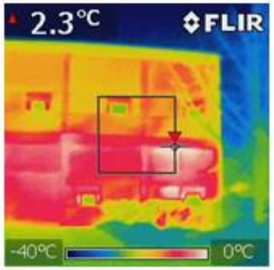
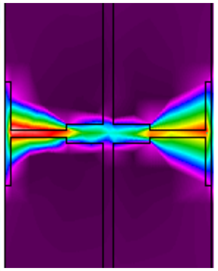
CAE 331/513
Building Science
Fall 2015





Week 3: September 8, 2015
Heat transfer in buildings: Radiation

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Last time

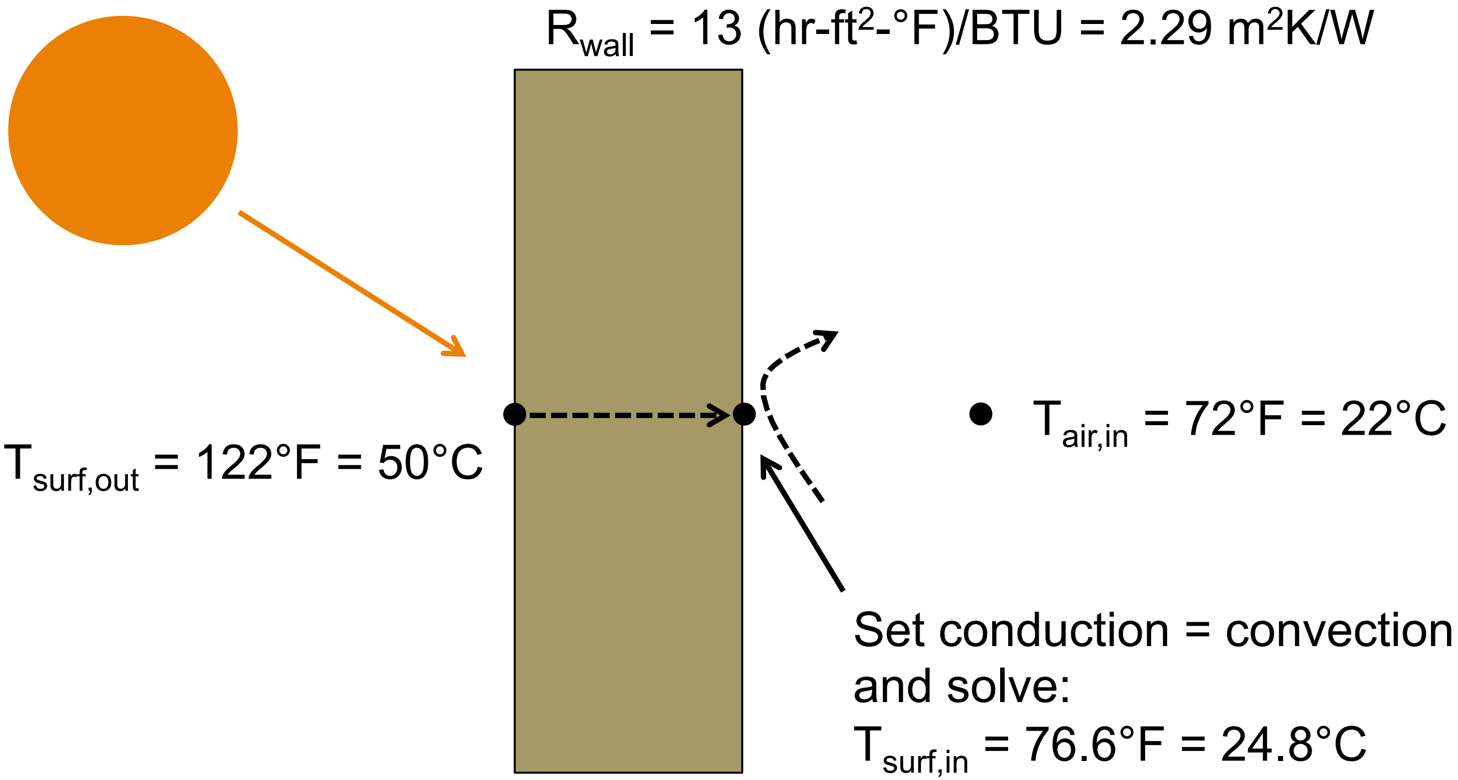
- Heat transfer in buildings: Convection $q_{conv} = h_{conv}\left(T_{fluid} - T_{surf}\right)$
  - "Types" of convection
    - Forced and natural
    - External and internal
  - Convective heat transfer coefficients
    - Theory
      - Nu = convection vs. conduction heat transfer
      - Pr = momentum vs. heat diffusivity (fluid property)
      - Re = inertial vs. viscous forces
      - Gr = buoyancy vs. viscosity
      - Ra = Gr x Pr
    - Empirical
    - Simplified empirical relationships
      - h_c = f(temperature difference, velocity, orientation, roughness)

Today's objectives

- Finish convection
- Introduce radiation

Finishing convection

- We presented an example problem last week that involved estimating the surface temperature of an interior wall whose exterior side was being warmed by the sun



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

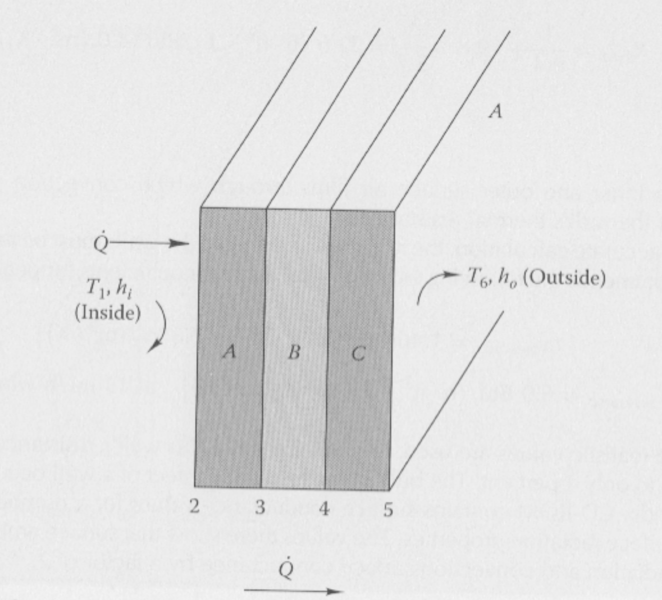
$T_{surf,out}$ = 122°F = 50°C

$T_{air,in}$ = 72°F = 22°C

Set conduction = convection and solve:
$T_{surf,in}$ = 76.6°F = 24.8°C

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 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

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)	

Internal flows within building HVAC systems

- Flows of fluids confined by boundaries (such as the sides of a duct) are called internal flows

- Mechanisms of convection are different
  - And so are the equations for h_c

Forced convection for fully developed turbulent flow

- Air flow through ducts:

$$h_{conv} \approx 8.8 \left(\frac{v^4}{D_h} \right)^{1/5}$$ [Kreider 2.26SI]

D_h = the hydraulic diameter: 4 times the ratio of the flow conduit's cross-sectional area divided by the perimeter of the conduit

$$D_h = \frac{4\left(\frac{\pi D^2}{4} \right)}{\pi D}$$ [Kreider 2.27SI]

- Water flow through pipes:

$$h_{conv} \approx 3580(1 + 0.015T) \left(\frac{v^4}{D_h} \right)^{1/5}$$ [Kreider 2.28SI]

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

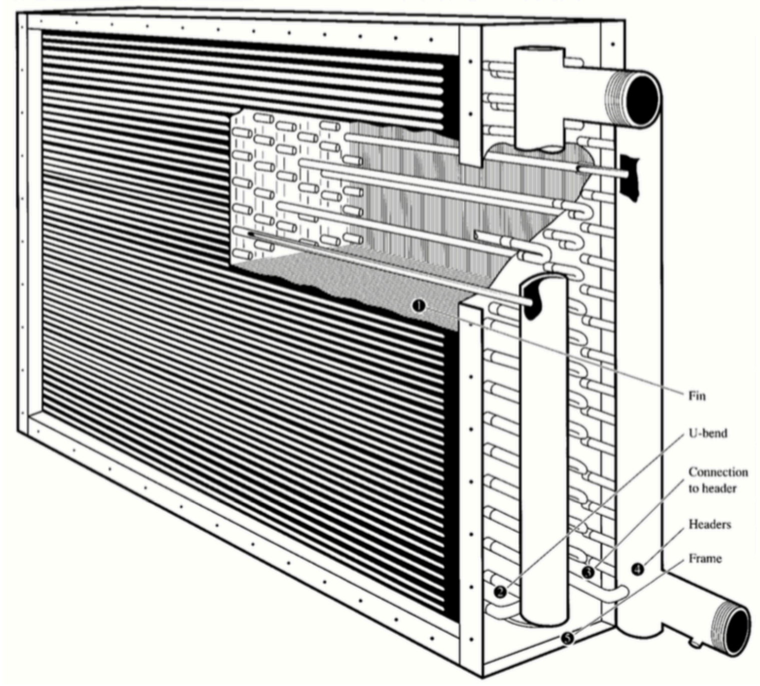
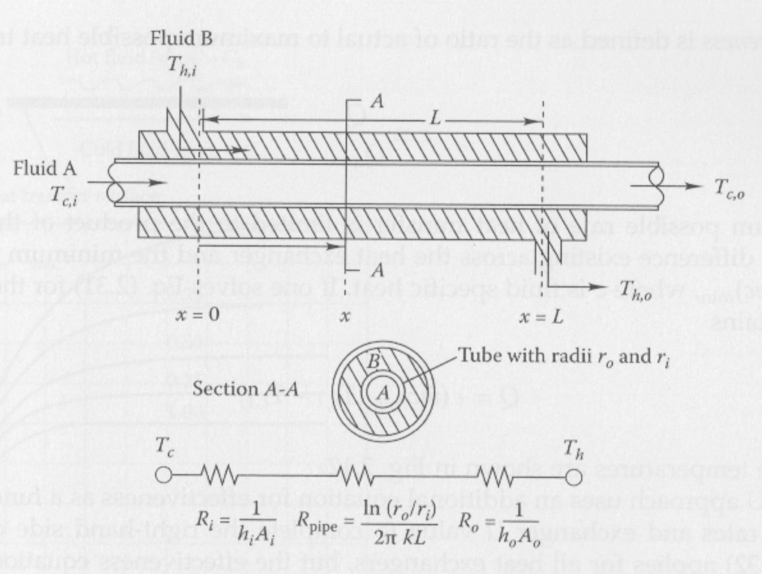


