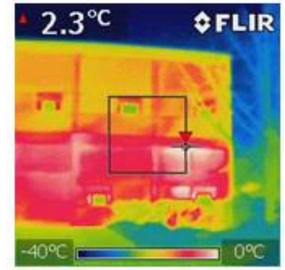
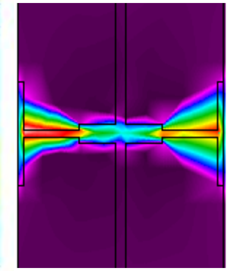
CAE 331/513
Building Science
Fall 2014



Week 4: September 16, 2014
Finish heat transfer in buildings

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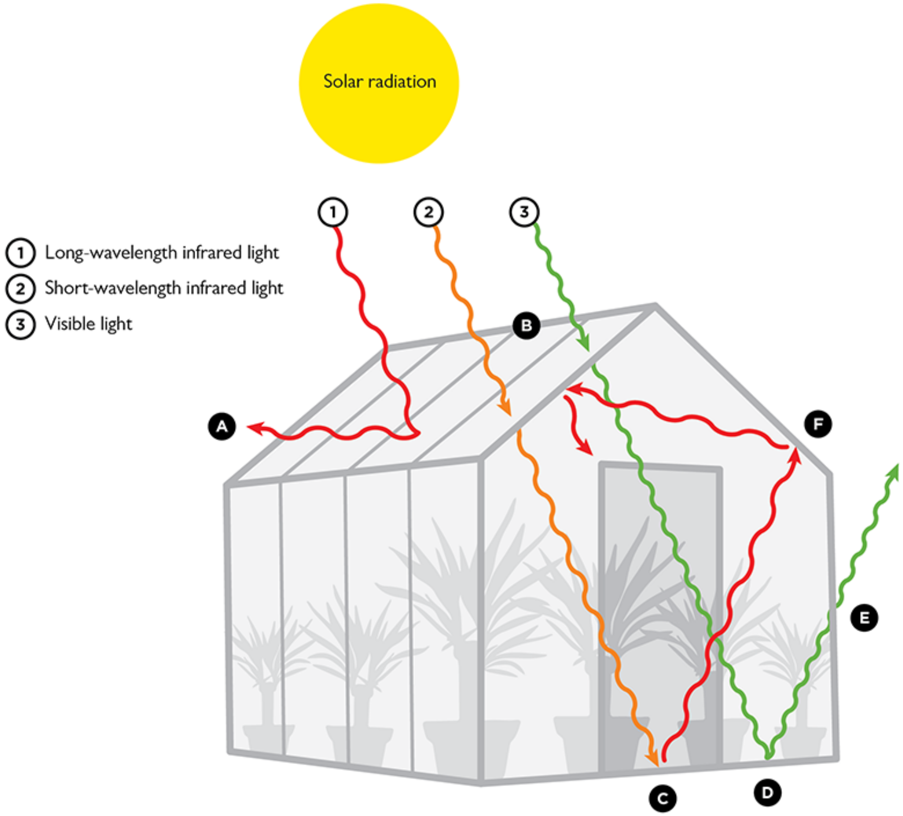


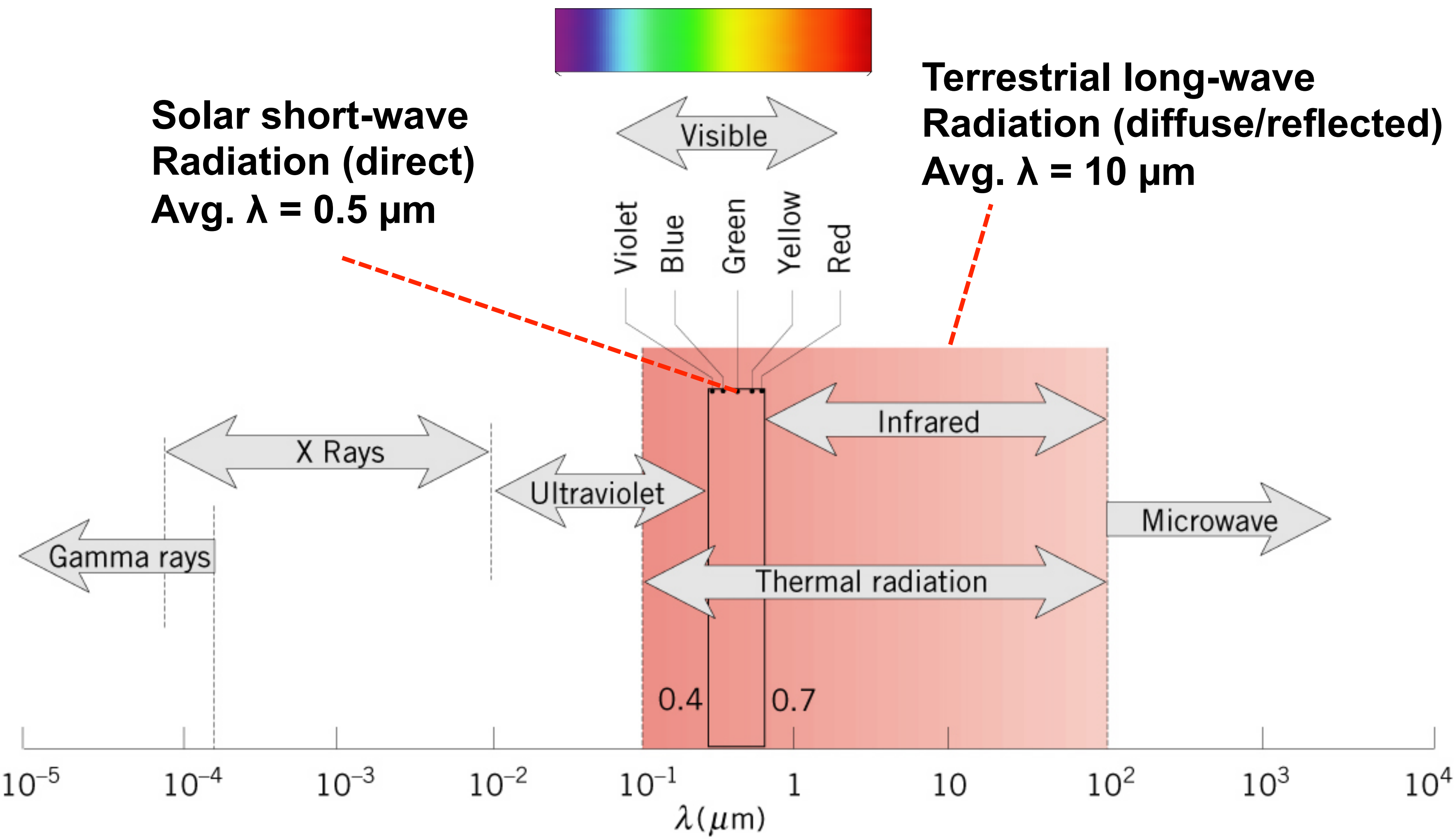
RADIATION

(finishing up)

Radiation: Short-wave and Long-wave

Solar short-wave Radiation (direct)
Avg. λ = 0.5 µm

Terrestrial long-wave Radiation (diffuse/reflected)
Avg. λ = 10 µm



Solar radiation striking a surface (high temperature)

- Most solar radiation is at short wavelengths

Solar radiation striking a surface:

$$I_{solar} \quad \left[\frac{\text{W}}{\text{m}^2}\right]$$

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

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

Absorptivity (α) for solar (short-wave) radiation

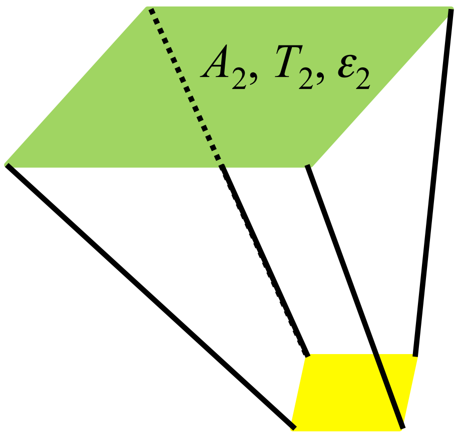
Surface	Absorptance for Solar Radiation
A small hole in a large box, sphere, furnace, or enclosure	0.97 to 0.99
Black nonmetallic surfaces such as asphalt, carbon, slate, paint, paper	0.85 to 0.98
Red brick and tile, concrete and stone, rusty steel and iron, dark paints (red, brown, green, etc.)	0.65 to 0.80
Yellow and buff brick and stone, firebrick, fire clay	0.50 to 0.70
White or light-cream brick, tile, paint or paper, plaster, whitewash	0.30 to 0.50
Window glass	—
Bright aluminum paint; gilt or bronze paint	0.30 to 0.50
Dull brass, copper, or aluminum; galvanized steel; polished iron	0.40 to 0.65
Polished brass, copper, monel metal	0.30 to 0.50
Highly polished aluminum, tin plate, nickel, chromium	0.10 to 0.40

Radiation heat transfer (surface-to-surface)

- We can write the net thermal radiation heat transfer between surfaces 1 and 2 as:

$$Q_{1\to 2} = \frac{A_1\sigma\left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{A_1}{A_2}\frac{1-\varepsilon_2}{\varepsilon_2} + \frac{1}{F_{12}}}$$

$$q_{1\to 2} = \frac{Q_{1\to 2}}{A_1}$$



where ε_1 and ε_2 are the surface emittances,

A_1 and A_2 are the surface areas

and $F_{1\to 2}$ is the view factor from surface 1 to 2

$F_{1\to 2}$ is a function of geometry only

σ = Stefan-Boltzmann constant = $5.67\times 10^{-8}\ \frac{\text{W}}{\text{m}^2\cdot\text{K}^4}$

T = Absolute temperature [K]

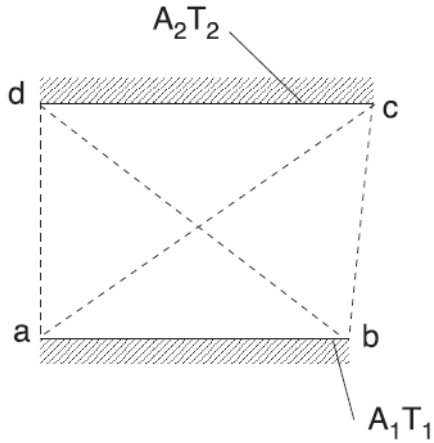
Emissivity (ε) of common materials

Surface	Emittance ε 50–100 °F
A small hole in a large box, sphere, furnace, or enclosure	0.97 to 0.99
Black nonmetallic surfaces such as asphalt, carbon, slate, paint, paper	0.90 to 0.98
Red brick and tile, concrete and stone, rusty steel and iron, dark paints (red, brown, green, etc.)	0.85 to 0.95
Yellow and buff brick and stone, firebrick, fire clay	0.85 to 0.95
White or light-cream brick, tile, paint or paper, plaster, whitewash	0.85 to 0.95
Window glass	0.90 to 0.95
Bright aluminum paint; gilt or bronze paint	0.40 to 0.60
Dull brass, copper, or aluminum; galvanized steel; polished iron	0.20 to 0.30
Polished brass, copper, monel metal	0.02 to 0.05
Highly polished aluminum, tin plate, nickel, chromium	0.02 to 0.04

