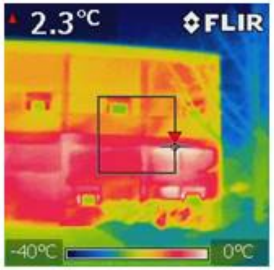
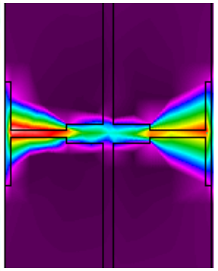
CAE 331/513
Building Science
Fall 2017





September 7, 2017
Radiation heat exchange

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Last time

- Convection
  - Natural vs. forced
  - Internal vs. external
  - Laminar vs. turbulent

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

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

Forced:

$$\text{Nu} = \frac{hL_c}{k} \qquad \text{Nu} = f(\text{Re}, \text{Pr}) \qquad \text{Re}_x = \frac{\rho \mathcal{V} x}{\mu} = \frac{\mathcal{V} x}{\upsilon} \qquad \text{Pr} = \frac{\mu C_p}{k}$$

Natural:

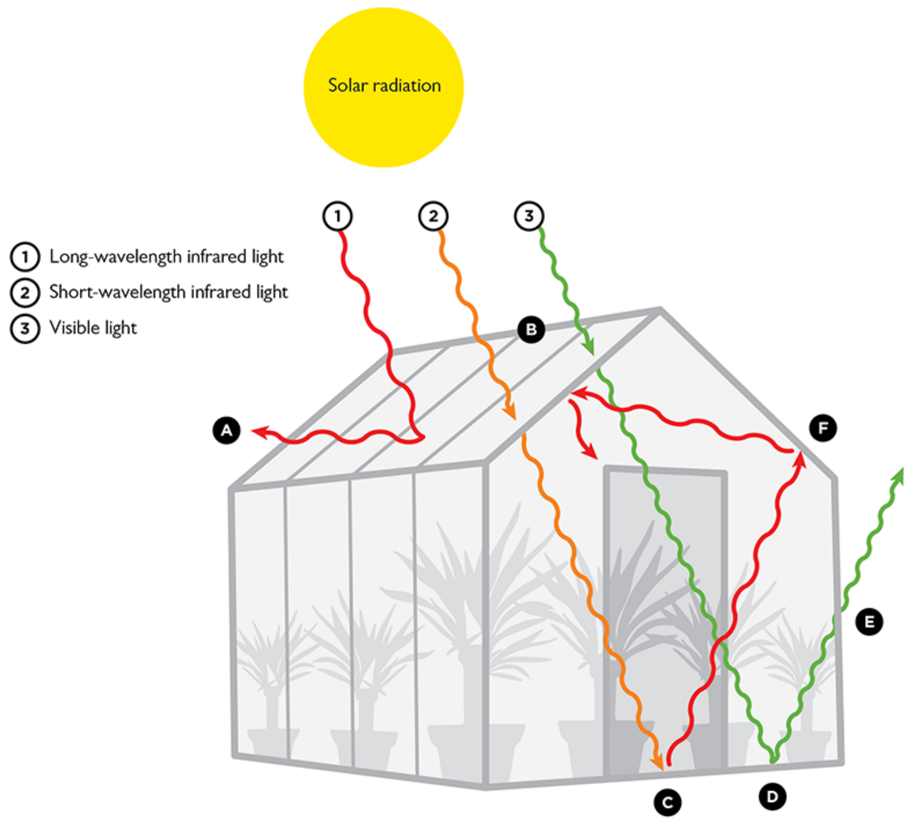
$$\text{Nu} = \frac{hL_c}{k} = f(\text{Ra}_{Lc}, \text{Pr}) \qquad \text{Gr}_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2}$$ for vertical flat plates

1. Theory
2. Empirical values
3. Simplified values

- Advection

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

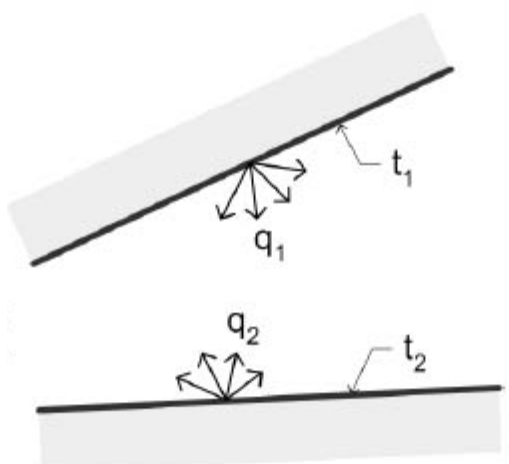
m "dot" = mass flow rate of fluid (kg/s)
C_p = specific heat capacity of fluid [J/(kgK)]

