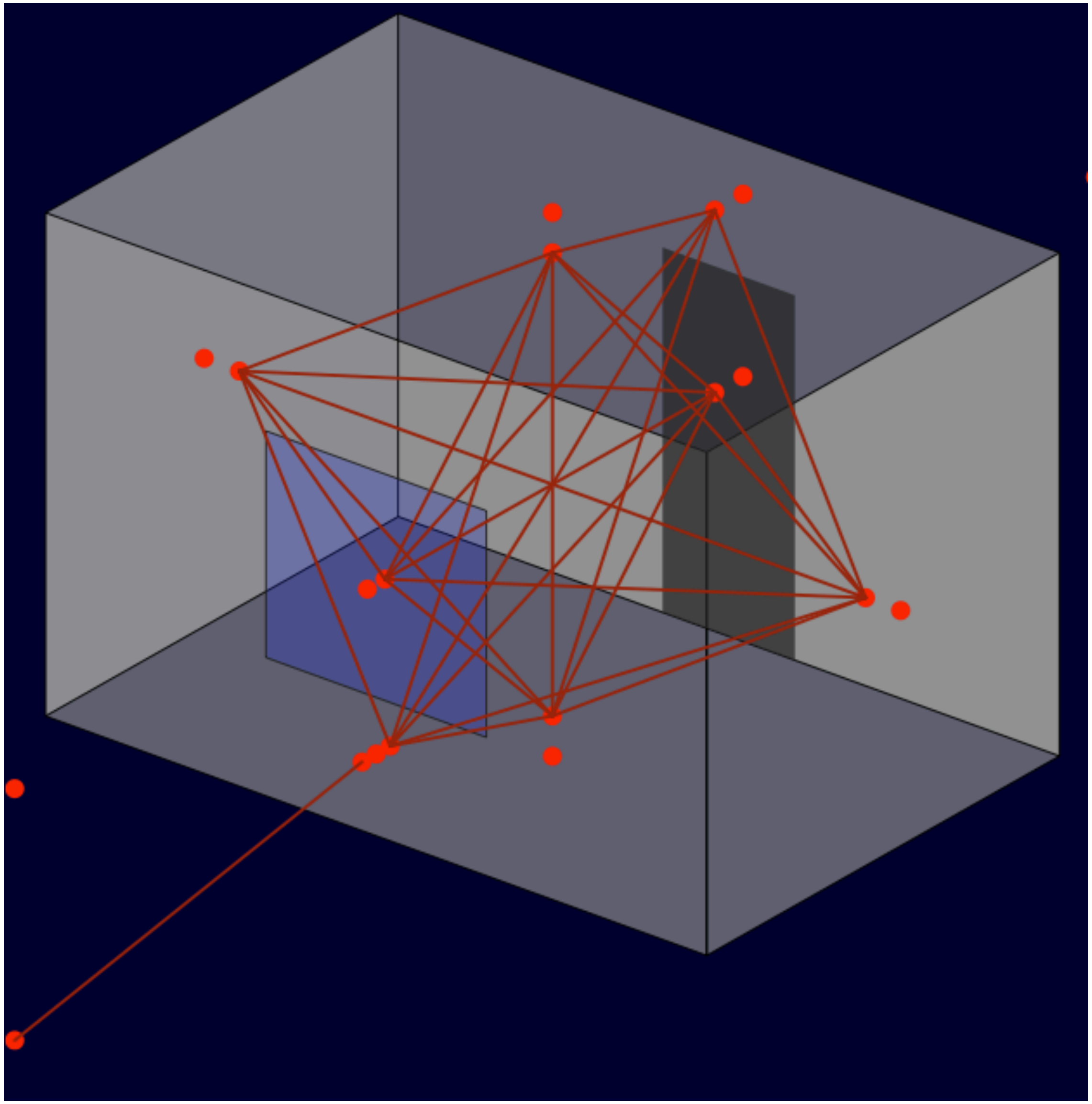
Simplest 'box' model: Long wave radiation elements



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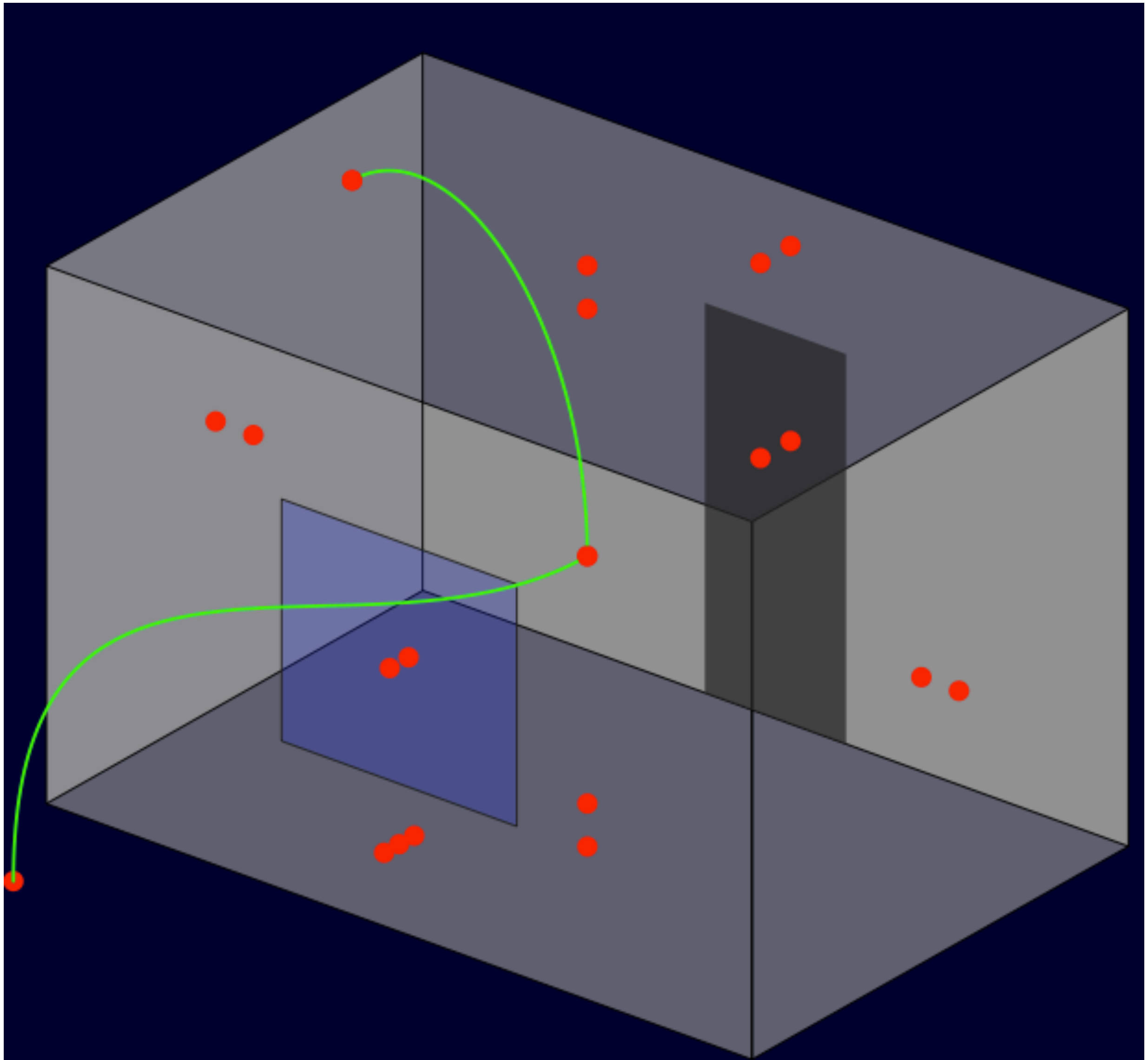
Simplest 'box' model: Ventilation/infiltration elements