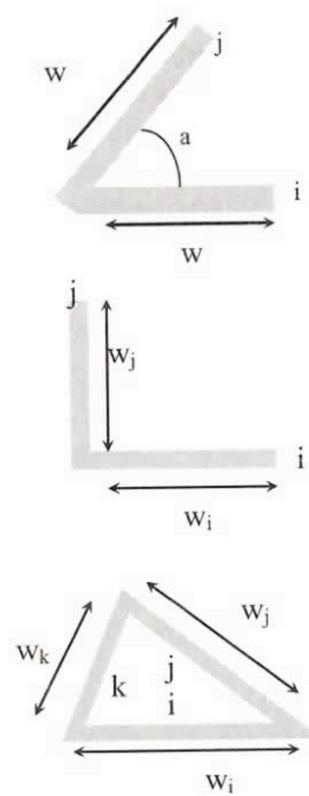
View factors, F_{12}

- Radiation travels in directional beams
  - Areas and angle of incidence between two exchanging surfaces influence radiative heat transfer

Some common "view factors"…



$$A_1 F_{1\to 2} = 0.5((ac + bd) - (ad + bc))$$



$$F_{ij} = 1 - \sin(\frac{a}{2})$$

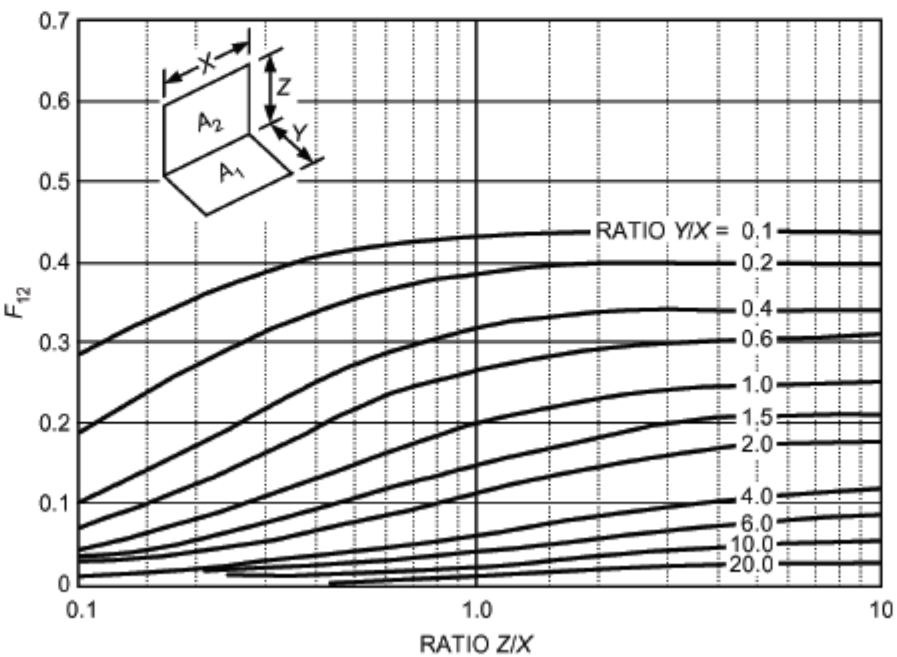
$$F_{ij} = \frac{1 + (w_j / w_i) - [1 + w_j / w_i)^2]^{1/2}}{2}$$

$$F_{ij} = \frac{w_j + w_i - w_k}{2w_i}$$

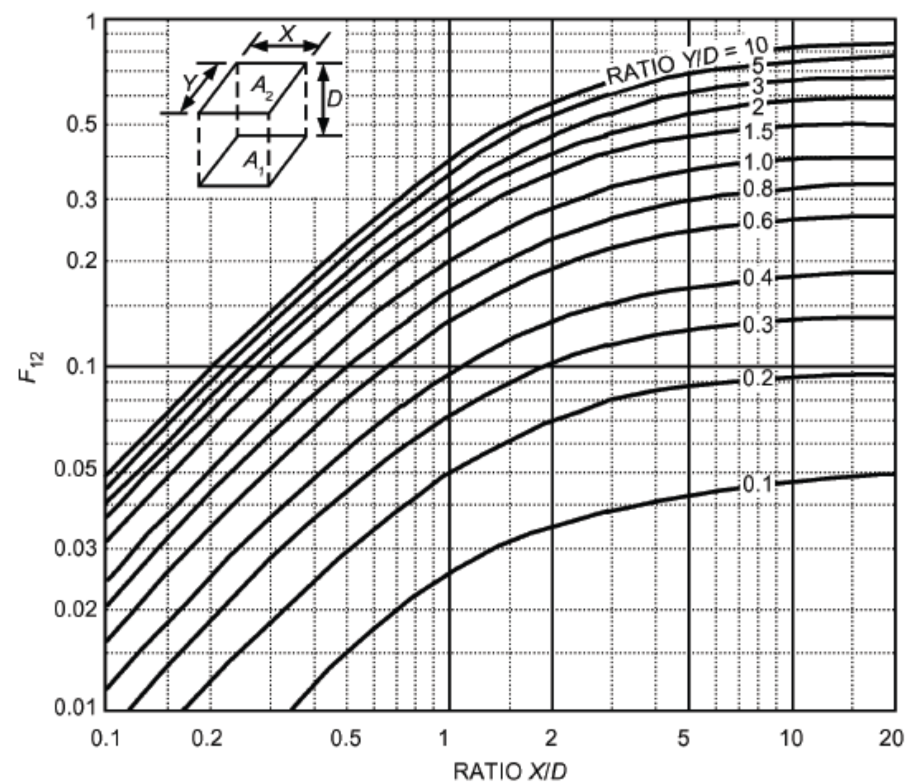
Figure 5.6: View factors for common situations in building enclosures [Hagentoft 2000]

Typical view factors

- Other common view factors from ASHRAE HOF



A. PERPENDICULAR RECTANGLES WITH COMMON EDGE



B. ALIGNED PARALLEL RECTANGLES

Long-wave radiation example

- What is the net radiative exchange between the wall behind me and the wall at the opposite end of the classroom?

Simplifying radiation

- We can also define a radiation heat transfer coefficient that is analogous to other heat transfer coefficients

$$Q_{rad,1\rightarrow 2} = \boxed{h_{rad}} A_1 \left(T_1 - T_2\right) = \frac{1}{R_{rad}} A_1 \left(T_1 - T_2\right)$$

- When $A_1 = A_2$, and T_1 and T_2 are within ~50°F of each other, we can approximate h_{rad} with a simpler equation:

$$h_{rad} = \frac{4\sigma T_{avg}^3}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

where

$$T_{avg} = \frac{T_1 + T_2}{2}$$

Simplifying surface radiation

- We can also often simplify radiation from:

$$Q_{1\rightarrow 2} = \frac{A_1 \sigma \left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{A_1}{A_2}\frac{1-\varepsilon_2}{\varepsilon_2} + \frac{1}{F_{12}}}$$

- To: $Q_{1\rightarrow 2} = \varepsilon_{surf} A_{surf} \sigma F_{12} \left(T_1^4 - T_2^4\right)$

Particularly when dealing with large differences in areas, such as sky-surface or ground-surface exchanges

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

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

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

Nearly every basic equation you need to know about heat transfer in buildings is on this slide!

Radiation

Long-wave

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

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

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

$$q_{1\rightarrow 2} = \varepsilon_{surf}\sigma F_{12}\left(T_{surf,1}^4 - T_{surf,2}^4\right)$$

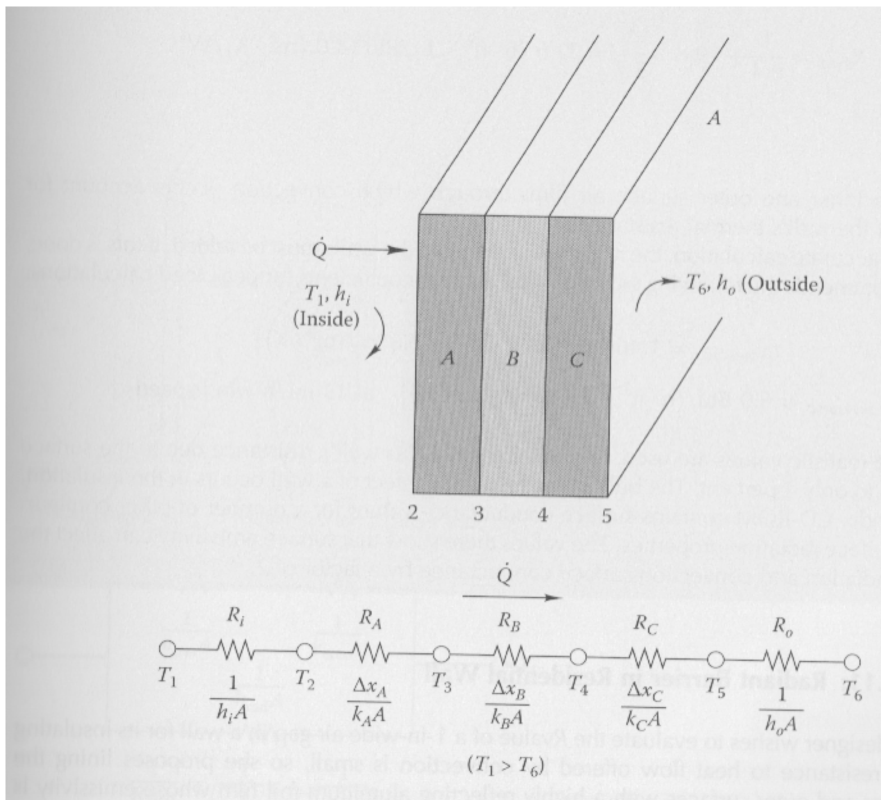
Solar radiation: (opaque surface) $q_{solar} = \alpha I_{solar}$

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

COMBINED-MODE HEAT TRANSFER

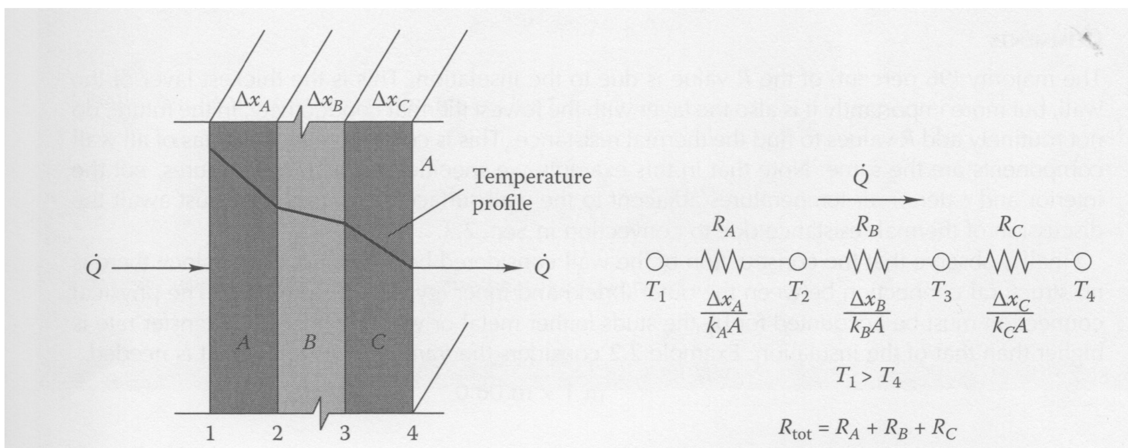
Combined mode heat transfer

- Nearly all heat transfer situations in buildings include more than one mode of heat transfer
- When more than one heat transfer mode is present, we can compute heat loss using resistances (of all kinds) in series



