CAE 463/524
Building Enclosure Design
Spring 2015

Lecture 2: January 20, 2015
Review of building science

Built
Environment
Research
@ IIT

Advancing energy, environmental, and sustainability research within the built environment

www.built-envi.com

Twitter: @built_envi

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

Last time

- Introduction to building enclosures
  - Keep the indoor in and the outdoor out
    - Unless we like what the outdoors has to offer
- Parameters that drive building enclosure physics
  - Temperature, humidity, wind, precipitation, solar radiation
- Nature of heat, air, and moisture
  - Pyschrometrics (2013 ASHRAE Handbook Chapter 1)
  - Calculating dew point temperatures, humidity ratio, enthalpy, etc.

Campus projects (Project 1)

Objective: Take what you learn about heat, air, and moisture transport (and failures) in building enclosures and apply those fundamentals to critically assess the enclosure of a building on IIT's campus. Expectations document on BB now.

- Will also recommend retrofits to increase performance
- In previous versions, all students used Crown Hall
  - We'll expand on that
- Use of thermal imaging and other tools
- "Real" field experience

Deliverables:

- Report of findings (ex. on BB)
- Presentation in class

Due date: March 10th

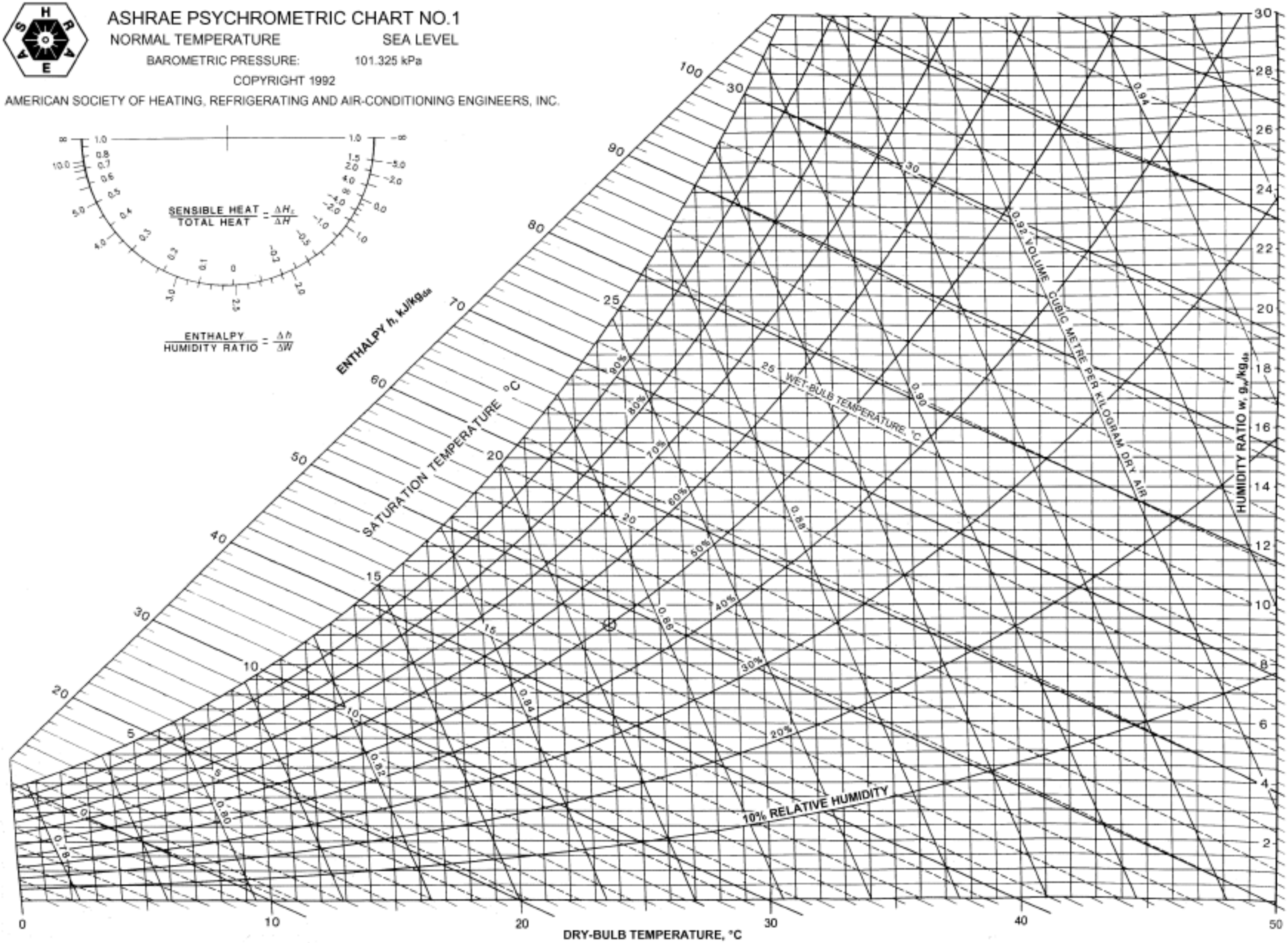
Campus projects: Expectations uploaded to BB

- Need to do thermal assessments by early March
  - 20 students in this class: Let's do 5 teams of 4 people

Course	Name	Major	Level	Campus building
CAE463-01	Behrens, Maria C.	ARCE	U4	
CAE463-01	Geoghegan, Thomas	ARC2	GR	
CAE463-01	Irazabal, Carlos H.	ARCE	U4	
CAE463-01	Jung, Yun Joon	ARCE	U4	
CAE463-01	Lis, Kimberly A.	ARCE	U5	
CAE463-01	Ng, Yin Ling	ARCE	U5	
CAE463-01	Theisen, Whitney A.	ARCE/EMGT	U5	
CAE463-01	Zanzinger, Zachary D.	ARCE	U5	
CAE524-01	Carrillo Garcia, Jose	ARCE	GR	
CAE524-01	Dorn, Lawrence E.	CM	GR	
CAE524-01	Erukulla, Dilip Kumar	ARCE	GR	
CAE524-01	Liang, Jinzhe	CE	GD	
CAE524-01	Mullin, Elizabeth M.	ARCE/ARCE	U5	
CAE524-01	Tuz, Oleg	CM	GR	
CAE524-02	Chandler, Julie A.	ARCE	GR	
CAE524-02	Chung, Allan	CM	GR	
CAE524-02	Fortune, Roger G.	ARCE	GR	
CAE524-02	Gadani, Dhaval S.	ARCH/CM	U5	
CAE524-02	Jarosz, Michelle M.	STE	GR	
CAE524-02	Linn, Rebecca C.	ARCE	GR	

Objectives for today's lecture

- Building science review
  - Heat transfer and building enclosures

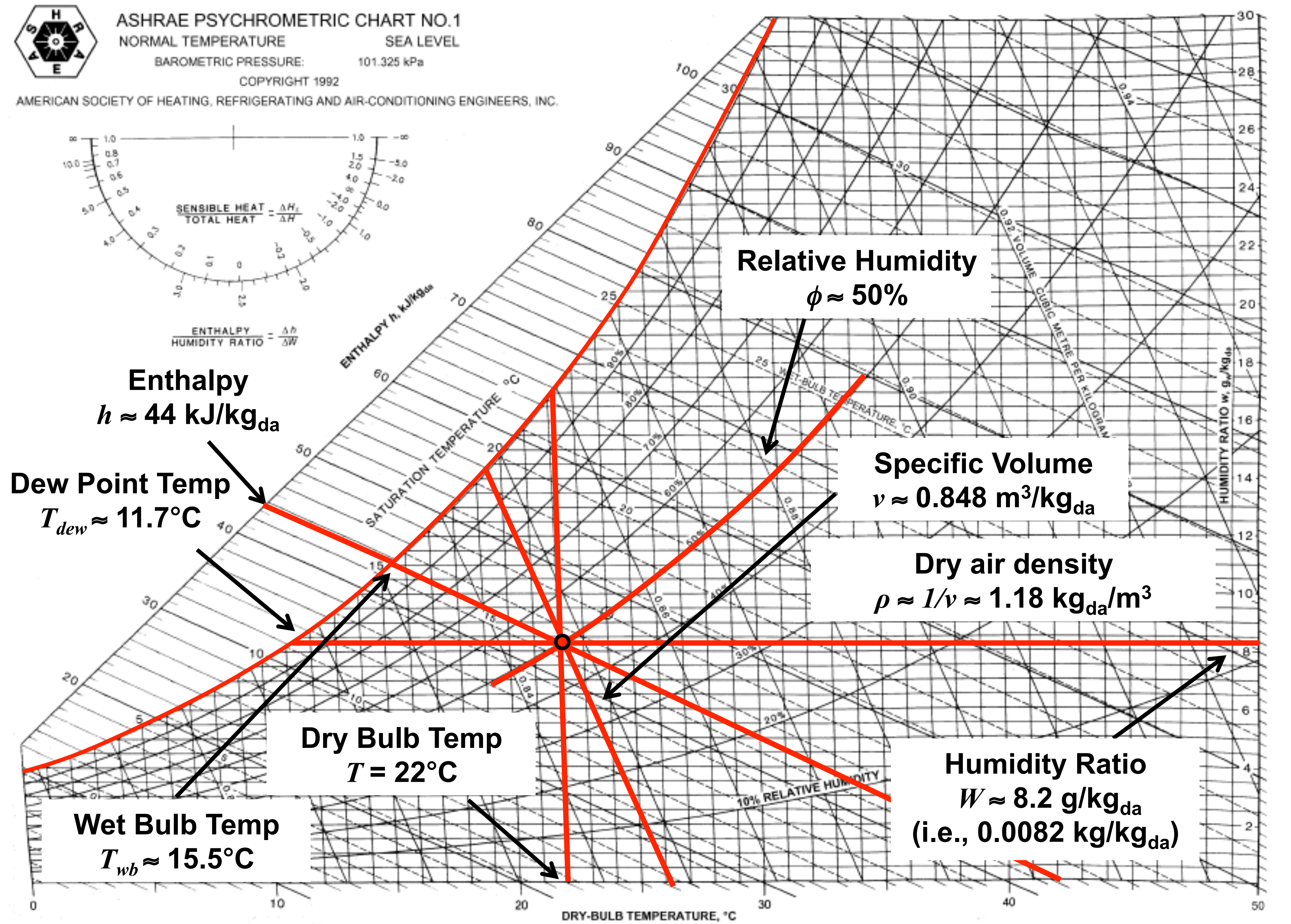

ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
COPYRIGHT 1992
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kgda
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, gw/kgda
DRY-BULB TEMPERATURE, °C

Key terms for describing moist air

- To describe and deal with moist air, we need to be able to describe the fractions of dry air and water vapor
- There are several different equivalent measures
  - Which one you use depends on what data you have to start with and what quantity you are trying to find

Key terms to know:

- Dry bulb temperature
- Vapor pressure
- Saturation
- Relative humidity
- Absolute humidity (or humidity ratio)
- Dew point temperature
- Wet bulb temperature
- Enthalpy
- Density
- Specific volume


ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
COPYRIGHT 1992
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kg da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM
HUMIDITY RATIO w, g/kg da
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C
Relative Humidity
φ ≈ 50%
Enthalpy
h ≈ 44 kJ/kg da
Dew Point Temp
T dew ≈ 11.7°C
Specific Volume
v ≈ 0.848 m³/kg da
Dry air density
ρ ≈ 1/v ≈ 1.18 kg da/m³
Dry Bulb Temp
T = 22°C
Wet Bulb Temp
T wb ≈ 15.5°C
Humidity Ratio
W ≈ 8.2 g/kg da
(i.e., 0.0082 kg/kg da)

HEAT TRANSFER

Review of building science

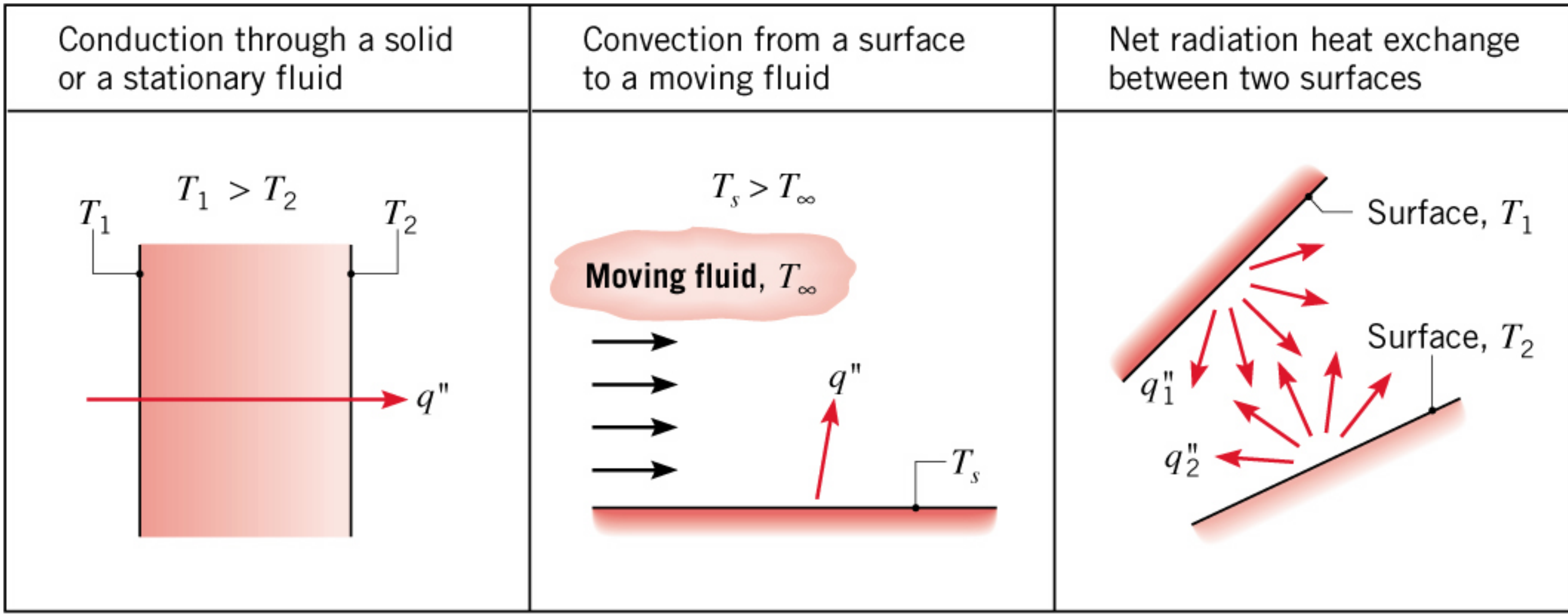
Heat transfer

- Heat flow can be steady-state or transient
  - Steady-state (temperature/heat flow **do not** vary w/ time)
    - Heat in = heat out
  - Transient (temperature & heat flow vary w/ time)
    - Can have storage of heat
  - Choice depends on complexity of the problem you're investigating and the types of materials involved

- Heat flow occurs in 1, 2, and 3 dimensions
  - In almost all real situations, heat flow occurs in 3-D
  - 1-D is often acceptable from a practical standpoint

Heat transfer

- Three modes of heat transfer



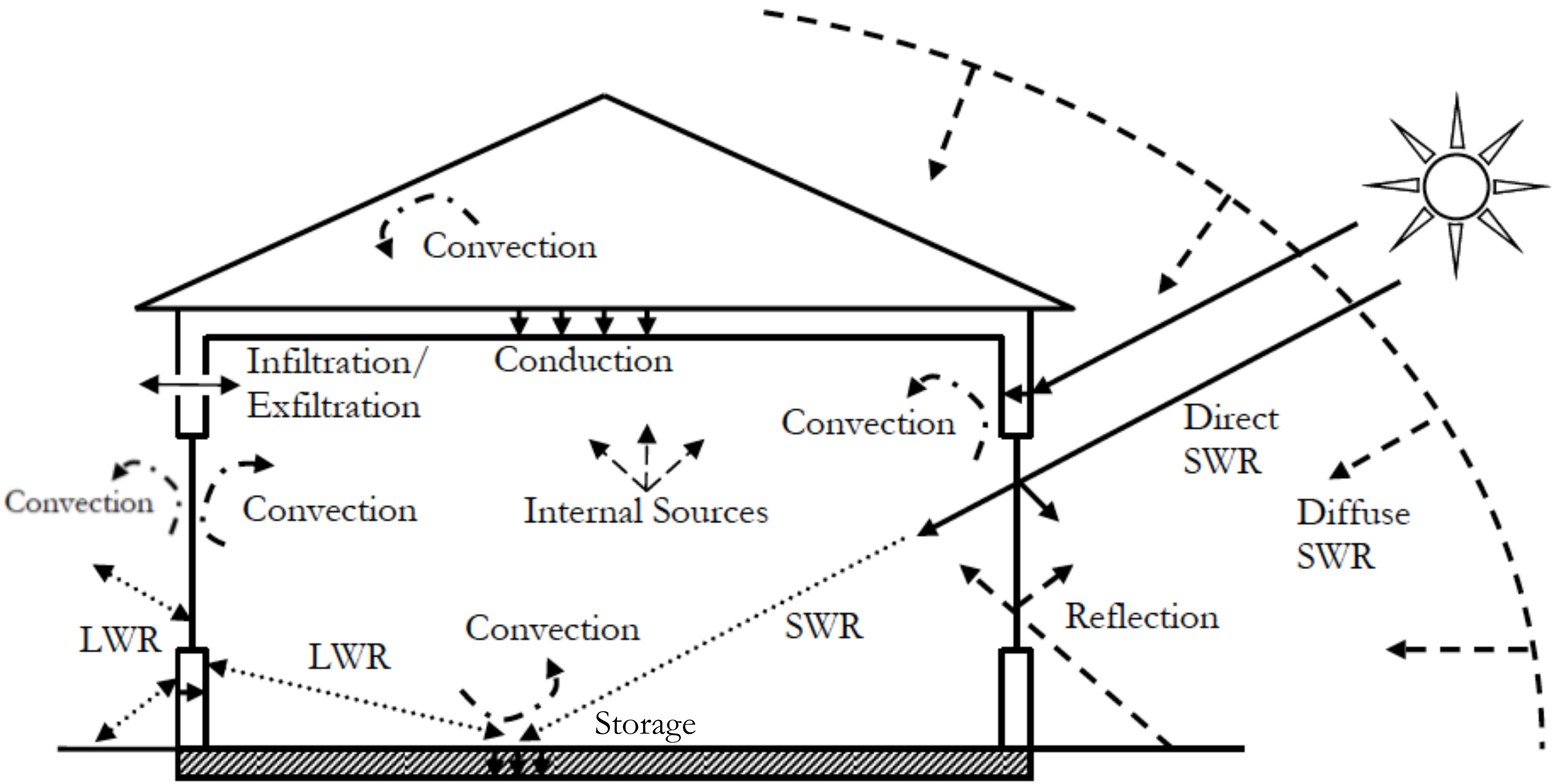
Conduction **Convection** **Radiation**

*Note: Change of physical state is also a mechanism of heat transfer

Example of heat transfer in a building enclosure

- The sun transmits heat energy by short wave radiation to the earth where it may be absorbed by a brick wall
- Heat energy is then transferred by conduction through the brick
  - Heat energy may also be stored temporarily according to the material's heat capacity
- Heat energy is then transferred by convection to indoor air and by long wave radiation to other indoor surfaces, which also affect indoor air temperatures by convection

Building enclosures and heat transfer, visualized



Units of heat transfer

- We denote the total rate of heat energy transfer by the symbol Q
  - It is a rate of energy transfer (i.e., a *power*)
  - Heat **flow**
  - So the units are W (J/s) or BTU/hr (1 W = 3.412 BTU/hr)

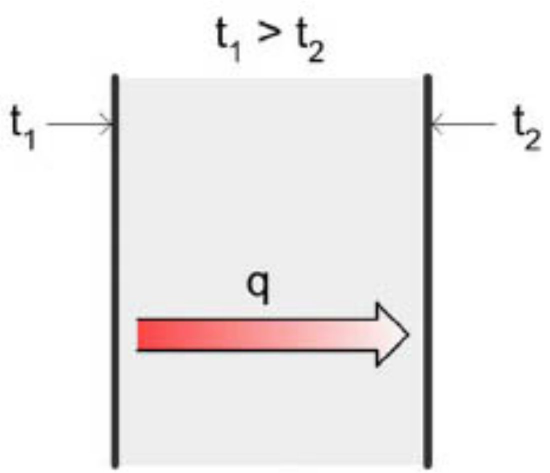
- We denote the rate of heat transfer per unit area by the symbol q
  - By definition $q = Q/A$
    - Where A is the area through which the heat is moving
  - Heat **flux**
  - The units of q are W/m^2 or BTU/(hr·ft^2)
    - 1 W/m^2 = 0.317 BTU/(hr·ft^2)