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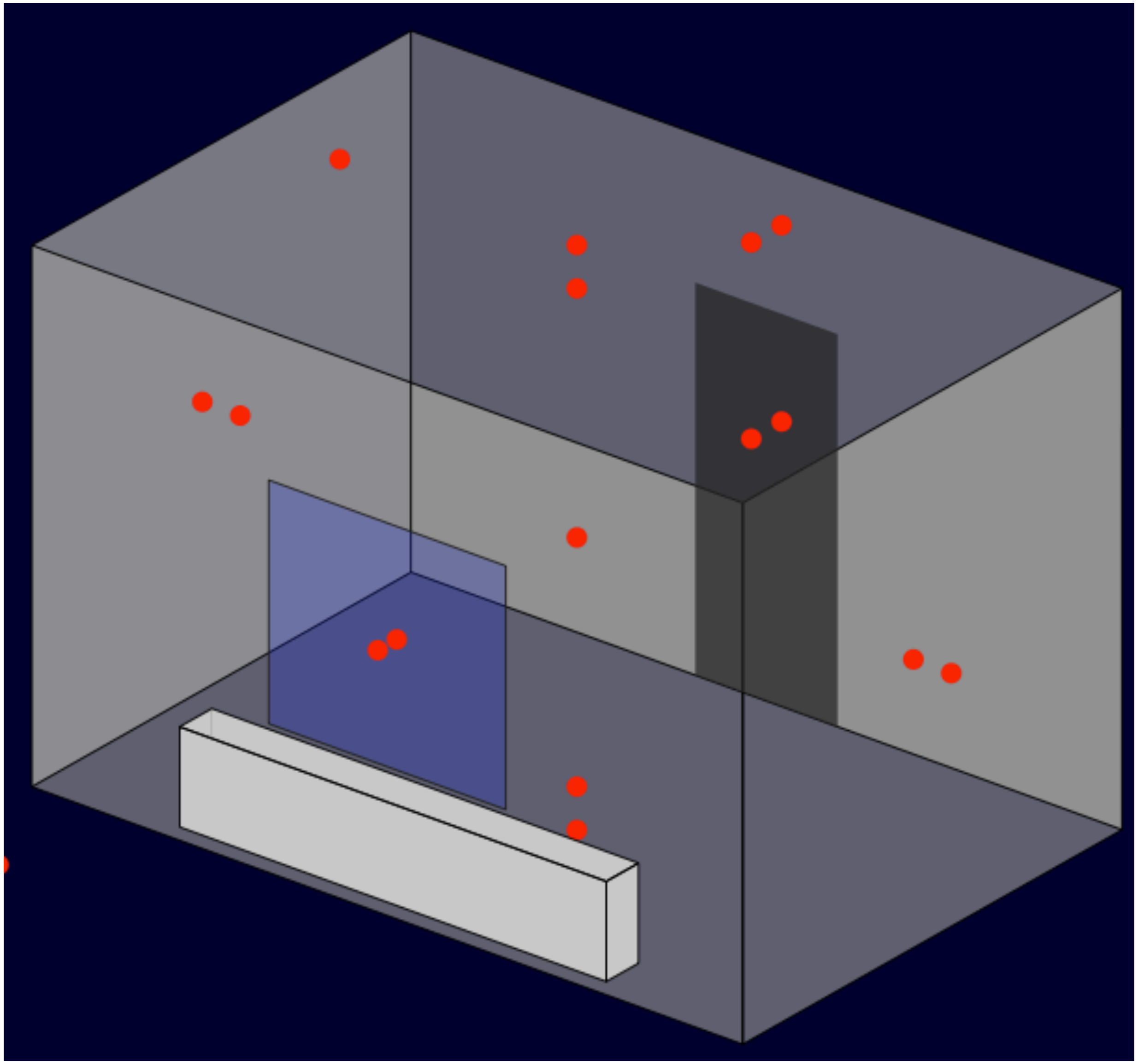
Simplest 'box' model: Internal mass (e.g., furniture)



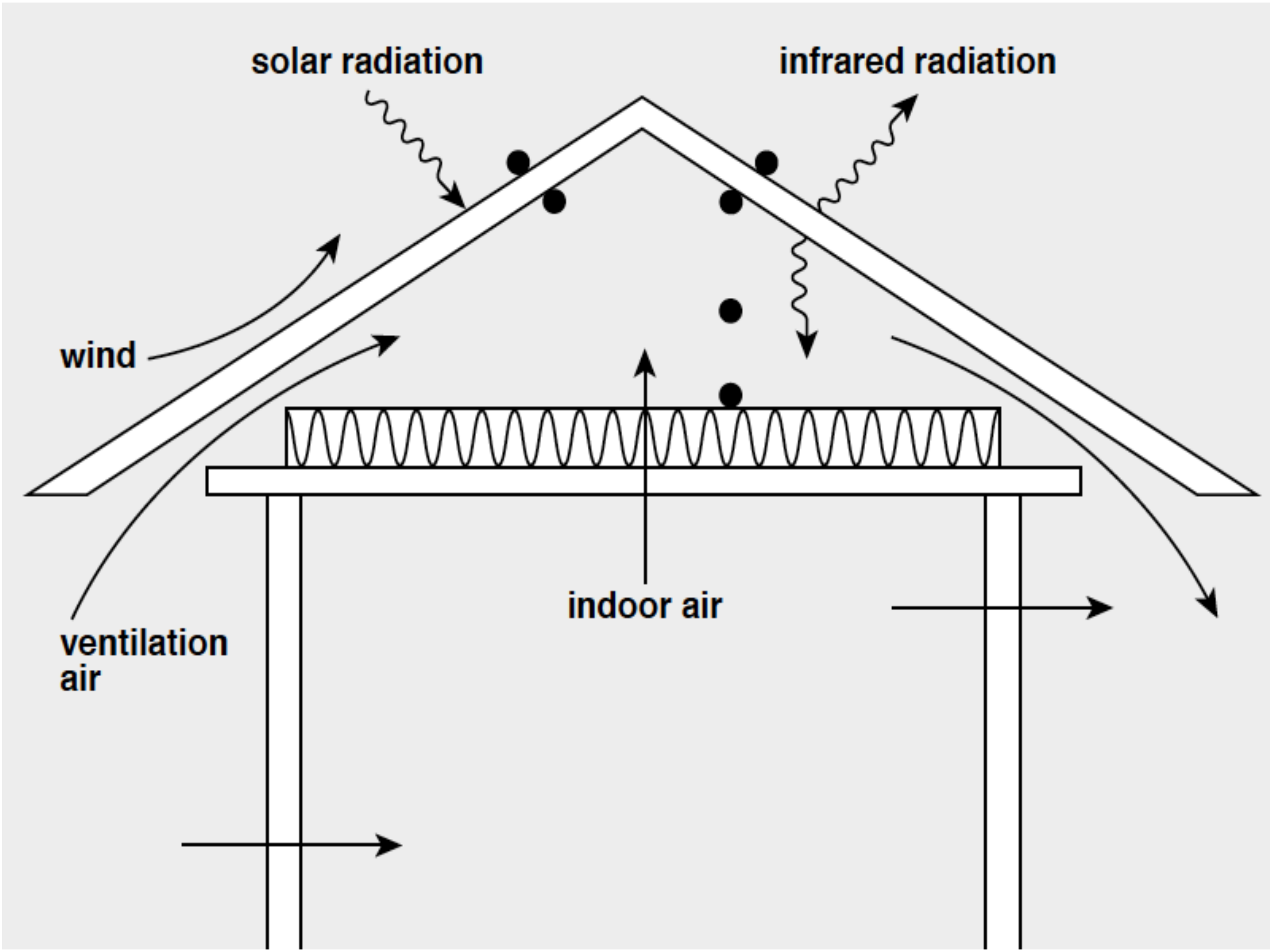
http://www.ibpsa.us/pub/simbuild2008/presentations/SB08-PPT-IS06-Augenbroe.pdf