Combined modes of heat transfer

- Example problem: Convection and wall R-values
- An R-21 stud wall should also include the effect of inner and outer surface convection coefficients
  - Assume typical interior surface convection coefficients and assume the outer surface coefficient during winter conditions is appropriate



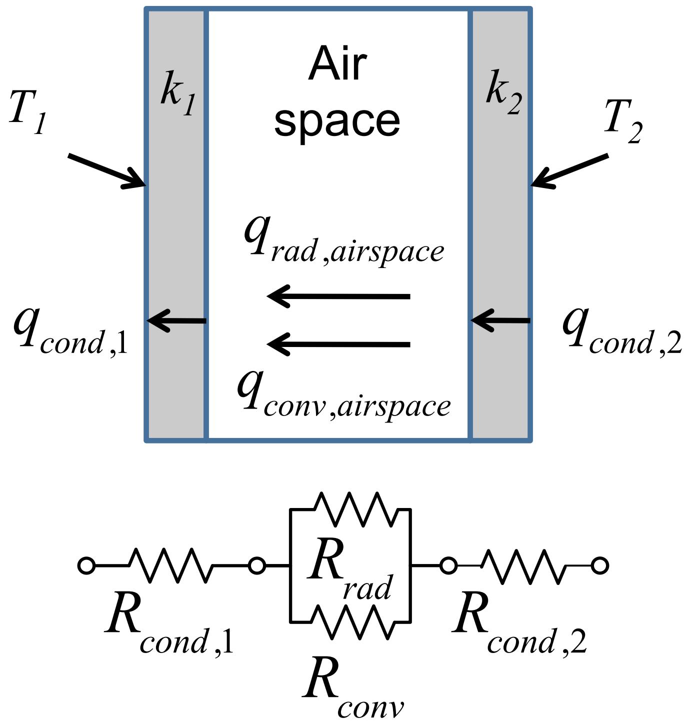
Typical convective surface resistances

- We often use the values given below for most conditions

Surface Conditions	Horizontal Heat Flow	Upwards Heat Flow	Downwards Heat Flow
Indoors: R_{in}	0.12 m^2K/W (SI) 0.68 $h{\cdot}ft^2{\cdot}°F/Btu$ (IP)	0.11 m^2K/W (SI) 0.62 $h{\cdot}ft^2{\cdot}°F/Btu$ (IP)	0.16 m^2K/W (SI) 0.91 $h{\cdot}ft^2{\cdot}°F/Btu$ (IP)
R_{out}: 6.7 m/s wind (Winter)	0.030 m^2K/W (SI) 0.17 $h{\cdot}ft^2{\cdot}°F/Btu$ (IP)		
R_{out}: 3.4 m/s wind (Summer)	0.044 m^2K/W (SI) 0.25 $h{\cdot}ft^2{\cdot}°F/Btu$ (IP)		

More combined heat transfer

- When more than one mode of heat transfer exists at a location (usually convection + radiation), resistances get placed in parallel
  - Example: Heat transfer in a cavity

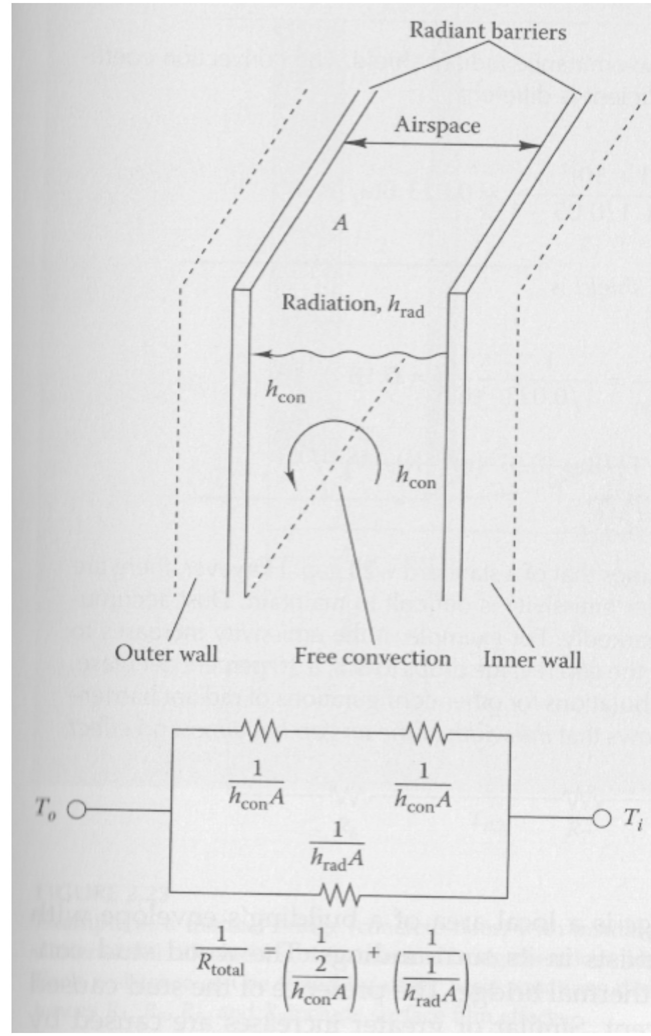


Combined modes of heat transfer

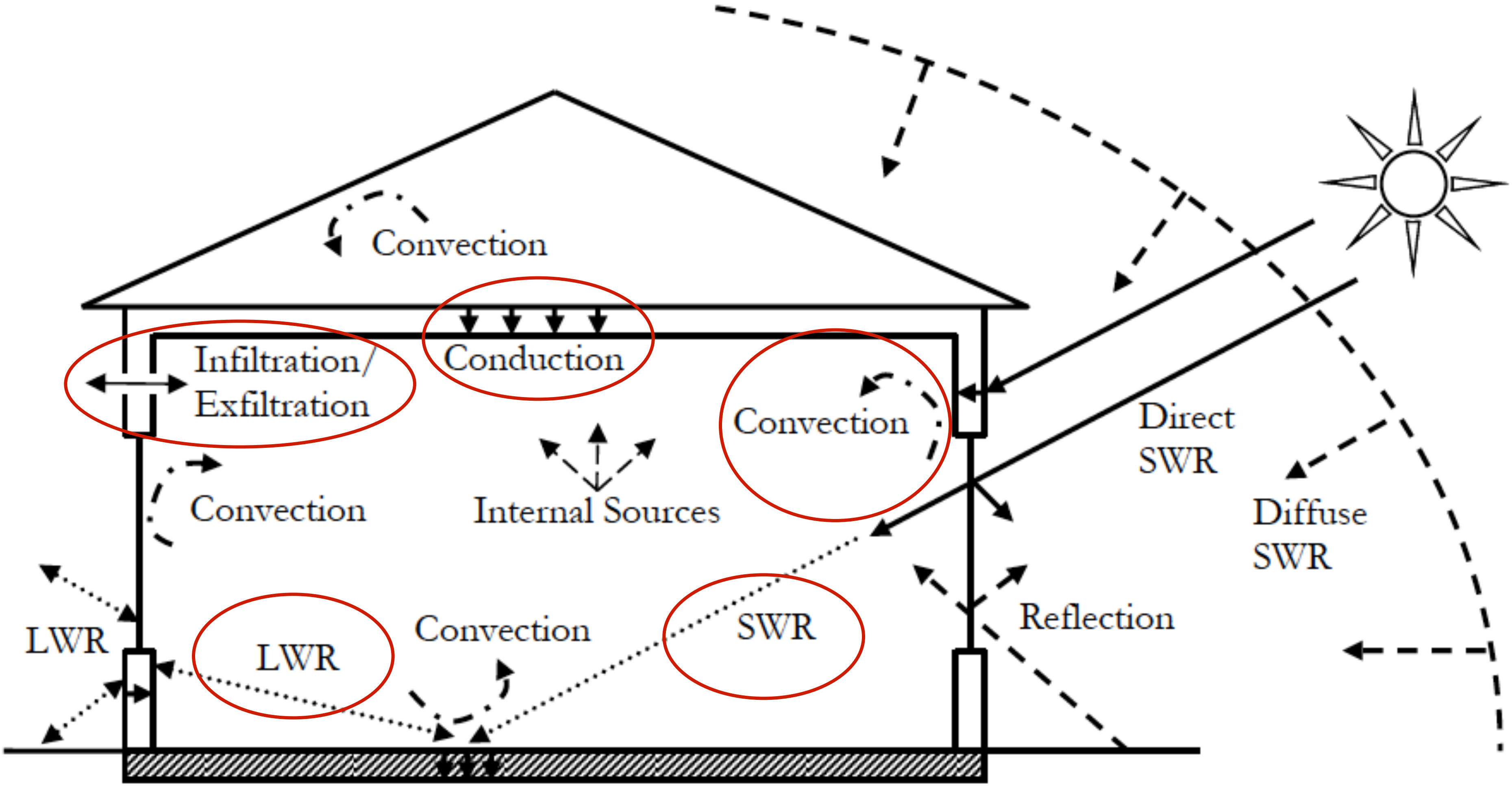
- Example problem: Radiant barrier in a residential wall

A building designer wishes to evaluate the R-value of a 1 inch wide air gap in a wall for its insulation effect. The resistance to heat flow offered by convection is small, so she proposes lining the cavity's inner and outer surfaces with a highly reflecting aluminum foil film whose emissivity is 0.05.

Find the R-value of this cavity, including both radiation and convection effects, if the surface temperatures facing the gap are 7.2°C and 12.8°C.