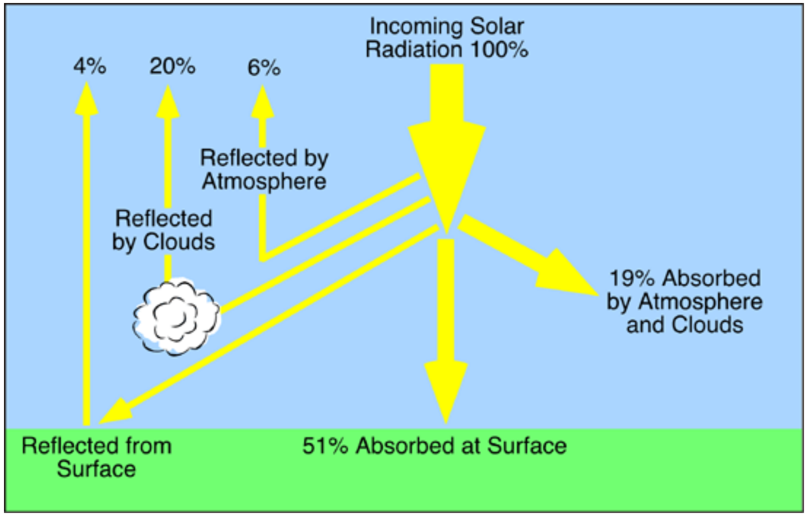

Solar radiation
1
2
3
1 Long-wavelength infrared light
2 Short-wavelength infrared light
3 Visible light
A
B
C
D
E
F