FIGURE 15.26a Structure of a water cooling coil. (*Source: York International Corporation. Reprinted with permission.*)

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)



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

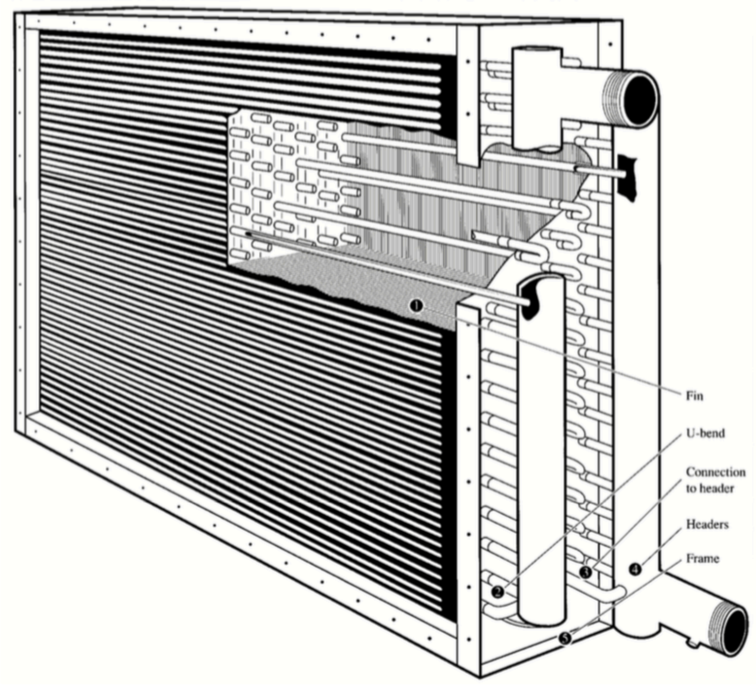
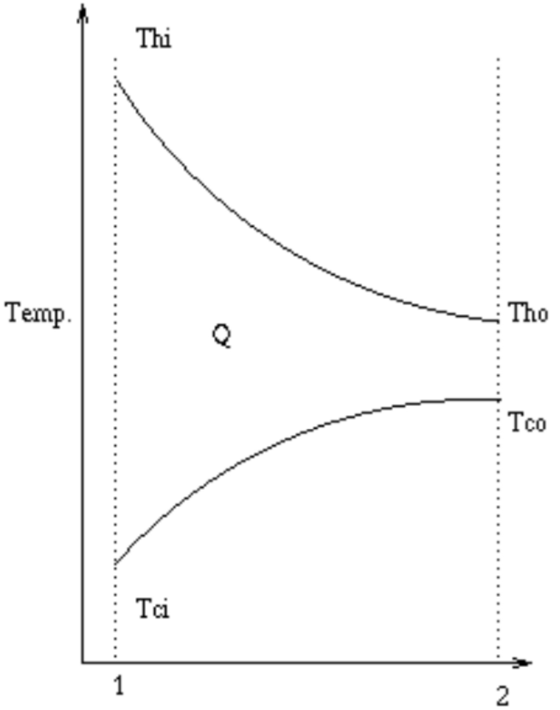


FIGURE 15.26a Structure of a water cooling coil. (*Source: York International Corporation. Reprinted with permission.*)

Heat exchangers

- **Parallel flow**: fluids flowing in the same direction

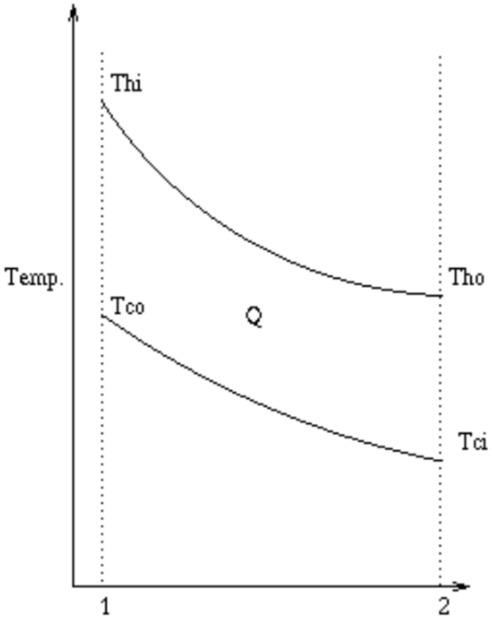
What happens to the two temperature profiles?



Heat exchangers

- **Counterflow**: one fluid flows in the opposite direction
  - More efficient than parallel flow

What happens to the two temperature profiles?



Heat exchangers: ∊-NTU method

$$\varepsilon_{\mathrm{dry}} = \frac{1 - \exp[-\mathrm{NTU}(1 - C)]}{1 - C\exp[-\mathrm{NTU}(1 - C)]}$$

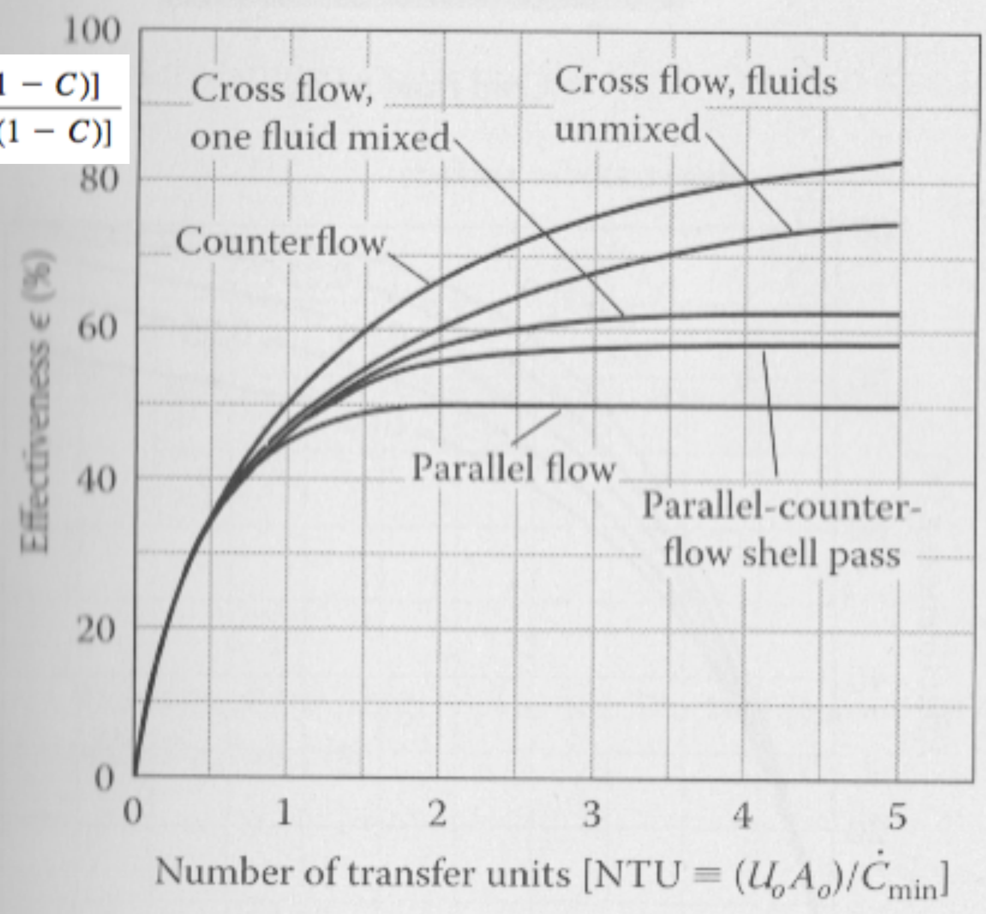
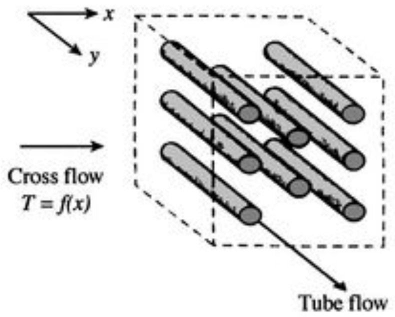
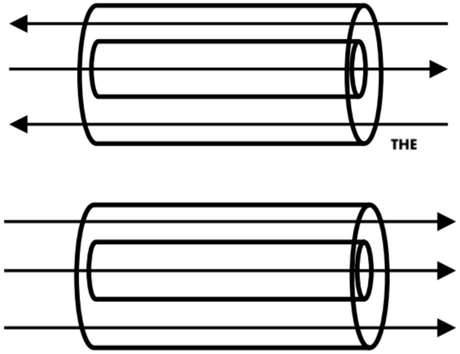


FIGURE 2.14
Comparison of effectiveness of several heat exchanger designs for equal hot- and cold-side capacitance rates, $\dot{C}_{\min} = \dot{C}_{\max}$.





