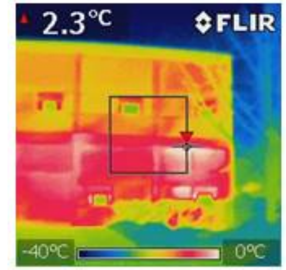
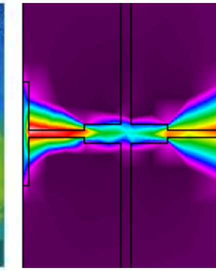
CAE 331/513
Building Science
Fall 2016





Week 4: September 13, 2016
Combined modes of heat transfer and energy balances

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Scheduling updates

- **HW 2** now due Thurs September 15
  - Any questions?

- **Exam 1** is now scheduled for Thurs September 22 in class

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	Wang Ch. 3
	Sep 1	Heat transfer in buildings: convection		
3	Sep 6	Heat transfer in buildings: radiation		
	Sep 8	Heat transfer in buildings: solar radiation/windows		
4	Sep 13	Heat transfer in buildings: energy balances		
	Sep 15	Exam review: example problems	HW2	
5	Sep 20	Human thermal comfort		Wang Ch. 4
	Sep 22	**Exam 1**		
6	Sep 27	Psychrometrics: Chart		
	Sep 29	Psychrometrics: Equations		

Announcements

- New IIT ASHRAE Chapter has (finally) formed

- First meeting: Tuesday September 20th, 12:50 – 1:40 pm
  - Alumni Hall Room 222
  - Sign up at https://join.ashrae.org
  - Student grade memberships cost only $20 a year, and that includes a print copy of the journal and discounted events, of which there are many in Chicago
  - Contact Al Mitchel with any questions amitche8@hawk.iit.edu

Announcements

ILLINOIS INSTITUTE OF TECHNOLOGY – LEED GREEN ASSOCIATE TRAINING – SEPTEMBER 24 2016

When: September 24th 2016 – 1:00PM to 5:00 PM

Where: Illinois Institute of Technology – Wishnick Hall - Room 117 - https://goo.gl/maps/7KzU9uoW1Rq

Registration: http://leadinggreen.com/iit

Interested in getting involved in the Green Building Industry? Opportunities are plentiful in the field of sustainable design and LEED is at its forefront.

$200 for student registration

http://leadinggreen.com/iit/

Last time

- Finished radiation, solar radiation, and started windows

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

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

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

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

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

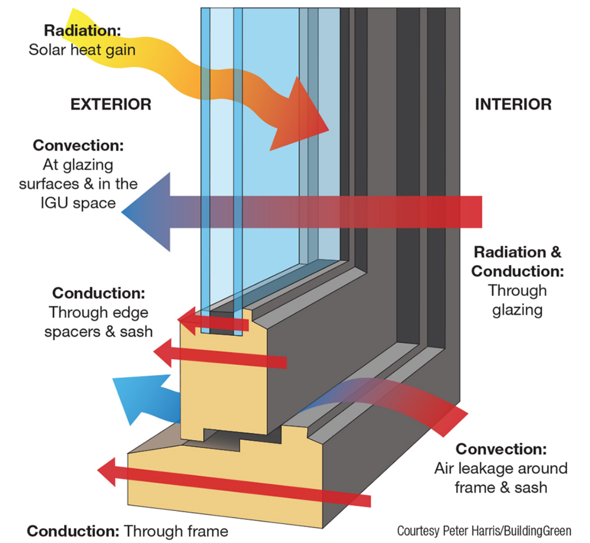
$$I_D = I_{DN}\cos\theta$$

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

$$Q_{window} = UA(T_{in} - T_{out})$$

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

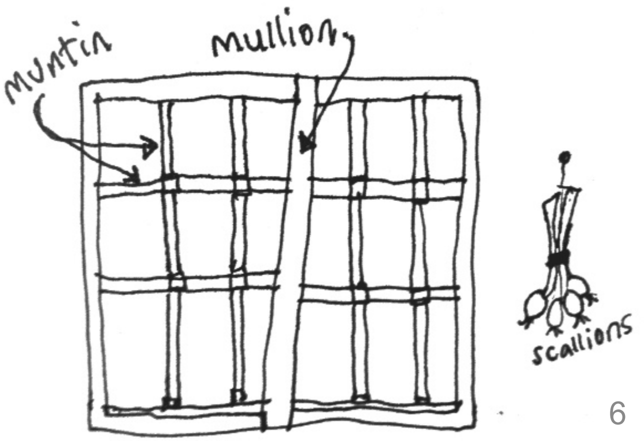
A_{pf} = total projected area of fenestration, m^2

T_{in} = indoor air temperature, K

T_{out} = outdoor air temperature, K

$SHGC$ = solar heat gain coefficient, -

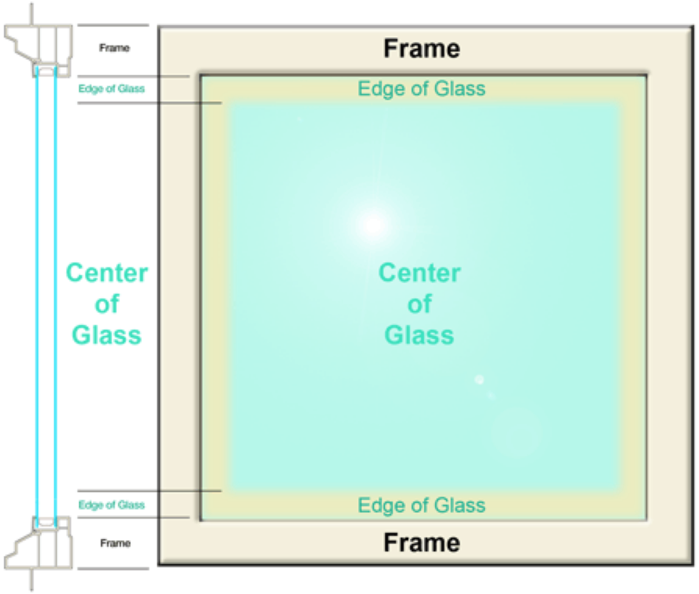
I_{solar} = incident total irradiance, W/m^2



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:

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



Combined U-factor data: ASHRAE 2013 HOF Ch. 15 (SI)

Table 4 U-Factors for Various Fenestration Products in W/(m²·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

Combined U-factor data: ASHRAE 2013 HOF Ch. 15 (IP)

Table 4 U-Factors for Various Fenestration Products in Btu/h·ft^2·°F

Product Type		Glass Only		Vertical Installation: Operable (including sliding and swinging glass doors)					Vertical Installation: Fixed				
ID	**Frame Type / 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	1/8 in. glass	1.04	1.04	1.23	1.07	0.93	0.91	0.85	1.12	1.07	0.98	0.98	1.04
2	1/4 in. acrylic/polycarbonate	0.88	0.88	1.10	0.94	0.81	0.80	0.74	0.98	0.92	0.84	0.84	0.88
3	1/8 in. acrylic/polycarbonate	0.96	0.96	1.17	1.01	0.87	0.86	0.79	1.05	0.99	0.91	0.91	0.96
	Double Glazing												
4	1/4 in. air space	0.55	0.64	0.81	0.64	0.57	0.55	0.50	0.68	0.62	0.56	0.56	0.55
5	1/2 in. air space	0.48	0.59	0.76	0.58	0.52	0.50	0.45	0.62	0.56	0.50	0.50	0.48
6	1/4 in. argon space	0.51	0.61	0.78	0.61	0.54	0.52	0.47	0.65	0.59	0.53	0.52	0.51
7	1/2 in. argon space	0.45	0.57	0.73	0.56	0.50	0.48	0.43	0.60	0.53	0.48	0.47	0.45
	Double Glazing, e = 0.60 on surface 2 or 3												
8	1/4 in. air space	0.52	0.62	0.79	0.61	0.55	0.53	0.48	0.66	0.59	0.54	0.53	0.52
9	1/2 in. air space	0.44	0.56	0.72	0.55	0.49	0.48	0.43	0.59	0.53	0.47	0.47	0.44
10	1/4 in. argon space	0.47	0.58	0.75	0.57	0.51	0.50	0.45	0.61	0.55	0.49	0.49	0.47
11	1/2 in. argon space	0.41	0.54	0.70	0.53	0.47	0.45	0.41	0.56	0.50	0.44	0.44	0.41
	Double Glazing, e = 0.40 on surface 2 or 3												
12	1/4 in. air space	0.49	0.60	0.76	0.59	0.53	0.51	0.46	0.63	0.57	0.51	0.51	0.49
13	1/2 in. air space	0.40	0.54	0.69	0.52	0.47	0.45	0.40	0.55	0.49	0.44	0.43	0.40
14	1/4 in. argon space	0.43	0.56	0.72	0.54	0.49	0.47	0.42	0.58	0.52	0.46	0.46	0.43
15	1/2 in. argon space	0.36	0.51	0.66	0.49	0.44	0.42	0.37	0.52	0.46	0.40	0.40	0.36
	Double Glazing, e = 0.20 on surface 2 or 3												
16	1/4 in. air space	0.45	0.57	0.73	0.56	0.50	0.48	0.43	0.60	0.53	0.48	0.47	0.45
17	1/2 in. air space	0.35	0.50	0.65	0.48	0.43	0.41	0.37	0.51	0.45	0.39	0.39	0.35
18	1/4 in. argon space	0.38	0.52	0.68	0.51	0.45	0.43	0.39	0.54	0.47	0.42	0.42	0.38
19	1/2 in. argon space	0.30	0.46	0.61	0.45	0.39	0.38	0.33	0.47	0.41	0.35	0.35	0.30