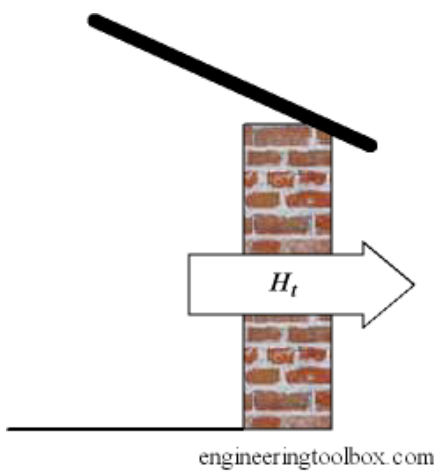
A tale of two Q's: Q and q

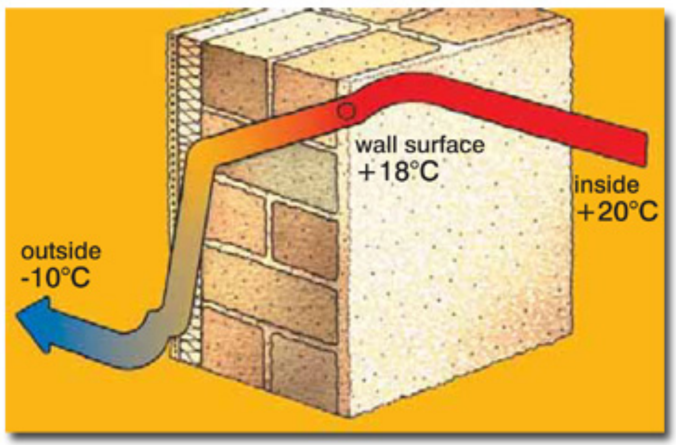
- Some books work with the total heat transfer Q as their fundamental quantity
- Most textbooks use heat transfer per unit area [$q = Q/A$] as the fundamental quantity
- Using q instead of Q makes it easier to compare the thermal properties of assemblies without regard to the actual size of them

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



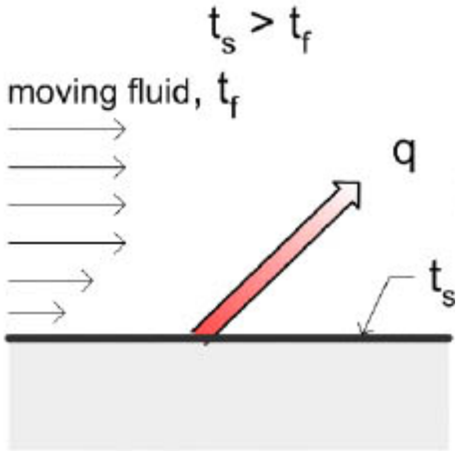


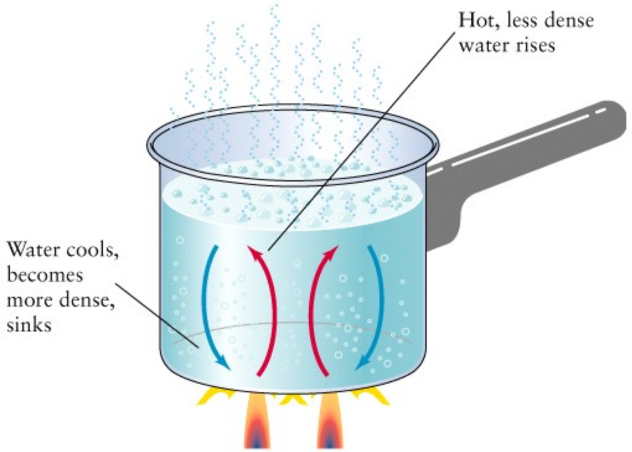


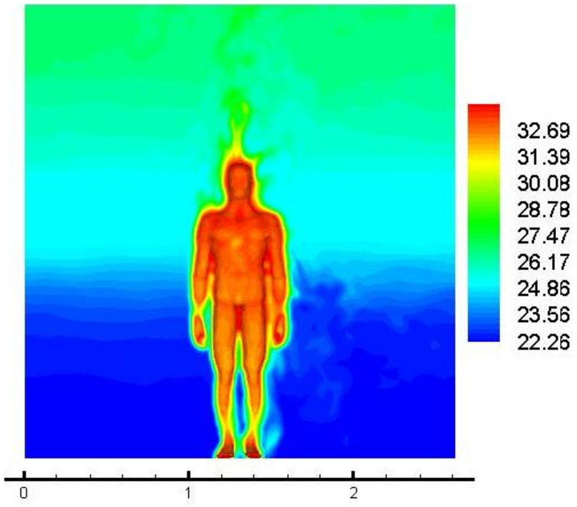
Conduction

Convection

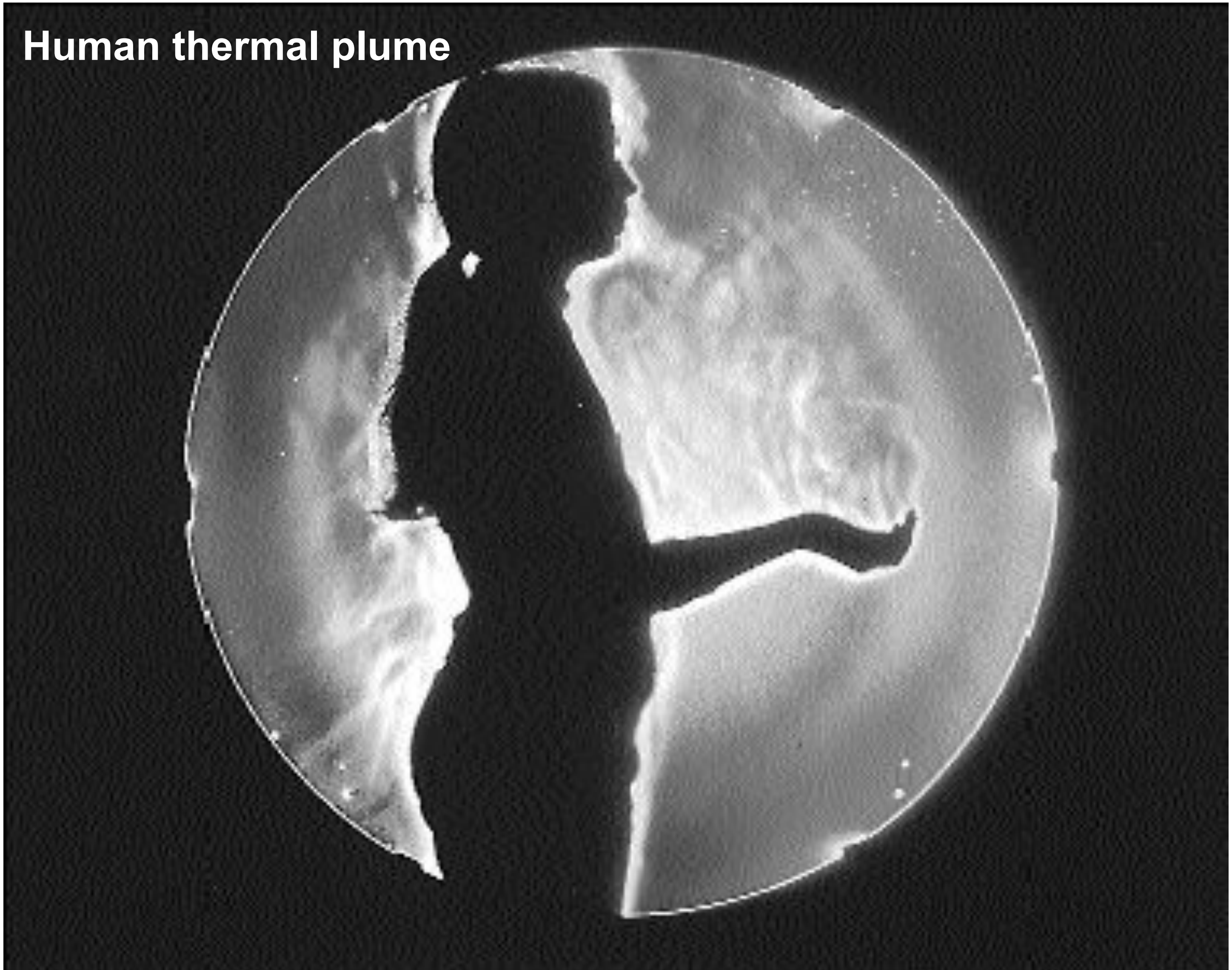
- **Convection** heat transfer is a result of larger-scale motions of a fluid, either liquid or gas
- The higher the velocity of fluid flow, the higher the rate of convection heat transfer
  - Also the greater the temperature difference the greater the heat flow
- Example: when a cold wind blows over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





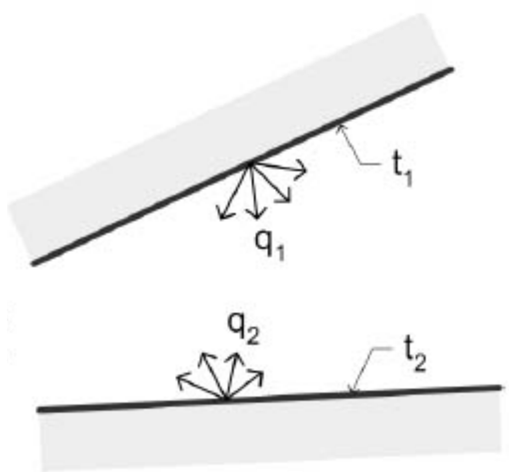


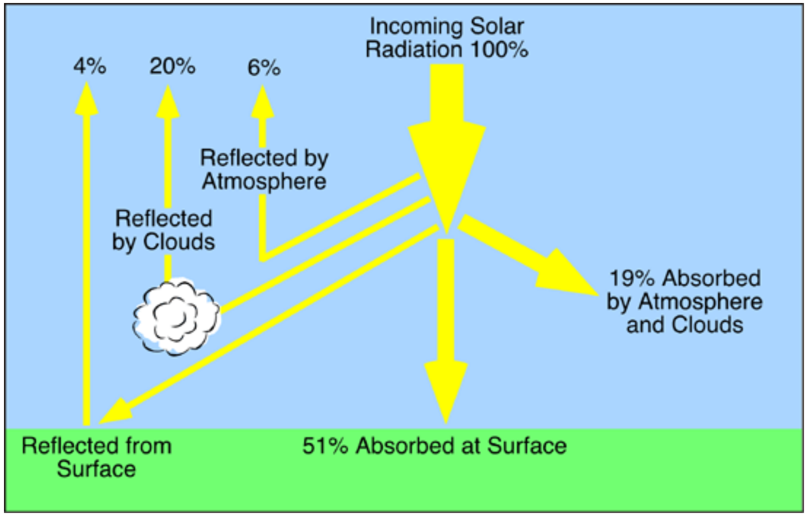
Convection



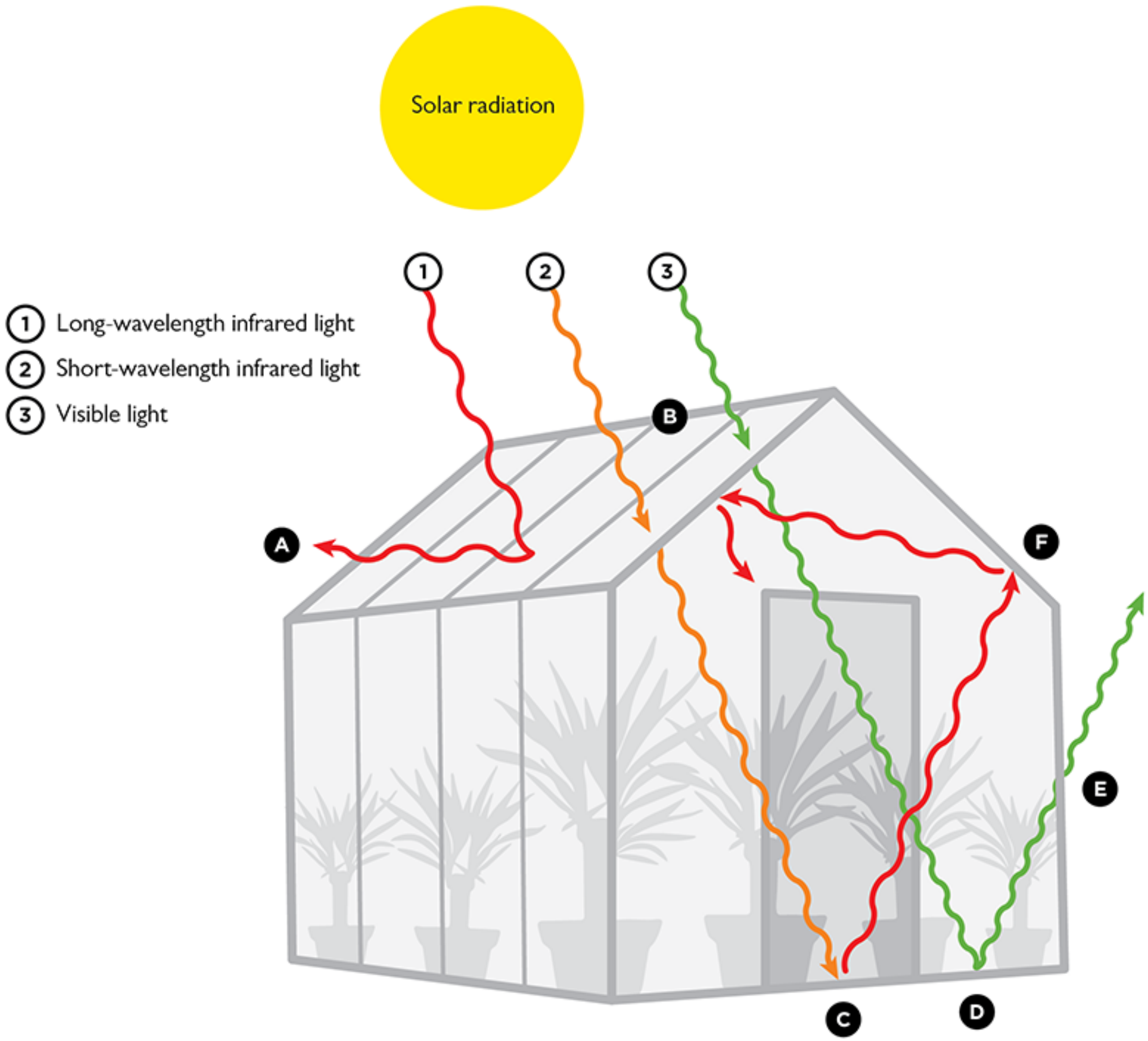
Radiation

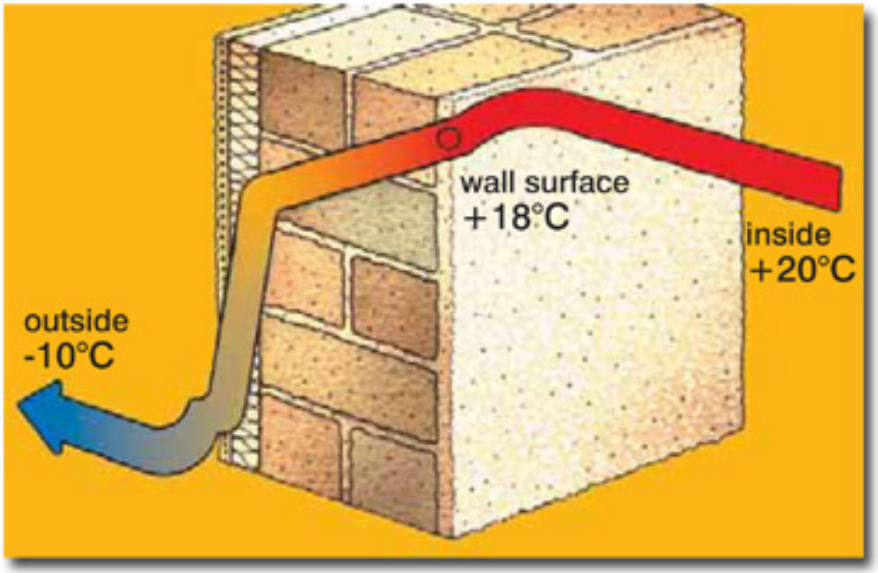
- **Radiation** heat transfer is the transport of energy by electromagnetic waves
  - Oscillations of electrons that comprise matter
  - Exchange between matter at different temperatures
- Radiation must be absorbed by matter to produce internal energy; emission of radiation corresponds to reduction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





Solar radiation striking a translucent surface





CONDUCTION

Review of fundamentals

Conduction

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

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

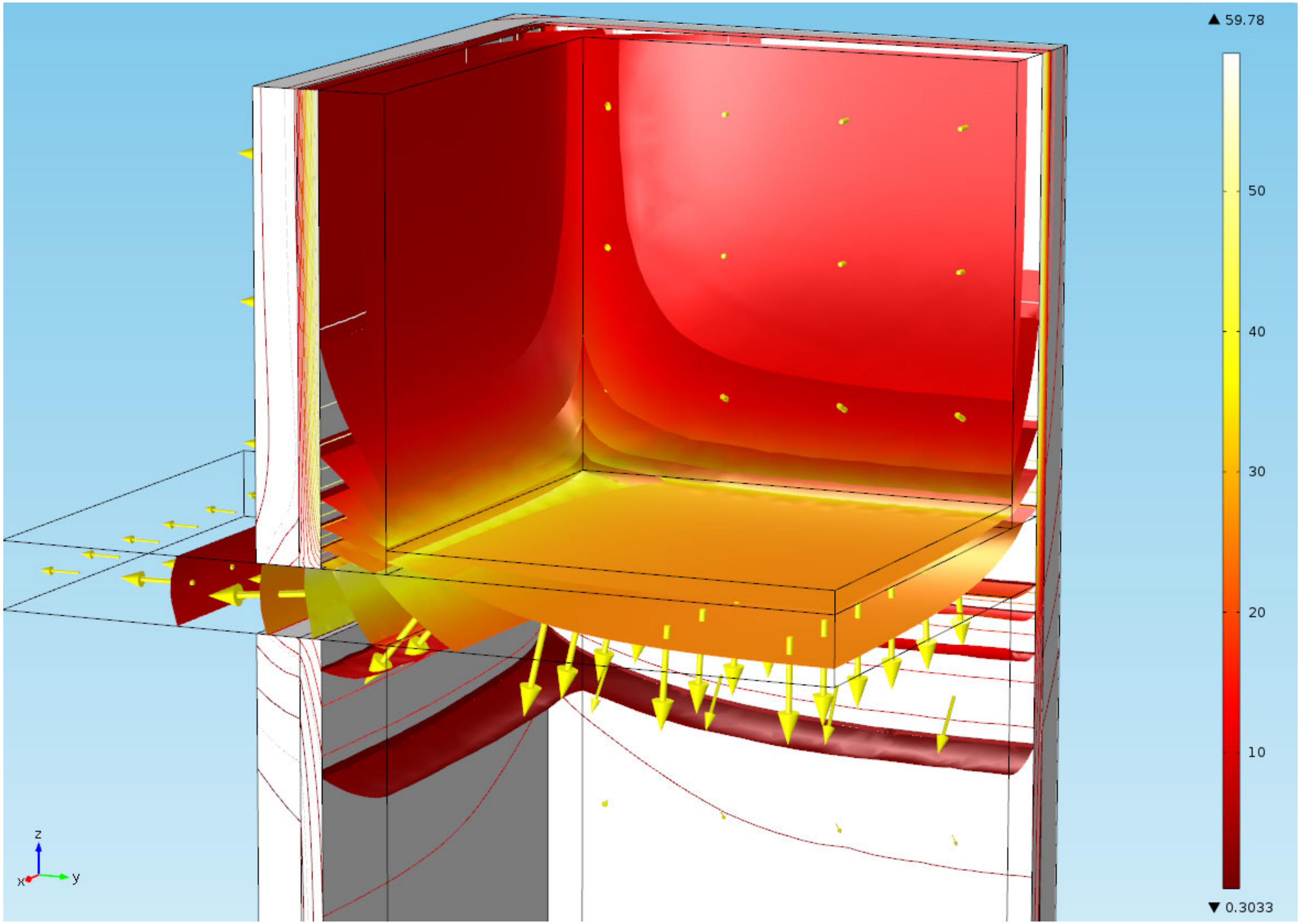
where:

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

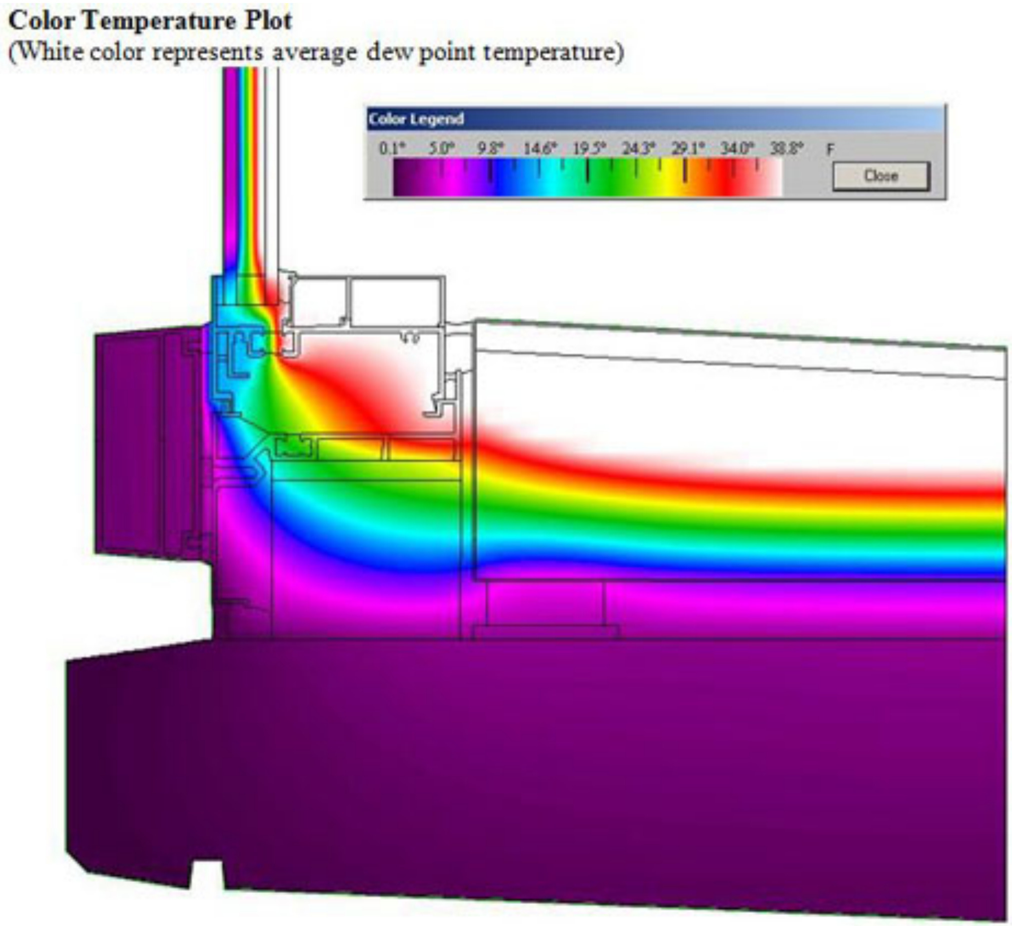
$k =$ thermal conducitivity [Btu/(h·ft·°F) or W/(m·K)]

$T =$ temperature [°F or K]

3D conduction and enclosures

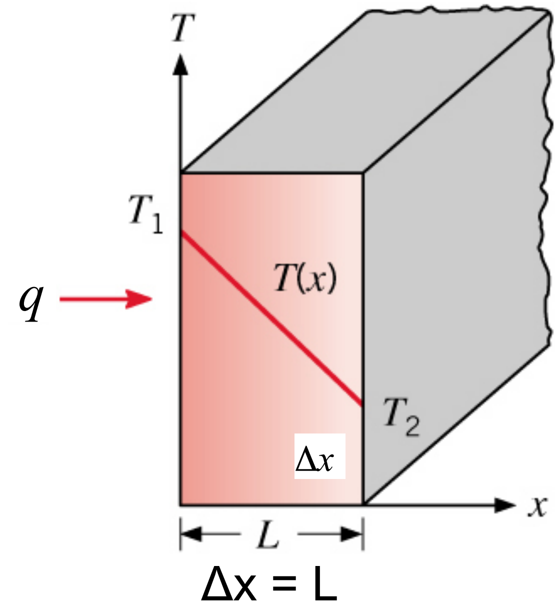


2D conduction and enclosures (simplified)



Even more simplified conduction: 1D

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/m²] by A [m²]

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

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

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

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

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 $[\mathrm{W/(m^2 \cdot K)}]$. 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 $[\mathrm{(m^2 \cdot K)/W}]$.

Therefore:

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

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

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

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

R-IP

Important note on conduction

- The R value of most materials is temperature **independent** (in *most* conditions), so …
- The rate of conductive heat transfer depends ONLY on the temp difference ΔT between the two sides of the material
  - Just as must heat is transferred if the interior is 90 and exterior is 70 as when the interior is 70 and the exterior is 50
- There are some exceptions to this

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/m^3	Conductivity[b] k, W/(m·K)	Resistance R, $(m^2 \cdot K)/W$	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/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)

Actual building materials

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

PRODUCT OVERVIEW

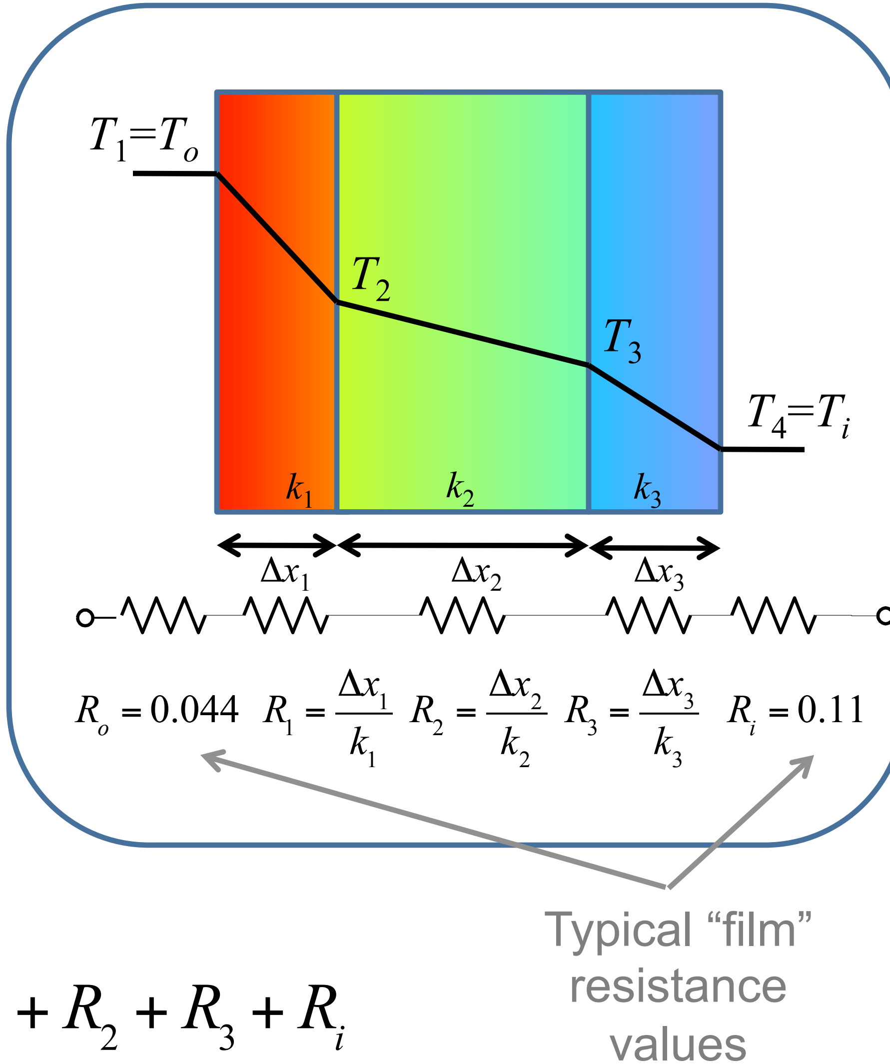
FOAMULAR 150 extruded polystyrene (XPS) rigid foam insulation contains hundreds of millions of densely packed closed cells to provide exceptional thermal performance. It's also virtually impervious to moisture, unlike other plastic foam insulation products, preventing loss of R-value due to moisture 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

Conduction through multiple layers

- Just as in electrical circuits, the overall thermal resistance of a series of elements (layers) can be expressed as the sum of the resistances of each layer
  - Do not forget the interior and exterior convective resistances!



- By continuity of energy we can write

$$q = \frac{T_1 - T_2}{R_1} = \frac{T_2 - T_3}{R_2} = \frac{T_3 - T_4}{R_3}$$

so

$$q = \frac{T_1 - T_4}{R_{total}} \quad \text{where} \quad R_{total} = R_o + R_1 + R_2 + R_3 + R_i$$

Can only add resistances (R-values) in series, not conductances (U-values)

Limitations to the summation rule

The summation rule for finding R_{total} has several limitations:

- Only works for **layers in series**
- Layers must be **same area**
- Layers must be **uniform thickness**
- Layers must have **constant material properties**
  - This is the **biggest** limitation

What do we do with more realistic constructions?

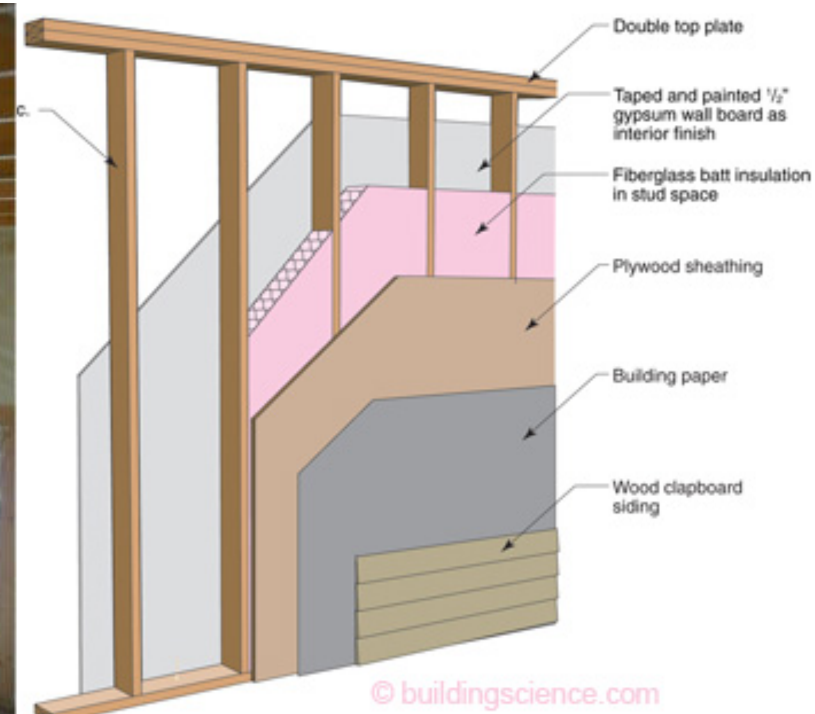
Parallel path or ISO thermal equivalents

2D or 3D modeling

* Will cover in subsequent lectures

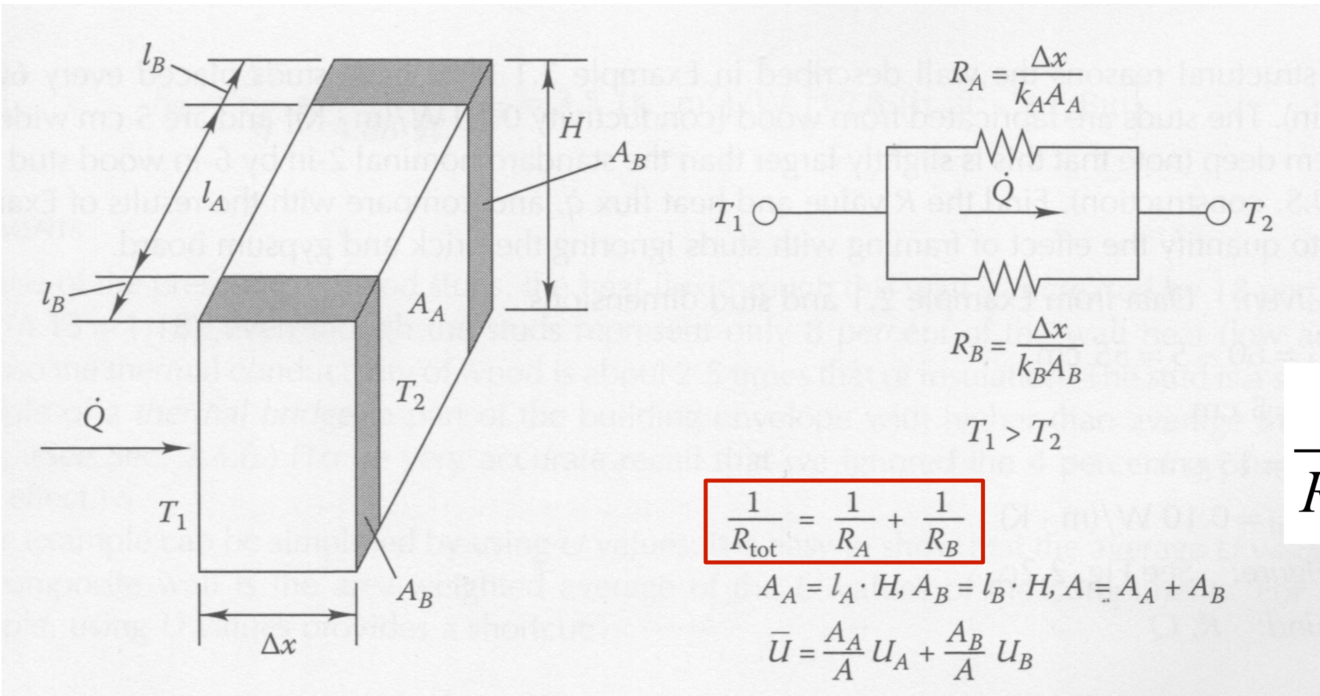
What about more realistic constructions?

- 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

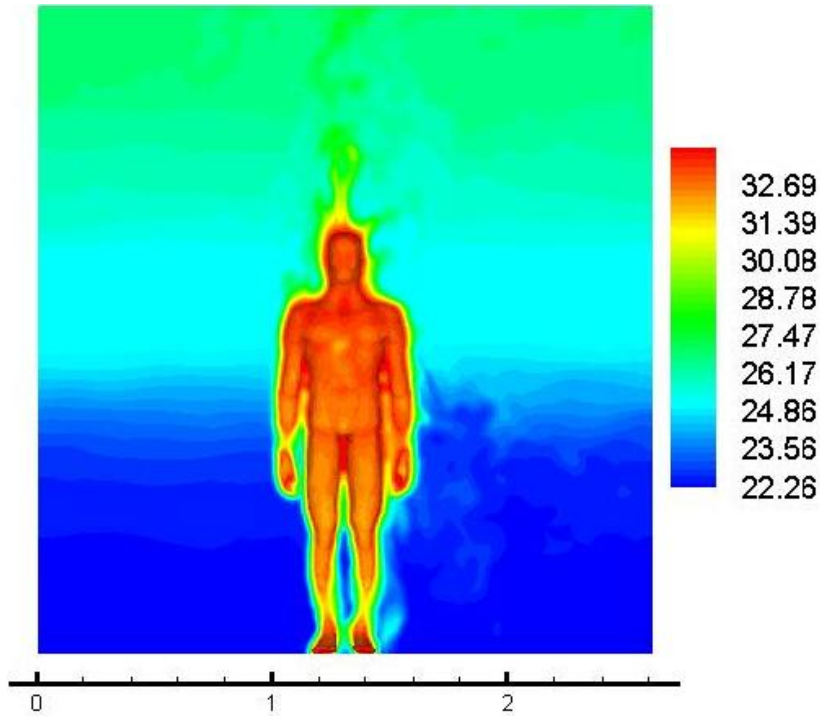


Treat resistances like resistors in series:

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

- Or use weighted average U values:

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

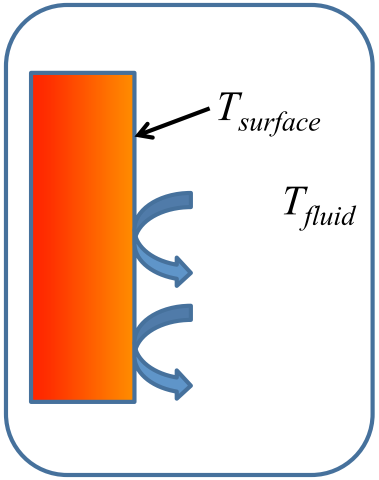


CONVECTION

Review of fundamentals

Convection

- Convective heat transfer occurs between a solid and a moving fluid
  - Since heat transfer to a still fluid causes buoyancy which moves the fluid, all solid-fluid heat transfer is convective
- The heat transfer coefficient, h_{conv}, relates the heat transfer to the difference between the solid temperature, $T_{surface}$, and the effective temperature of the fluid far from the surface, T_{fluid}



$$q_{conv} = h_{conv}\left(T_{fluid} - T_{surface}\right) = \frac{T_{fluid} - T_{surface}}{R_{conv}} = \frac{\Delta T}{R_{conv}}$$

where T_{fluid} = fluid temperature far enough not to be affected by $T_{surface}$

h_{conv} = convective heat transfer coefficient [W/(m$^2\cdot$K)]

and $R_{conv} = \dfrac{1}{h_{conv}}$ = convective thermal resistance [(m$^2\cdot$K)/W]

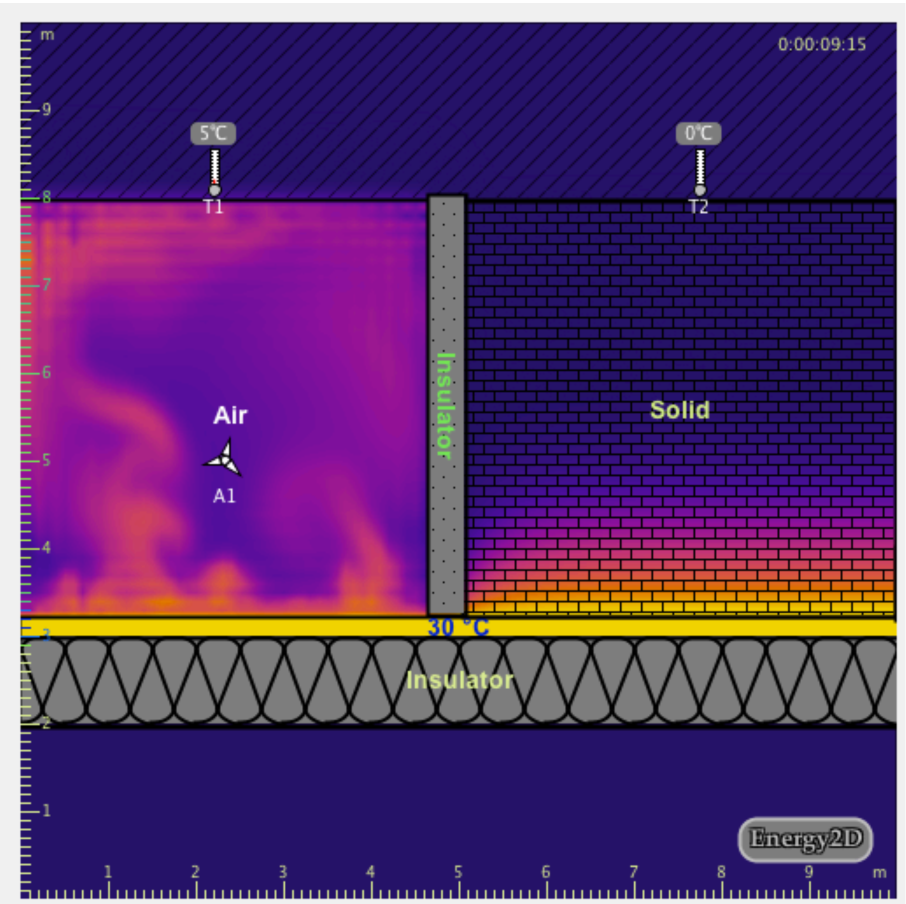
Types of convective heat transfer

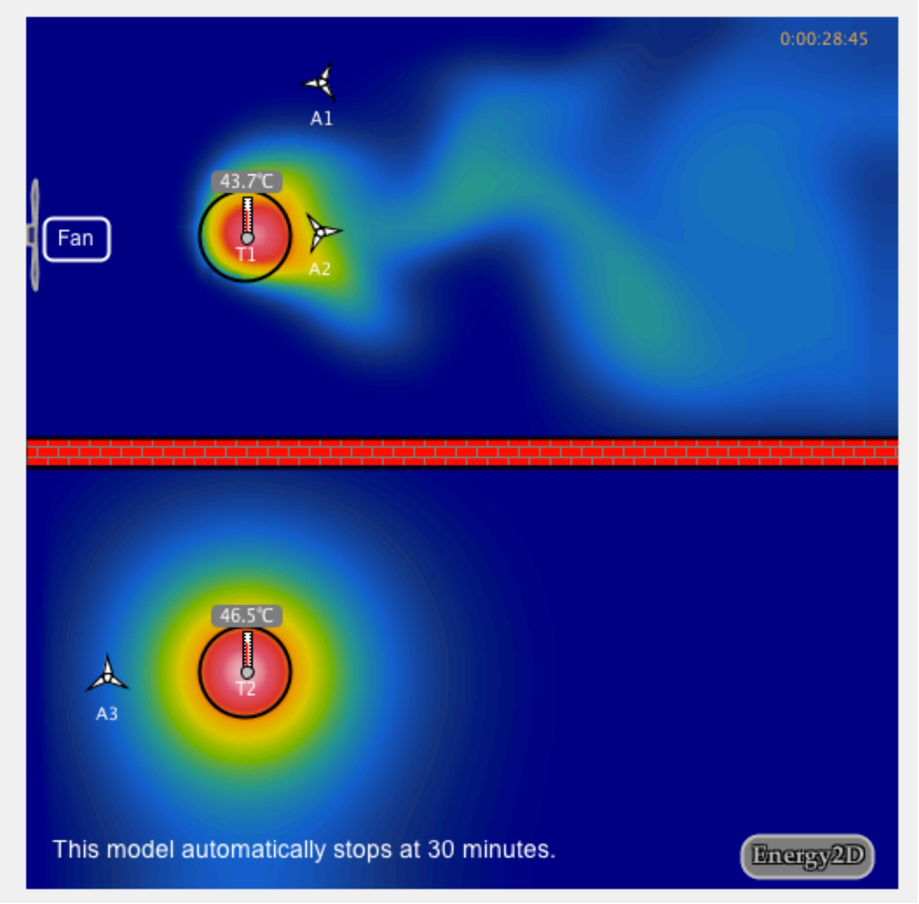
- In general, the higher the velocity of fluid flow, the higher the rate of convection heat transfer