This subject is covered in detail in CAE 464 HVAC Design

Bulk convective heat transfer: Advection

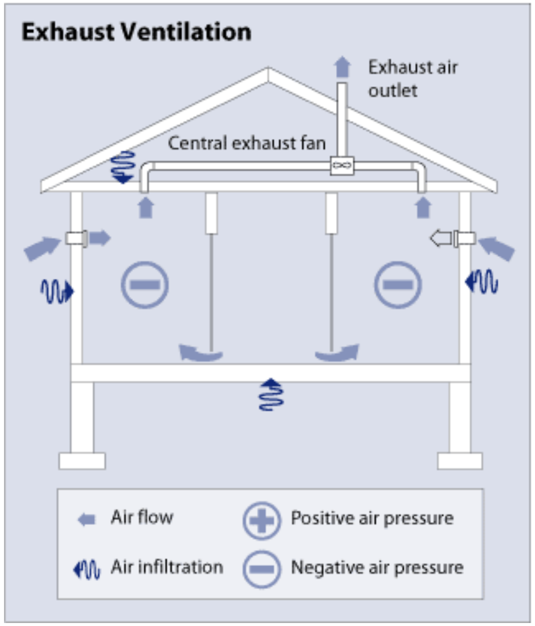
- Finally, there is one last type of convection
- Bulk convective heat transfer, or **advection**, is more direct than convection between surfaces and fluids
  - Bulk convective heat transfer is the transport of heat by fluid flow (e.g., air or water)
- Fluids, such as air, have the capacity to store heat, so fluids flowing into or out of a control volume also carry heat with it

$$Q_{bulk} = \dot{m} C_p \Delta T \qquad [\mathrm{W}] = [\frac{\mathrm{kg}}{\mathrm{s}} \cdot \frac{\mathrm{J}}{\mathrm{kg} \cdot \mathrm{K}} \cdot \mathrm{K}]$$

m "dot" = mass flow rate of fluid (kg/s)
C_p = specific heat capacity of fluid [J/(kgK)]

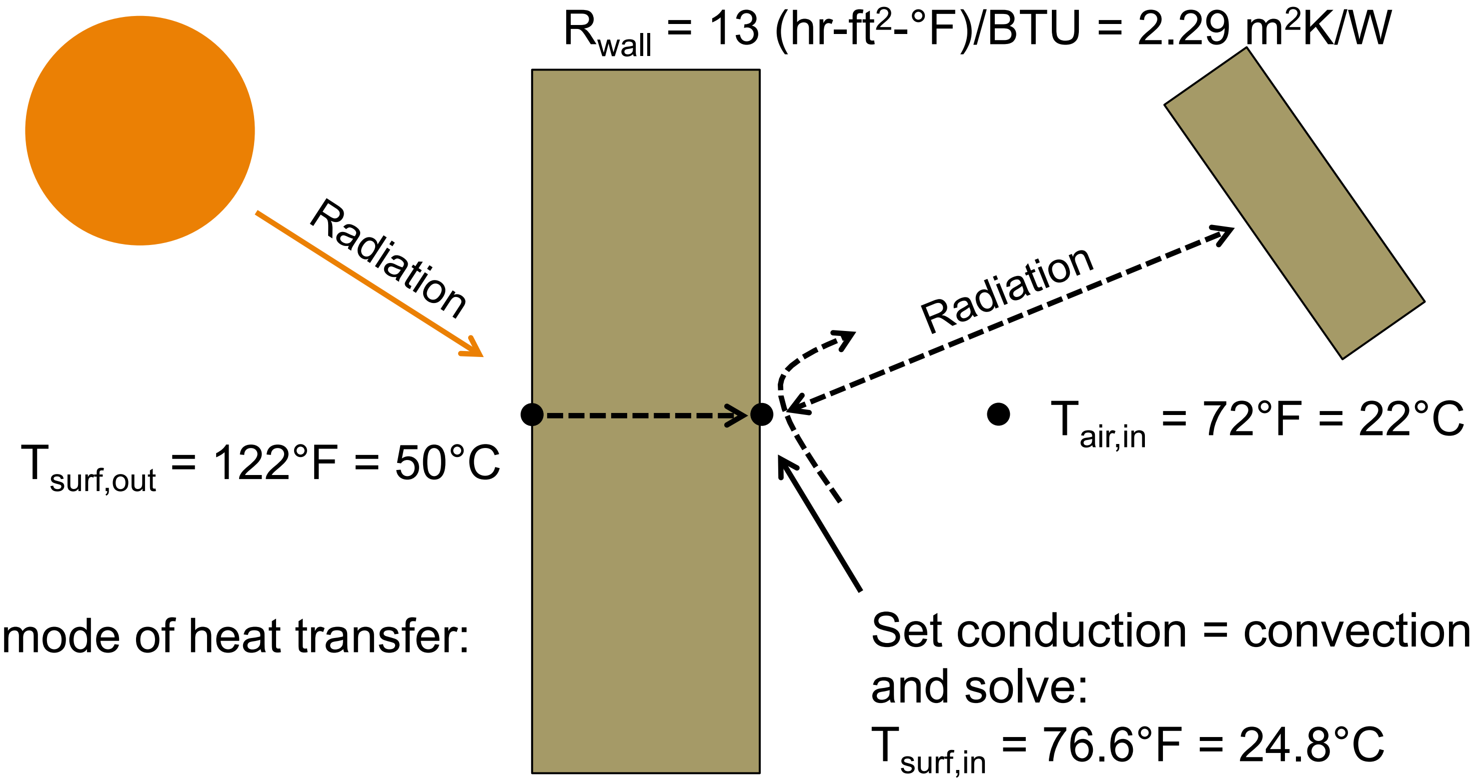
Bulk convective heat transfer: Advection

- Every time you take a shower at home, you use your bathroom exhaust fan to exhaust the hot/humid air generated by the shower
  - The fan operates at an airflow rate of 100 CFM
  - If it is 68°F inside the house and 10°F outside, what is the rate of heat loss via bulk convection during these conditions, assuming that the 100 CFM air comes in via infiltration through the building envelope



Back to our convection example…

- We presented an example problem last week that involved estimating the surface temperature of an interior wall whose exterior side was being warmed by the sun



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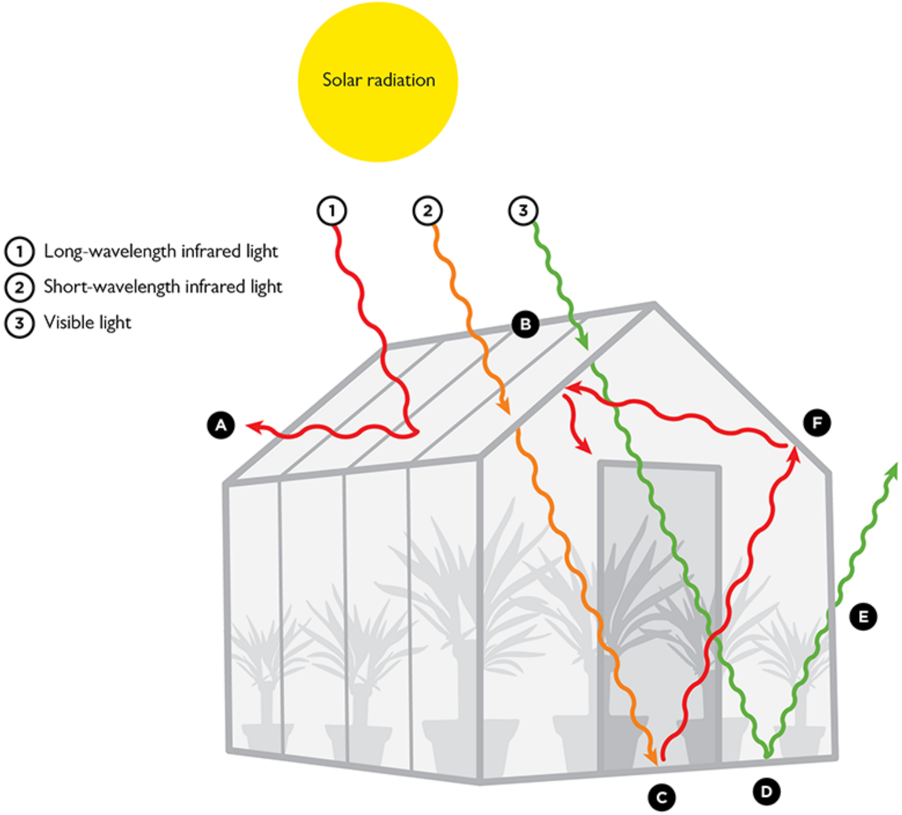
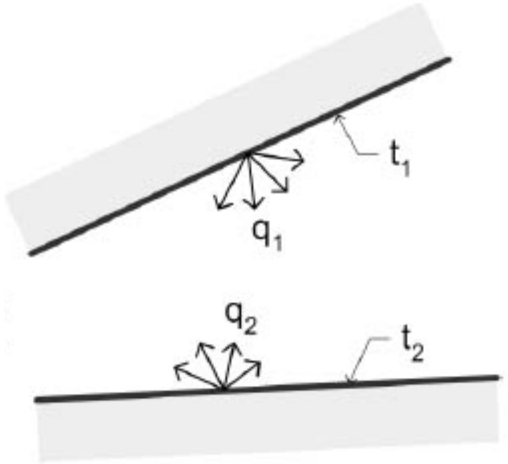
Another key mode of heat transfer:
Radiation