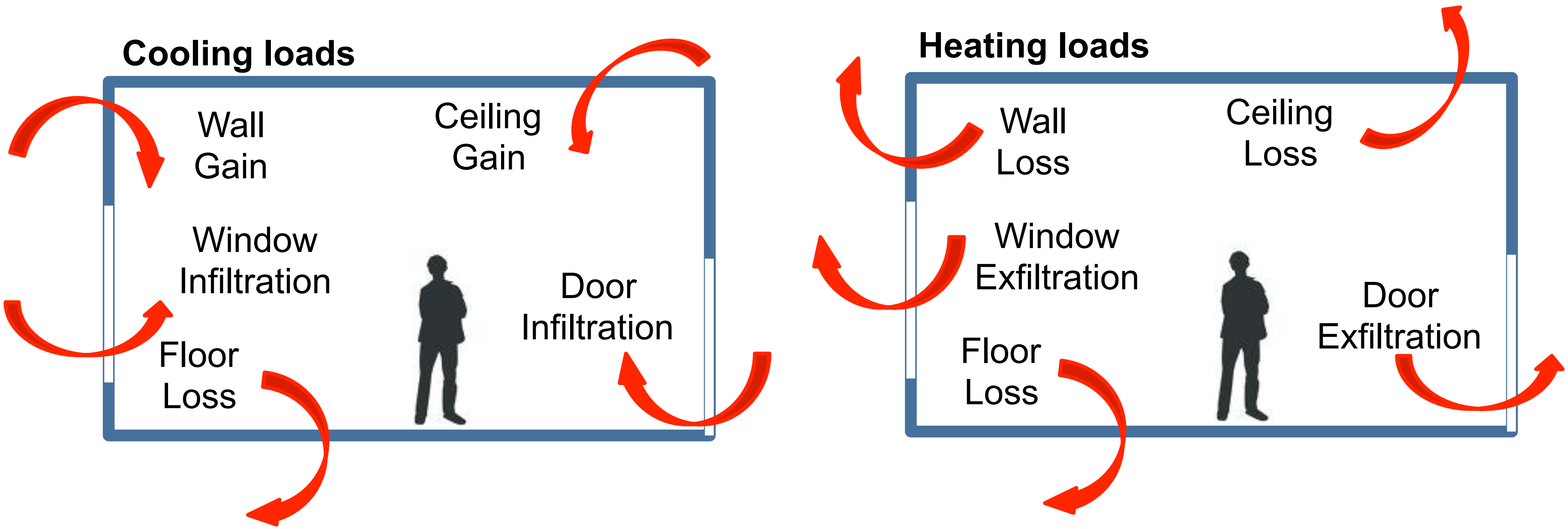


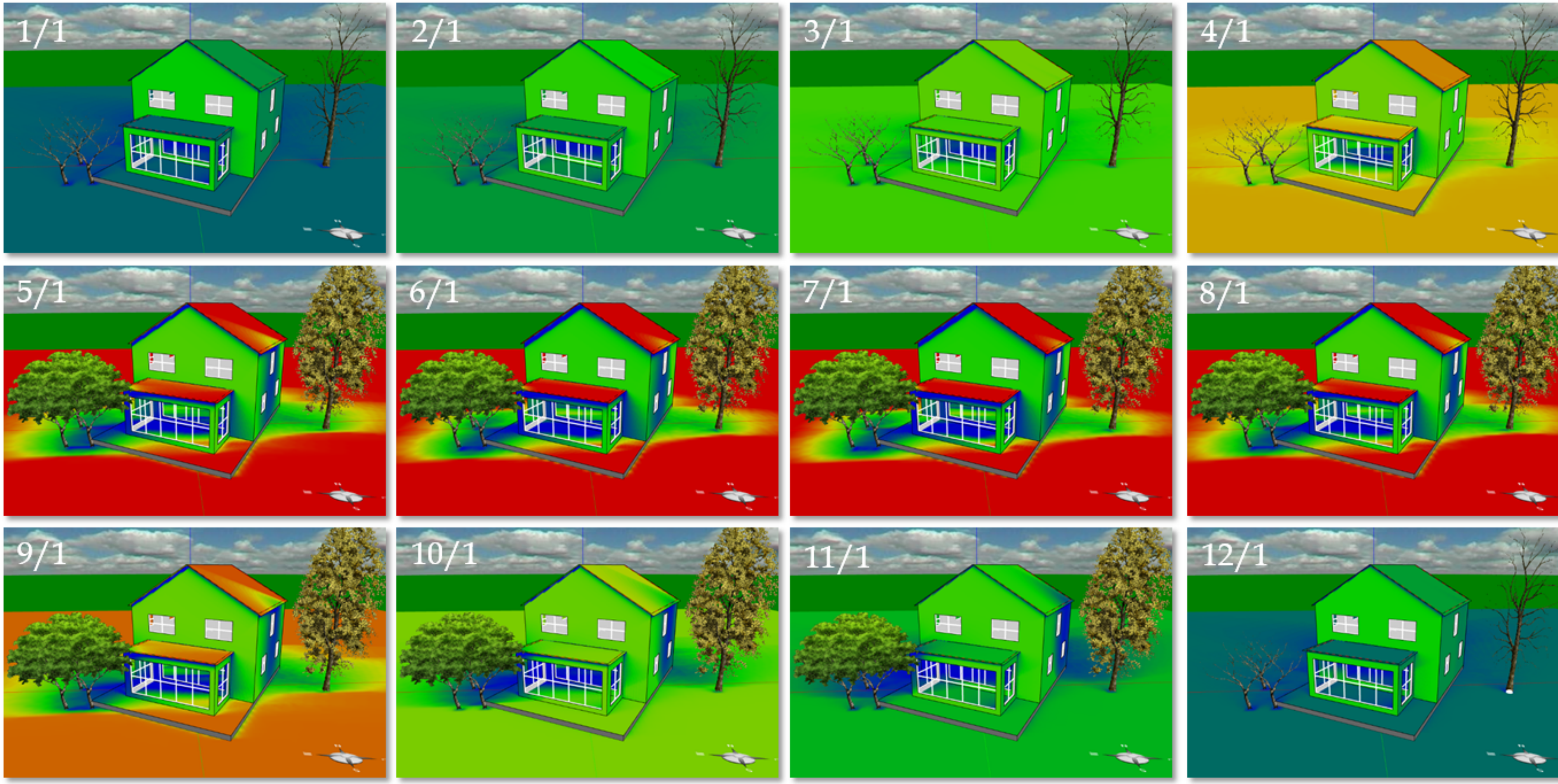
Modes of heat transfer in a building



Where are we going? Building energy balances

- Taken altogether, each of the heat transfer modes we've discussed can be combined with inputs for climate data, material properties, and geometry to make up a building's **energy balance**
  - We will revisit this for heating and cooling load calculations





A few notes on:

SOLAR RADIATION

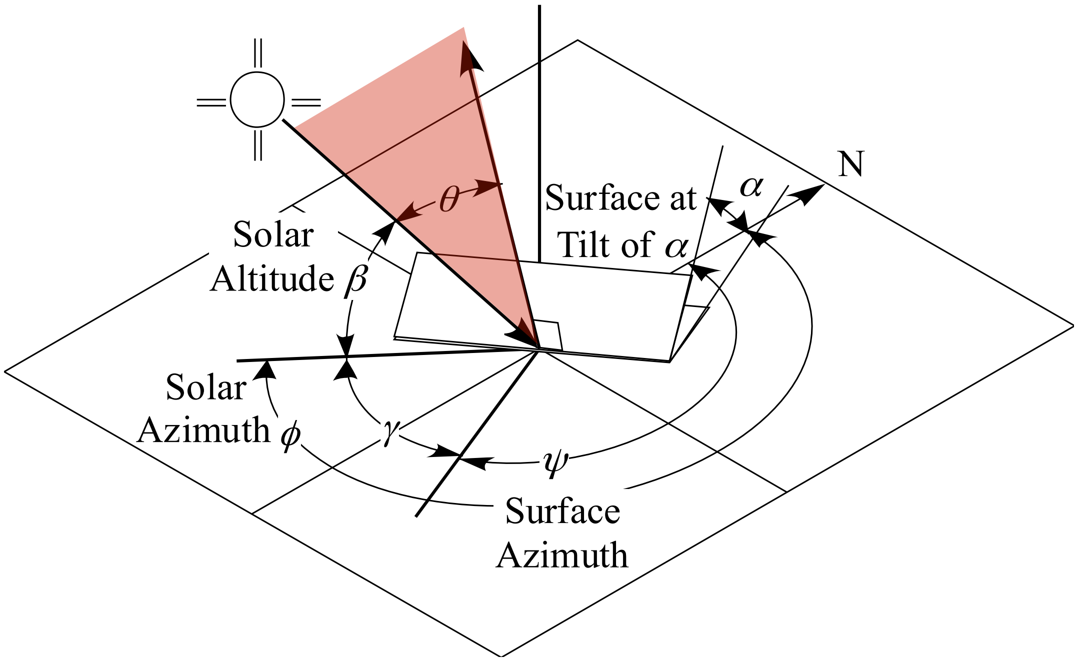
Solar radiation

- Solar radiation is an important term in the "energy balance" of a building
  - Must account for it while calculating loads
  - This is particularly true for perimeter zones and for peak cooling loads
- Solar radiation is also important for daylighting design
- We won't cover the full equations for predicting solar geometry and radiation striking a surface in this class
  - But will discuss basic relationships and where to download data
  - CAE 463/524 Building Enclosure Design goes into more detail

Solar radiation striking an exterior surface

- The amount of solar radiation received by a surface depends on the **incidence angle**, θ

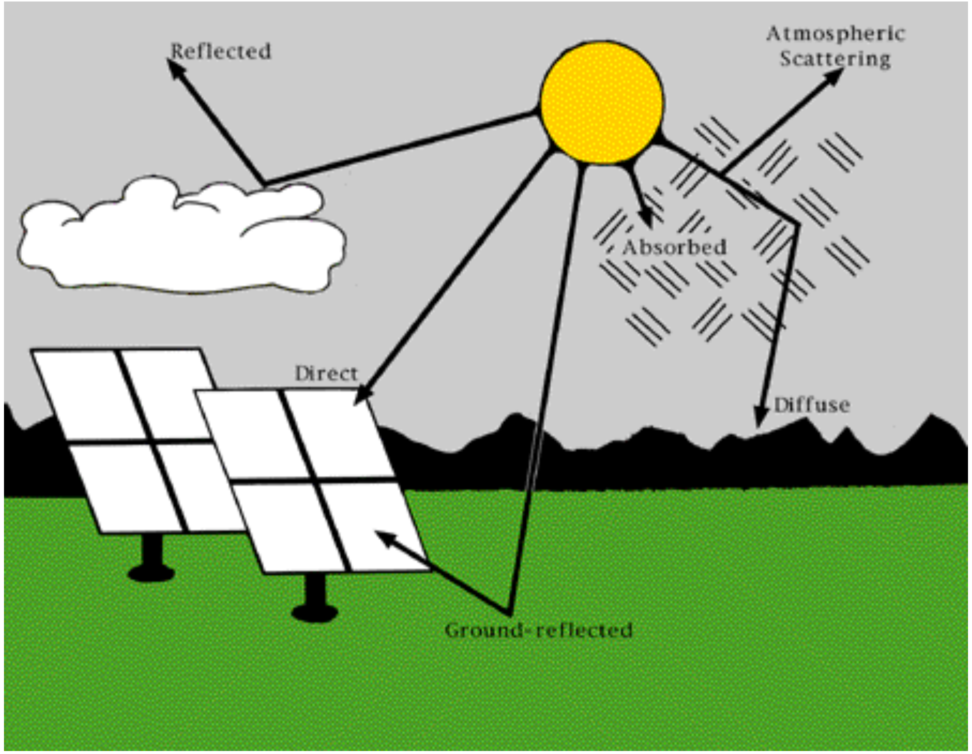
- This is a function of:
  - Solar geometry
    - Location
    - Time
  - Surface geometry
  - Shading/obstacles



Components of solar radiation

- Solar radiation striking a surface consists of three main components:

$$I_{solar} = I_{direct} + I_{diffuse} + I_{reflected} \quad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$