RADIATION

Radiation

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





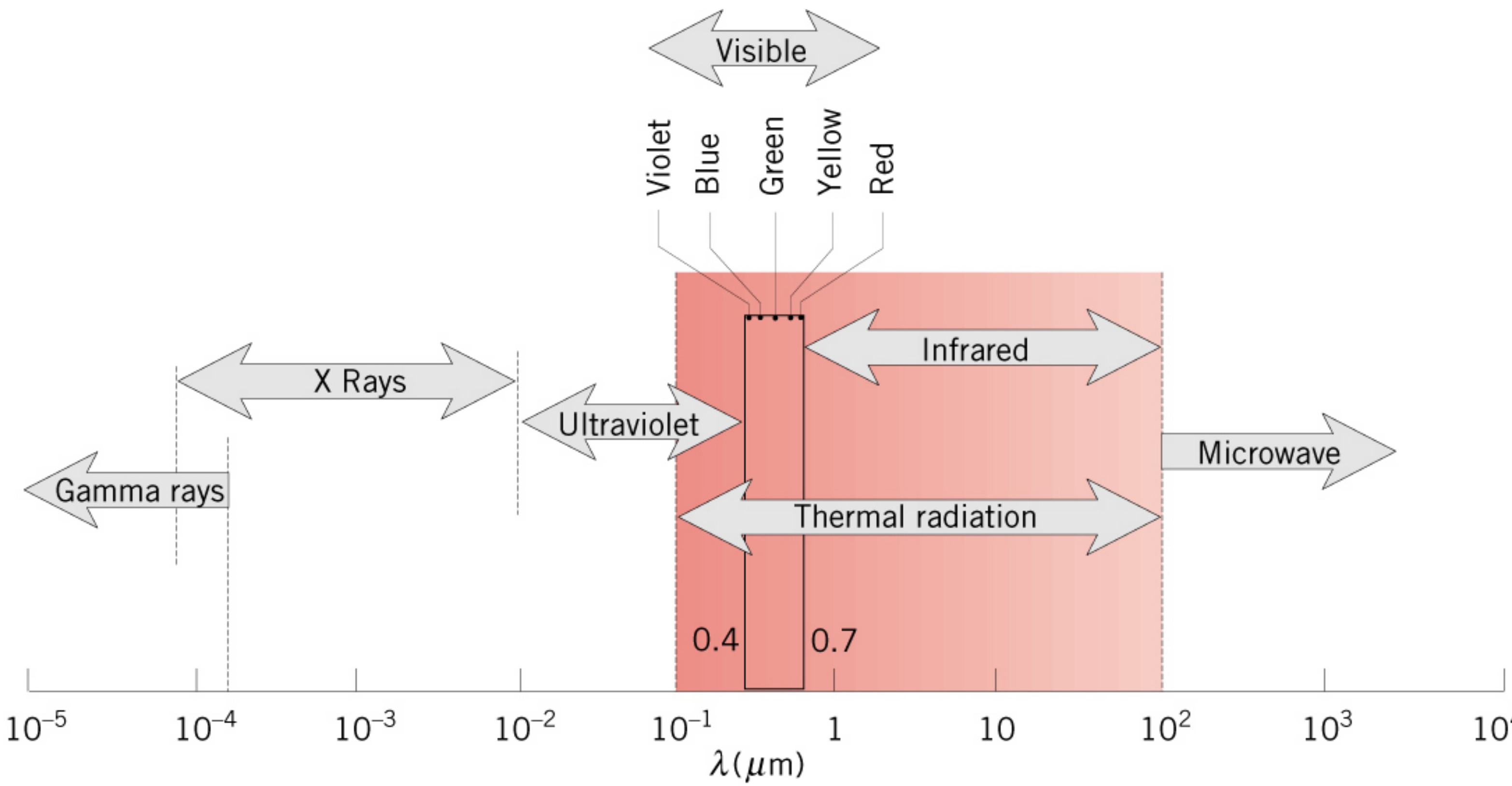
Radiation

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

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

Radiation: the electromagnetic spectrum

- <u>Thermal radiation</u> is confined to the infrared, visible, and ultraviolet regions (0.1 < λ < 100 μm)



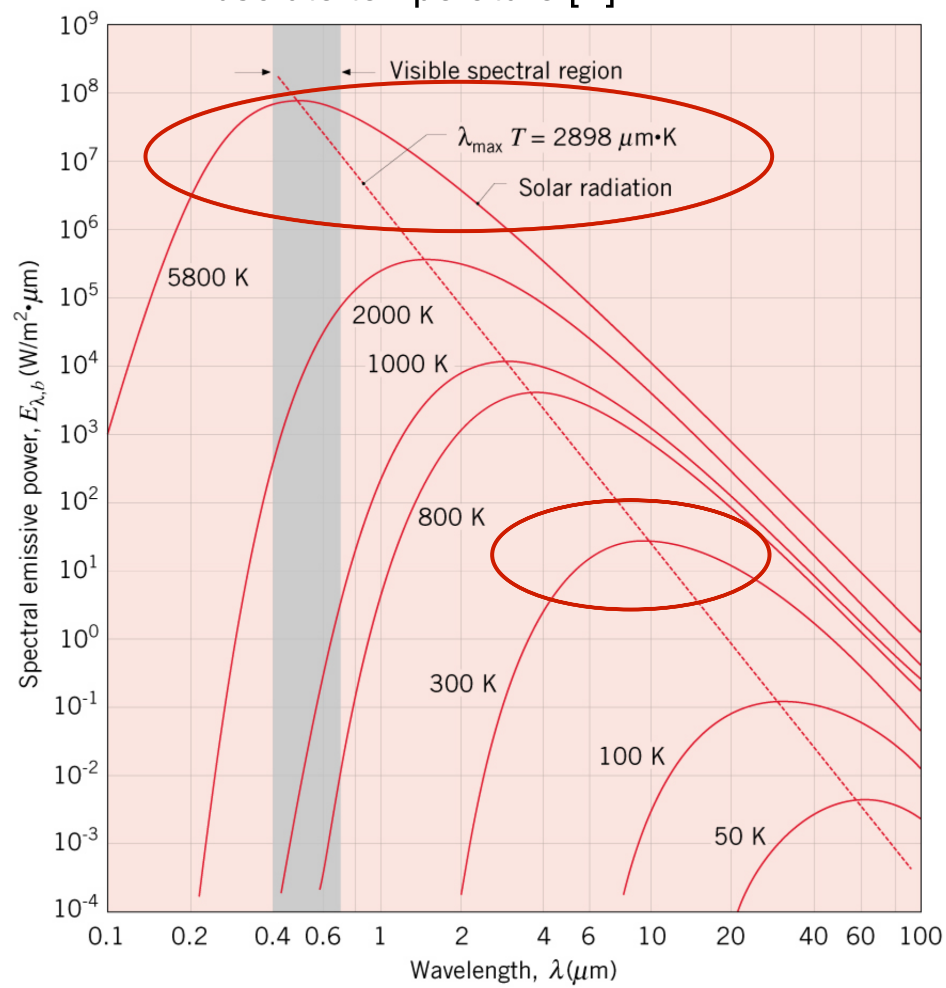
Black body radiation: Spectral (Planck) distribution