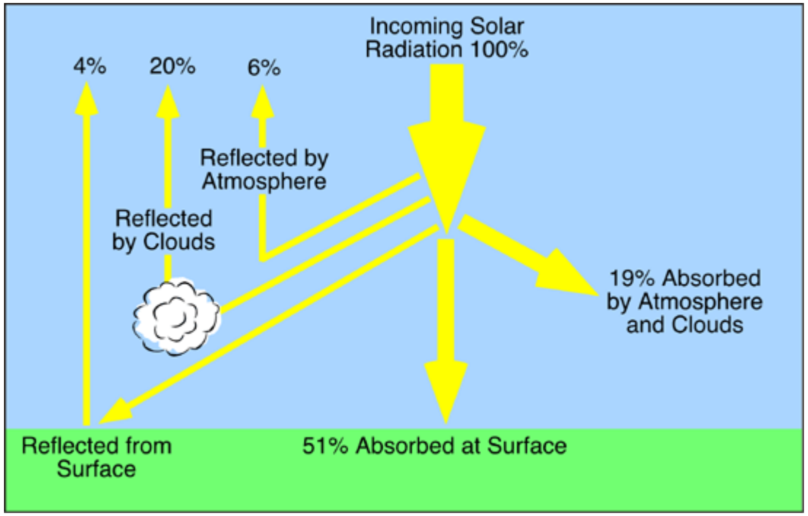

Solar radiation
① Long-wavelength infrared light
② Short-wavelength infrared light
③ Visible light
1
2
3
A
B
C
D
E
F

RADIATION

Radiation

- **Radiation** heat transfer is the transport of energy by electromagnetic waves
    - Oscillations of electrons that comprise matter
    - Exchange between matter at different temperatures
- Radiation must be absorbed by matter to produce internal energy; emission of radiation corresponds to reduction in stored thermal energy





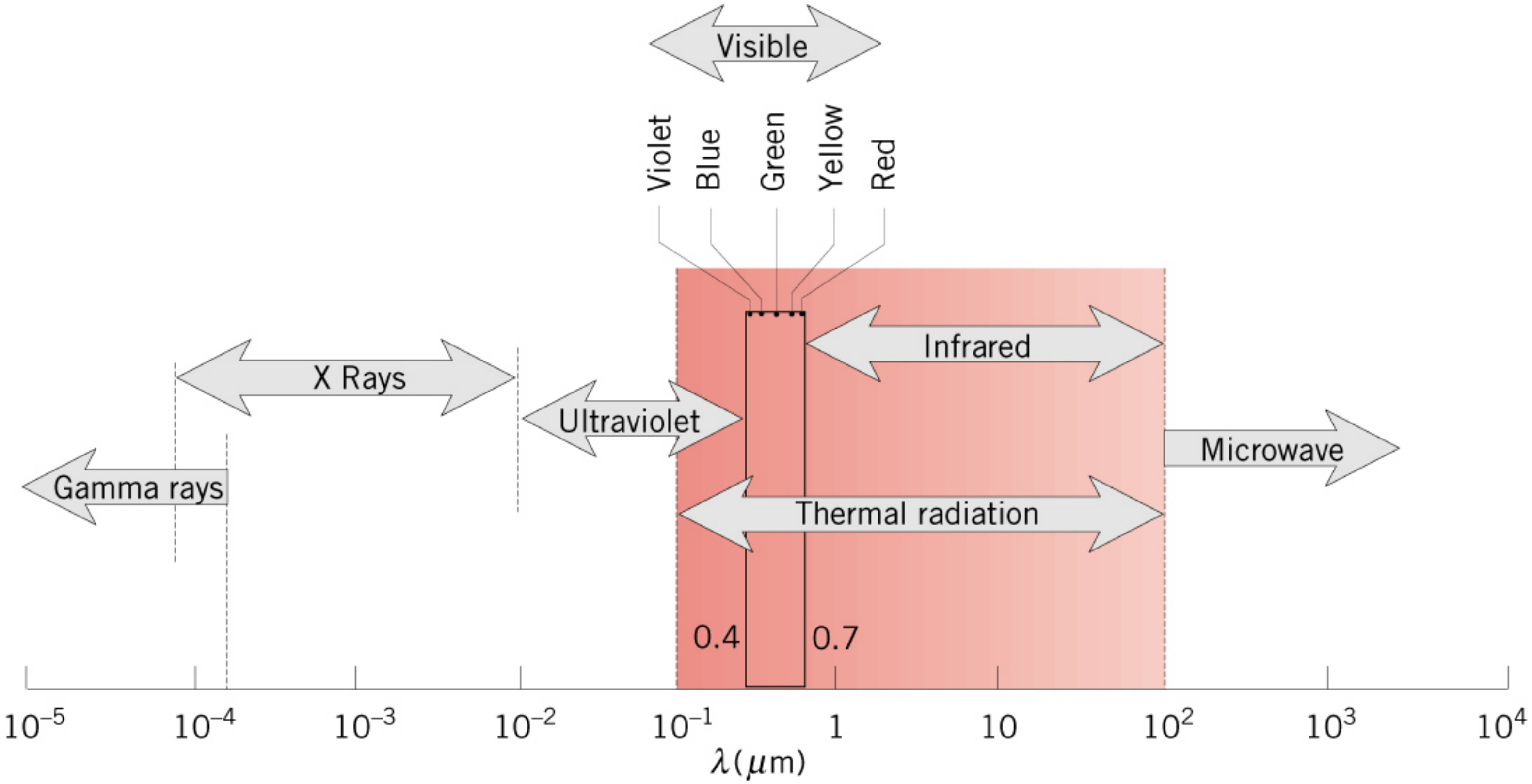
Radiation

- Radiation needs to be dealt with in terms of wavelength (λ)
  - Different wavelengths of solar radiation pass through the earth's atmosphere *more* or *less* efficiently than other wavelengths
  - Materials also *absorb* and *re-emit* solar radiation of different wavelengths with different efficiencies

- For our purposes, it's generally appropriate to treat radiation in two groups:
  - Short-wave (solar radiation)
  - Long-wave (emitted and re-emitted radiation)

Radiation: the electromagnetic spectrum

- Thermal radiation is confined to the infrared, visible, and ultraviolet regions ($0.1 < \lambda < 100$ μm)



Black body radiation: Spectral (Planck) distribution

- Radiation from a perfect radiator follows the “black body” curve (ideal, black body *emitter*)

- The peak of the black body curve depends on the object’s temperature
  - Lower T, larger λ peak

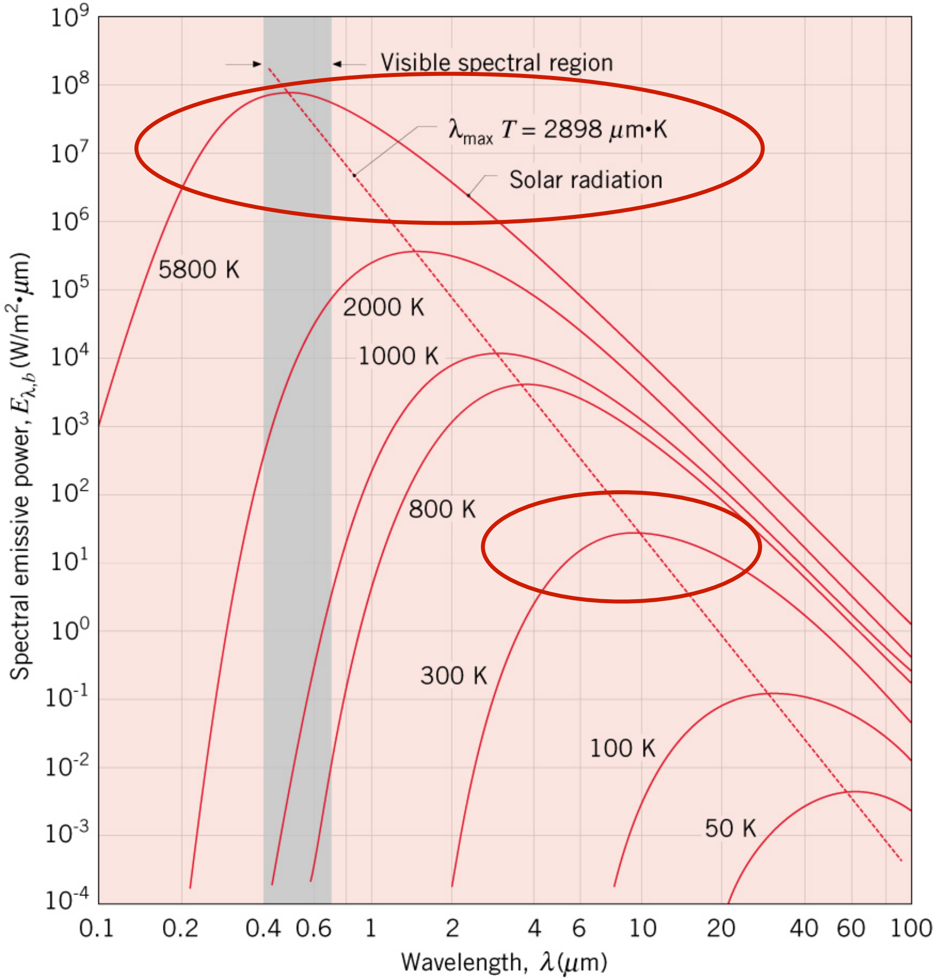
- Peak radiation from the sun is in the visible region
  - About 0.4 to 0.7 μm