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

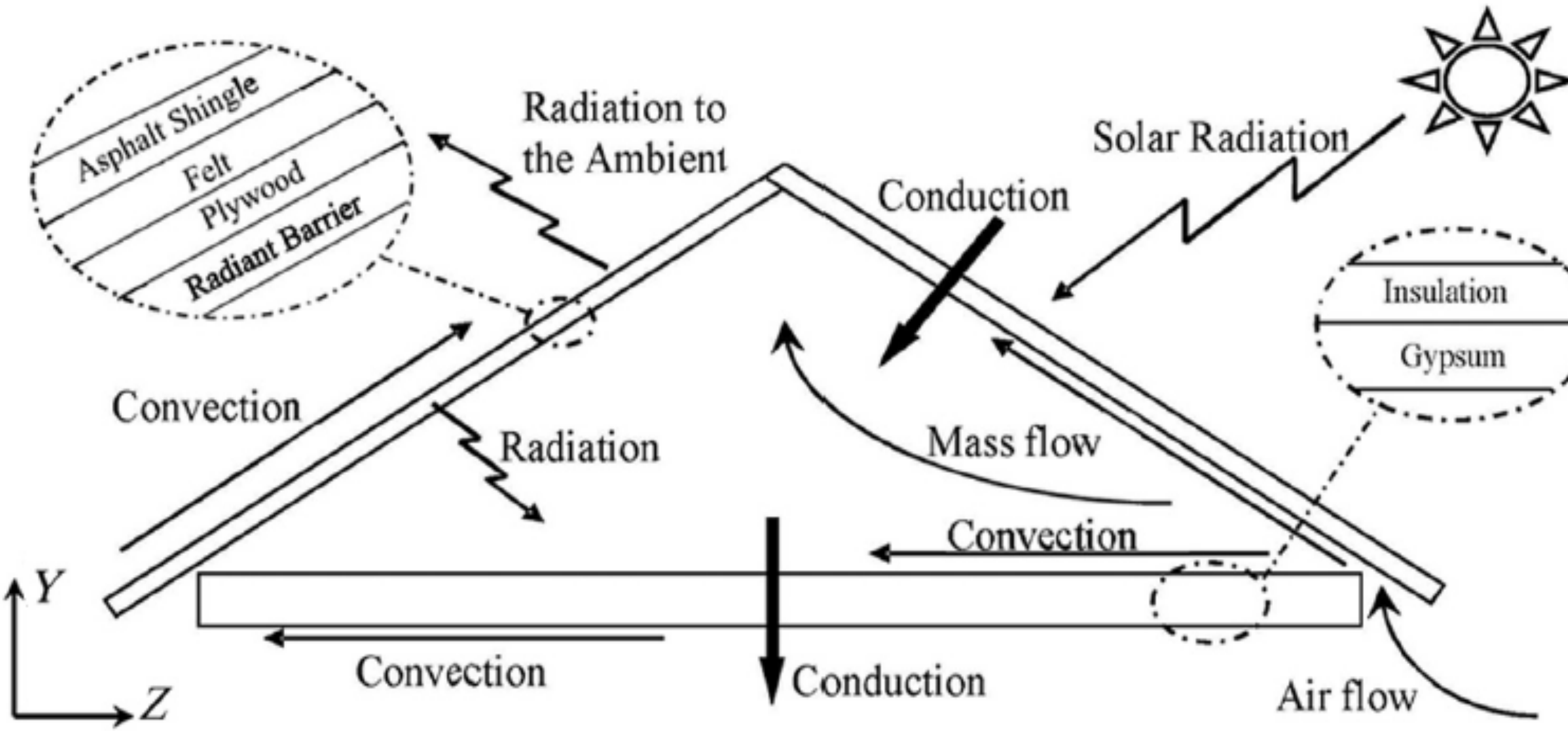
BUILDING ENERGY SIMULATION EXAMPLE: ATTIC HEAT TRANSFER

Attic simulation example



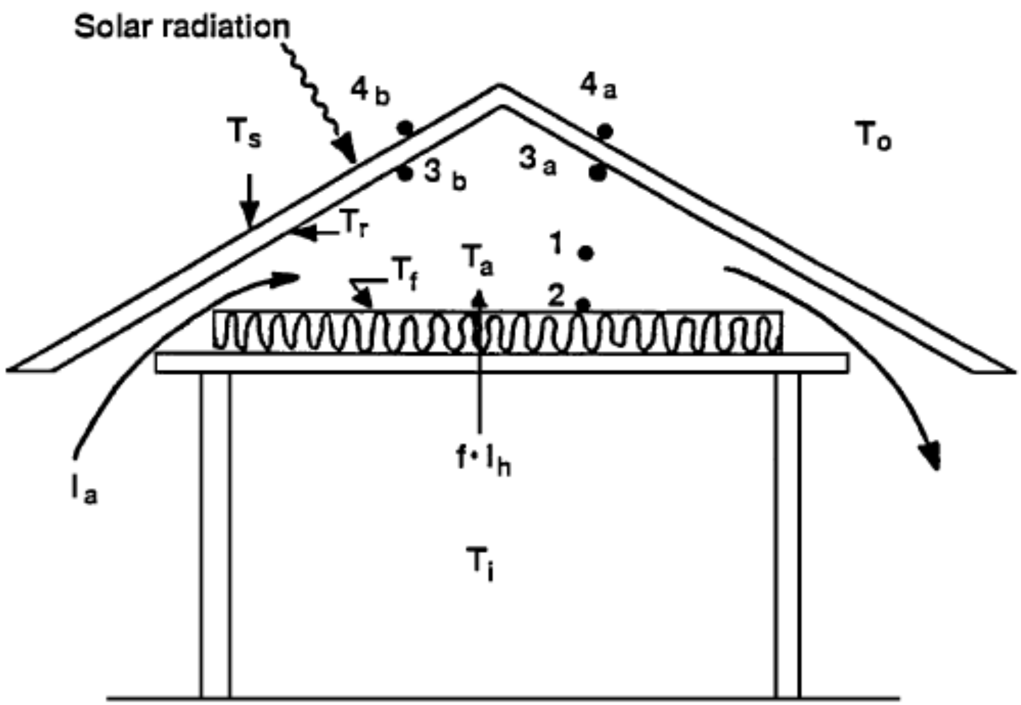
TenWolde, Anton. 1997. FPL roof temperature and moisture model: Description and verification. Res. Pap. FPL–RP–561. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 48 p.

Attic heat transfer



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

Attic heat transfer



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

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

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

$$\frac{T_i - T_f}{R_c} = h_f(T_f - T_a) + \frac{F_1}{2}(T_f - T_{r,1}) + \frac{F_2}{2}(T_f - T_{r,2}) \qquad (3)$$

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:

$$F_n = \frac{\sigma}{(1/\varepsilon_f) + (1/\varepsilon_r) - 1}(T_f^2 + T_{r,n}^2)(T_f + T_{r,n}) \quad n = 1,2$$

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 ($h \cdot ft^2 \cdot °F/Btu$)
$T_{s,n}$ = 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