- Two kinds of convection exist:
  - **Natural (or free) convection:** Results from density differences in the fluid caused by contact with the surface to or from which the heat transfer occurs
    - Buoyancy is the main driver
    - Example: The gentle circulation of air in a room caused by the presence of a solar-warmed window or wall (no mechanical system) is a manifestation of natural/free convection
  - **Forced convection:** Results from a force external to the problem (other than gravity or other body forces) moves a fluid past a warmer or cooler surface
    - Usually much higher velocities, driven by mechanical forces (e.g. fans)
    - Example: Heat transfer between cooling coils and an air stream

Natural vs. forced convection (both vs. conduction)

- http://energy.concord.org/energy2d/comparing-convection.html





Q versus q for convection

- Same story as conduction…

$$q_{conv} = h_{conv}\left(T_{fluid} - T_{surface}\right) \qquad \left[\frac{\text{W}}{\text{m}^2}\right]$$

- To get Q, just multiply by surface area, A

$$Q_{conv} = h_{conv} A\left(T_{fluid} - T_{surface}\right) \qquad \left[\text{W}\right]$$

Also known as Newton's law of cooling

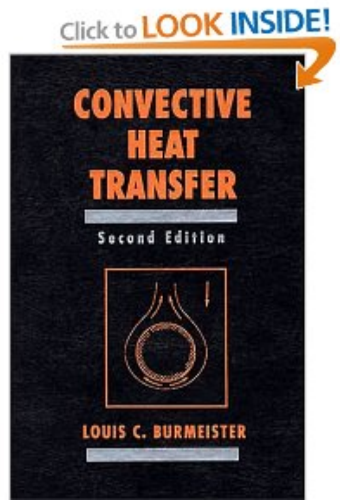
TABLE 2.9

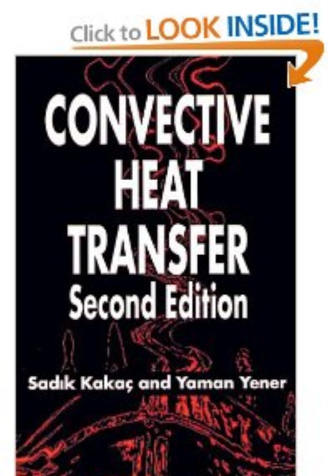
Magnitude of Convection Coefficients

Arrangement	$W/(m^2 \cdot K)$	$Btu/(h \cdot ft^2 \cdot F)$
Air, free convection	6–30	1–5
Superheated steam or air, forced convection	30–300	5–50
Oil, forced convection	60–1800	10–300
Water, forced convection	300–6000	50–1000
Water, boiling	3000–60,000	500–10,000
Steam, condensing	6000–120,000	1000–20,000

The conversion between SI and USCS units is 5.678 $W/(m^2 \cdot K) = 1$ $Btu/(h \cdot ft^2 \cdot °F)$.

Convection is really a field of its own





Important notes on convection in building science

- Convective heat transfer coefficients can depend upon details of the surface-fluid interface
  - Rough surfaces have higher rates of convection
  - Orientation is important for natural convection
  - Convective heat transfer coefficients for natural convection can depend upon the actual fluid temperature and not just the temperature difference

- Convection is really a field of its own
  - We use specific cases for our work in building science

Convective heat transfer coefficient, h_{conv}

- The convective heat transfer coefficient, h_{conv}, will take on many forms depending upon whether the convection is forced or natural
  - Natural convection occurs when buoyancy effects induce air motion
    - Temperature-dependent density differences

$$\rho = \frac{n}{V} = \frac{P}{RT}$$

Hold P and R constant…

$T \downarrow \rho \uparrow \qquad T \uparrow \rho \downarrow$

  - Forced convection occurs when an external force (e.g. fan or wind) imposes air motion (more random and chaotic)
  - h_c is also known as the film coefficient or the surface conductance
- The next few slides show some of the important convective equations that arise in computing heat transfer to/from walls, floors

Convection and building science

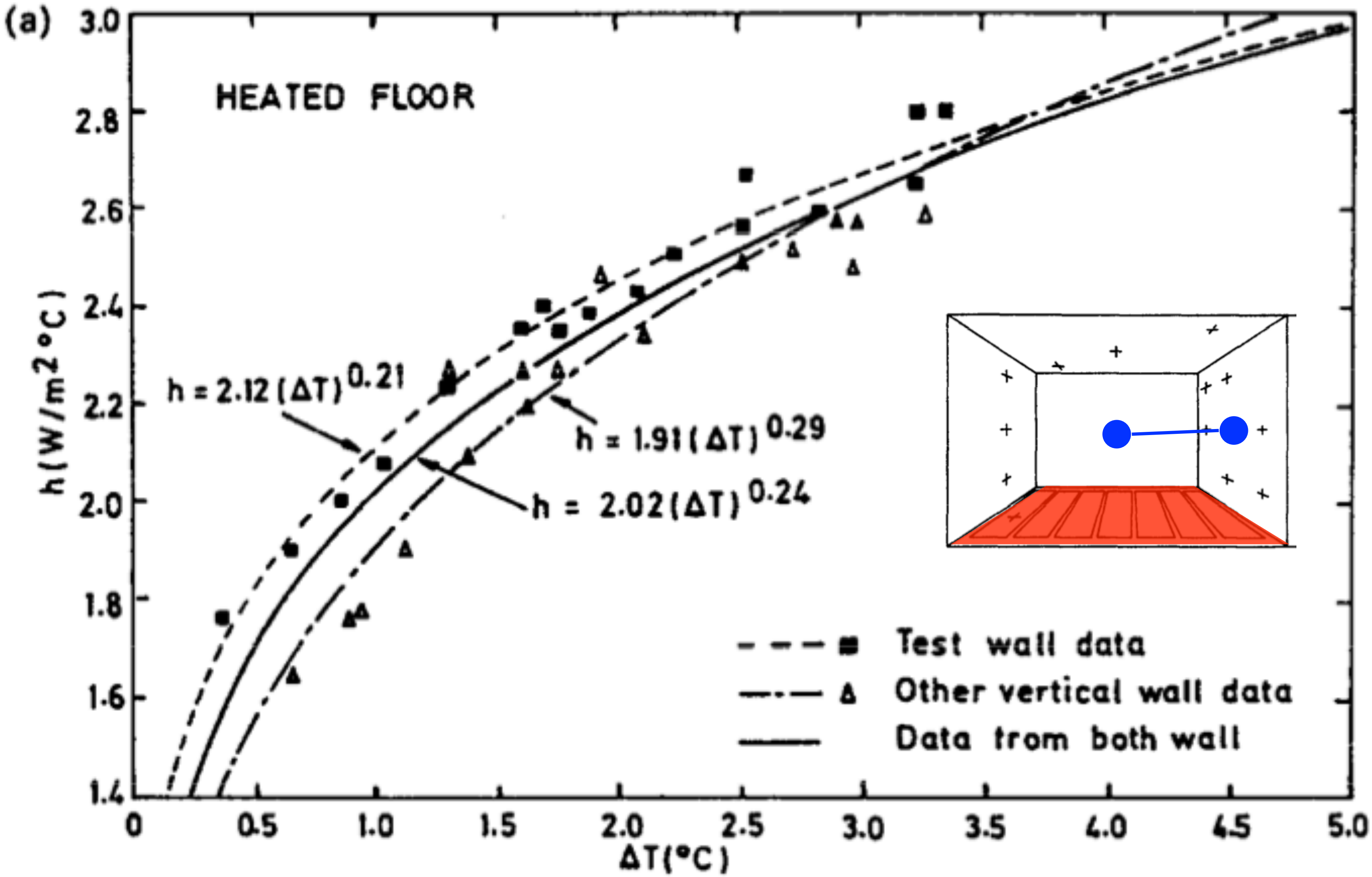
- Laminar versus turbulent
  - When the temperature differences are high enough the natural motion is turbulent, the result is more mixing and higher heat transfer
    - So, for high temperature differences, the heat transfer coefficient is larger and has a different equation than for lower ΔT
  - Nearly all forced convection is turbulent
  - Free convection can be either

- Laminar flow occurs for cases when: $L^3 \Delta T < 1.0$ in SI units
  - Indoor environments are almost always turbulent
  - Outdoor environments definitely are

Convection: Complex approach

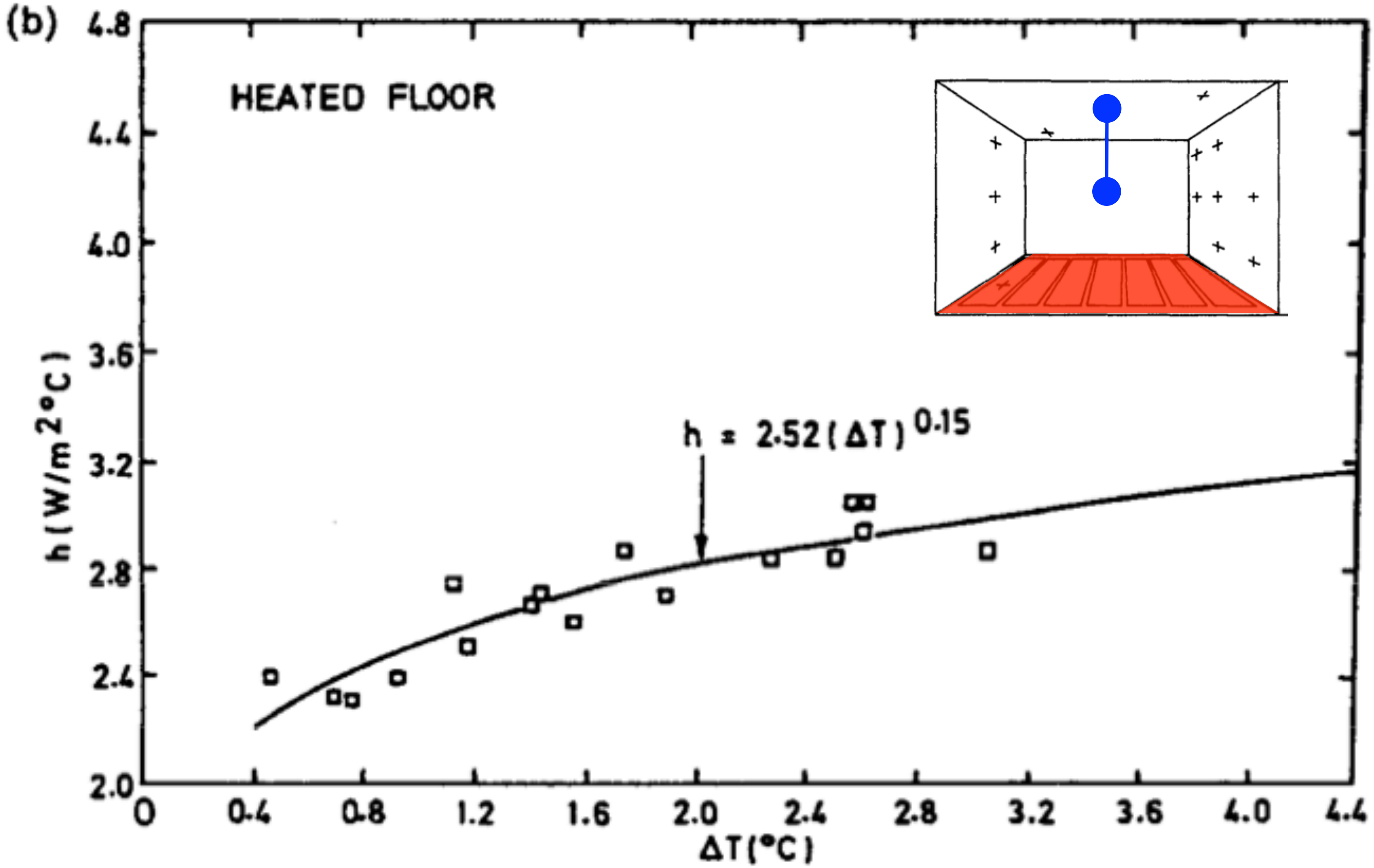
- Convection coefficients depend on orientation, air speeds, and temperature differences
- There are fundamental approaches to estimating convective heat transfer coefficients
  - And then there are A LOT of empirical/experimental estimates
  - For a wide range of conditions

Example: h_{conv} vs. ΔT for vertical walls and a heated floor



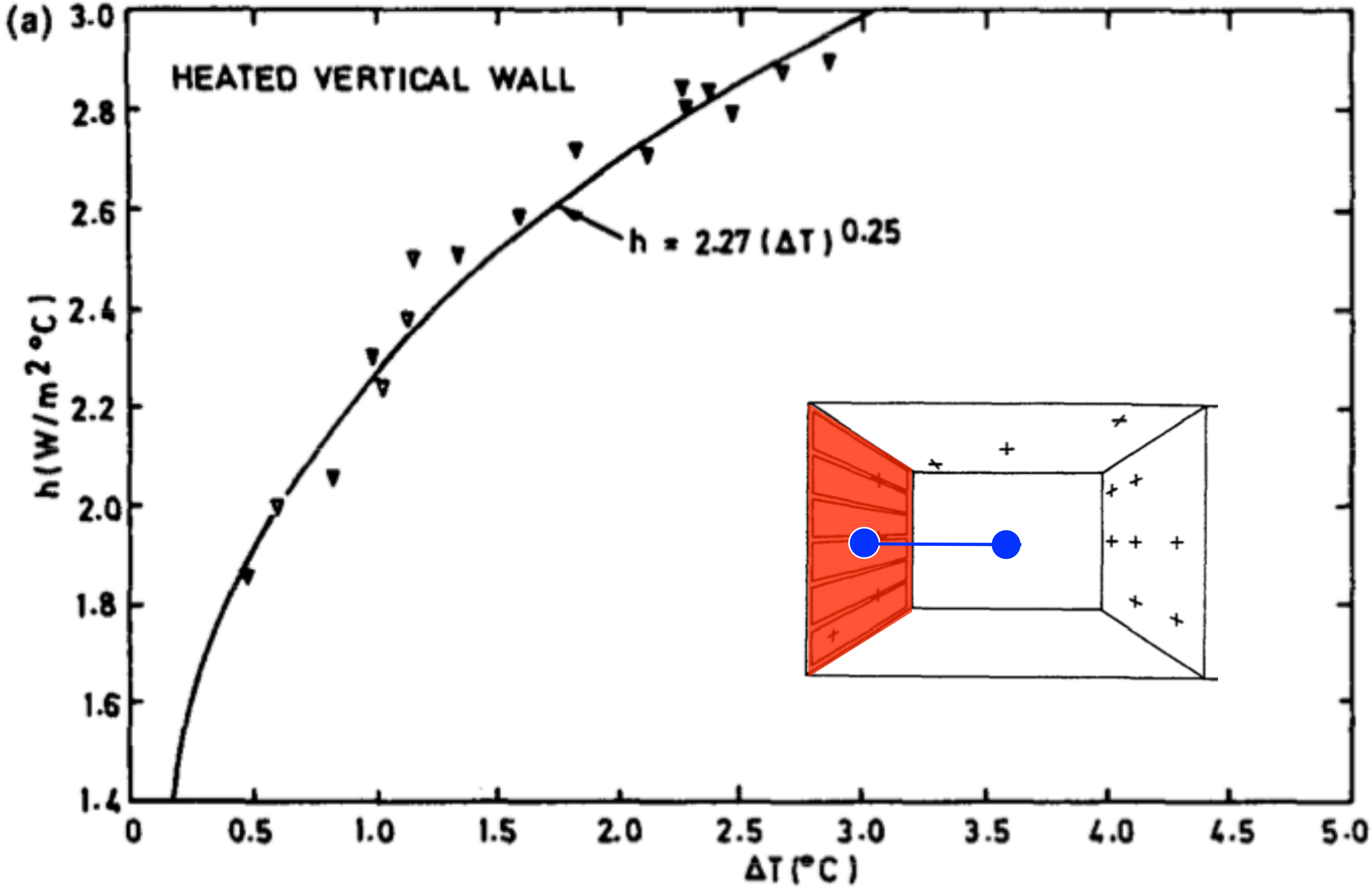
Khalifa and Marshall (1990) *Int J Heat Mass Transfer*

Example: h_{conv} vs. ΔT for a ceiling and a heated floor



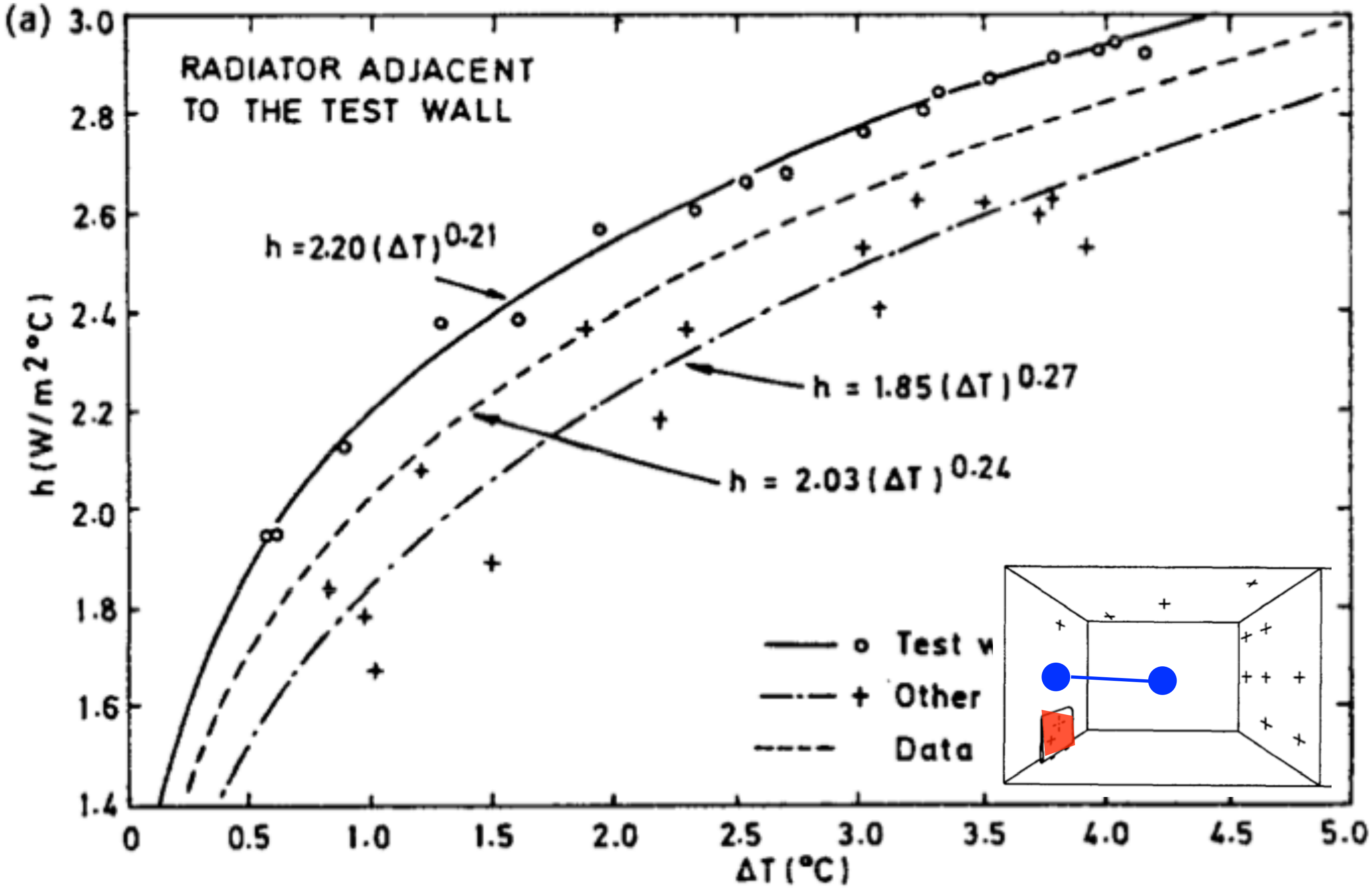
Khalifa and Marshall (1990) *Int J Heat Mass Transfer*

