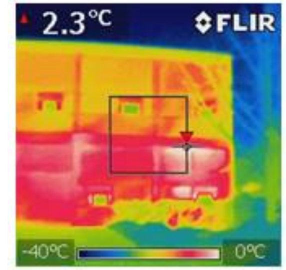
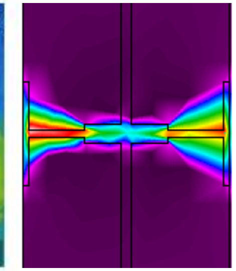
CAE 331/513
Building Science
Fall 2014





Week 3: September 9, 2014
Heat transfer in buildings (cont.)

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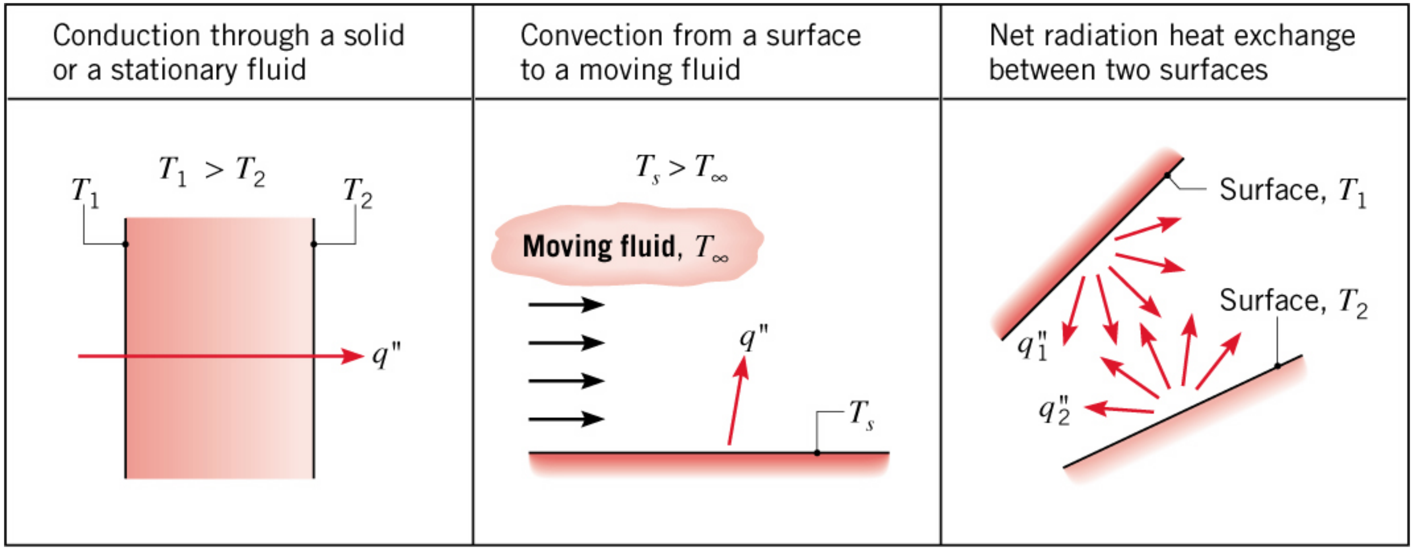
Today's objectives

- Finish up from last lecture on basics of heat transfer in buildings
  - Finish convection
- Introduce radiation

Heat transfer in building science



Conduction **Convection** **Radiation**

$$q = \frac{k}{L}\left(T_{surf,1} - T_{surf,2}\right)$$

$$\frac{k}{L} = U = \frac{1}{R} \qquad R_{total} = \frac{1}{U_{total}}$$

$$R_{total} = R_1 + R_2 + R_3 + \ldots$$

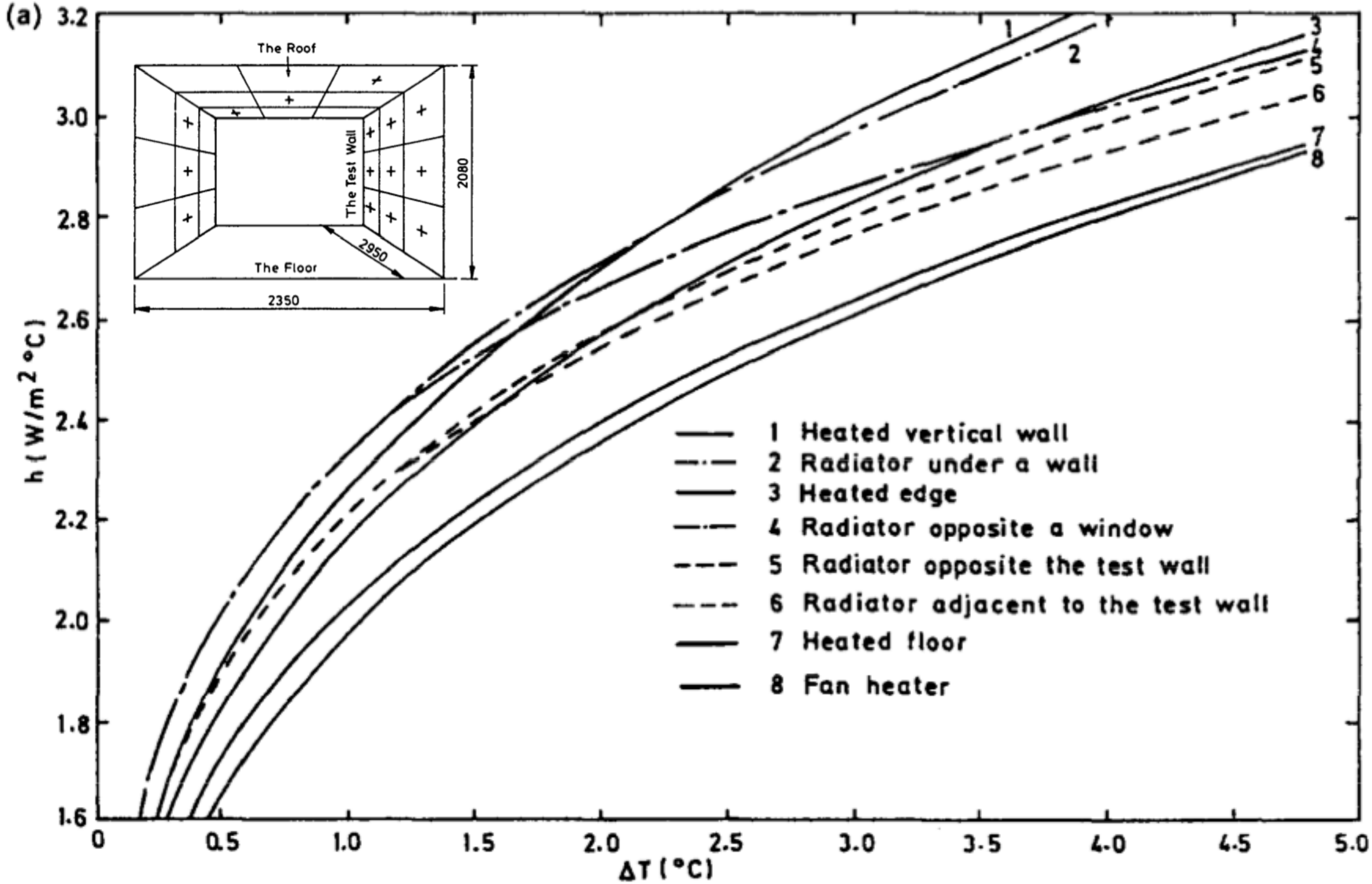
$$U_{total} = \frac{A_1}{A_{total}} U_1 + \frac{A_2}{A_{total}} U_2 + \ldots$$

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

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

Today…

Example: h_{conv} vs. ΔT for interior walls



Khalifa and Marshall (1990) *Int J Heat Mass Transfer*

Example: Forced convection in a duct

- Air is flowing in a 2’ x 2’ square duct at 1600 CFM
- What is the convective heat transfer coefficient between the surface of the duct walls and the air moving through the duct?

Convective "R-value"

- Convective heat transfer can also be translated to an 'effective conductive layer' in contact with air
  - Allows us to assign an R-value to it

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

Convection example

- What were the **convective resistances** from the previous example of the classroom wall?
- How does the convective thermal resistance compare to that of insulation in building walls and roofs?