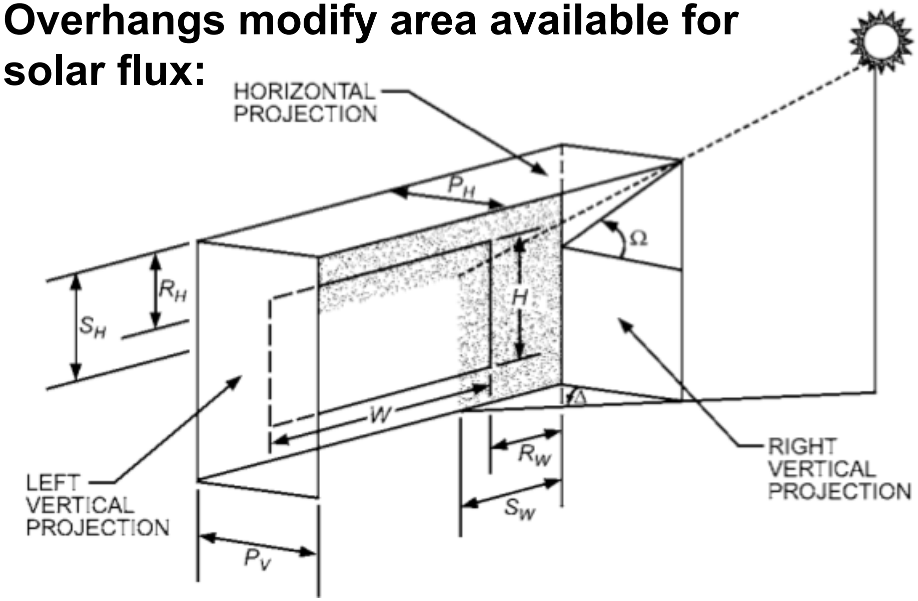
What about shading?

- Shading devices, including overhangs, 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:

Overhangs modify area available for solar flux:

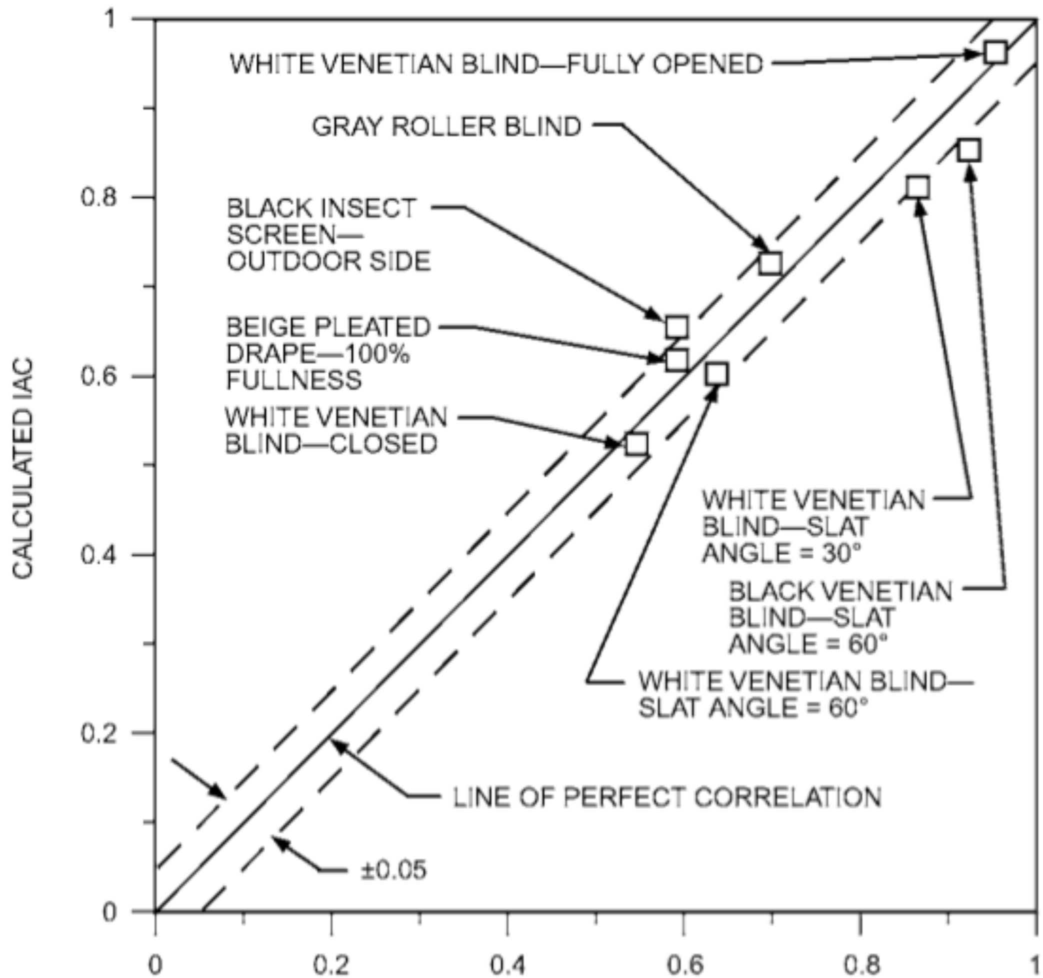


$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{direct} A_{pf} SHGC(\theta) IAC(\theta,\Omega) + (I_{diffuse+reflected}) A_{pf} SHGC_{diffuse+reflected} IAC_{diffuse+reflected}$$

