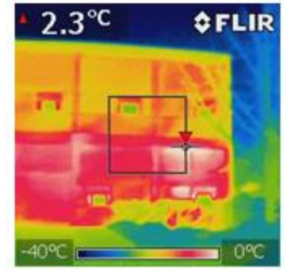
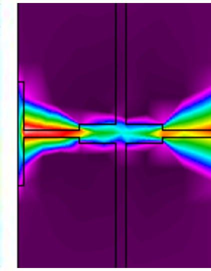
CAE 331/513
Building Science
Fall 2015





Week 3: September 10, 2015
Heat transfer in buildings:
Solar radiation and heat transfer through windows

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Last time

- Finished convection
  - Internal flows (e.g., in HVAC systems)
  - Bulk convection (advection)

- Radiation
  - Long wave
    - Emissivity
    - View factors

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

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

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

  - Short wave
    - Transmittance
    - Absorptivity

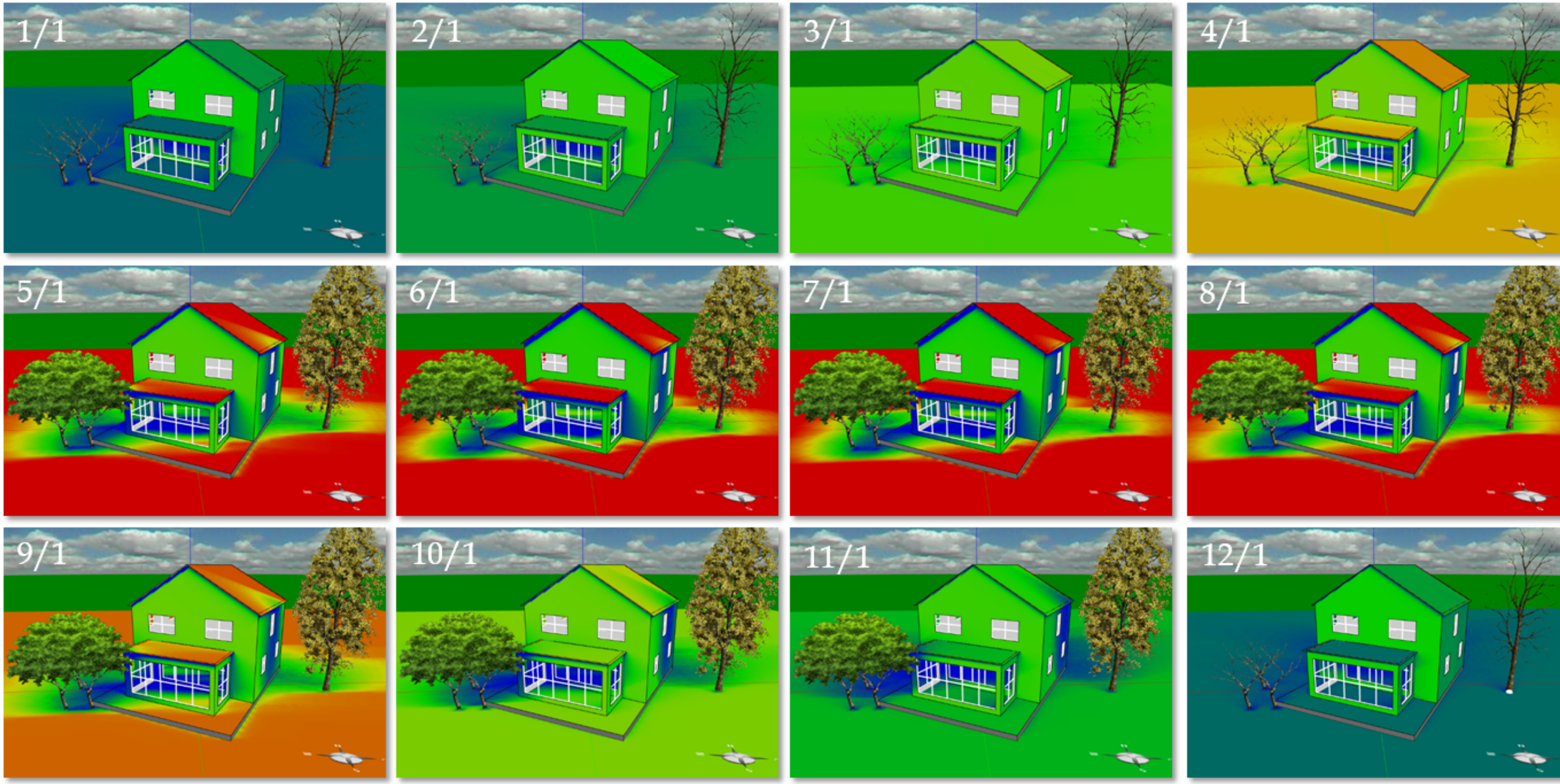
$$I_{solar} \quad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \qquad q_{solar} = \alpha I_{solar} \qquad q_{solar} = \tau I_{solar}$$

- Combined modes of heat transfer
  - Example of a radiant barrier in a wall w/ convection & radiation

Today's objectives

- Understand solar radiation (short wave radiation)
  - Basic solar geometry

- Understand heat transfer through windows
  - Combined modes of heat transfer



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 day lighting design

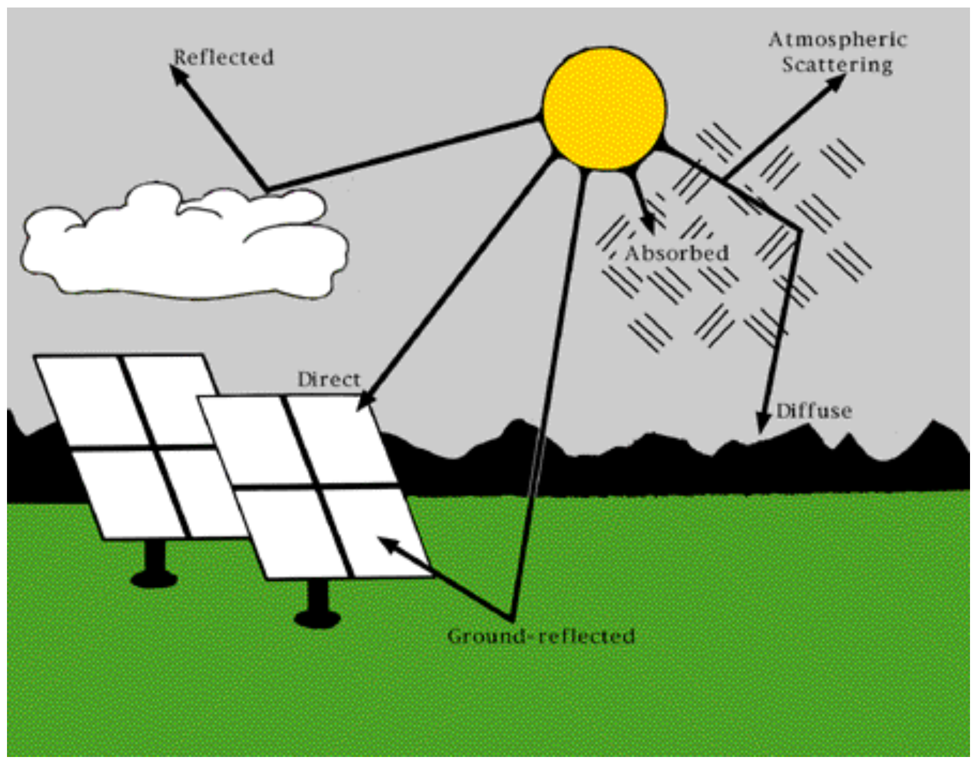
- We won't cover the full equations for predicting solar geometry and radiation striking a surface in this class
  - CAE 463/524 Building Enclosure Design goes into more detail
  - But will discuss basic relationships and where to get solar data

