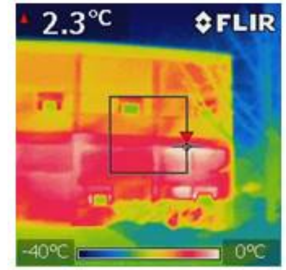
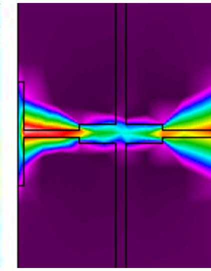
CAE 331/513
Building Science
Fall 2016





Week 3: September 8, 2016
Heat transfer in buildings: Finish radiation, then solar radiation and windows

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Last time

- Finished convection
  - Convective heat transfer coefficients
    - Theory for natural convection
      - Gr = buoyancy vs. viscosity
      - Ra = Gr x Pr
    - Empirical measurements
    - Simplified empirical relationships
      - h_c = f(temperature difference, velocity, orientation, roughness)

- Radiation

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

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

Today's objectives

- Finish radiation heat transfer
- Understand solar radiation (short wave radiation)
  - Basic solar geometry
- Understand heat transfer through windows
  - Combined modes of heat transfer
- Assign HW #2 (due Tues Sep 13)
- Discuss Exam #1 (scheduled for Tues Sep 20)
  - *Should we move to Thurs Sep 22?*

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

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

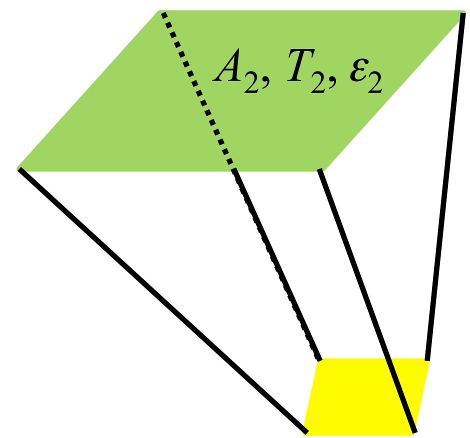
Absorptivity (α) for solar (short-wave) radiation

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:

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



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

Emissivity (“gray bodies”)

- Real surfaces emit less radiation than ideal “black” ones
  - The ratio of energy radiated by a given body to a perfect black body at the same temperature is called the emissivity: ε

- ε is dependent on wavelength, but for most common building materials (e.g. brick, concrete, wood…), ε = 0.9 at most wavelengths

Emissivity (ε) of common materials

Surface	Emittance (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

Emissivity (ε) of common building materials

TABLE 2.11

Emissivities of Some Common Building Materials at Specified Temperatures

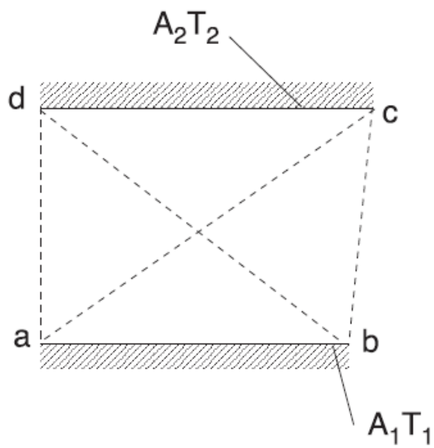
Surface	Temperature, °C	Temperature, °F	ϵ
Brick			
Red, rough	40	100	0.93
Concrete			
Rough	40	100	0.94
Glass			
Smooth	40	100	0.94
Ice			
Smooth	0	32	0.97
Marble			
White	40	100	0.95
Paints			
Black gloss	40	100	0.90
White	40	100	0.89–0.97
Various oil paints	40	100	0.92–0.96
Paper			
White	40	100	0.95
Sandstone	40–250	100–500	0.83–0.90
Snow	−12–−6	10–20	0.82
Water			
0.1 mm or more thick	40	100	0.96
Wood			
Oak, planed	40	100	0.90
Walnut, sanded	40	100	0.83
Spruce, sanded	40	100	0.82
Beech	40	100	0.94

Source: Courtesy of Sparrow, E.M. and Cess, R.D., *Radiation Heat Transfer*, augmented edn, Hemisphere, New York, 1978. With permission.

View factors, F_{12}

- Radiation travels in directional beams
  - Thus, areas and angle of incidence between two exchanging surfaces influences radiative heat transfer

Some common view factors:



$$A_1F_{1\rightarrow 2} = 0.5((ac+bd)-(ad+bc))$$

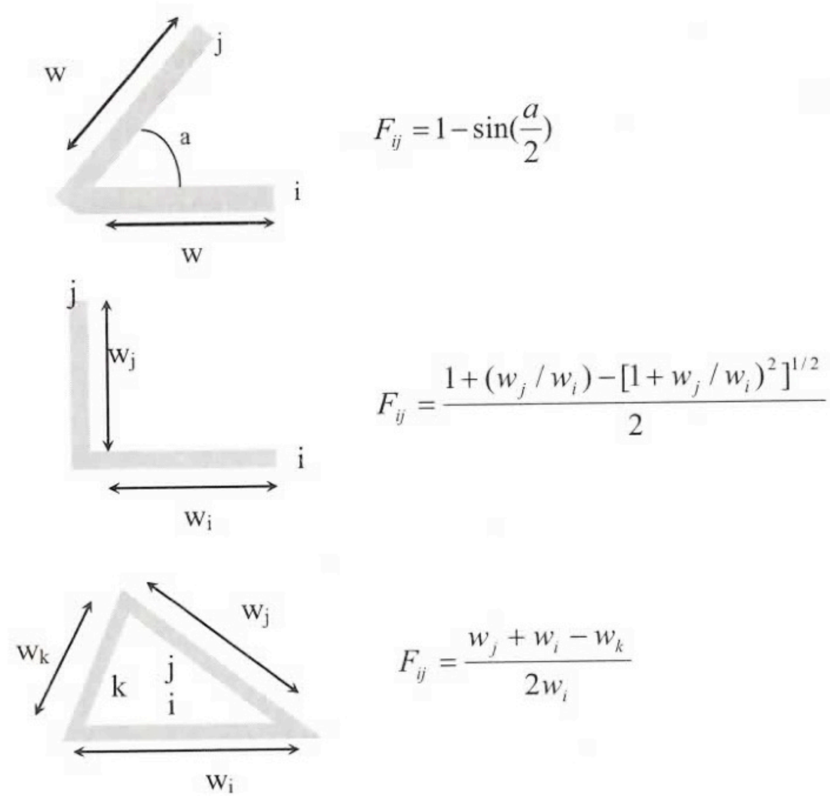
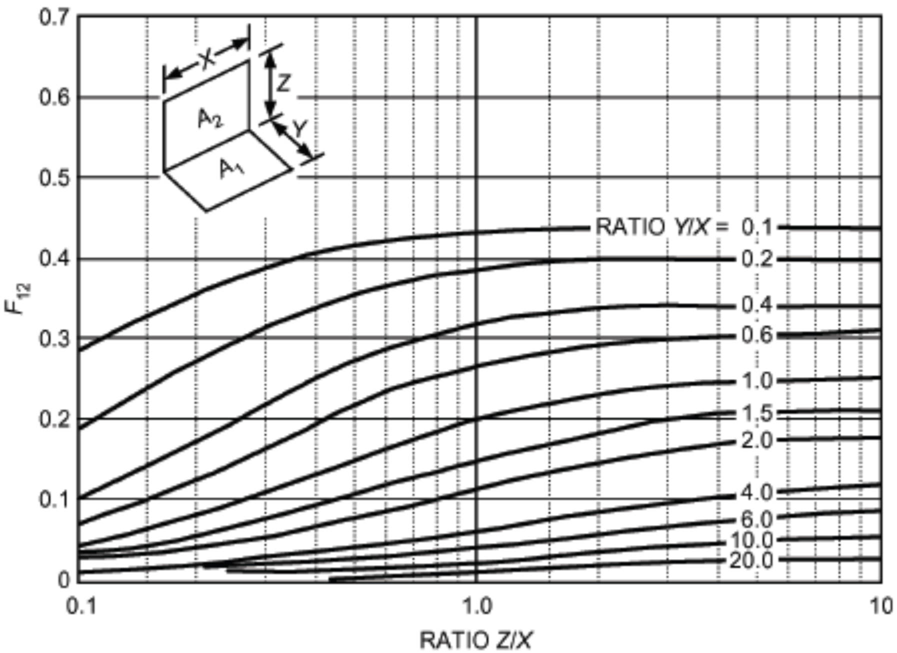


Figure 5.6: View factors for common situations in building enclosures [Hagentoft 2000]

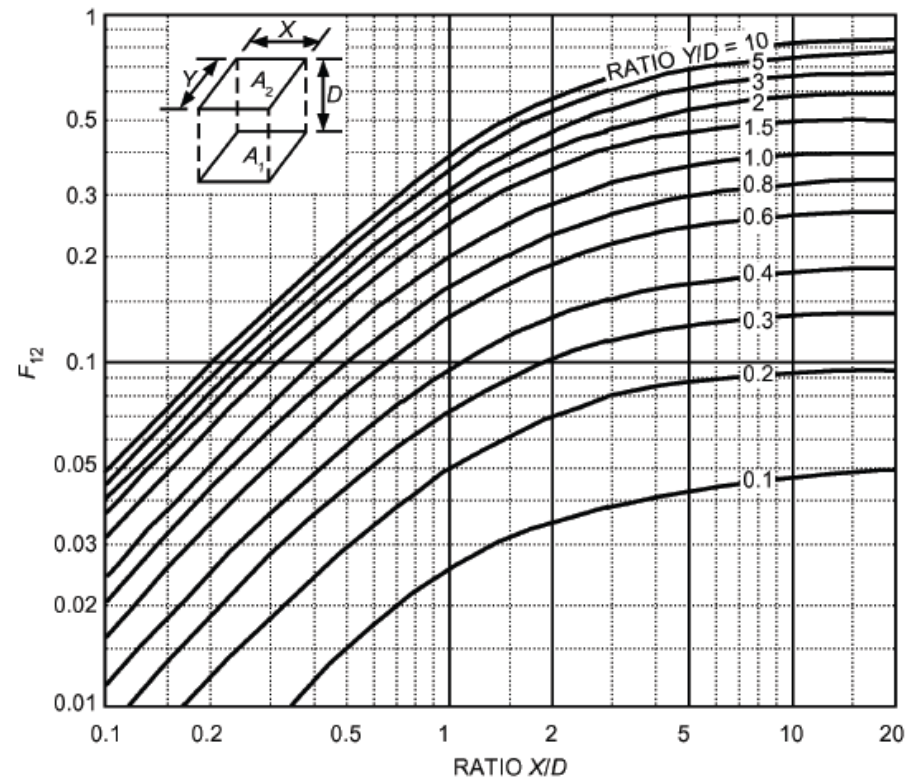
Online radiation view factors textbook:
http://www.thermalradiation.net/tablecon.html