- Radiation involved in building surfaces is in the infrared region
  - Greater than 0.7 μm

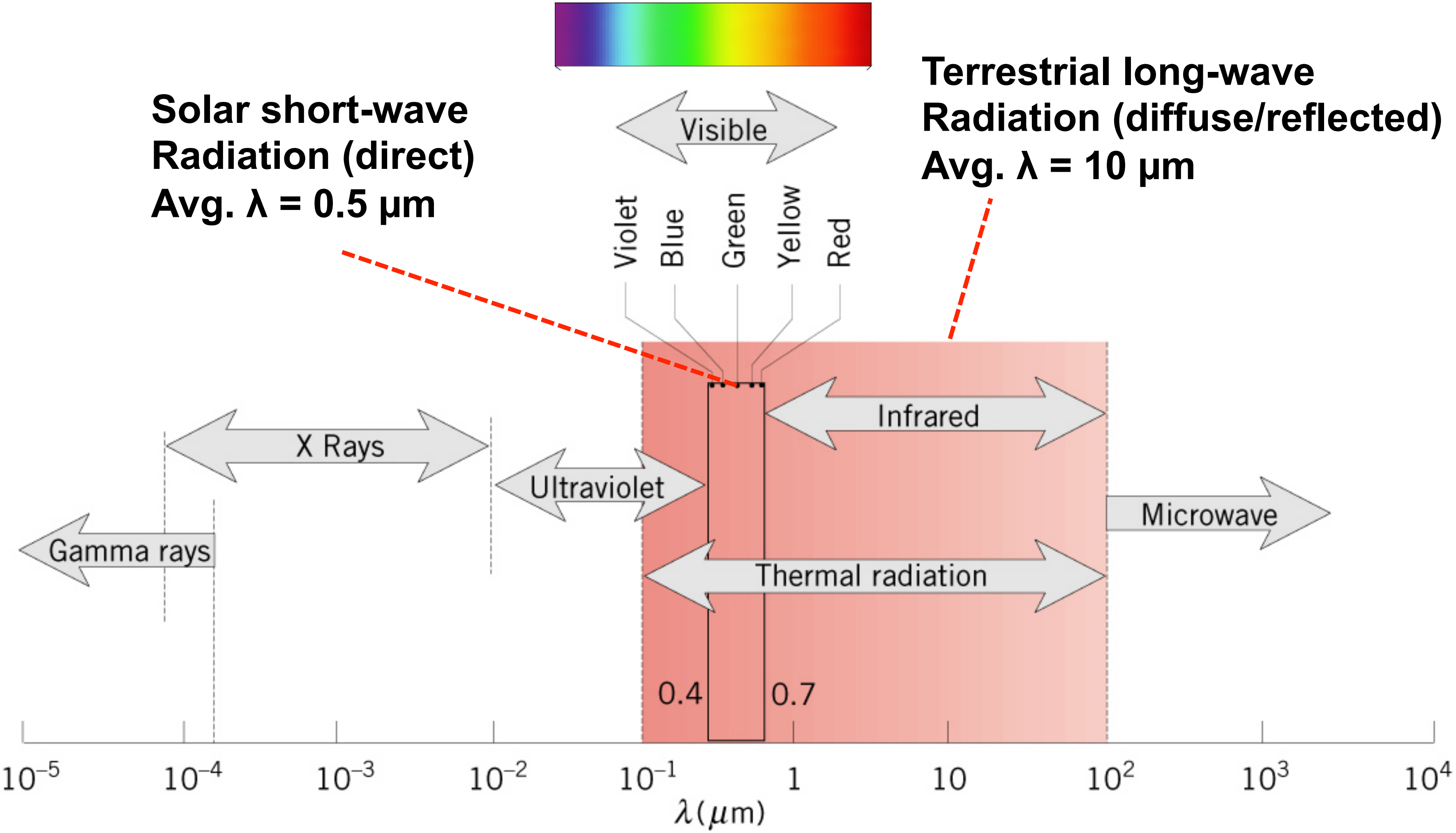
$q = \sigma T^4$

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

T = Absolute temperature [K]



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:

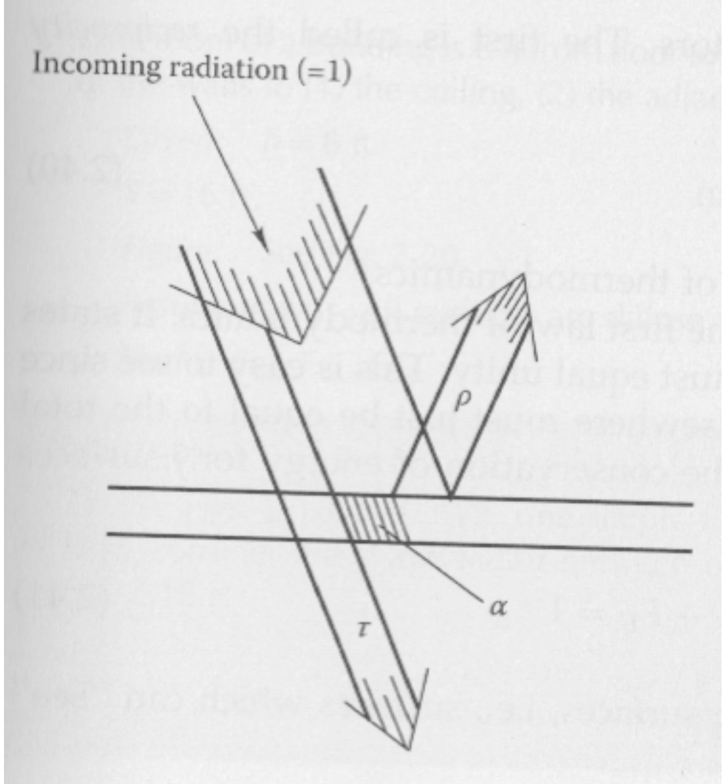
$$I_{solar} \quad \left[\frac{\text{W}}{\text{m}^2}\right]$$

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

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

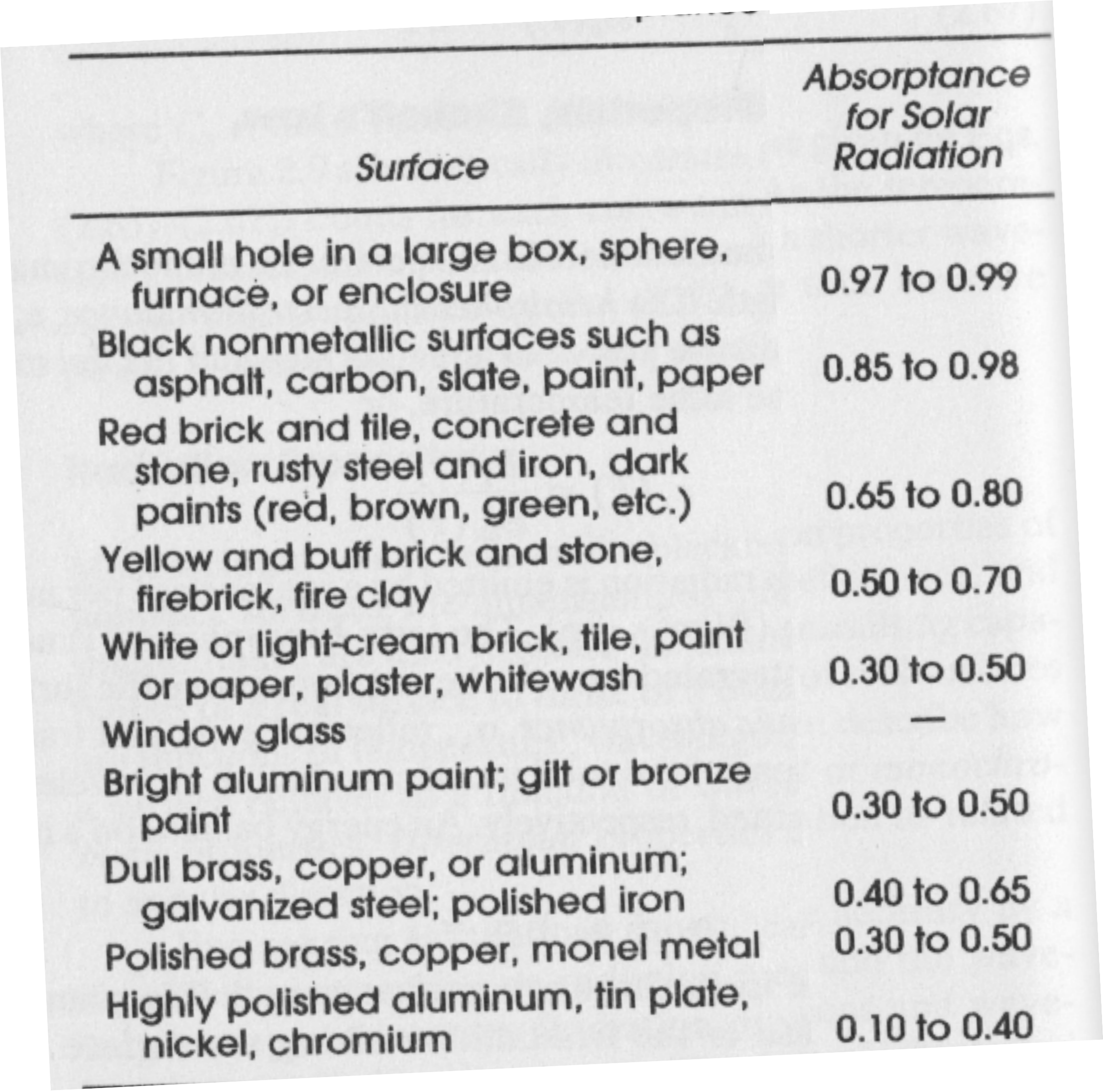
Absorptivity, transmissivity, and reflectivity