Components of solar radiation

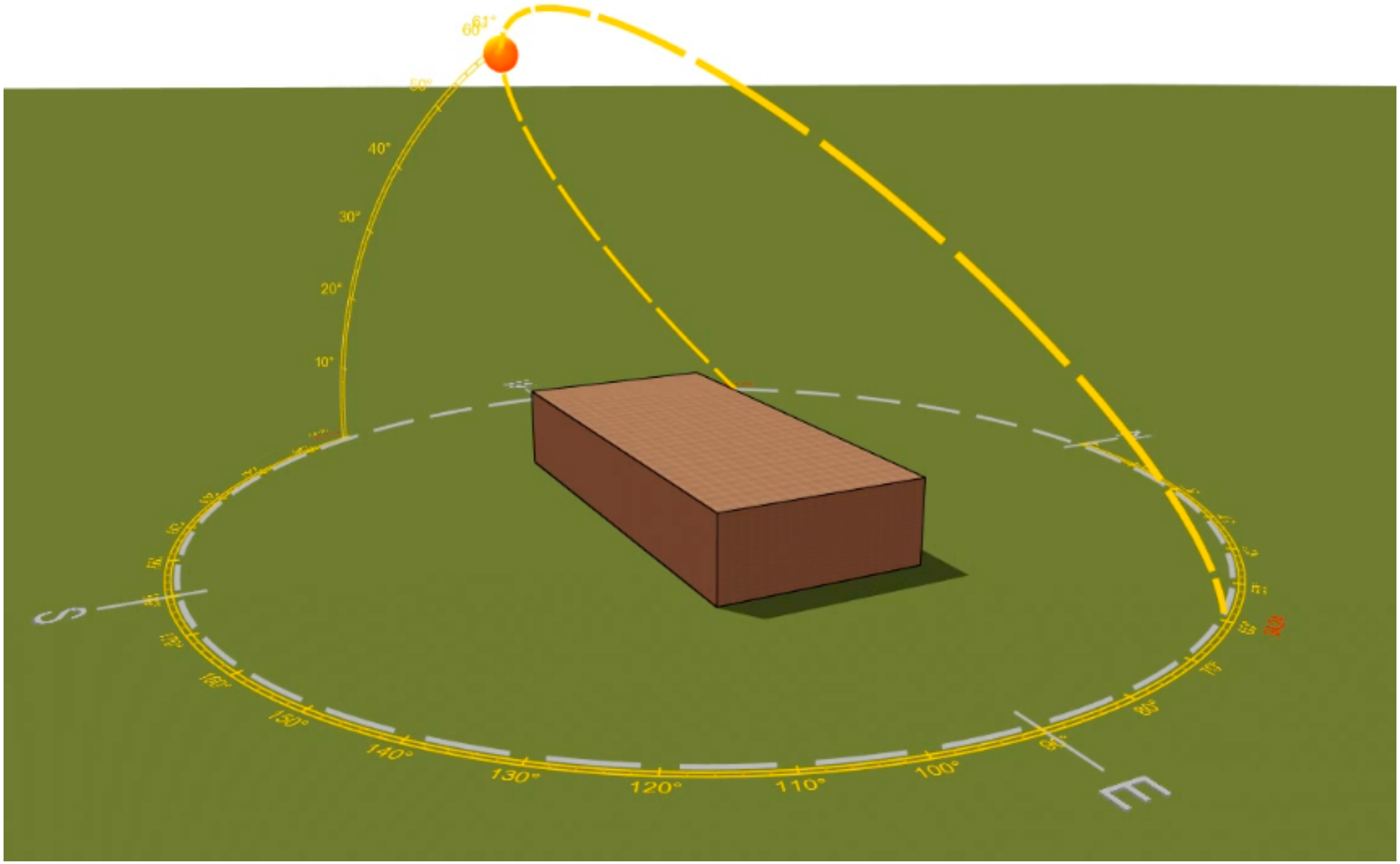
- **Direct solar radiation** (I_{direct}) is a function of the **normal incident irradiation** (I_{ND}) on the earth's surface and the solar incidence angle of the surface of interest, θ
  - Where I_{ND} is a function of day of the year and atmospheric properties

- **Diffuse solar radiation** ($I_{diffuse}$) is the irradiation that is **scattered** by the atmosphere
  - Function of I_{ND}, atmospheric properties, and surface's tilt angle

- **Reflected solar radiation** ($I_{reflected}$) is the irradiation that is **reflected** off the ground (it becomes diffuse)
  - Function of I_{ND}, solar geometry, ground reflectance, and surface tilt angle

Visualizing solar relationships

- For visualizing geometry, using programs like IES-VE



Downloading solar data

- For hourly sun positions, you can build a calculator or use one from the internet
  - http://www.susdesign.com/sunposition/index.php
  - http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html

- For solar position and intensity (from time and place)
  - http://www.nrel.gov/midc/solpos/solpos.html
  - Output of interest = "global irradiance on a tilted surface"

- For *actual* hourly solar data (direct + diffuse in W/m^2)
  - http://rredc.nrel.gov/solar/old_data/nsrdb/
  - Output of interest = "direct normal radiation" → adjust using $\cos\theta$
    - Note: "typical meteorological years"

Typical meteorological year (TMY)

- For heating and cooling load calculations and for hourly building energy simulations we often rely on a collection of weather data for a specific location
- We generate this data to be representative of more than just the previous year
  - Represents a wide range of weather phenomena for our location
  - TMY3: Data for 1020 locations from 1960 to 2005
    - Composed of 12 typical meteorological months
    - Each month is pulled from a random year in the range
    - Actual time-series climate data
    - Mixture of measured and modeled solar values
    - http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/
  - Variables include: outdoor temperature, direct normal

What to do with solar data once you have it?

- Solar data can be used on exterior opaque surfaces to help determine **exterior surface temperatures**

$$q_{solar} = \alpha I_{solar}$$

- Solar data can also be used on exterior transparent surfaces (e.g. **windows and skylights**) to determine how much solar radiation enters an indoor environment

$$q_{solar} = \tau I_{solar}$$

Sol-air temperatures

- If we take an external surface with a combined convective and radiative heat transfer coefficient, $h_{conv+rad}$

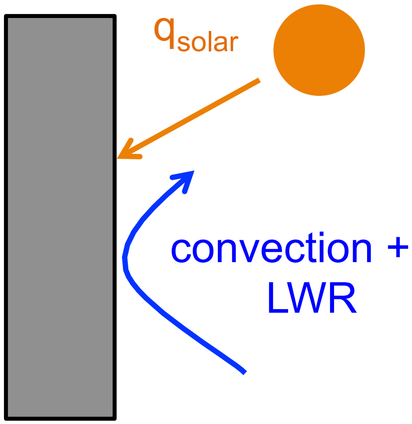
$$q_{conv+rad} = h_{conv+rad}\left(T_{air} - T_{surf}\right)$$

- If that surface now absorbs solar radiation (αI_{solar}), the total heat flow at the exterior surface becomes:

$$q_{conv+rad} = h_{conv+rad}\left(T_{air} - T_{surf}\right) + \alpha I_{solar}$$

- To simplify our calculations, we can define a "**sol-air**" temperature that accounts for all of these impacts:

$$T_{sol-air} = T_{air} + \frac{\alpha I_{solar}}{h_{conv+rad}}$$



- Now we can describe heat transfer at that surface as:

$$q_{total} = h_{conv+rad}\left(T_{sol-air} - T_{surf}\right)$$

Sol-air temperatures

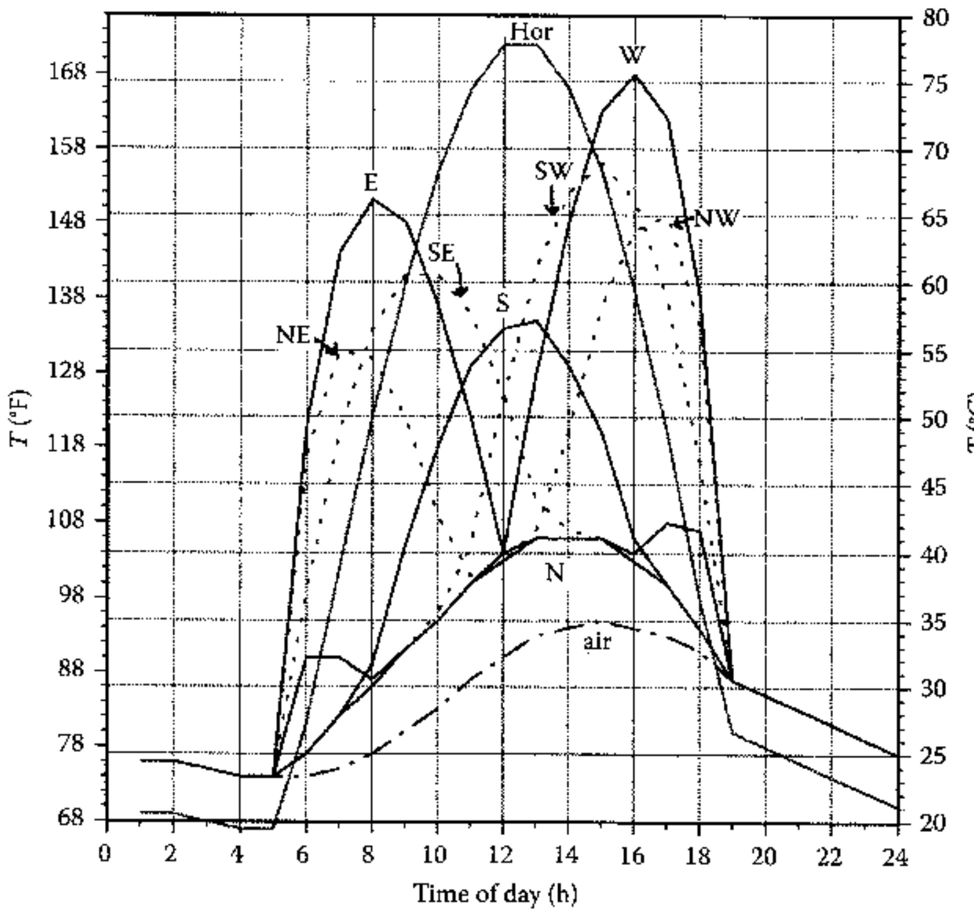


FIGURE 6.17
Sol-air temperature for horizontal and vertical surfaces as a function of time of day for summer design conditions, July 21 at 40° latitude, assuming $\alpha/h_o = 0.30$ (h · ft^2 · °F)/Btu [0.052 (m^2 · K)/W]. The curves overlap when there is no direct radiation on a surface. (Courtesy of ASHRAE, *Handbook of Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 1989, Table 26.1.)