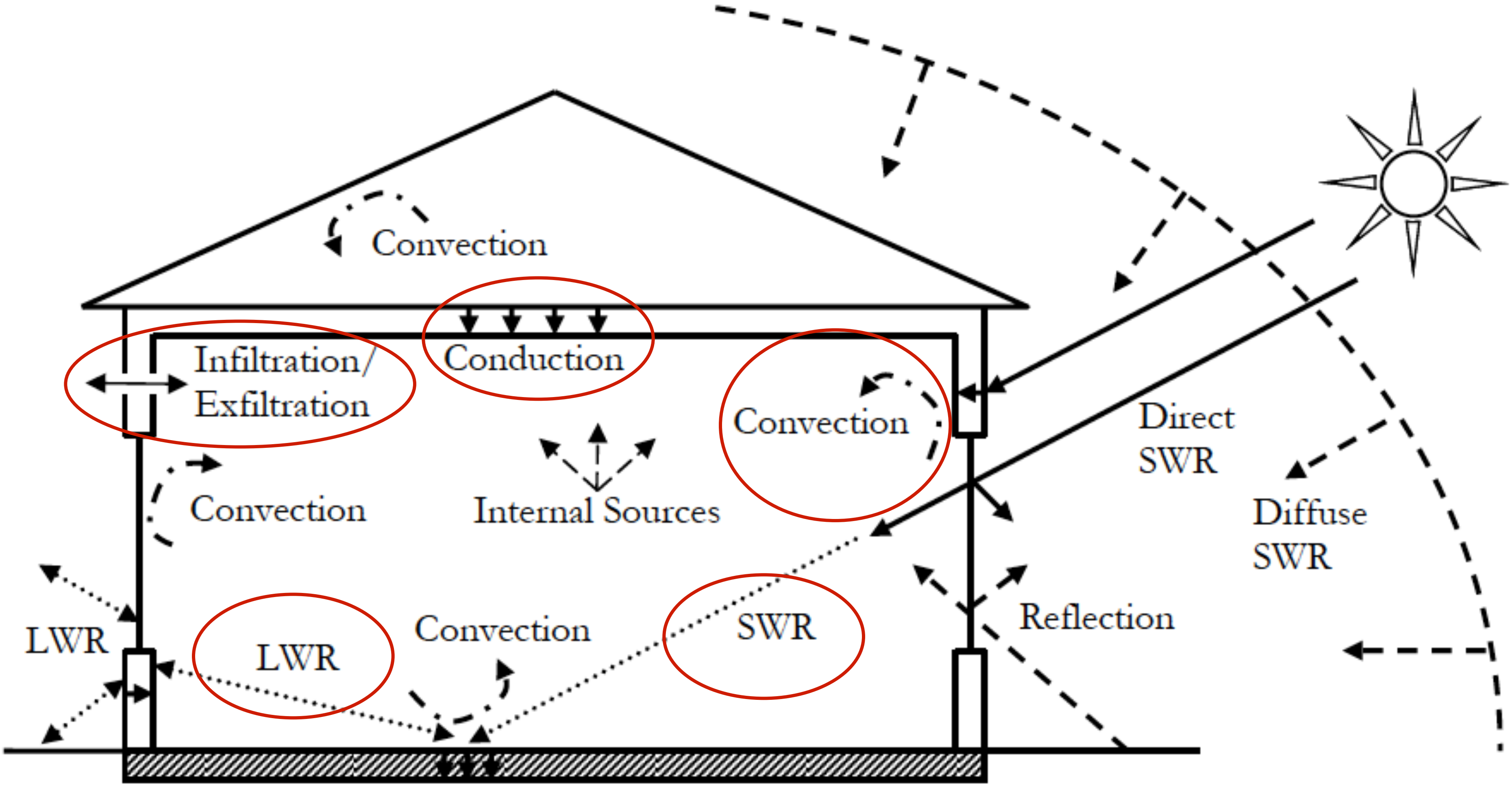
IAC is a function of incidence angle, θ, and the angle created by a shading device

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

$$q_{1\to2} = \frac{\sigma\left(T^4_{surf,1} - T^4_{surf,2}\right)}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{A_1}{A_2}\frac{1-\varepsilon_2}{\varepsilon_2} + \frac{1}{F_{12}}}$$

$$q_{rad,1\to2} = h_{rad}\left(T_{surf,1} - T_{surf,2}\right)$$

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

$$q_{1\to2} = \varepsilon_{surf}\sigma F_{12}\left(T^4_{surf,1} - T^4_{surf,2}\right)$$

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

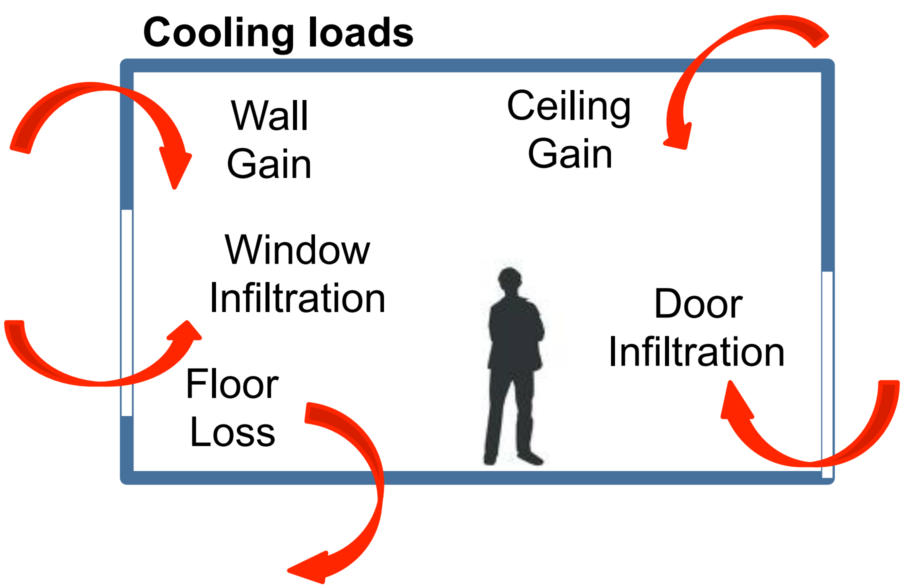
Transmitted solar radiation: (transparent surface) $q_{solar} = \tau I_{solar}$

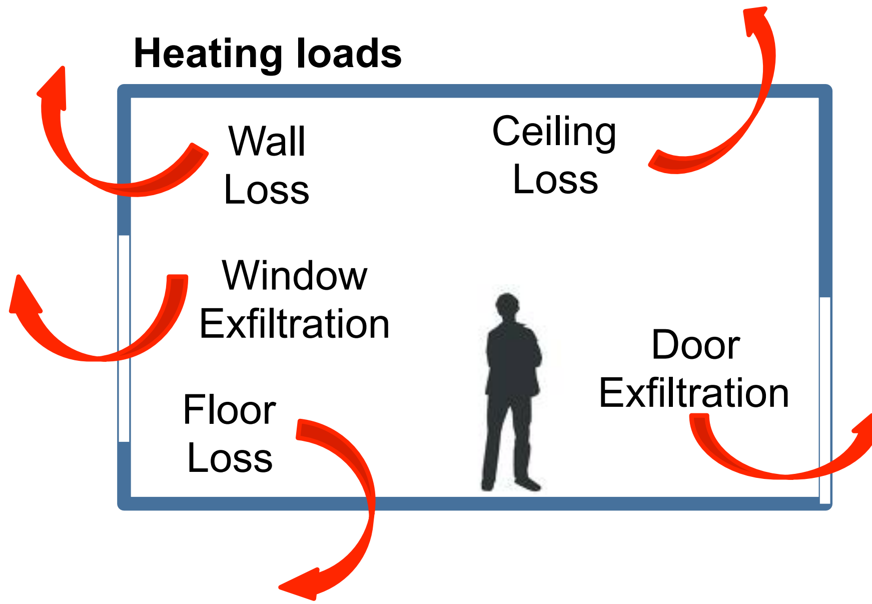
Window (combined modes)