- Radiation from a perfect radiator follows the "black body" curve (ideal, black body *emitter*)
- The peak of the black body curve depends on the object's temperature
  - Lower T, larger λ peak
- Peak radiation from the sun is in the visible region
  - About 0.4 to 0.7 μm
- Radiation involved in building surfaces is in the infrared region
  - Greater than 0.7 μm

$q = \sigma T^4$

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

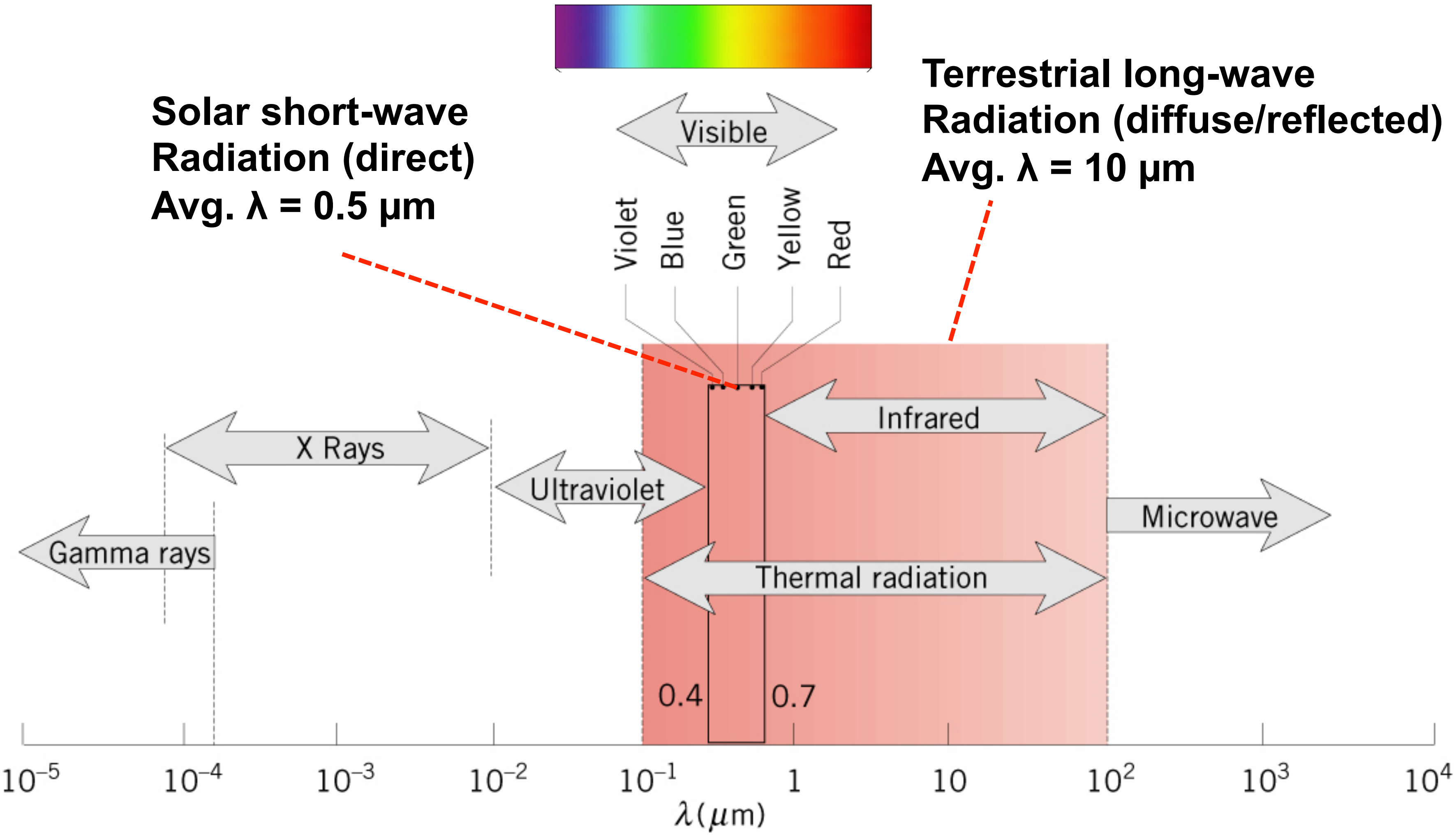
T = Absolute temperature [K]

