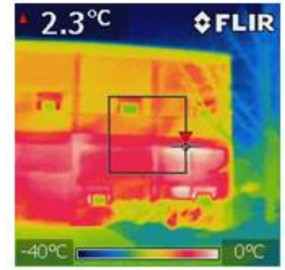
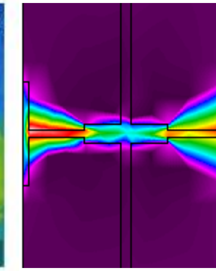
CAE 331/513
Building Science
Fall 2014



Week 2: September 2, 2014
Finish energy concepts
Elements of heat transfer in buildings

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Last time

- Reviewed energy concepts and unit conversions
- Assigned HW 1 (due Thurs)

Objectives for today's lecture

- Finish energy concepts (costs and efficiency)

- Introduce the elements of heat transfer in buildings
  - Generally follows Kreider Chapter 2

- Begin our review of heat transfer fundamentals
  - Conduction
  - Convection
  - Radiation

- In context: heat transfer in buildings
  - Walls, roofs, windows, floors, HVAC, plumbing
  - Description of building systems

APPLYING BUILDING SCIENCE: DESIGN FOR EFFICIENCY

Designing for **energy efficiency**

- We strive for energy efficiency in building science
- Energy and economic analysis early in the design stage can optimize balances between first costs and operating costs
- First costs
  - Equipment size, capacity, and efficiency
  - Building and system design parameters
- Operating costs
  - Built-in equipment
  - Operational characteristics
  - Human beings

Designing for energy efficiency: Payback periods

- Making a design choice is easy when Option A has a lower first cost (purchase + installation) AND costs less to operate than Option B
  - But the decision is usually more complicated

- Suppose model A costs $600 and draws electricity at an average rate of 150 W
- Model B costs $700 and draws only 100 W
- If the cost of electricity is 10 cents per kWh and we assume these two pieces of equipment operation 24/7 (8760 hrs/yr):
  - What are the annual savings due to Model B?
  - Is it worth the additional cost for Model B?

Designing for energy efficiency: Payback periods

- Payback period = ($ investment) / ($ annual savings)

General rules of thumb:

- If a payback period is less than 1/3 of the estimated lifetime of the investment, it is a ***very profitable*** investment

- If a payback period is less than ½ of the estimated lifetime of the investment, it is considered a ***profitable*** investment

Alternate measure: Rate of return = inverse of payback period

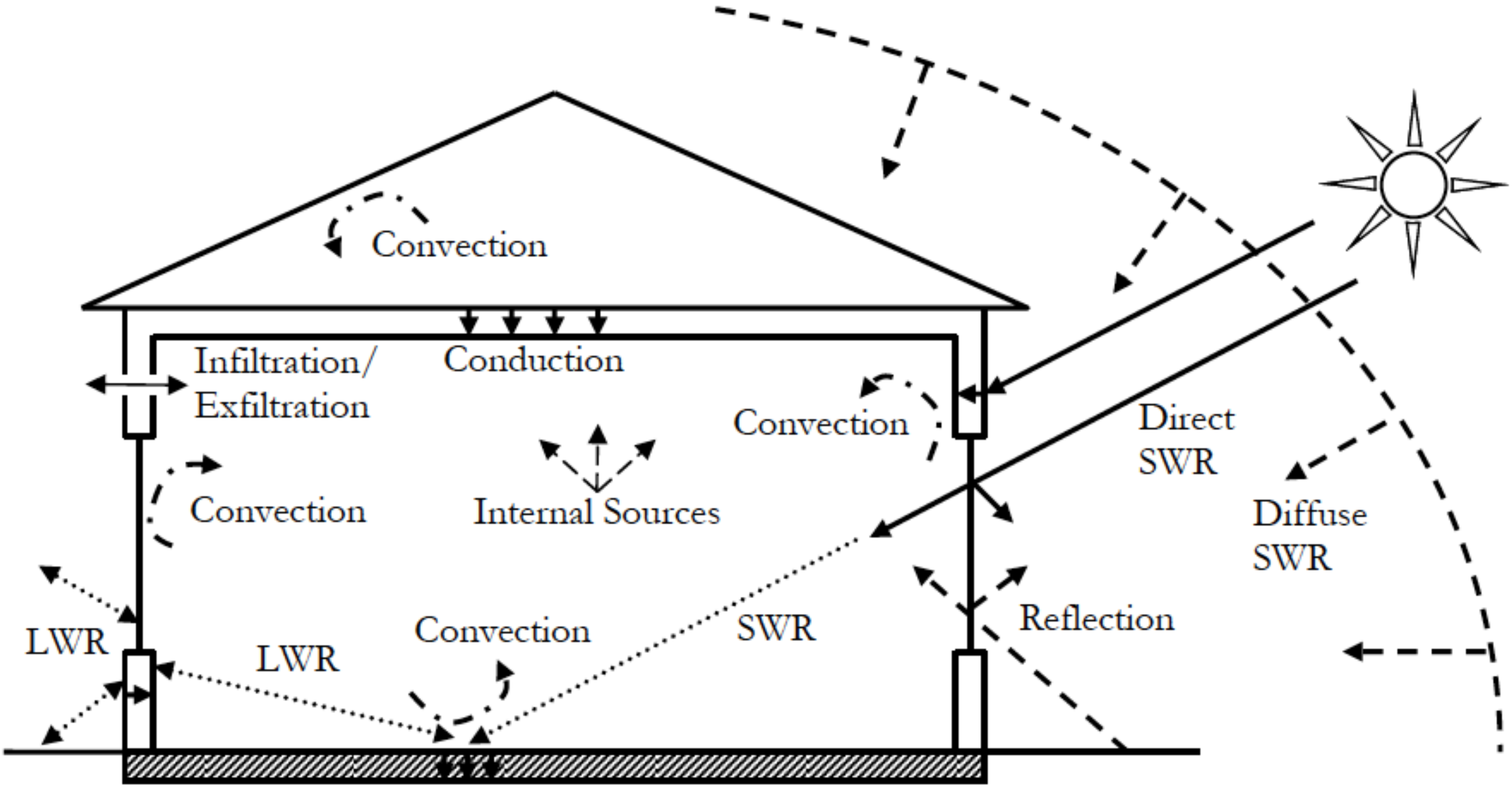
What is the rate of return on your checking/savings account?

BUILDING SCIENCE FUNDAMENTALS: HEAT TRANSFER IN BUILDINGS

Heat transfer

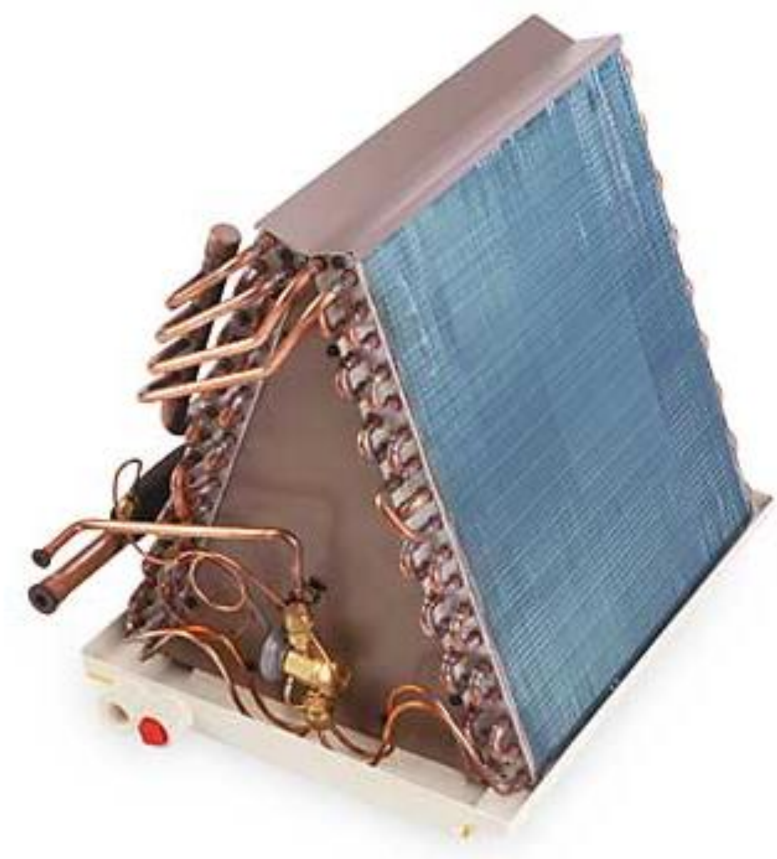
- Heat transfer is the transfer of thermal energy between objects of different temperatures
- In building science, we work mainly with temperature differences between the interior and exterior of the building
  - The element that separates indoors from outdoors is the building enclosure (or building envelope)
    - Walls, roofs, floors, and fenestration (i.e., windows, doors, skylights)
  - We also need to understand heat transfer to understand HVAC and plumbing systems
  - We also have internal heat gains that contribute to higher temperatures in indoor environments