Typical convective surface resistances

- We often use the values given below for most conditions

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

Bulk convective heat transfer: Advection

- 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)]

Convection and 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 **convection** and **conduction**
  - One fluid is typically heated, one is typically cooled
    - Fluids may be gases, liquids, or vapors

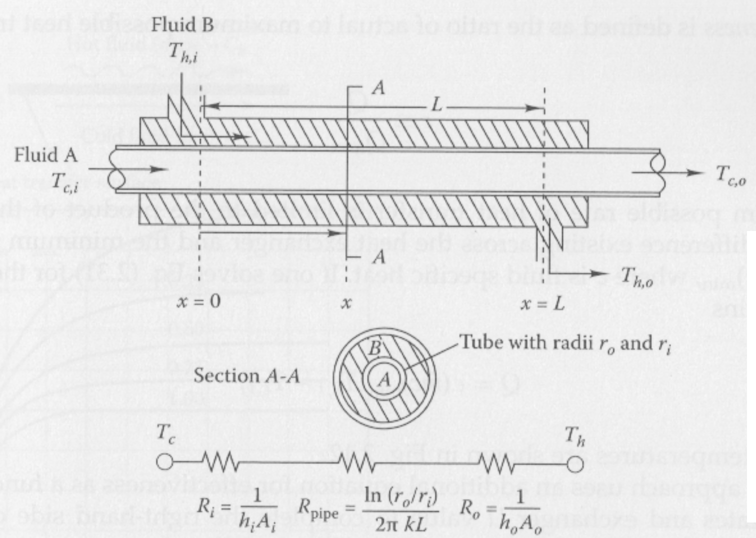
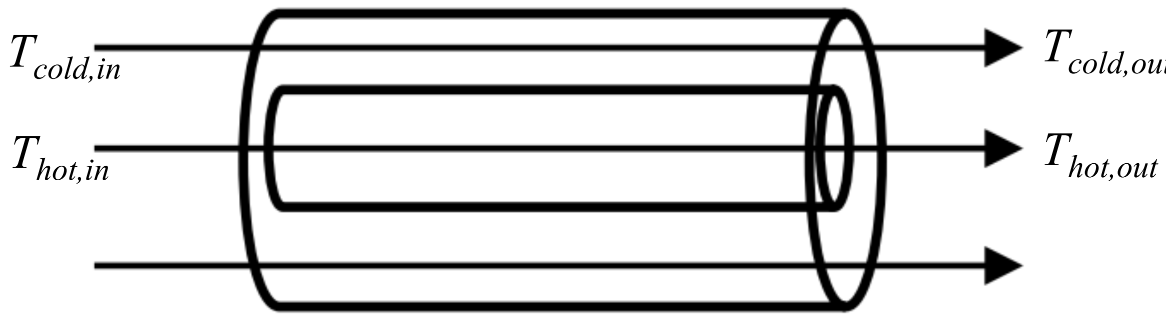


FIGURE 2.12
Schematic diagram of parallel-flow shell-and-tube heat exchanger showing fluid temperatures and equivalent thermal circuit.

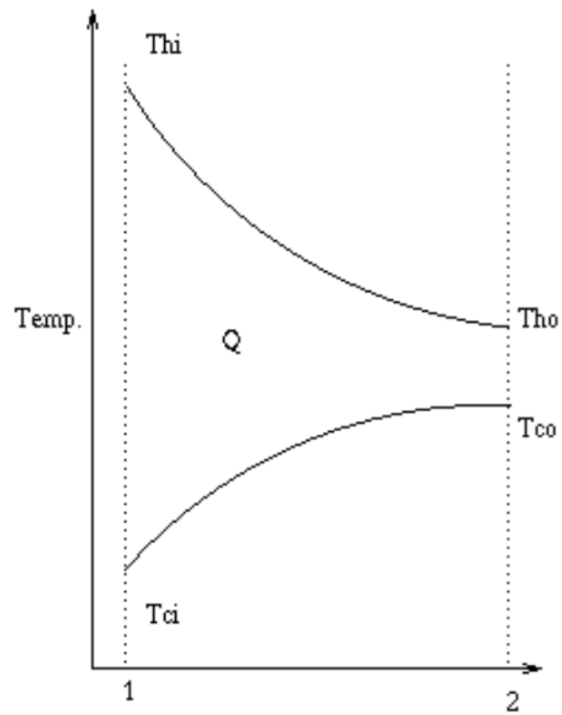
$$U_o A_o = \frac{1}{\frac{1}{h_{conv,i} A_{pipe}} + \frac{R_{pipe}}{A_{pipe}} + \frac{1}{h_{conv,o} A_{pipe}}}$$

Heat exchangers

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

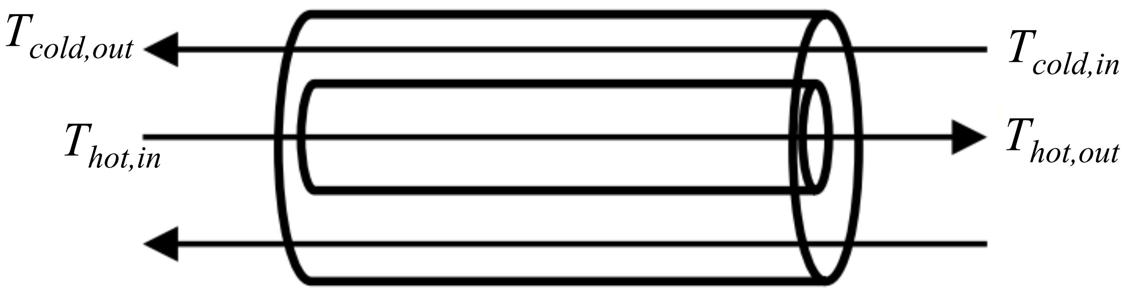


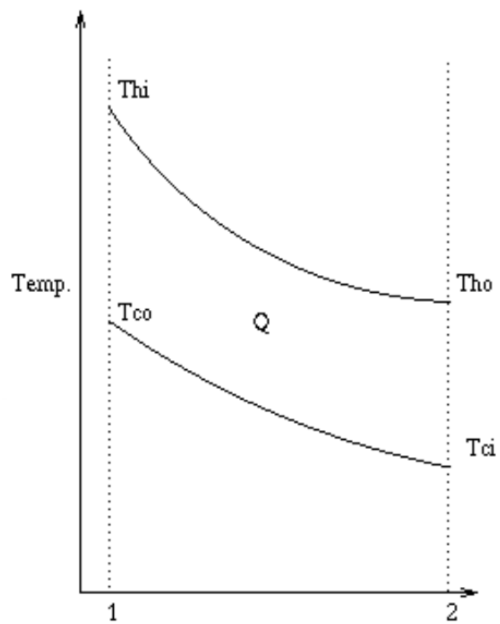
What happens to the two temperature profiles?



Heat exchangers

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





Heat exchangers

- Method for predicting heat transfer rate in heat exchangers:
  - ϵ**-NTU method**: Effectiveness number-of-transfer-units approach

Heat exchangers: $\in$-NTU method

- Define **effectiveness**: ratio of actual to maximum possible heat transfer rates

$$\in = \frac{Q}{Q_{\max}}$$

- This maximum rate of heat transfer is limited to the product of the maximum temperature difference across the heat exchanger and the **minimum fluid capacitance rate**:

$$Q = \in (\dot{m}C_p)_{\min}\left(T_{hot,in} - T_{cold,in}\right)$$

- The idea is that heat transfer will almost never be its maximum because the hot and cold T's are constantly changing (and changing the driving force)

Heat exchangers: ∈-NTU method

- The effectiveness of different types of heat exchangers can be described with various equations, all using the term number of transfer units, or "NTU"

$$NTU = \frac{U_o A_o}{(\dot{m}C_p)_{\min}}$$

Where the denominator is the smaller of the two fluid capacitance rates: $\dot{C}_{\min} = (\dot{m}C_p)_{\min}$

TABLE 2.10

Heat Exchanger Effectiveness Relations $N = \mathrm{NTU} = \frac{U_o A_o}{\dot{C}_{\min}}$ $C = \frac{\dot{C}_{\min}}{\dot{C}_{\max}}$

Flow Geometry	Relation
Double pipe	
Parallel flow	$\varepsilon = \frac{1 - \exp[-N(1+C)]}{1+C}$
Counterflow	$\varepsilon = \frac{1 - \exp[-N(1-C)]}{1 - C\exp[-N(1-C)]}$
Crossflow	
Both fluids unmixed	$\varepsilon = 1 - \exp\left\{\frac{1}{Cn}[\exp(-NCn) - 1]\right\}$ where $n = N^{-0.22}$
Both fluids unmixed	$\varepsilon = N\left[\frac{N}{1-\exp(-N)} + \frac{NC}{1-\exp(-NC)} - 1\right]^{-1}$
$\dot{C}_{\max}$ mixed, $\dot{C}_{\min}$ unmixed	$\varepsilon = \frac{1}{C}\{1 - \exp[-C + C\ \exp(-N)]\}$
$\dot{C}_{\max}$ unmixed, $\dot{C}_{\min}$ mixed	$\varepsilon = 1 - \exp\left\{-\frac{1}{C}[1 - \exp(-NC)]\right\}$
Shell and tube	
One shell pass; two, four, six tube passes	$\varepsilon = 2\left[1 + C + \sqrt{1+C^2}\,\frac{1+\exp(-N\sqrt{1+C^2})}{1-\exp(-N\sqrt{1+C^2})}\right]^{-1}$

