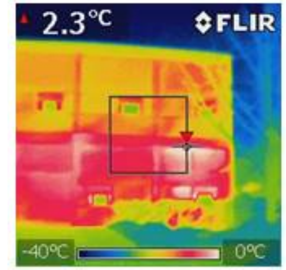
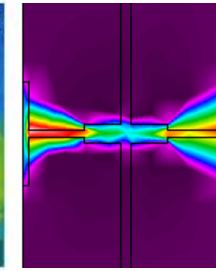
CAE 331/513 Building Science

Fall 2018





August 28, 2018

Heat transfer in buildings: Conduction

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Dr. Brent Stephens, Ph.D.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
brent@iit.edu

Guest speaker announcement

Chris Wilson
VP Operations - Environmental Systems Design

Tuesday September 11th
12:40-1:40 pm
RE 103 Auditorium
Complete registration form

On Tuesday September 11th at 12:40pm, Environmental Systems Design, a Global Leader in providing comprehensive energy solutions within the Built Environment, will have their VP of Operations, Chris Wilson presenting.
Chris will discuss ESD's energy reduction initiative through ASHRAE Energy Auditing, LEED Consulting, Renewable Energy Feasibility Studies and Carbon Footprint Analysis. Chris will review how the ESD Team identifies, designs and implements energy solutions. He will highlight projects in facilities ranging from Mission Critical Data Centers to Industrial, Hospital and Corporate Facilities. Chris will share his career path and provide advice on how engineering students can pursue opportunities within low carbon technologies to be part of the solution to Climate Change.

Last time

- Reviewed energy concepts and unit conversions
- Assigned HW 1 (due Thursday August 30)

Objectives for today's lecture

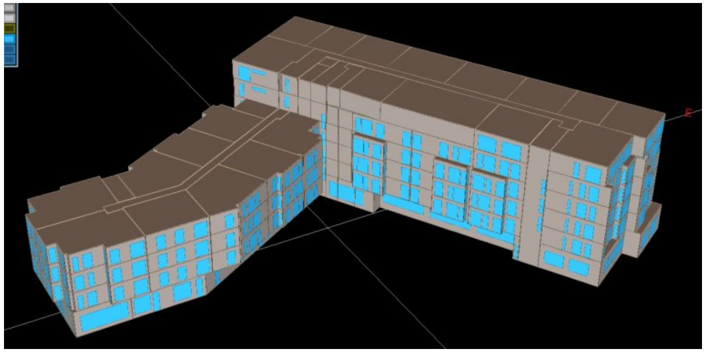
- Begin our review of heat transfer fundamentals
  - Generally follows ASHRAE Handbook Chapter 4 (with some modifications) with reference to Chapter 25 and 26
  - Focus is on applications of heat transfer fundamentals in buildings

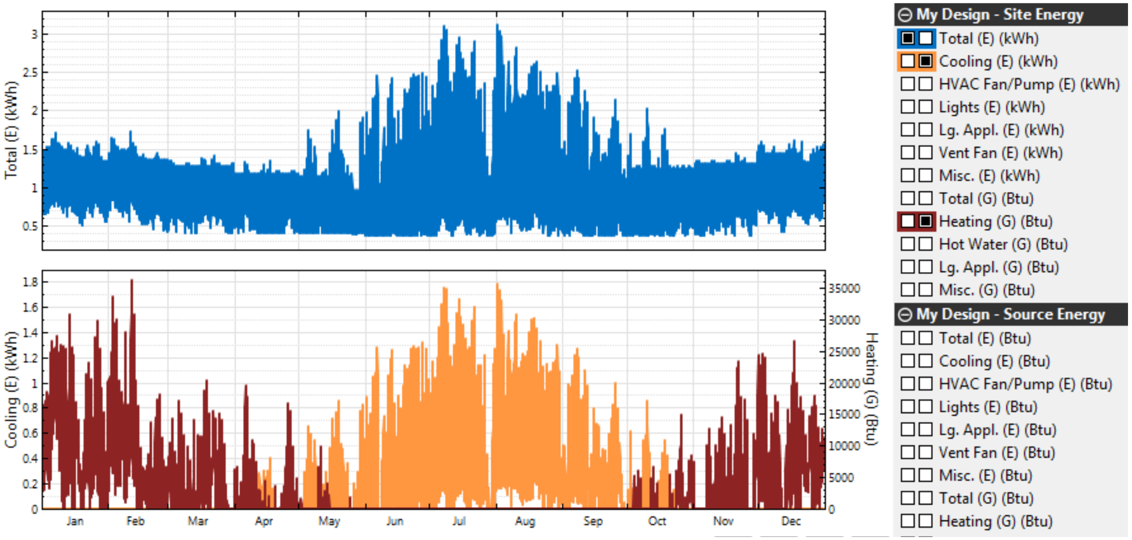
BUILDING SCIENCE FUNDAMENTALS: HEAT TRANSFER IN BUILDINGS

Heat transfer in buildings

- Heat transfer is the transfer of thermal energy between objects of different temperatures

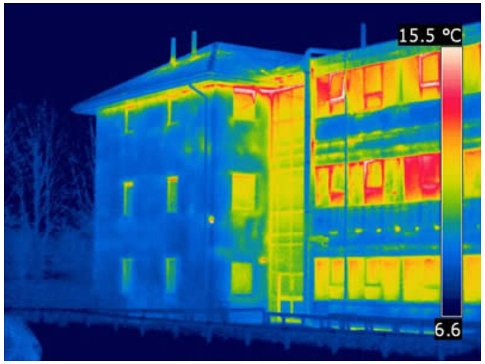
- If we can understand heat transfer in buildings, we can:
  - Select and properly size HVAC equipment to maintain comfort
  - Predict annual building energy use and energy costs
  - Understand trade-offs in designing energy efficient buildings





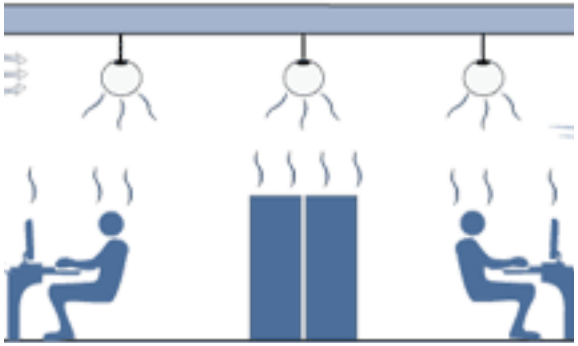
Heat transfer in buildings

- In <u>building science</u>, we begin 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, windows, doors, etc.



- We also need to understand heat transfer to understand HVAC systems and piping systems

- We also have internal heat gains that impact heating and cooling loads



Heat transfer in buildings

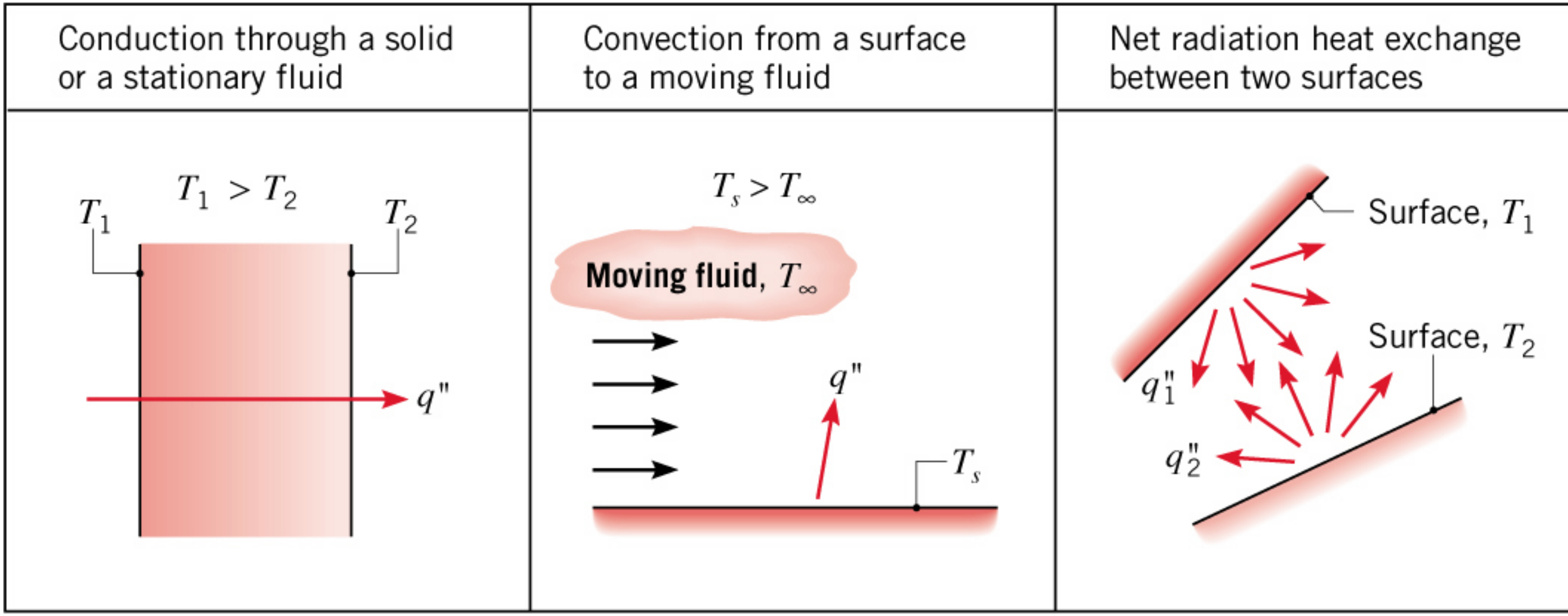
- **Heat transfer** is the science and art of predicting the rates at which heat flows through substances under various conditions