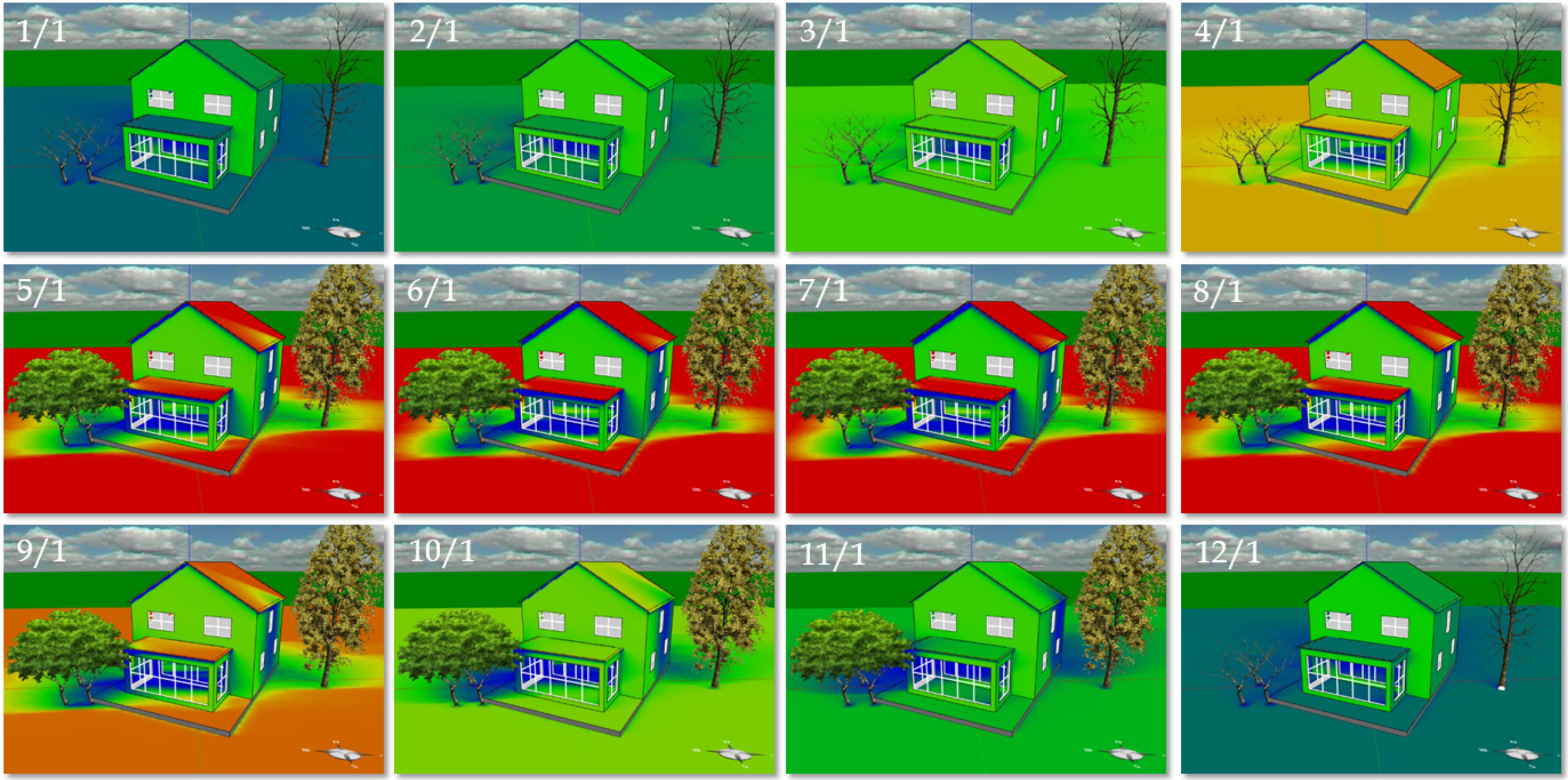


Radiation: Short-wave and Long-wave

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

Terrestrial long-wave Radiation (diffuse/reflected)
Avg. λ = 10 μm





SOLAR (SHORT-WAVE) RADIATION

Solar radiation

- Solar radiation is a very important term in the energy balance of a building
  - We must account for it while calculating loads
  - This is particularly true for perimeter zones and for peak cooling loads
- Solar radiation is also important for daylighting design
- We won't cover the full equations for predicting solar geometry and radiation striking a surface in this class
  - CAE 463/524 Building Enclosure Design goes into more detail
  - But will discuss basic relationships and where to get solar data