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

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

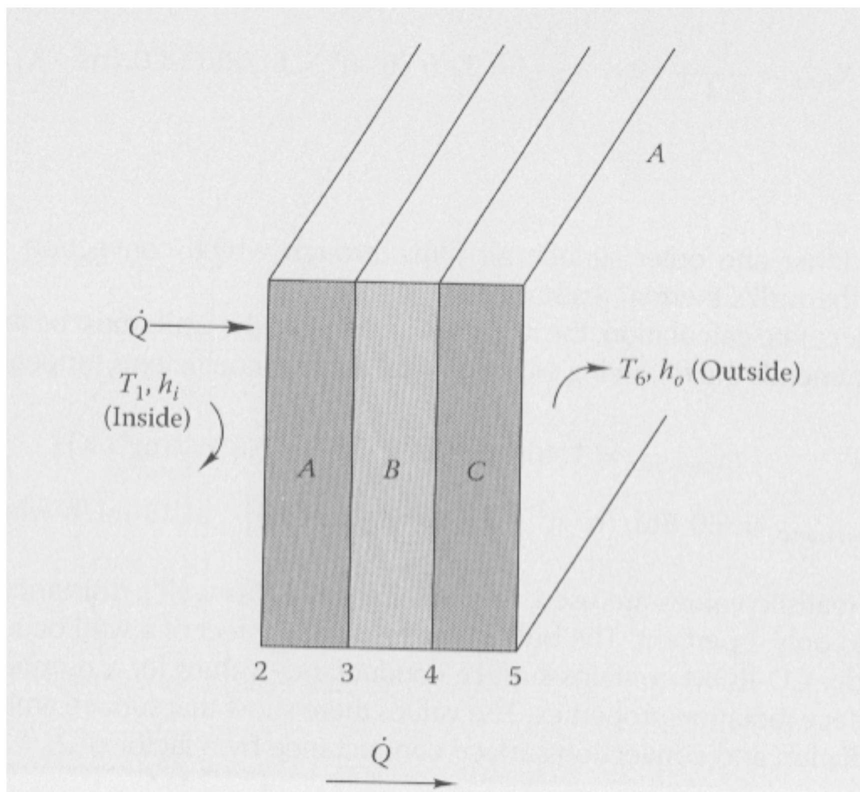




COMBINED MODE HEAT TRANSFER

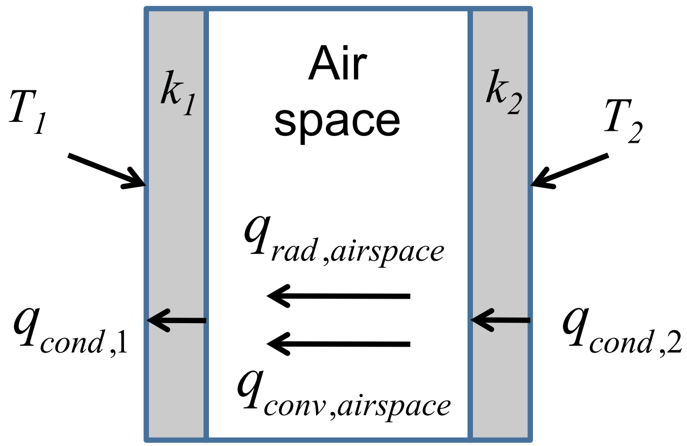
Combined mode heat transfer

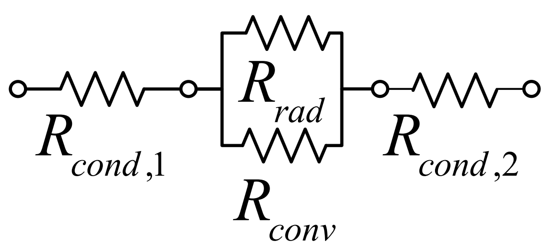
- Nearly all heat transfer situations in buildings include more than one mode of heat transfer
- When more than one heat transfer mode is present, we can compute heat loss using resistances (of all kinds) in series
  - Sum resistances in series



Combined mode 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 building cavity





Combined convection + conduction: Heat exchangers

- Heat exchangers are used widely in buildings
- Heat exchangers are devices in which two fluid streams, usually separated from each other by a solid wall, exchange thermal energy by both convection and conduction
  - One fluid is typically heated, one is typically cooled
    - Fluids may be gases, liquids, or vapors

$k_{aluminum}$ = 205 W/mK
k_{copper} = 385 W/mK

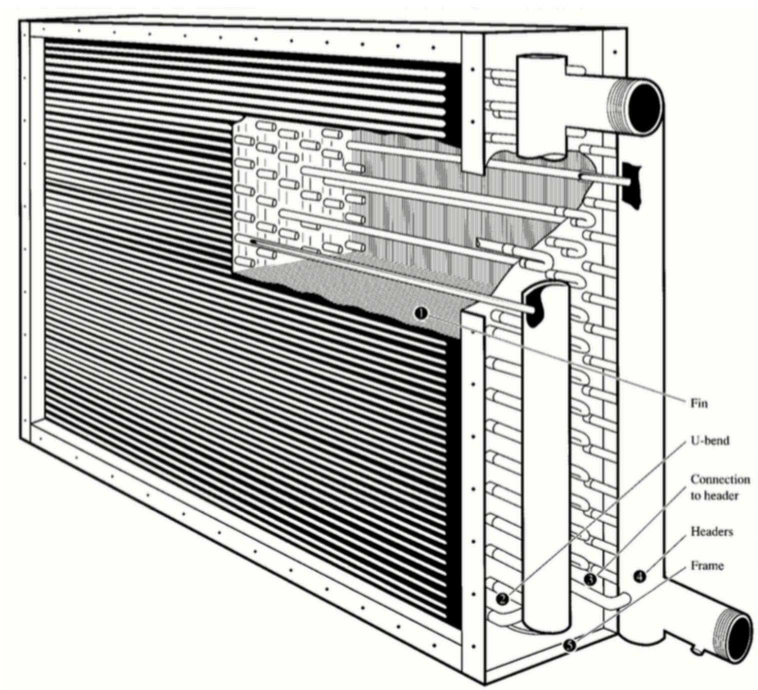
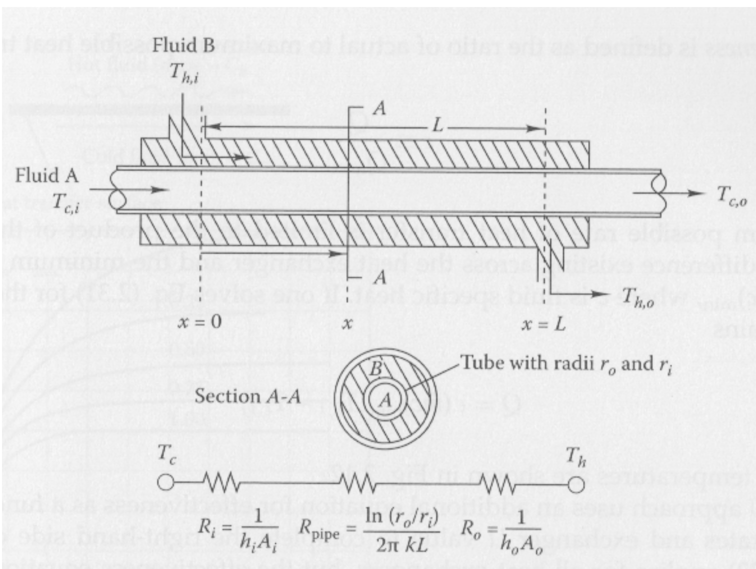


FIGURE 15.26a Structure of a water cooling coil. (*Source: York International Corporation. Reprinted with permission.*)

Combined convection + conduction: Heat exchangers

- The effectiveness of a heat exchanger depends on:
  - The flow rates of fluids in the heat exchanger
  - The overall UA-value of the heat exchanger
    - U is governed by convection and conduction resistance
    - A is governed by heat exchanger design (high surface A)



$$U_o A_o = \frac{1}{R_{conv,i} + R_{pipe} + R_{conv,o}}$$

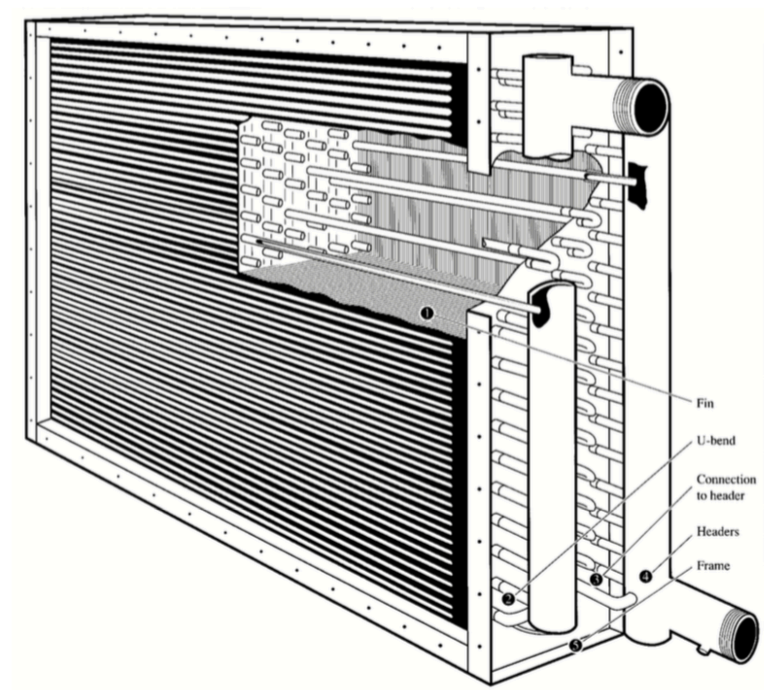


FIGURE 15.26a Structure of a water cooling coil. (*Source: York International Corporation. Reprinted with permission.*)