Typical view factors

Other common view factors from the ASHRAE Handbook of Fundamentals:



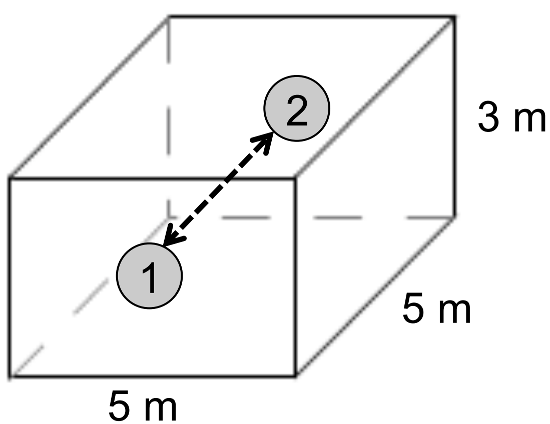
A. PERPENDICULAR RECTANGLES WITH COMMON EDGE

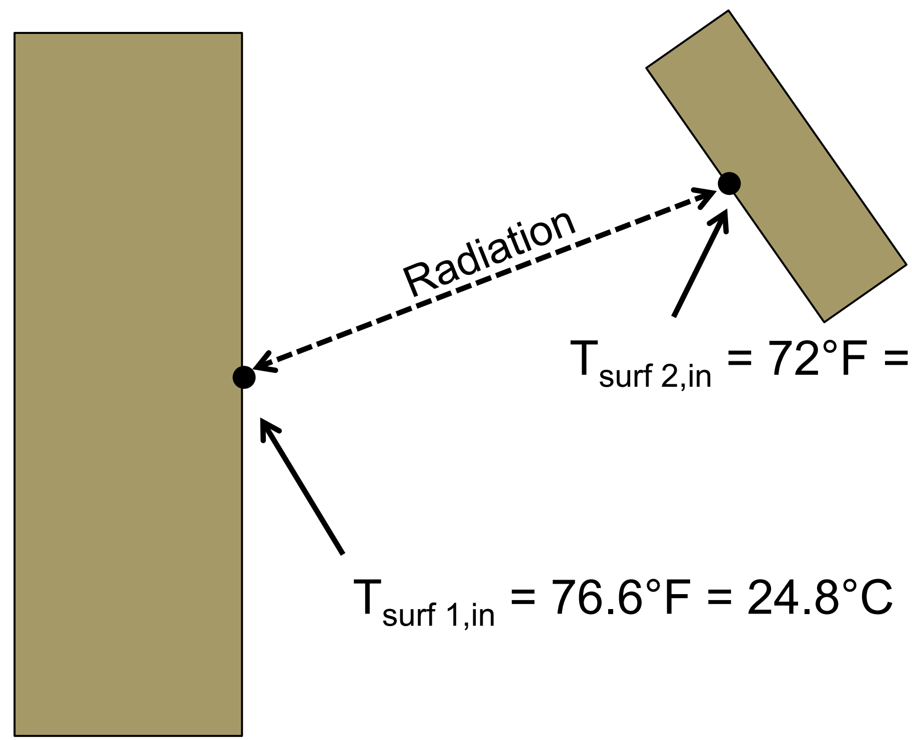


B. ALIGNED PARALLEL RECTANGLES

Long-wave radiation example

- What is the net radiative exchange between the two interior wall surfaces below end of the room if the room is 5 m x 5 m x 3 m?





Simplifying surface radiation

- We can also often simplify radiation from:

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

- 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

Simplifying radiation

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

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

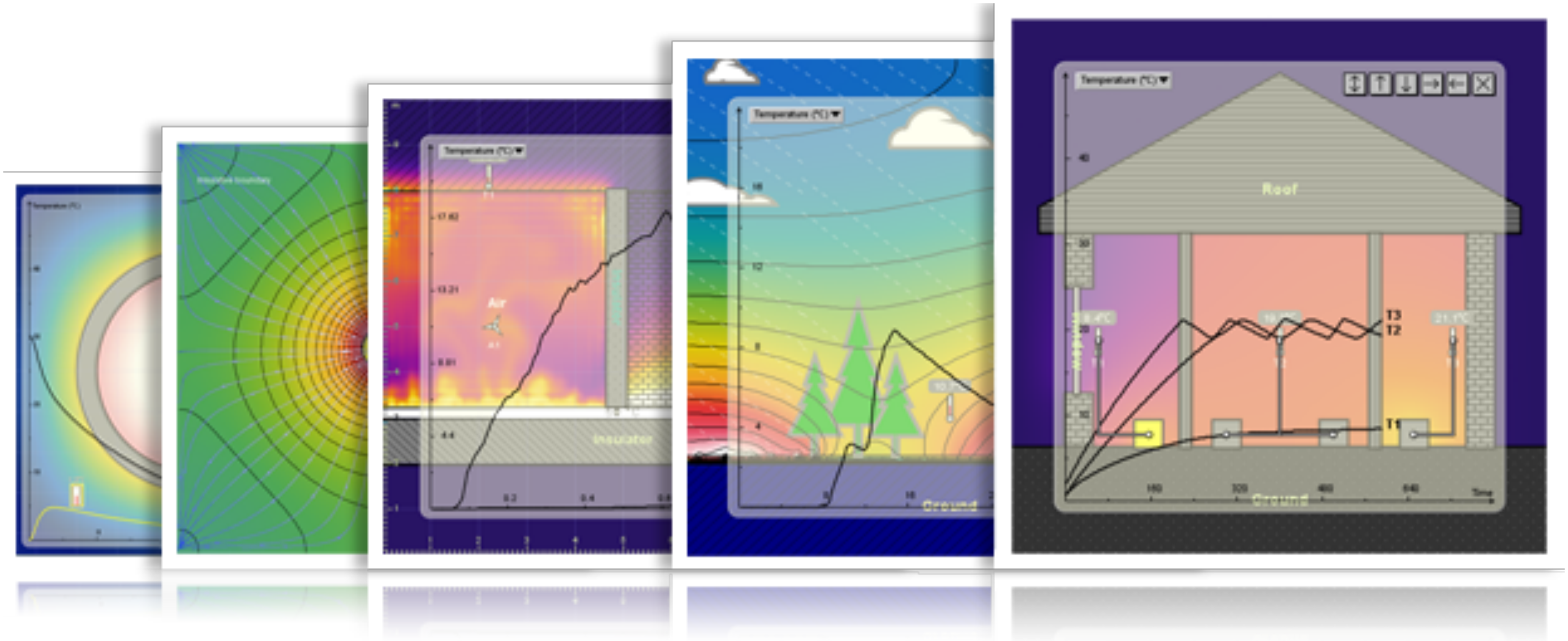
- When $A_1 = A_2$, and T_1 and T_2 are within ~50°F of each other, we can approximate h_{rad} with a simpler equation:

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

where

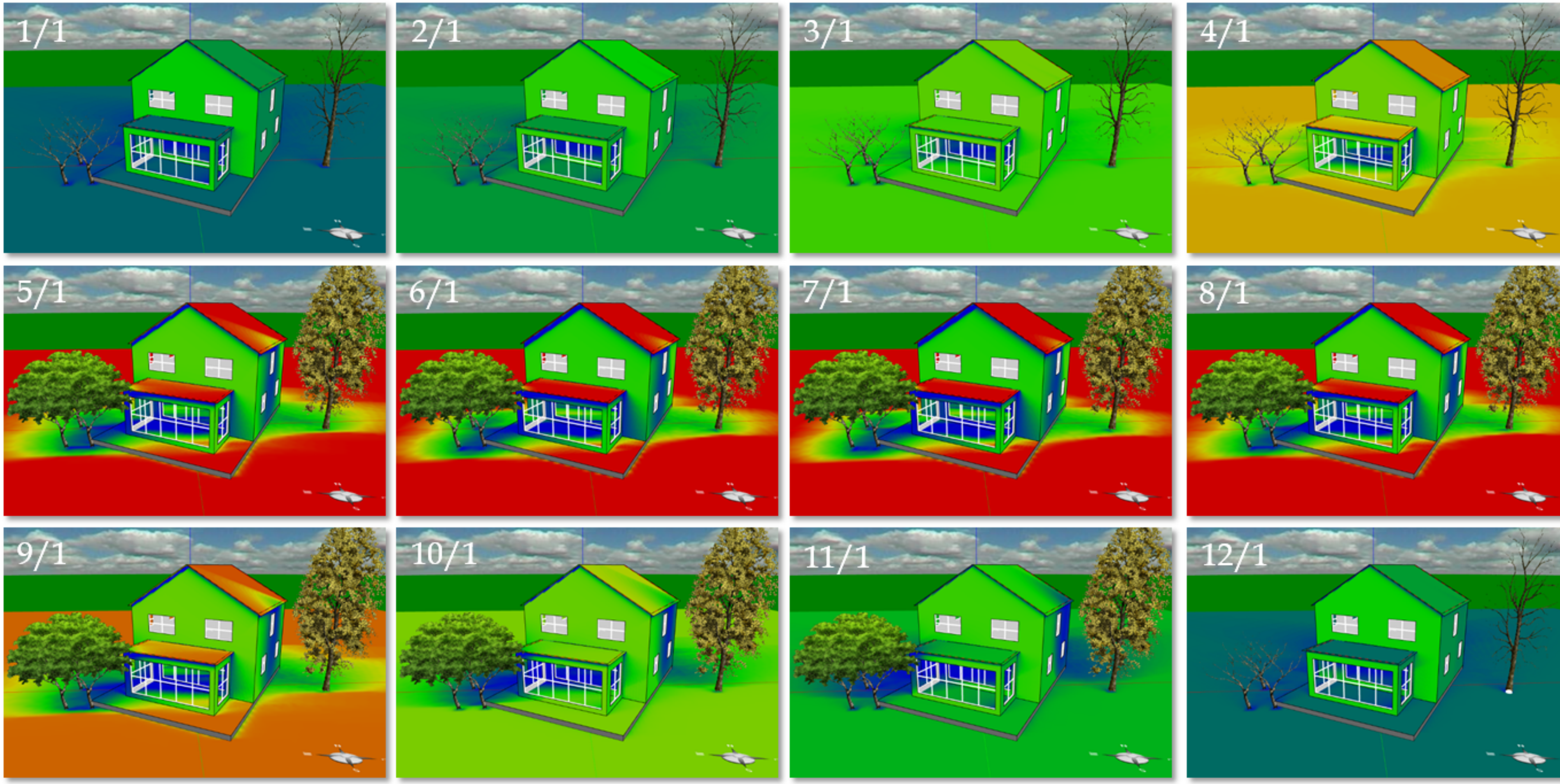
$$T_{avg} = \frac{T_1 + T_2}{2}$$

Radiation visualizations



Energy2D

Interactive Heat Transfer Simulations for Everyone



SOLAR RADIATION

Solar radiation

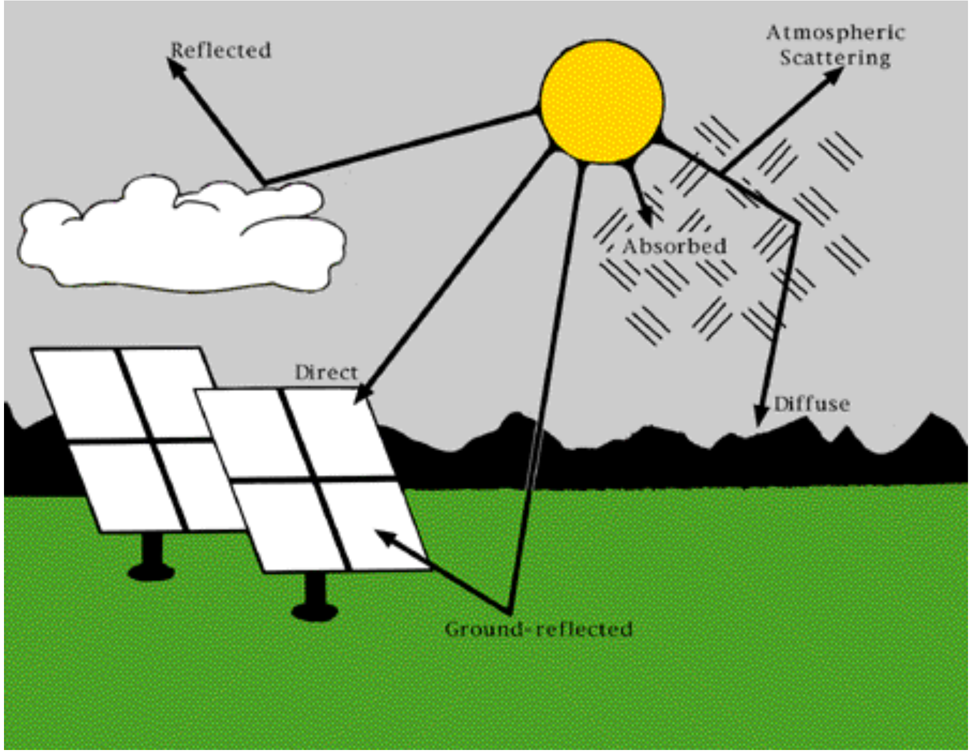
- Solar radiation is a very important term in the energy balance of a building
  - We must account for it while calculating loads
  - This is particularly true for perimeter zones and for peak cooling loads
- Solar radiation is also important for daylighting design
- We won't cover the full equations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

Components of solar radiation

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

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

- Direct
- Diffuse
- Reflected



Components of solar radiation

- **<u>Direct solar radiation</u>** (I_{direct}) is a function of the **normal incident irradiation** (I_{DN}) on the earth's surface and the solar incidence angle of the surface of interest, θ
  - Where I_{DN} is the amount of solar radiation received per unit area by a surface that is always perpendicular to the sun's direct rays
  - Function of day of the year and atmospheric properties

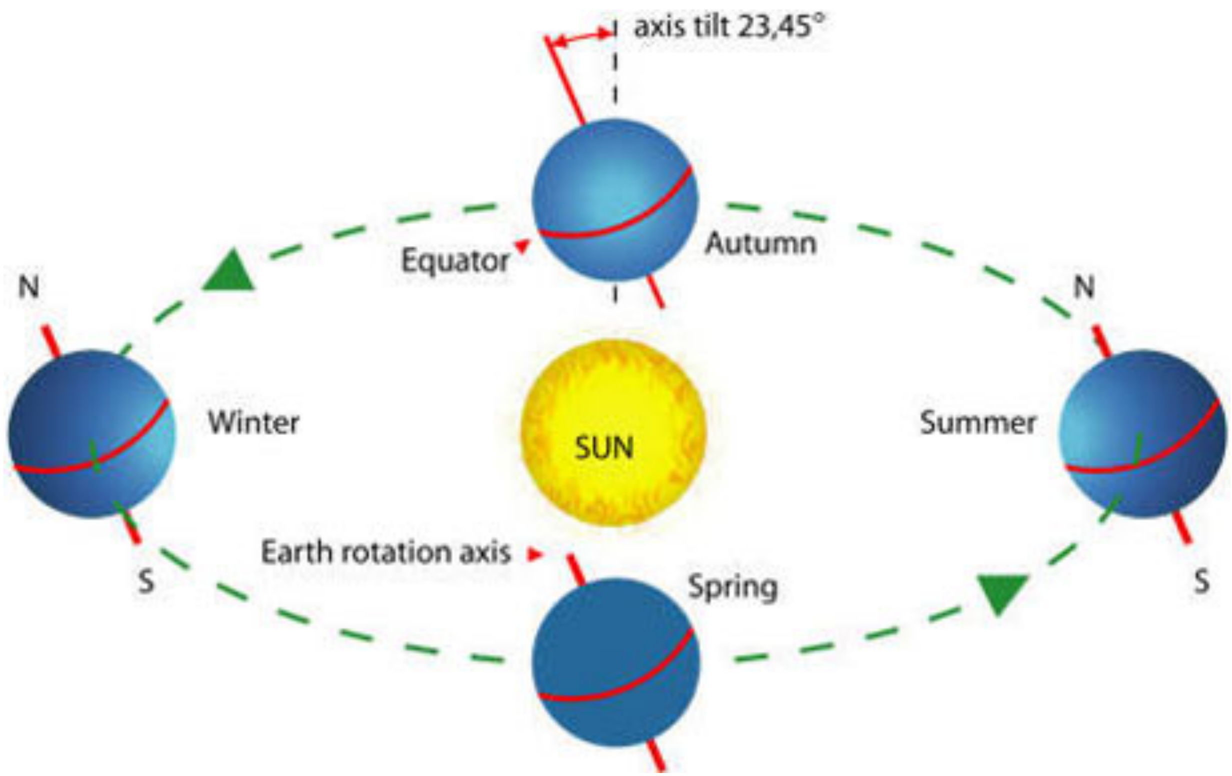
$$I_D = I_{DN} \cos\theta$$

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

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

Solar radiation: earth-sun relationships

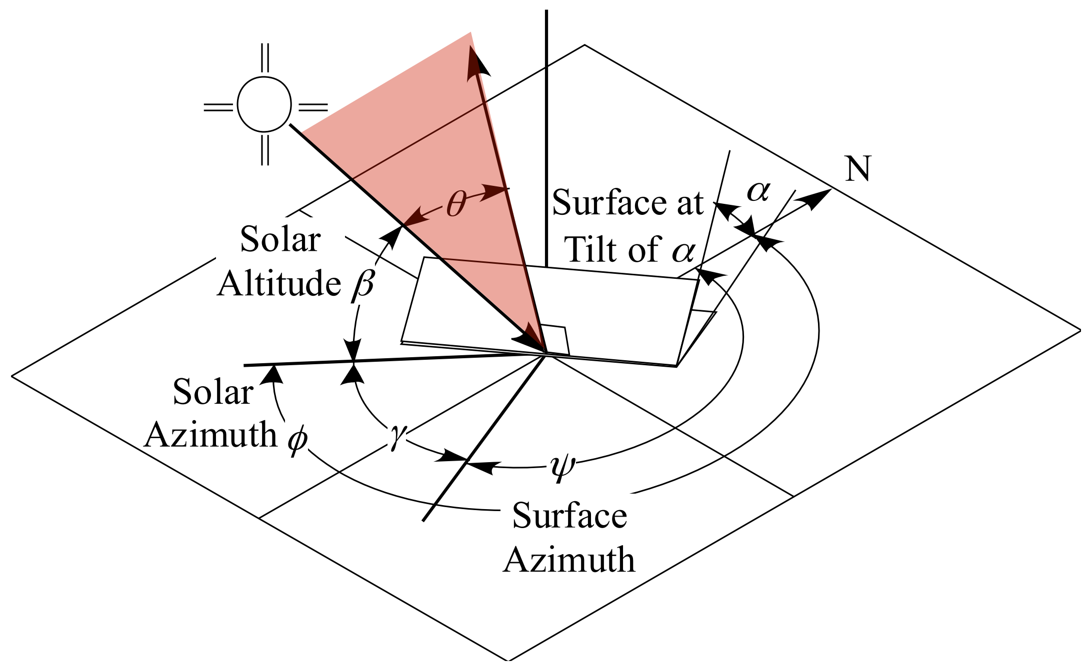
- Earth rotates about its axis every 24 hours
- Earth revolves around sun every 365.2425 days
- Earth is titled at an angle of 23.45°
  - Therefore, different locations on earth receive different levels of solar radiation during different times of the year (and different times of the day)