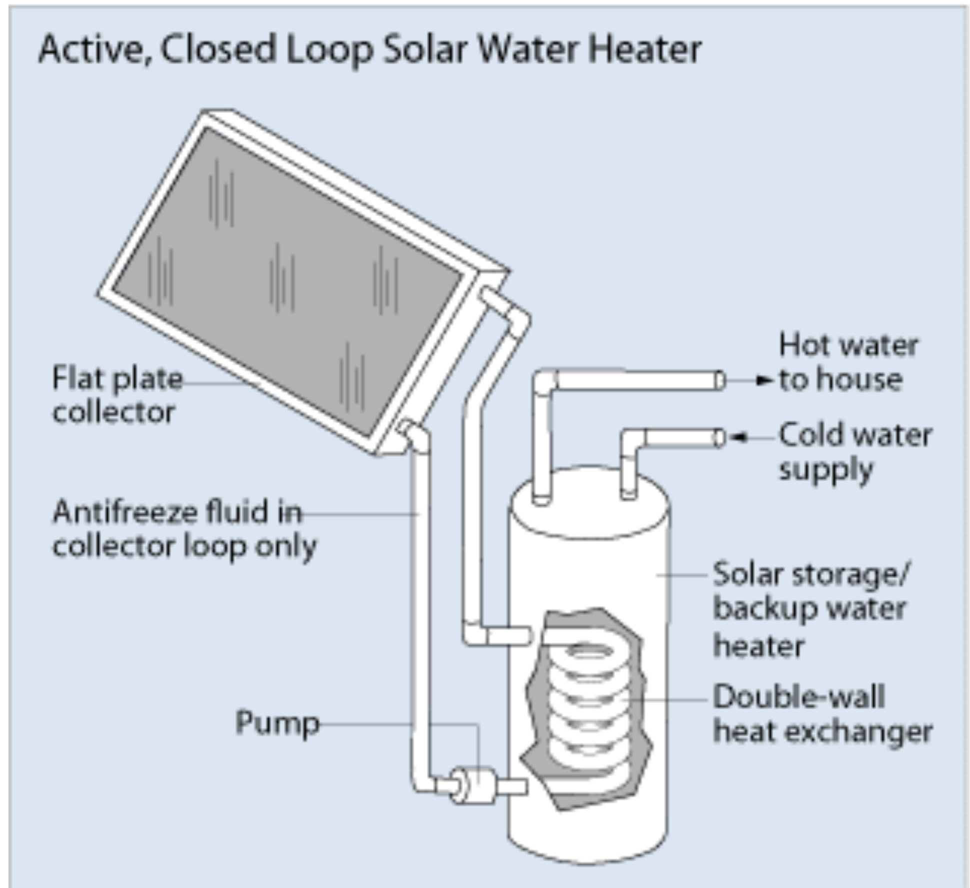
Primary modes of heat transfer in a building



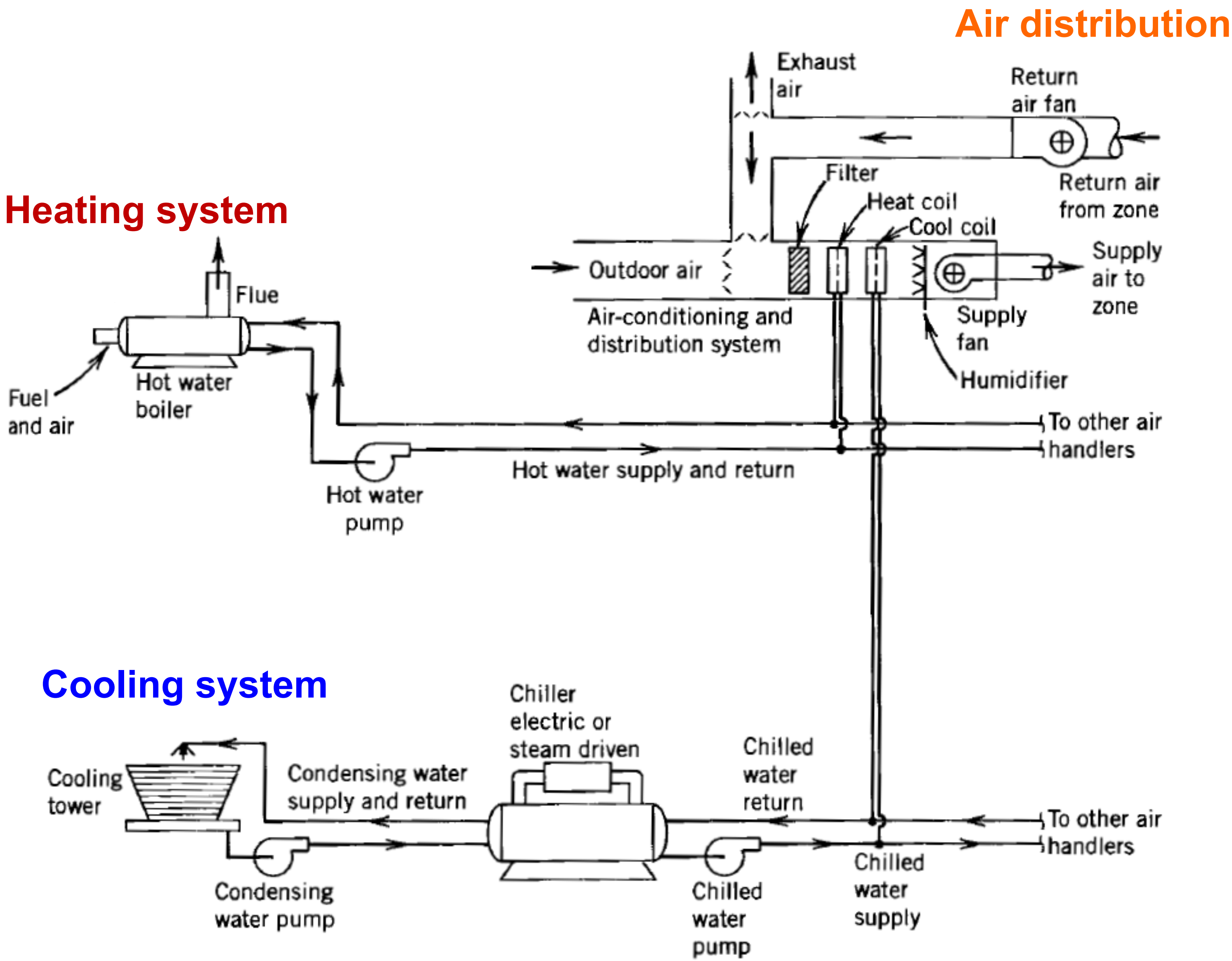
More heat transfer examples

- We also deal with heat transfer within HVAC systems, water heating, and many other applications





Heat transfer in HVAC systems



Building heat transfer

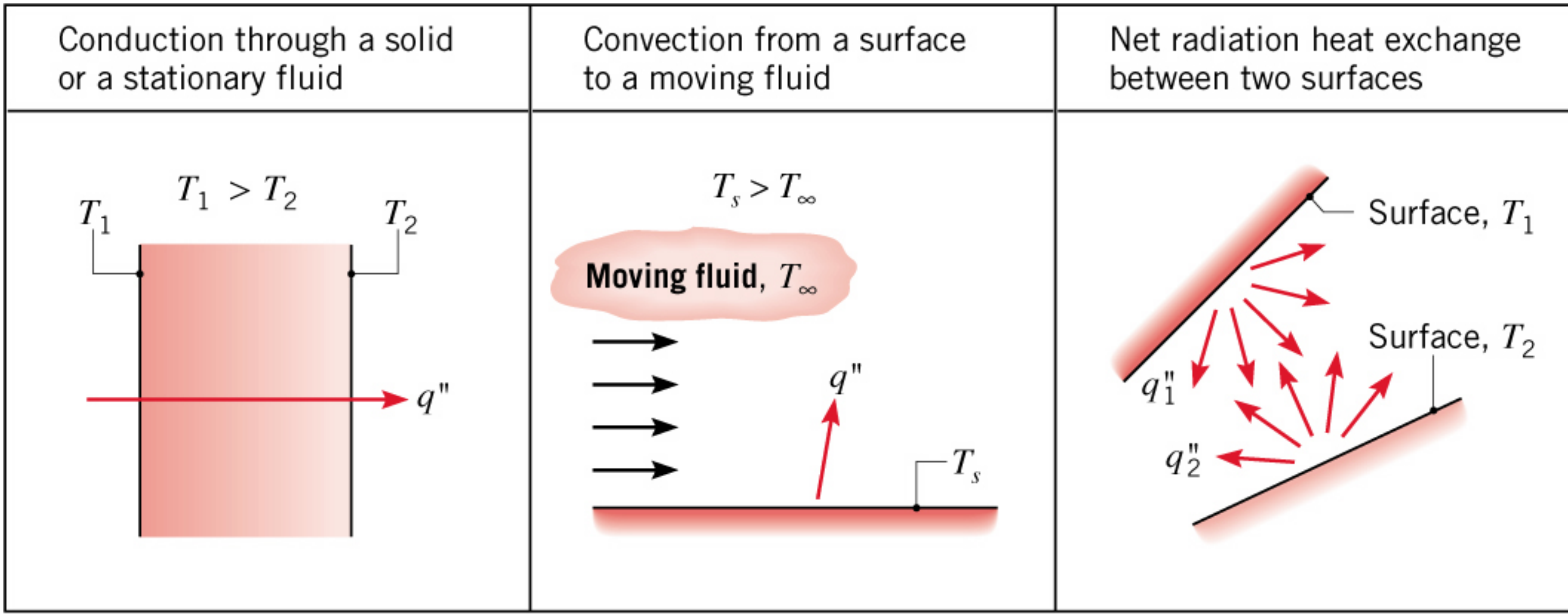
- Heat transfer is the science and art of predicting the rate at which heat flows through substances under various conditions