- 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 loads for whole buildings

Heat transfer

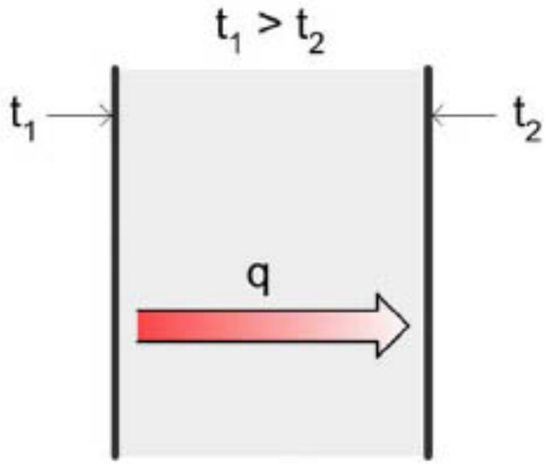
- Three primary modes of heat transfer:

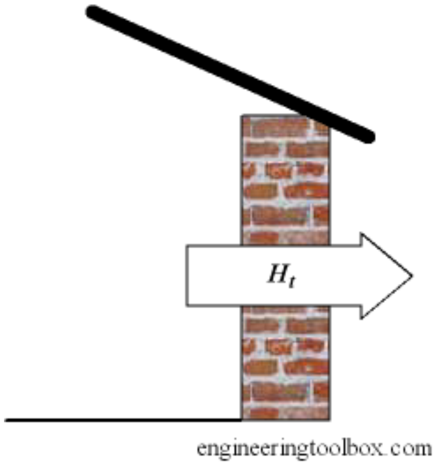


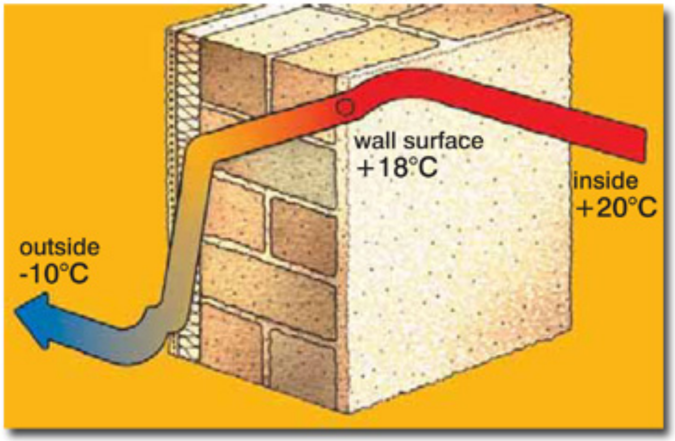
Conduction **Convection** **Radiation**

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



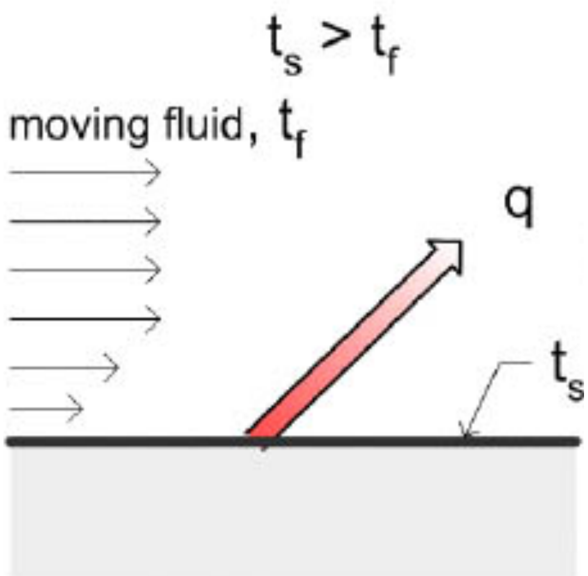


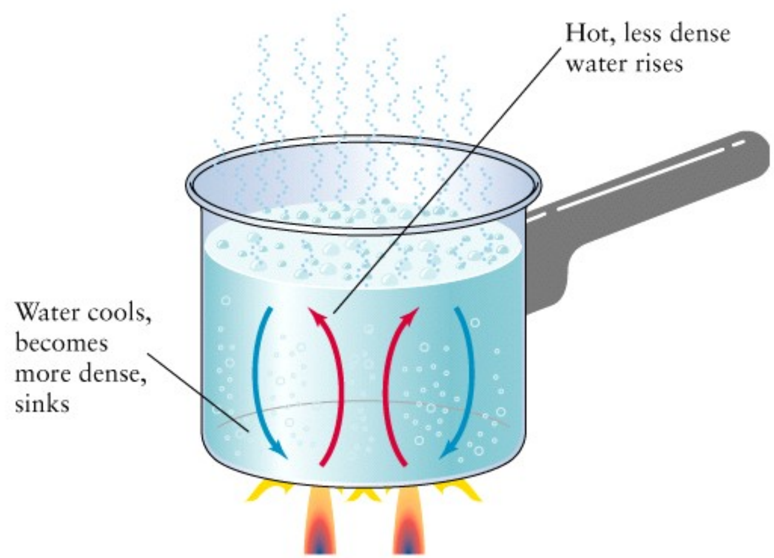


Conduction in buildings

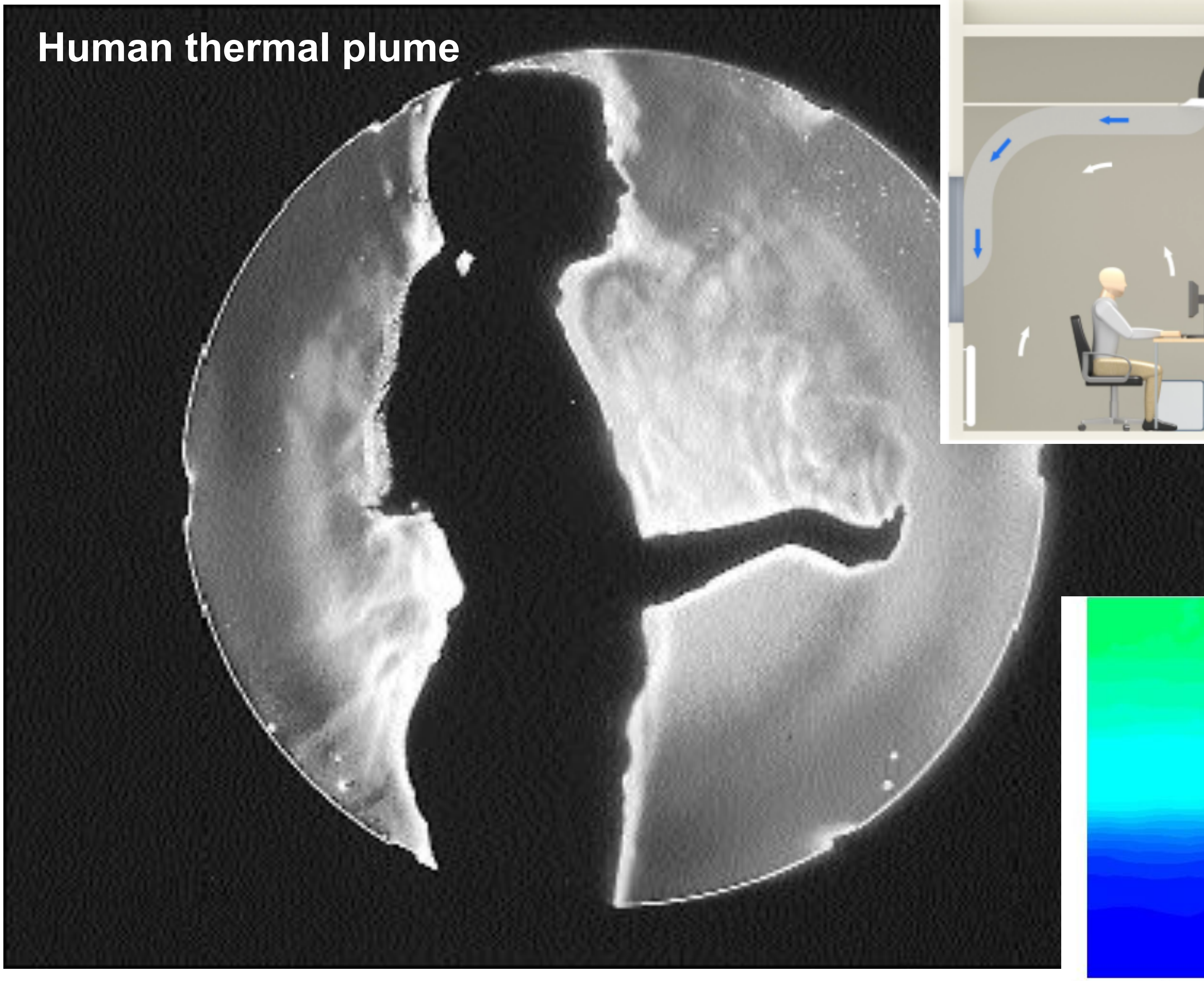
Convection

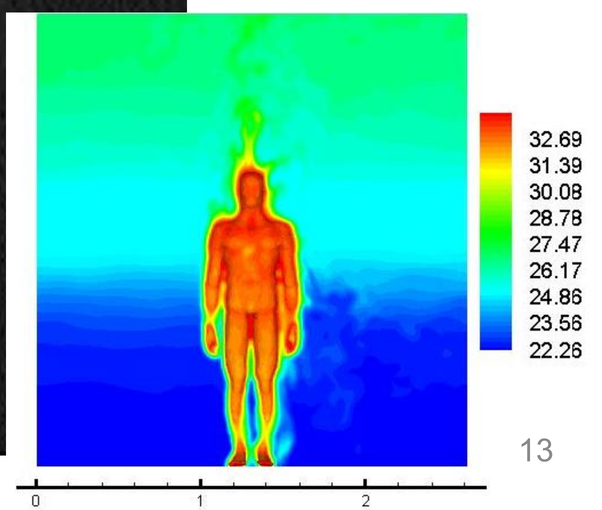
- **Convection** heat transfer is a result of larger-scale motions of a fluid, either liquid or gas
- The higher the velocity of fluid flow, the higher the rate of convection heat transfer
  - Also the greater the temperature difference the greater the heat flow
- Example: when a cold wind blows over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