Solar radiation striking an exterior surface

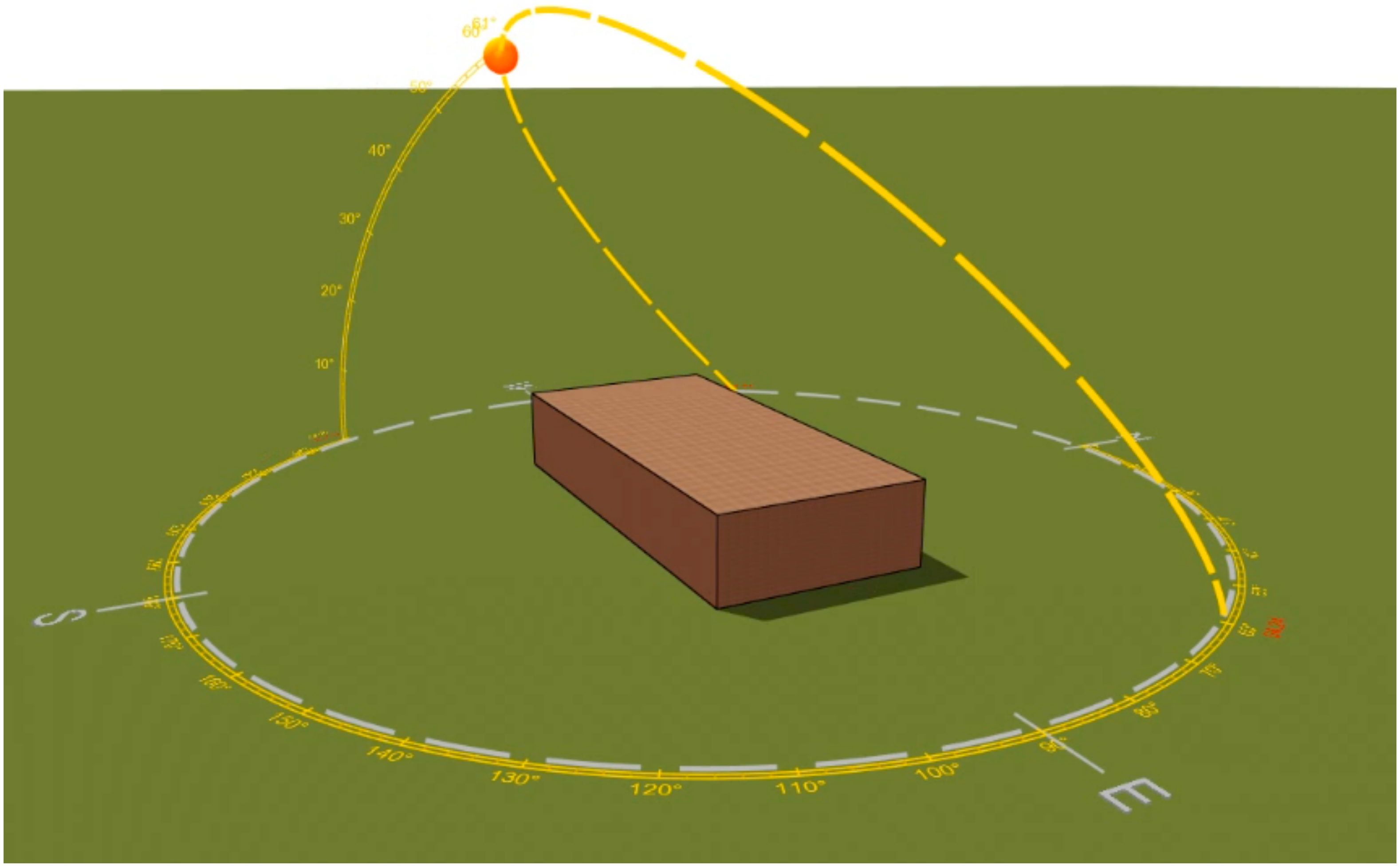
- The amount of solar radiation received by a surface depends on the **incidence angle**, θ

- This is a function of:
  - Solar geometry (I_{DN})
    - Location
    - Time
  - Surface geometry
  - Shading/obstacles



$$I_D = I_{DN} \cos\theta$$

Visualizing solar relationships



http://energy.concord.org/energy3d/

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”

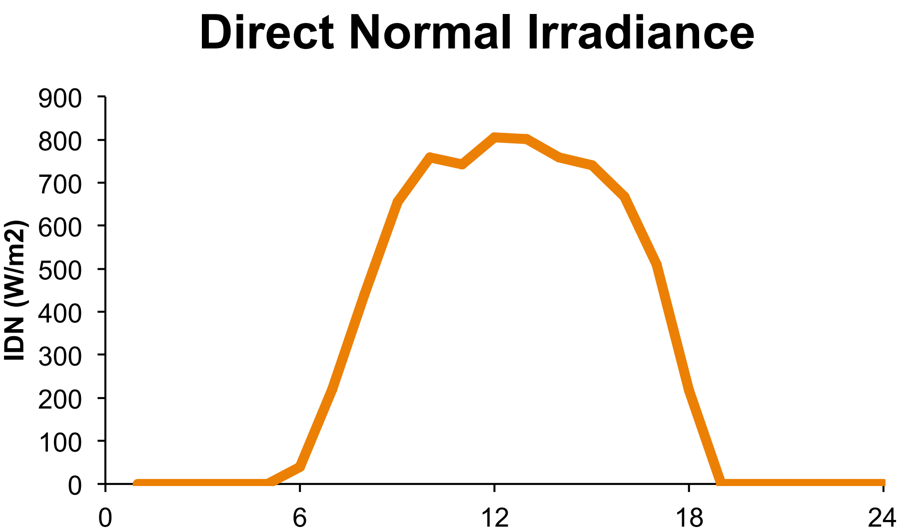
- For *actual* hourly solar data (direct + diffuse in W/m^2)
  - http://rredc.nrel.gov/solar/old_data/nsrdb/
  - Output of interest = “direct normal radiation” → adjust using $\cos\theta$
    - Note: “typical meteorological years”

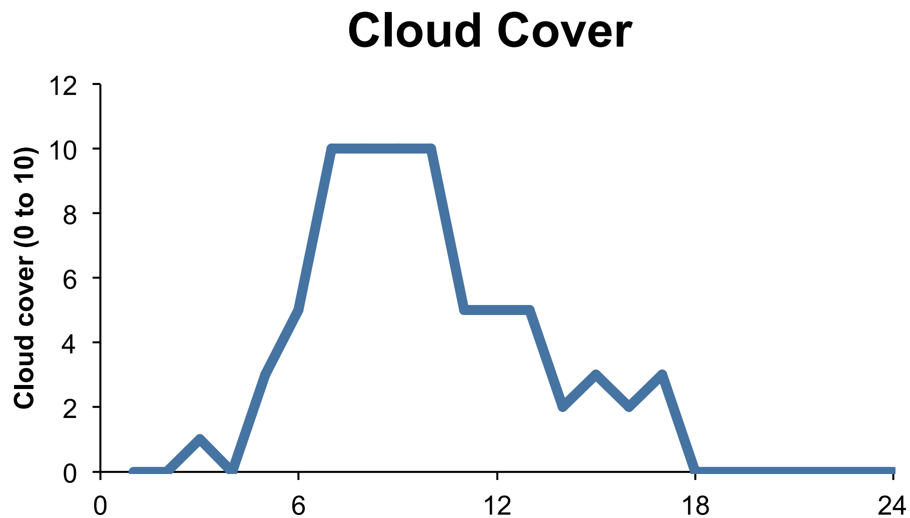
Typical meteorological year (TMY)

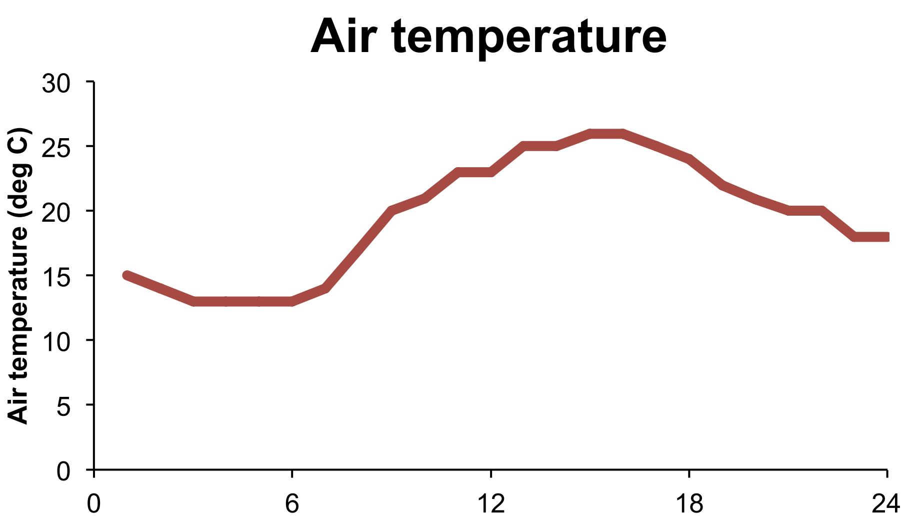
- For heating and cooling load calculations and for hourly building energy simulations, we often rely on a collection of weather data for a specific location
- We generate this data to be representative of more than just the previous year
  - Represents a wide range of weather phenomena for our location
  - 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 radiation, wind speed, wind direction, outdoor RH, cloud cover, and more