- The laws of heat transfer govern the rate at which heat energy must be supplied to or removed from a building to maintain the comfort of occupants or to meet other thermal requirements of buildings

- We will review heat transfer fundamentals here and then use these concepts later in the course to estimate heating and cooling needs for whole buildings

Heat transfer

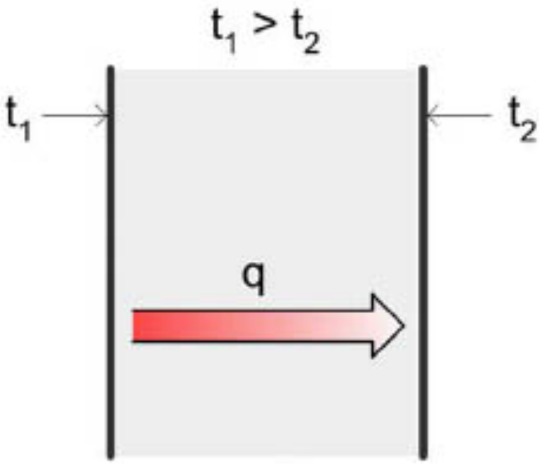
- Three primary modes of heat transfer

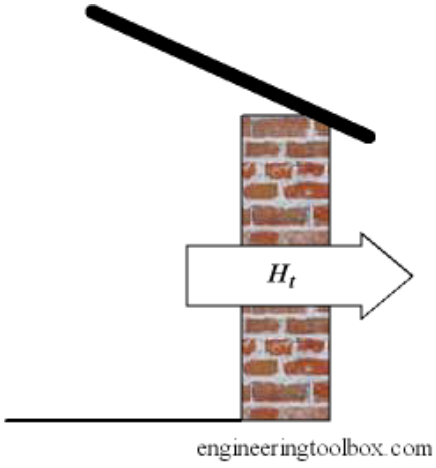


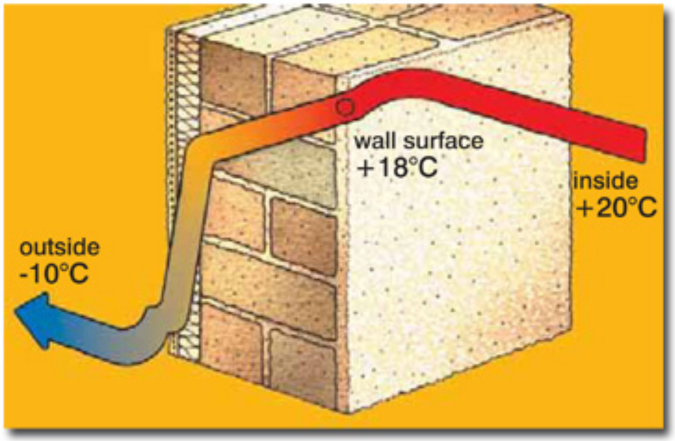
Conduction **Convection** **Radiation**

Conduction

- **Conduction** heat transfer is a result of molecular-level kinetic energy transfers in solids, liquids, and gases
  - Analogous electrical conduction in solids
- Conduction heat flow occurs in the direction of decreasing temperature
  - From high temperature to low temperature
- Example: heat loss through opaque walls in winter