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



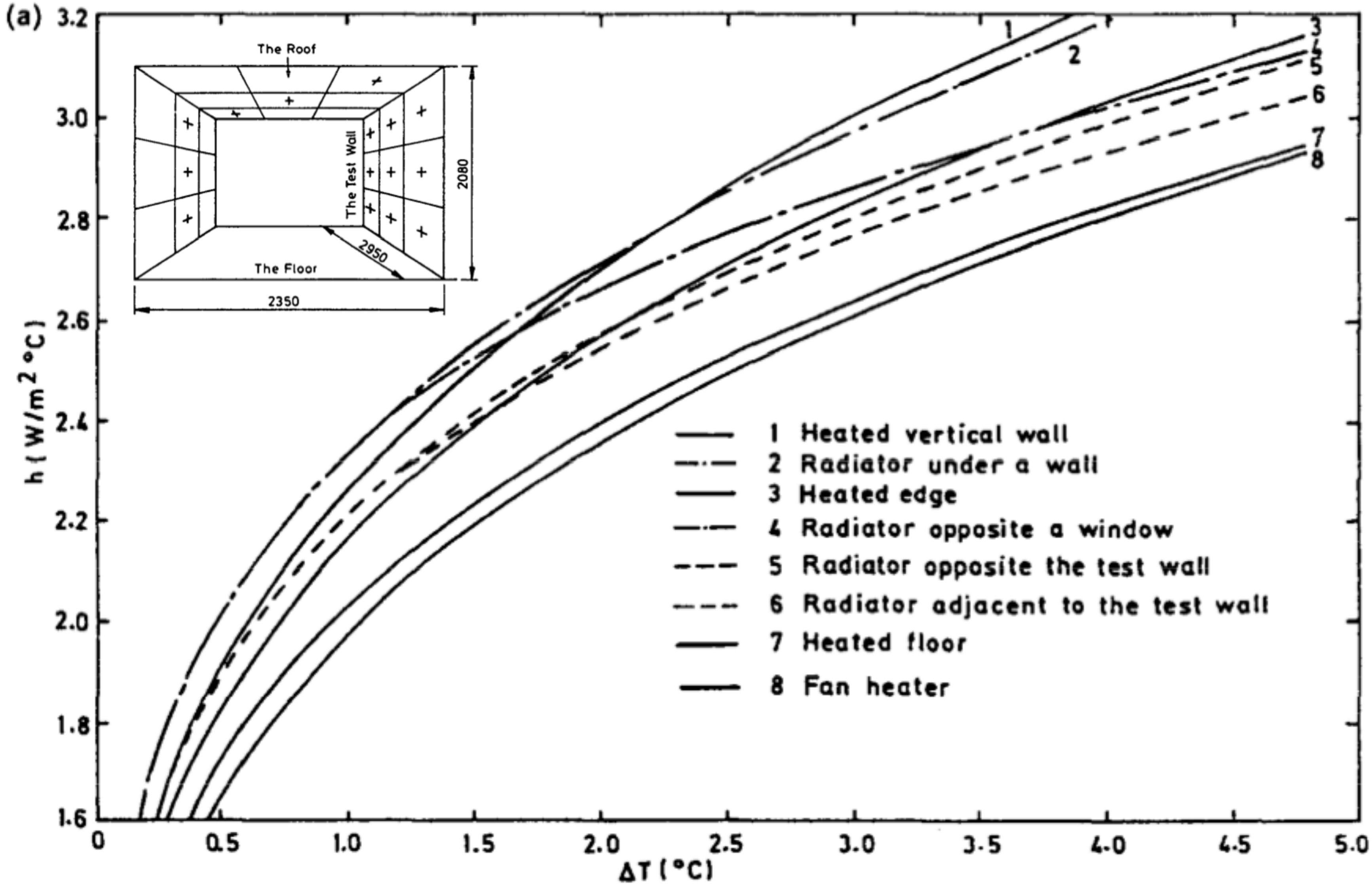
Khalifa and Marshall (1990) *Int J Heat Mass Transfer*

Example: h_{conv} vs. ΔT for a wall w/ a radiator on it



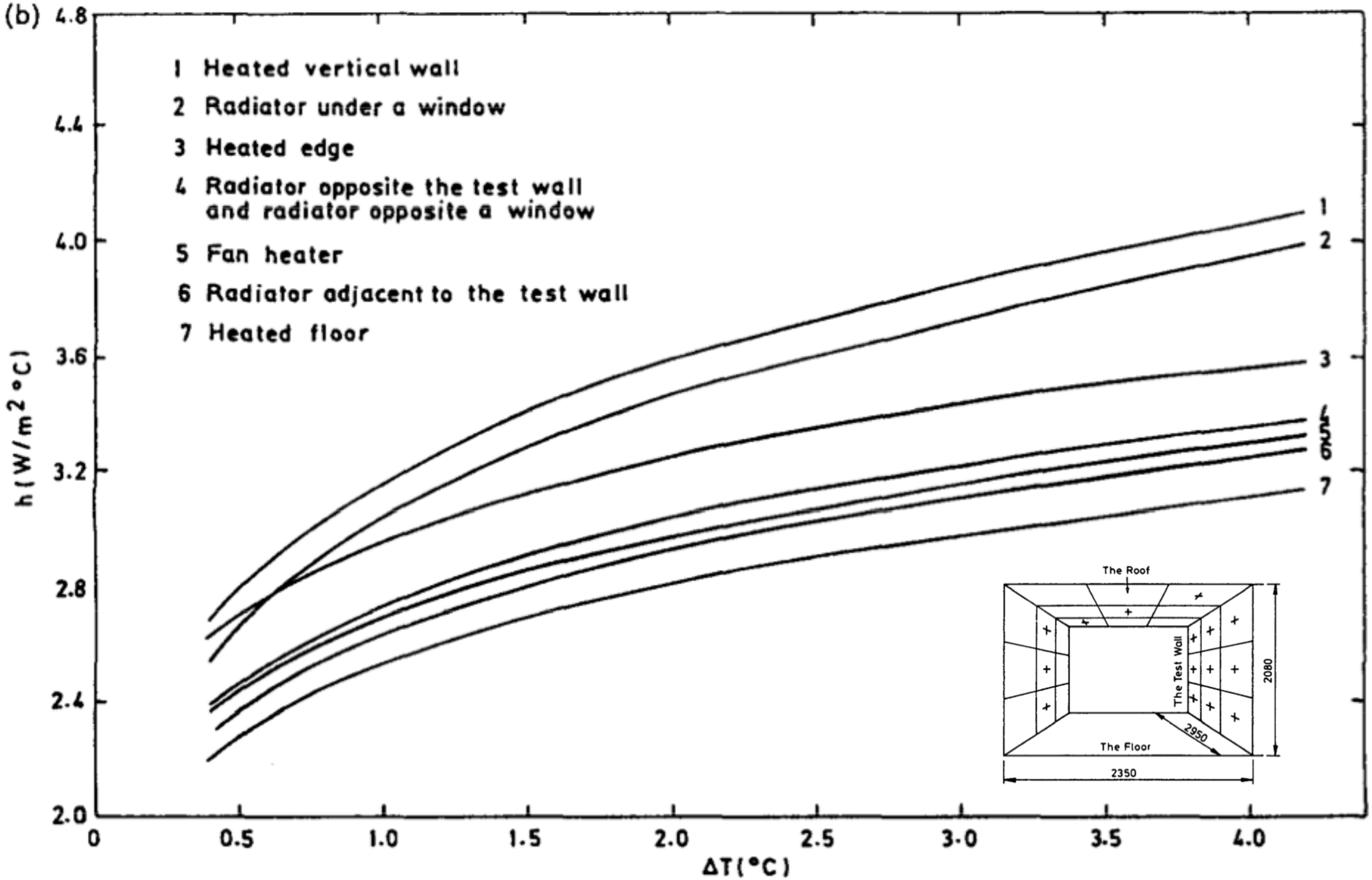
Khalifa and Marshall (1990) *Int J Heat Mass Transfer*

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



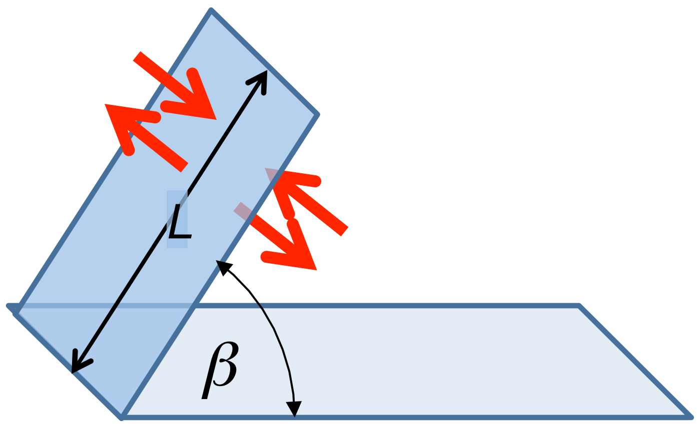
Khalifa and Marshall (1990) *Int J Heat Mass Transfer*

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



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

Free convection in air from a tilted surface: Simplified



h_{conv} in [W/(m^2 K)]

For natural convection to or from either side of a vertical surface or a sloped surface with $\beta > 30°$

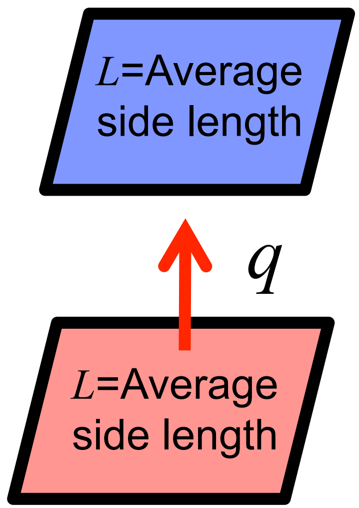
For laminar: $$h_{conv} = 1.42\left(\frac{\Delta T}{L}\sin\beta\right)^{\frac{1}{4}}$$ [Kreider 2.18SI]

For turbulent: $$h_{conv} = 1.31\left(\Delta T\sin\beta\right)^{\frac{1}{3}}$$ [Kreider 2.19SI]

Note that these equations are dimensional, so they are different for IP and SI

Free convection for surfaces: Simplified

- Warm horizontal surfaces facing up
  - e.g. up from a warm floor to a cold ceiling

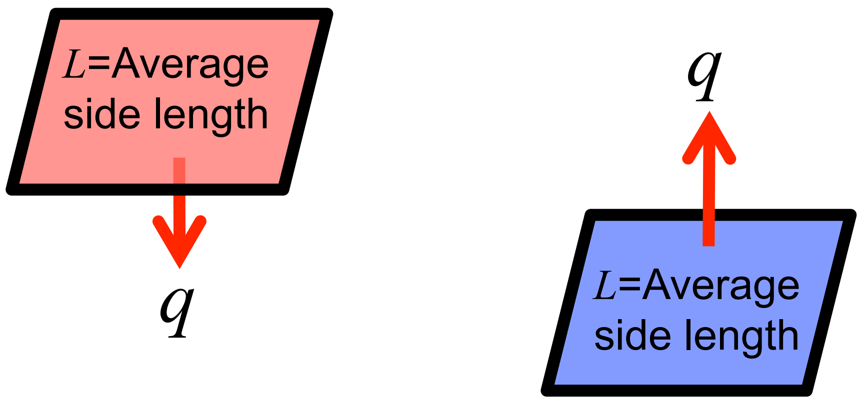


laminar: $$h_{conv} \approx 1.32\left(\frac{\Delta T}{L}\right)^{1/4}$$ [Kreider 2.22SI]

turbulent: $$h_{conv} \approx 1.52\left(\Delta T\right)^{1/3}$$ [Kreider 2.23SI]

Free convection for surfaces: Simplified

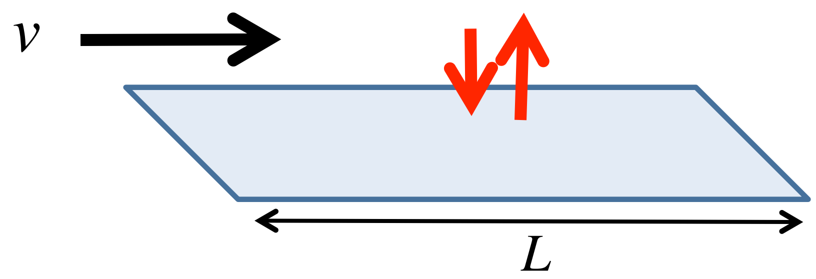
- Warm horizontal surface facing down
  - Convection is reduced because of stratification
    - e.g. a warm ceiling facing down (works against buoyancy)
    - Also applies for cooled flat surfaces facing up (like a cold floor)

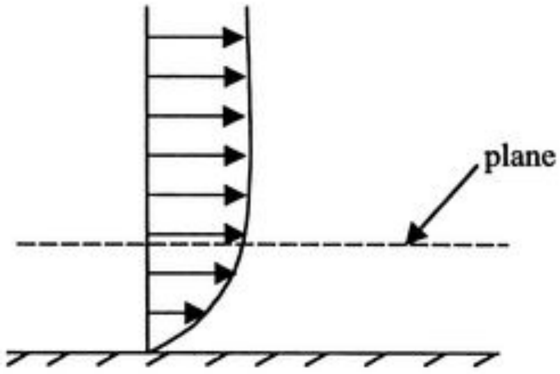


$$h_{conv} \approx 0.59\left(\frac{\Delta T}{L}\right)^{1/4}$$ both laminar and turbulent

Forced convection over planes: Simplified

- Does not depend on orientation





laminar: $$h_{conv} \approx 2.0\left(\frac{v}{L}\right)^{1/2}$$ [Kreider 2.24SI]

turbulent: $$h_{conv} \approx 6.2\left(\frac{v^4}{L}\right)^{1/5}$$ [Kreider 2.25SI]

*Velocity is in m/s

Summary of h_{conv} equations for natural convection (SI)

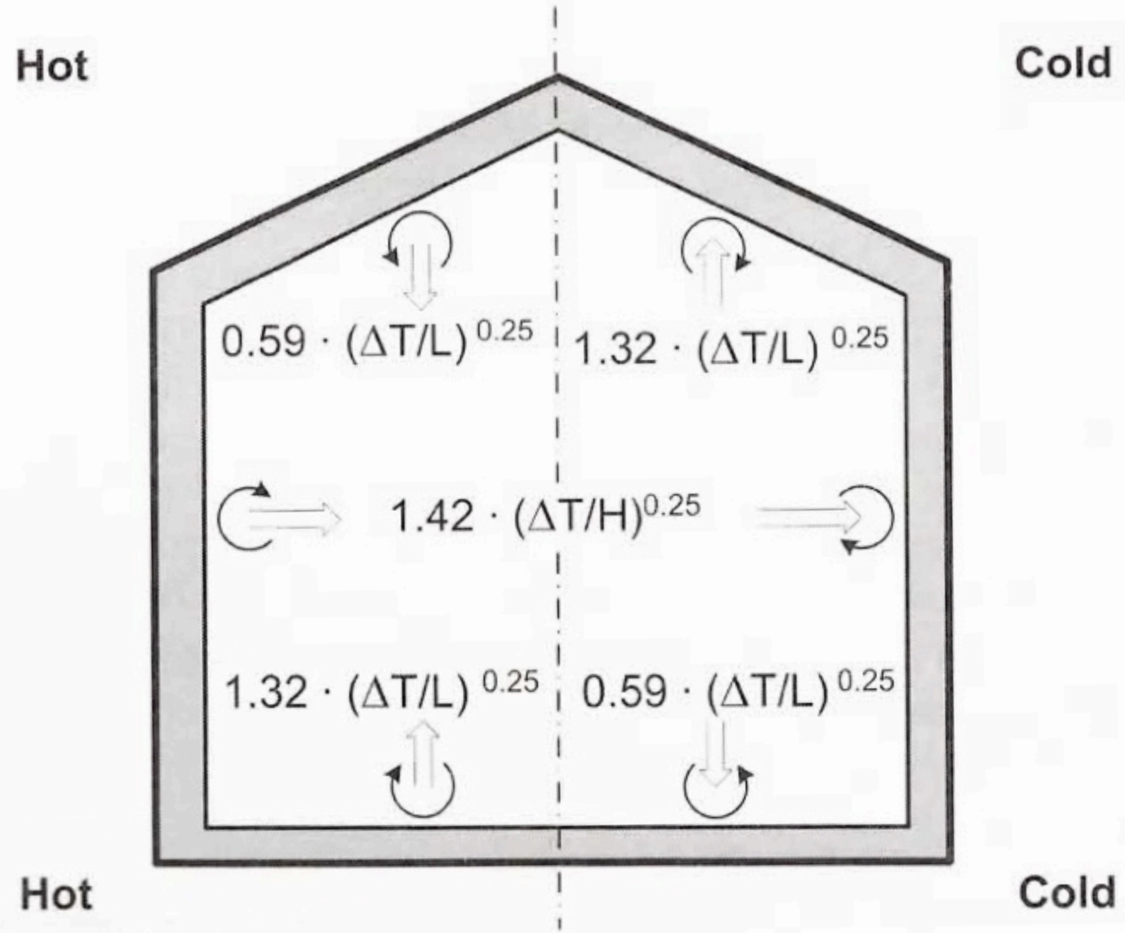
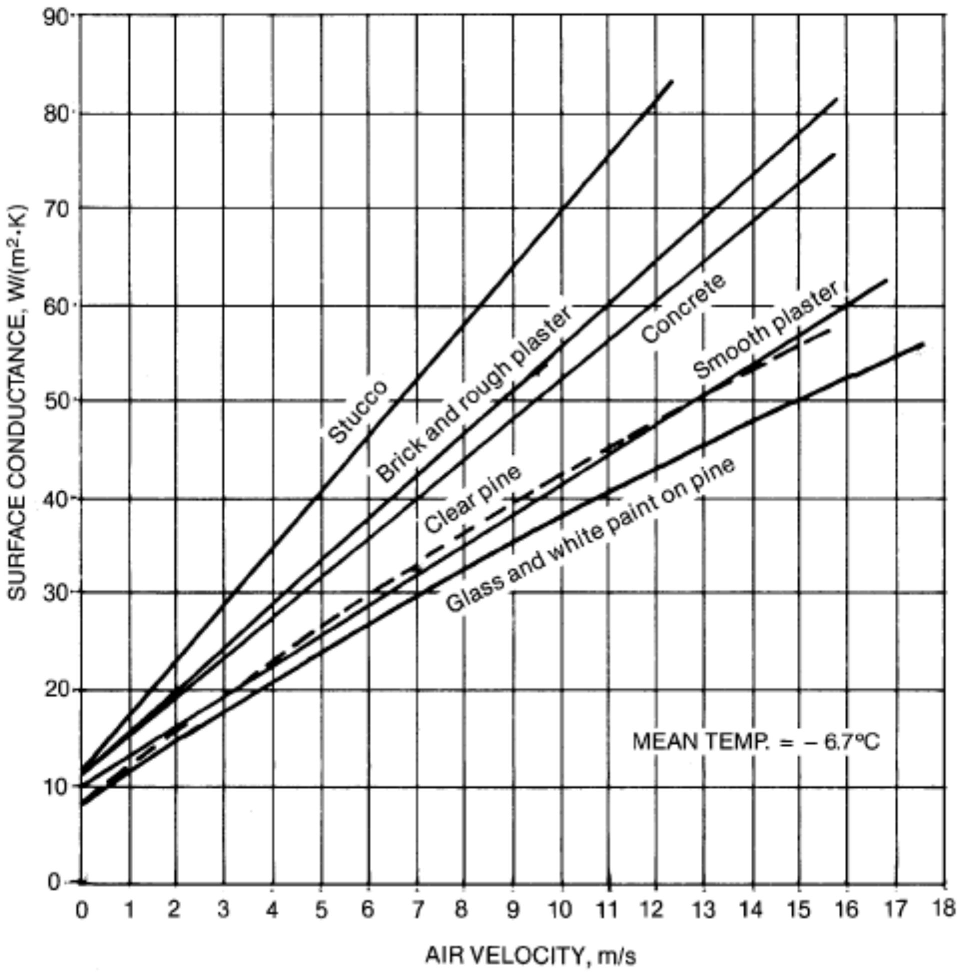