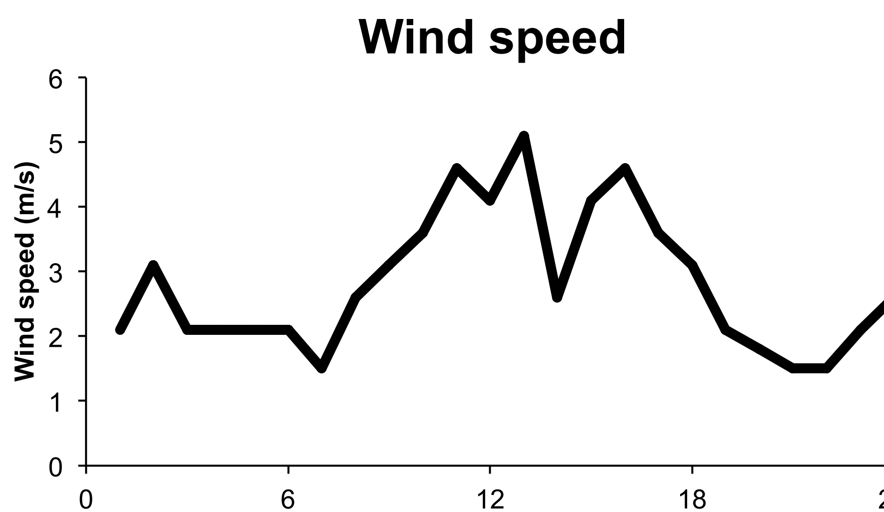
Typical meteorological year (TMY): Solar data

Data for typical September 10th at Midway, Chicago, IL









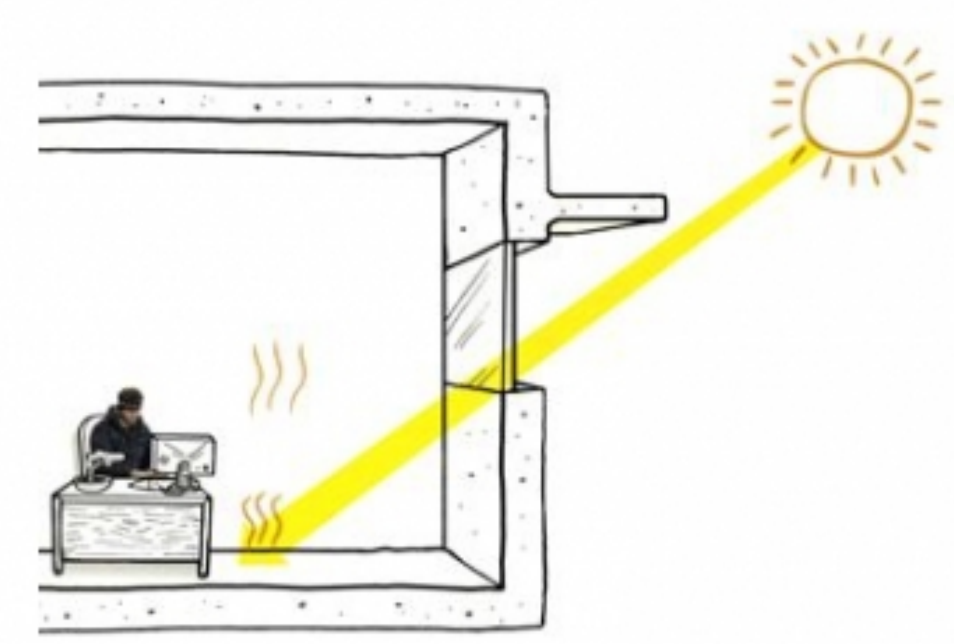
What to do with solar data once you have it?

- 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 fenestration (e.g. **windows and skylights**) to determine how much solar radiation enters an indoor environment

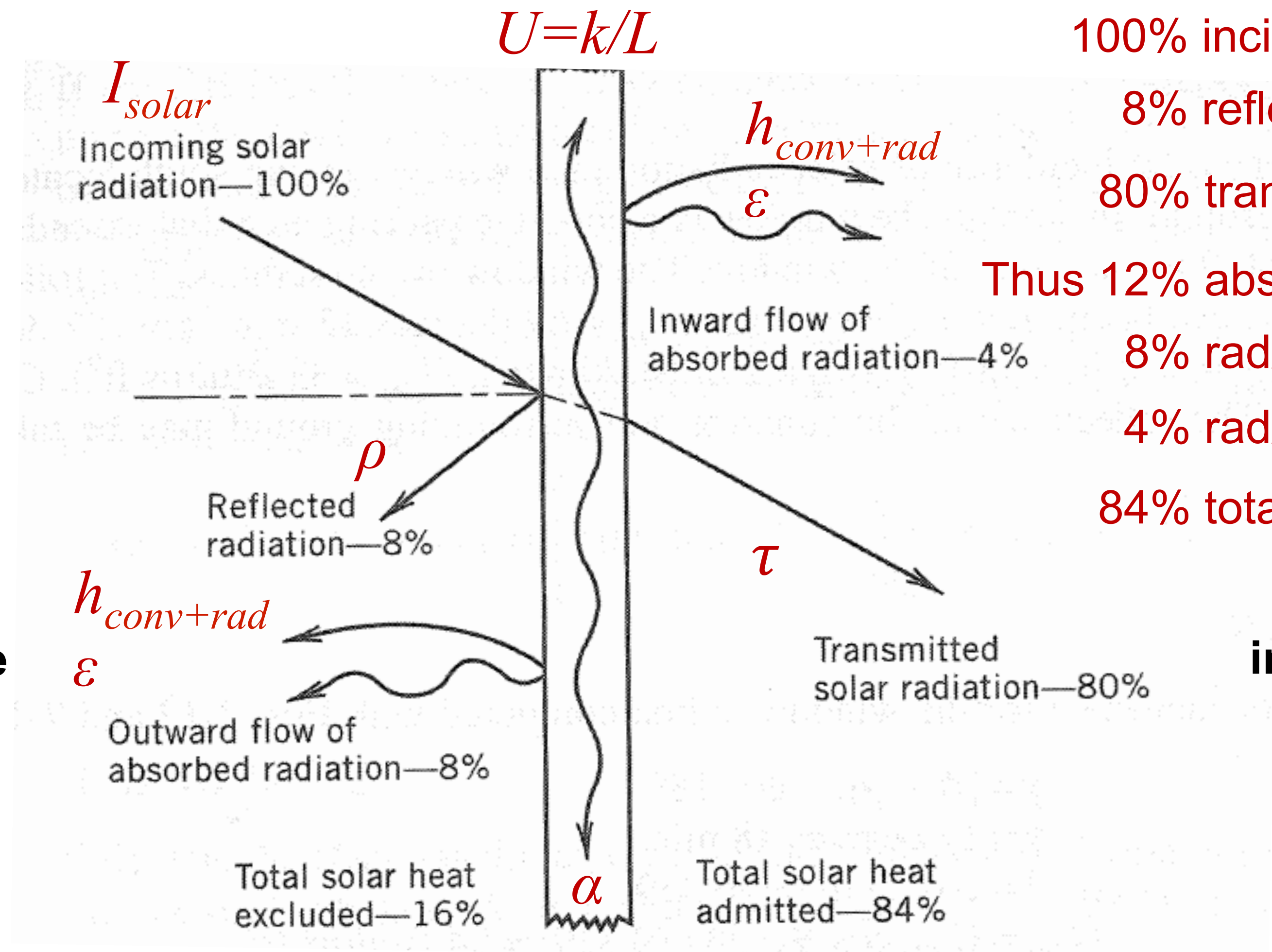
$$q_{solar} = \tau I_{solar}$$



SOLAR RADIATION AND WINDOWS

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

- Solar radiation through a single glaze



outside

inside

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 amount of heat gain from solar radiation passing through
  - Combined conductive/convective/LWR thermal heat gain or loss from the temperature difference between the interior and exterior
- In the summer, both terms are positive towards the interior and add to heat gains
- In the winter, solar is positive inwards (gain) but conduction/convection/LWR is negative towards the exterior (loss)
  - Net heat gain may be in either direction