Combined U-factor data: ASHRAE 2013 HOF Ch. 15 (SI)

Table 4 U-Factors for Various Fenestration Products in W/(m²·K)

Product Type		Glass Only		Vertical Installation									
				Operable (including sliding and swinging glass doors)					Fixed				
Frame 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
ID	Glazing Type												
	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
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	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
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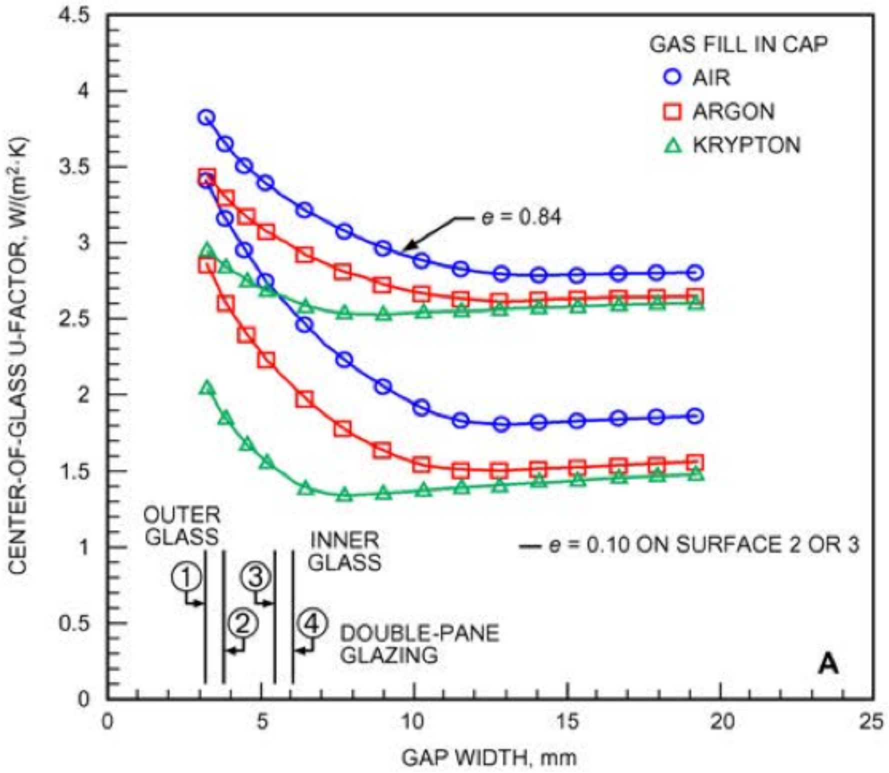
	Double Glazing, e = 0.60 on surface 2 or 3												
8	6 mm airspace	*2.95*	*3.52*	4.48	3.48	3.12	3.02	2.73	3.73	3.38	3.04	3.02	2.90
9	13 mm airspace	*2.50*	*3.20*	4.11	3.14	2.80	2.70	2.42	3.34	2.99	2.67	2.65	2.53
10	6 mm argon space	*2.67*	*3.32*	4.25	3.27	2.92	2.82	2.54	3.49	3.13	2.81	2.79	2.67
11	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

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 <u>double pane</u> 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

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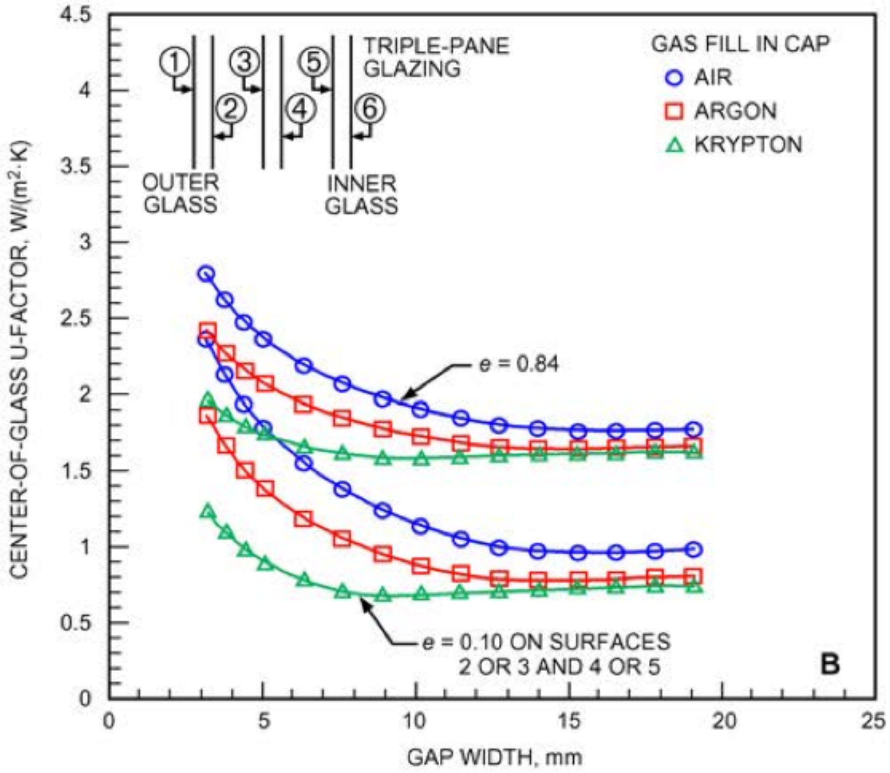
U-values and multiple layers of glazing

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

Center of glass U-values for <u>triple pane</u> glazing



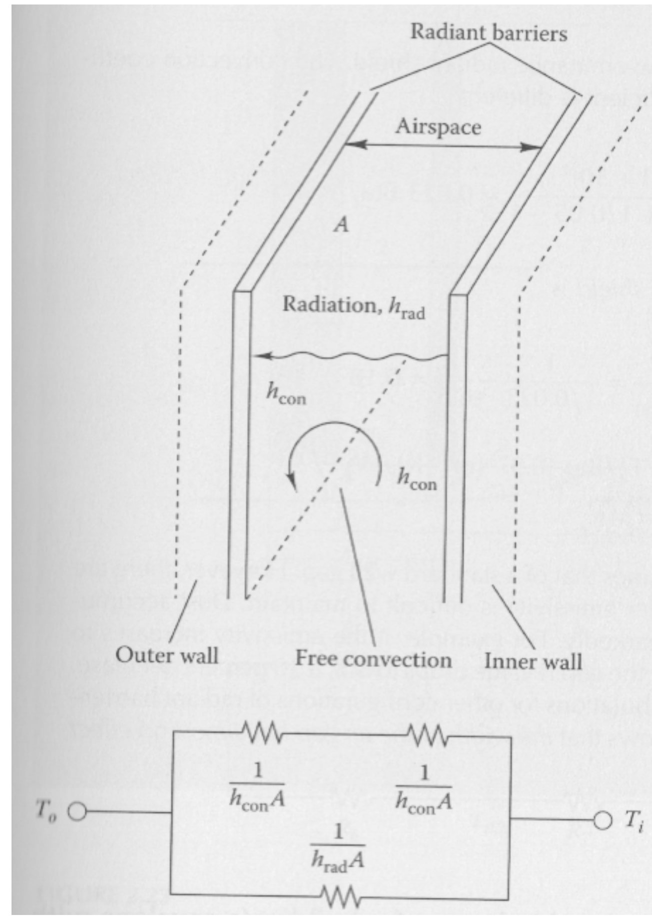
Combined modes of heat transfer

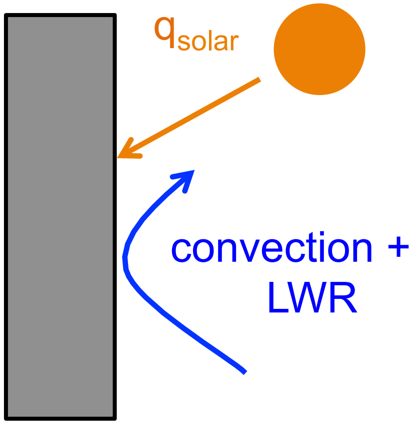
- Example problem: <u>Radiant barrier</u> in a residential wall

A building designer wishes to evaluate the R-value of a 1-inch wide ventilated air gap in a wall for its insulation effect