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

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

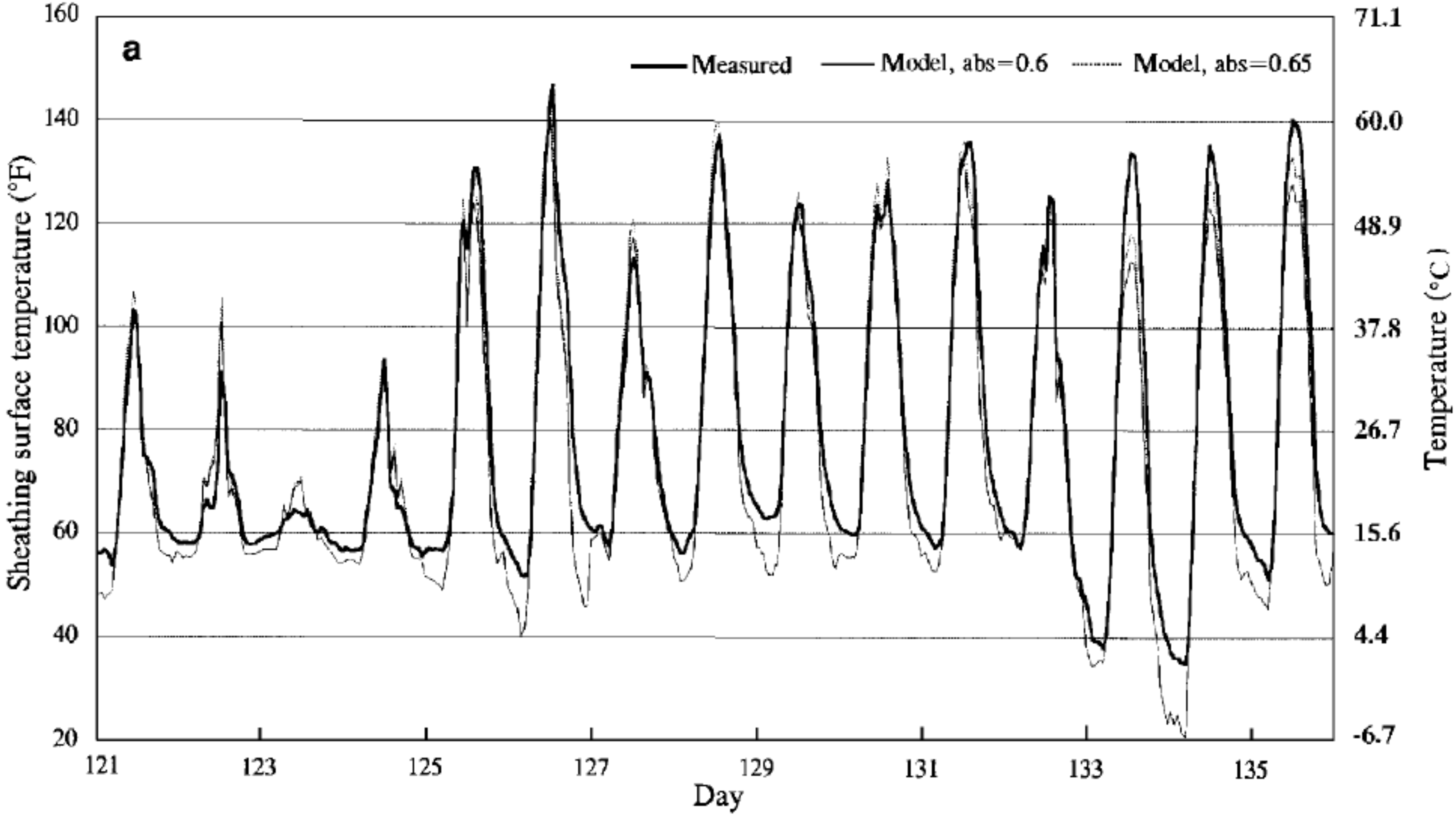


Figure 4—Exterior sheathing surface temperature, bay 2, May 1–15, 1993.

Attic heat transfer

Attic air temperature: Measured vs. modeled

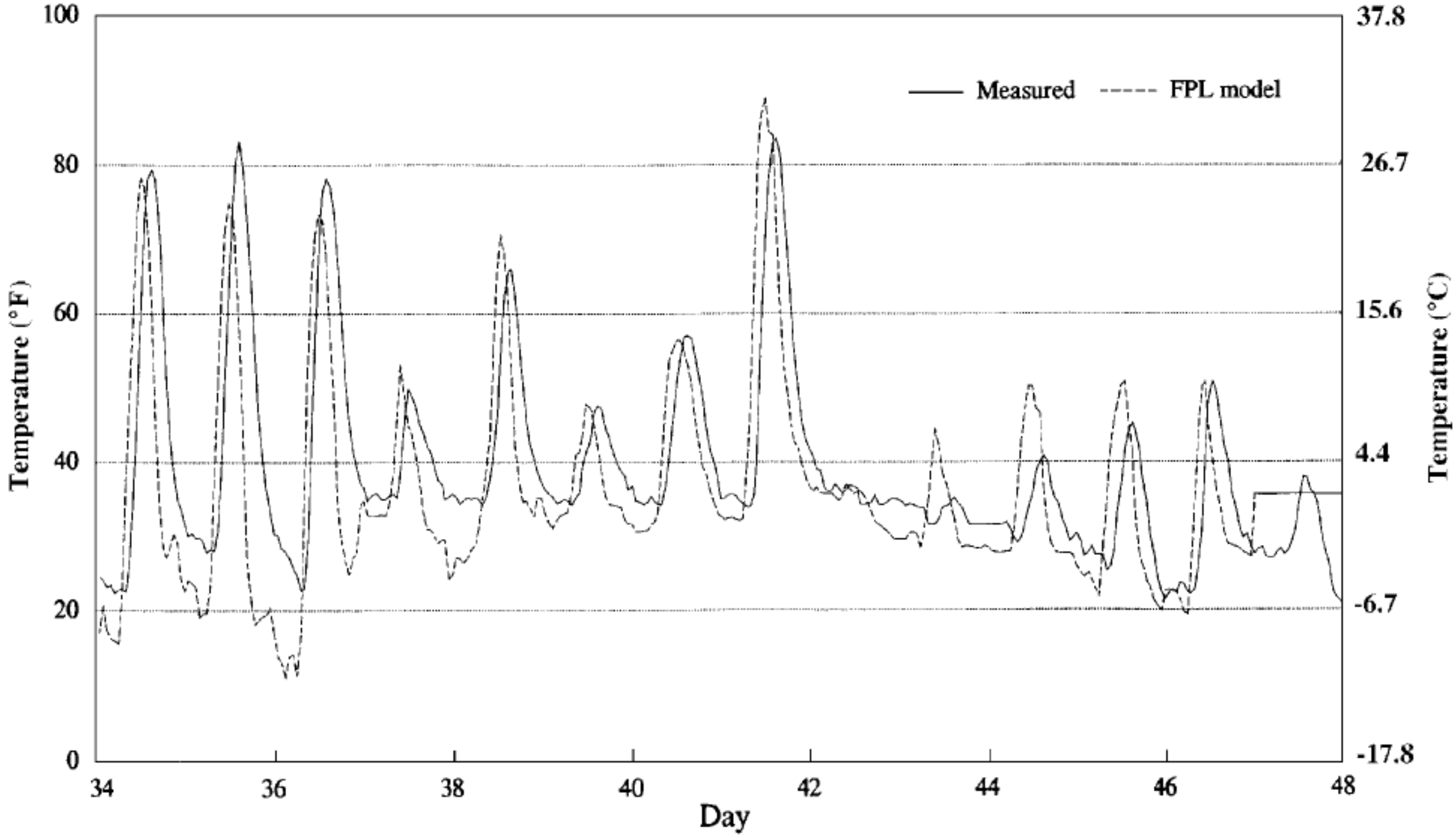


Figure 5—Attic air temperature, bay 2, February 3–16, 1993; absorptance = 0.65.