Figure 5.4: Natural convection coefficients for laminar flow

h_{conv} for exterior forced convection

- For forced convection, h_{conv} depends upon surface roughness and air velocity but not orientation



Most used h_{conv} for exterior forced convection

There are two relationships for h_{conv} (forced convection) which are commonly used, depending on wind speed:

- For $1 < v_{wind} < 5$ m/s

  $h_c = 5.6 + 3.9v_{wind}$ [W/(m²·K)] [Straube 5.15]

- For $5 < v_{wind} < 30$ m/s

  $h_c = 7.2{v_{wind}}^{0.78}$ [W/(m²·K)] [Straube 5.16]

*Good for use with external surfaces like walls and windows

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

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

Typical convective surface resistances

- We often use the values given below for most "design" conditions

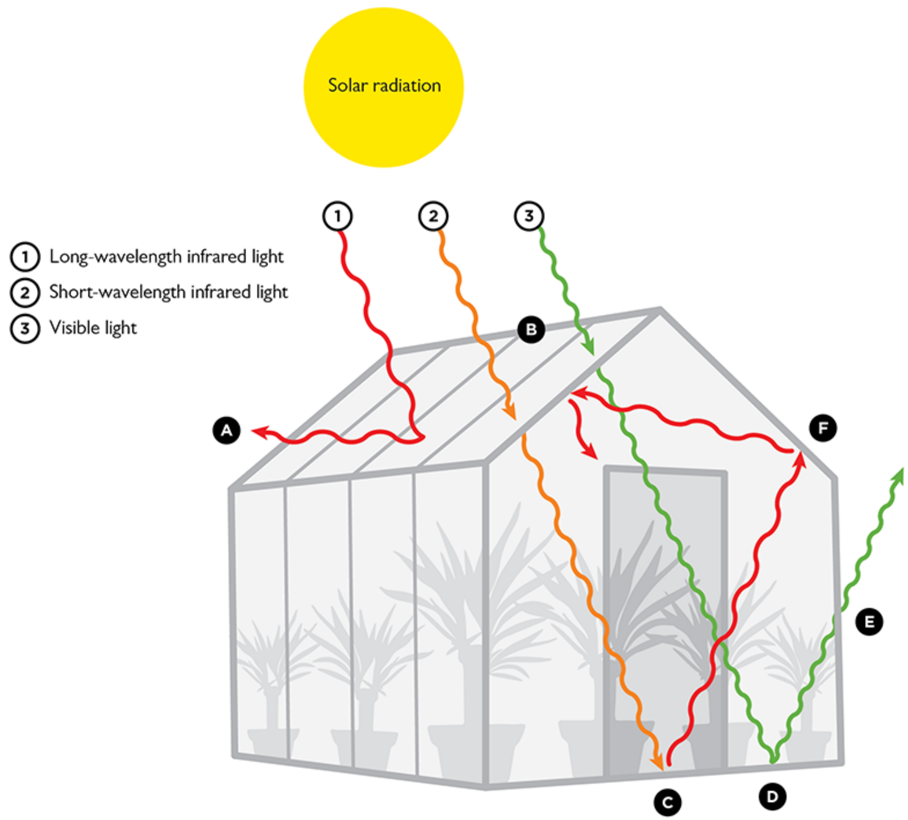
Surface Conditions	Horizontal Heat Flow	Upwards Heat Flow	Downwards Heat Flow
Indoors: R_{in}	0.12 m^2K/W (SI) 0.68 $h\cdot ft^2\cdot°F/Btu$ (IP)	0.11 m^2K/W (SI) 0.62 $h\cdot ft^2\cdot°F/Btu$ (IP)	0.16 m^2K/W (SI) 0.91 $h\cdot ft^2\cdot°F/Btu$ (IP)
R_{out}: 6.7 m/s wind (Winter)		0.030 m^2K/W (SI) 0.17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

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)]



RADIATION

Review of fundamentals

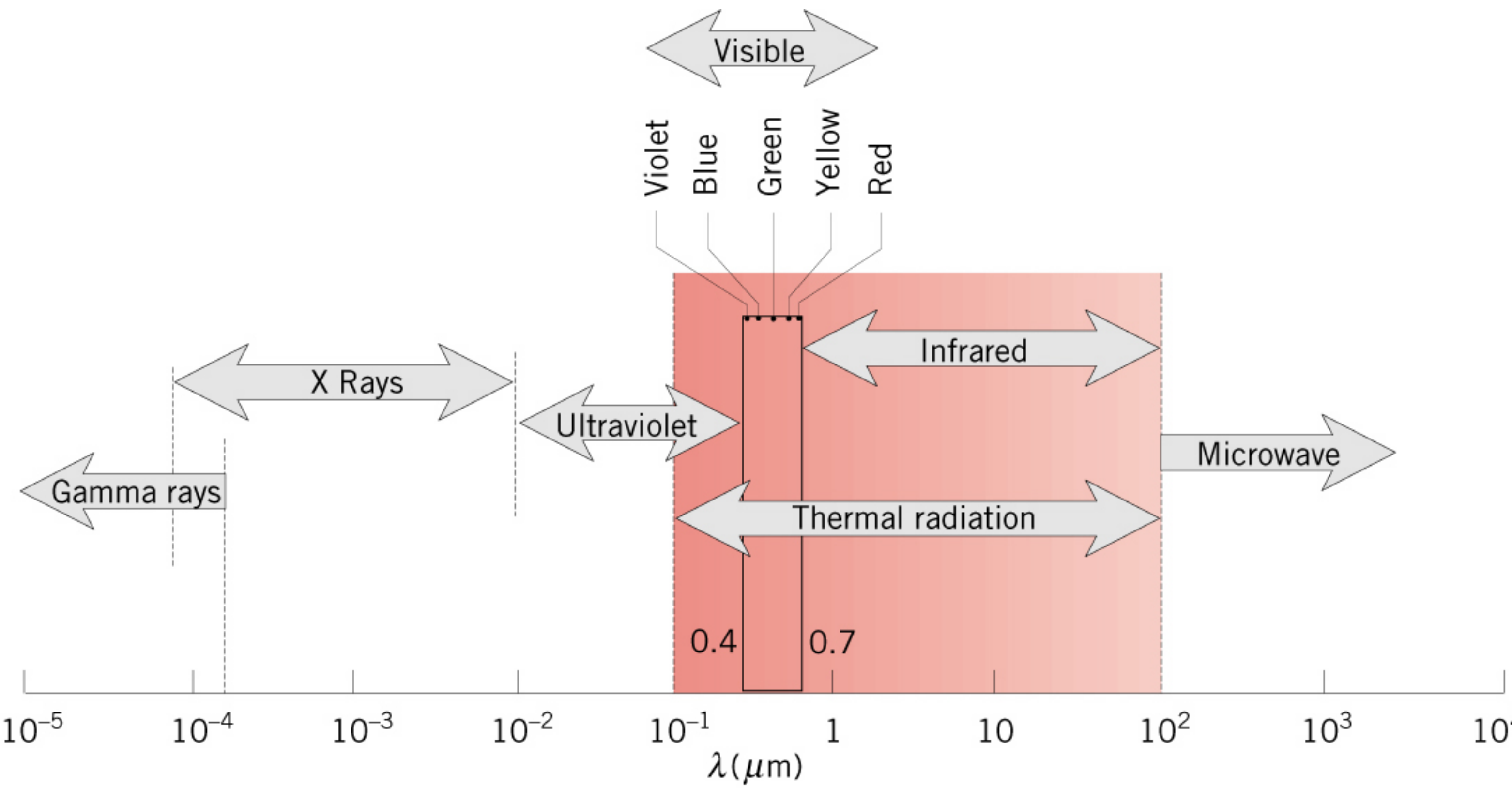
Radiation

- 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 (refracted or re-emitted radiation)

Radiation: the electromagnetic spectrum

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



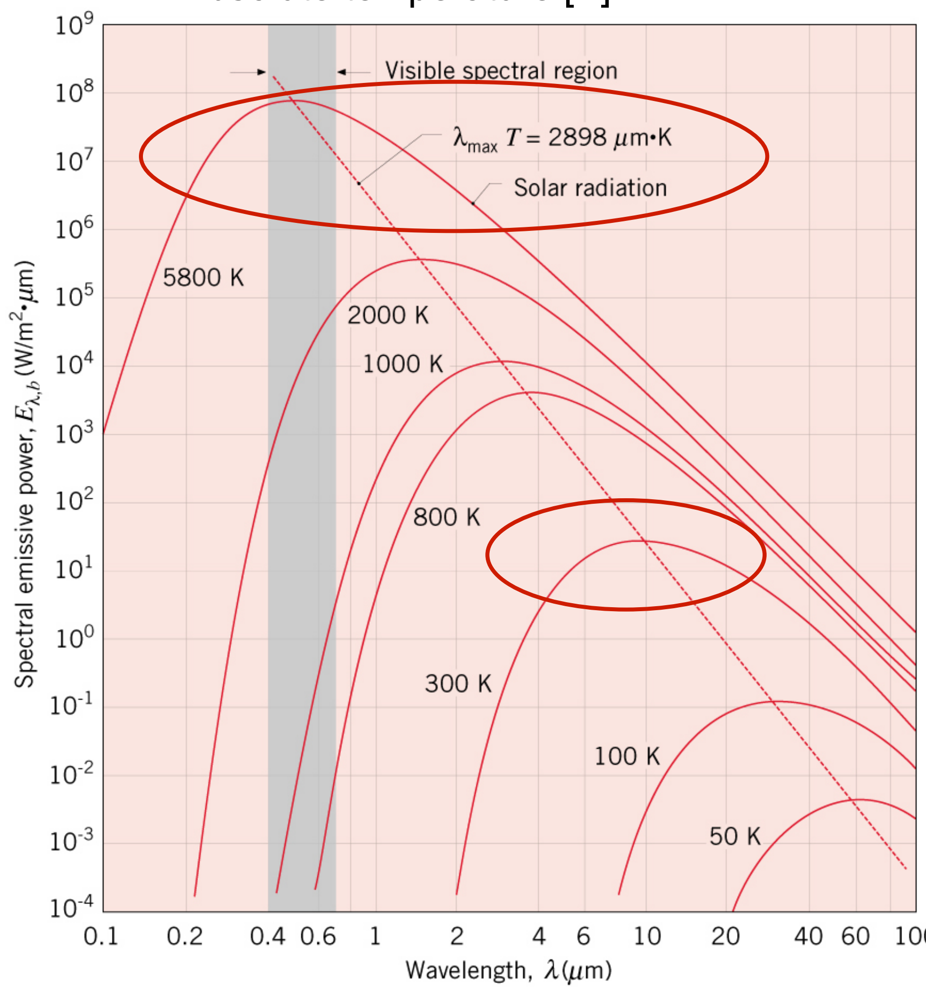
Black body radiation: Spectral (Planck) distribution

- 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

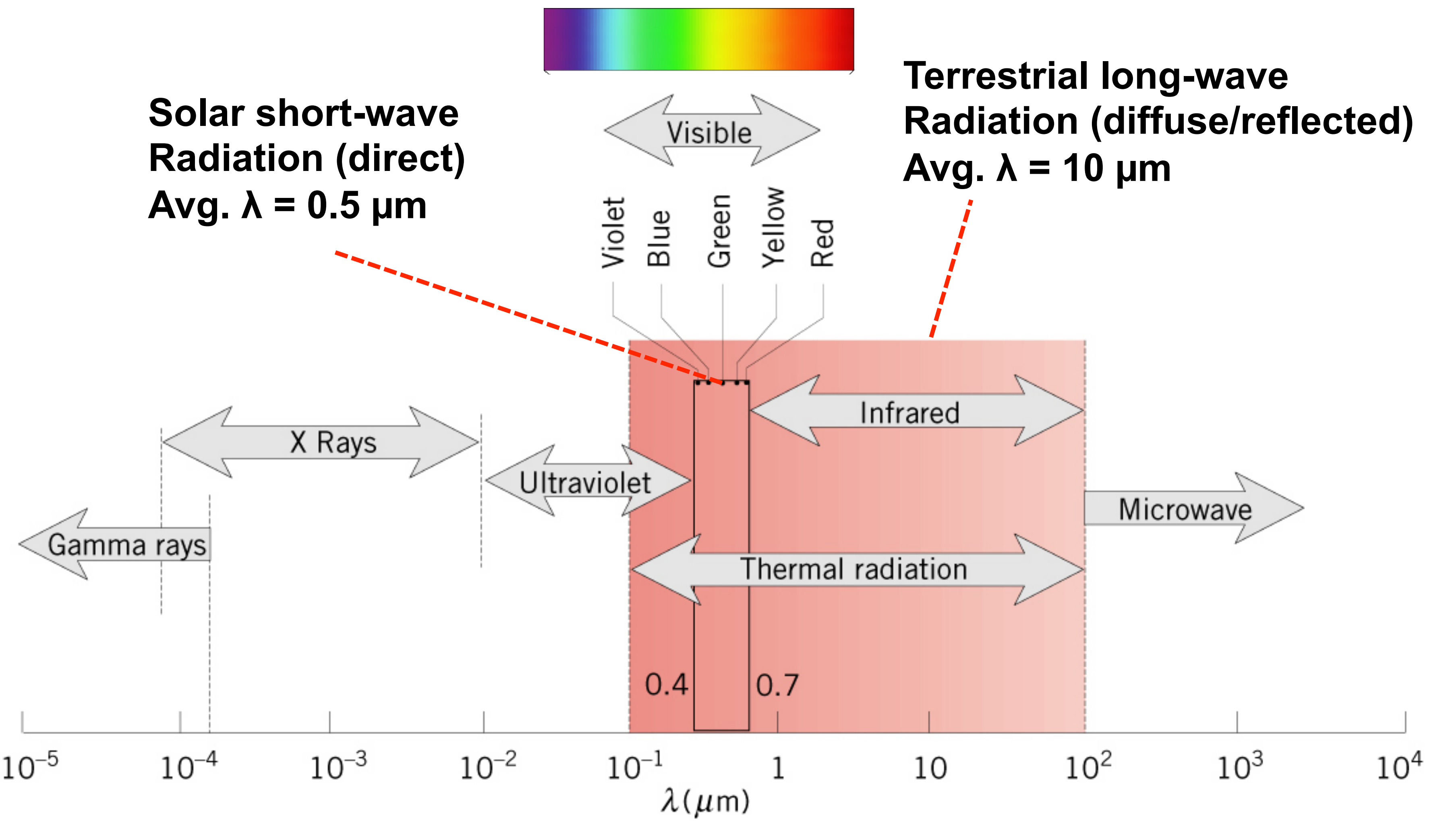
$q = \sigma T^4$

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

T = Absolute temperature [K]

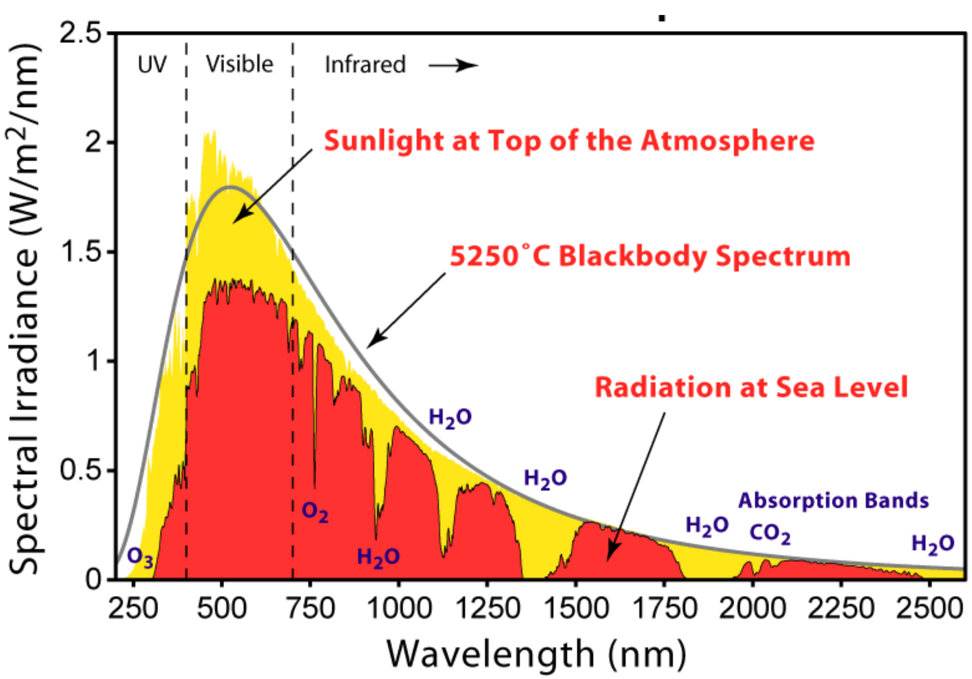


Radiation: Short-wave and Long-wave



Solar radiation striking a surface (high temperature)

- Most solar radiation is at short wavelengths

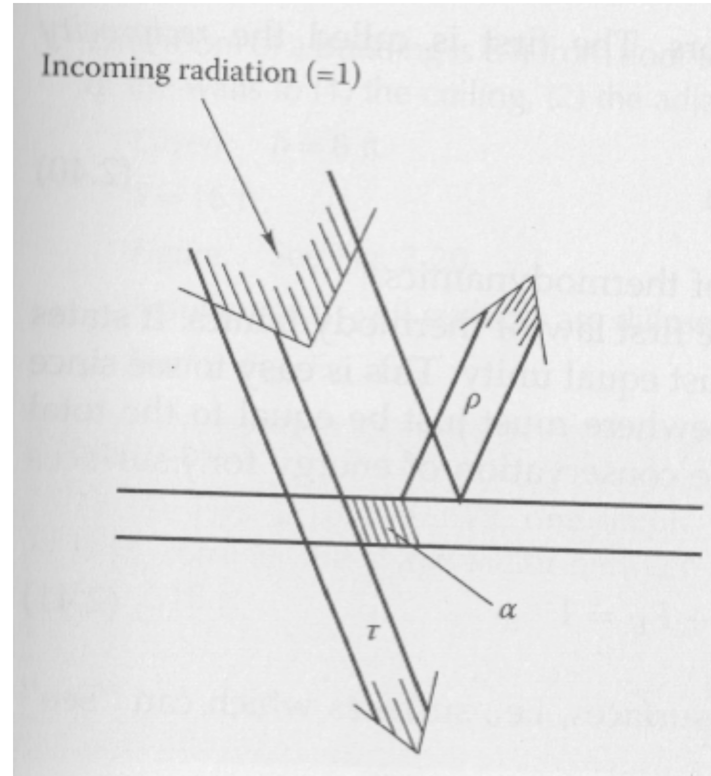


Solar radiation striking a surface:

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

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



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

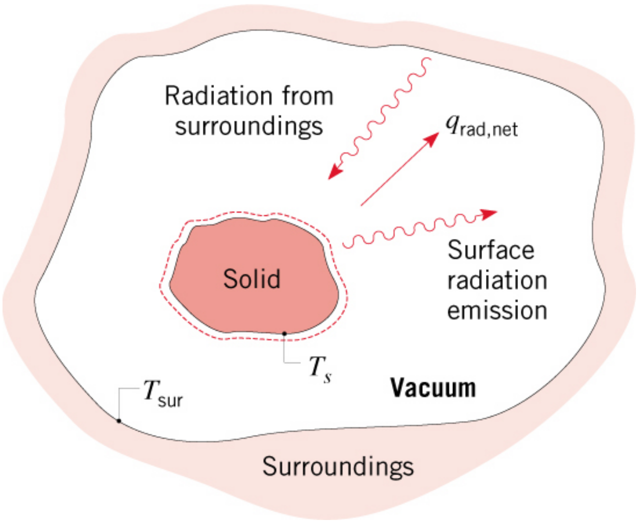
Absorptivity (α) for solar (short-wave) radiation

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

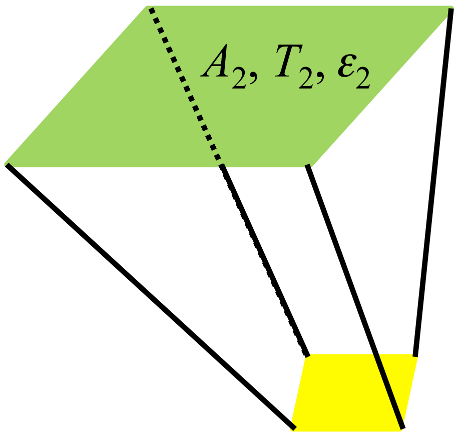
T = Absolute temperature [K]