Heat exchangers: ∊-NTU method

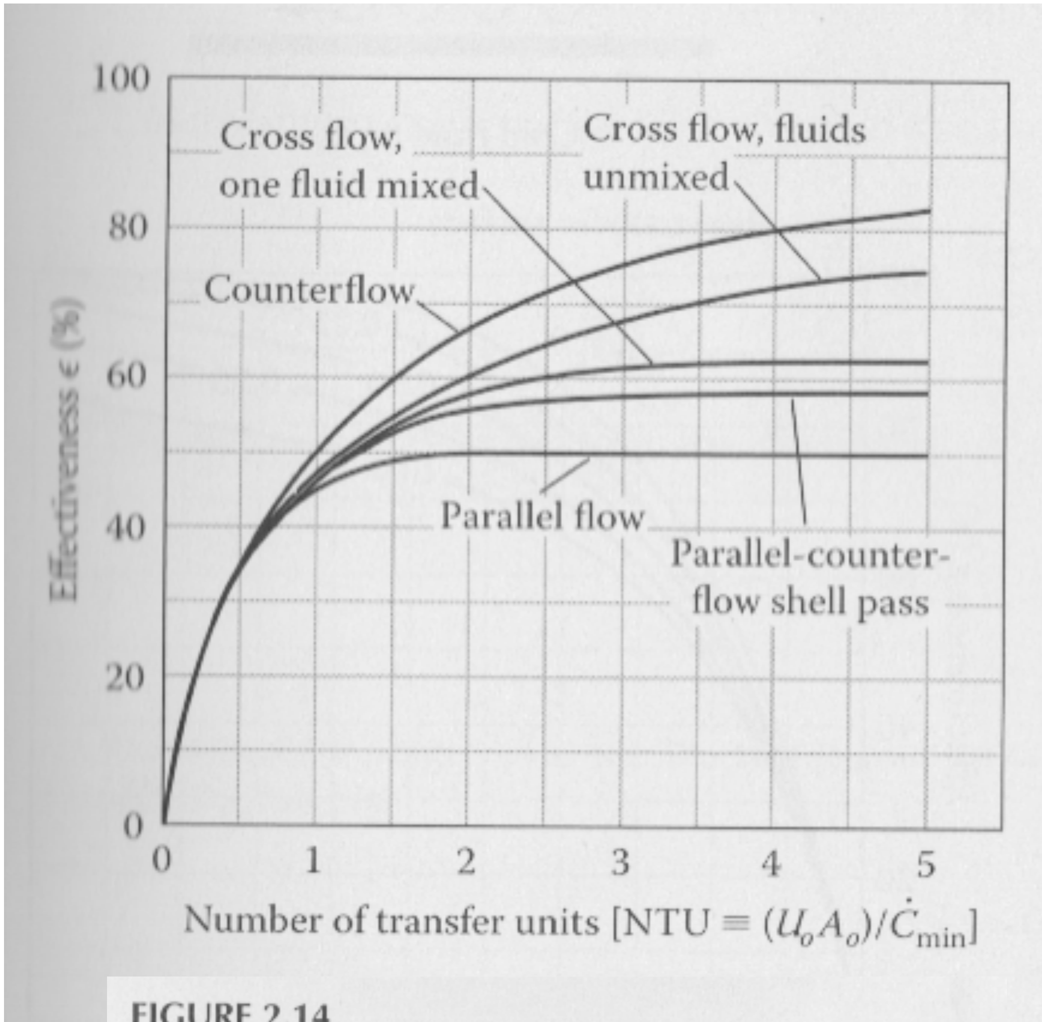
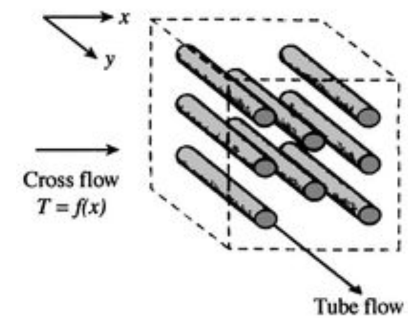
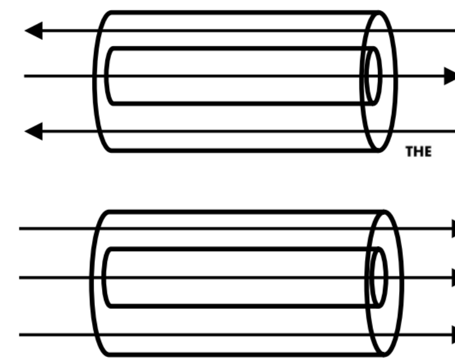


FIGURE 2.14
Comparison of effectiveness of several heat exchanger designs for equal hot- and cold-side capacitance rates, $\dot{C}_{min} = \dot{C}_{max}$.

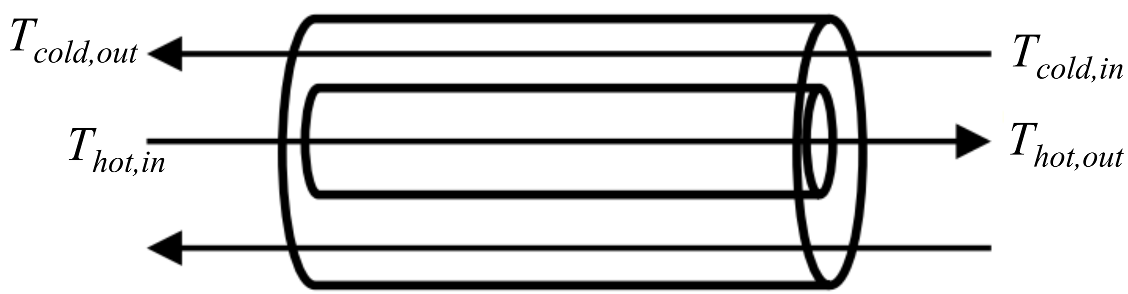


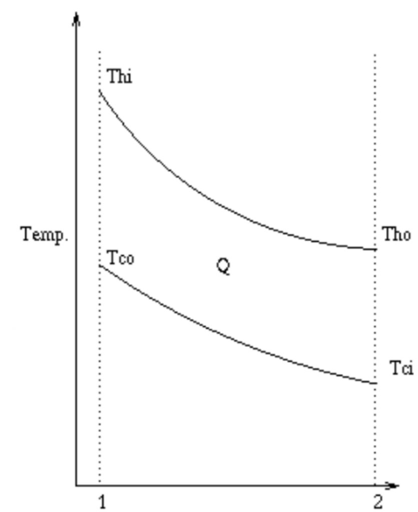


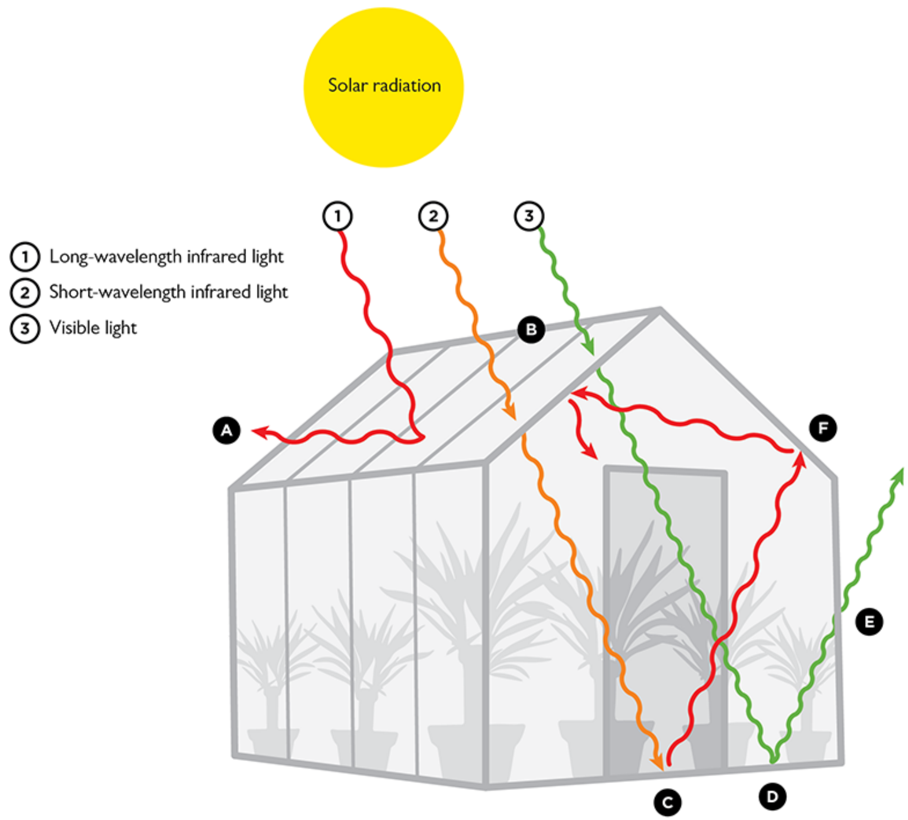
This subject is covered in detail in CAE 464 HVAC Design