Solar radiation striking a surface (high temperature)

- Most solar radiation is at short wavelengths

Solar radiation striking a surface:

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

Solar radiation striking a surface (high temperature)

- Solar radiation data (I_{solar}) can be used on **opaque surfaces** to help determine **surface temperatures**

$$q_{solar} = \alpha I_{solar}$$

- Solar radiation data (I_{solar}) can also be used on exterior **fenestration** (e.g. **windows and skylights**) to determine how much solar radiation enters an indoor environment

$$q_{solar} = \tau I_{solar}$$

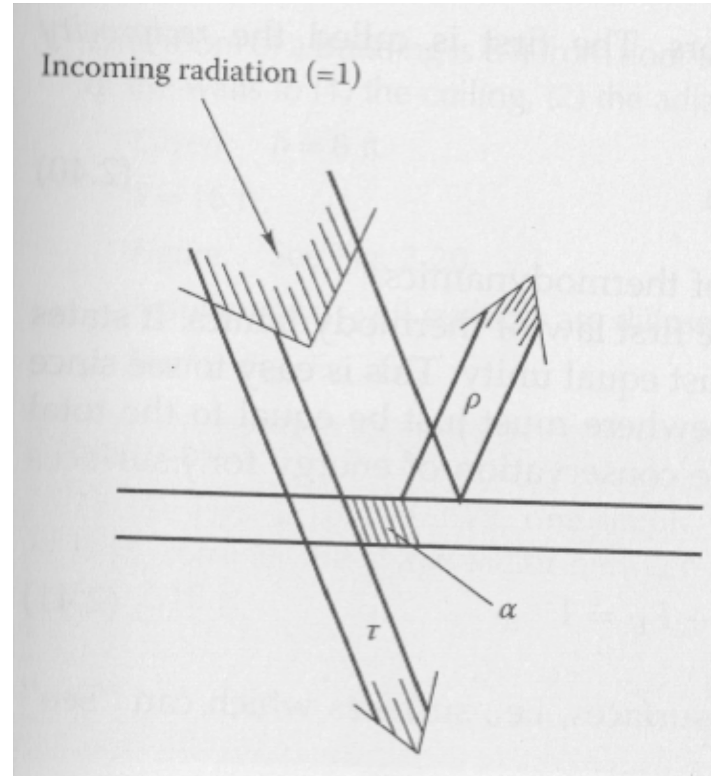
Absorptivity, transmissivity, and reflectivity

- The absorptivity, α, is the fraction of energy hitting an object that is actually absorbed

- Transmissivity, τ, is a measure of how much radiation passes through an object

- Reflectivity, ρ, is a measure of how much radiation is reflected off an object

- We use these terms primarily for solar radiation
  - For an opaque surface ($\tau = 0$): $q_{solar} = \alpha I_{solar}$
  - For a transparent surface ($\tau > 0$): $q_{solar} = \tau I_{solar}$