Solar radiation and external surface temperatures

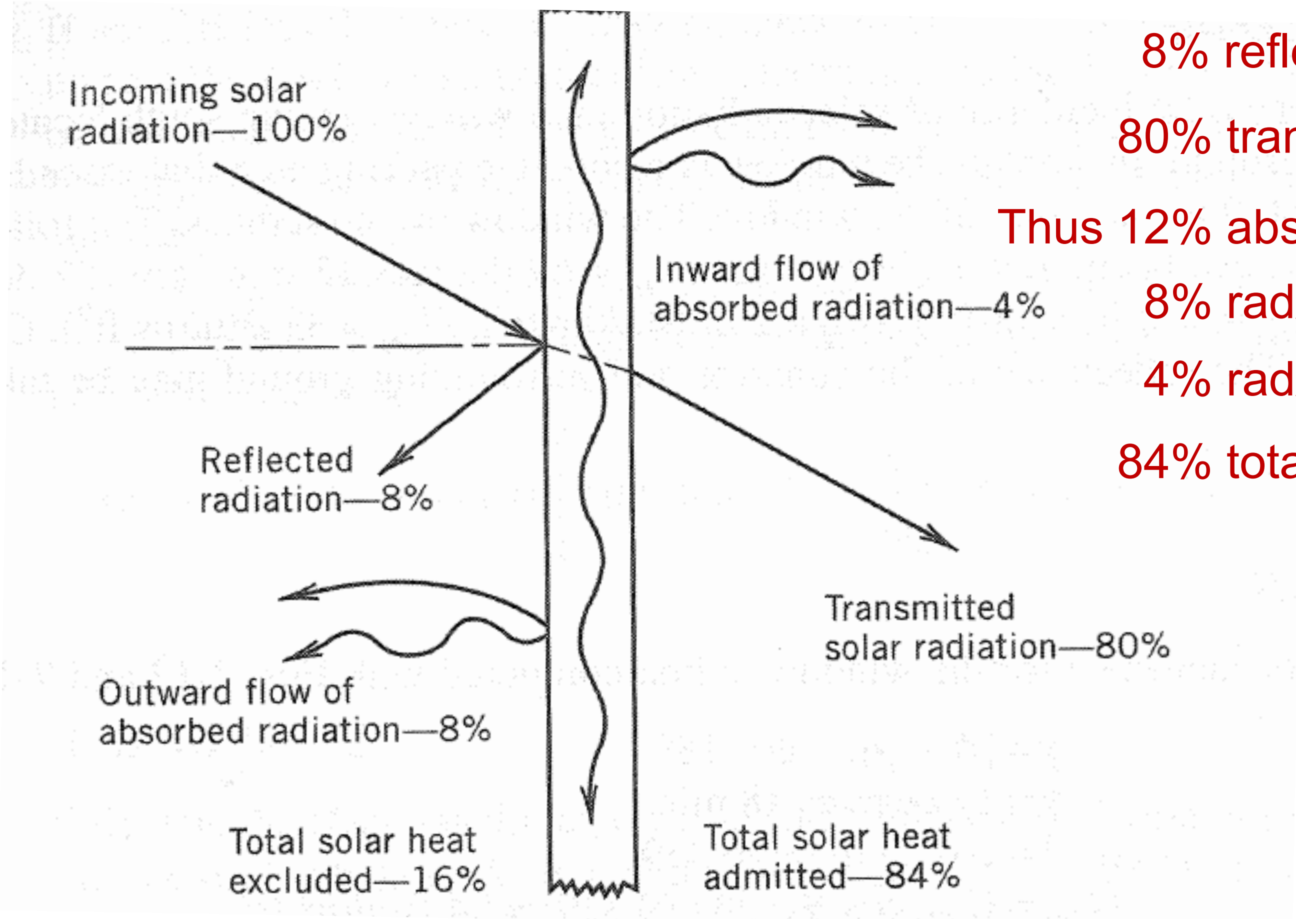
- We can also use air temperatures and material properties (emissivity and absorptance) to estimate exterior surface temperatures that are exposed to radiation
  - These are not perfectly accurate but provide a reasonable estimate

Situation	Thermally massive	Thermally lightweight
Roofs: direct sun	$t_a + 42\,\alpha$	$t_a + 55\,\alpha$
Roof: sun + reflected /emitted radiation	$t_a + 55\,\alpha$	$t_a + 72\,\alpha$
Roof exposed to night sky	$t_a - 5\,\varepsilon$	$t_a - 10\,\varepsilon$
Walls: winter sun	$t_a + 35\,\alpha$	$t_a + 48\,\alpha$
Walls: summer sun	$t_a + 28\,\alpha$	$t_a + 40\,\alpha$
Walls exposed to night sky	$t_a - 2\,\varepsilon$	$t_a - 4\,\varepsilon$

Source: Straube and Burnett

Solar radiation and windows (i.e., fenestration)

- Solar radiation through a single glaze



100% incident

8% reflected

80% transmitted

Thus 12% absorbed

8% rad/conv outward

4% rad/conv inward

84% total transmitted

Windows and total heat gain

- The total heat gain of a window is the sum of two terms:
  - The solar radiation heat gain from solar irradiation (transmittance)
  - Conductive/convective/radiative thermal heat gain from the temperature difference between the interior and exterior
- In the summer, both terms are positive towards the interior and add heat gains
- In the winter, solar is positive inwards but the other is negative towards the exterior
  - Net heat gain may vary in direction

Heat gain through windows

- Calculating the **conductive** heat gain through a window is easy:

$$Q = UA\Delta T$$

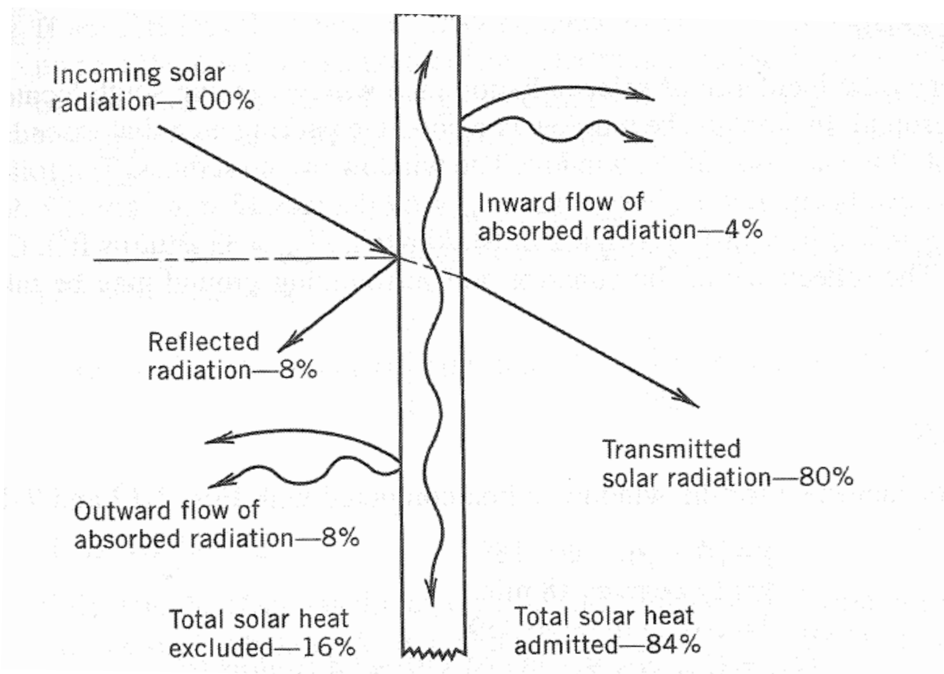
- Accounting for **solar** heat gain is more complicated
  - Need to include absorption of solar energy and re-radiation of thermal energy
  - Need to include spectral and angular characteristics of radiation and glazing
- We can do this with a simplified metric
  - The solar heat gain coefficient (SHGC): $Q_{solar,window} = \left(I_{solar}A\right)SHGC$

Solar heat gain coefficient, SHGC

- For a single pane of glass:

$$SHGC = \tau + \alpha \frac{U}{h_{ext}} \qquad \frac{1}{U} = \frac{1}{h_{int}} + \frac{1}{R_{glass}} + \frac{1}{h_{ext}}$$

$^{*}R_{glass}$ is negligible



$$Q_{solar,window} = \left(I_{solar} A\right) SHGC$$

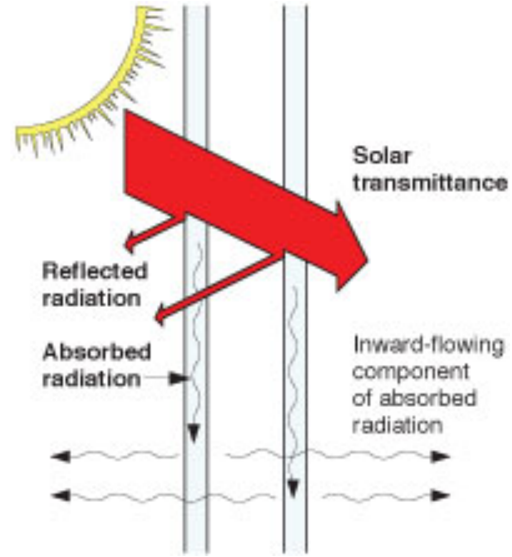
Solar heat gain coefficient, SHGC

- For double glazing with a small air space:

$$SHGC = \tau + \alpha_{outer\ pane} \frac{U}{h_{ext}} + \alpha_{inner\ pane} U \left(\frac{1}{h_{ext}} + \frac{1}{h_{airspace}} \right)$$

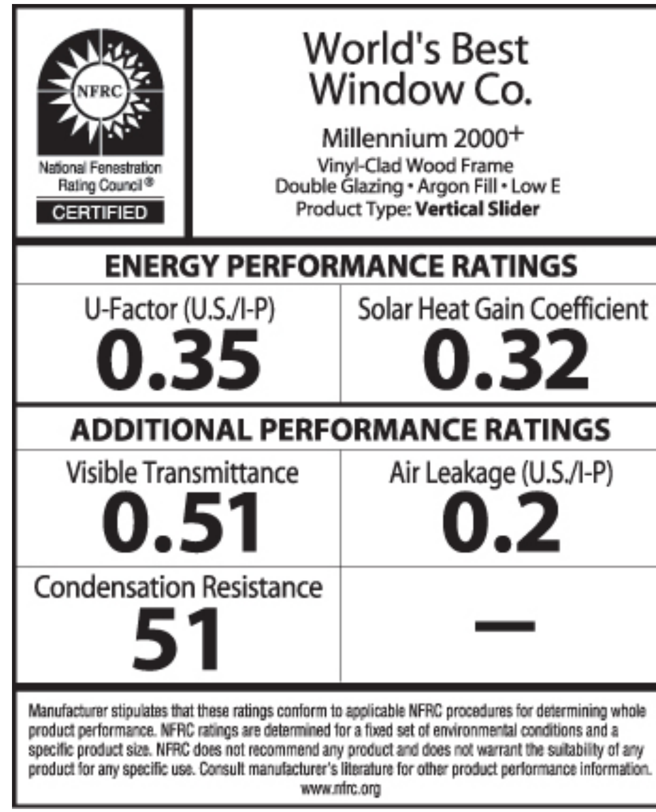
$$\frac{1}{U} = \frac{1}{h_{int}} + \frac{1}{R_{outer\ pane}} + \frac{1}{h_{airspace}} + \frac{1}{R_{inner\ pane}} + \frac{1}{h_{ext}}$$

$^{*}R_{outer\ pane}$ and $R_{inner\ pane}$ are negligible



Manufacturer supplied SHGC

- Glazing manufacturers will measure and present SHGC for normal incidence according to the methods of NFRC 200
  - National Fenestration Rating Council has developed methods for rating and labeling SHGC, U factors, air leakage, visible transmittance and condensation resistance of fenestration products
- In reality, SHGC is a function of incidence angle (θ)



$$Q_{solar,window} = I_{direct} SHGC(\theta) A + (I_{diffuse+reflected}) SHGC_{diffuse+reflected} A$$