Heat gain through windows

- Calculating the heat gain/loss through a window based on indoor/outdoor temperature differences is relatively easy:

$$Q = UA(T_{in} - T_{out}) = UA\Delta T$$

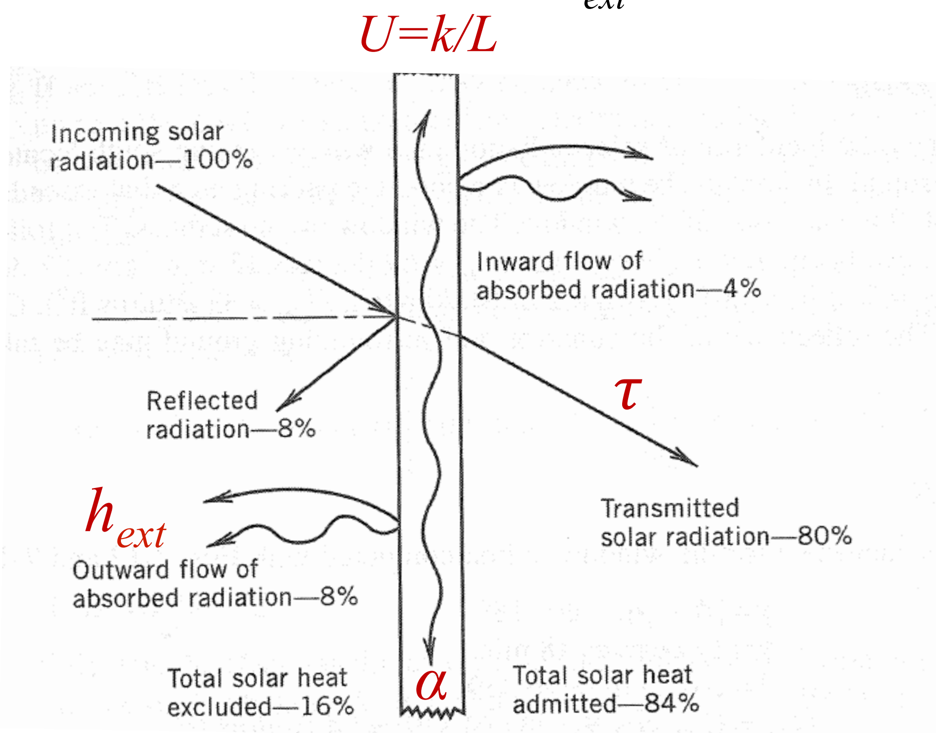
- Accounting for **solar heat gain** is more complicated
  - Need to include absorption of solar energy and re-radiation of thermal energy
  - Need to include spectral and angular characteristics of radiation and glazing
- We can do this with a simplified metric
  - The solar heat gain coefficient (SHGC):

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

Solar heat gain coefficient, SHGC

- For a <u>single pane of glass</u>:

$$SHGC = \tau + \alpha \frac{U}{h_{ext}} \longrightarrow R = \frac{1}{U} = \frac{1}{h_{int}} + \frac{L_{glass}}{k_{glass}} + \frac{1}{h_{ext}}$$



k_{glass} = ~1 W/mK
L_{glass} = ~5 mm (0.2”)
*R_{glass} is negligible (~0.005 m^{2}K/W)

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

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

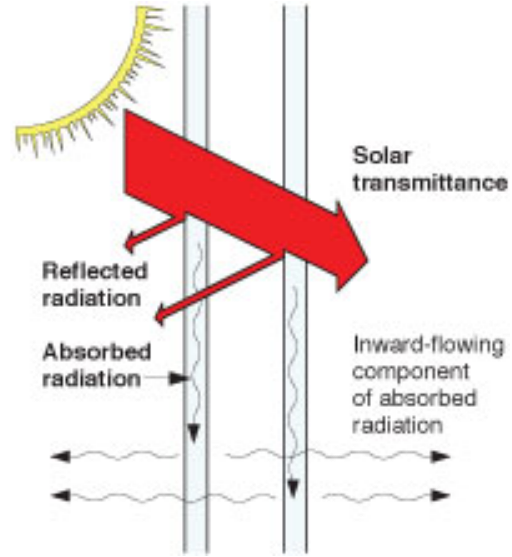
Solar heat gain coefficient, SHGC

- For <u>double glazing</u> with a small still air gap:

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

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

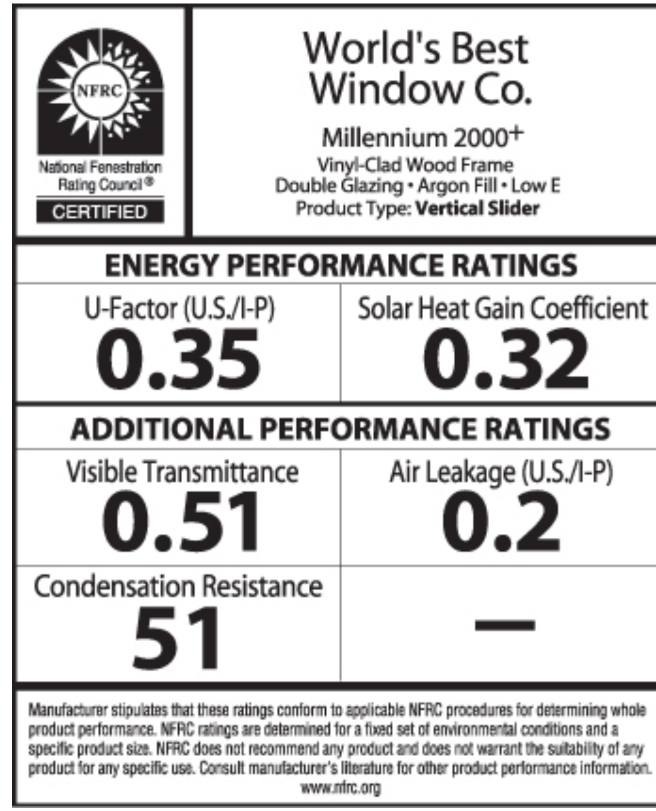
*$R_{outer\ pane}$ and $R_{inner\ pane}$ are negligible



It gets complicated quickly!

Manufacturer supplied SHGC

- Glazing manufacturers will measure and report SHGC values 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)



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

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

Complex SHGC

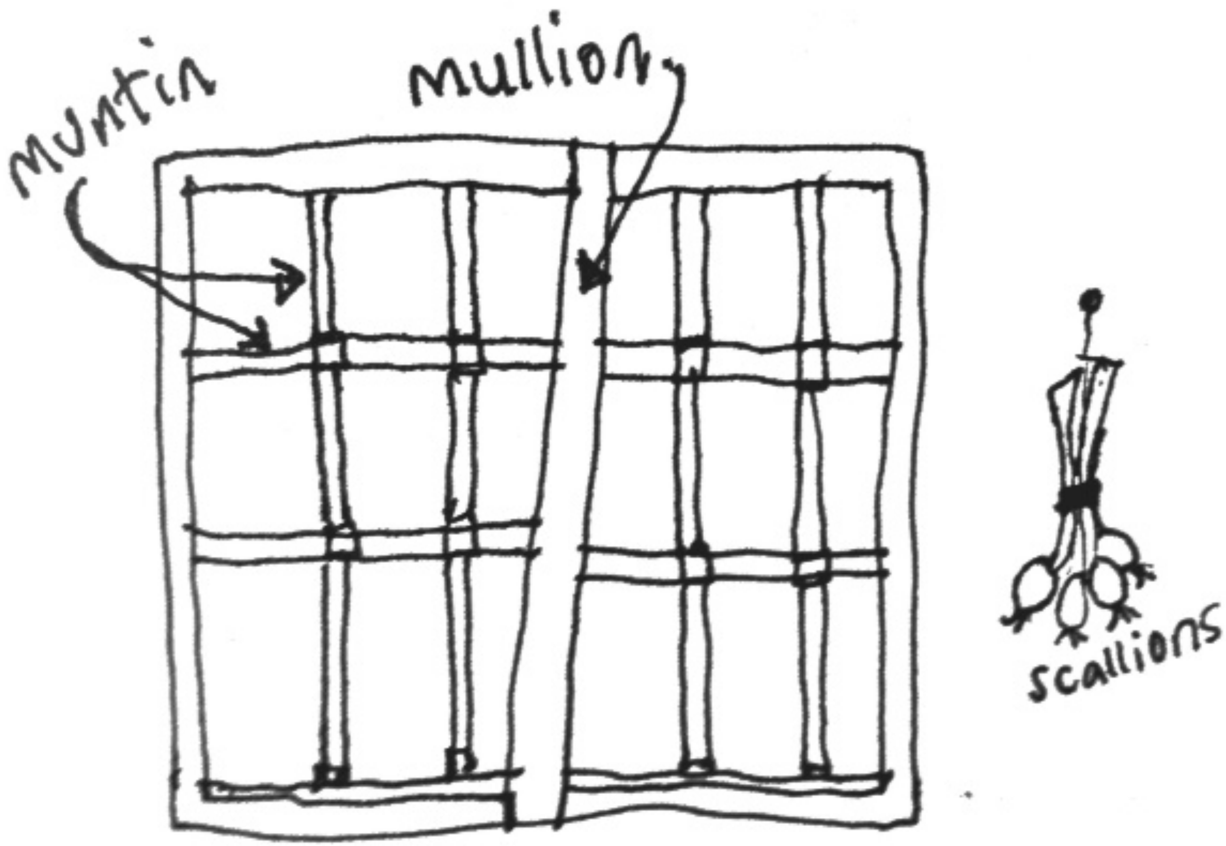
- SHGC, solar transmittance, reflectance, and absorptance properties for glazing all vary with incidence angles of solar radiation (θ)
- The ASHRAE Handbook of Fundamentals 2013 **Chapter 15** provides data for a large variety of glazing types

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								

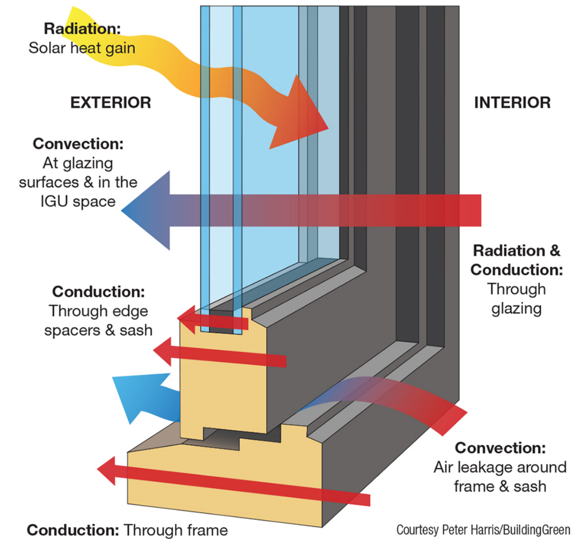
What about window <u>assemblies</u>?