- The absorptivity, α, is the fraction of energy hitting an object that is actually absorbed
- Transmissivity, τ, is a measure of how much radiation passes through an object
- Reflectivity, ρ, is a measure of how much radiation is reflected off an object
- We use these terms primarily for solar radiation
  - For an opaque surface ($\tau = 0$): $q_{solar} = \alpha I_{solar}$
  - For a transparent surface ($\tau > 0$): $q_{solar} = \tau I_{solar}$



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

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



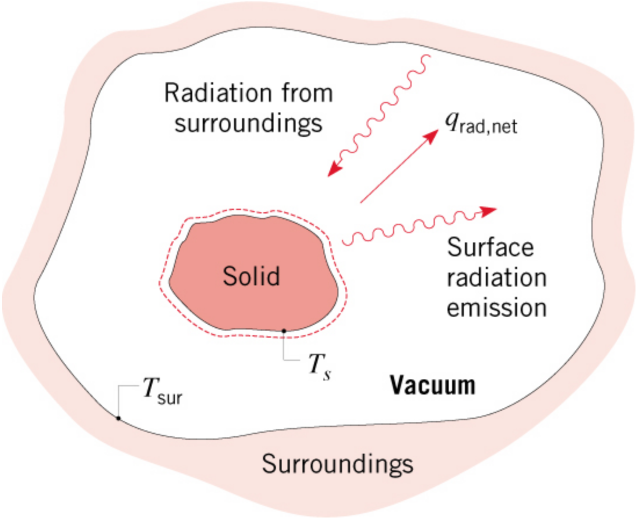
Surface	Absorptance for Solar Radiation
A small hole in a large box, sphere, furnace, or enclosure	0.97 to 0.99
Black nonmetallic surfaces such as asphalt, carbon, slate, paint, paper	0.85 to 0.98
Red brick and tile, concrete and stone, rusty steel and iron, dark paints (red, brown, green, etc.)	0.65 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

Surface radiation (lower temperature: long-wave)

- All objects above absolute zero radiate electromagnetic energy according to:

"Gray bodies"

$$q_{rad} = \varepsilon \sigma T^4$$



Where ε = emissivity

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

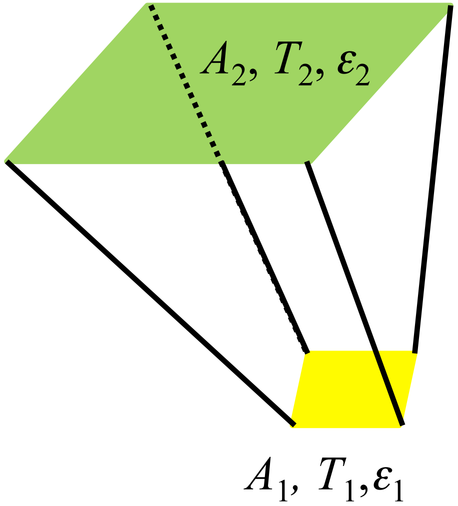
T = Absolute temperature [K]

- Net radiation heat transfer occurs when an object radiates a different amount of energy than it absorbs
- If all the surrounding objects are at the same temperature, the net will be zero

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

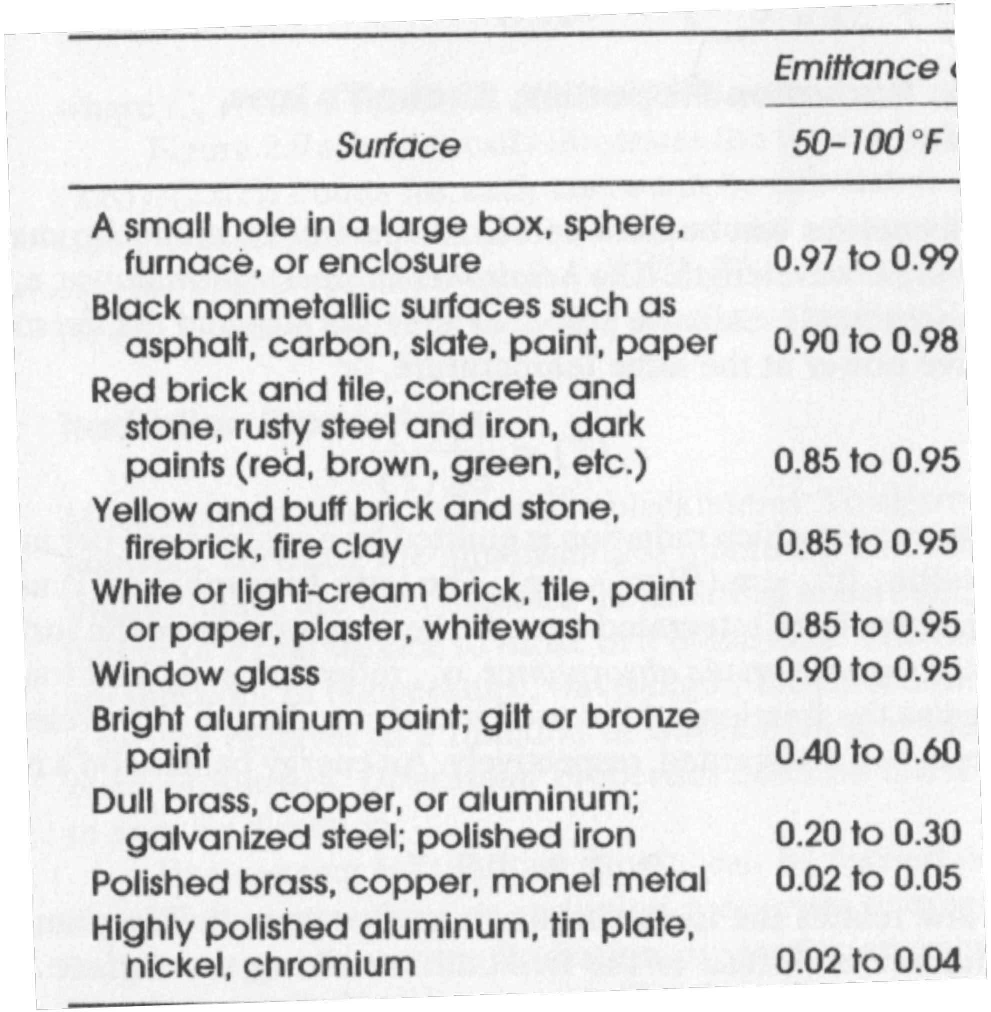
and $F_{1\to 2}$ is the view factor from surface 1 to 2

$F_{1\to 2}$ 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…), $\varepsilon = 0.9$ at most wavelengths

Emissivity (ε) of common materials



	Emittance
Surface	*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
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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