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

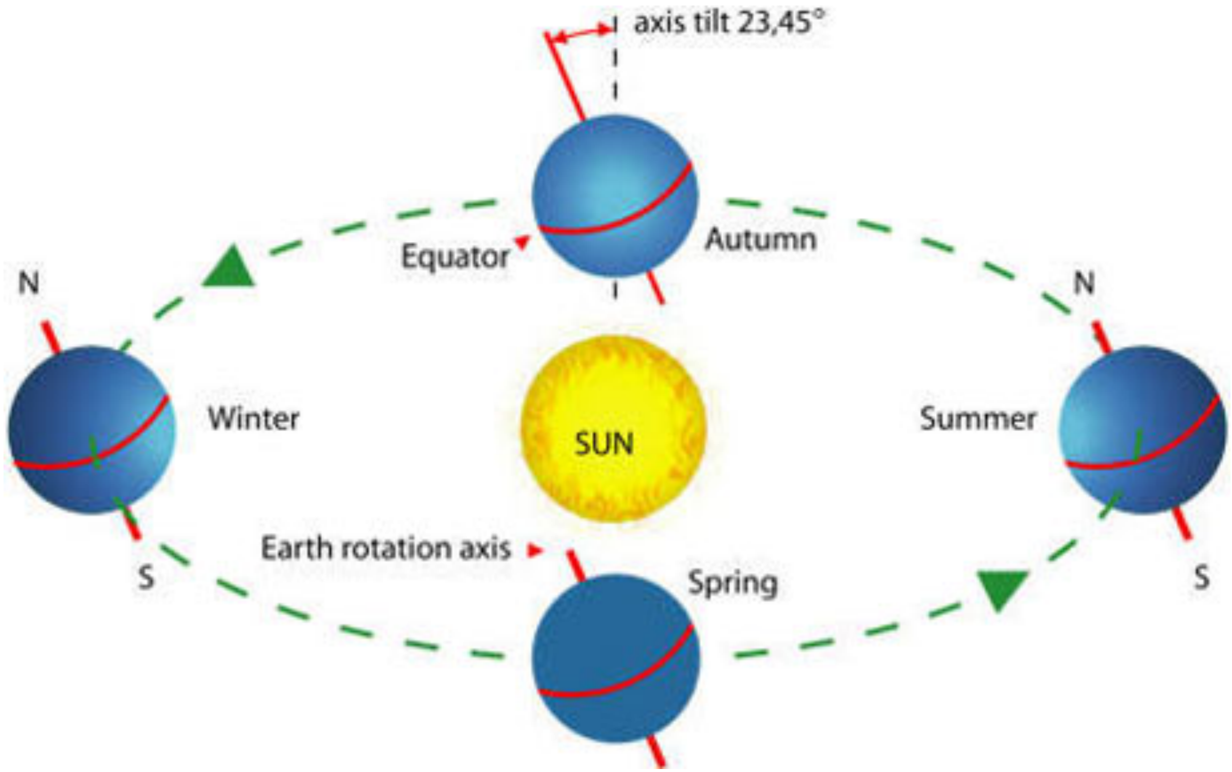
$$I_D = I_{DN} \cos\theta$$

- **Diffuse solar radiation** ($I_{diffuse}$) is the irradiation that is **scattered** by the atmosphere
  - Function of I_{DN}, 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_{DN}, solar geometry, ground reflectance, and surface tilt angle

Solar radiation: earth-sun relationship

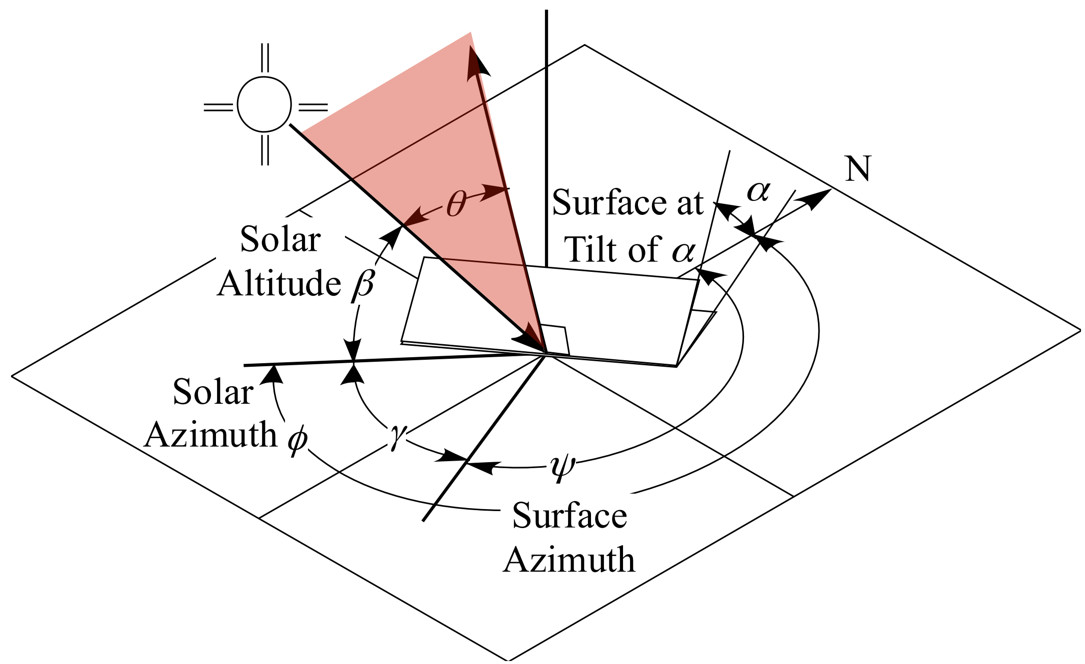
- Earth rotates about its axis every 24 hours
- Earth revolves around sun every 365.2425 days
- Earth is titled at an angle of 23.45°
  - Therefore, different locations on earth receive different levels of solar radiation during different times of the year (and different times of the day)



Solar radiation striking an exterior surface

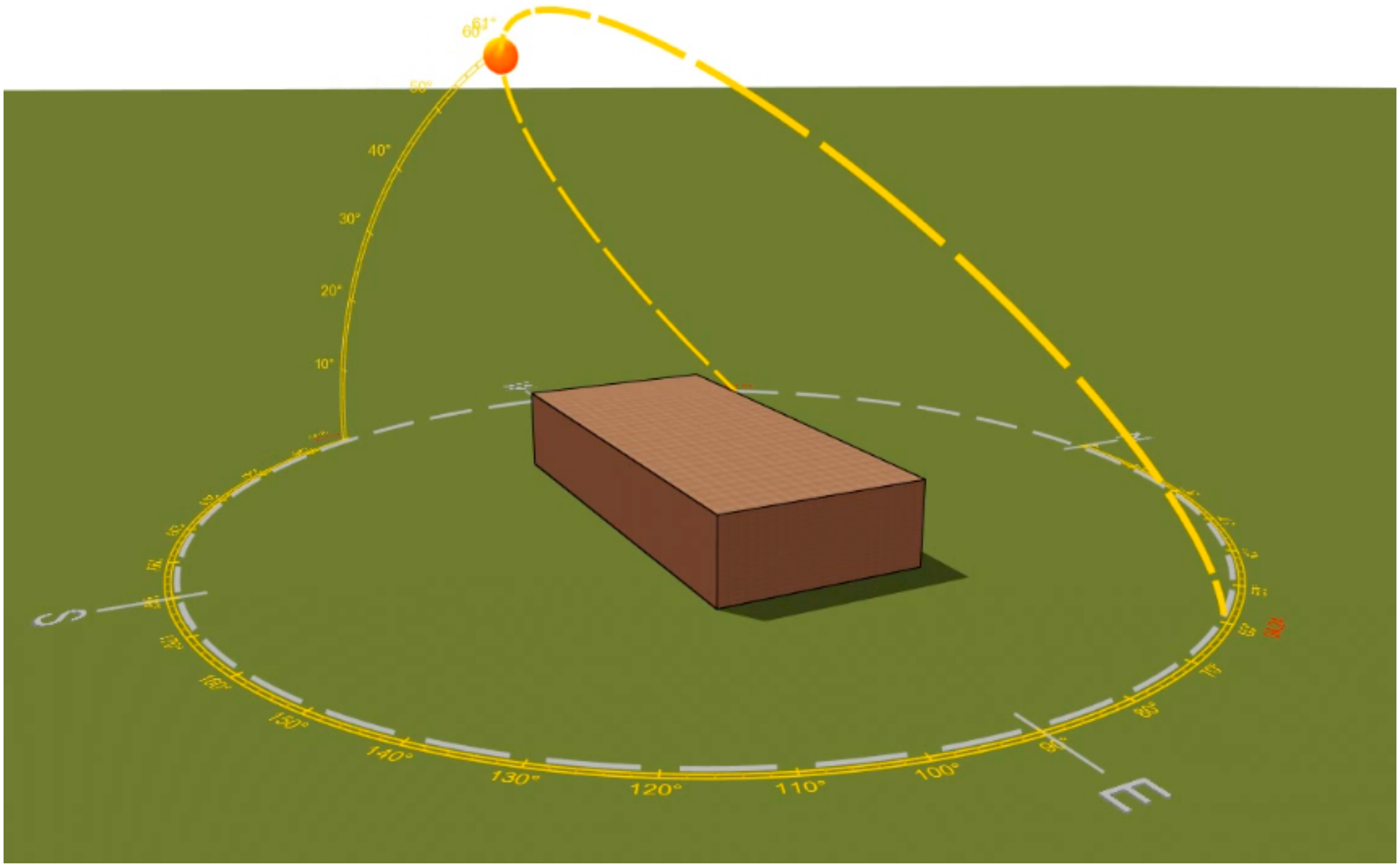
- The amount of solar radiation received by a surface depends on the **incidence angle**, θ