Heat exchanger example

- **Example:** Potable service water is heated in a building from 20°C at a rate of 70 kg/min by using nonpotable pressurized water from a boiler at 110°C in a single-pass counterflow heat exchanger
- Find the heat transfer rate if the hot water flow is 90 kg/min
- Also find exit temperatures of both streams
  - Note: The overall U value is 320 W/(m²K) and the transfer area is 20 m²



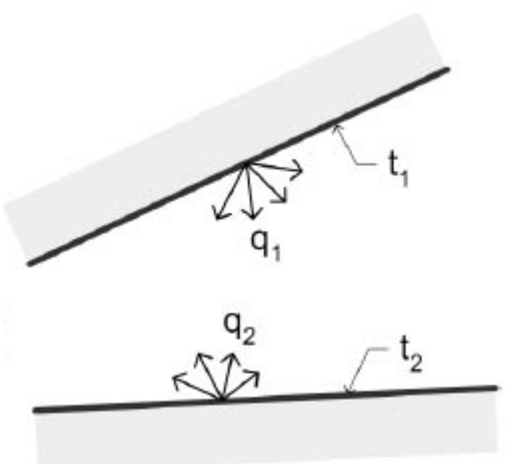


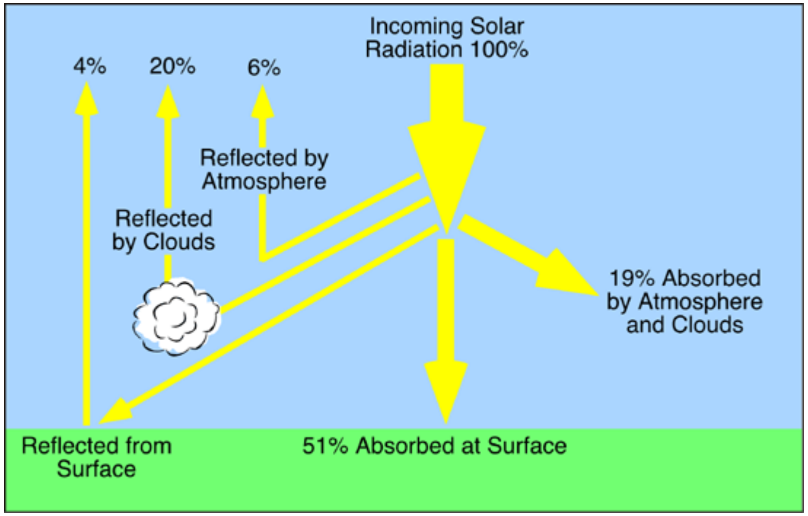

Solar radiation
1 Long-wavelength infrared light
2 Short-wavelength infrared light
3 Visible light
1
2
3
A
B
C
D
E
F

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





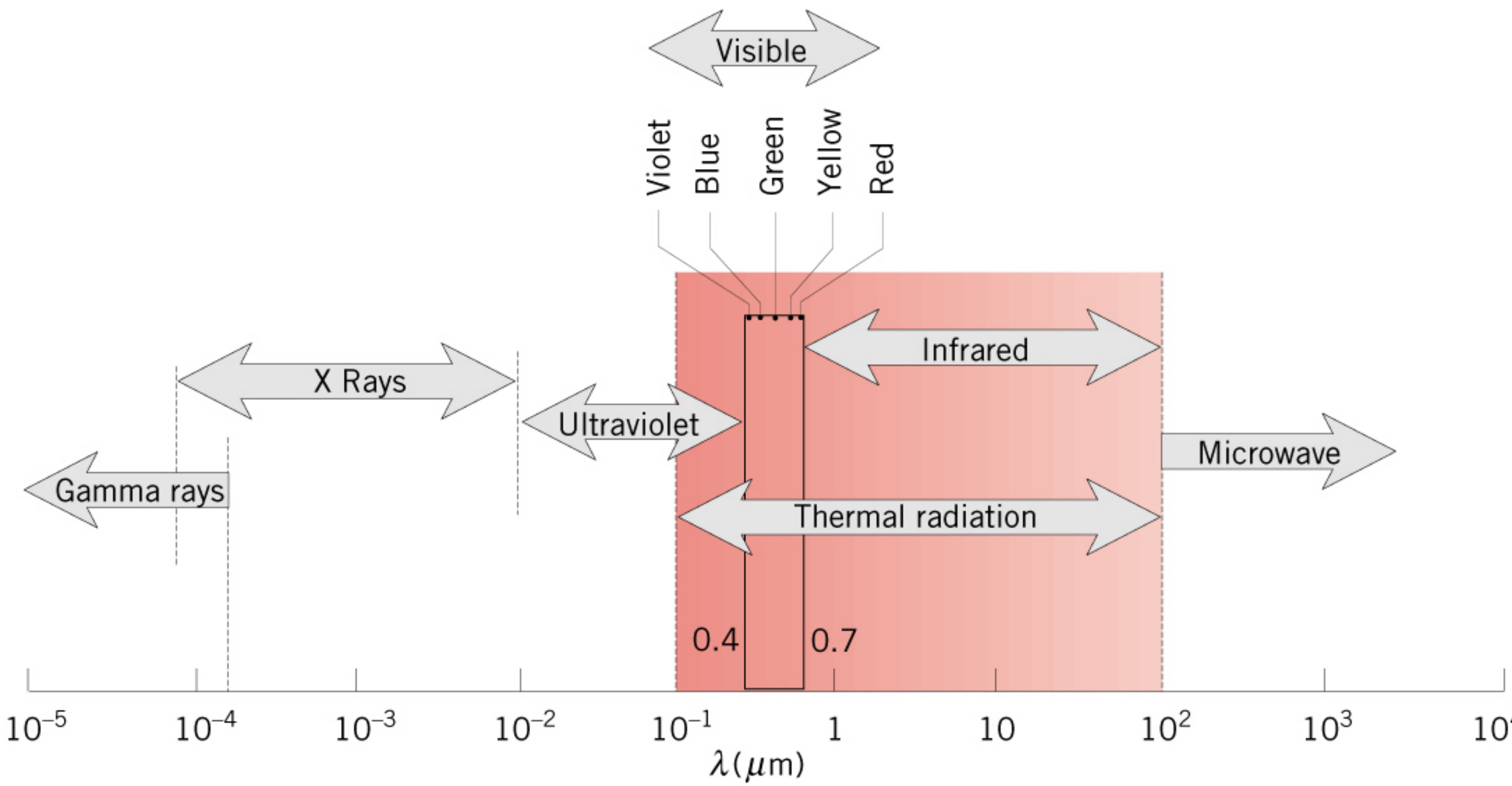
Radiation

- 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 (diffuse, refracted, or re-emitted radiation)

Radiation: the electromagnetic spectrum

- Thermal radiation is confined to the infrared, visble, and ultraviolet regions (0.1 < λ < 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