Complex SHGC

- SHGC, solar transmittance, reflectance, and absorptance properties for glazing all vary with incidence angles of solar radiation
- The ASHRAE Handbook of Fundamentals 2013 Chapter 15 provides data for a large variety of glazing types

Table 10 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptance ($\mathcal{A}_n^f$) for Glazing and Window Systems

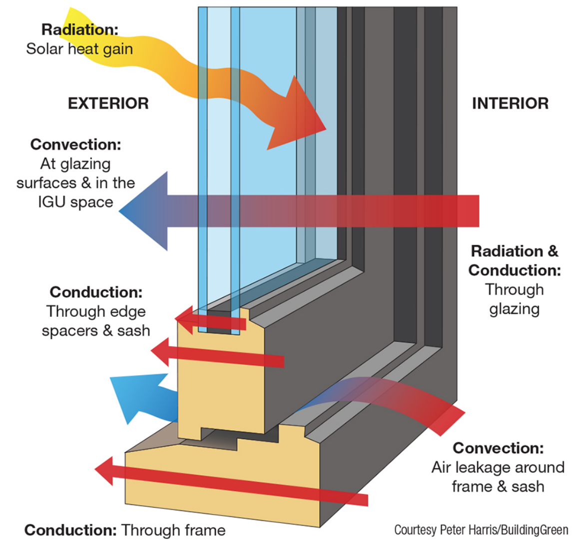
	Glazing System				Center-of-Glazing Properties							Total Window SHGC at Normal Incidence				Total Window T_v at Normal Incidence			
					Incidence Angles							Aluminum		Other Frames		Aluminum		Other Frames	
ID	Glass Thick., mm		Center Glazing T_v		Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
Uncoated Single Glazing																			
1a	3	CLR	0.90	SHGC	0.86	0.84	0.82	0.78	0.67	0.42	0.78	0.78	0.79	0.70	0.76	0.80	0.81	0.72	0.79
				T	0.83	0.82	0.80	0.75	0.64	0.39	0.75								
				R^f	0.08	0.08	0.10	0.14	0.25	0.51	0.14								
				R^b	0.08	0.08	0.10	0.14	0.25	0.51	0.14								
				$\mathcal{A}_1^f$	0.09	0.10	0.10	0.11	0.11	0.11	0.10								
1b	6	CLR	0.88	SHGC	0.81	0.80	0.78	0.73	0.62	0.39	0.73	0.74	0.74	0.66	0.72	0.78	0.79	0.70	0.77
				T	0.77	0.75	0.73	0.68	0.58	0.35	0.69								
				R^f	0.07	0.08	0.09	0.13	0.24	0.48	0.13								
				R^b	0.07	0.08	0.09	0.13	0.24	0.48	0.13								
				$\mathcal{A}_1^f$	0.16	0.17	0.18	0.19	0.19	0.17	0.17								

What about window assemblies?

- In addition to glazing material, windows also include framing, mullions, muntin bars, dividers, and shading devices
  - These all combine to make **fenestration systems**
- Total heat transfer through an assembly:

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

Where:
U = overall coefficient of heat transfer (U-factor), W/m^2K
A_{pf} = total *projected* area of fenestration, m^2
T_{in} = indoor air temperature, K
T_{out} = outdoor air temperature, K
SHGC = solar heat gain coefficient, -
I_{solar} = incident total irradiance, W/m^2



Window U-factors

- U-values (or U-factors) for windows include all of the elements of the fenestration system
  - Center of glass properties (cg)
  - Edge of glass properties (eg)
  - Frame properties (f)
- The overall U-factor is estimated using area-weighted U-factors for each:

$$U = \frac{U_{cg}A_{cg} + U_{eg}A_{eg} + U_{f}A_{f}}{A_{pf}}$$

U-values and multiple layers of glazing

- We can separate glass panes with air-tight layers of air or other gases

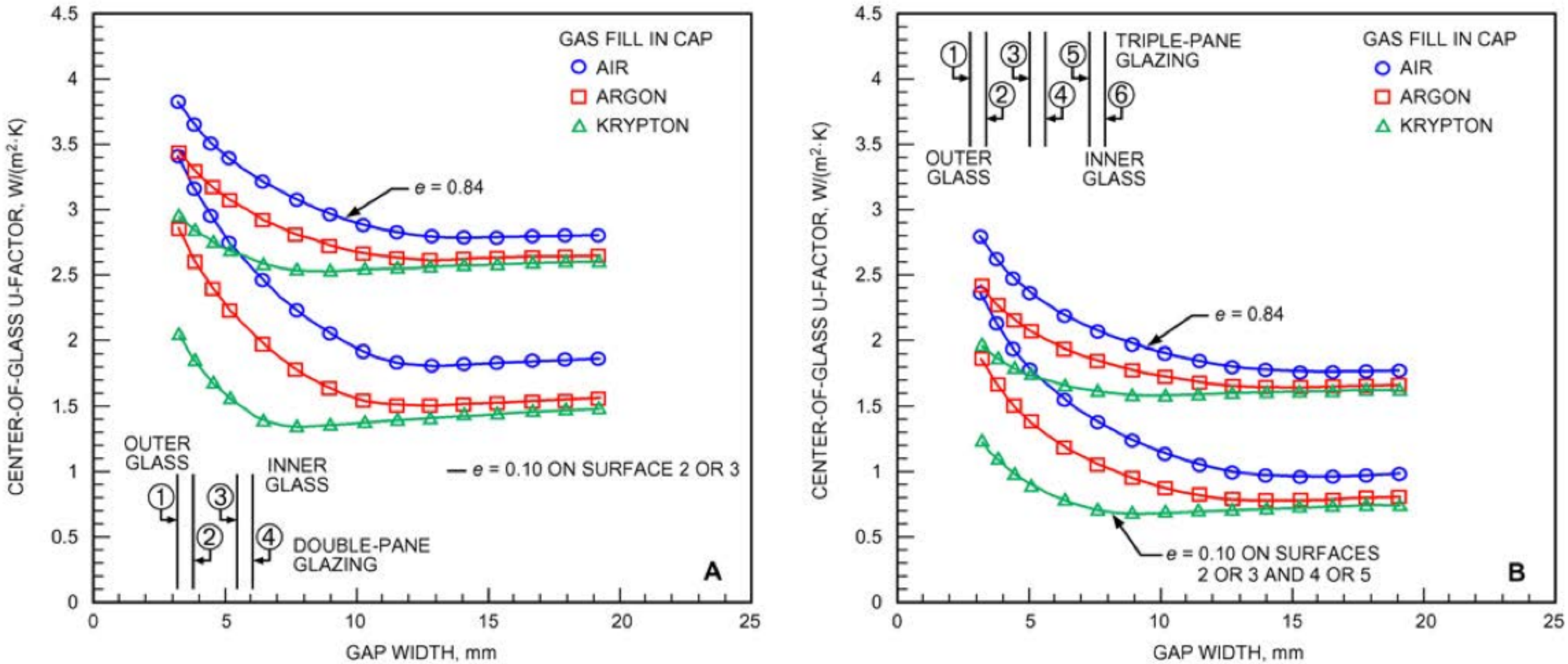


Fig. 3 Center-of-Glass U-Factor for Vertical Double- and Triple-Pane Glazing Units

2013 ASHRAE Handbook of Fundamentals: Chapter 15

Combined U-factor data: ASHRAE 2013

Table 4 U-Factors for Various Fenestration Products in $W/(m^2 \cdot K)$

Product Type / Frame Type		Glass Only		Vertical Installation									
				Operable (including sliding and swinging glass doors)					Fixed				
ID	Glazing Type	Center of Glass	Edge of Glass	Aluminum Without Thermal Break	Aluminum With Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl	Aluminum Without Thermal Break	Aluminum With Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl
	Single Glazing												
1	3 mm glass	*5.91*	*5.91*	7.01	6.08	5.27	5.20	4.83	6.38	6.06	5.58	5.58	5.40
2	6 mm acrylic/polycarb	*5.00*	*5.00*	6.23	5.35	4.59	4.52	4.18	5.55	5.23	4.77	4.77	4.61
3	3.2 mm acrylic/polycarb	*5.45*	*5.45*	6.62	5.72	4.93	4.86	4.51	5.96	5.64	5.18	5.18	5.01
	Double Glazing												
4	6 mm airspace	*3.12*	*3.63*	4.62	3.61	3.24	3.14	2.84	3.88	3.52	3.18	3.16	3.04
5	13 mm airspace	*2.73*	*3.36*	4.30	3.31	2.96	2.86	2.58	3.54	3.18	2.85	2.83	2.72
6	6 mm argon space	*2.90*	*3.48*	4.43	3.44	3.08	2.98	2.69	3.68	3.33	3.00	2.98	2.86
7	13 mm argon space	*2.56*	*3.24*	4.16	3.18	2.84	2.74	2.46	3.39	3.04	2.71	2.69	2.58
	Double Glazing, $e = 0.60$ on surface 2 or 3												
8	6 mm airspace	*2.95*	*3.52*	4.48	3.48	3.12	3.02	2.73	3.73	3.38	3.04	3.02	2.90
9	13 mm airspace	*2.50*	*3.20*	4.11	3.14	2.80	2.70	2.42	3.34	2.99	2.67	2.65	2.53
10	6 mm argon space	*2.67*	*3.32*	4.25	3.27	2.92	2.82	2.54	3.49	3.13	2.81	2.79	2.67
11	13 mm argon space	*2.33*	*3.08*	3.98	3.01	2.68	2.58	2.31	3.20	2.84	2.52	2.50	2.39
	Double Glazing, $e = 0.40$ on surface 2 or 3												
12	6 mm airspace	*2.78*	*3.40*	4.34	3.35	3.00	2.90	2.61	3.59	3.23	2.90	2.88	2.77
13	13 mm airspace	*2.27*	*3.04*	3.93	2.96	2.64	2.54	2.27	3.15	2.79	2.48	2.46	2.35
14	6 mm argon space	*2.44*	*3.16*	4.07	3.09	2.76	2.66	2.38	3.30	2.94	2.62	2.60	2.49
15	13 mm argon space	*2.04*	*2.88*	3.75	2.79	2.48	2.38	2.11	2.95	2.60	2.29	2.27	2.16
	Double Glazing, $e = 0.20$ on surface 2 or 3												
16	6 mm airspace	*2.56*	*3.24*	4.16	3.18	2.84	2.74	2.46	3.39	3.04	2.71	2.69	2.58
17	13 mm airspace	*1.99*	*2.83*	3.70	2.75	2.44	2.34	2.07	2.91	2.55	2.24	2.22	2.12
18	6 mm argon space	*2.16*	*2.96*	3.84	2.88	2.56	2.46	2.19	3.05	2.70	2.38	2.36	2.26
19	13 mm argon space	*1.70*	*2.62*	3.47	2.53	2.24	2.14	1.88	2.66	2.30	2.00	1.98	1.88
	Double Glazing, $e = 0.10$ on surface 2 or 3												
20	6 mm airspace	*2.39*	*3.12*	4.02	3.05	2.72	2.62	2.34	3.25	2.89	2.57	2.55	2.44
21	13 mm airspace	*1.82*	*2.71*	3.56	2.62	2.32	2.22	1.96	2.76	2.40	2.10	2.08	1.98
22	6 mm argon space	*1.99*	*2.83*	3.70	2.75	2.44	2.34	2.07	2.91	2.55	2.24	2.22	2.12
23	13 mm argon space	*1.53*	*2.49*	3.33	2.40	2.12	2.02	1.76	2.51	2.16	1.86	1.84	1.74