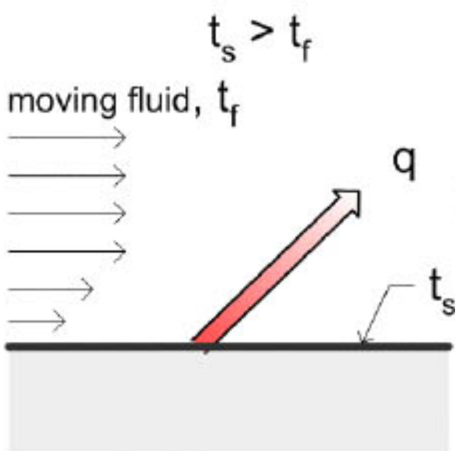


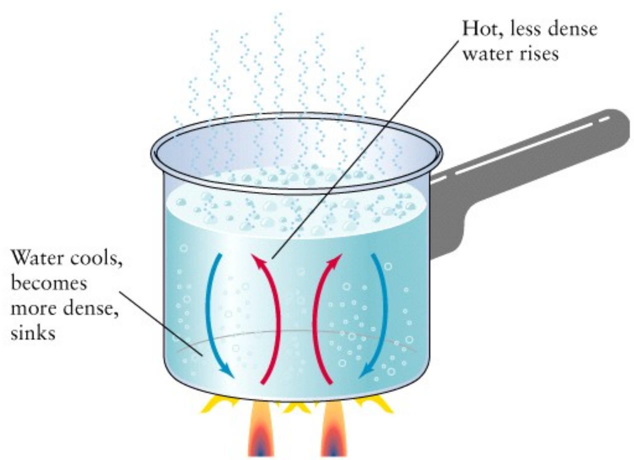


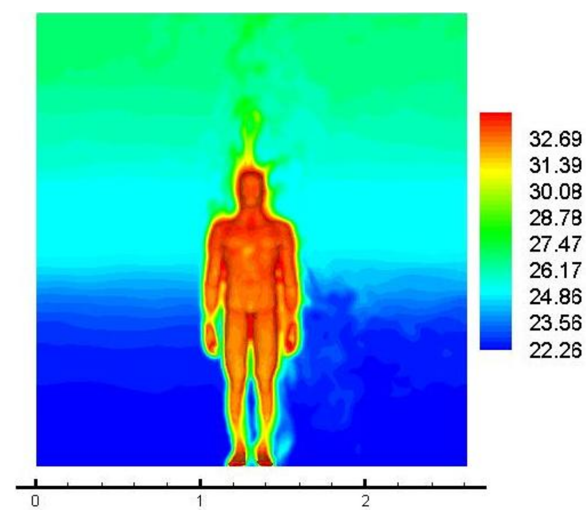
Conduction

Convection

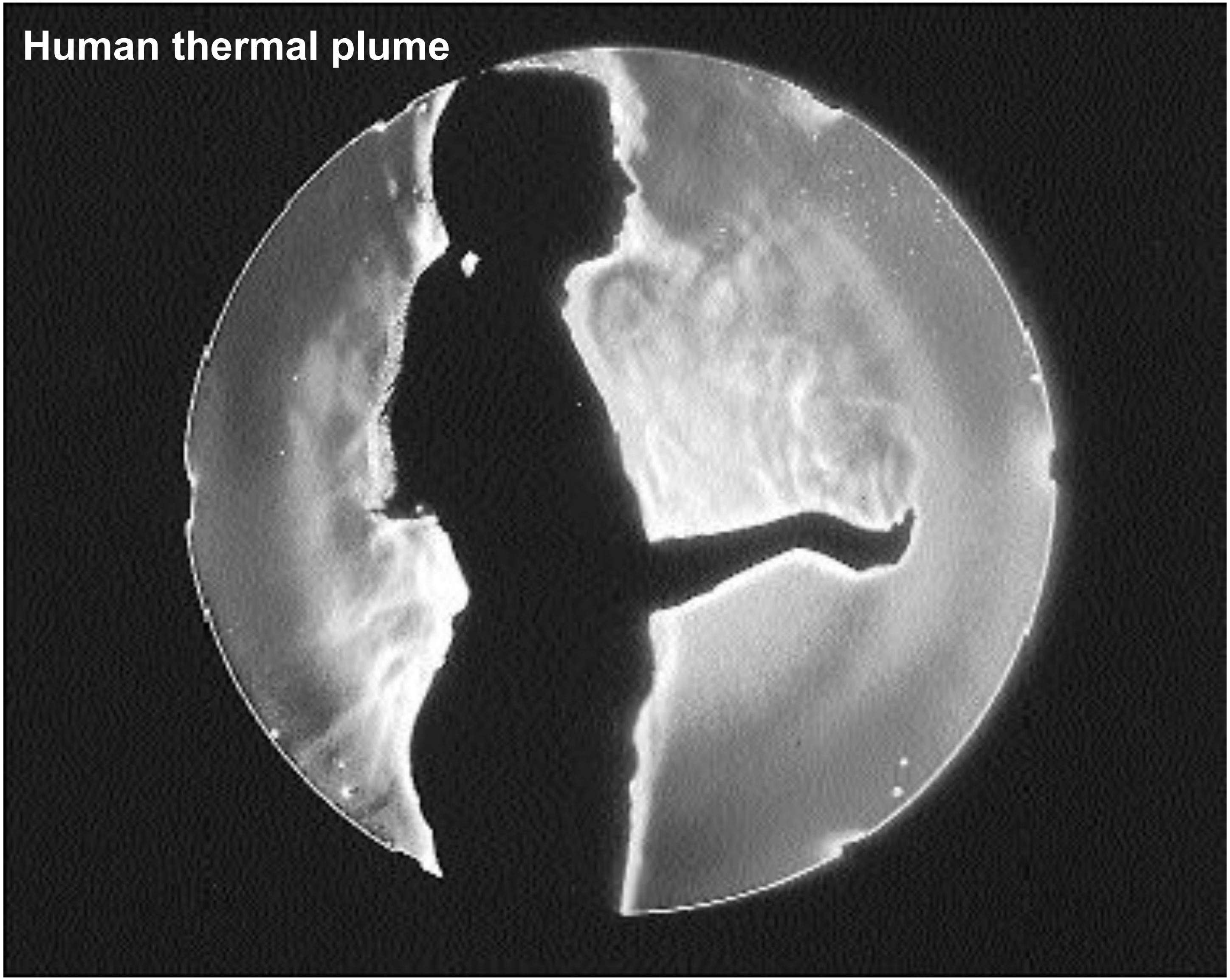
- **Convection** heat transfer is a result of larger-scale motions of a fluid, either liquid or gas
- The higher the velocity of fluid flow, the higher the rate of convection heat transfer
  - Also the greater the temperature difference the greater the heat flow
- Example: when a cold wind blows over a person's skin and removes heat from it





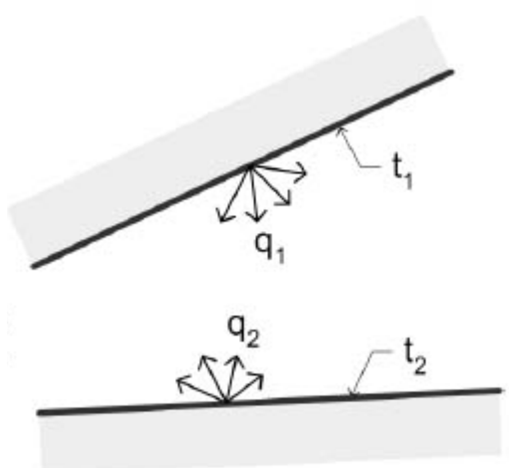


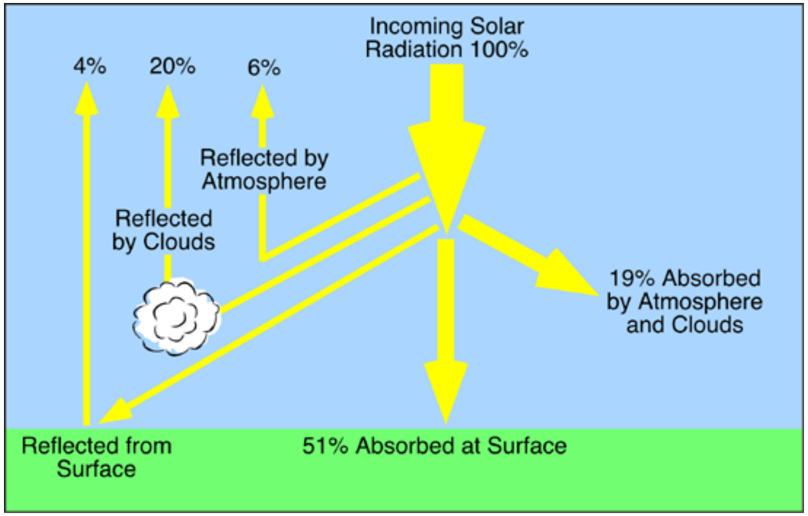
Convection



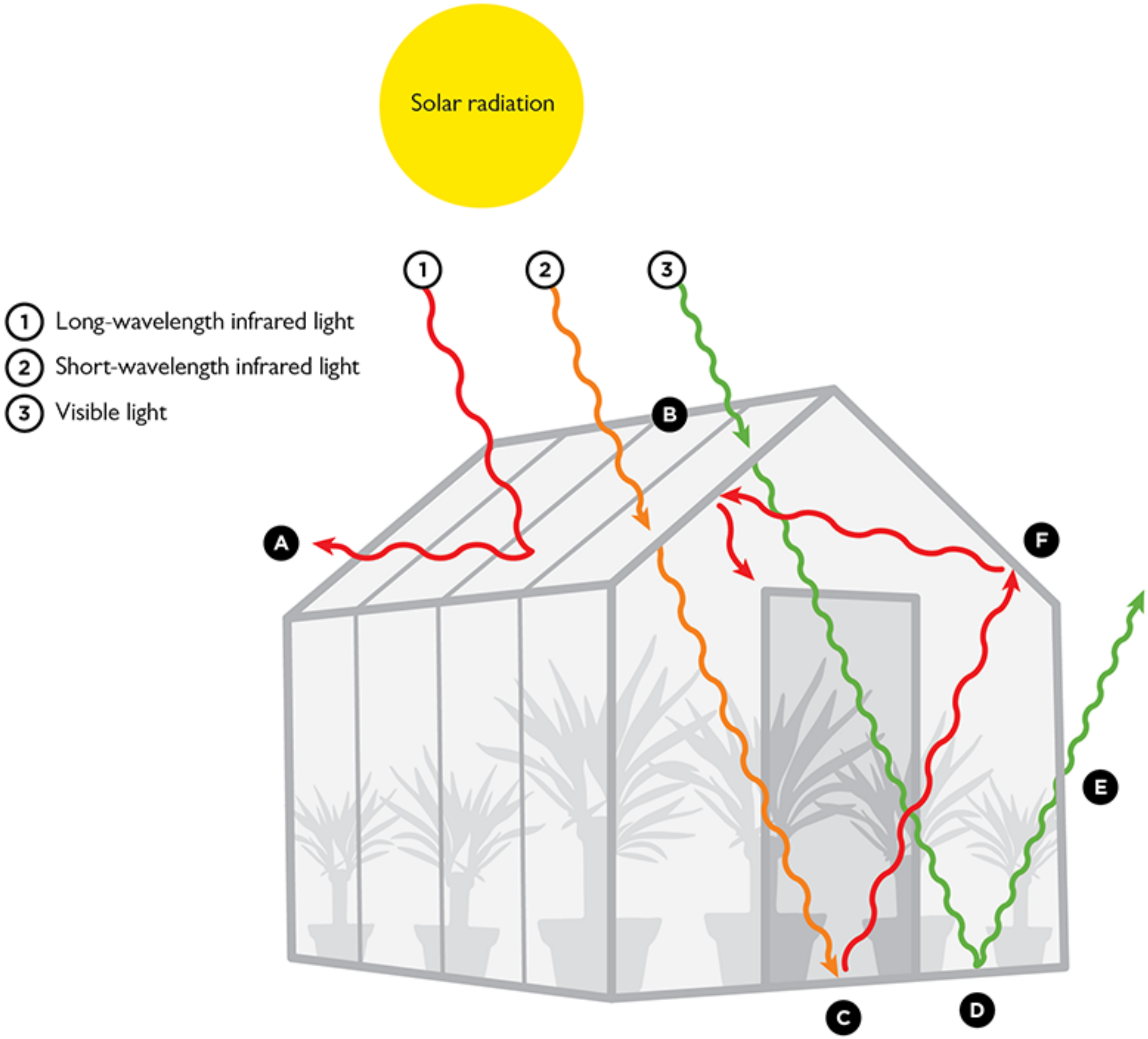
Radiation

- **Radiation** heat transfer is the transport of energy by electromagnetic waves
  - Exchange between two surfaces at different temperatures
- Radiation must be absorbed by matter to produce internal energy
- Example: energy transported from the sun to the earth