She finds the resistance to heat flow to be quite 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 in both emissivity conditions, including both radiation and convection effects, if the surface temperatures facing the gap are 7.2°C and 12.8°C





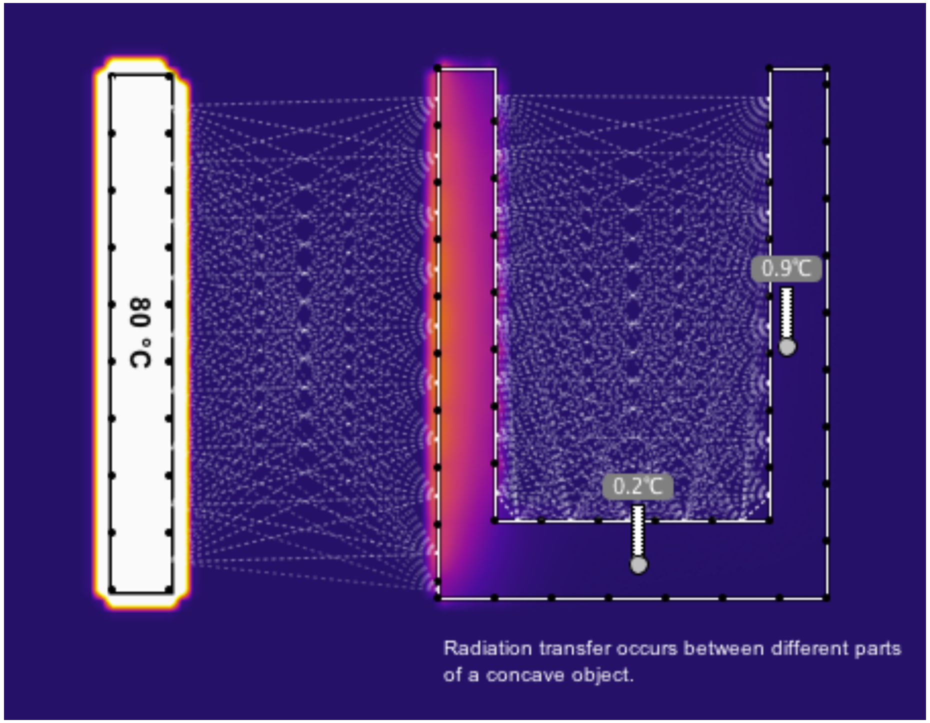
ENERGY BALANCES

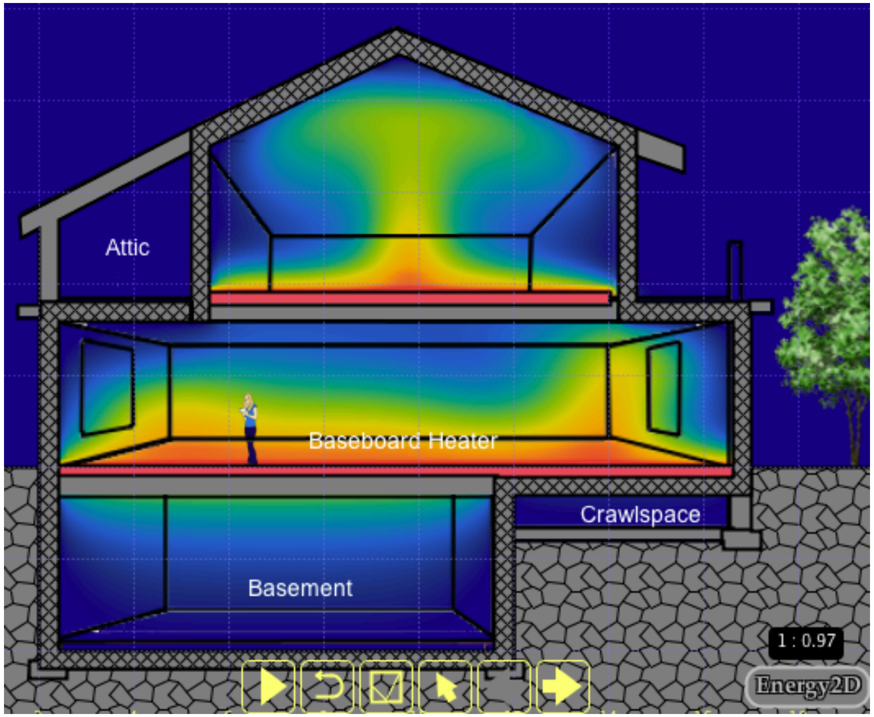
Building energy balances

- Multiple modes of heat transfer are typically acting at the same time at a particular point in/on a building

- We can write expressions to quantify heat flow/flux to/from these points by accounting for all relevant modes of heat transfer
  - "Building energy balances"

Building energy balances

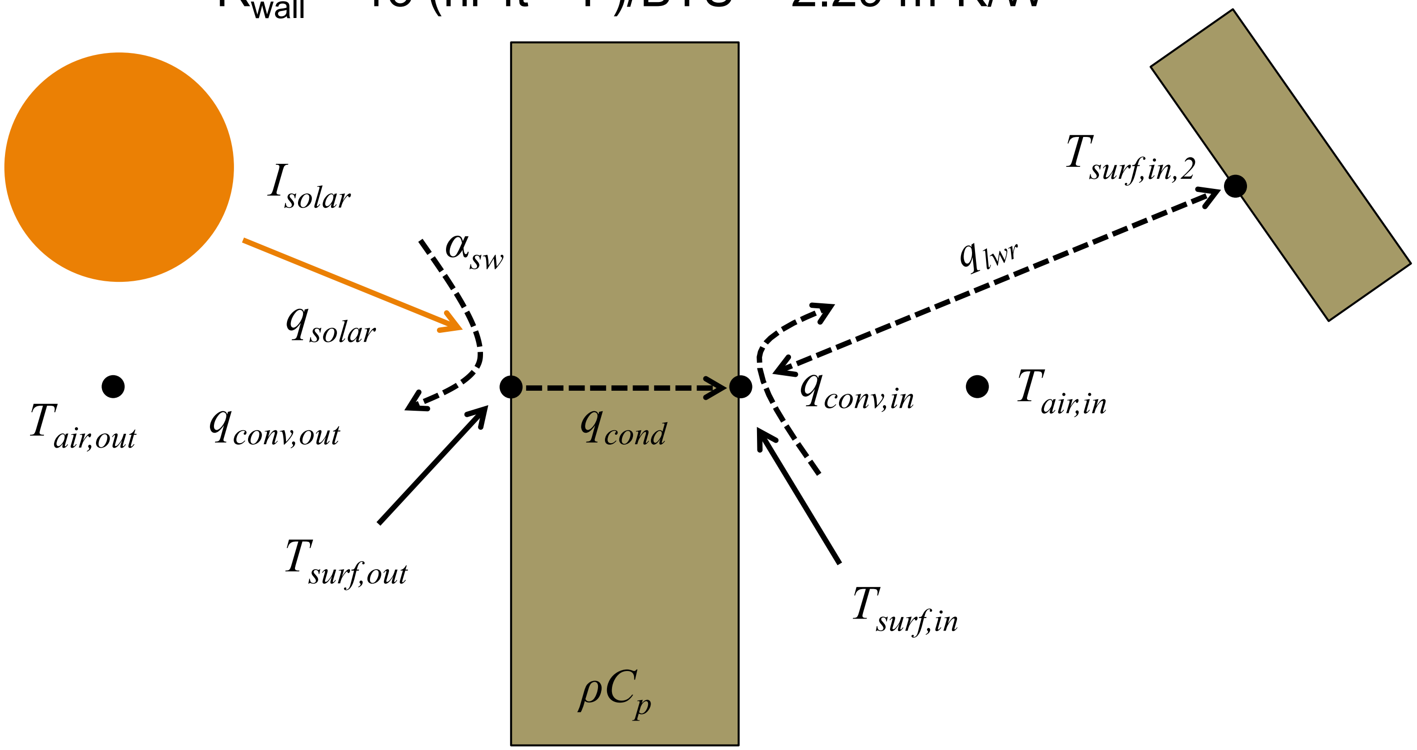




Building energy balances

Imagine an external wall of a building:

R_{wall} = 13 (hr-ft^2-°F)/BTU = 2.29 m^{2}K/W



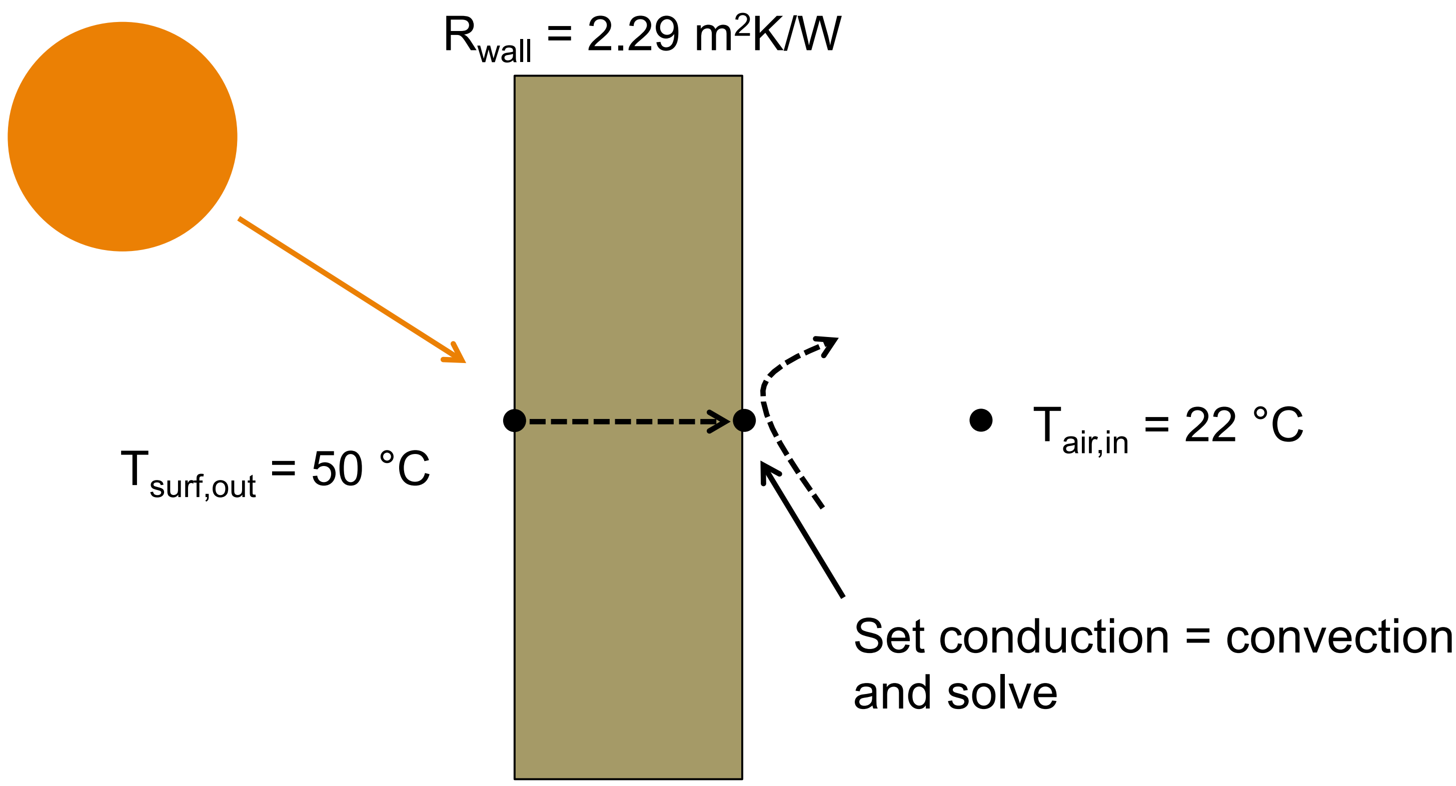
How is this helpful to us?

- Imagine the classroom wall is being heated by the sun on the other side
- The exterior surface temperature is 122°F (50°C)
- The interior air temperature is 72°F (22°C)
- The R-value of the wall is R-13 (IP) (2.29 m^2K/W)
- What is the <u>interior surface temperature</u> of the wall?

- This interior surface temperature impacts the heat flux to indoor air, as well as the surrounding surface temperatures (via radiation), which all impact the building's <u>energy balance</u>

Building energy balance example

- Estimate the surface temperature of an interior wall whose exterior side is being warmed by the sun
  - Assume that LWR can be ignored and assume steady-state

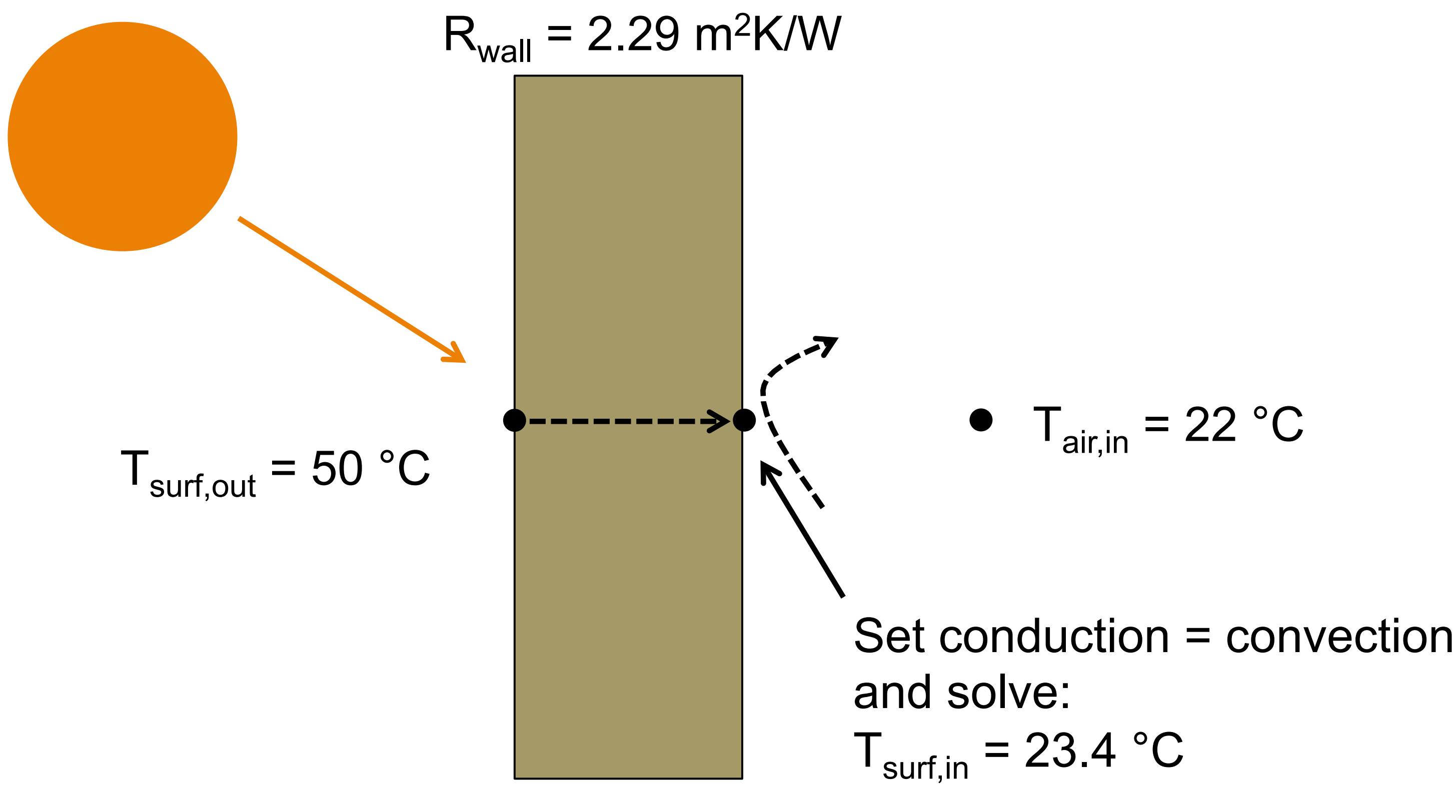


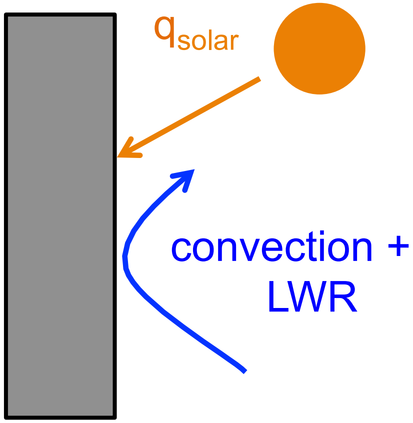
Convective film resistances

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)	