Thermal resistances of still air cavities

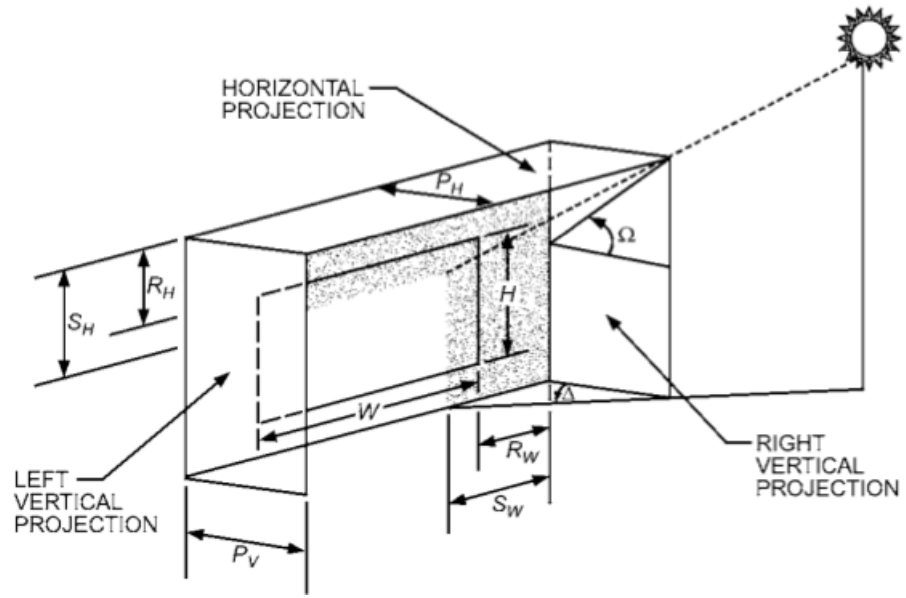
Table 3 Thermal Resistances of Plane Air Spaces,[a,b,c] $(m^2 \cdot K)/W$

Position of Air Space	Direction of Heat Flow	Air Space: Mean Temp.[d], °C	Air Space: Temp. Diff.,[d] K	Effective Emittance ε_{eff}[d,e]: 13 mm Air Space[c]					20 mm Air Space[c]				
				0.03	0.05	0.2	0.5	0.82	0.03	0.05	0.2	0.5	0.82
		32.2	5.6	0.37	0.36	0.27	0.17	0.13	0.41	0.39	0.28	0.18	0.13
		10.0	16.7	0.29	0.28	0.23	0.17	0.13	0.30	0.29	0.24	0.17	0.14
		10.0	5.6	0.37	0.36	0.28	0.20	0.15	0.40	0.39	0.30	0.20	0.15
Horiz.	Up ↑	−17.8	11.1	0.30	0.30	0.26	0.20	0.16	0.32	0.32	0.27	0.20	0.16
		−17.8	5.6	0.37	0.36	0.30	0.22	0.18	0.39	0.38	0.31	0.23	0.18
		−45.6	11.1	0.30	0.29	0.26	0.22	0.18	0.31	0.31	0.27	0.22	0.19
		−45.6	5.6	0.36	0.35	0.31	0.25	0.20	0.38	0.37	0.32	0.26	0.21
		32.2	5.6	0.43	0.41	0.29	0.19	0.13	0.52	0.49	0.33	0.20	0.14
		10.0	16.7	0.36	0.35	0.27	0.19	0.15	0.35	0.34	0.27	0.19	0.14
		10.0	5.6	0.45	0.43	0.32	0.21	0.16	0.51	0.48	0.35	0.23	0.17
45° Slope	Up ↗	−17.8	11.1	0.39	0.38	0.31	0.23	0.18	0.37	0.36	0.30	0.23	0.18
		−17.8	5.6	0.46	0.45	0.36	0.25	0.19	0.48	0.46	0.37	0.26	0.20
		−45.6	11.1	0.37	0.36	0.31	0.25	0.21	0.36	0.35	0.31	0.25	0.20
		−45.6	5.6	0.46	0.45	0.38	0.29	0.23	0.45	0.43	0.37	0.29	0.23
		32.2	5.6	0.43	0.41	0.29	0.19	0.14	0.62	0.57	0.37	0.21	0.15
		10.0	16.7	0.45	0.43	0.32	0.22	0.16	0.51	0.49	0.35	0.23	0.17
		10.0	5.6	0.47	0.45	0.33	0.22	0.16	0.65	0.61	0.41	0.25	0.18
Vertical	Horiz. →	−17.8	11.1	0.50	0.48	0.38	0.26	0.20	0.55	0.53	0.41	0.28	0.21
		−17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.66	0.63	0.46	0.30	0.22
		−45.6	11.1	0.51	0.50	0.41	0.31	0.24	0.51	0.50	0.42	0.31	0.24
		−45.6	5.6	0.56	0.55	0.45	0.33	0.26	0.65	0.63	0.51	0.36	0.27

2005 ASHRAE Handbook of Fundamentals: Chapter 25; 2013 ASHRAE Handbook of Fundamentals: Chapter 26

What about shading?

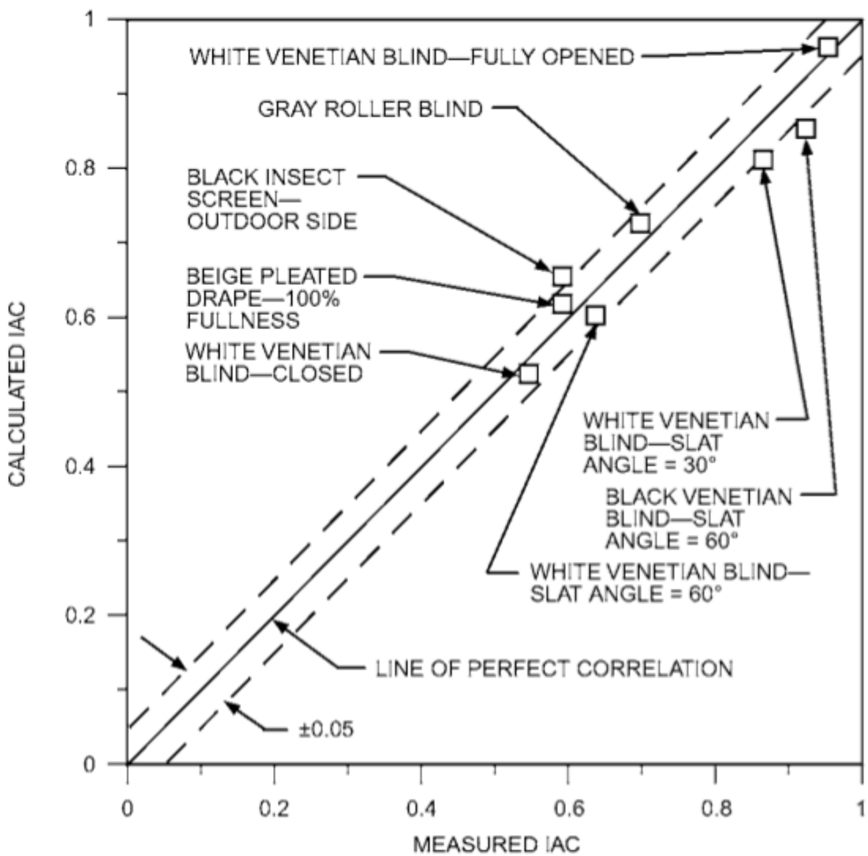
- Shading devices, including drapes and blinds, can mitigate some solar heat gain
- We can attempt to describe this with an **indoor solar attenuation coefficient (IAC)**
- Heat gain through a window can be modified as follows:

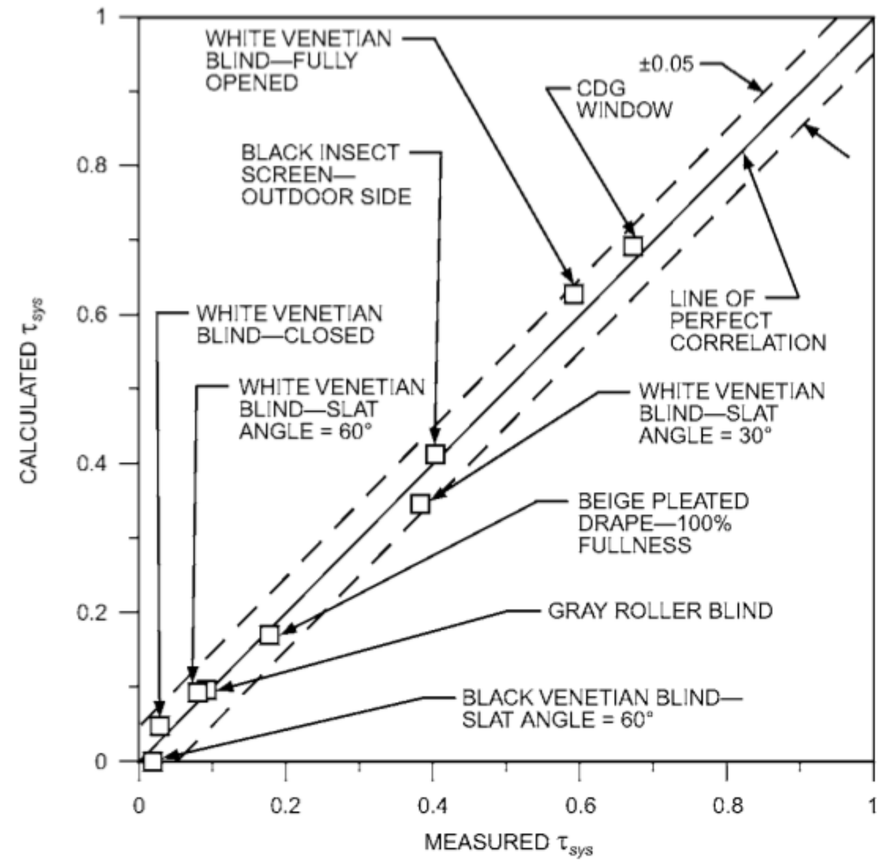


$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{direct}A_{pf}SHGC(\theta)IAC(\theta,\Omega) + (I_{diffuse+reflected})A_{pf}SHGC_{diffuse+reflected}IAC_{diffuse+reflected}$$

IAC is a function of incidence angle, θ, and the angle created by a shading device

Blinds and drapes: ASHRAE Handbook





Combined thermal transmittance for walls + fenestration

- Single assemblies of walls, windows, doors, etc. can be combined into an overall U-value for a building's enclosure
  - **Combined thermal transmittance**: U_o or U_{total}
    - Area-weighted average U-value
    - Just like center of glass, edge of glass, frame analysis for windows

$$U_{total} = \frac{U_{wall}A_{wall} + U_{windows}A_{windows} + U_{doors}A_{doors}}{A_{total}}$$

We will use this later for calculating heating and cooling loads