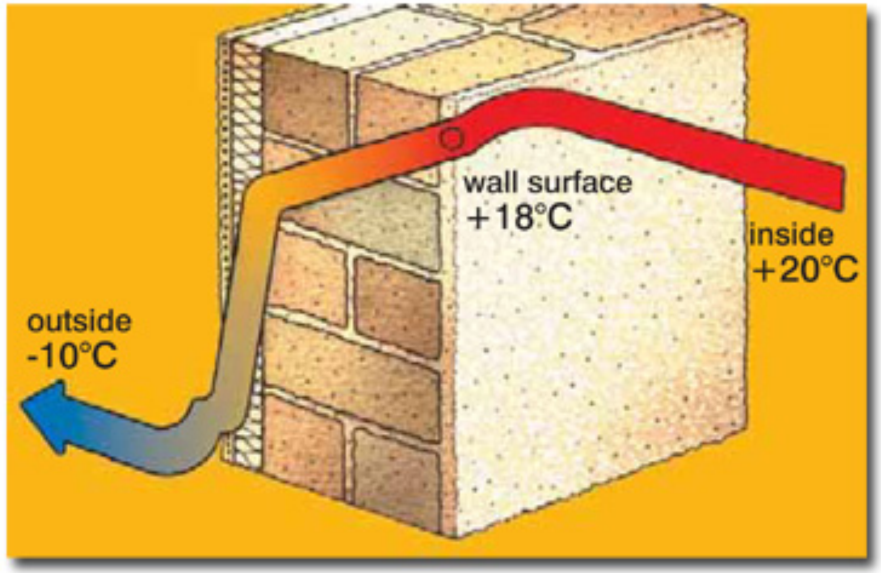




Radiation



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



CONDUCTION

Conduction

- **Conduction** follows Fourier's Law: $q = -k\nabla T$

$$q = -k\nabla T = -k\left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z}\right)$$

where:

$q =$ heat flux per unit area [Btu/(h·ft^2) or W/m^2]

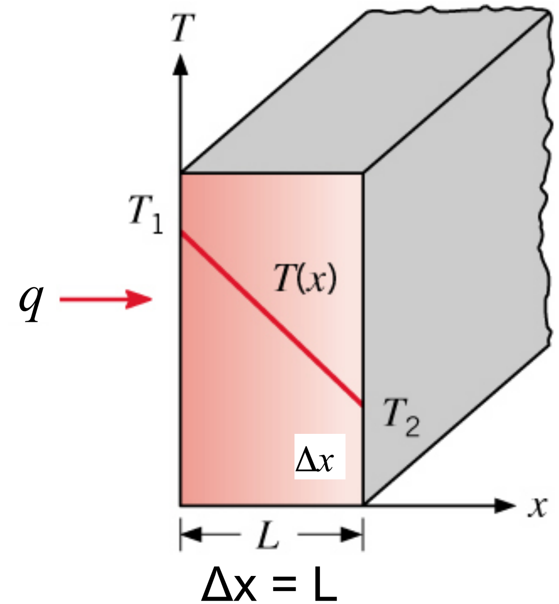
$k =$ thermal conducitivity [Btu/(h·ft·°F) or W/(m·K)]

$T =$ temperature [°F or K]

- In 1-D, this becomes: $q = -k\dfrac{dT}{dx}$

Simplified conduction: 1-dimension

If a material has uniform thermal conductivity throughout & consists of parallel surfaces with uniform temperatures, then:



$$q = k\frac{\Delta T}{\Delta x} = k\frac{T_1 - T_2}{x_2 - x_1} = \frac{k}{L}\left(T_1 - T_2\right)$$

Here T_1 and T_2 are the surface temperatures at x_1 and x_2

Notice that this equation differs from the last by a minus sign

I suggest you use the $\Delta T/\Delta x$ formulation and note that heat will always flow from high to low temperature

Conduction: Heat flow vs. heat flux

- To get Q in [W], simply multiply q [W/m^2] by A [m^2]

$$Q = qA = A\frac{k}{L}\left(T_1 - T_2\right)$$

where:

$Q =$ heat flux [Btu/h or W]

$A =$ area normal to heat flow [m^2]

Thermal conductance and resistance

- Conductivity and length can also be described in other terms

$$Q = A\boxed{\frac{k}{L}}\left(T_1 - T_2\right)$$

$$\frac{k}{L} = U \qquad \text{and} \qquad R = \frac{1}{U}$$

where:

U = unit thermal conductance [$\frac{\text{Btu}}{\text{h·ft}^2\text{·°F}}$] or [$\frac{\text{W}}{\text{m}^2\text{K}}$]

R = unit thermal resistance [$\frac{\text{h·ft}^2\text{·°F}}{\text{Btu}}$] or [$\frac{\text{m}^2\text{K}}{\text{W}}$]

Thermal resistance of common materials (SI units)

- We will often be concerned more with the ability of a material to **resist** heat flow rather than conduct it

$$q = \frac{k}{L}\left(T_1 - T_2\right) = U\left(T_1 - T_2\right) = \frac{1}{R}\left(T_1 - T_2\right)$$

Here the thermal conductivity (k) divided by thickness (L) yields "Conductance" of a material, with units of $[\mathrm{W}/(\mathrm{m}^2 \cdot \mathrm{K})]$. Conductance is also called the U-value.

The inverse of conductance (C) is the resistance (R), or R-value.

Where 1/C = R, with units of $[(\mathrm{m}^2 \cdot \mathrm{K})/\mathrm{W}]$.

Therefore:

$C = U = \frac{k}{L} =$ unit thermal conductance = U-value $[\mathrm{W}/(\mathrm{m}^2 \cdot \mathrm{K})]$

$R = \frac{1}{U} = \frac{L}{k} =$ unit thermal resistance = R-value $[(\mathrm{m}^2 \cdot \mathrm{K})/\mathrm{W}]$

Units of R and U-Value

- R values are typically used for insulating materials
  - For example: wall insulation materials
- U values are typically used for conductive materials
  - For example: windows
- SI units are easier for most to work with, but most products in the US are sold in IP units
  - Remember this conversion: R(IP) = R(SI) × 5.678

R-SI

$$1\,\frac{\mathrm{m^2K}}{\mathrm{W}} = 5.678\,\frac{\mathrm{h{\cdot}ft^2{\cdot}{}^\circ F}}{\mathrm{Btu}}$$

R-IP

R-values and R-values

- Our textbook defines two different R-values
  - R (resistance to heat transfer):

$$R = \frac{1}{\left(A\frac{k}{L}\right)} = \frac{L}{kA} \qquad [\frac{\mathrm{K}}{\mathrm{W}}]$$

  - R_{th} (unit thermal resistance, or "R-value"):

$$R_{th} = \frac{1}{\left(\frac{k}{L}\right)} = \frac{L}{k} \qquad [\frac{\mathrm{m^2K}}{\mathrm{W}}]$$

This unit R-value is most useful for our purposes

- **It is independent of area**

Thermal conductivity of building materials (*k*)

- Thermal conductivity data for some typical materials:

TABLE 2.2

Representative Magnitudes of Thermal Conductivity

Material	Conductivity, Btu/(h · ft · °F)	Conductivity, W/(m · K)
Atmospheric-pressure gases	0.004–0.10	0.007–0.17
Insulating materials	0.02–0.12	0.034–0.21
Nonmetallic liquids	0.05–0.40	0.086–0.69
Nonmetallic solids (brick, stone, concrete)	0.02–1.50	0.034–2.6
Metal alloys	8–70	14–120
Pure metals	30–240	52–410

- These can also be found in the ASHRAE 2013 Handbook (Ch. 26)

Thermal conductivity of building materials

TABLE 2.3

Values of Thermal Conductivity for Building Materials

Material	k, Btu/(h · ft · °F)	T, °F	k, W/(m · K)	T, °C
Construction materials				
Asphalt	0.43–0.44	68–132	0.74–0.76	20–55
Cement, cinder	0.44	75	0.76	24
Glass, window	0.45	68	0.78	20
Concrete	1.0	68	1.73	20
Marble	1.2–1.7	—	2.08–2.94	—
Balsa	0.032	86	0.055	30
White pine	0.065	86	0.112	30
Oak	0.096	86	0.166	30
Insulating materials				
Glass fiber	0.021	75	0.036	24
Expanded polystyrene	0.017	75	0.029	24
Polyisocyanurate	0.012	75	0.020	24
Gases at atmospheric pressure				
Air	0.0157	100	0.027	38
Helium	0.0977	200	0.169	93
Refrigerant 12	0.0048	32	0.0083	0
	0.0080	212	0.0038	100
Oxygen	0.00790	−190	0.0137	−123
	0.02212	350	0.0383	175

Source: Courtesy of Karlekar, B. and Desmond, R.M., *Engineering Heat Transfer*, West Publishing, St. Paul, MN, 1982. With permission.