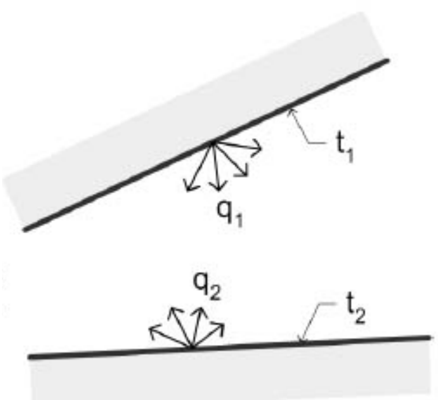
Convection in buildings

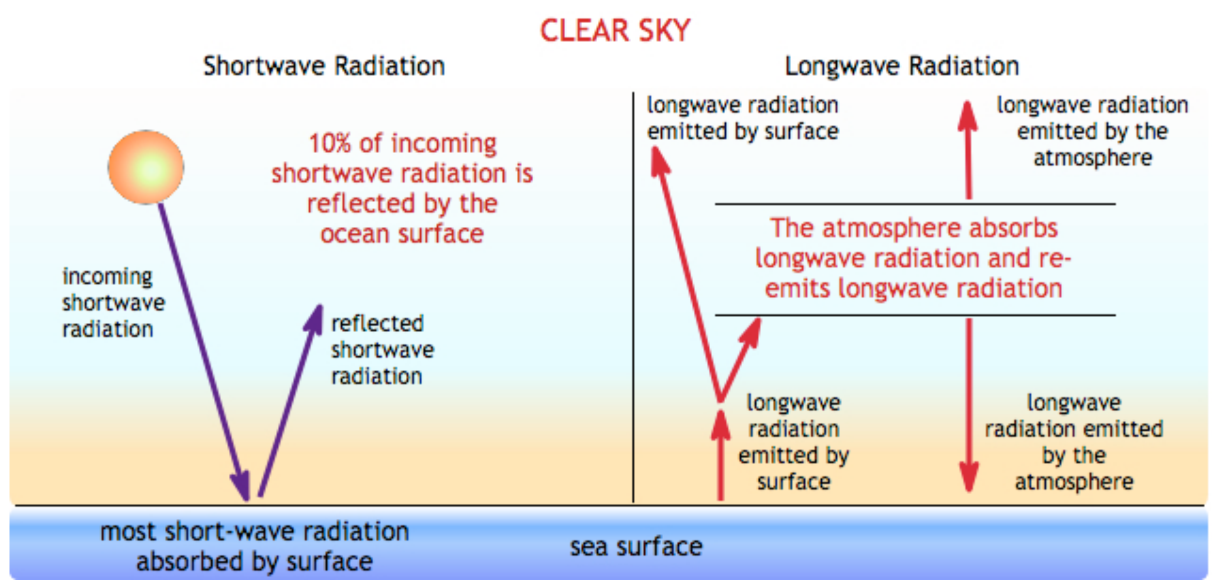




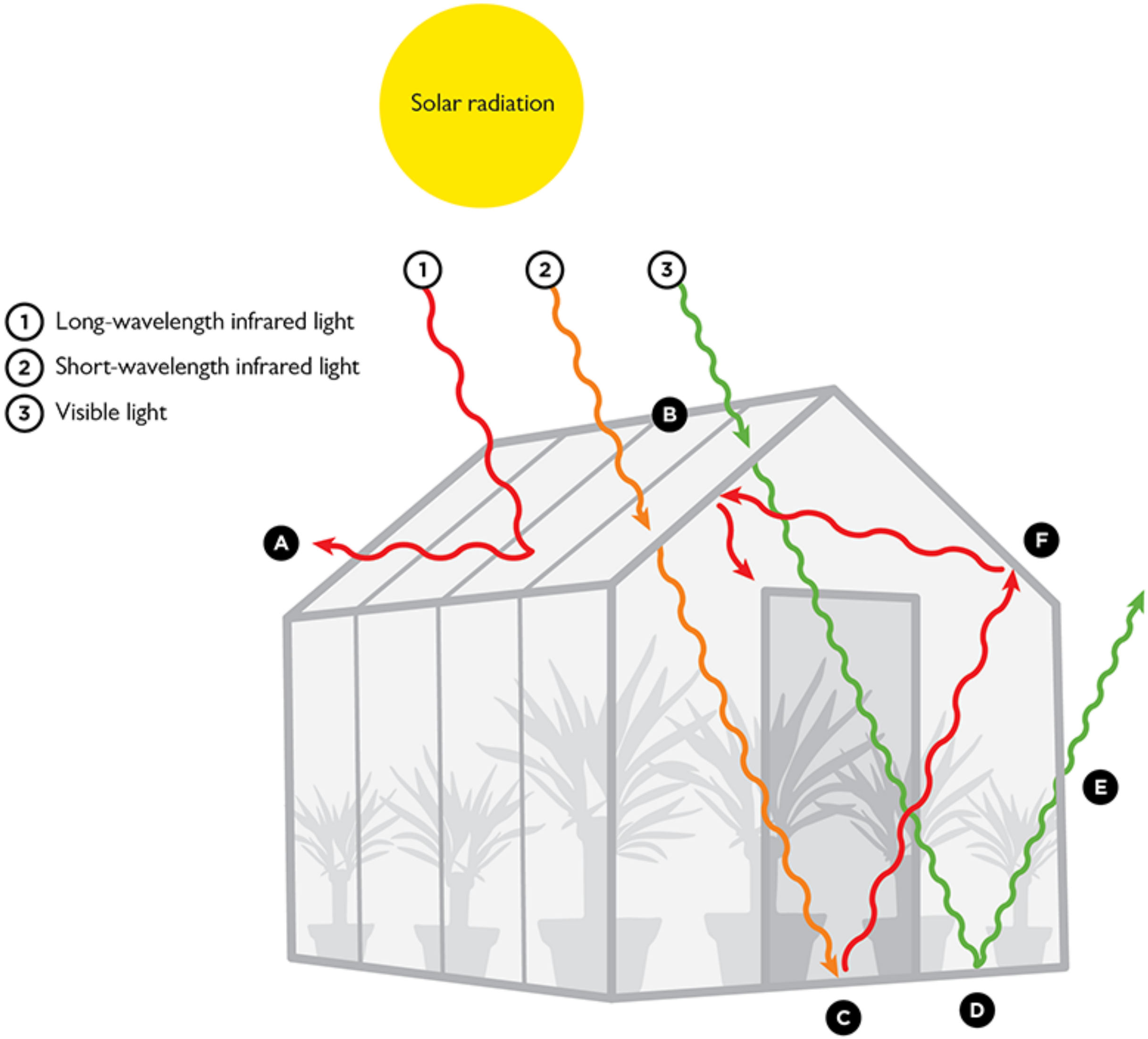
Radiation

- **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 (short wave) or from the earth to the sky (long wave)

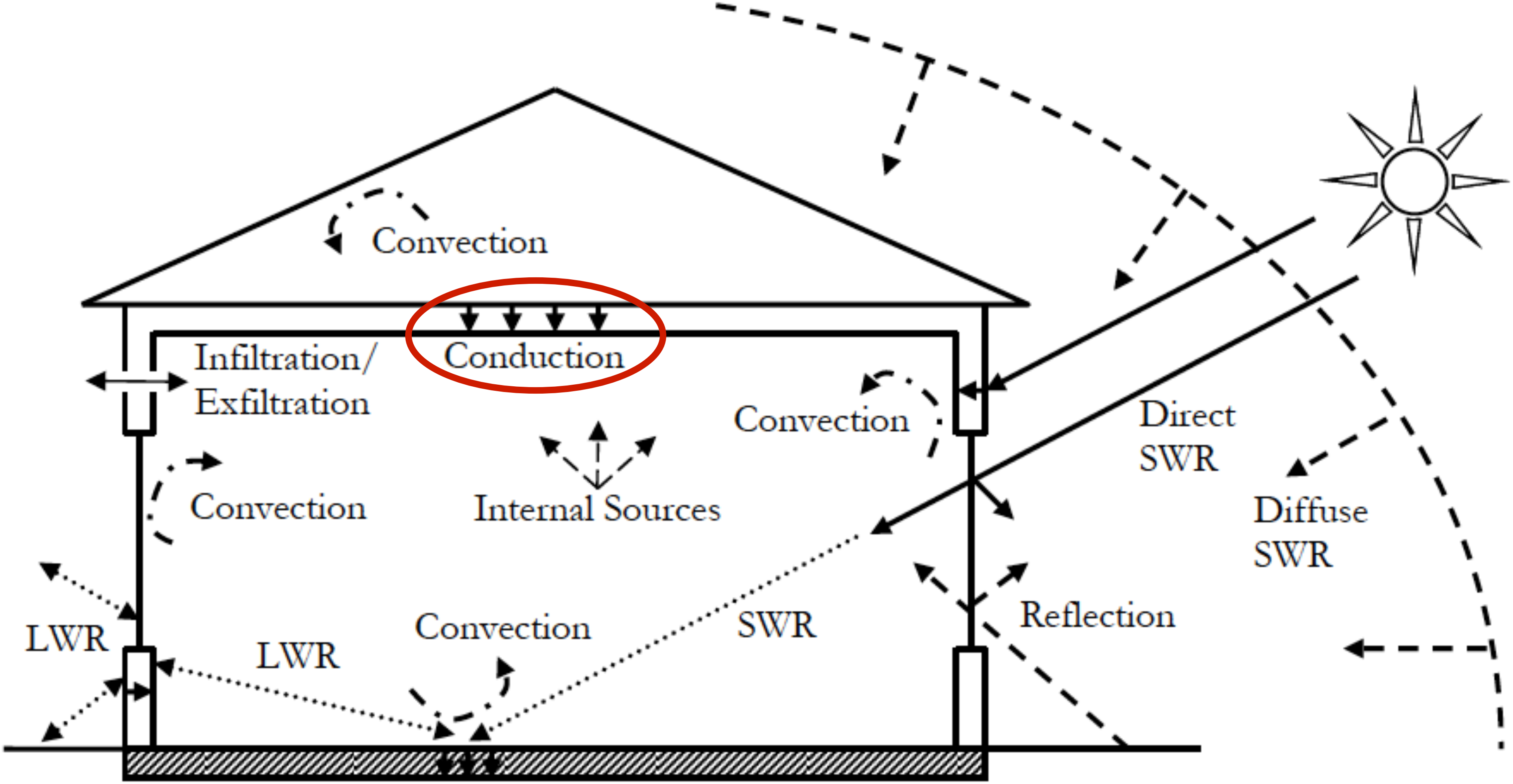


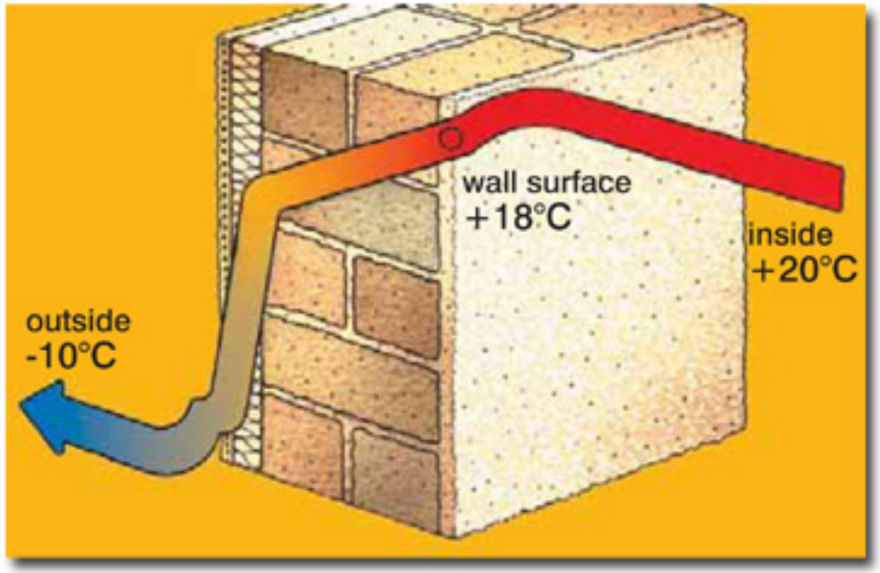


Radiation in buildings



Primary modes of heat transfer in buildings





CONDUCTION

Conduction equation

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

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

"The time rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient, through which heat flows."

where:

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

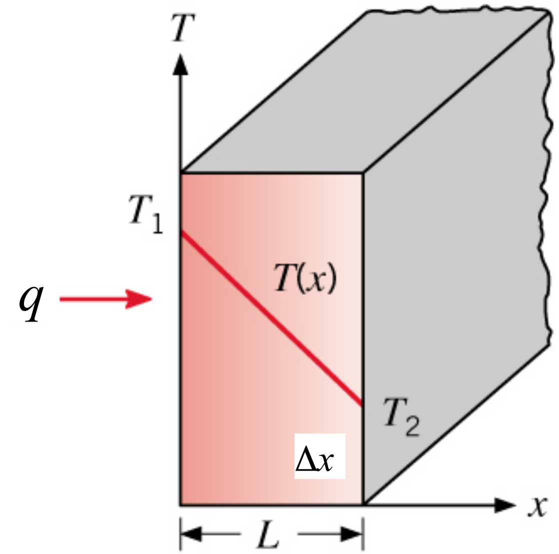
$k =$ thermal conductivity [Btu/(h·ft·°F) or W/(m·K)]