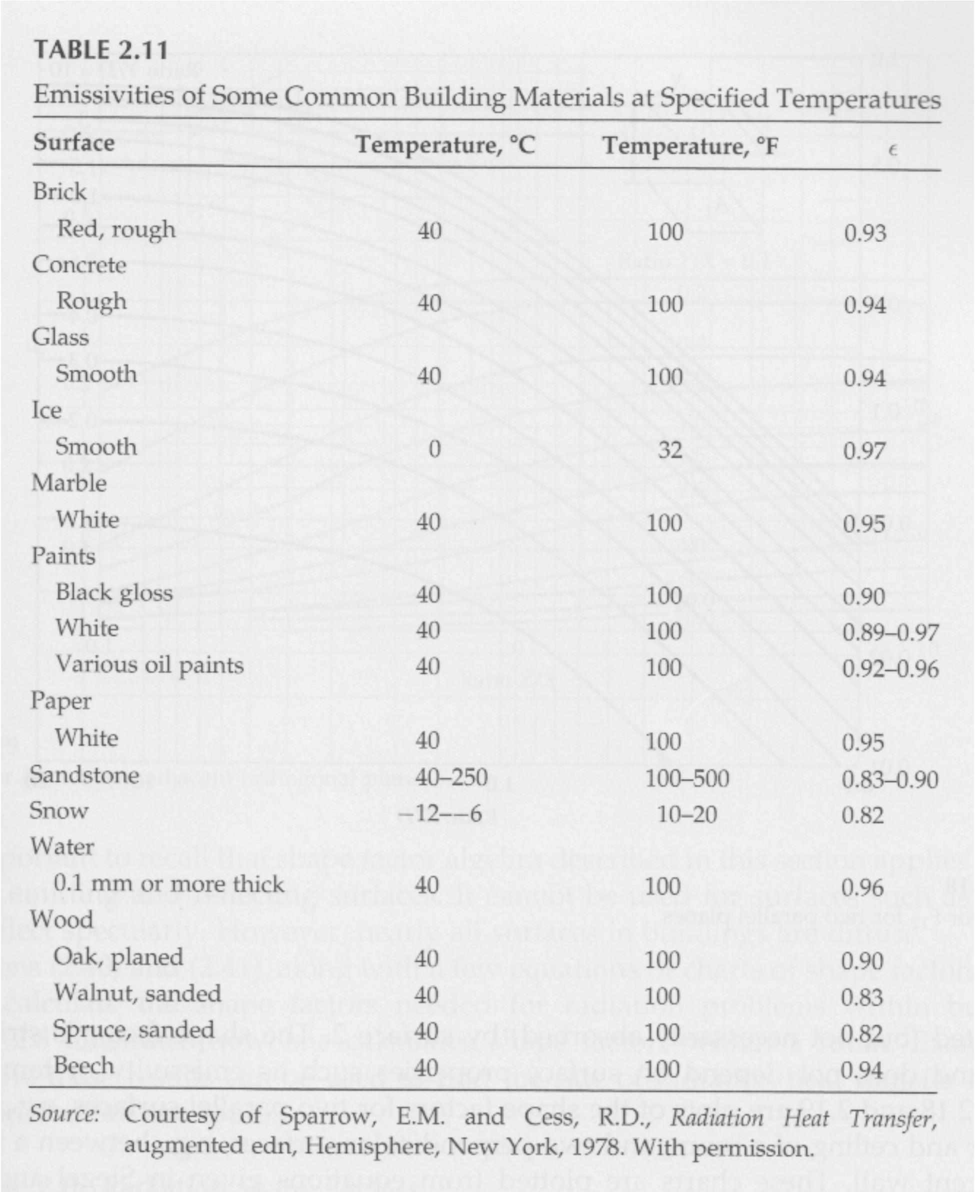


TABLE 2.11

Emissivities of Some Common Building Materials at Specified Temperatures

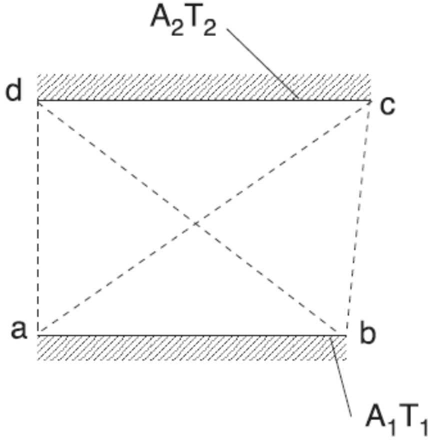
Surface	Temperature, °C	Temperature, °F	ϵ
Brick			
Red, rough	40	100	0.93
Concrete			
Rough	40	100	0.94
Glass			
Smooth	40	100	0.94
Ice			
Smooth	0	32	0.97
Marble			
White	40	100	0.95
Paints			
Black gloss	40	100	0.90
White	40	100	0.89–0.97
Various oil paints	40	100	0.92–0.96
Paper			
White	40	100	0.95
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:



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

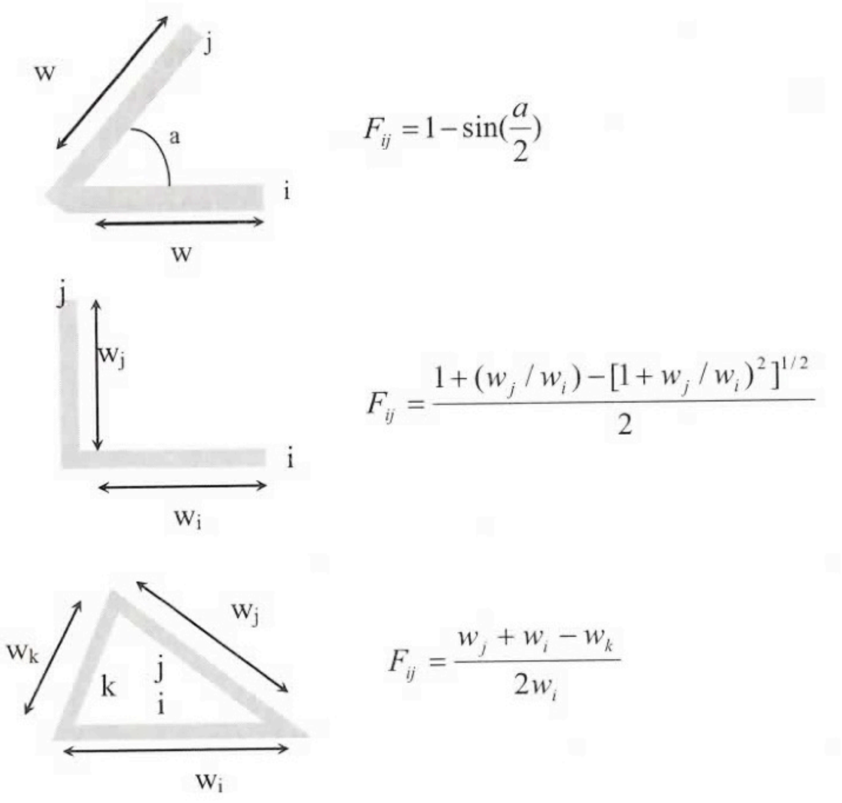
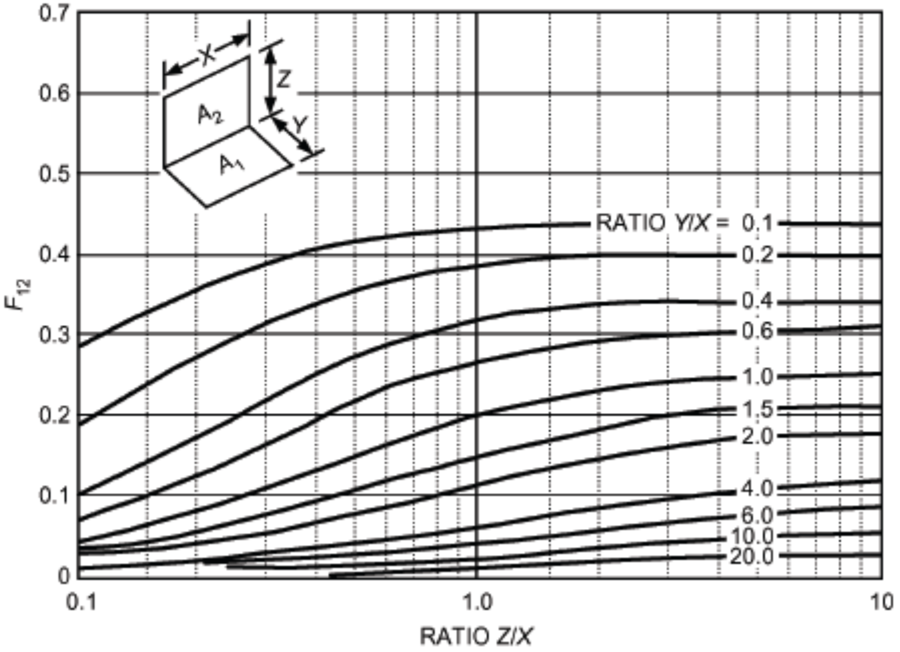


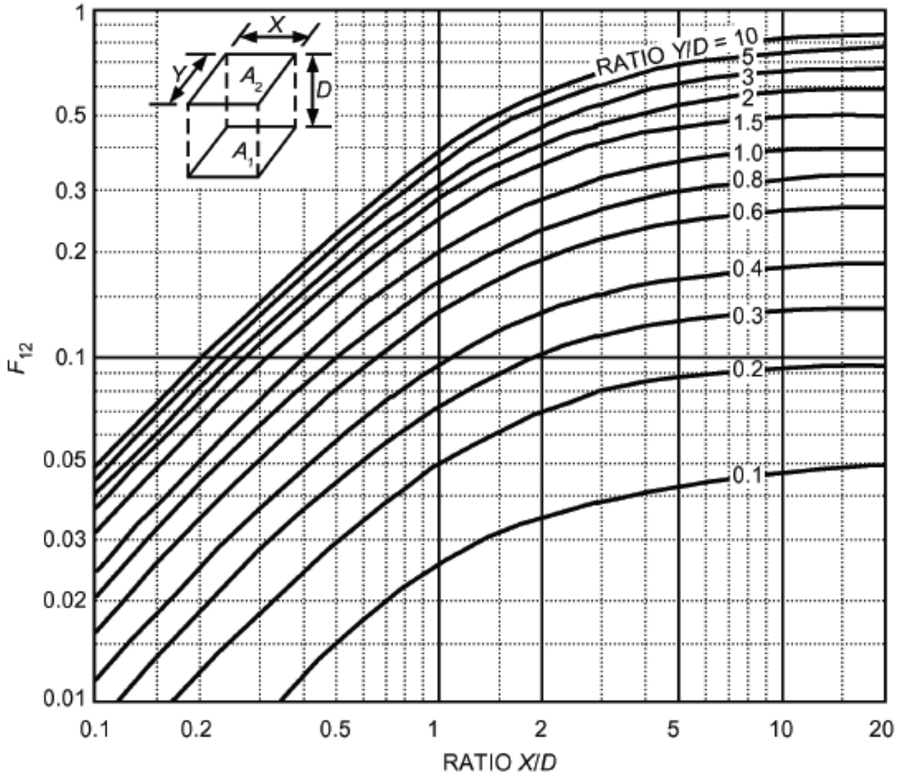
Figure 5.6: View factors for common situations in building enclosures [Hagentoft 2000]