Building energy balance example

- Estimate the surface temperature of an interior wall whose exterior side is being warmed by the sun
  - Assume that LWR can be ignored and assume steady-state

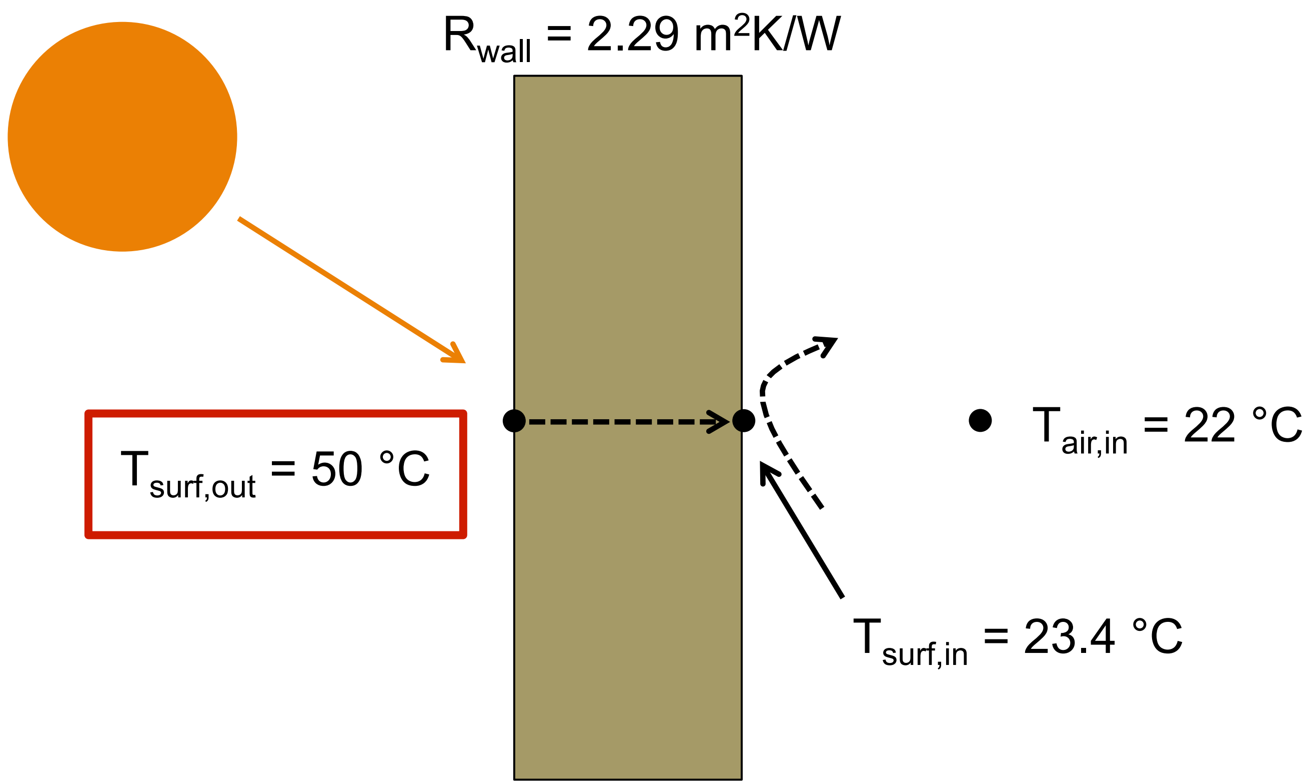




“SOL-AIR” TEMPERATURES

Sol-air temperatures

- In the last example, 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, $h_{conv+rad}$

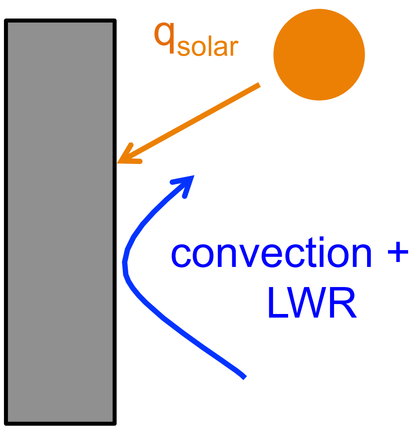
$$q_{conv+rad} = h_{conv+rad}\left(T_{air} - T_{surf}\right)$$

- 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:

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

Example **sol-air** temperatures

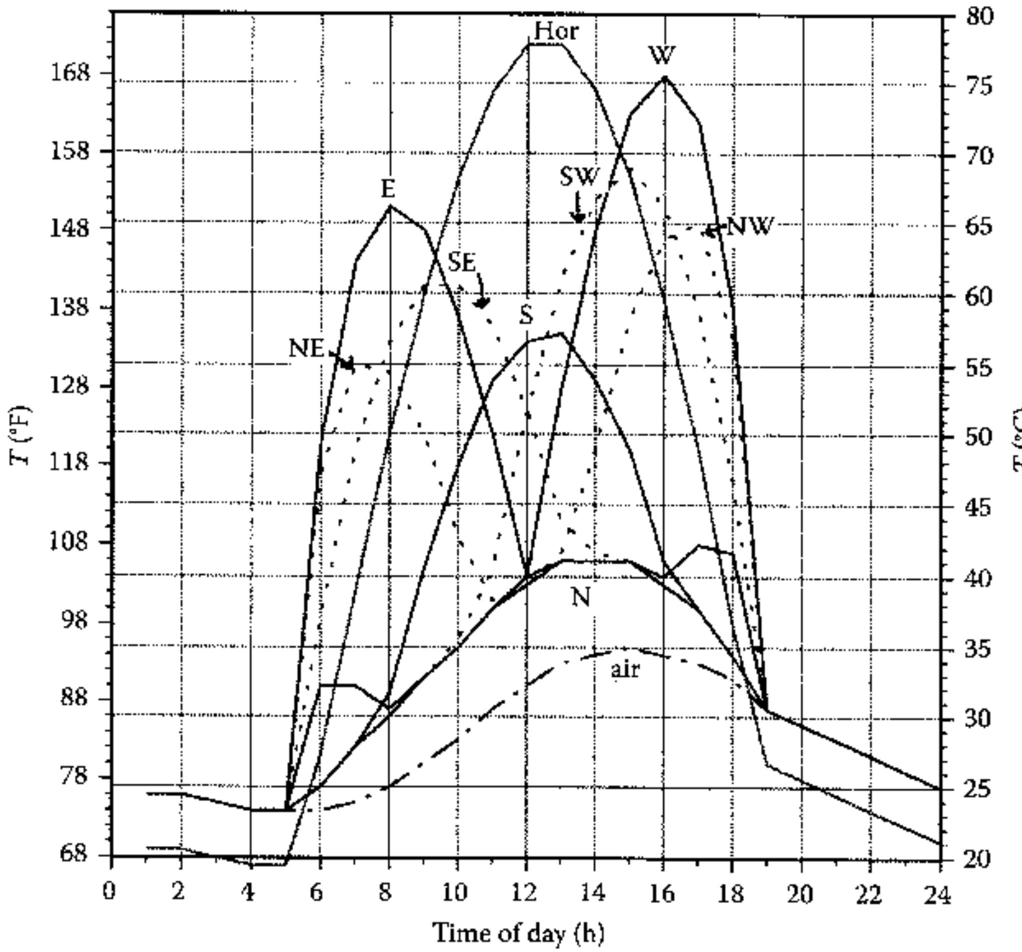


FIGURE 6.17
Sol-air temperature for horizontal and vertical surfaces as a function of time of day for summer design conditions, July 21 at 40° latitude, assuming $\alpha/h_o = 0.30$ (h · ft^2 · °F)/Btu [0.052 (m^2 · K)/W]. The curves overlap when there is no direct radiation on a surface. (Courtesy of 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

Next time

- Review for Exam 1: Example problems
- Assign graduate project expectations