- 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”

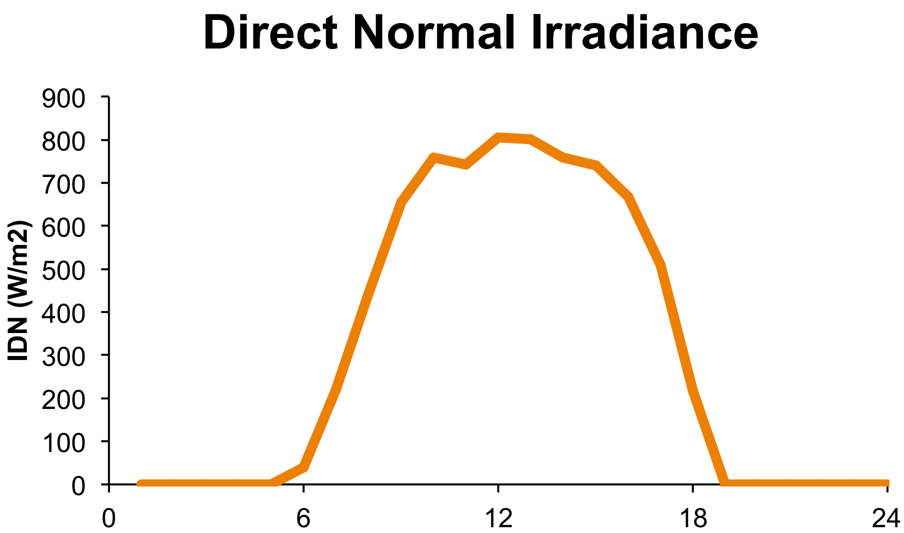
- For *actual* hourly solar data (direct + diffuse in W/m^2)
  - http://rredc.nrel.gov/solar/old_data/nsrdb/
  - Output of interest = “direct normal radiation” → adjust using $\cos\theta$
    - Note: “typical meteorological years”

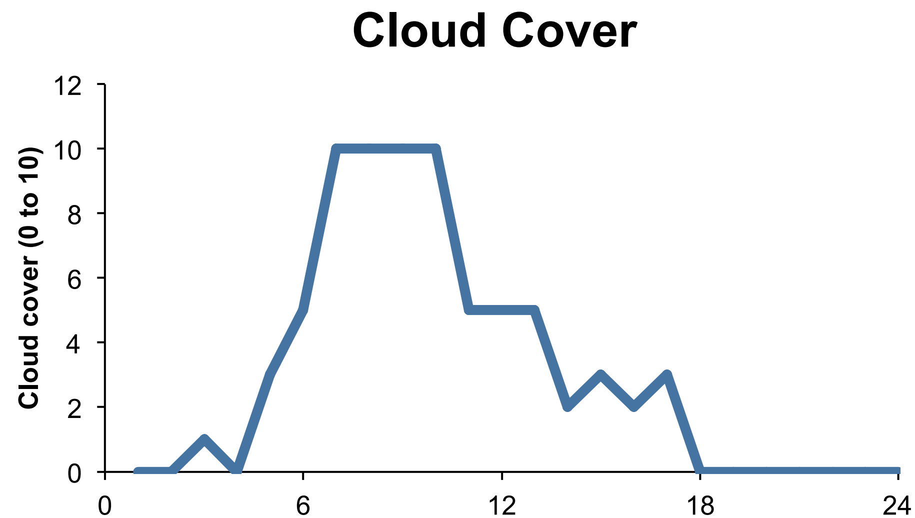
Typical meteorological year (TMY)

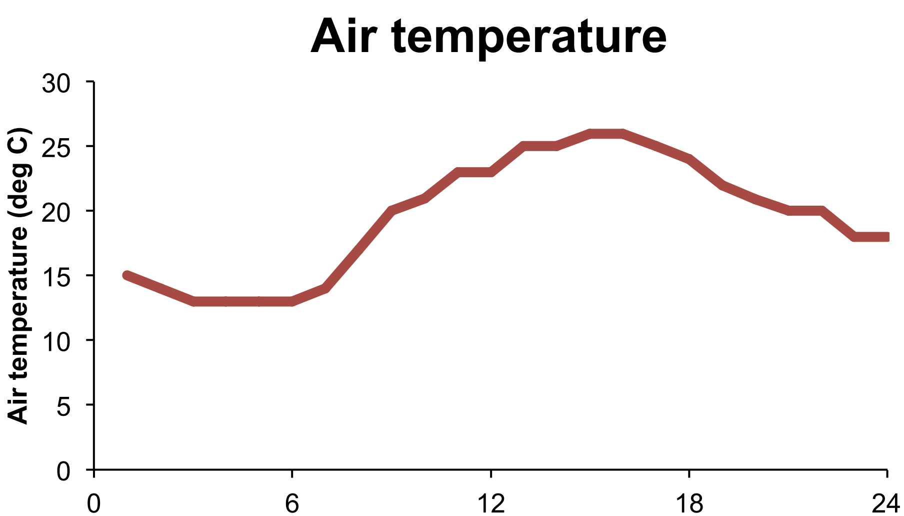
- For heating and cooling load calculations and for hourly building energy simulations, we often rely on a collection of weather data for a specific location
- We generate this data to be representative of more than just the previous year
  - Represents a wide range of weather phenomena for our location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

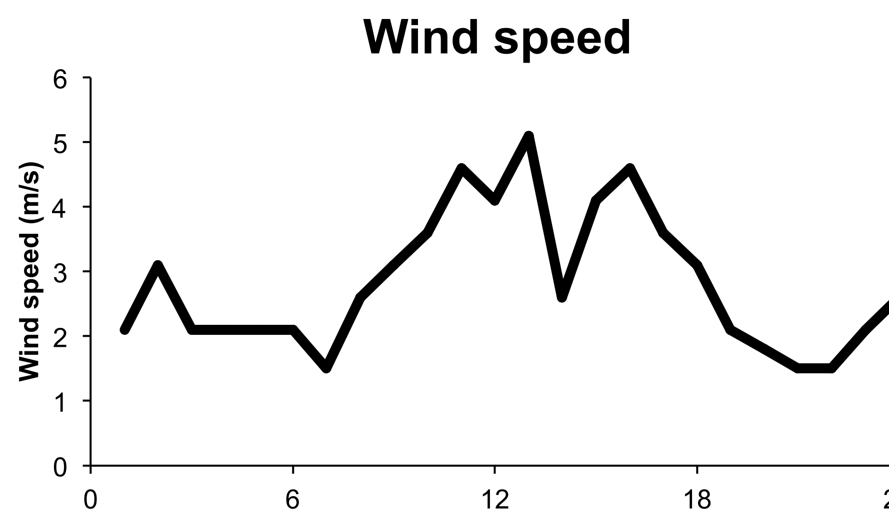
Typical meteorological year (TMY): Solar data

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









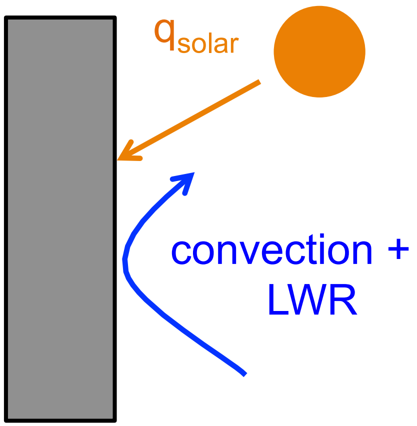
What to do with solar data once you have it?