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

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

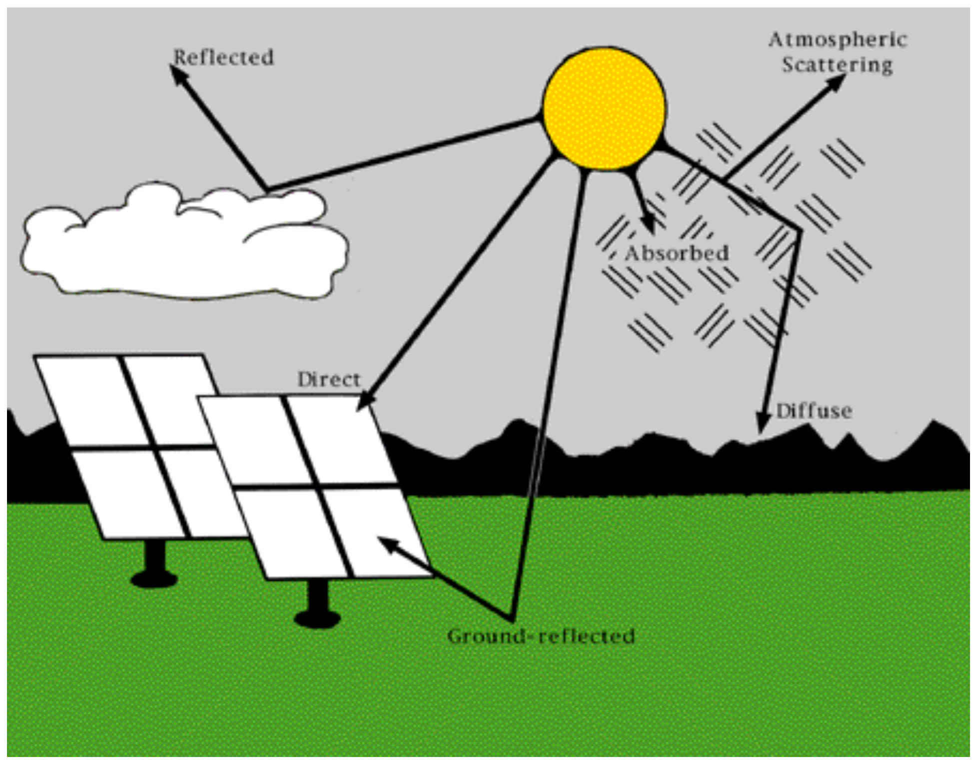
Surface	Absorptance for Solar Radiation
A small hole in a large box, sphere, furnace, or enclosure	0.97 to 0.99
Black nonmetallic surfaces such as asphalt, carbon, slate, paint, paper	0.85 to 0.98
Red brick and tile, concrete and stone, rusty steel and iron, dark paints (red, brown, green, etc.)	0.65 to 0.80
Yellow and buff brick and stone, firebrick, fire clay	0.50 to 0.70
White or light-cream brick, tile, paint or paper, plaster, whitewash	0.30 to 0.50
Window glass	—
Bright aluminum paint; gilt or bronze paint	0.30 to 0.50
Dull brass, copper, or aluminum; galvanized steel; polished iron	0.40 to 0.65
Polished brass, copper, monel metal	0.30 to 0.50
Highly polished aluminum, tin plate, nickel, chromium	0.10 to 0.40

Components of solar radiation (I_{solar})

- Solar radiation striking a surface consists of three main components:

$$I_{solar} = I_{direct} + I_{diffuse} + I_{reflected} \quad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

- Direct
- Diffuse
- Reflected



Components of solar radiation

- **<u>Direct solar radiation</u>** (I_{direct}) is a function of the **normal incident irradiation** (I_{DN}) on the earth's surface and the solar incidence angle of the surface of interest, θ
  - Where I_{DN} is the amount of solar radiation received per unit area by a surface that is always perpendicular to the sun's direct rays
  - Function of day of the year and atmospheric properties