- 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

TABLE 2.11

Emissivities of Some Common Building Materials at Specified Temperatures

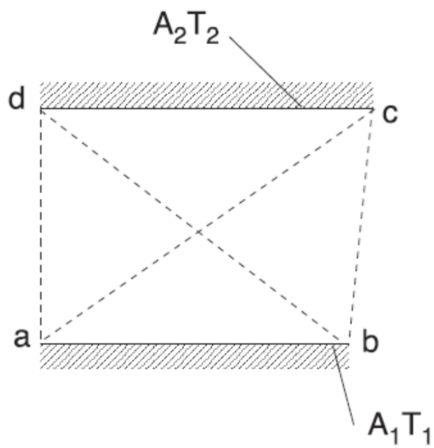
Surface	Temperature, °C	Temperature, °F	ϵ
Brick			
Red, rough	40	100	0.93
Concrete			
Rough	40	100	0.94
Glass			
Smooth	40	100	0.94
Ice			
Smooth	0	32	0.97
Marble			
White	40	100	0.95
Paints			
Black gloss	40	100	0.90
White	40	100	0.89–0.97
Various oil paints	40	100	0.92–0.96
Paper			
White	40	100	0.95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

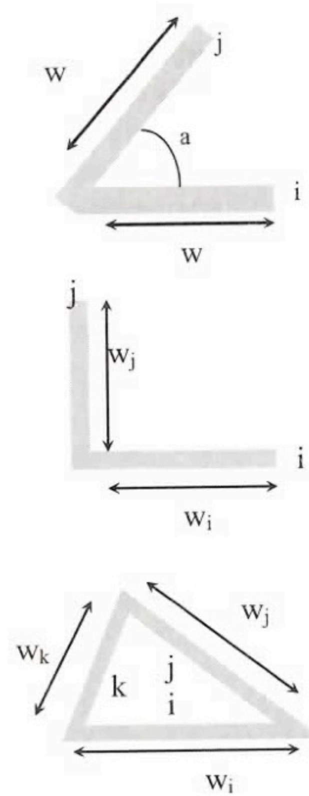
View factors, F_{12}

- Radiation travels in directional beams
  - Thus, areas and angle of incidence between two exchanging surfaces influences radiative heat transfer

Some common view factors:



$$A_1 F_{1\rightarrow 2} = 0.5((ac + bd) - (ad + bc))$$



$$F_{ij} = 1 - \sin(\frac{a}{2})$$

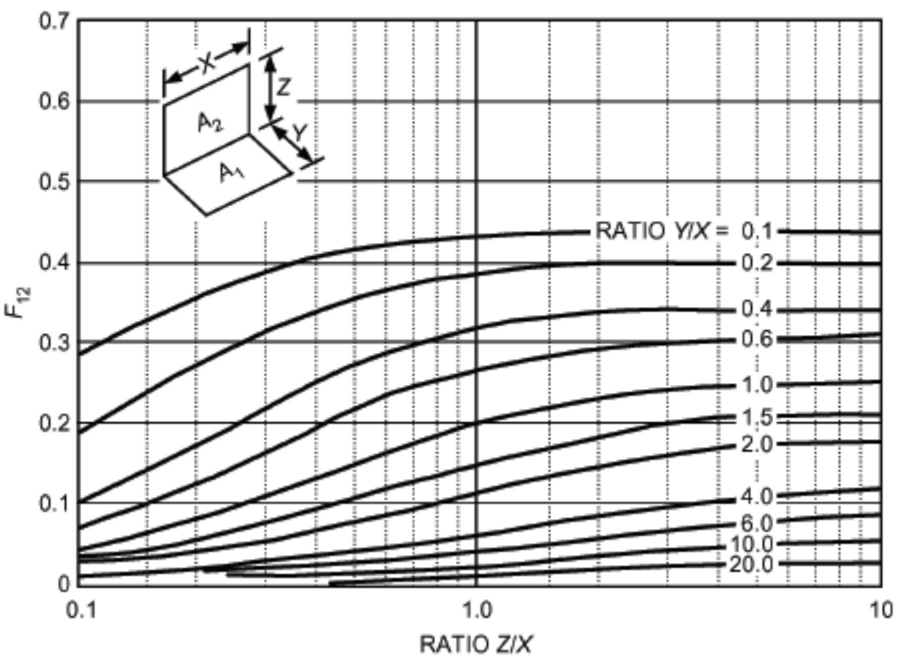
$$F_{ij} = \frac{1 + (w_j / w_i) - [1 + w_j / w_i)^2]^{1/2}}{2}$$

$$F_{ij} = \frac{w_j + w_i - w_k}{2w_i}$$

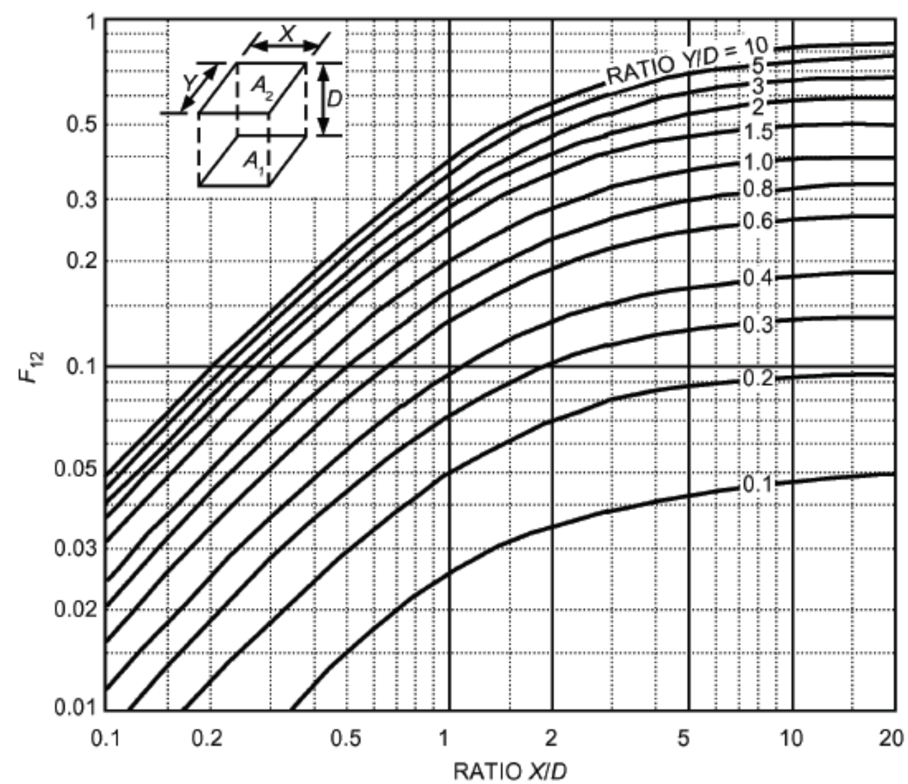
Figure 5.6: View factors for common situations in building enclosures [Hagentoft 2000]

Typical view factors

- Other common view factors from ASHRAE HOF



A. PERPENDICULAR RECTANGLES WITH COMMON EDGE



B. ALIGNED PARALLEL RECTANGLES

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, as is typical in dealing with building enclosures

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

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

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

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

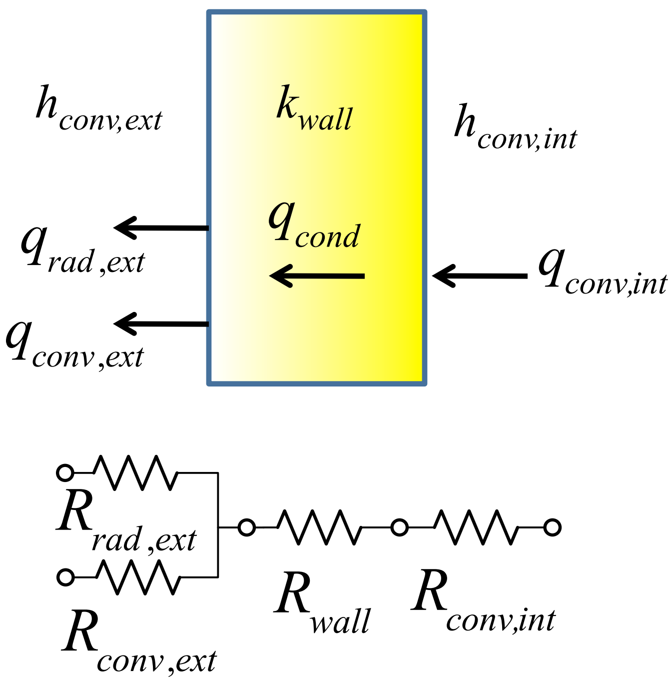
$$q_{1\to 2} = \varepsilon_{surf}\sigma F_{12}\left(T_{surf,1}^4 - T_{surf,2}^4\right)$$

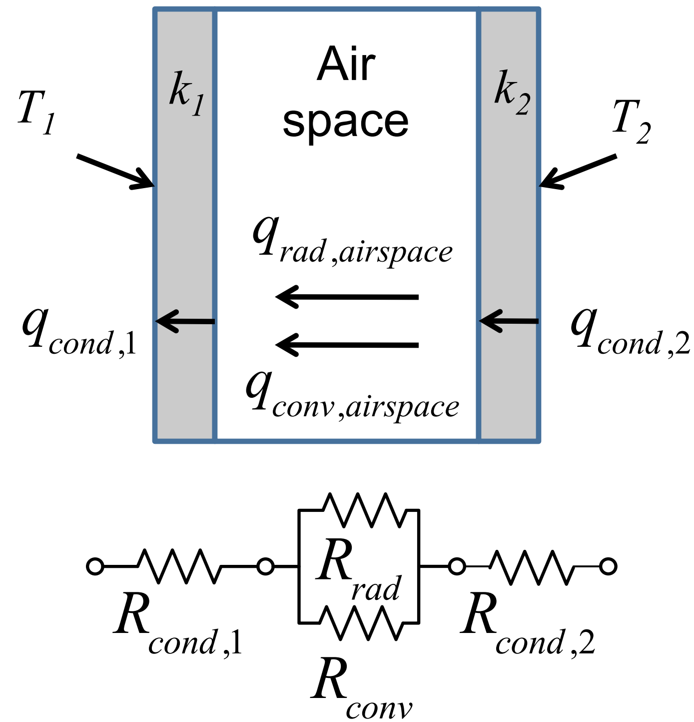
Solar radiation: (opaque surface) $q_{solar} = \alpha I_{solar}$

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

Combined 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





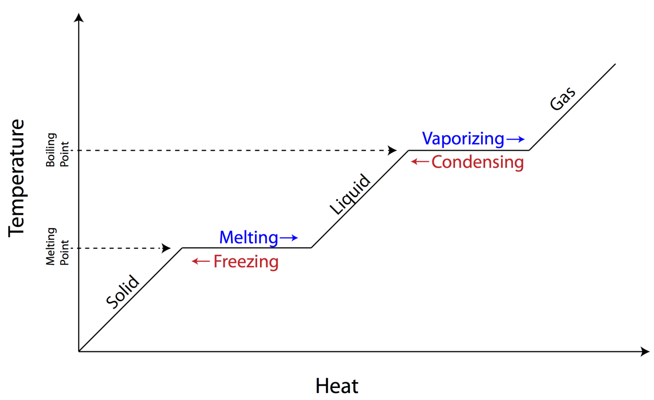
State change

- When materials change state, they release or absorb a material-specific amount of latent energy
  – Usually concerned with water evaporation/condensation
- All materials above absolute zero contain some heat energy
  – This amount of energy (E, in J or kJ) is equal to:

$$E = C_p m T$$

where C_p is the specific heat capacity [kJ/(kgK)]

m is the mass (kg), T is absolute temperature (K)



State change

- The amount of heat energy required to change a material from one temperature to another is:

$$E = C_p m \Delta T$$

where C_p is the specific heat capacity [kJ/(kgK)]

m is the mass (kg), ΔT is the temperature difference (K)

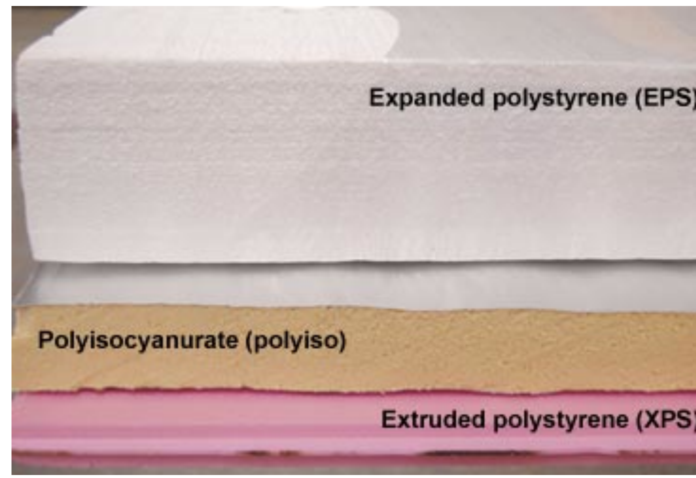
Single-mode heat transfer examples

- Let’s perform some example calculations, first treating conduction, convection, and radiation individually

BASIC HEAT TRANSFER THROUGH BUILDING ENCLOSURES

Example 2.1: Single-layer conduction

- A 2 m wide, 3 m high, and 50 mm thick piece of extruded polystyrene material has a surface temperature of 20°C on one side and 40°C on the other
  - a) Calculate steady state heat flow rate and heat flux
  - b) Calculate conductance (U-value)
  - c) Calculate resistance (R-value)



ASHRAE Handbook of Fundamentals

Table 4 Typical Thermal Properties of Common Building and Insulating Materials—Design Values[a] (*Continued*)

Description	Density, kg/m^3	Conductivity[b] (k), $W/(m \cdot K)$	Conductance (C), $W/(m^2 \cdot K)$	Resistance[c] (R): $1/k$, $(m \cdot K)/W$	Resistance[c] (R): For Thickness Listed ($1/C$), $(m^2 \cdot K)/W$	Specific Heat, $kJ/(kg \cdot K)$
Expanded polystyrene, extruded (smooth skin surface) (HCFC-142b exp.)[h]	29-56	0.029	—	34.7	—	1.21

A note on insulation materials

- All materials in an enclosure assembly will have some resistance to heat transfer
- Materials with thermal conductivities (k) less than about 0.05 W/mK are used specifically for insulation
  - 0.05 W/mK divided by 3-inches of typical thickness (0.076 m) yields U-value of ~0.66 W/m^2K
  - R = 1/U = 1/0.66 = ~1.5 m^2K/W RSI (or ~R-9 in English units)

Example from product literature

Johns Manville

AVAILABLE FORMS*

Specification Compliance	R-Value (hr•ft²•°F/Btu)	RSI-Value (m²•°C/Watts)	Thickness** (in)	(mm)
ASTM C 665	38c	6.7	10 ¼	260
Kraft-Faced	38	6.7	13	330
Type II, Class C	30c	5.3	8 ¼	210
Category 1	30	5.3	10 ¼	260
	25	4.4	8 ½	216
	22	3.9	7 ½	191
	21	3.7	5 ½	140
	19	3.3	6 ½	165
	15	2.6	3 ½, 3 ⅝	89, 92
	13	2.3	3 ½, 3 ⅝	89, 92
	11	1.9	3 ½, 3 ⅝	89, 92

Another note on insulation materials

- **Still air** is also a low-cost insulator
  - Density ~1.2 kg/m^3
  - Conductivity, k ~ 0.03 W/mK
  - So many insulation materials rely on creating air voids

- Example: fiberglass insulation
  - Glass, with a density of 2500 kg/m^3 and k = 1 W/mK, is spun into fibers and made into a fiberglass insulation batt, which is ~99.4% air voids (~0.6% glass fibers) by volume
    - Yields a product with a density of 16 kg/m^3 and thermal conductivity of 0.043 W/mK
    - Both values are very close to that of **still** air

Example 2.2: Convection

- The interior face of an insulated exterior enclosure wall 2.4 m wide and 2.4 m high is 3°C cooler than the indoor air
  (T_{indoor} = 21°C)
  a) Calculate convective heat transfer coefficient at the face
  b) Calculate rate of convective heat transfer

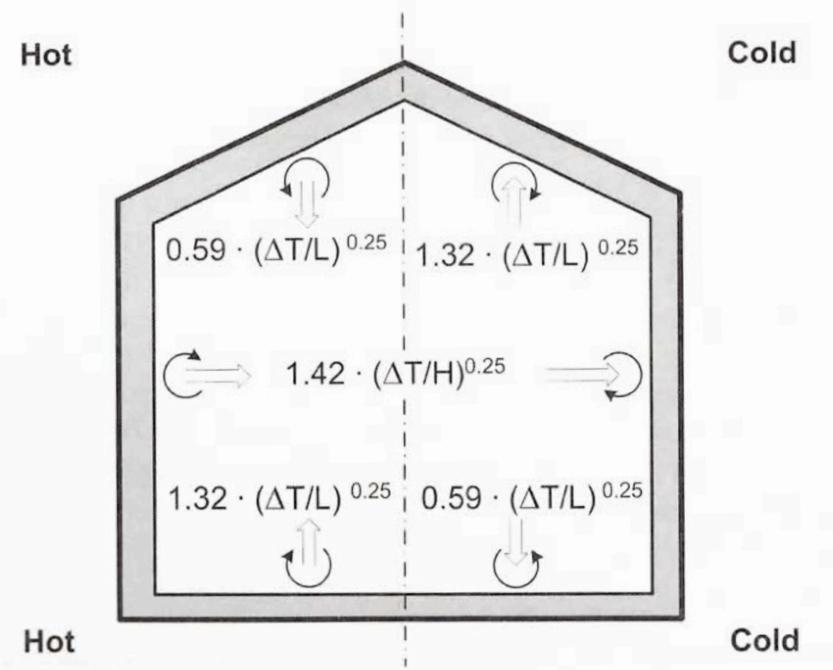


Figure 5.4: Natural convection coefficients for laminar flow

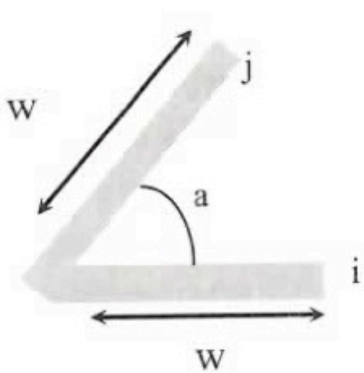
Example 2.3: Bulk convection

- An 800 m^3 building has an outdoor air exchange rate of 0.5 air changes per hour. The outdoor temperature is 35°C. The indoor air temperature is 20°C.
  a) Calculate the rate at which heat is added to the indoor air from outdoors

Example 2.4: Radiation

- Interior surfaces of two perpendicular walls (both are 2.4 m by 2.4 m) are 3°C different from each other. One is at 294 K, the other at 291 K. They both have an emissivity of 0.90.
  a) Calculate the rate of radiative heat transfer between the two surfaces

  b) What if the emissivity of one surface decreases to 0.1?



$$F_{ij} = 1 - \sin(\frac{a}{2})$$

ENERGY BALANCES

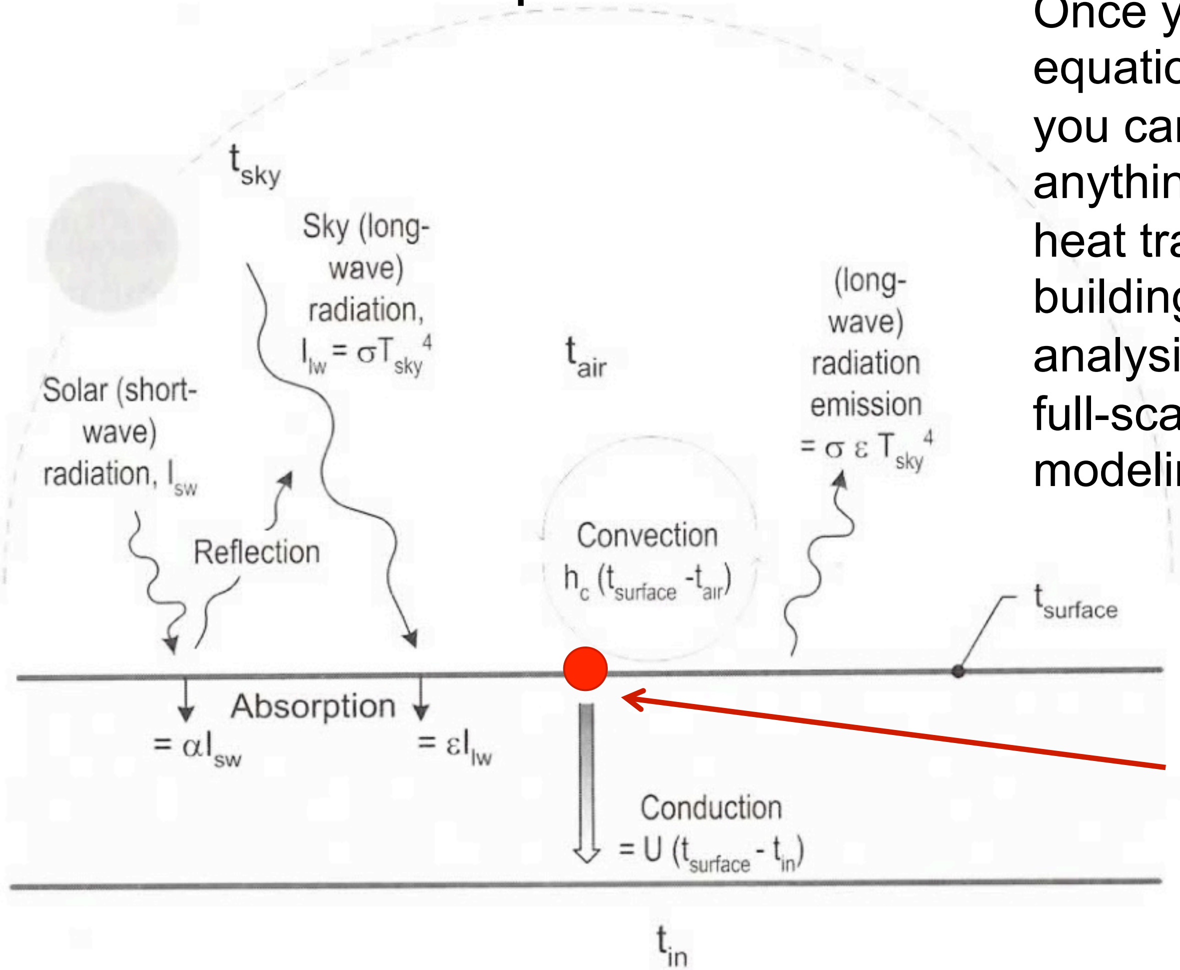
How do these modes all work together?