Attic heat transfer summary

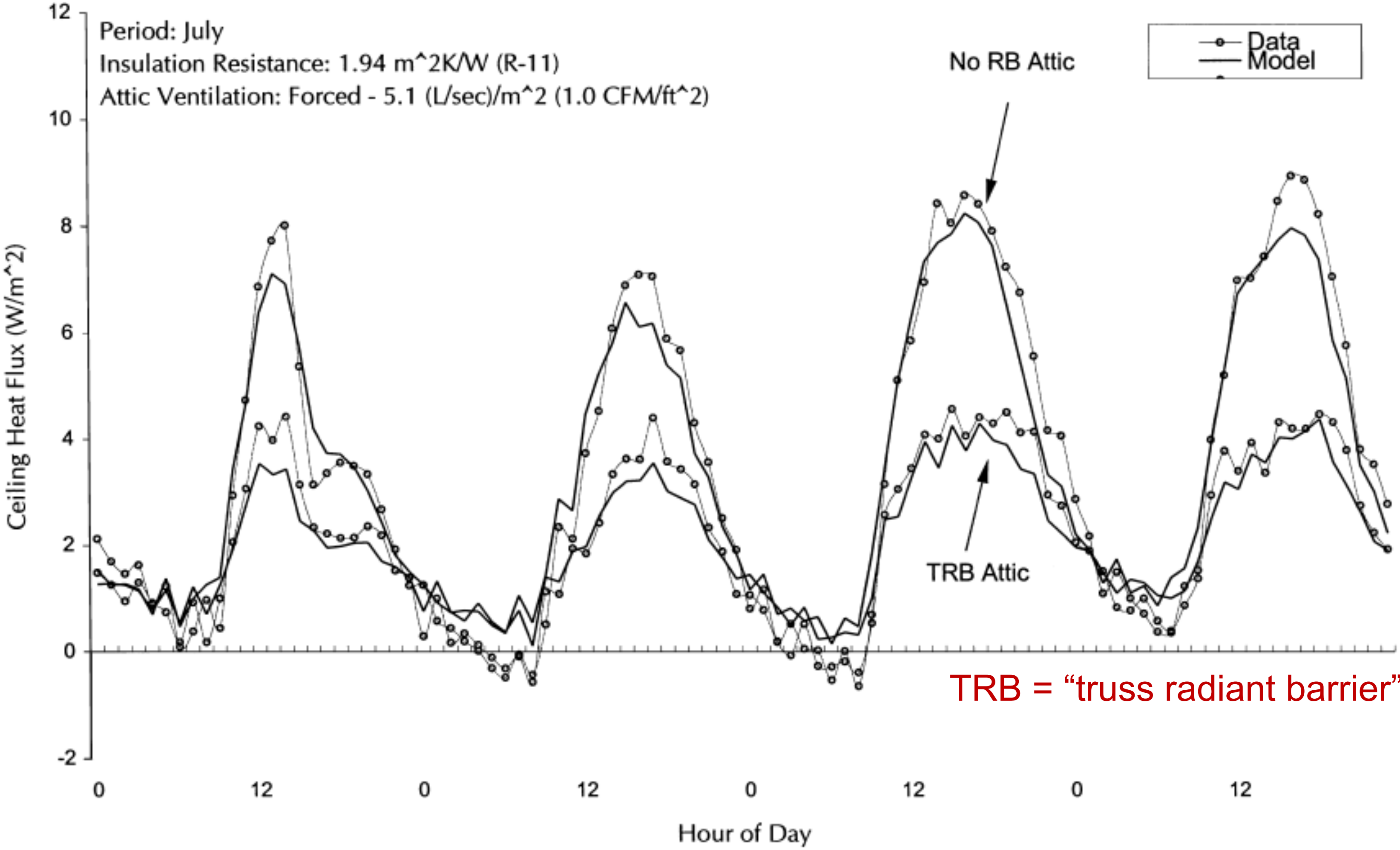
- Attic temperature is important
  - HVAC equipment is often located in attics
  - Impacts conduction across ceiling into interior space

- 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

Impacts of radiant barriers



TRB = “truss radiant barrier”

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.

Impacts of radiant barriers

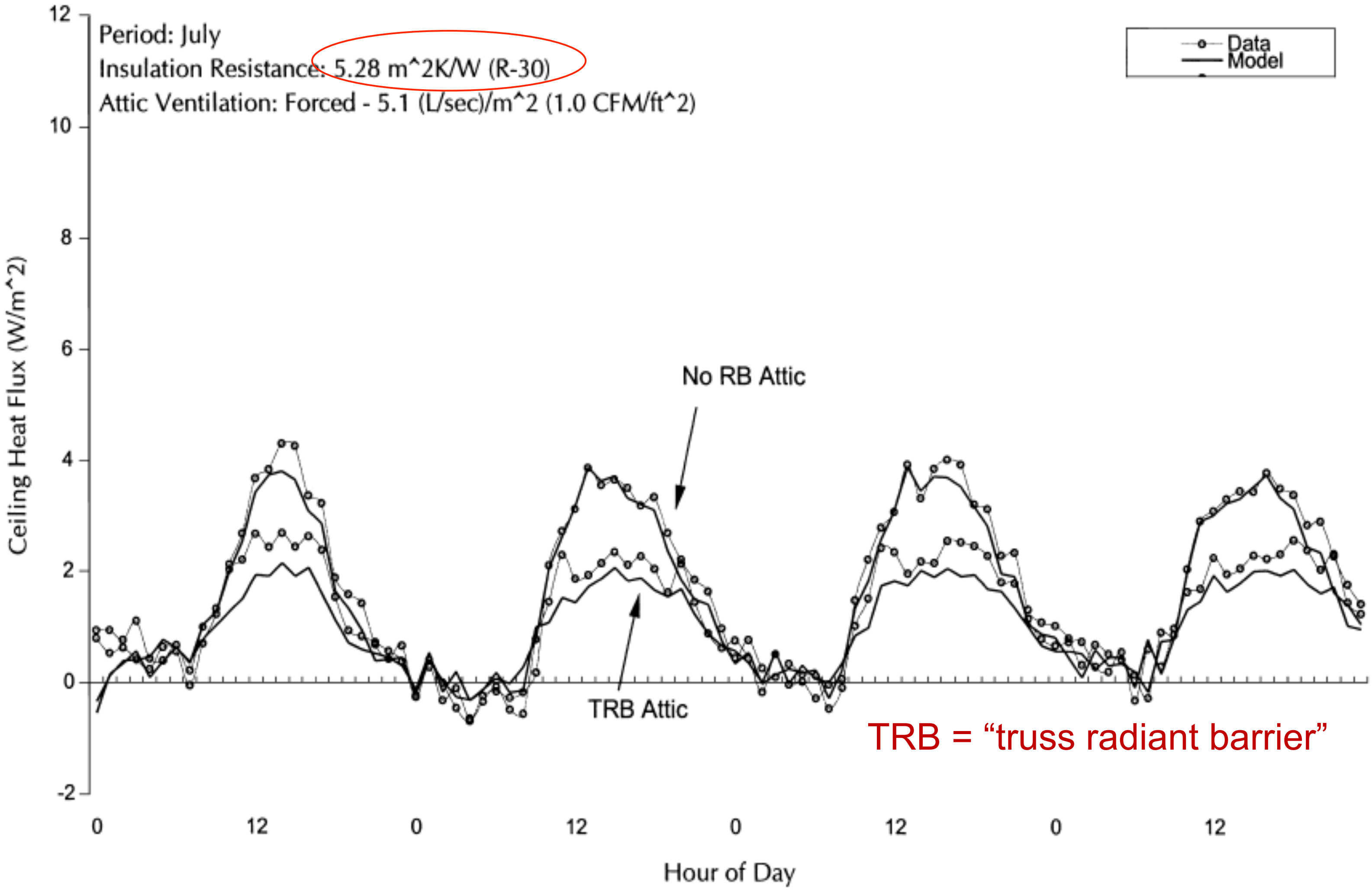
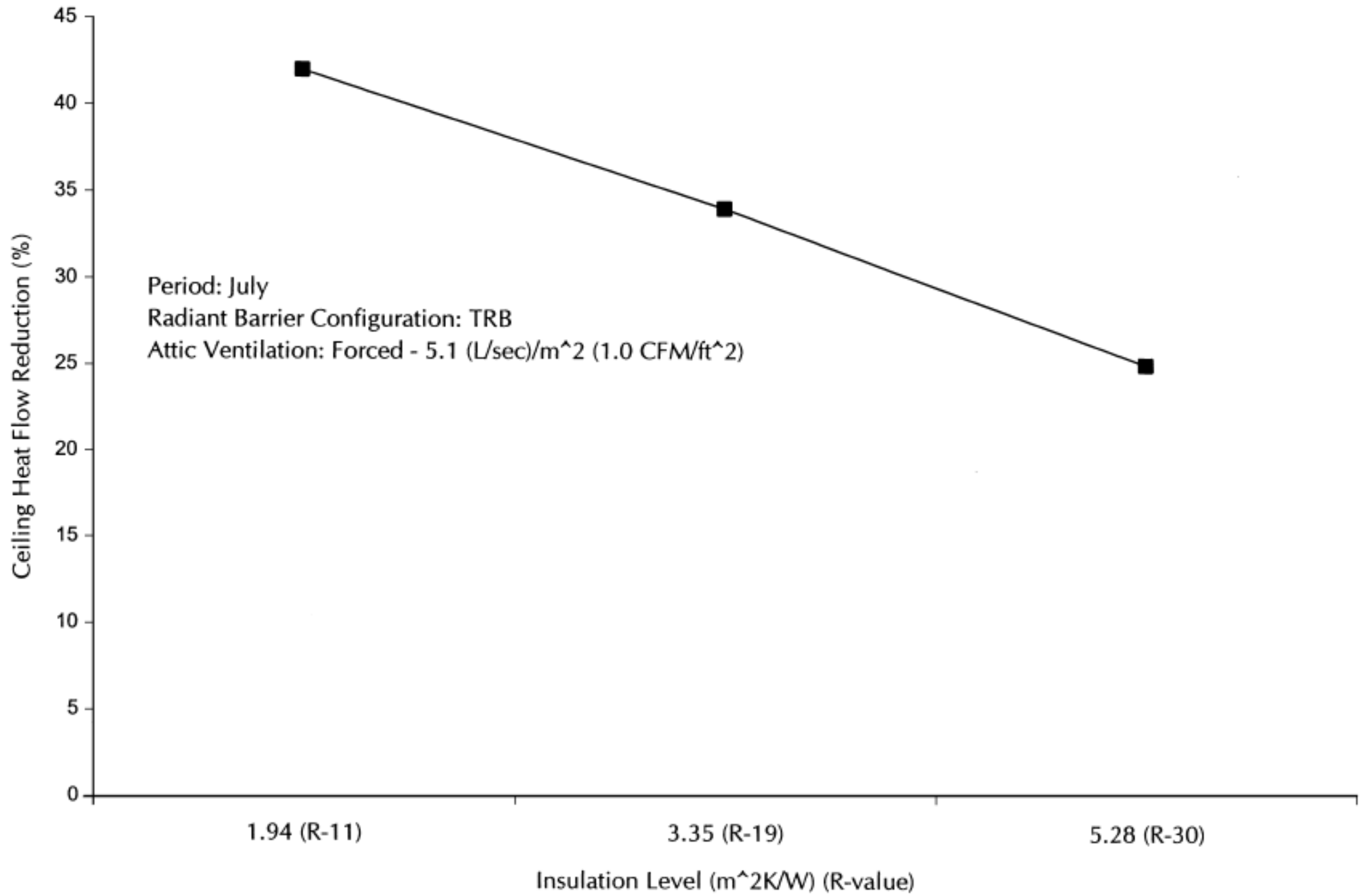