Thermal properties of building materials

Table 1 Building and Insulating Materials: Design Values[a]

Description	Density, kg/m³	Conductivity[b] *k*, W/(m·K)	Resistance *R*, (m²·K)/W	Specific Heat, kJ/(kg·K)	Reference[l]
Insulating Materials					
Blanket and batt[c,d]					
Glass-fiber batts				0.8	Kumaran (2002)
	7.5 to 8.2	0.046 to 0.048	—	—	Four manufacturers (2011)
	9.8 to 12	0.040 to 0.043	—	—	Four manufacturers (2011)
	13 to 14	0.037 to 0.039	—	—	Four manufacturers (2011)
	22	0.033	—	—	Four manufacturers (2011)
Rock and slag wool batts	—	—	—	0.8	Kumaran (1996)
	32 to 37	0.036 to 0.037	—	—	One manufacturer (2011)
	45	0.033 to 0.035	—	—	One manufacturer (2011)
Mineral wool, felted	16 to 48	0.040	—	—	CIBSE (2006), NIST (2000)
	16 to 130	0.035	—	—	NIST (2000)
Board and slabs					
Cellular glass	120	0.042	—	0.8	One manufacturer (2011)
Cement fiber slabs, shredded wood with Portland cement binder	400 to 430	0.072 to 0.076	—	—	
with magnesia oxysulfide binder	350	0.082	—	1.3	
Glass fiber board	—	—	—	0.8	Kumaran (1996)
	24 to 96	0.033 to 0.035	—	—	One manufacturer (2011)
Expanded rubber (rigid)	64	0.029	—	1.7	Nottage (1947)
Extruded polystyrene, smooth skin	—	—	—	1.5	Kumaran (1996)
aged per Can/ULC *Standard* S770-2003	22 to 58	0.026 to 0.029	—	—	Four manufacturers (2011)
aged 180 days	22 to 58	0.029			One manufacturer (2011)
European product	30	0.030			One manufacturer (2011)
aged 5 years at 24°C	32 to 35	0030	—	—	One manufacturer (2011)
blown with low global warming potential (GWP) (<5) blowing agent		0.035 to 0.036	—	—	One manufacturer (2011)
Expanded polystyrene, molded beads	—	—	—	1.5	Kumaran (1996)
	16 to 24	0.035 to 0.037	—	—	Independent test reports (2008)
	29	0.033	—	—	Independent test reports (2008)

Thermal properties of building materials

Table 1 Building and Insulating Materials: Design Values[a] (*Continued*)

Description	Density, kg/m³	Conductivity[b] k, W/(m·K)	Resistance R, (m²·K)/W	Specific Heat, kJ/(kg·K)	Reference[l]
	1760	0.71 to 0.85	—	—	Valore (1988)
	1600	0.61 to 0.74	—	—	Valore (1988)
	1440	0.52 to 0.62	—	—	Valore (1988)
	1280	0.43 to 0.53	—	—	Valore (1988)
	1120	0.36 to 0.45	—	—	Valore (1988)
Clay tile, hollow					
1 cell deep .... 75 mm	—	—	0.14	0.88	Rowley and Algren (1937)
.... 100 mm	—	—	0.20	—	Rowley and Algren (1937)
2 cells deep .... 150 mm	—	—	0.27	—	Rowley and Algren (1937)
.... 200 mm	—	—	0.33	—	Rowley and Algren (1937)
.... 250 mm	—	—	0.39	—	Rowley and Algren (1937)
3 cells deep .... 300 mm	—	—	0.44	—	Rowley and Algren (1937)
Lightweight brick	800	0.20	—	—	Kumaran (1996)
	770	0.22	—	—	Kumaran (1996)
Concrete blocks[f, g]					
Limestone aggregate					
~200 mm, 16.3 kg, 2200 kg/m³ concrete, 2 cores	—	—	—	—	
with perlite-filled cores	—	—	0.37	—	Valore (1988)
~300 mm, 25 kg, 2200 kg/m³ concrete, 2 cores	—		—	—	
with perlite-filled cores	—	—	0.65	—	Valore (1988)
Normal-weight aggregate (sand and gravel)					
~200 mm, 16 kg, 2100 kg/m³ concrete, 2 or 3 cores…	—	—	0.20 to 0.17	0.92	Van Geem (1985)
with perlite-filled cores	—	—	0.35	—	Van Geem (1985)
with vermiculite-filled cores	—	—	0.34 to 0.24	—	Valore (1988)
~300 mm, 22.7 kg, 2000 kg/m³ concrete, 2 cores	—	—	0.217	0.92	Valore (1988)
Medium-weight aggregate (combinations of normal and lightweight aggregate)					
~200 mm, 13 kg, 1550 to 1800 kg/m³ concrete, 2 or 3 cores	—	—	0.30 to 0.22	—	Van Geem (1985)
with perlite-filled cores	—	—	0.65 to 0.41	—	Van Geem (1985)
with vermiculite-filled cores	—	—	0.58	—	Van Geem (1985)
with molded-EPS-filled (beads) cores	—	—	0.56	—	Van Geem (1985)
with molded EPS inserts in cores	—	—	0.47	—	Van Geem (1985)

Actual building materials

- Insulation manufacturers often sell their products in terms of "R-value per inch"

PRODUCT OVERVIEW

FOAMULAR 150 extruded polystyrene (XPS) rigid foam insulation contains hundreds of millions of densely packed closed cells to provide exceptional thermal performance. It's also virtually impervious to moisture, unlike other plastic foam insulation products, preventing loss of R-value due to moisture penetration. FOAMULAR weighs considerably less than plywood, OSB or other non-insulation materials so it's easier, faster and safer to install. Plus, the product's built-in rigidity means it can be scored and snapped, cut, or sawed with common tools. Sagging and settling are never a problem. Retains it's long-term R-value year after year, even following prolonged exposure to water leakage, humidity, condensation, ground water and freeze/thaw cycling. Contains a minimum of 20% certified recycled content, certified GreenGuard Indoor Air Quality for Children and Schools, Energy Star Seal and Insulate Program, and NAHB Green approved. Owens Corning Foam Insulation, LLC now warrants a Lifetime Limited Warranty on FOAMULAR Extruded Polystyrene (XPS) Foam Insulation products. This new, enhanced warranty indicates that for the lifetime of the product, FOAMULAR XPS Insulation products are free from defects in material and/or workmanship that materially affect the performance of the product in a building installation.

- Exceptional thermal performance at r-5 per in.
- Virtually impervious to moisture penetration
- For exterior wall sheathing, wall furring, perimeter/foundation, cavity wall, crawlspace, pre-cast concrete, under slab and other applications
- Fast, easy installation
- Available in a wide range of sizes, thicknesses and edge trims
- Compressive strength of 15 psi; astm c578 type x
- Will retain at least 90 percent of their advertised r-value
- MFG Model # : 45W
- MFG Part # : 270895

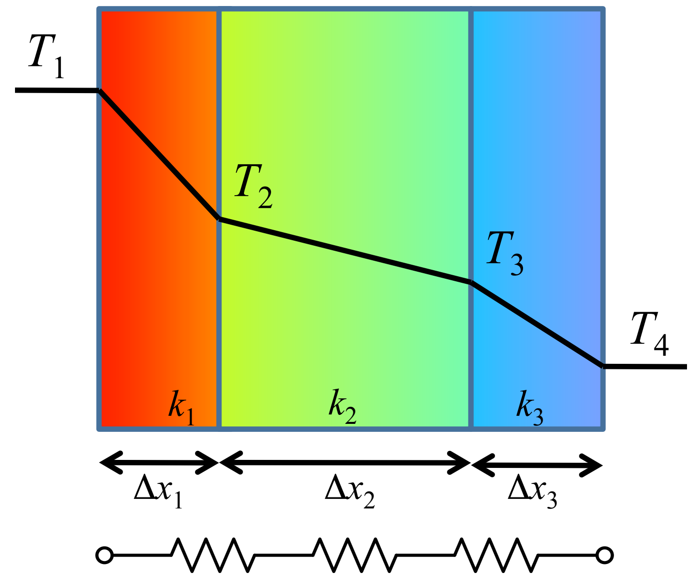
Owens Corning FOAMULAR 2 inch x 48 inch x 8 feet foamboard

Extruded polystyrene rigid foam insulation – closed cell

Thermal resistances of series/layers of materials

- Just as in electrical circuits, the overall thermal resistance of a series of elements can be expressed as the sum of the resistances of each layer:

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



$$R_1 = \frac{\Delta x_1}{k_1} \qquad R_2 = \frac{\Delta x_2}{k_2} \qquad R_3 = \frac{\Delta x_3}{k_3}$$

$$q = \frac{1}{R_{total}}\left(T_1 - T_4\right)$$

$$q = U_{total}\left(T_1 - T_4\right)$$

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

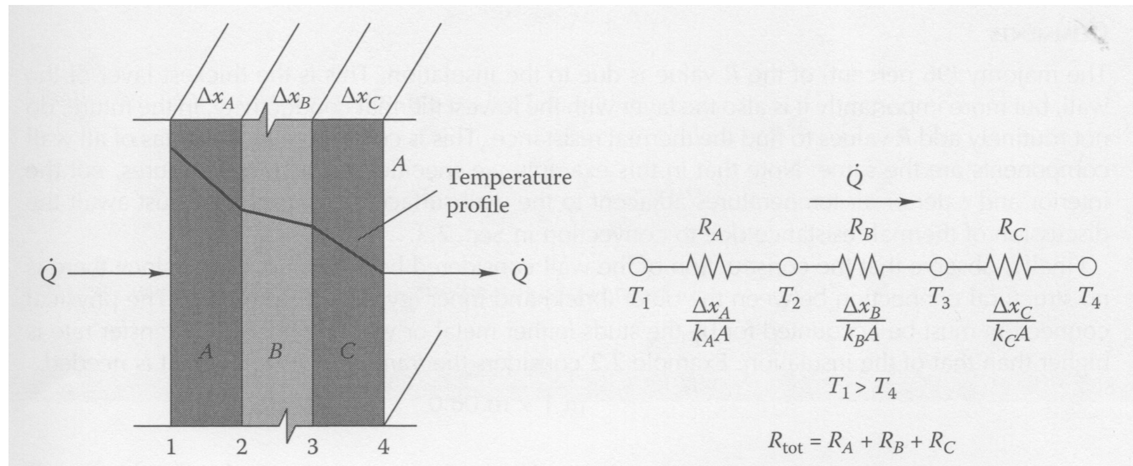
Example of conduction through multiple layers

- R-value calculation for a building wall:

The outside wall of a home consist of a 4 inch (10cm) layer of brick, a 6 inch (15cm) layer of fiberglass insulation, and a 0.5 inch (1.2cm) layer of gypsum board.

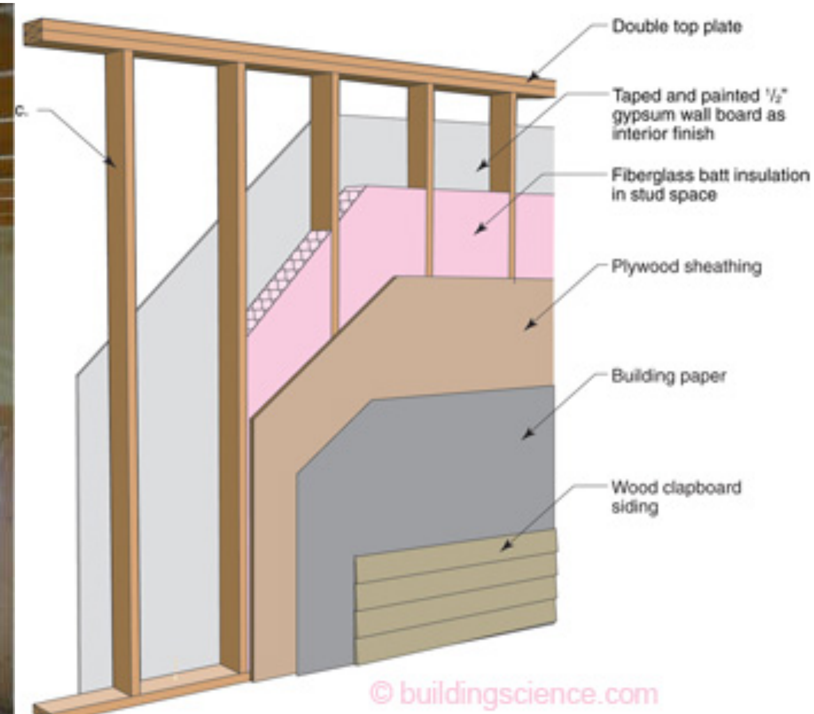
1) What is the overall R-value?

2) What is the heat flux through the wall if the interior surface temperature is 22°C and the exterior surface is 5°C?



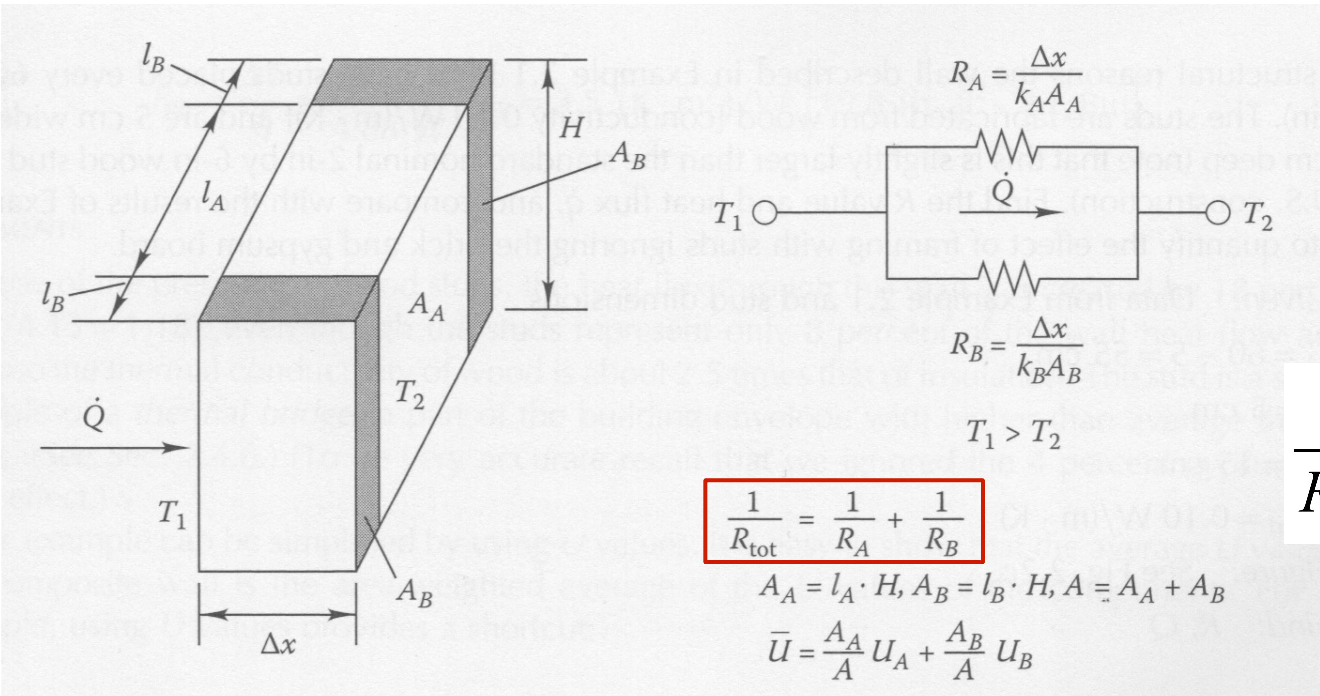
What about more realistic constructions?