$T =$ temperature [°F or K]

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

Simplified conduction equation: 1-dimension

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



Δx = L

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

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 [$\frac{\text{Btu}}{\text{h}\cdot\text{ft}^2\cdot°\text{F}}$] or [$\frac{\text{W}}{\text{m}^2\text{K}}$]

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

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

Units of R-values and U-values

- 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 often easier 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

Thermal conductivity of some typical materials (*k*)

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

Thermal conductivity of building materials (*k*)

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 (ASHRAE)

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)

From the ASHRAE 2013 Handbook SI (Ch. 26)

Thermal properties of building materials (ASHRAE)

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

Description	Density, kg/m^3	Conductivity[b] k, $W/(m \cdot K)$	Resistance R, $(m^2 \cdot K)/W$	Specific Heat, $kJ/(kg \cdot K)$	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/m^3 concrete, 2 cores	—	—	—	—	
with perlite-filled cores..	—	—	0.37	—	Valore (1988)
~300 mm, 25 kg, 2200 kg/m^3 concrete, 2 cores	—		—	—	
with perlite-filled cores..	—	—	0.65	—	Valore (1988)
Normal-weight aggregate (sand and gravel)					
~200 mm, 16 kg, 2100 kg/m^3 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/m^3 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/m^3 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)

From the ASHRAE 2013 Handbook SI (Ch. 26)

Thermal properties of building materials (ASHRAE)

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

Description	Density, lb/ft³	Conductivity[b] *k*, Btu·in/h·ft²·°F	Resistance *R*, h·ft²·°F/Btu	Specific Heat, Btu/lb·°F	Reference[l]
Insulating Materials					
Blanket and batt[c,d]					
Glass-fiber batts				0.2	Kumaran (2002)
	0.47 to 0.51	0.32 to 0.33	—	—	Four manufacturers (2011)
	0.61 to 0.75	0.28 to 0.30	—	—	Four manufacturers (2011)
	0.79 to 0.85	0.26 to 0.27	—	—	Four manufacturers (2011)
	1.4	0.23	—	—	Four manufacturers (2011)
Rock and slag wool batts.	—	—	—	0.2	Kumaran (1996)
	2 to 2.3	0.25 to 0.26	—	—	One manufacturer (2011)
	2.8	0.23 to 0.24	—	—	One manufacturer (2011)
Mineral wool, felted	1 to 3	0.28	—	—	CIBSE (2006), NIST (2000)
	1 to 8	0.24	—	—	NIST (2000)
Board and slabs					
Cellular glass	7.5	0.29	—	0.20	One manufacturer (2011)
Cement fiber slabs, shredded wood with Portland cement					
binder	25 to 27	0.50 to 0.53	—	—	
with magnesia oxysulfide binder	22	0.57	—	0.31	
Glass fiber board	—	—	—	0.2	Kumaran (1996)
	1.5 to 6.0	0.23 to 0.24	—	—	One manufacturer (2011)
Expanded rubber (rigid)	4	0.2	—	0.4	Nottage (1947)
Extruded polystyrene, smooth skin	—	—	—	0.35	Kumaran (1996)
aged per Can/ULC *Standard* S770-2003	1.4 to 3.6	0.18 to 0.20	—	—	Four manufacturers (2011)
aged 180 days	1.4 to 3.6	0.20			One manufacturer (2011)
European product	1.9	0.21			One manufacturer (2011)
aged 5 years at 75°F	2 to 2.2	0.21	—	—	One manufacturer (2011)
blown with low global warming potential (GWP) (<5) blowing agent		0.24 to 0.25	—	—	One manufacturer (2011)
Expanded polystyrene, molded beads	—	—	—	0.35	Kumaran (1996)
	1.0 to 1.5	0.24 to 0.26	—	—	Independent test reports (2008)
	1.8	0.23	—	—	Independent test reports (2008)

From the ASHRAE 2013 Handbook IP (Ch. 26)

Thermal properties of building materials (ASHRAE)

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

Description	Density, lb/ft³	Conductivity[b] *k*, Btu·in/h·ft²·°F	Resistance *R*, h·ft²·°F/Btu	Specific Heat, Btu/lb·°F	Reference[l]
Phenolic foam board with facers, aged	—	0.14 to 0.16	—	—	One manufacturer (2011)
Loose fill					
Cellulose fiber, loose fill	—	—	—	0.33	NIST (2000), Kumaran (1996)
attic application up to 4 in.	1.0 to 1.2	0.31 to 0.32	—	—	Four manufacturers (2011)
attic application > 4 in.	1.2 to 1.6	0.27 to 0.28	—	—	Four manufacturers (2011)
wall application, densely packed	3.5	0.27 – 0.28	—	—	One manufacturer (2011)
Perlite, expanded	2 to 4	0.27 to 0.31	—	0.26	(Manufacturer, pre-2001)
	4 to 7.5	0.31 to 0.36	—	—	(Manufacturer, pre-2001)
	7.5 to 11	0.36 to 0.42	—	—	(Manufacturer, pre-2001)
Glass fiber[d]					
attics, ~4 to 12 in.	0.4 to 0.5	0.36 to 0.38	—	—	Four manufacturers (2011)
attics, ~12 to 22 in.	0.5 to 0.6	0.34 to 0.36	—	—	Four manufacturers (2011)
closed attic or wall cavities	1.8 to 2.3	0.24 to 0.25	—	—	Four manufacturers (2011)
Rock and slag wool[d]					
attics, ~3.5 to 4.5 in.	1.5 to 1.6	0.34	—	—	Three manufacturers (2011)
attics, ~5 to 17 in.	1.5 to 1.8	0.32 to 0.33	—	—	Three manufacturers (2011)
closed attic or wall cavities	4.0	0.27 to 0.29	—	—	Three manufacturers (2011)
Vermiculite, exfoliated	7.0 to 8.2	0.47	—	0.32	Sabine et al. (1975)
	4.0 to 6.0	0.44	—	—	Manufacturer (pre-2001)
Spray applied					
Cellulose, sprayed into open wall cavities	1.6 to 2.6	0.27 to 0.28	—	—	Two manufacturers (2011)
Glass fiber, sprayed into open wall or attic cavities	1.0	0.27 to 0.29	—	—	Manufacturers' association (2011)
	1.8 to 2.3	0.23 to 0.26	—	—	Four manufacturers (2011)
Polyurethane foam	—	—	—	0.35	Kumaran (2002)
low density, open cell	0.45 to 0.65	0.26 to 0.29	—	—	Three manufacturers (2011)
medium density, closed cell, aged 180 days	1.9 to 3.2	0.14 to 0.20	—	—	Five manufacturers (2011)

From the ASHRAE 2013 Handbook IP (Ch. 26)