Fig. 7. Ceiling heat fluxes (TRB case, insulation resistance: 5.28 m^2 K/W, *R*-30; with attic airflow rate: 5.1 l/s/m^2, 1.0 CFM/ft^2).

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

Impacts of radiant barriers

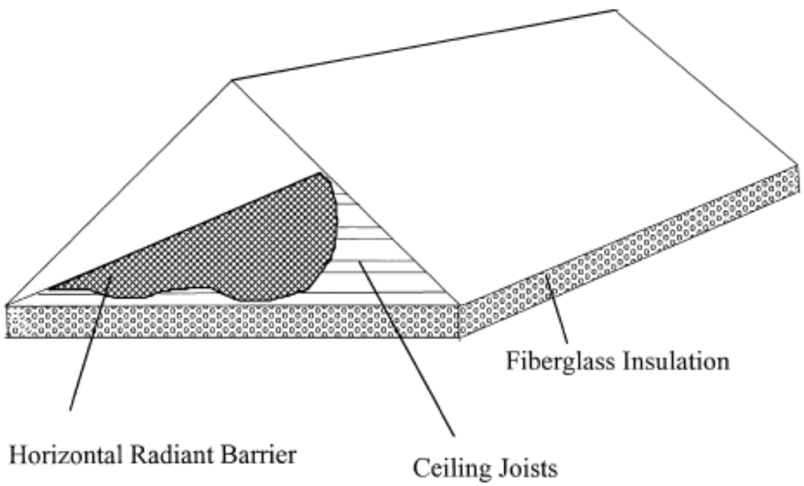
- Radiant barriers have less of an impact on well-insulated roofs

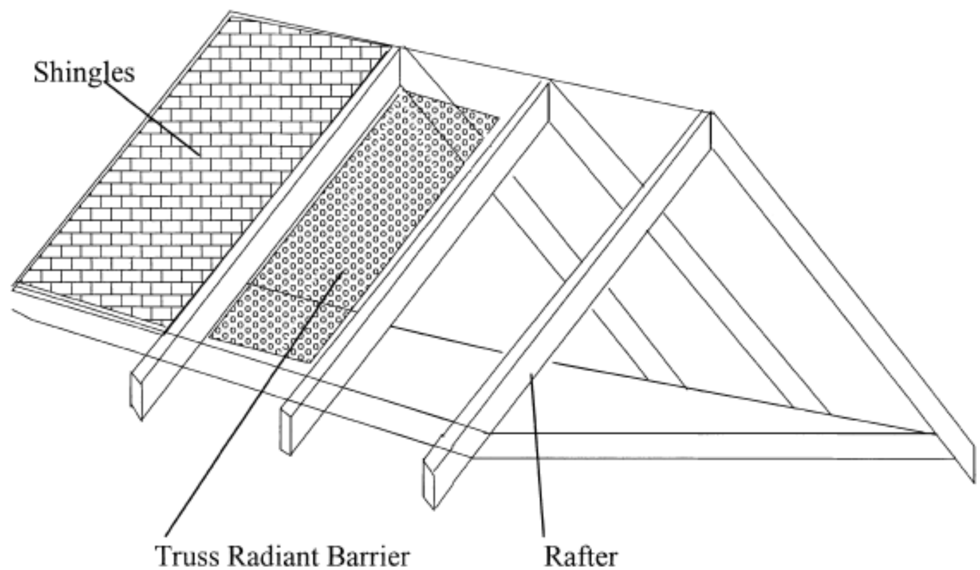


Medina, M. 2000. On the performance of radiant barriers in combination with different attic insulation levels. *Energy and Buildings* 33:31-40.

Impacts of radiant barriers

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





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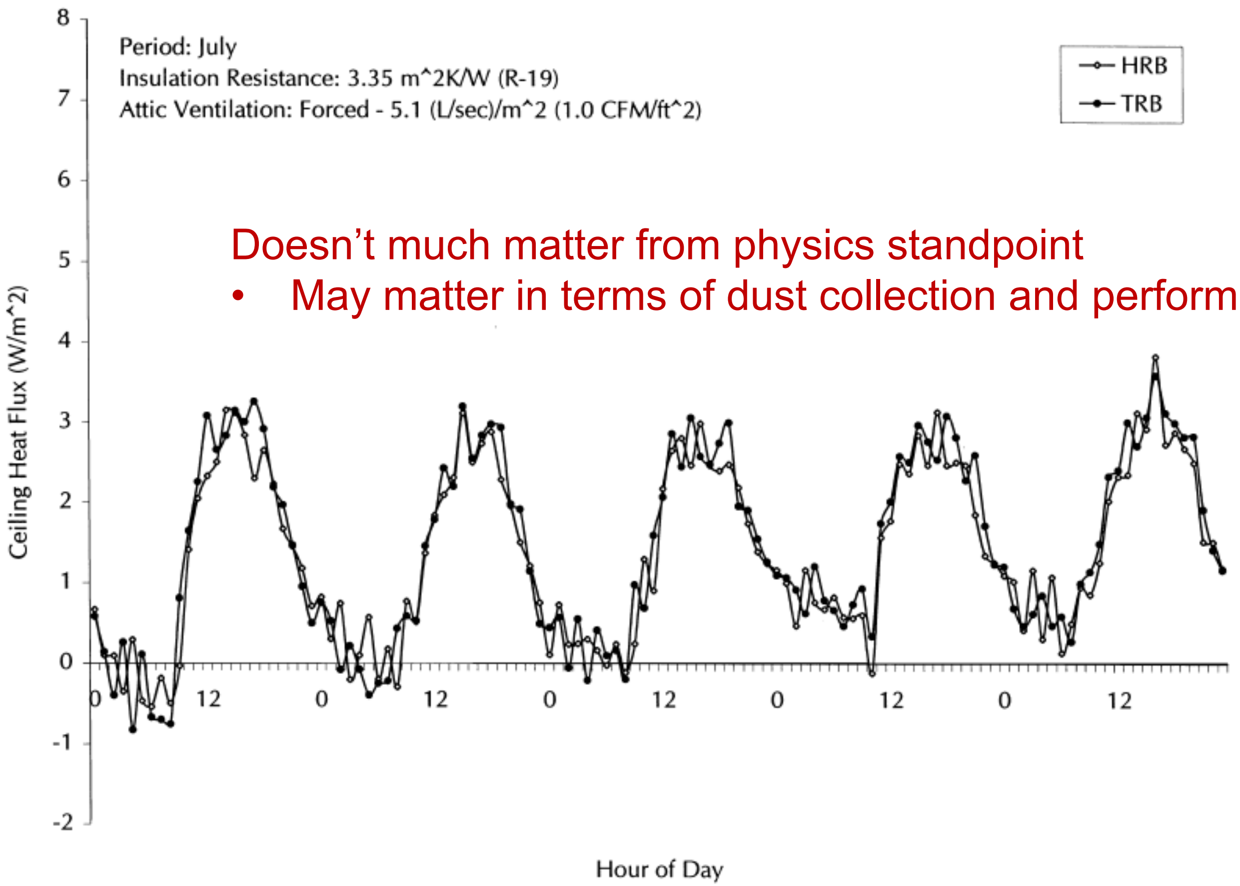
Impacts of radiant barriers