- 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

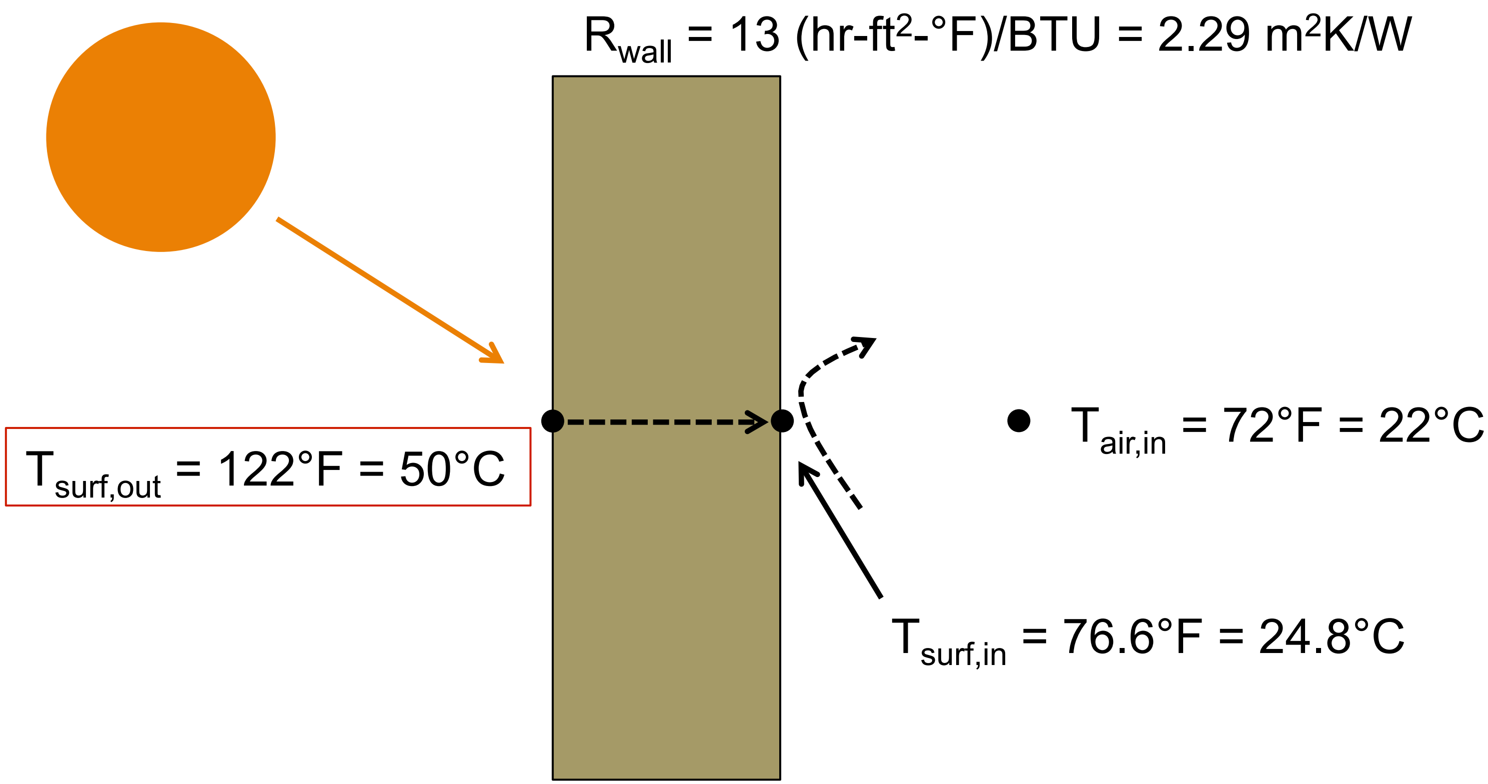
$$q_{solar} = \tau I_{solar}$$



EXTERNAL OPAQUE SURFACES AND SOL-AIR TEMPERATURES

Sol-air temperatures

- In our example of an exterior wall over the last few classes, we were given that the exterior surface temperature was 122°F (50°C)
  - **How did we know that?**



Sol-air temperatures

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

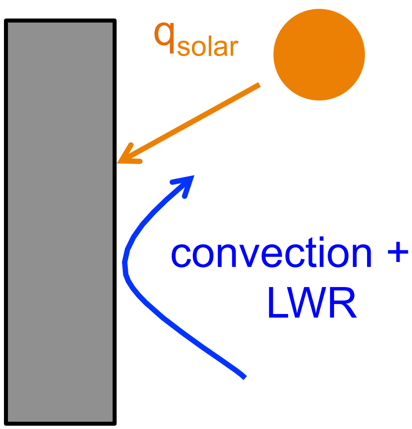
$$q_{conv+rad} = h_{conv+rad}\left(T_{air} - T_{surf}\right)$$