How building materials are actually sold

- 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

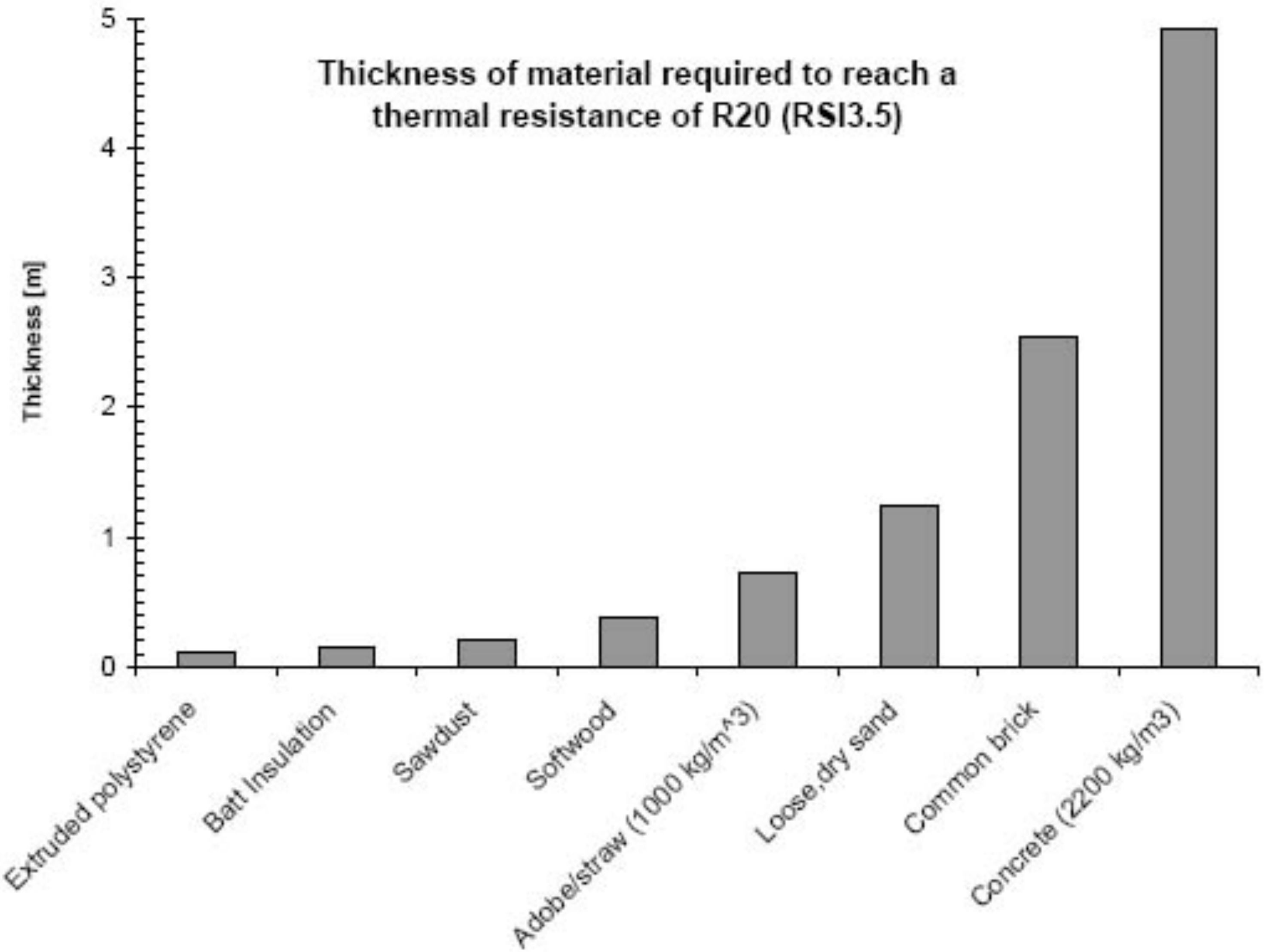
Q: What is the thermal conductivity of an R-5 per inch (IP) XPS board?

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 (XPS) rigid foam insulation – closed cell

Thickness, conductivity, and thermal resistance



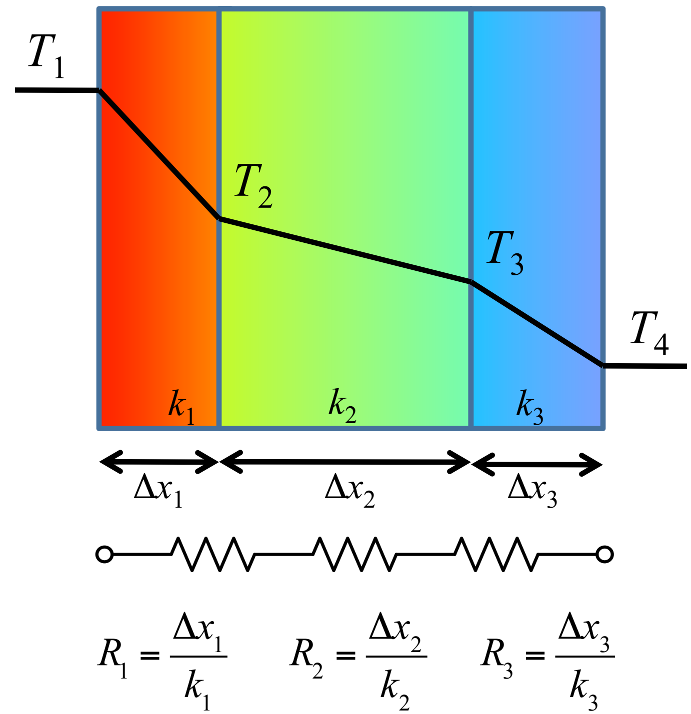
https://buildingscience.com/documents/digests/bsd-011-thermal-control-in-buildings

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:

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

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



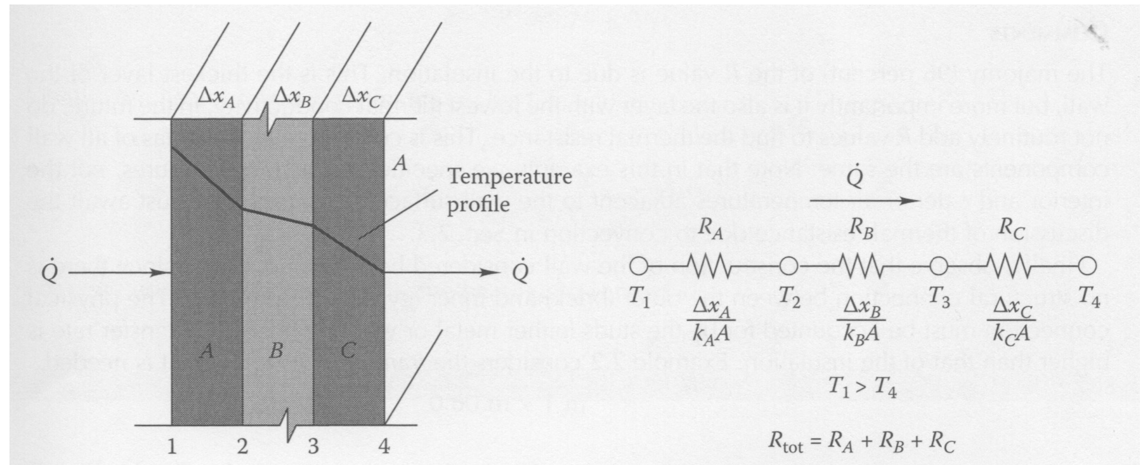
$$q = U_{total}\left(T_1 - T_4\right)$$

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

Example of conduction through multiple layers

- R-value calculation for a building wall:

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



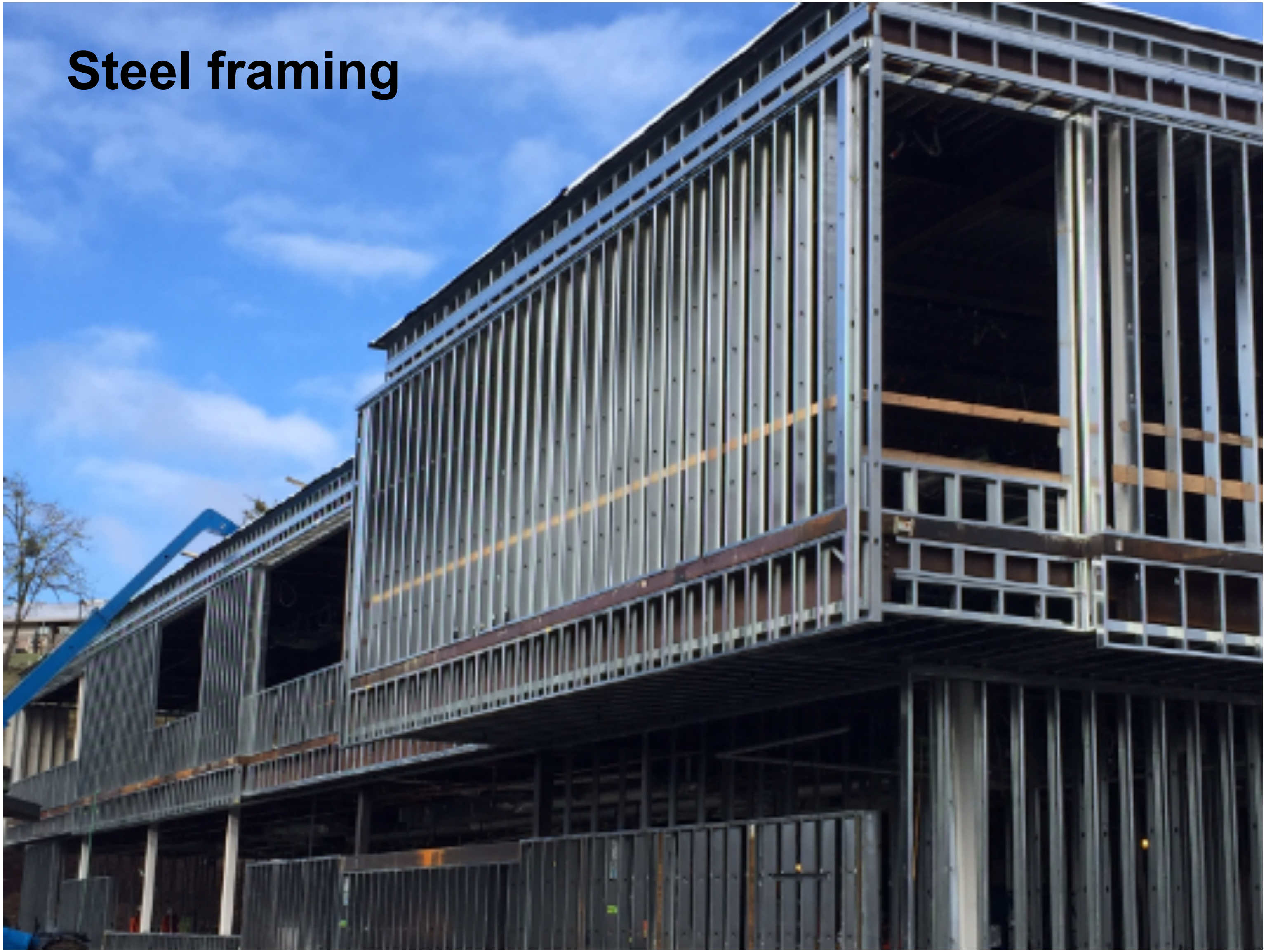
1) What is the overall R-value?