Combined heat transfer

- In some cases, heat transfer from a surface is dominated by either convection or radiation
  - In many cases both are about the same magnitude
- In cavities (window spaces, wall cavities, crawl spaces) this is usually the case
  - So, heat transfer is fairly complicated
- We need to be able to describe all heat transfer mechanisms acting on each surface of an enclosure to understand how the enclosure affects heat, air, and moisture performance

Bringing all the modes together

- Exterior surface example: roof



Once you have this equation described, you can do just about anything regarding heat transfer in building enclosure analysis, leading into full-scale energy modeling

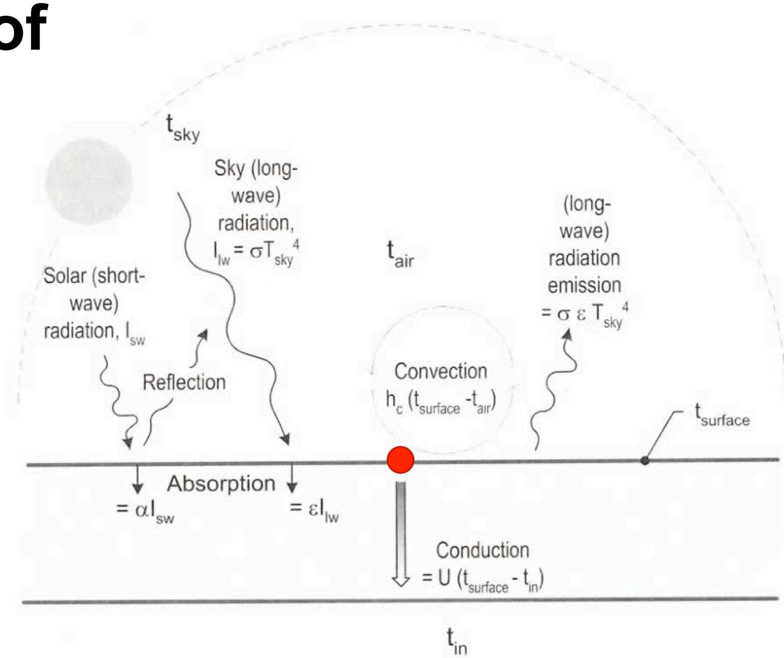
Steady-state energy balance at this exterior surface:
What enters must also leave (no storage)

$$q_{solar} + q_{longwaveradiation} + q_{convection} - q_{conduction} = 0$$

Bringing all the modes together

- Exterior surface example: **Roof**

$$\sum q = 0$$



We can use this equation to estimate indoor and outdoor surface temperatures

At steady state, net energy balance is zero

- Because of T^4 term, often requires iteration

Solar gain	αI_{solar}	$q_{sw,solar}$
Surface-sky radiation	$+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surface}^4)$	$+q_{lw,surface-sky}$
Convection on external wall	$+h_{conv}(T_{air} - T_{surface})$	$+q_{convection}$
Conduction through wall	$-U(T_{surface} - T_{surface,interior}) = 0$	$-q_{conduction} = 0$

A note on sign conventions

- Move from left to right (or top to bottom)
- Assume that the temperature to the left (or upstream) is higher than the temperature to the right (or downstream)
  - The signs will work themselves out and let you know if that is not the case
  - Be consistent!

A note on sky temperatures

- Many ways to get sky temperature
  - Varying levels of detail and accuracy
- For a partly cloudy night sky: $T_{sky} = T_{air}\left[0.8 + \frac{(T_{dewpoint} - 273)}{250}\right]^{1/4}$
  - 50% cloud cover
- For daytime: $T_{sky} = \left(\varepsilon_{sky} T_{air}^{4}\right)^{0.25}$

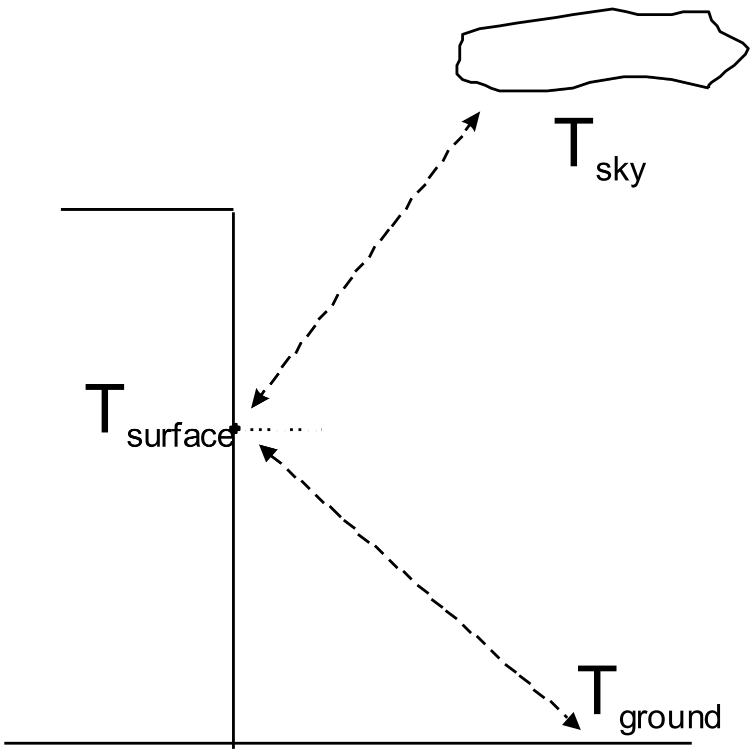
$$\varepsilon_{sky} = \left[0.787 + 0.764 \ln\left(\frac{T_{dewpoint}}{273}\right)\right]\left(1 + 0.0224N - 0.0035N^{2} + 0.00028N^{3}\right)$$

  - For a clear sky: N = 0
  - For 50% cloud cover, N = 0.5

Where N = cloud cover (tenths)

A note on typical view factors, F_{1-2}

- Some typical view factors from surfaces to ground or sky



View ("shape") factors for:

Vertical surfaces:

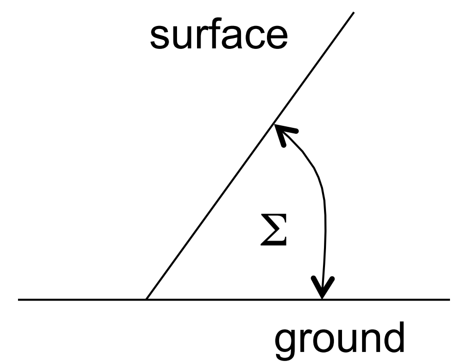
- To sky ($F_{surface-sky}$) 0.5
- To ground ($F_{surface-ground}$) 0.5

Horizontal surfaces:

- To sky ($F_{surface-sky}$) 1
- To ground ($F_{surface-ground}$) 0

3) Tilted surfaces

- To sky $(1+\cos\Sigma)/2$
- To ground $(1-\cos\Sigma)/2$



Typically assume:

$$T_{ground} = T_{air}$$

*Note that other surrounding buildings complicate view factors, but their net temperature differences probably aren't that different so long-wave radiation can be negligible

Example 2.5: Roof surface temperature

- Estimate the surface temperature that might be reached by a bituminous roof (absorptance of 0.9) installed over a highly insulating substrate (R-20 IP) exposed to intense sun (q_{solar} = 1000 W/m^2) on a calm, cloudless day with an ambient temperature of 20°C, RH = 30%, and wind speed of 2 m/s
  - Indoor surface temperature is 22°C

- Then: what happens if α is reduced to 0.3?

Example 2.5: Solution

Surface energy balance		Add W/m^2	Subtract W/m^2
Solar (short-wave)		900	
Surface-sky long-wave radiation		-338	
Convection on roof		-551	
Conduction through roof			11
	SUM	0	

Given	alpha	0.9	bituminous membrane		
Given	Itotal, W/m2	1000			
Assume	Fsurface-sky	1			
Assume	e,surface	0.9			
Given	Tair,out, K	293.15	20	degC	
Assume	Tair,out,dewpoint, K	275.06	1.91	degC	*psych chart*
Calculate	e,sky	0.79	N = 0		
Calculate	Tsky, K	276.61	Tsky equation for clear day		
Guess	**Tsurface, K**	**334.25**	**61.1**	**degC**	
Given	Tsurf,in, K	295.15	22.0	degC	
Constant	stef-boltz, W/(m2K4)	5.6704E-08			
Calculate	hconv, Wm2K	13.4			
Given	R-value IP, h-ft2-F/Btu	20			
Given	R-value, SI	3.52			
Given	U-value, W/m2K	0.28			

Adjust $T_{surface}$ until sum of all heat transfer modes equals zero

Example 2.5: Solution (low absorptivity)

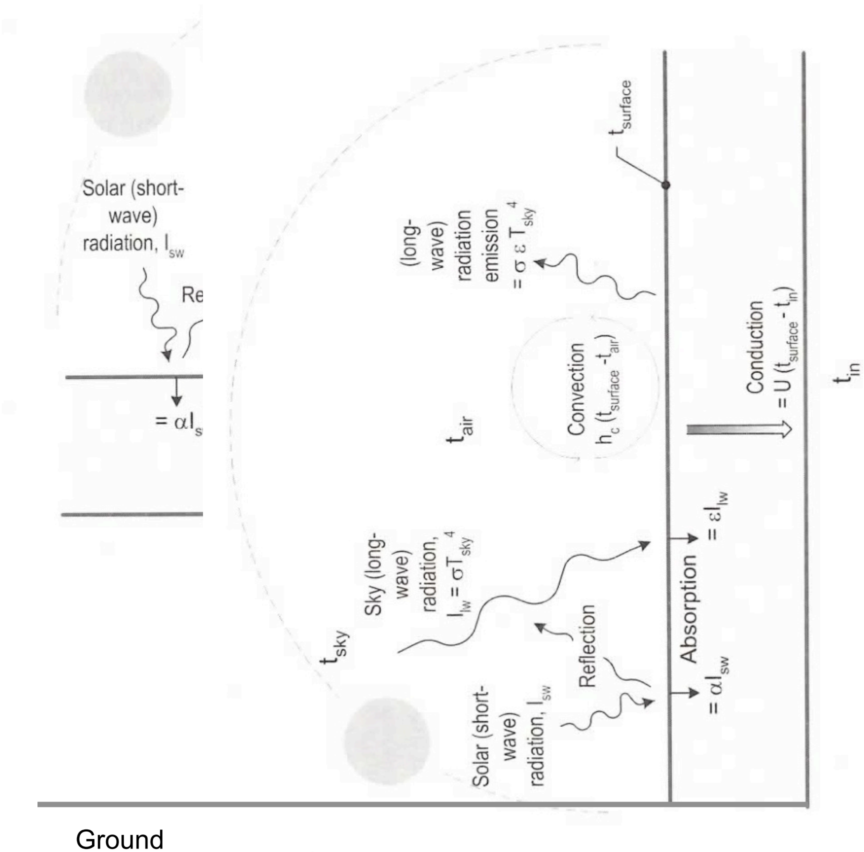
Surface energy balance	***Add***	***Subtract***
	W/m^2	W/m^2
Solar (short-wave)	300	
Surface-sky long-wave radiation	-141	
Convection on roof	-155	
Conduction through roof		3
SUM	0	

Given	alpha	0.3	bituminous membrane		
Given	Itotal, W/m2	1000			
Assume	Fsurface-sky	1			
Assume	e,surface	0.9			
Given	Tair,out, K	293.15	20	degC	
Assume	Tair,out,dewpoint, K	275.06	1.91	degC	*psych chart*
Calculate	e,sky	0.79	N = 0		
Calculate	Tsky, K	276.61	Tsky equation for clear day		
Guess	**Tsurface, K**	**304.75**	**31.6**	**degC**	
Given	Tsurf,in, K	295.15	22.0	degC	
Constant	stef-boltz, W/(m2K4)	5.6704E-08			
Calculate	hconv, Wm2K	13.4			
Given	R-value IP, h-ft2-F/Btu	20			
Given	R-value, SI	3.52			
Given	U-value, W/m2K	0.28			

Bringing all the modes together

- Similarly, for a vertical surface:

$$q_{solar} + q_{lwr} + q_{conv} - q_{cond} = 0$$



$$\alpha I_{solar}$$

$$+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surface}^4)$$

$$+\varepsilon_{surface}\sigma F_{ground}(T_{ground}^4 - T_{surface}^4)$$

$$+h_{conv}(T_{air} - T_{surface})$$

$$-U(T_{surface} - T_{surface,interior}) = 0$$

Next couple of lectures

Bringing all modes (and nodes) together

- For an example room like this, you would setup a system of equations where the temperature at each node (either a surface or within a material) is unknown
  - 12 material nodes + 1 indoor air node

At surface nodes:

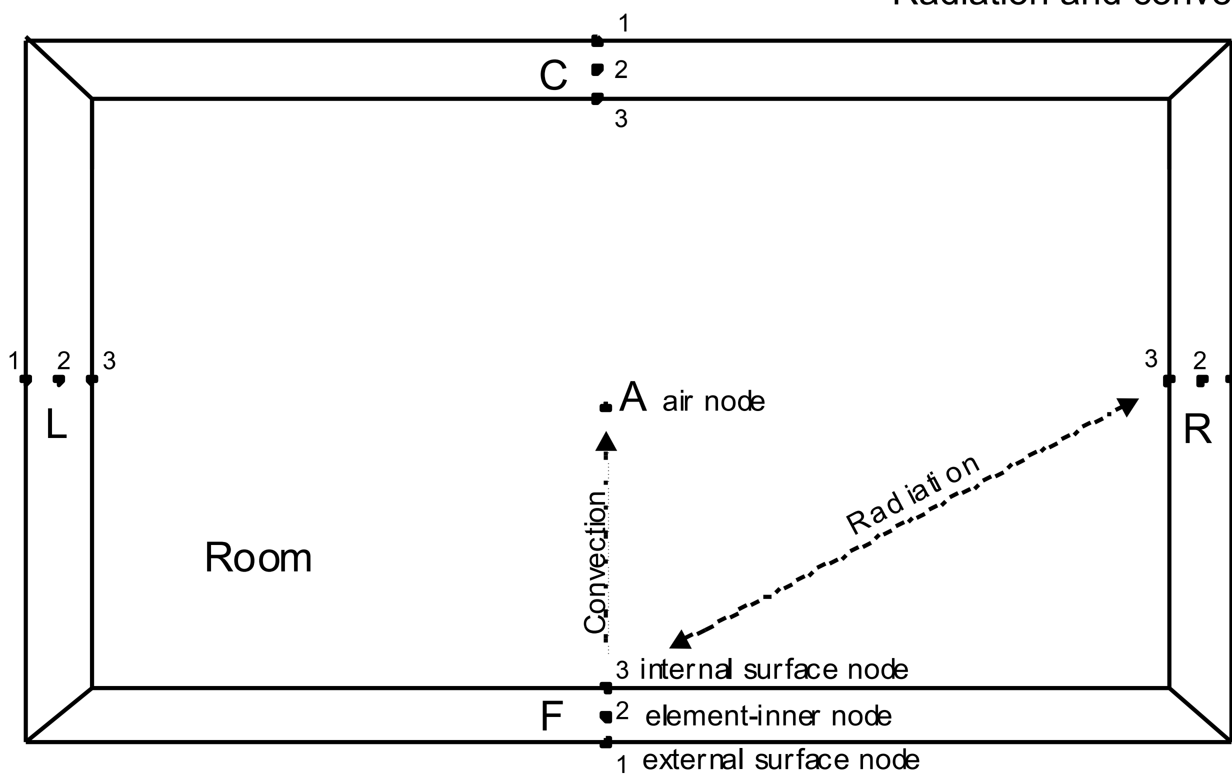
$$\sum q = 0$$

At nodes inside materials:

$$mc_p \frac{dT}{dt} = \sum q_{at\ boundaries}$$

Based on density and heat capacity of material…

Heat Xfer @ external surfaces: Radiation and convection

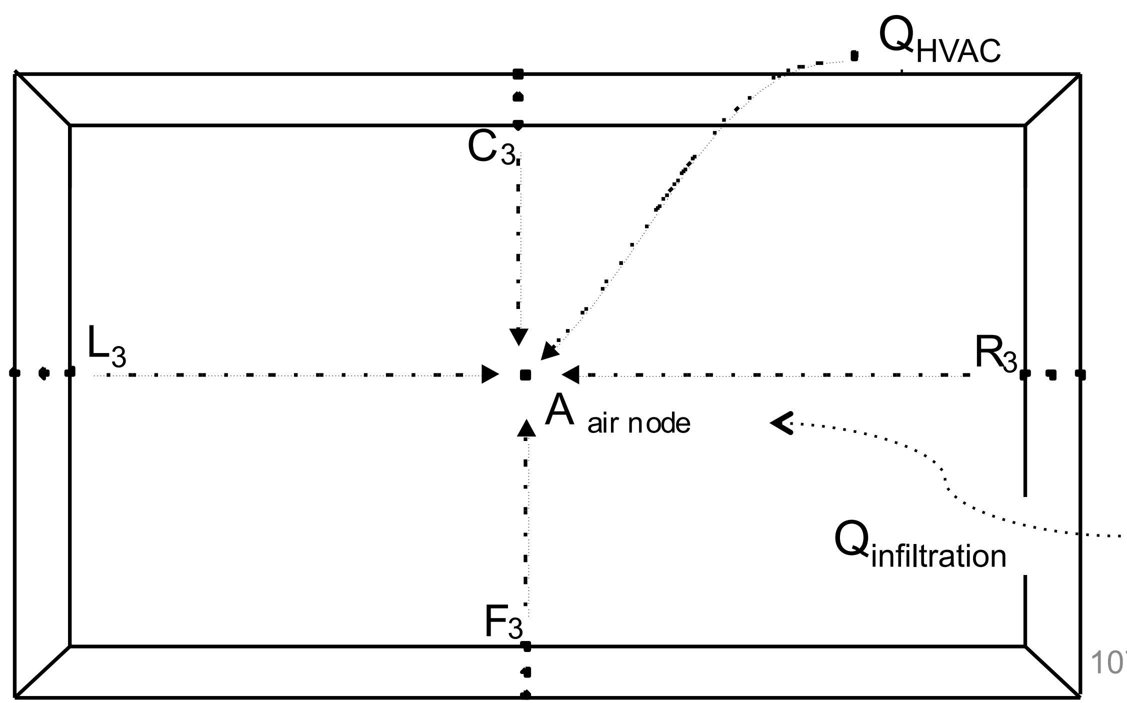


Bringing all modes (and nodes) together

- To get the impact on indoor air temperature (and close the system of equations)
  - Write an energy balance on the indoor air node
  - Air impacted directly only by convection (bulk and/or surface)

$$(V_{room}\rho_{air}c_{p,air})\frac{dT_{air,in}}{dt} = \sum_{i=1}^{n} h_i A_i \left(T_{i,surf} - T_{air,in}\right) + \dot{m}c_p\left(T_{out} - T_{air,in}\right) + Q_{HVAC}$$

In plain English:
The change in indoor air temperature is equal to the sum of convection from each interior surface plus outdoor air delivery (by infiltration or dedicated outdoor air supply), plus the bulk convective heat transfer delivered by the HVAC system



Next lectures

- No class January 27 (ASHRAE)

- Next class: February 3
  - Finish energy balances
  - Solar radiation
  - Complex conduction