- In addition to glazing material, windows also include framing, mullions, muntin bars, dividers, and shading devices
  - These all combine to make **fenestration systems**



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^{2}K

A_{pf} = total projected area of fenestration, m^2

T_{in} = indoor air temperature, K

T_{out} = outdoor air temperature, K

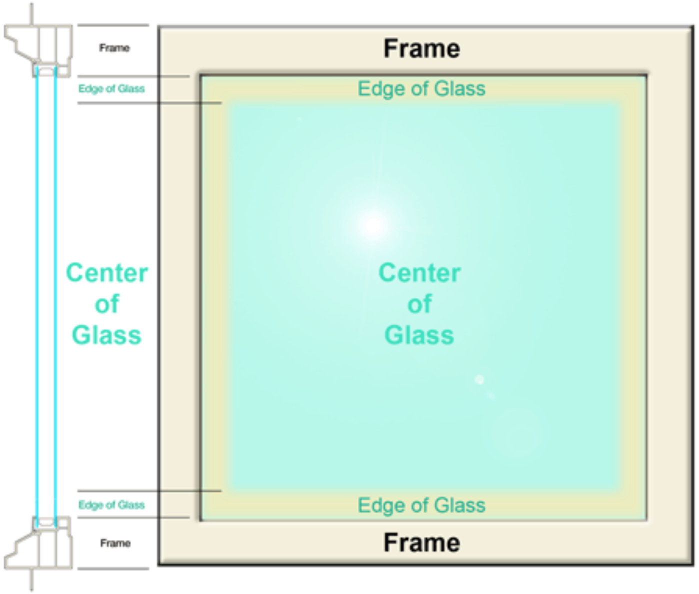
$SHGC$ = solar heat gain coefficient, -

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:

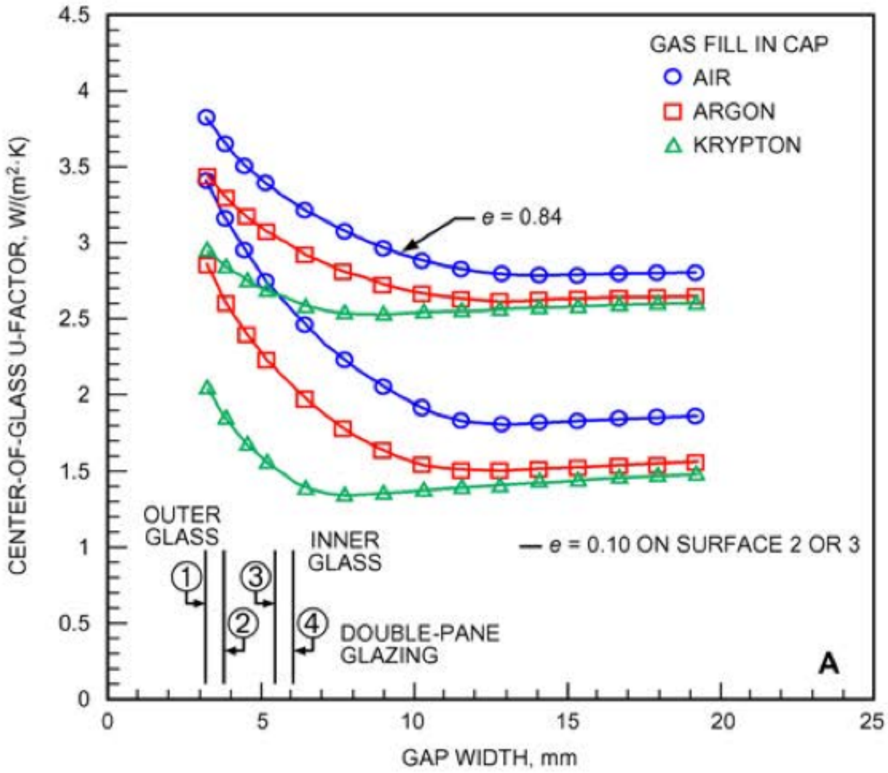
$$U = \frac{U_{cg}A_{cg} + U_{eg}A_{eg} + U_f A_f}{A_{pf}}$$



U-values and multiple layers of glazing

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

Center of glass U-values for double pane glazing



Q: Why does argon filled have lower U value than air filled?

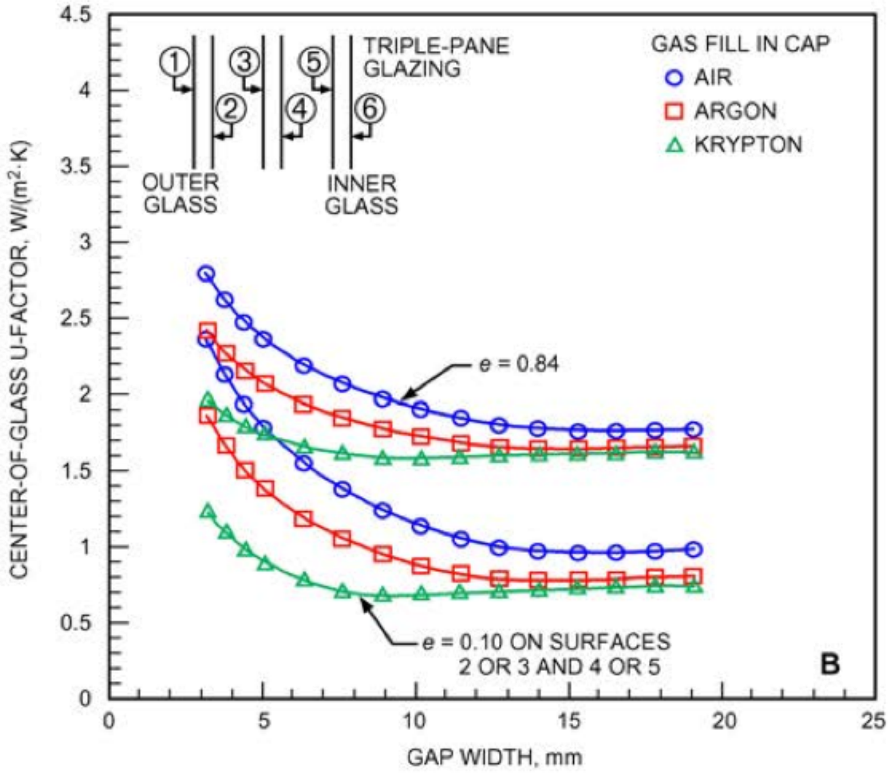
k_{air} = 0.025 W/mK
k_{argon} = 0.016 W/mK
$k_{krypton}$ = 0.0088 W/mK

2013 ASHRAE Handbook of Fundamentals: Chapter 15

U-values and multiple layers of glazing

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

Center of glass U-values for triple pane glazing



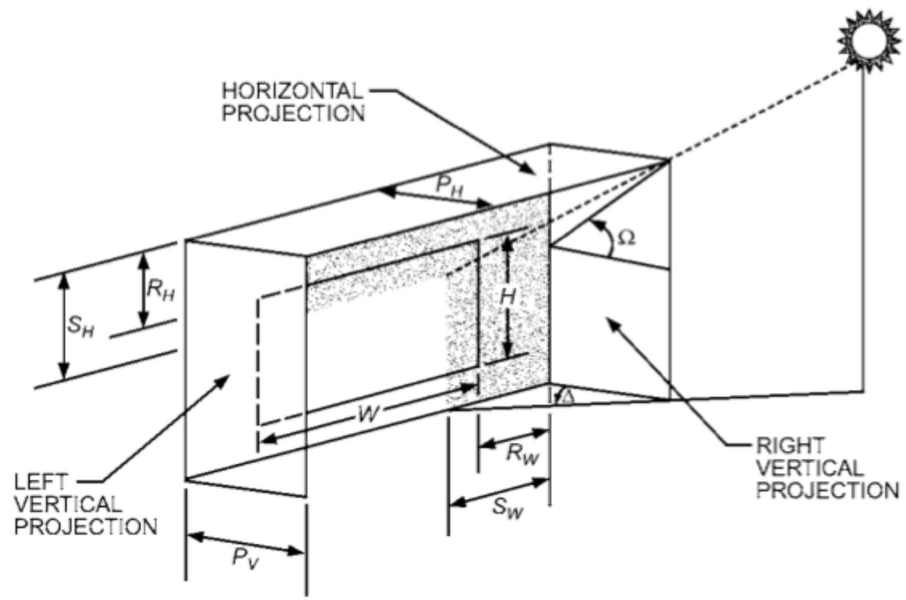
Combined U-factor data: ASHRAE 2013 HOF

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

Product Type		Glass Only		Vertical Installation: Operable (including sliding and swinging glass doors)					Vertical Installation: Fixed				
Frame Type													
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

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:

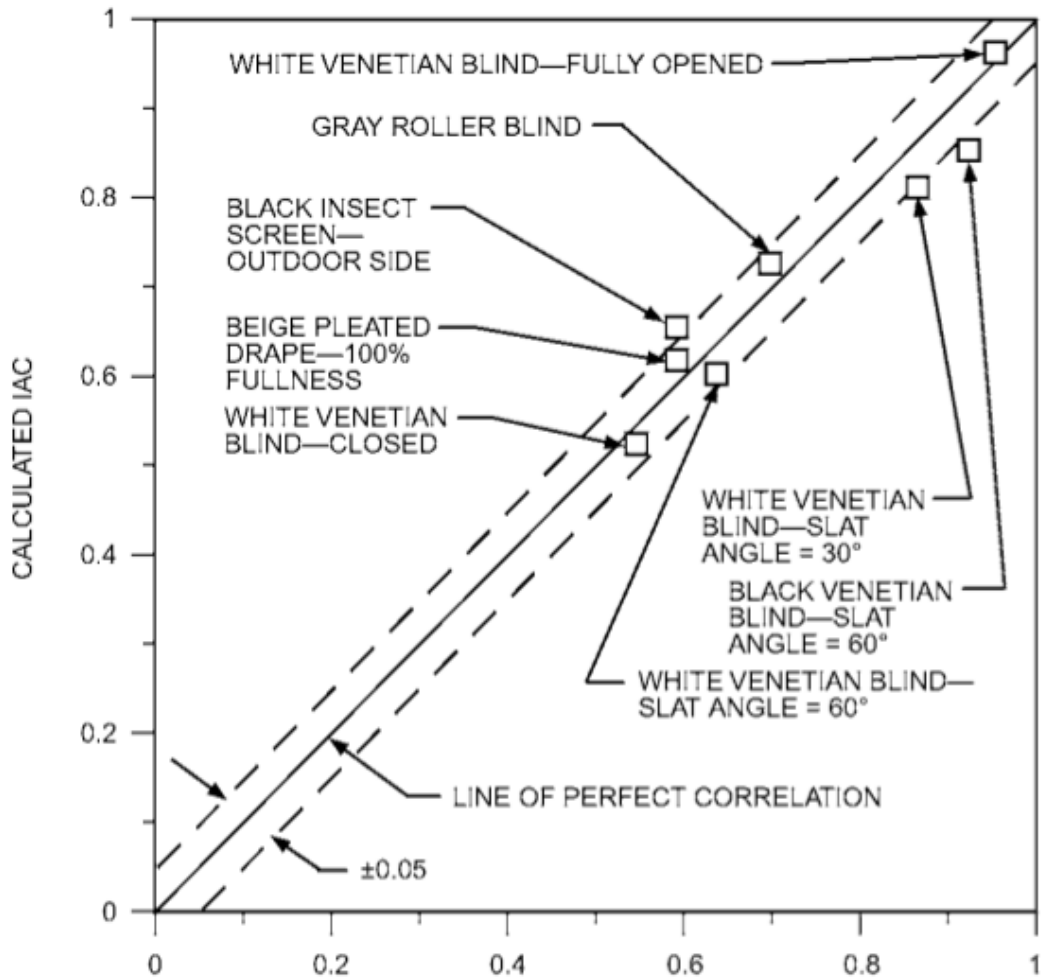


$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{direct}A_{pf}SHGC(\theta)IAC(\theta,\Omega) + (I_{diffuse+reflected})A_{pf}SHGC_{diffuse+reflected}IAC_{diffuse+reflected}$$

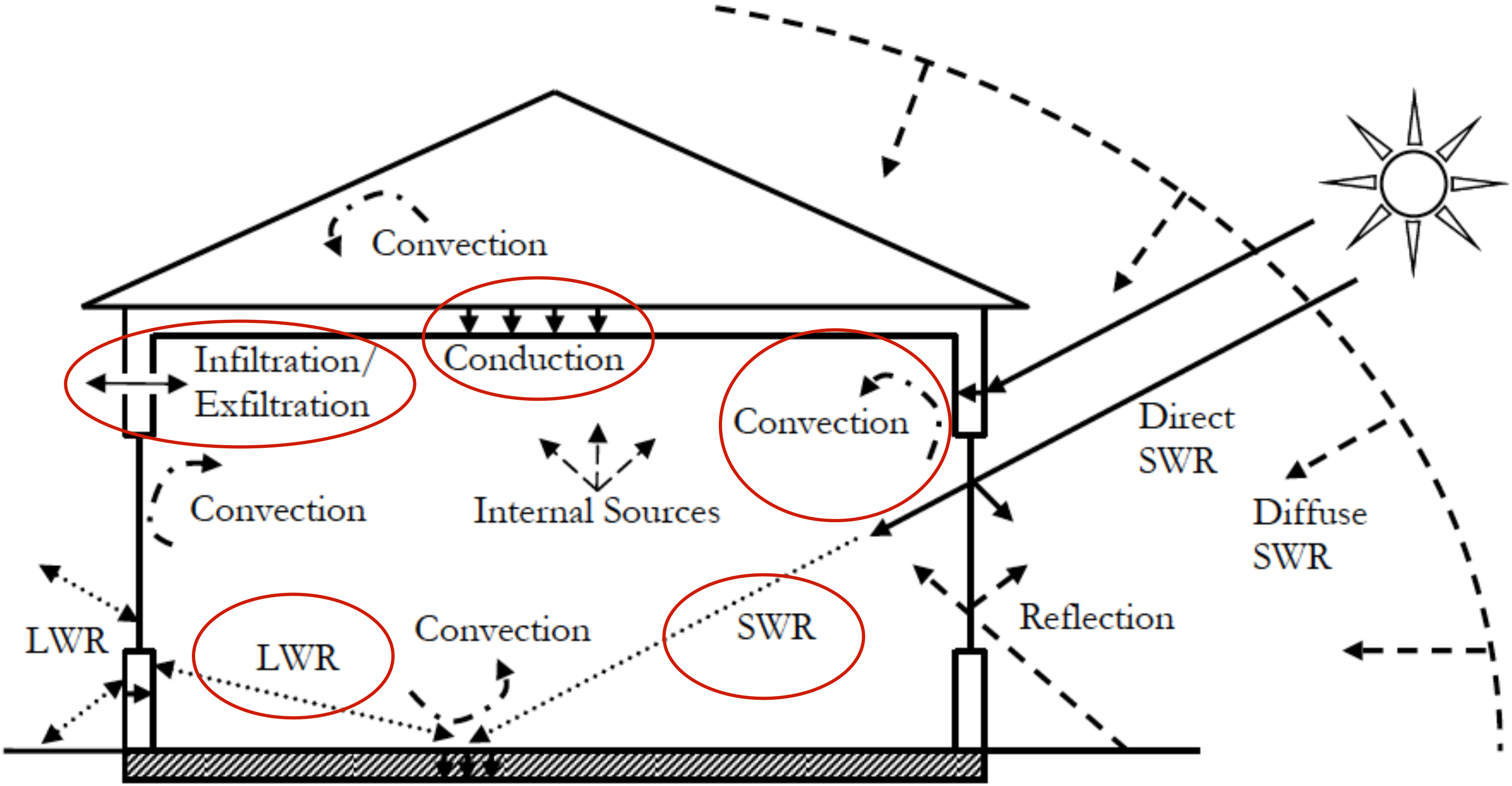
IAC is a function of incidence angle, θ, and the angle created by a shading device

Or more simply: $$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{solar}A_{pf}SHGC \cdot IAC$$

IAC for blinds and drapes: ASHRAE HOF 2013



Summary: Modes of heat transfer in a building



Summary: Modes of heat transfer in a building

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

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

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

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

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

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

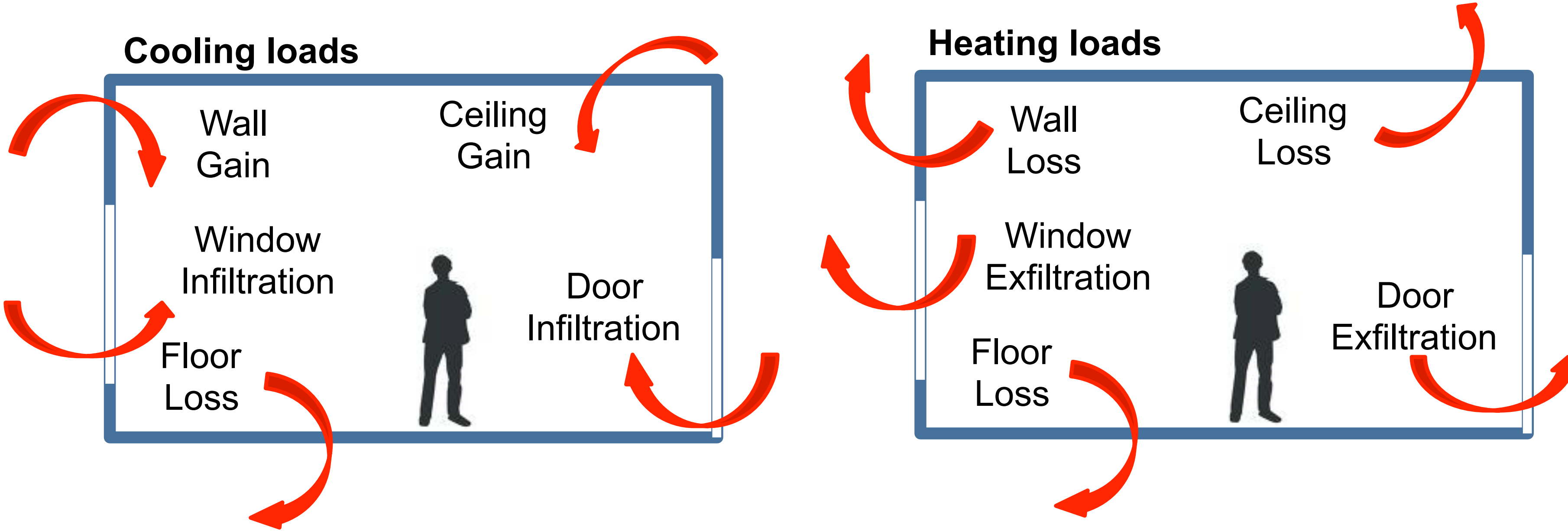
Transmitted solar radiation: (transparent surface) $q_{solar} = \tau I_{solar}$

Window (combined modes)

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

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 also revisit this for heating and cooling load calculations



Next time

- HW #2 assigned today
  - Due Tues Sep 13

Course Topics and Tentative Schedule

Week	Date	Lecture Topics	HW Due	Reading
1	Aug 23	Introduction to building science		Wang Ch. 1
	Aug 25	Pre-requisite review, energy concepts, and units		
2	Aug 30	Heat transfer in buildings: conduction	HW1	
	Sep 1	Heat transfer in buildings: convection		
3	Sep 6	Heat transfer in buildings: radiation		Wang Ch. 3
	Sep 8	Heat transfer: solar radiation and windows		
4	Sep 13	Heat transfer in buildings: energy balances	HW2	
	Sep 15	Human thermal comfort		Wang Ch. 4
5	Sep 20	**Exam 1**		
	Sep 22	Psychrometrics: Chart		Wang Ch. 2 & 8