2) What is the steady-state heat flux through the wall if the interior surface temperature is 72°F (22°C) and the exterior surface is 41°F (5°C)?

What about more realistic constructions?

Wood framing

What about more realistic constructions?

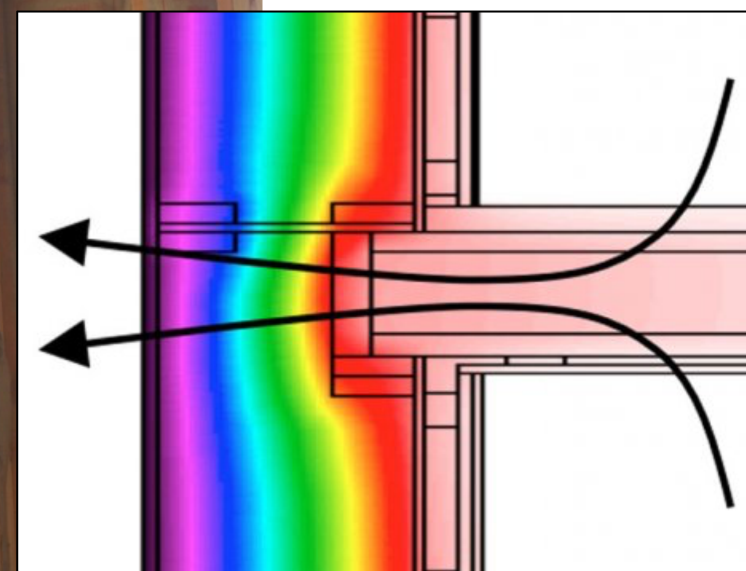


What about more realistic constructions?

- Time-lapse of a house build #1: https://www.youtube.com/watch?v=zBIa3M9XJeM
- Time-lapse of a house build #2: https://www.youtube.com/watch?v=C3iI6S7TuCA
- Time-lapse of fiberglass batt insulation install: https://www.youtube.com/watch?v=eNRc1em-XTM

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
  - Structural elements form what we call **thermal bridges**



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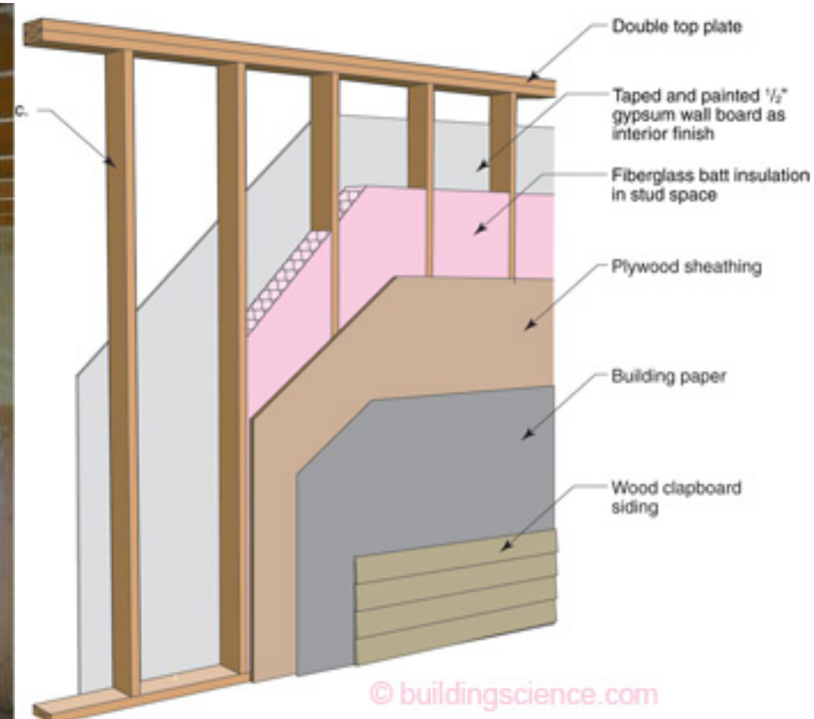

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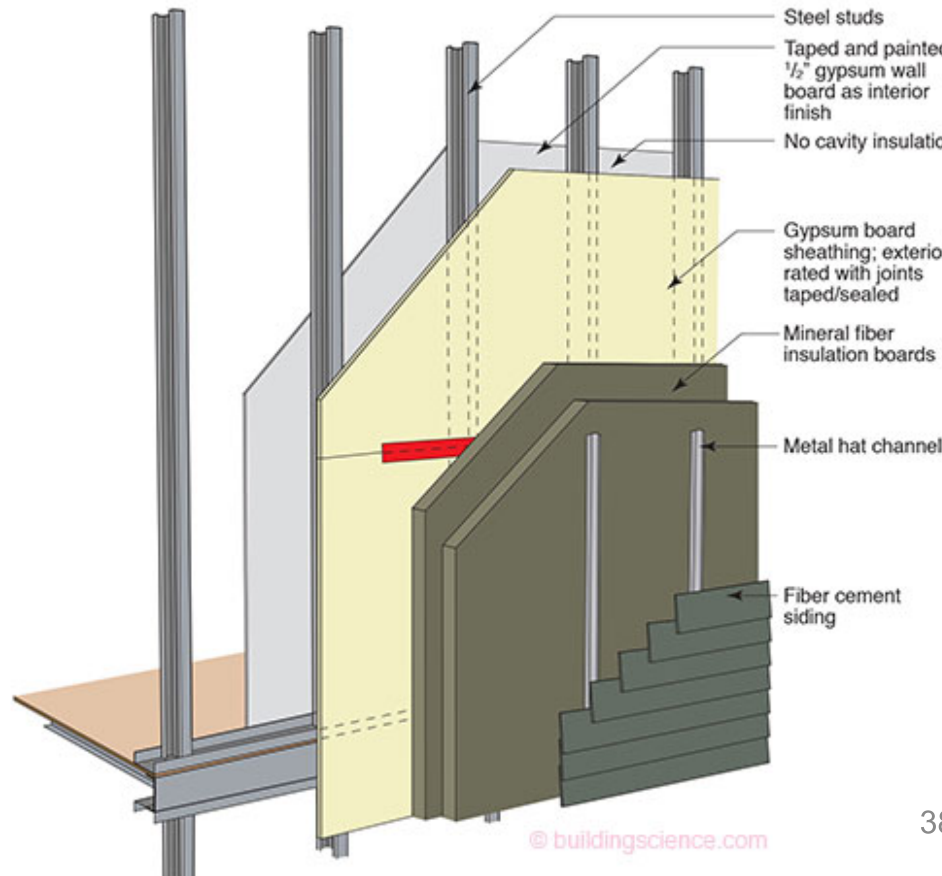