- 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 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 our 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)

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

EnergyPlus Engineering Reference, 2012

Example engineering calculations for BES program

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

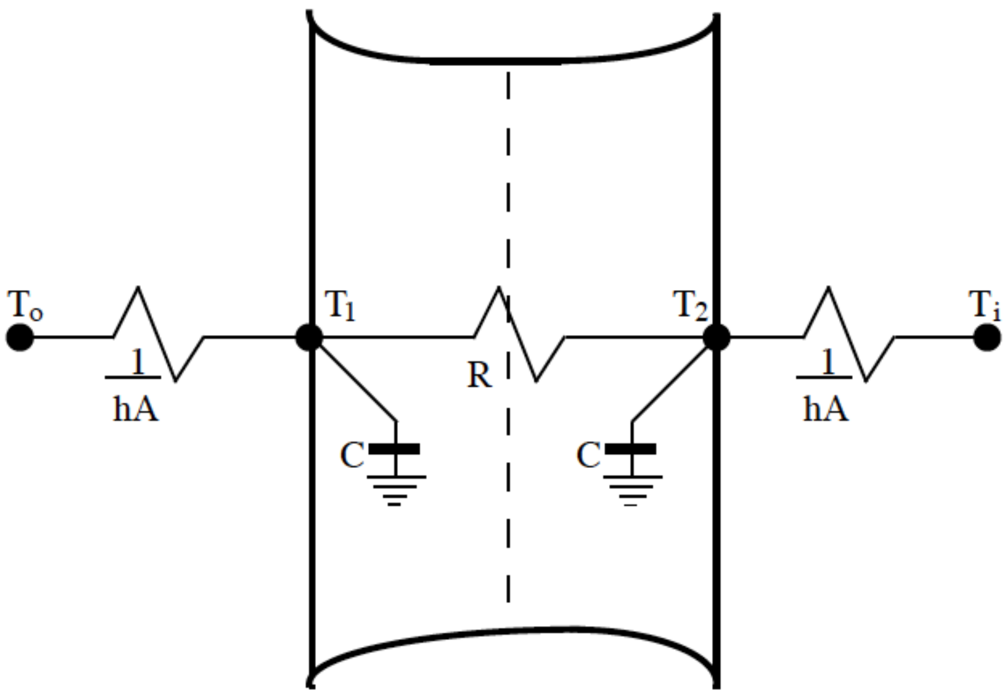


Figure 9. Two Node State Space Example.

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

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

where:

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

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

EnergyPlus Engineering Reference, 2012

Lumped capacitance model for conduction

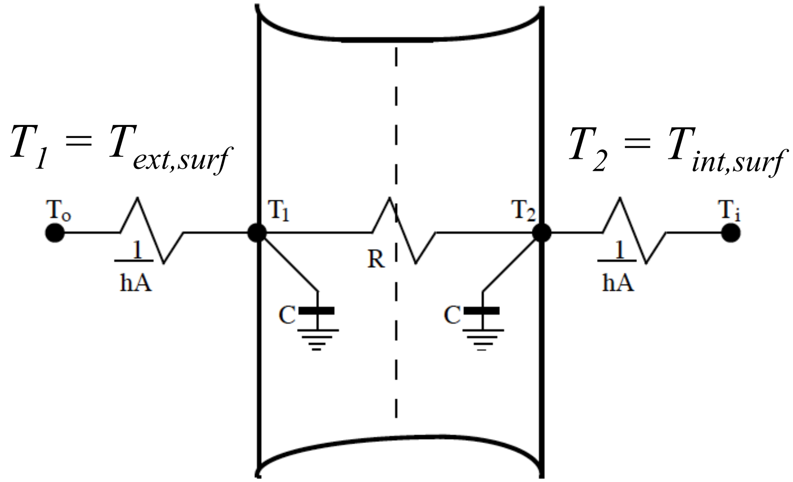


Figure 9. Two Node State Space Example.

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:

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

Example engineering calculations for BES program

Outside Surface Heat Balance

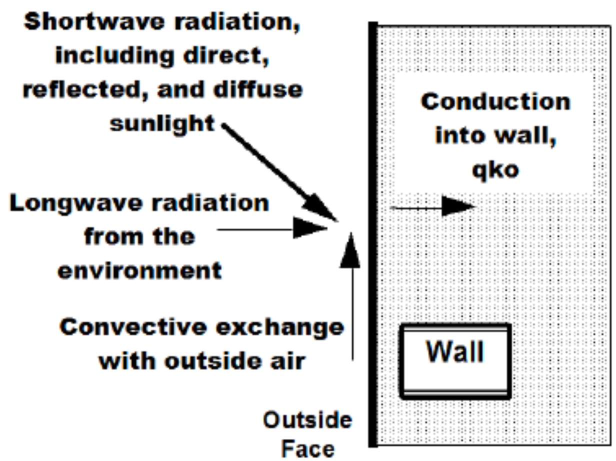


Figure 17. Outside Heat Balance Control Volume Diagram

The heat balance on the outside face is:

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

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.

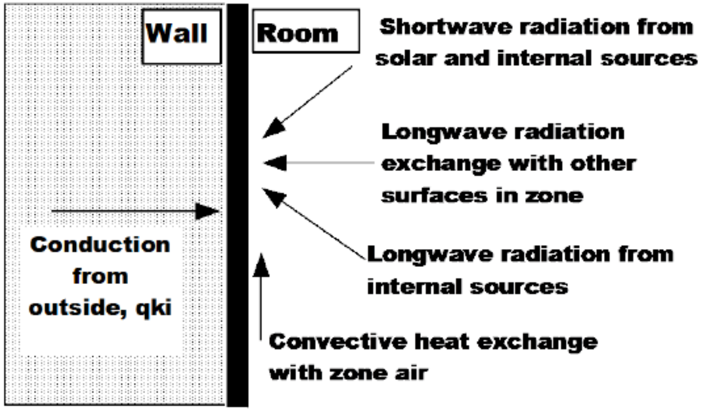
q''_{LWS} = Longwave radiation flux from equipment in zone.