Typical view factors

Other common view factors from the ASHRAE Handbook of Fundamentals:



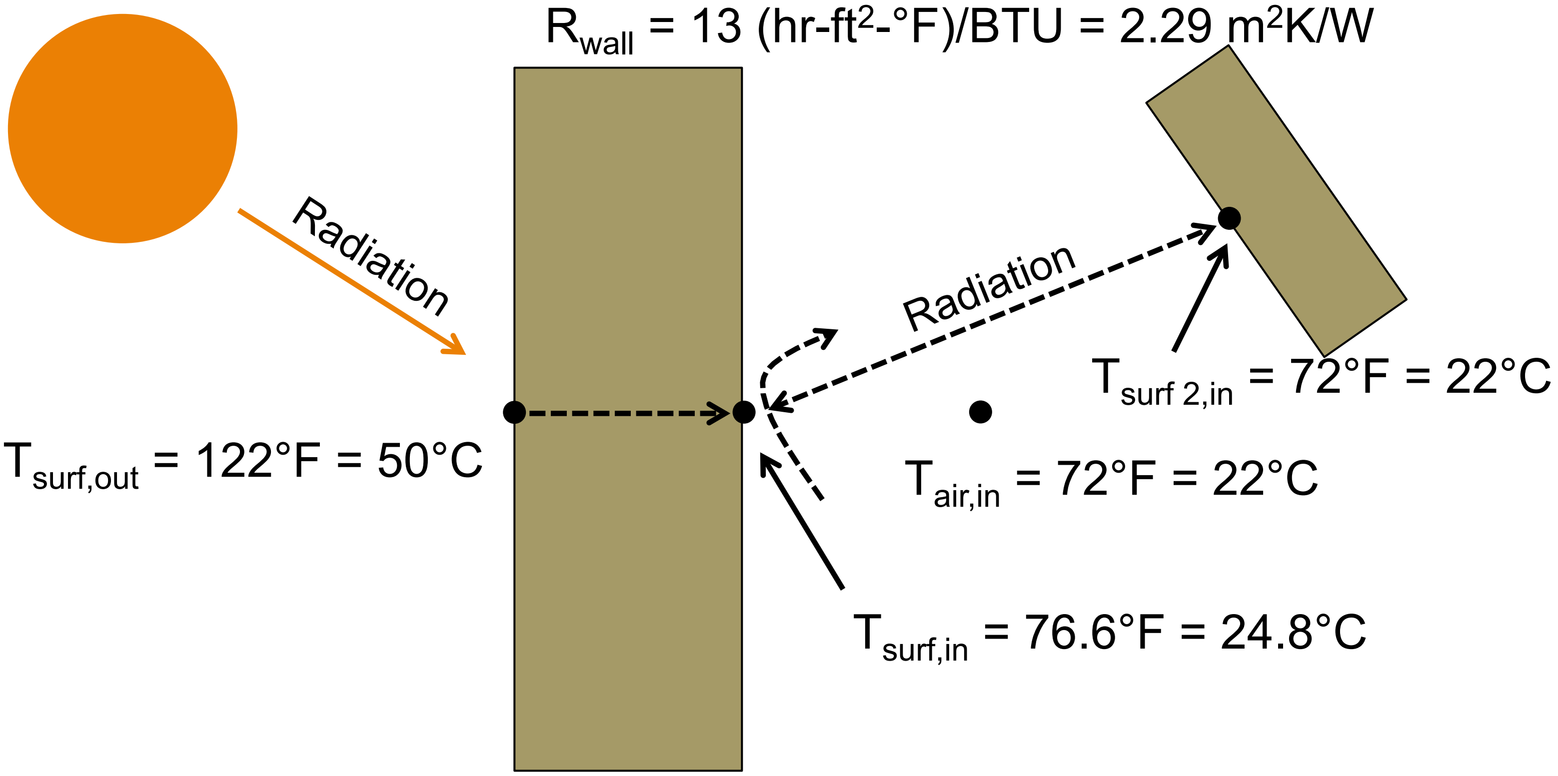
A. PERPENDICULAR RECTANGLES WITH COMMON EDGE



B. ALIGNED PARALLEL RECTANGLES

Long-wave radiation example

- What is the net radiative exchange between the interior wall surface in our last example and a wall at the opposite end of the room if the room is 5 m x 5 m x 3 m?



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$T_{air,in}$ = 72°F = 22°C

$T_{surf,in}$ = 76.6°F = 24.8°C

Simplifying surface radiation

- We can also often simplify radiation from:

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

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

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:

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

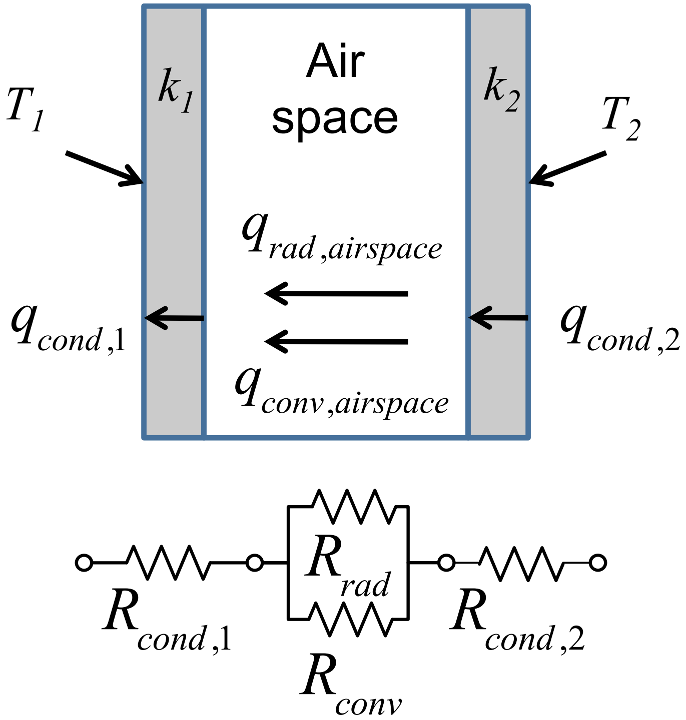
where

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

COMBINED-MODE HEAT TRANSFER

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 building cavity



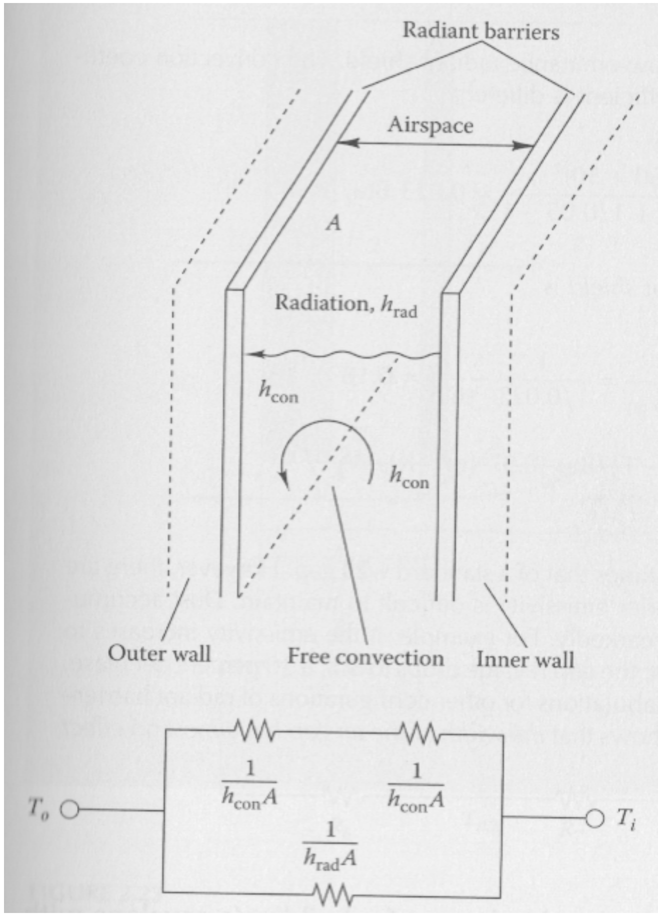
Combined modes of heat transfer

- Example problem: Radiant barrier in a residential wall

A building designer wishes to evaluate the R-value of a 1-inch wide ventilated 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



Next class

- Solar radiation
- Heat transfer through windows