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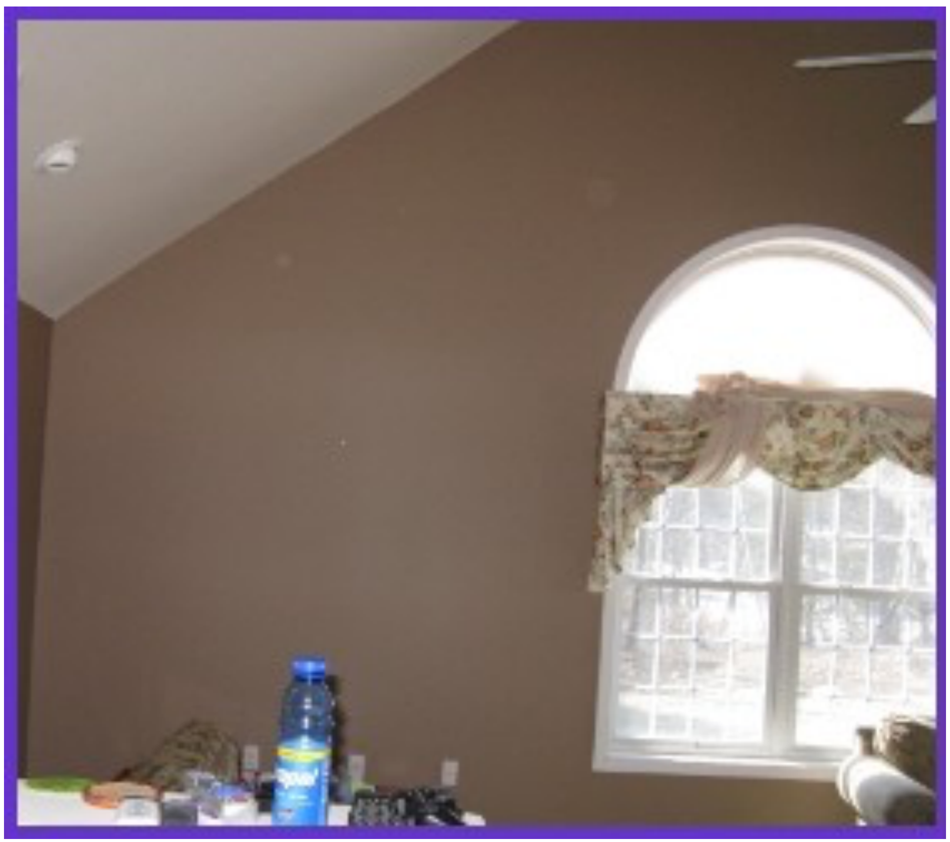

http://www.massinfrared.com/files/insulated_wall.jpg

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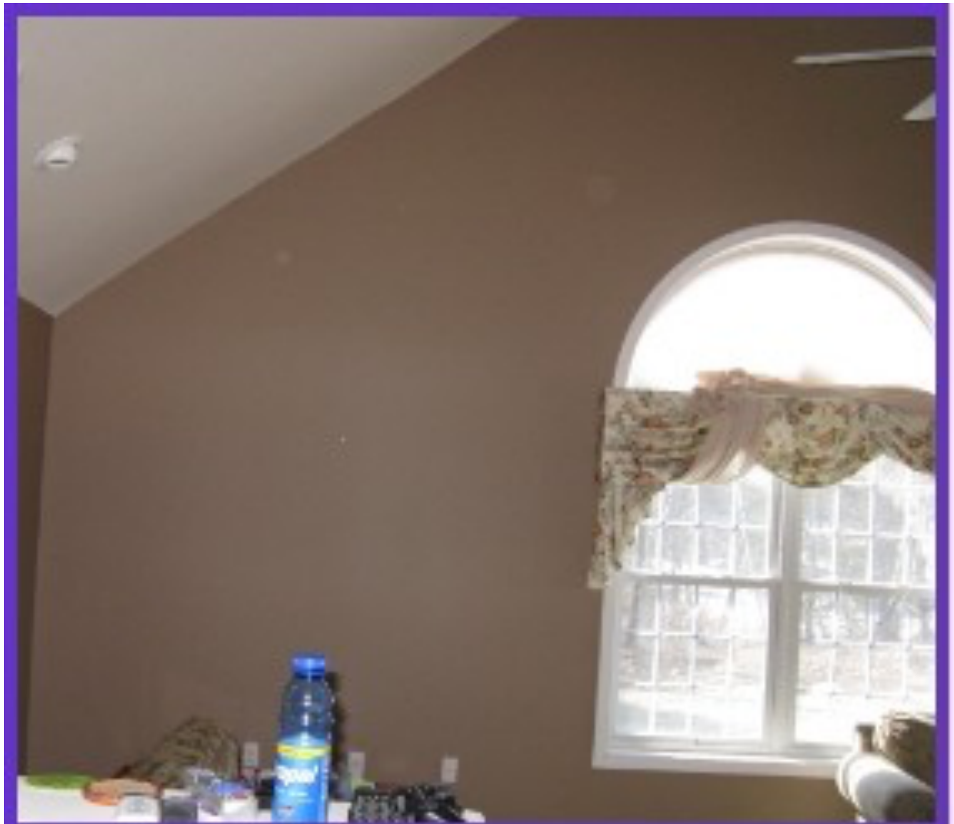

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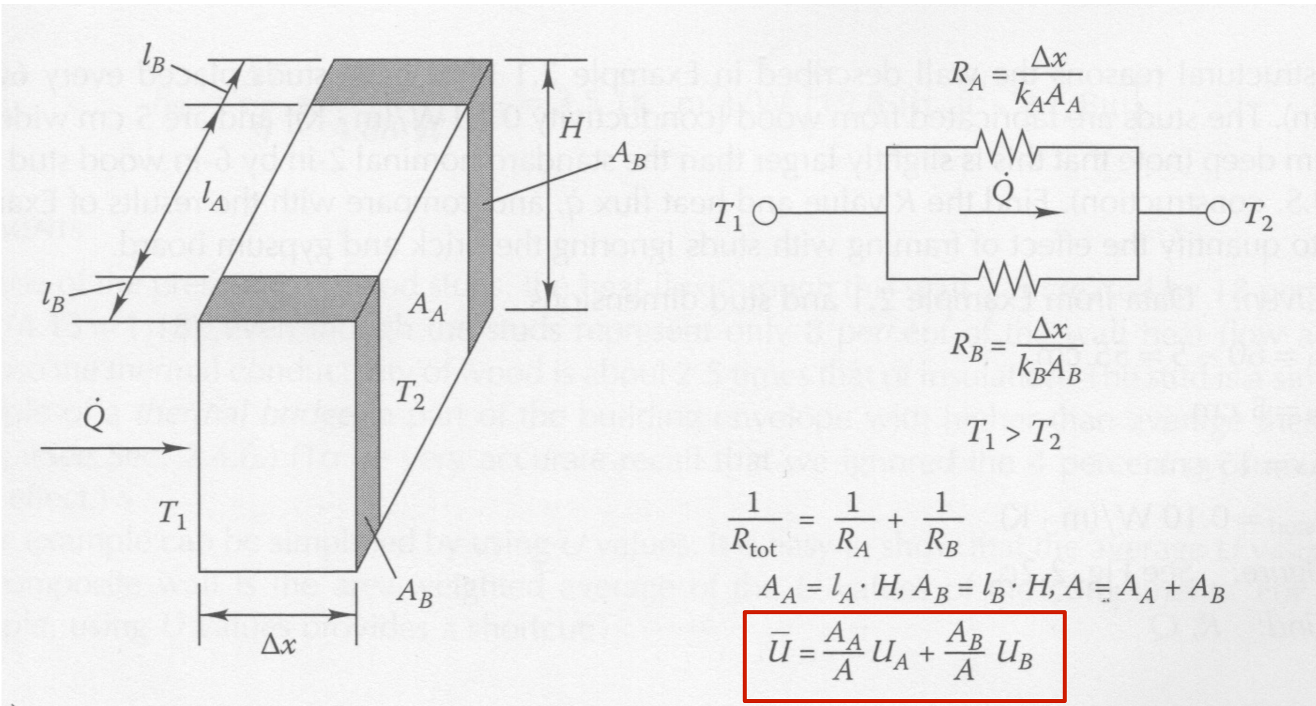
Accounting for structural elements (studs)

- Parallel-resistance heat flow **ASHRAE HoF 20017: Ch. 25 & 27**



Treat resistances as resistors in parallel

- Simply 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)
  - "24 in o.c." = 24 inches on center
- The studs are wood with k = 1 BTU-in/hr-ft^2-°F and are 2 inches (5 cm) wide and 6 inches (15 cm) deep
- **Problem:** Find the "effective" R-value of this assembly and compare to the previous example

Next time

- Continuing heat transfer (transient conduction)