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

Cost analysis during design

- Were any of those enclosure design changes worth it financially?
- For any energy efficiency improvement, you expect lower energy bills
  - But that improvement also had an upfront (capital) cost
- Payback periods
  - How long will it take for energy savings to cover the initial cost?
  - Several methods to calculate
    - Simple payback
    - Cash flow analysis
    - Net present value
    - Internal rate of return
    - Return on investment

Cost analysis during design

- Simple payback
  - Say you are considering a $5,000 improvement
  - Your energy simulations predict $350 per year in savings on energy bills
    - Assuming rates stay constant
  - The simple payback period is: $Payback = \frac{\$5000}{\$350 / year} = 14.3\ years$
  - After ~14 years, you will have covered your upfront costs

- Rate of return on investment
  - Inverse of payback period

$$ROI = \frac{1}{14.3\ years} = 7\%$$

Cost analysis during design

- Cash flow analysis and net present value methods
  - If you take out a loan to pay for efficiency improvements, you need to factor in the interest rate on that loan/mortgage
    - Will likely extend the payback period to cover principal + interest
- Other considerations:
  - Inflation
    - Somewhat predictable
  - Changes in energy costs
    - More variable
    - Most assume energy costs will rise at a constant rate
    - Not always the case (e.g., natural gas prices today)
    - If energy costs rise above predicted, payback period shortens
      - Vice versa for falling energy costs
- Overall: who pays capital costs and who pays for energy costs?

Life cycle cost in design

- New methods of energy simulation are taking advantage of optimization algorithms to find least cost, most effective solutions for energy efficiency
- EnergyPlus and DOE2 engines both now integrate with BEopt

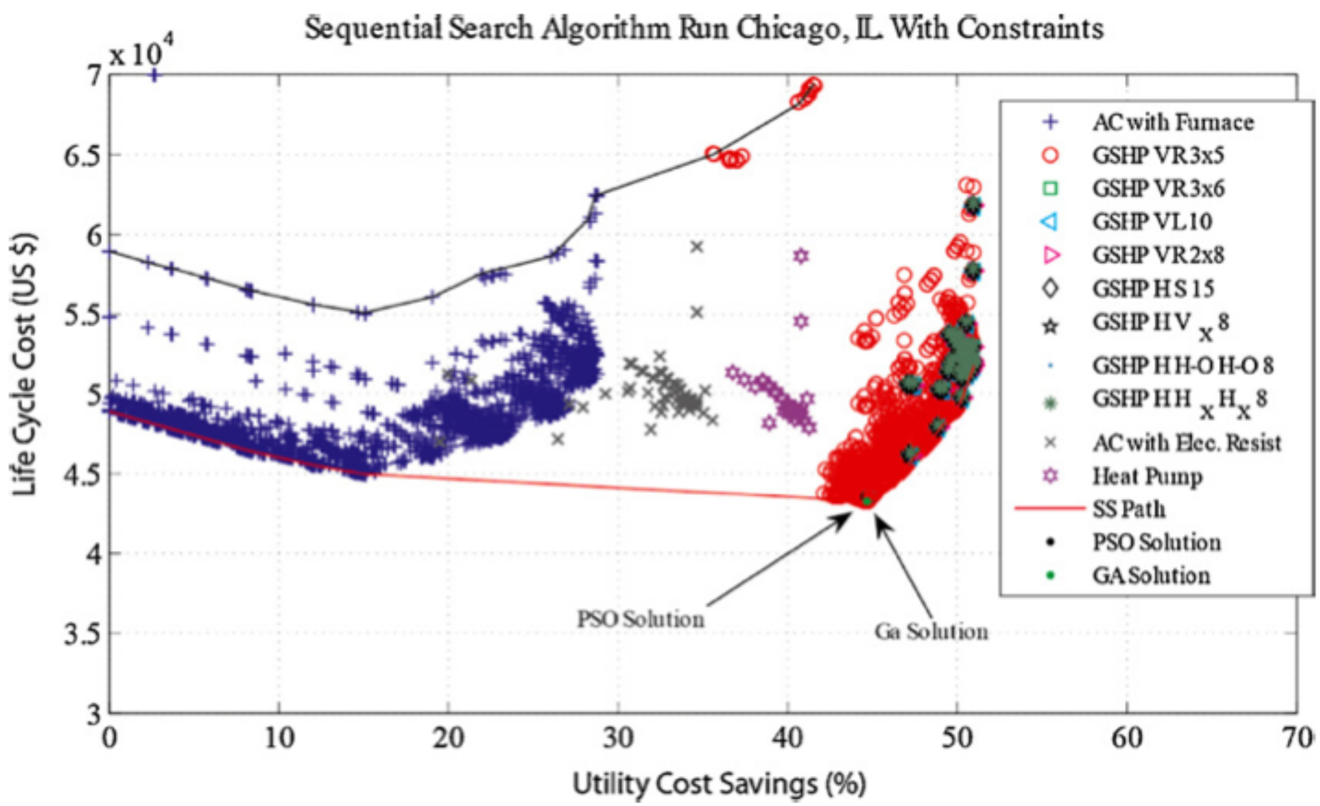
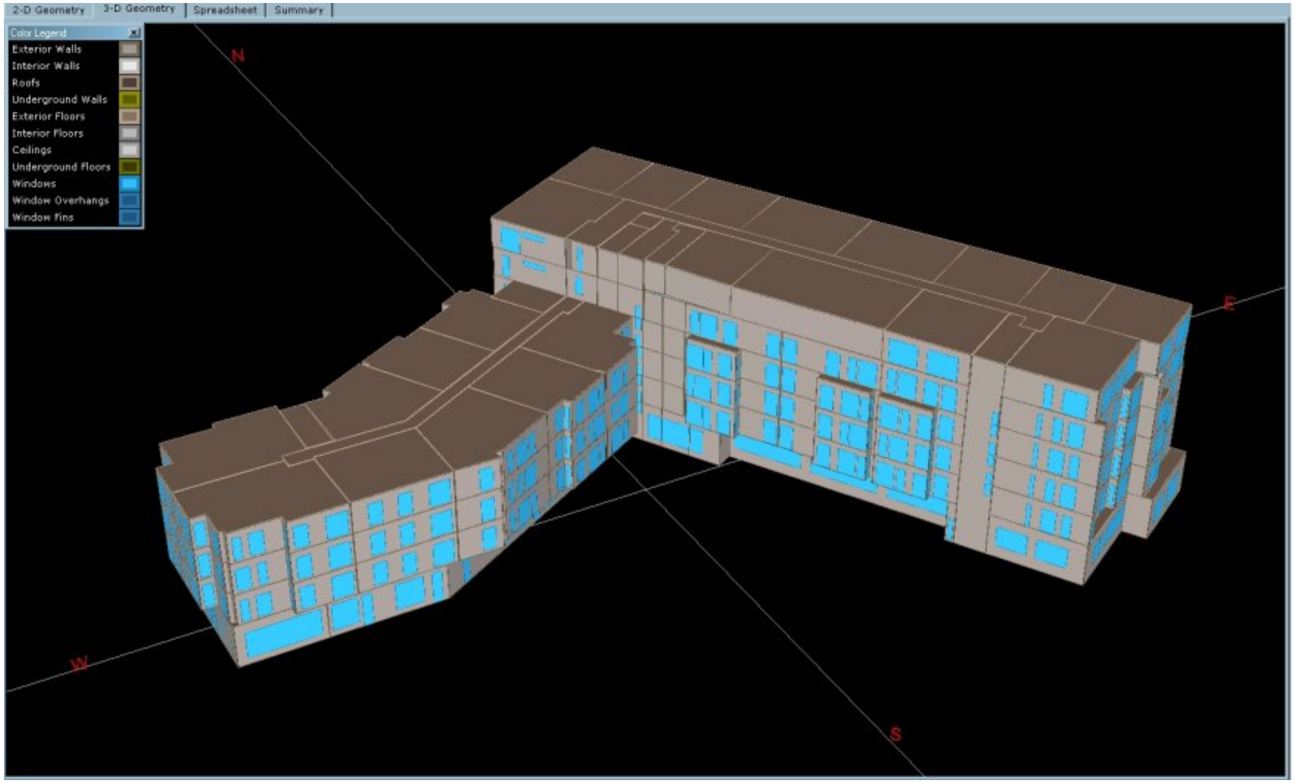


Fig. 6. LCC as a function of utility cost reduction for Chicago, IL.

Bichiou and Krarti 2011, *Energy and Buildings*

Demonstration of eQUEST

- eQUEST demonstration
  - Launch program



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

HW #4

- HW #4 will involve modeling a commercial building in eQUEST

- http://www.doe2.com/equest/

- Current version: 3.65 (released March 2014)