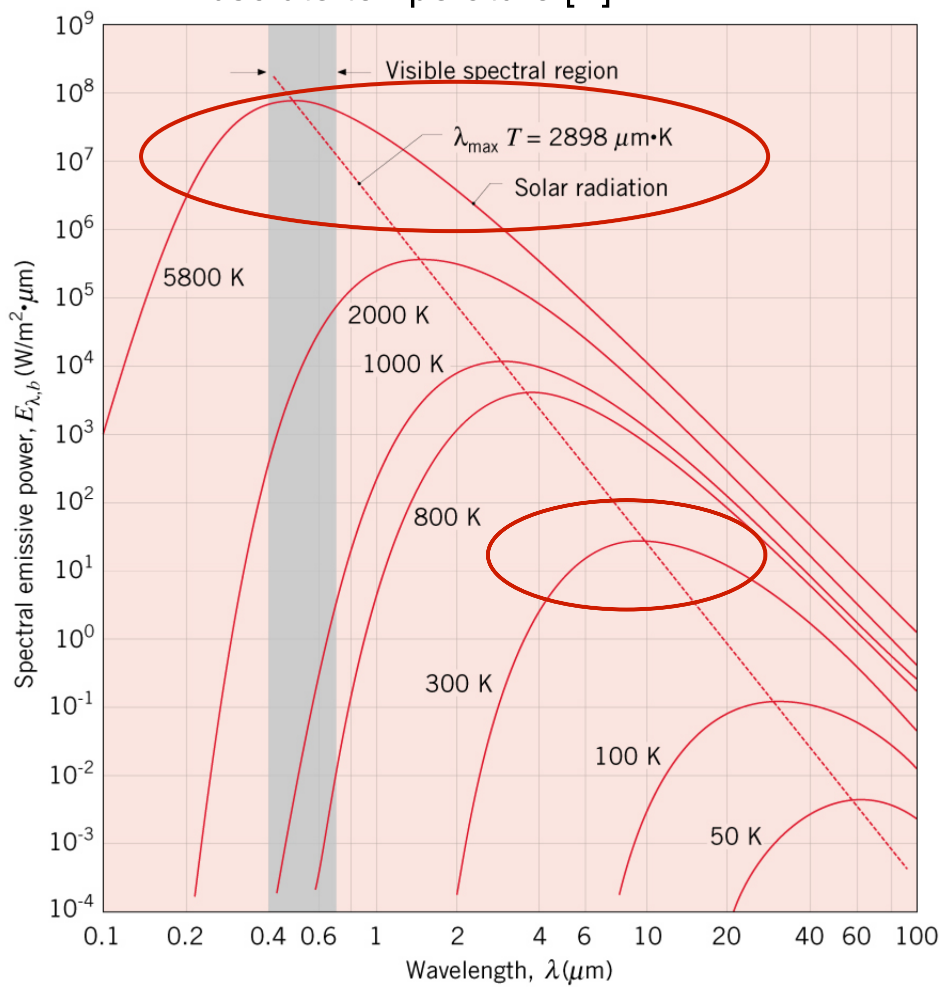
- Peak radiation from the sun is in the visible region
  - About 0.4 to 0.7 μm

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

$q = \sigma T^4$

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

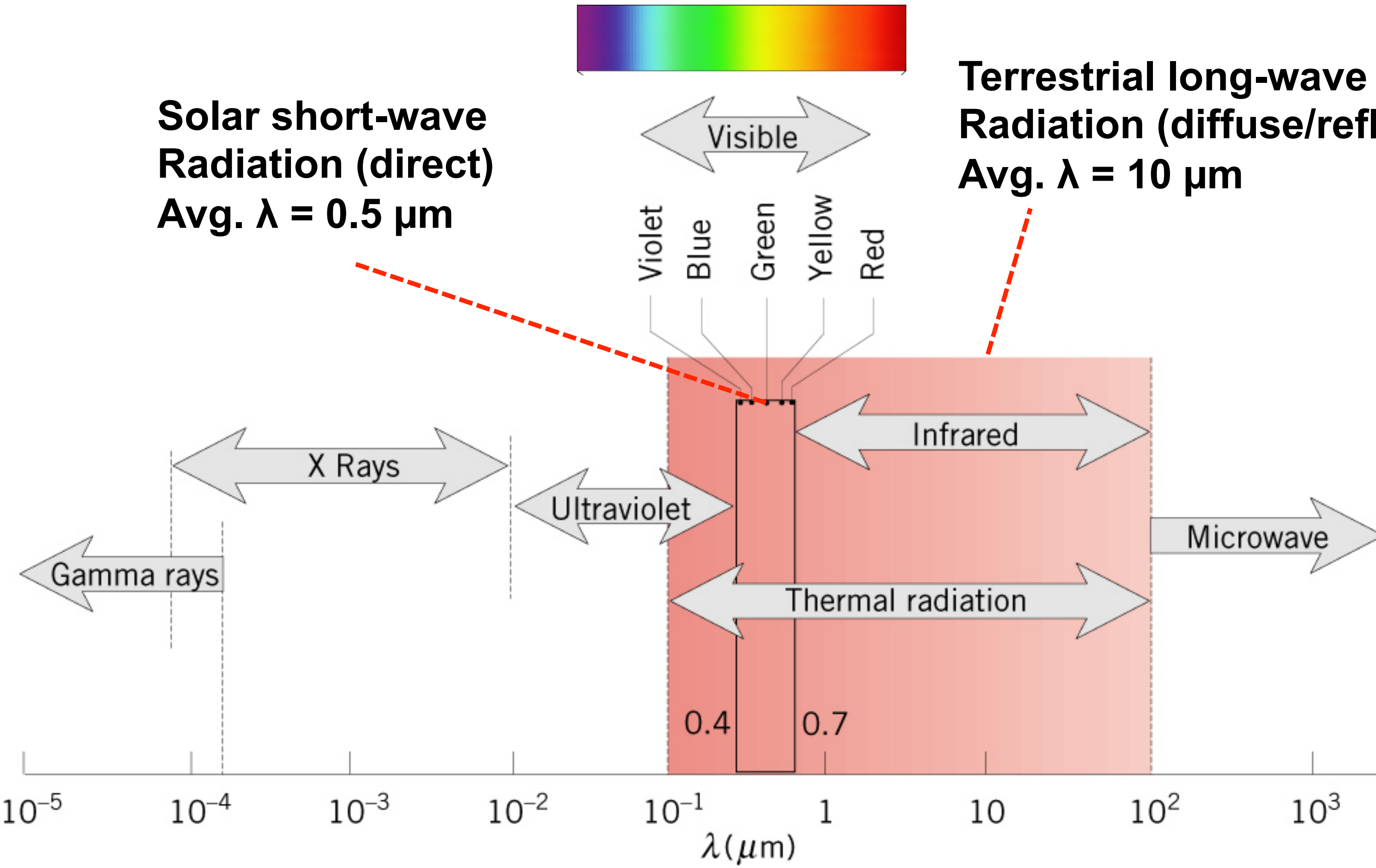
T = Absolute temperature [K]



Radiation: Short-wave and Long-wave

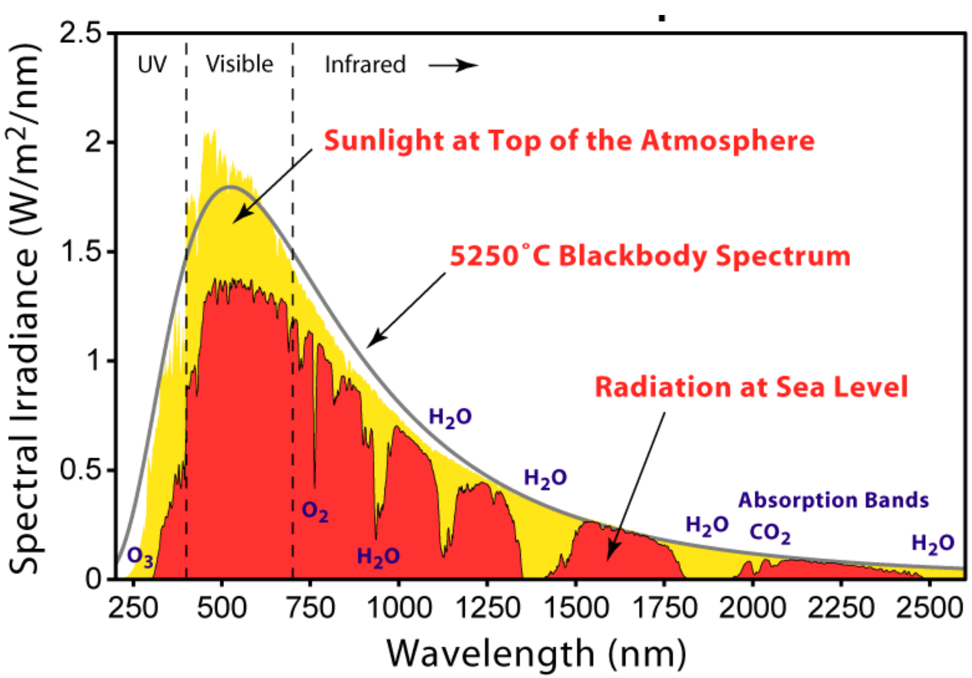
Solar short-wave Radiation (direct)
Avg. λ = 0.5 μm

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:

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

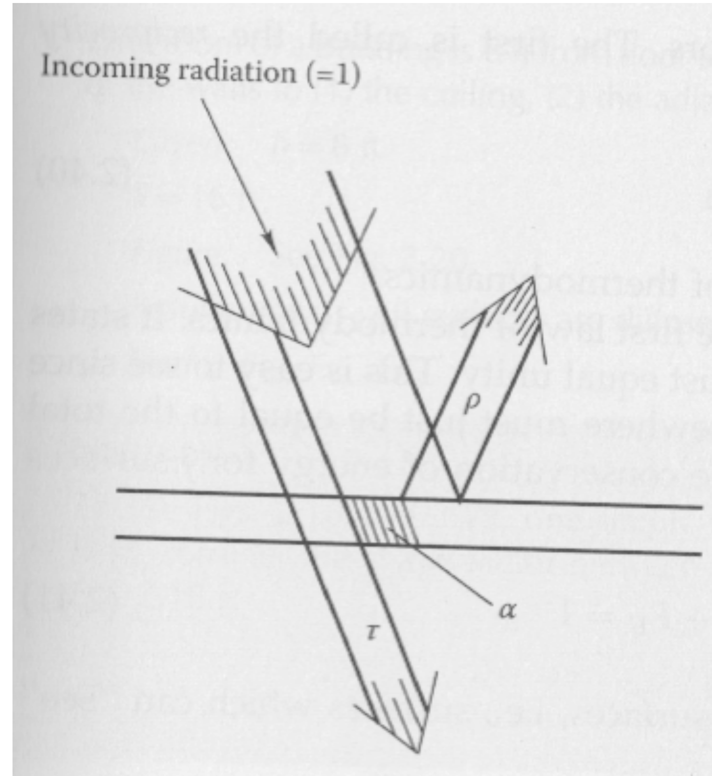
Absorptivity, transmissivity, and reflectivity

- 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 (τ = 0): $q_{solar} = \alpha I_{solar}$
  - For a transparent surface (τ > 0): $q_{solar} = \tau I_{solar}$



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

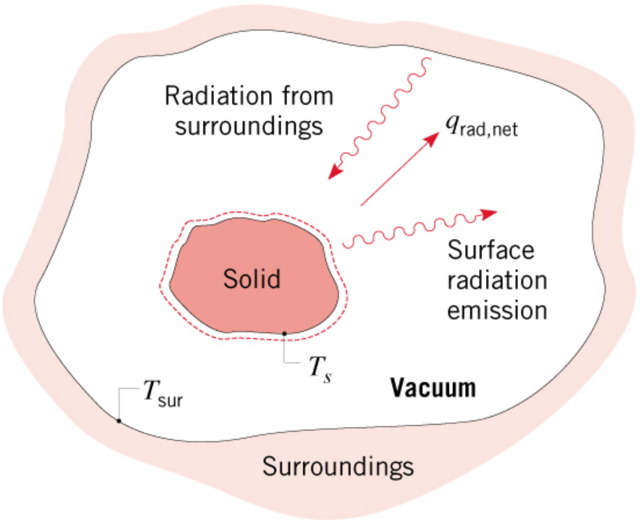
Absorptivity (α) for solar (short-wave) radiation

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

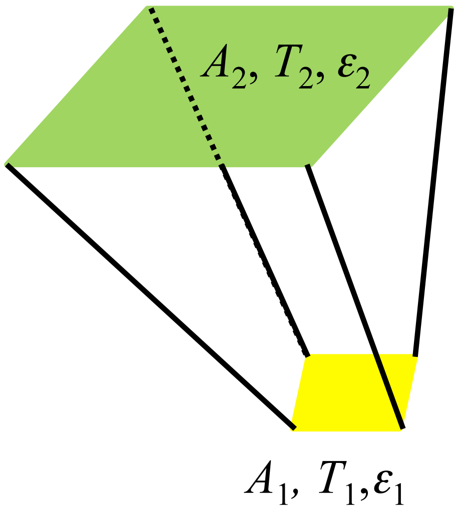
T = Absolute temperature [K]

- 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…), ε = 0.9 at most wavelengths

Emissivity (ε) of common materials

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

Emissivity (ε) of common building materials

TABLE 2.11

Emissivities of Some Common Building Materials at Specified Temperatures

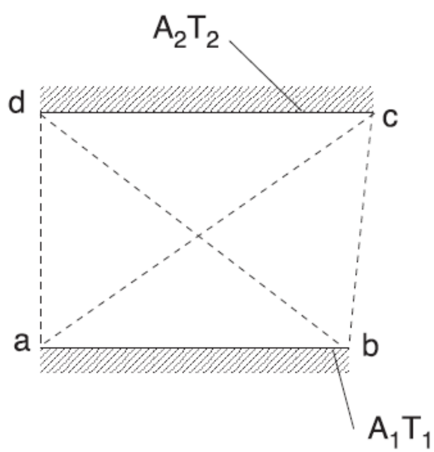
Surface	Temperature, °C	Temperature, °F	ϵ
Brick			
Red, rough	40	100	0.93
Concrete			
Rough	40	100	0.94
Glass			
Smooth	40	100	0.94
Ice			
Smooth	0	32	0.97
Marble			
White	40	100	0.95
Paints			
Black gloss	40	100	0.90
White	40	100	0.89–0.97
Various oil paints	40	100	0.92–0.96
Paper			
White	40	100	0.95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



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

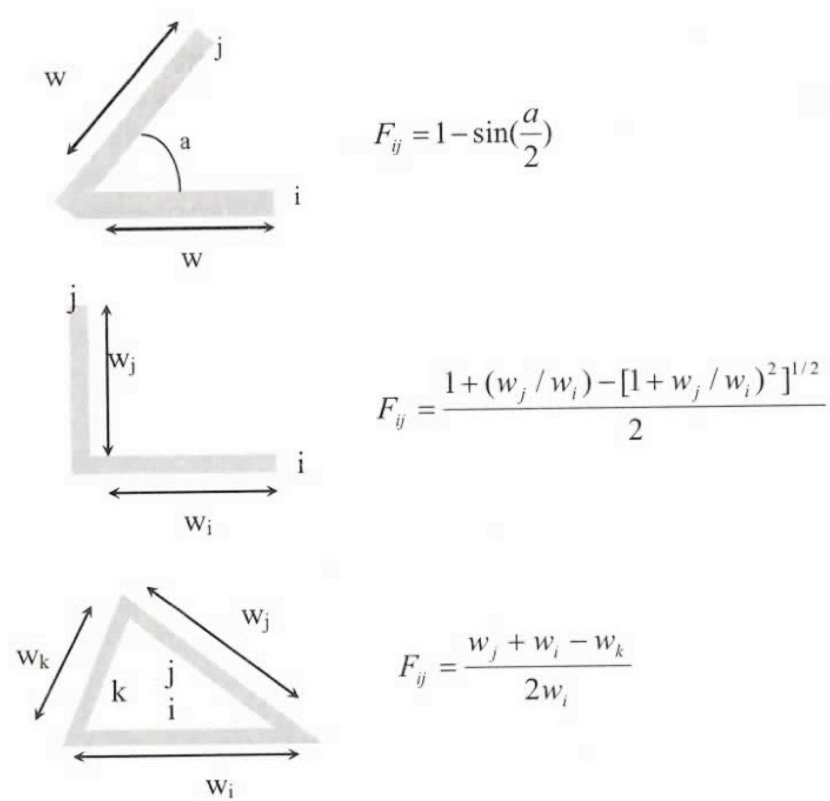
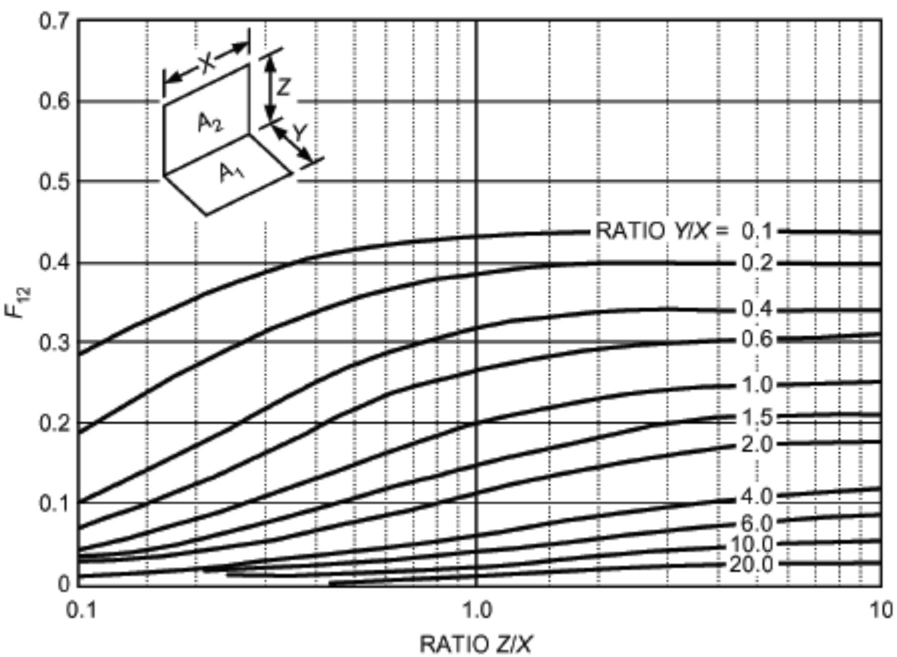