- 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

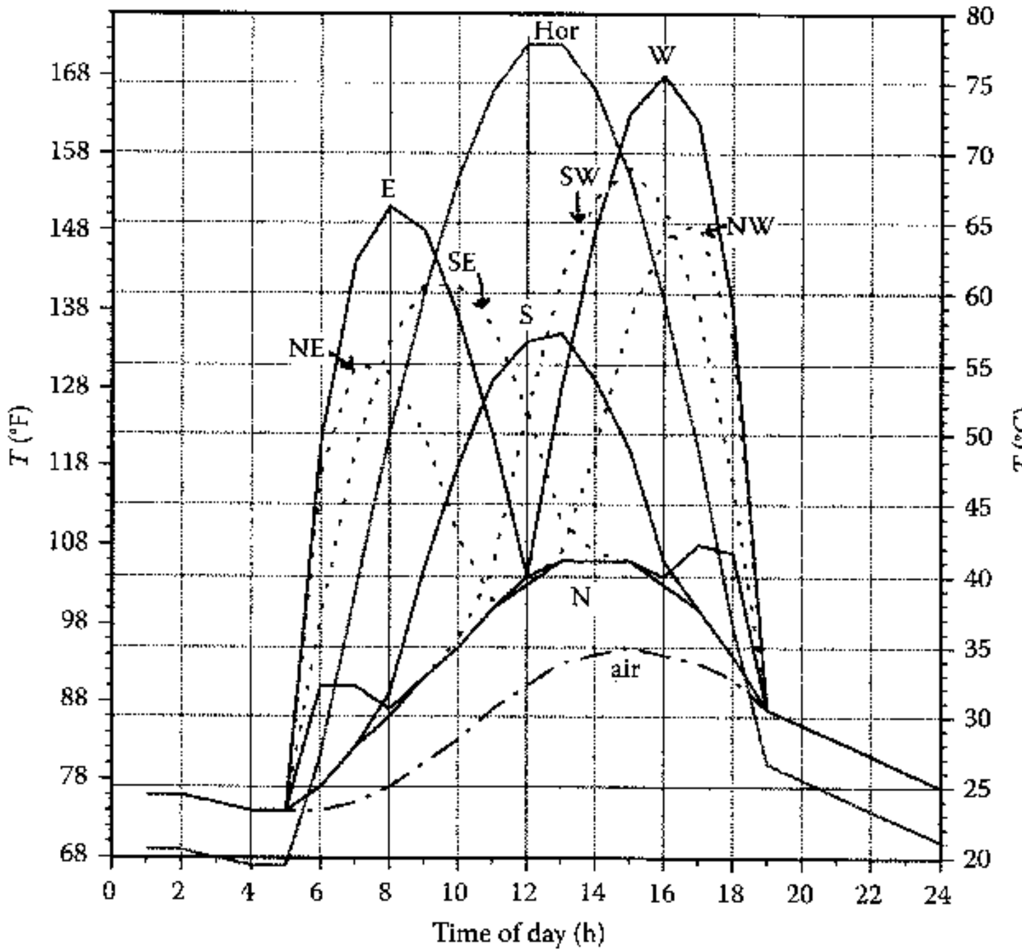


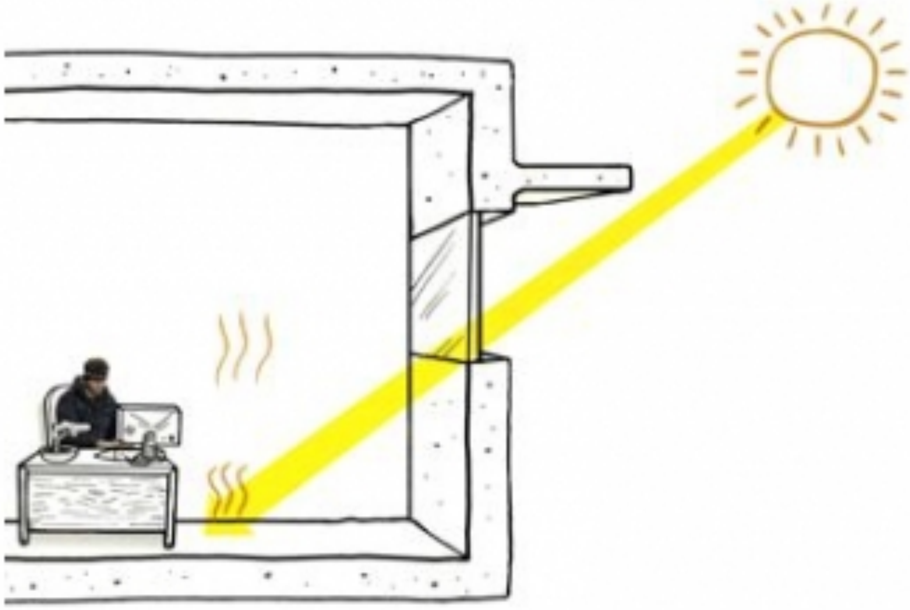
FIGURE 6.17
Sol-air temperature for horizontal and vertical surfaces as a function of time of day for summer design conditions, July 21 at 40° latitude, assuming $\alpha/h_o = 0.30$ (h · ft^2 · °F)/Btu [0.052 (m^2 · K)/W]. The curves overlap when there is no direct radiation on a surface. (Courtesy of 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 (absorptivity and emissivity) to estimate exterior surface temperatures that are exposed to radiation
  - These are not extremely 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	$t_a - 2\,\varepsilon$	$t_a - 4\,\varepsilon$

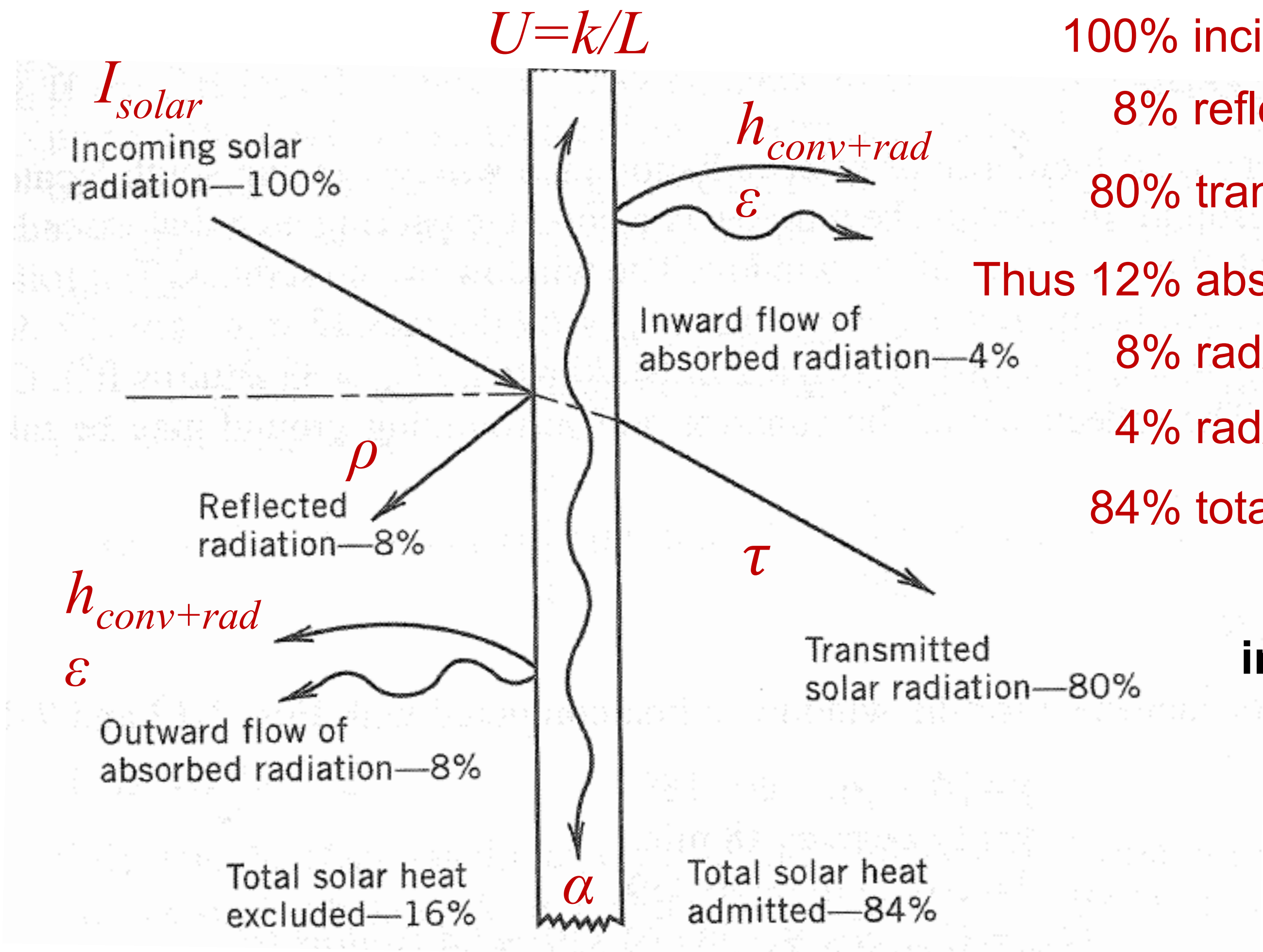
Source: Straube and Burnett



SOLAR RADIATION AND WINDOWS

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):

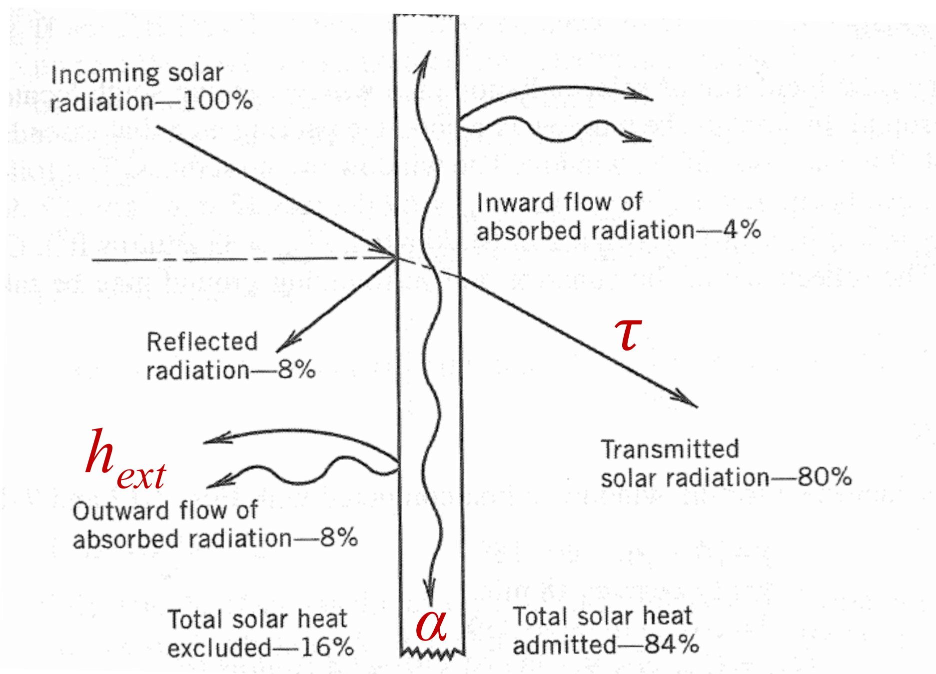
$$Q_{solar,window} = \left(I_{solar} A\right) SHGC$$