- Building walls rarely exist in complete, homogenous layers
- Structural elements – studs – are usually located within the envelope matrix at regular intervals



Accounting for structural elements (studs)

- Parallel-resistance heat flow



Treat resistances like resistors in series:

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$

- Or use weighted average U values:

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

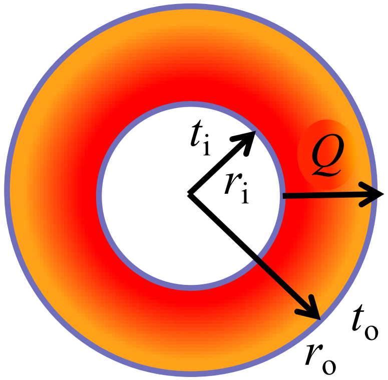
Example: Accounting for structural elements (studs)

- For structural reasons the wall described in the last example must have studs placed every 24 inches (60 cm)
  - Structural elements form what we call “thermal bridges”
- The studs are wood and are 2 inches (5 cm) wide and 6 inches (15 cm) deep
- **Problem:** Find the R value of this assembly and heat flux, and compare to the previous example

Thermal resistances of other shapes: cylinders

- Thermal resistances can be defined for non-planar elements
  - For example, to determine heat transfer through the walls of pipes and pipe insulation, we should also understand heat transfer through cylinders
- For example, a hollow cylinder with length L, inner radius r_i and outer radius r_o:
  - If you integrate $q = -k\frac{dT}{dx}$ in cylindrical coordinates:

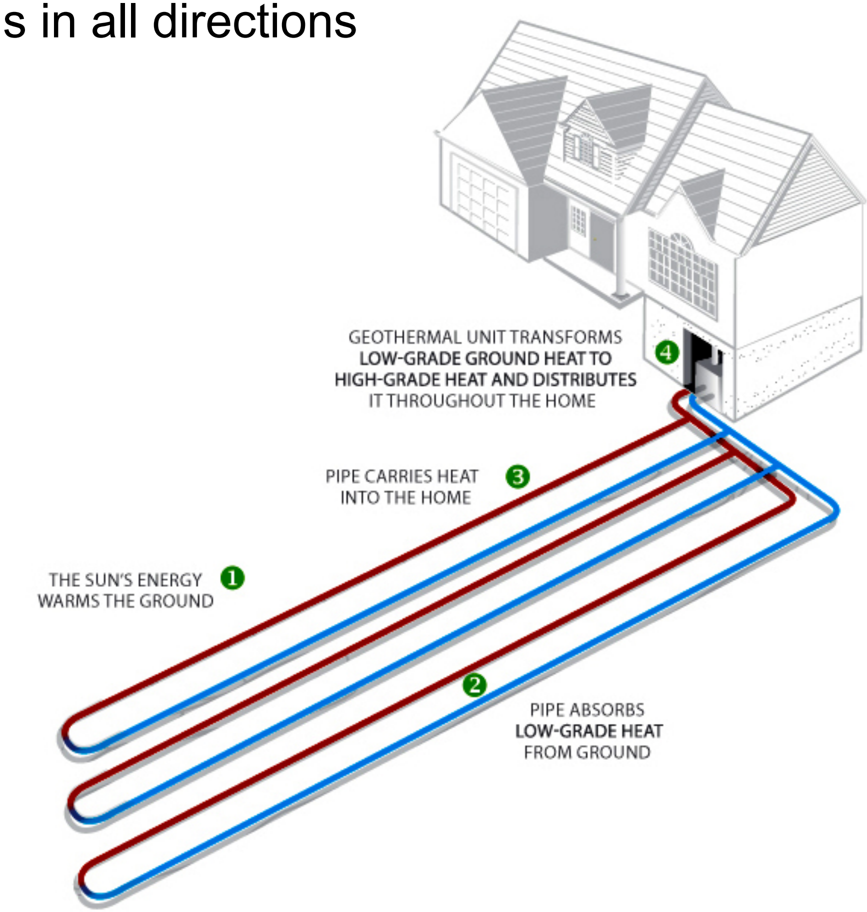
$$Q = \frac{2\pi kL}{\ln\left(r_o/r_i\right)}\left(T_i - T_o\right)$$



$$R'_{cyl} = \frac{\ln\left(r_o/r_i\right)}{2\pi kL}$$

Conduction in other geometries

- Often heat transfer is not limited to one dimension (1-D)
  - Example: a pipe is carrying a heated or cooled fluid from a central plant, underground to a building for heating or cooling
    - Interactions with surroundings in all directions



Conduction in other geometries

- One way to account for this is the use of a "shape factor"
  - Shape factors account for 2-dimensional effects

$$Q = kS\Delta T$$

Where S = shape factor [m]

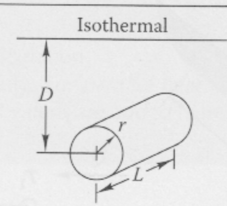
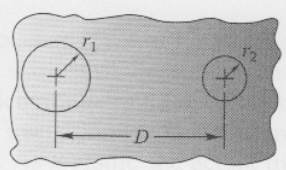
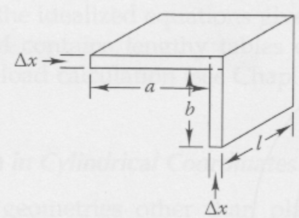
- Another approach is a full two-dimensional analysis, although we don't cover in this class
  - Some coverage in CAE 463/524 Building Enclosure Design

Shape factor example

- **Example:** Heat loss from a buried pipe
  - A pipe with an outer surface temperature of 100°C and a radius of 15 cm is buried 30 cm deep in earth with a thermal conductivity of 1.7 W/mK. If the surface temperature of the pipe is 20°C and the pipe is uninsulated and 10 m long, what is the heat loss for the pipe?

TABLE 2.1

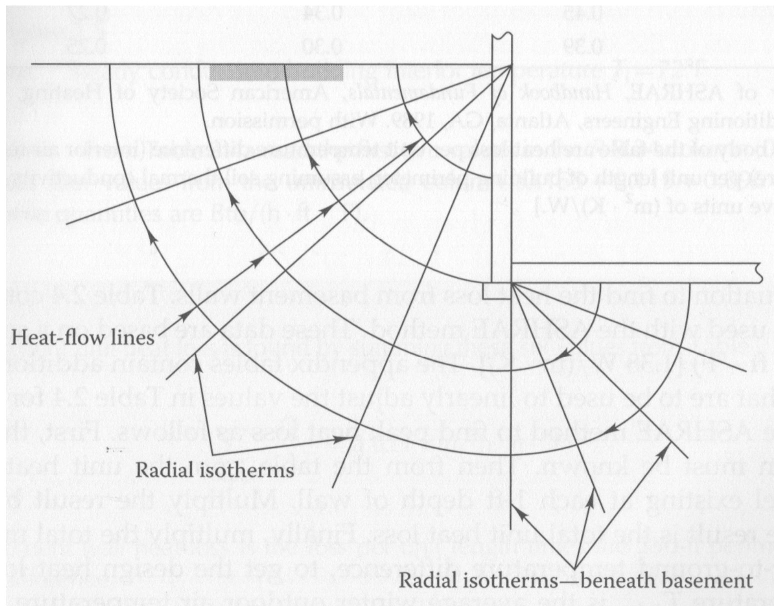
Conduction Shape Factors

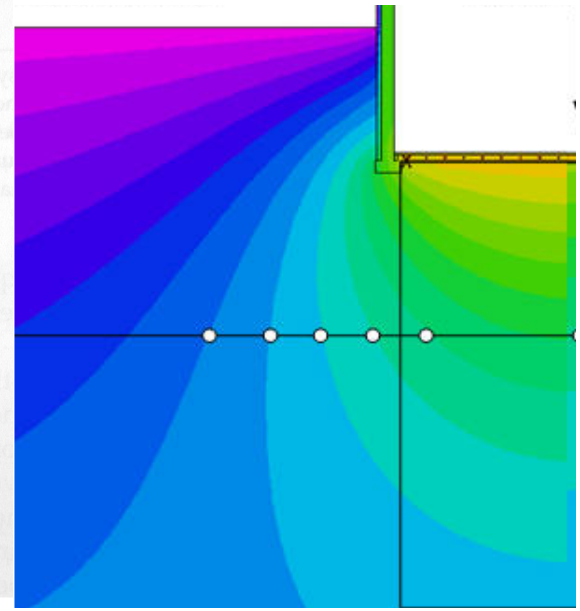
Physical System	Schematic	Shape Factor	Restrictions
Isothermal cylinder of radius r buried in semi-infinite medium having isothermal surface		$\dfrac{2\pi L}{\cosh^{-1}(D/r)}$	$L \gg r$
		$\dfrac{2\pi L}{\ln(2D/r)}$	$L \gg r$ $D > 3r$
		$\dfrac{2\pi L}{\ln\left(\frac{L}{r}\right)\left\{1 - \frac{\ln[L/2D)]}{\ln(L/r)}\right\}}$	$D \gg r$ $L \gg D$
Conduction between two isothermal cylinders buried in infinite medium		$\dfrac{2\pi L}{\cosh^{-1}\left(\frac{D^2 - r_1^2 - r_2^2}{2r_1r_2}\right)}$	$L \gg r_1, r_2$ $L \gg D$
Conduction through two plane sections and the edge section of two walls of thermal conductivity k—inner and outer surface temperatures uniform		$\dfrac{al}{\Delta x} + \dfrac{bl}{\Delta x} + 0.54l$	

Source: Courtesy of Holman, J.P., *Heat Transfer*, 8th edn, McGraw-Hill, New York, 1997. With permission.

Ground coupled heat transfer

- What about heat transfer through a basement or floor slab of a building?





- This is fairly complicated
  - Depends on estimation method, soil type, etc.
  - Because this is one of the least accurate procedures of any building thermal analysis, and the level of complexity is rather high, we will save this for CAE 463/524

Next time

- HW 1 due
- Continuing heat transfer (convection, radiation…)