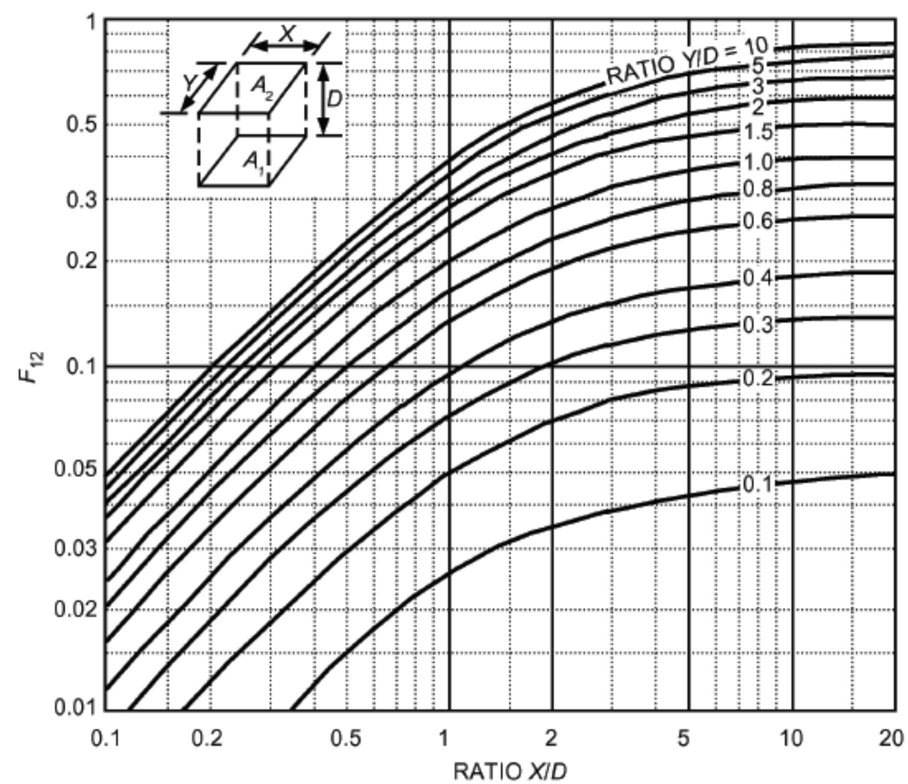
Figure 5.6: View factors for common situations in building enclosures [Hagentoft 2000]

Typical view factors

- Other common view factors from ASHRAE HOF



A. PERPENDICULAR RECTANGLES WITH COMMON EDGE



B. ALIGNED PARALLEL RECTANGLES

Long-wave radiation example

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

Simplifying radiation

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

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

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

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

where

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

Simplifying surface radiation

- We can also often simplify radiation from:

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

- 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

Heat transfer in building science: Summary

Conduction

$$q = \frac{k}{L}\left(T_{surf,1} - T_{surf,2}\right)$$

$$\frac{k}{L} = U = \frac{1}{R}$$

$$R_{total} = \frac{1}{U_{total}}$$

$$R_{total} = R_1 + R_2 + R_3 + \ldots$$

For thermal bridges and combined elements:

$$U_{total} = \frac{A_1}{A_{total}} U_1 + \frac{A_2}{A_{total}} U_2 + \ldots$$

Convection

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

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

Nearly everything you need to know about heat transfer in buildings!

Radiation

Long-wave

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

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

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

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

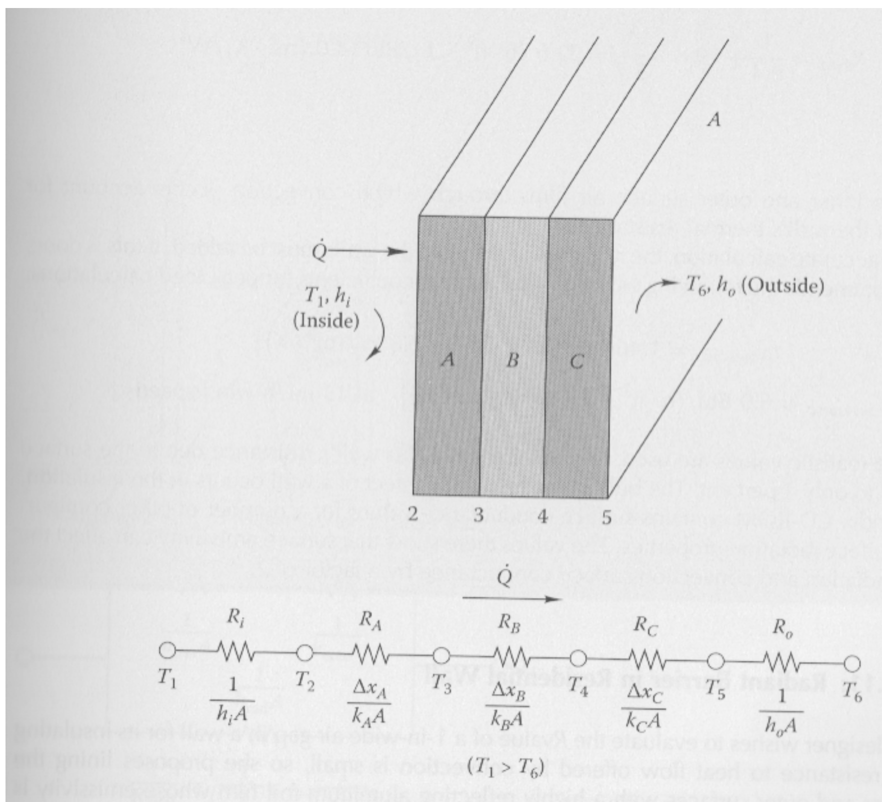
Solar radiation: (opaque surface) $q_{solar} = \alpha I_{solar}$