Solar heat gain coefficient, SHGC

- For a single pane of glass:

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

$U = k/L$



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

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

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

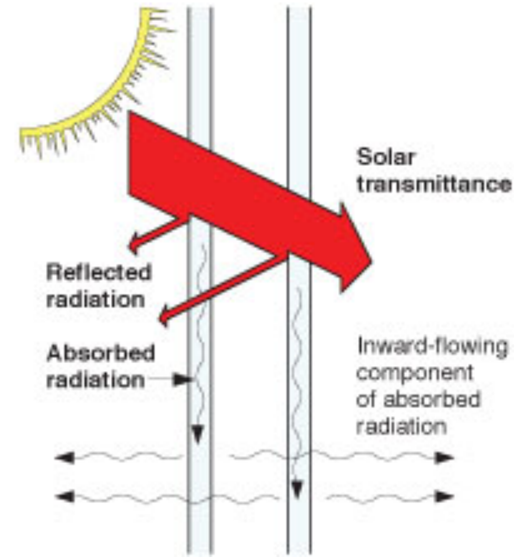
Solar heat gain coefficient, SHGC

- For double glazing with a small still air gap:

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

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

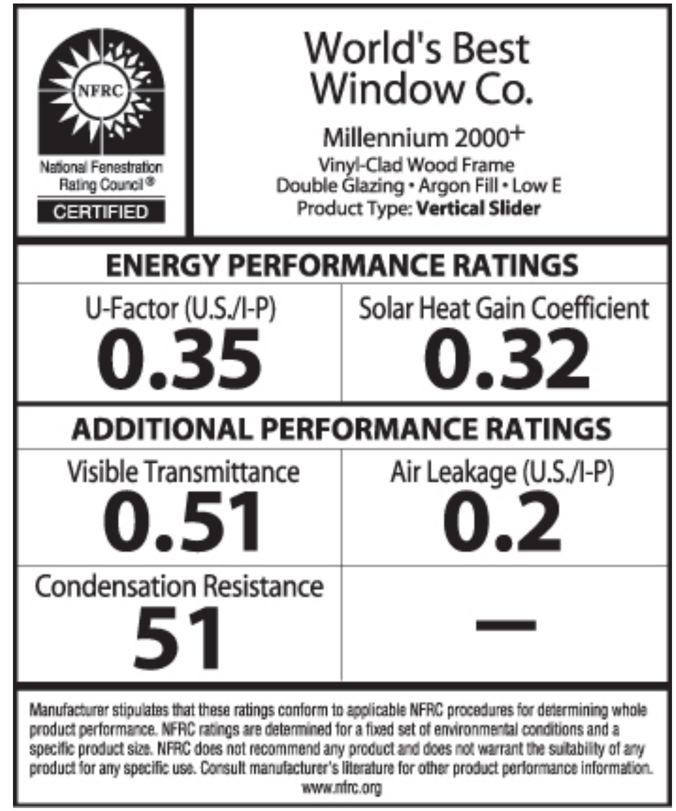
$^{*}R_{outer\ pane}$ and $R_{inner\ pane}$ are negligible



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

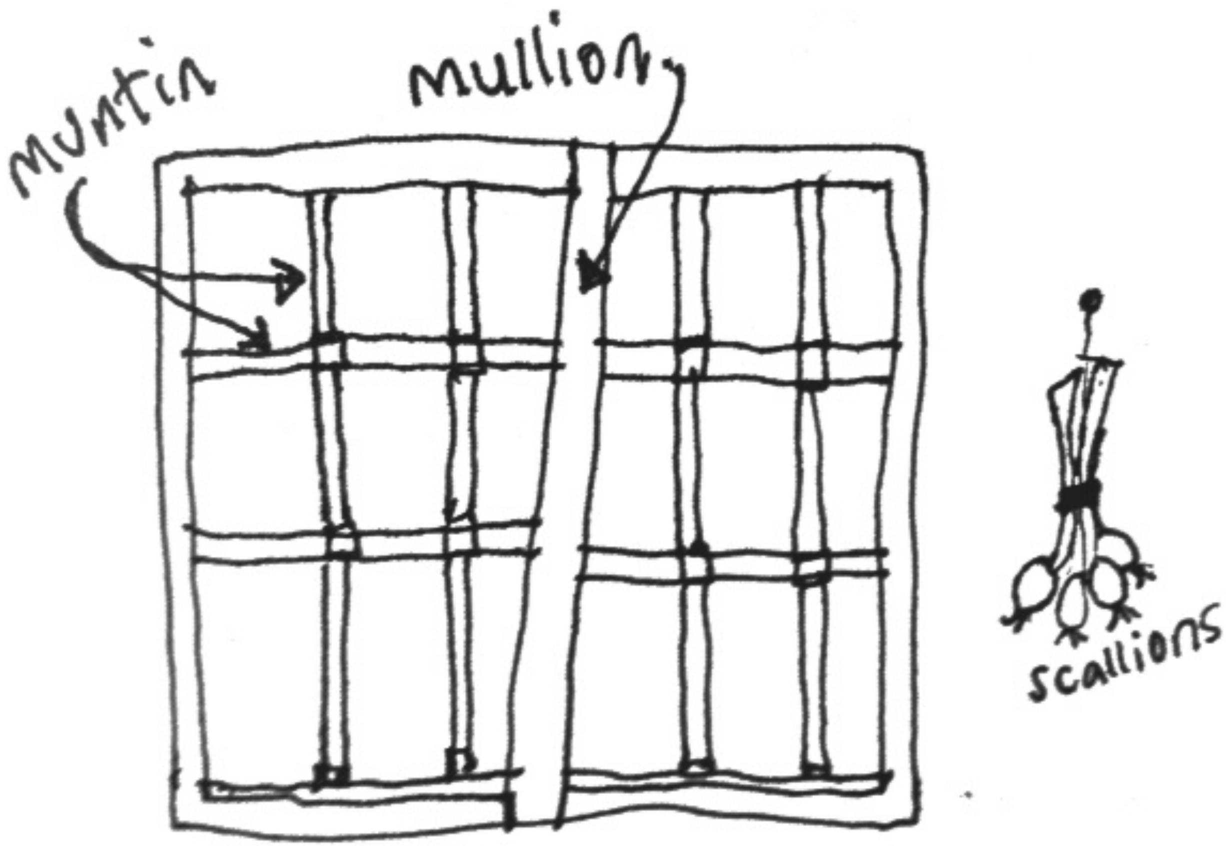
- SHGC, solar transmittance, reflectance, and absorptance properties for glazing all vary with incidence angles of solar radiation (θ)
- The ASHRAE Handbook of Fundamentals 2013 Chapter 15 provides data for a large variety of glazing types

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 ($\mathcal{A}^f_n$) 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								
				$\mathcal{A}^f_1$	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								
				$\mathcal{A}^f_1$	0.16	0.17	0.18	0.19	0.19	0.17	0.17								

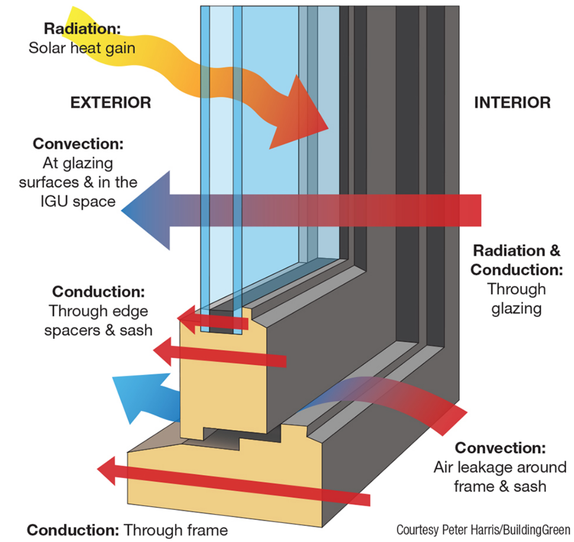
What about window <u>assemblies</u>?