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

COMBINED-MODE HEAT TRANSFER

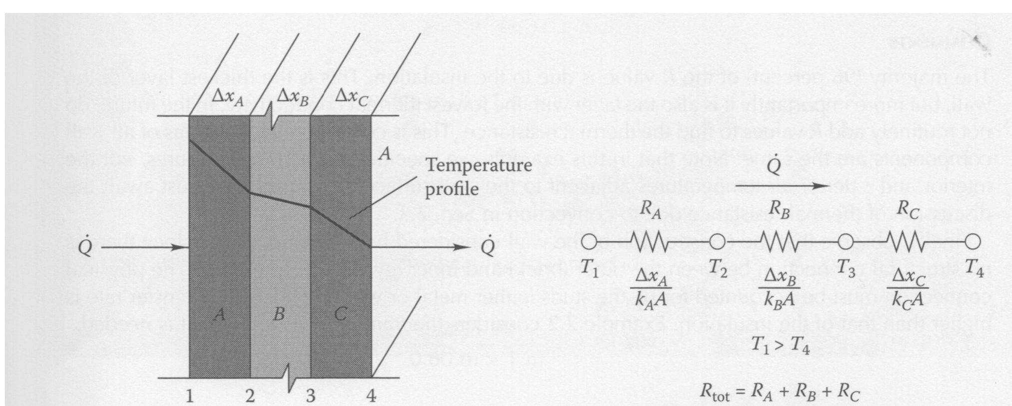
Combined mode heat transfer

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



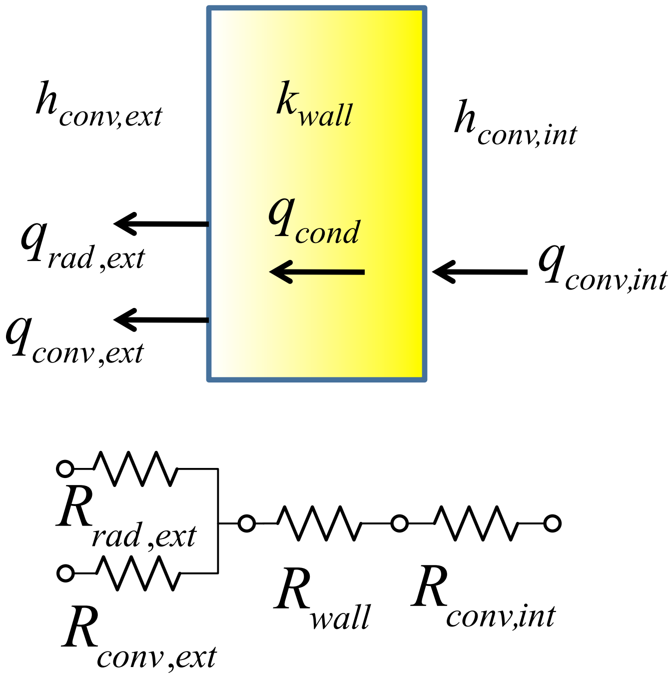
Combined modes of heat transfer

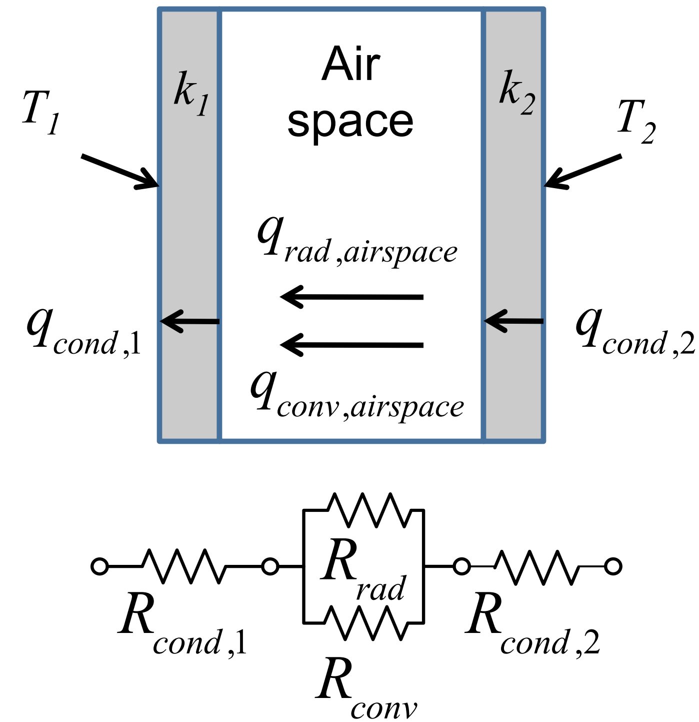
- Example problem: Convection and wall R-values
- Repeat example from last class for a stud wall to include the effect of inner and outer surface convection coefficients
- Assume the same interior surface resistance from our previous classroom problem
  - Assume the outer surface coefficient during winter conditions is appropriate



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 to/from exterior wall or in a cavity



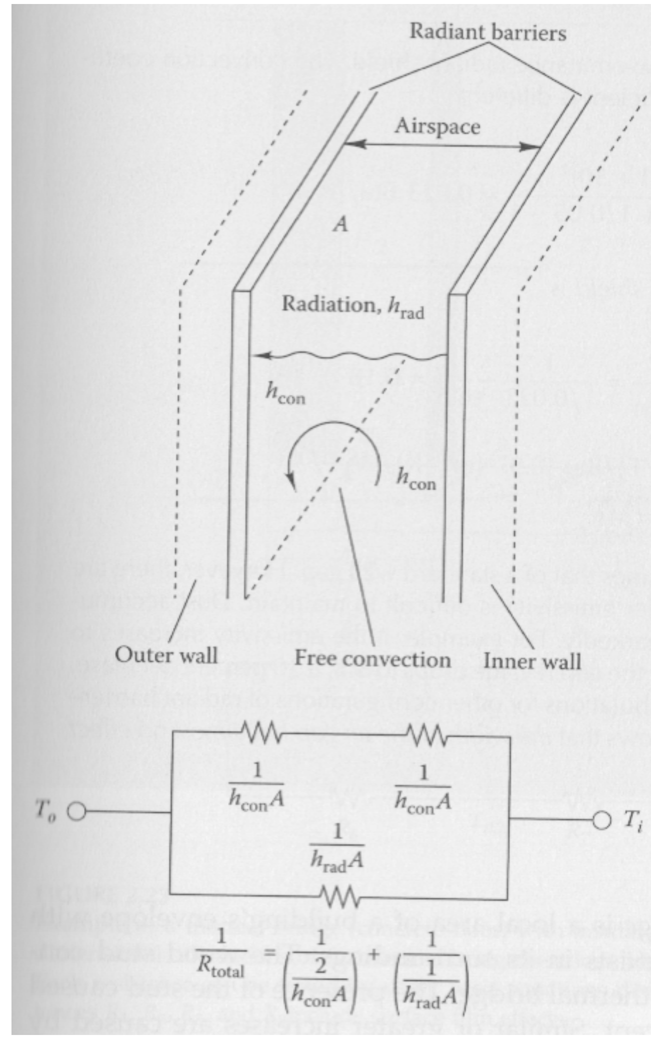


Combined modes of heat transfer

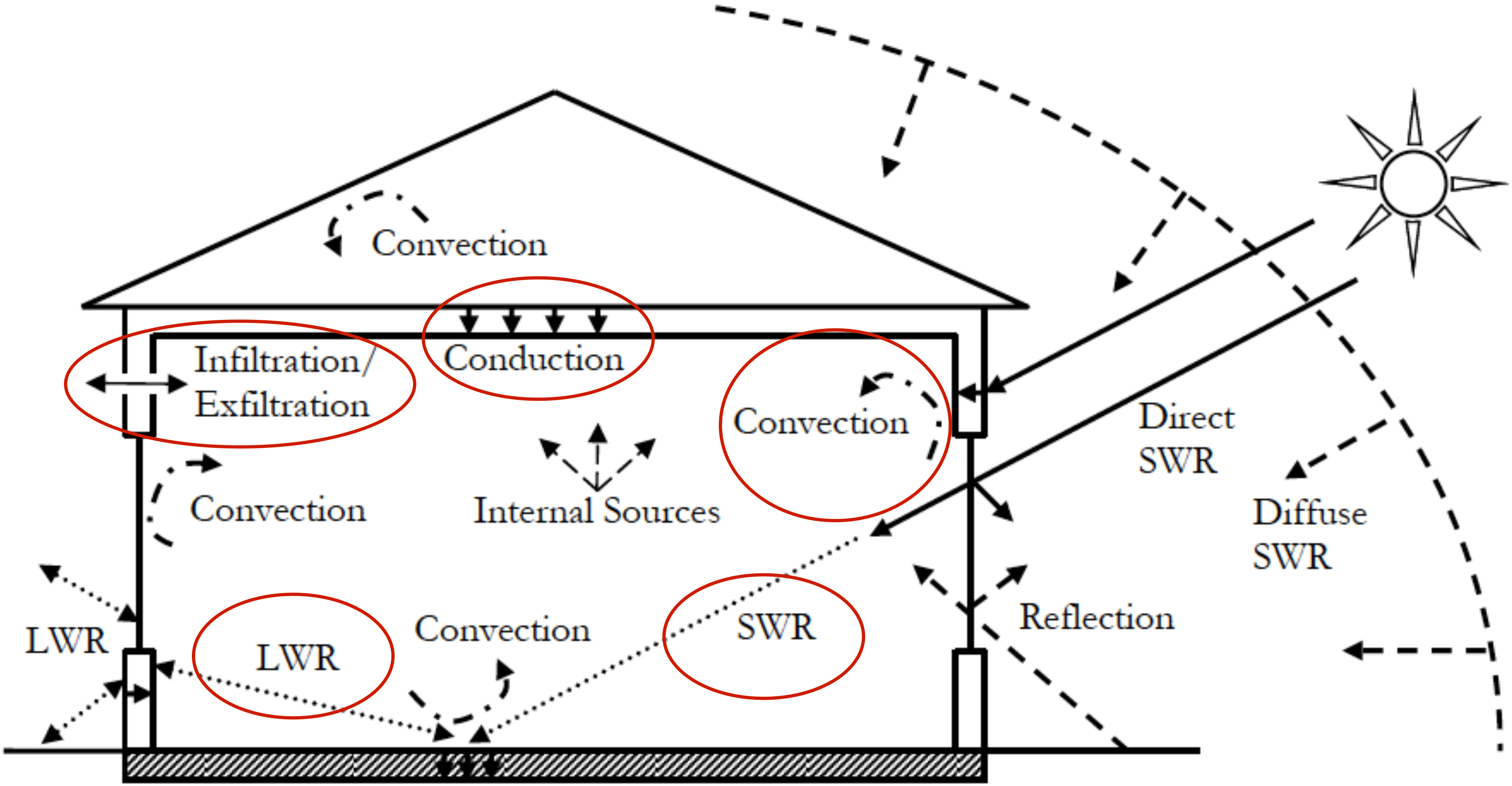
- Example problem: Radiant barrier in a residential wall

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

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



Modes of heat transfer in a building



Where are we going? Building energy balances

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