- 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 <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**
- 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

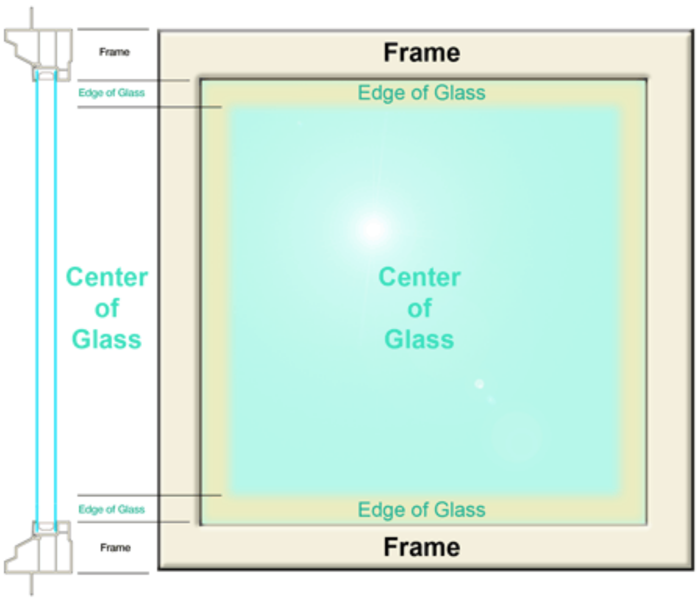
$SHGC$ = solar heat gain coefficient, -

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:

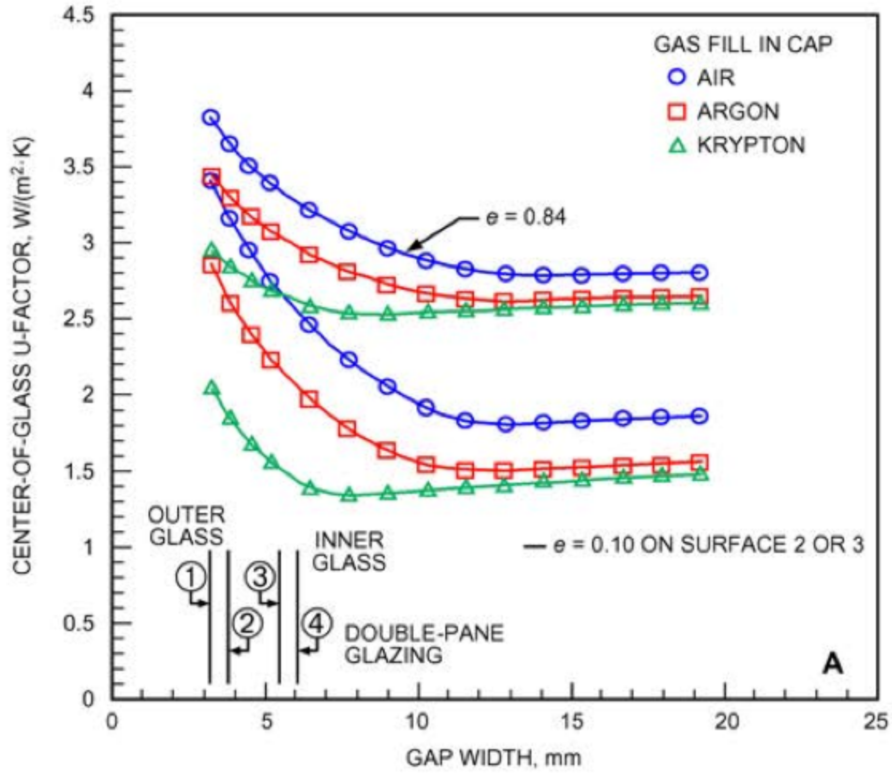
$$U = \frac{U_{cg}A_{cg} + U_{eg}A_{eg} + U_f A_f}{A_{pf}}$$



U-values and multiple layers of glazing

- We can separate glass panes with **<u>air-tight</u> layers** of air or other gases

Center of glass U-values for double pane glazing



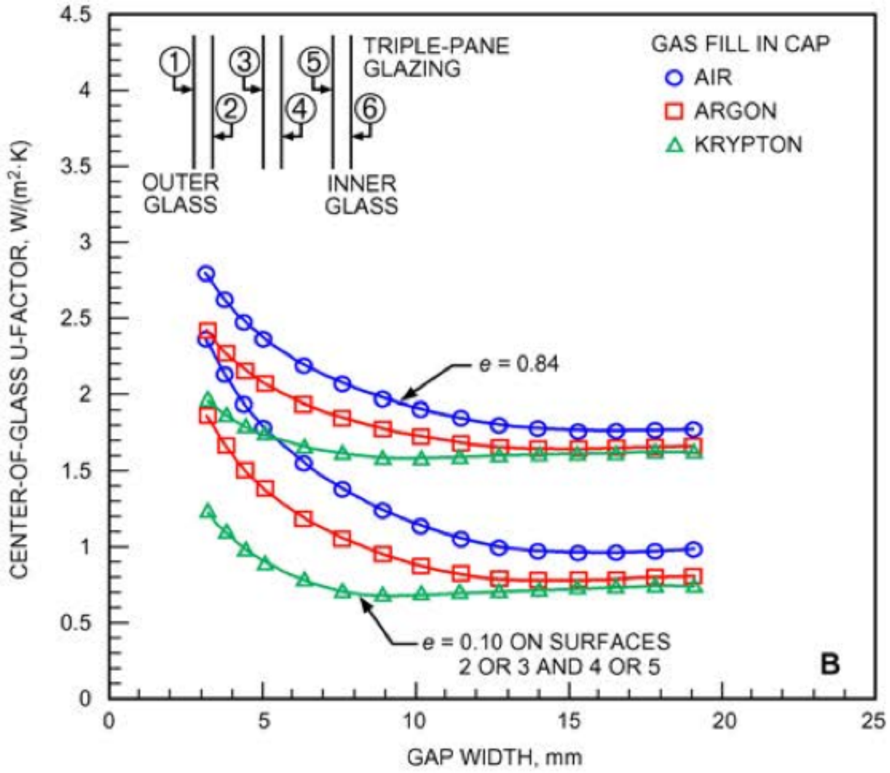
Q: Why does argon filled have lower U value than air filled?

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

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



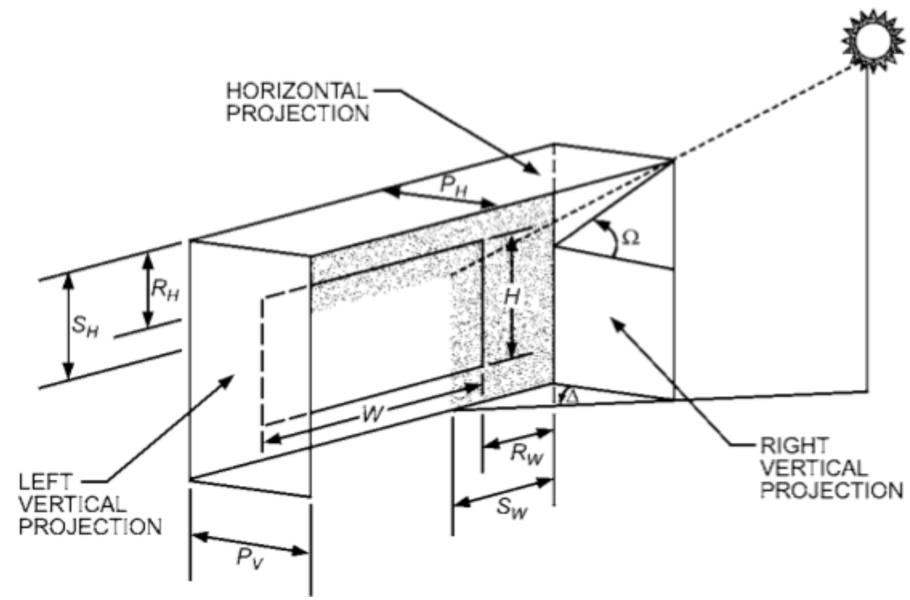
Combined U-factor data: ASHRAE 2013 HOF

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)					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:

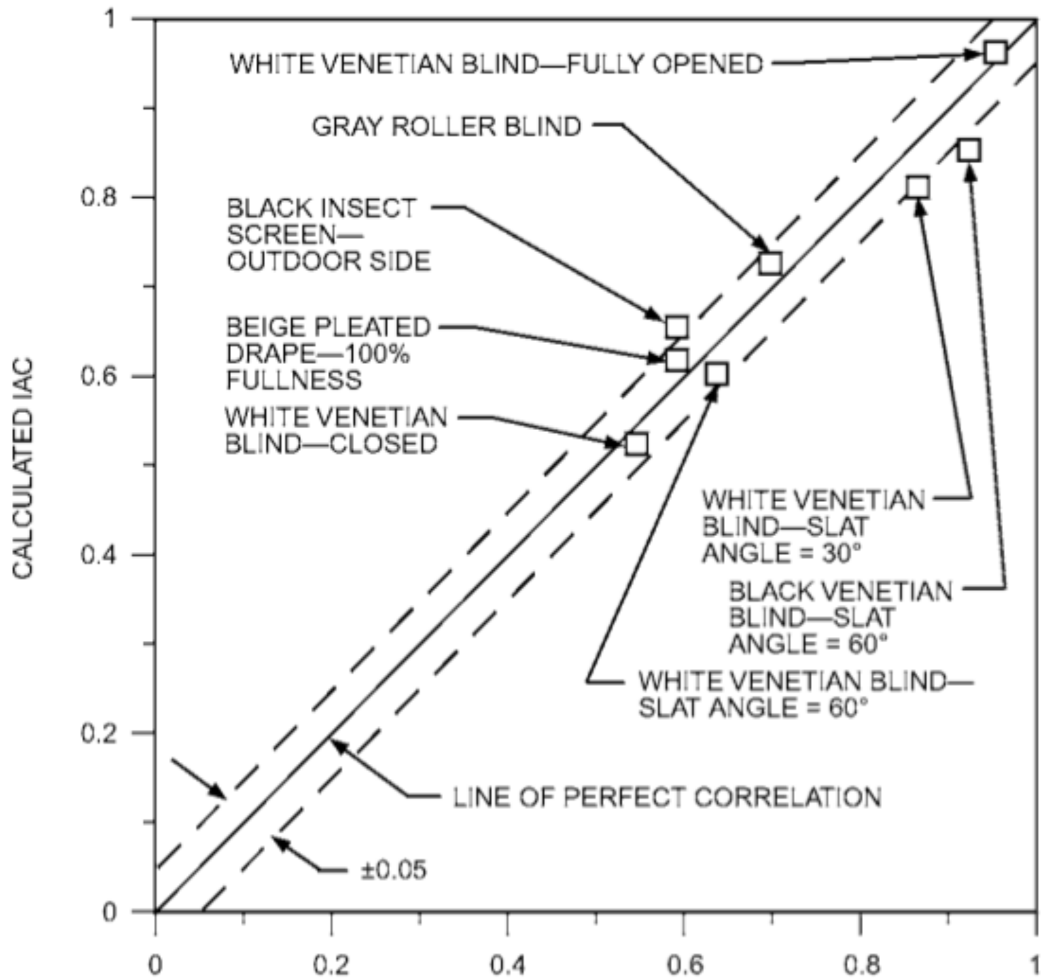


$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{direct}A_{pf}SHGC(\theta)IAC(\theta,\Omega) + (I_{diffuse+reflected})A_{pf}SHGC_{diffuse+reflected}IAC_{diffuse+reflected}$$

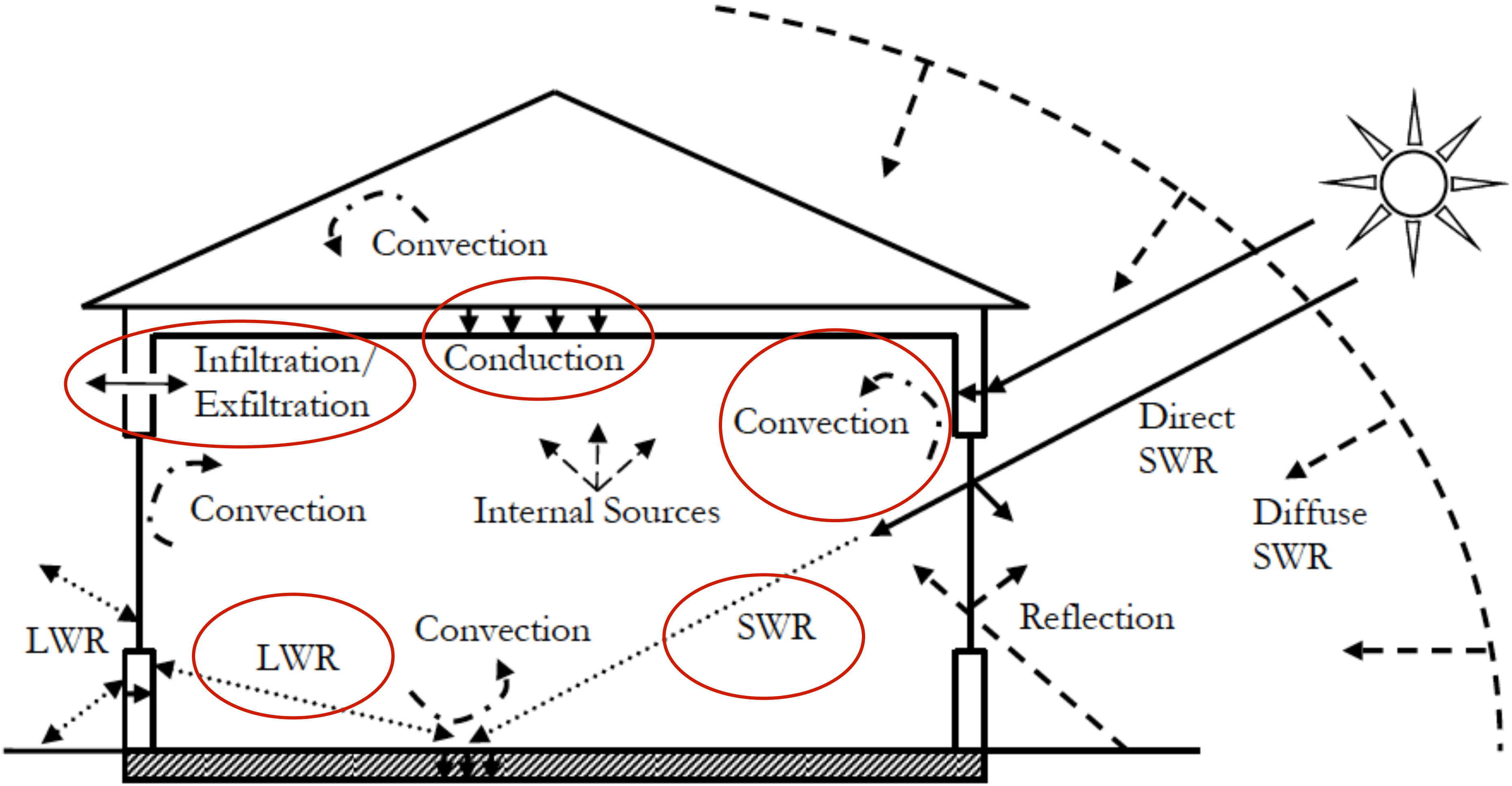
IAC is a function of incidence angle, θ, and the angle created by a shading device

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



<u>Summary:</u> Modes of heat transfer in a building



<u>Summary:</u> 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

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

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

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

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

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

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

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 revisit this for heating and cooling load calculations