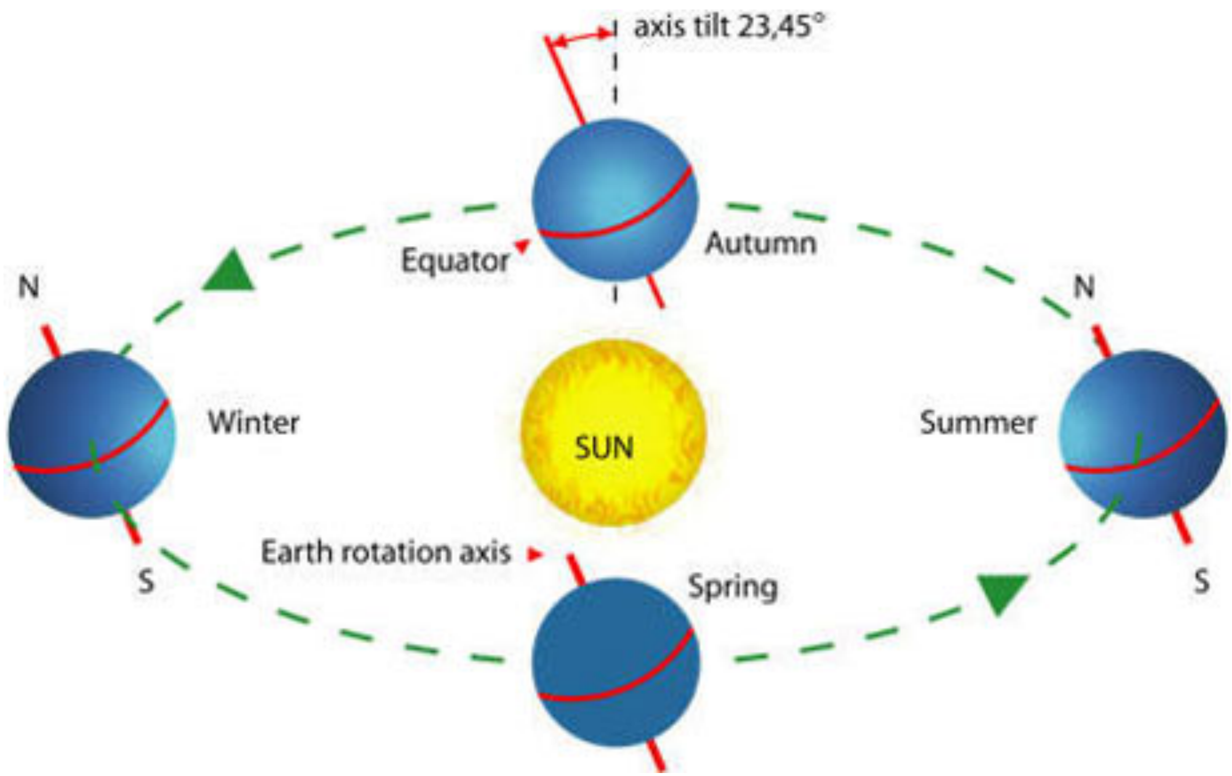
$$I_D = I_{DN} \cos\theta$$

- **<u>Diffuse solar radiation</u>** ($I_{diffuse}$) is the irradiation that is **scattered** by the atmosphere
  - Function of I_{DN}, atmospheric properties, and surface's tilt angle

- **<u>Reflected solar radiation</u>** ($I_{reflected}$) is the irradiation that is **reflected** off the ground (it becomes diffuse)
  - Function of I_{DN}, solar geometry, ground reflectance, and surface tilt angle

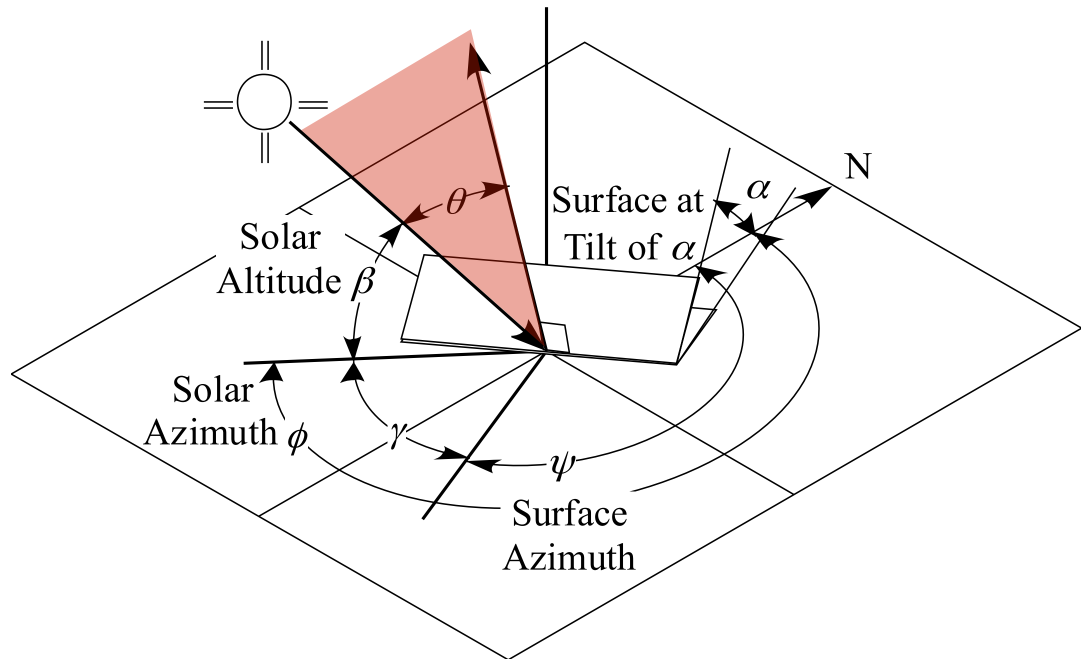
Solar radiation: earth-sun relationships

- Earth rotates about its axis every 24 hours
- Earth revolves around sun every 365.2425 days
- Earth is titled at an angle of 23.45°
  - Therefore, different locations on earth receive different levels of solar radiation during different times of the year (and different times of the day)



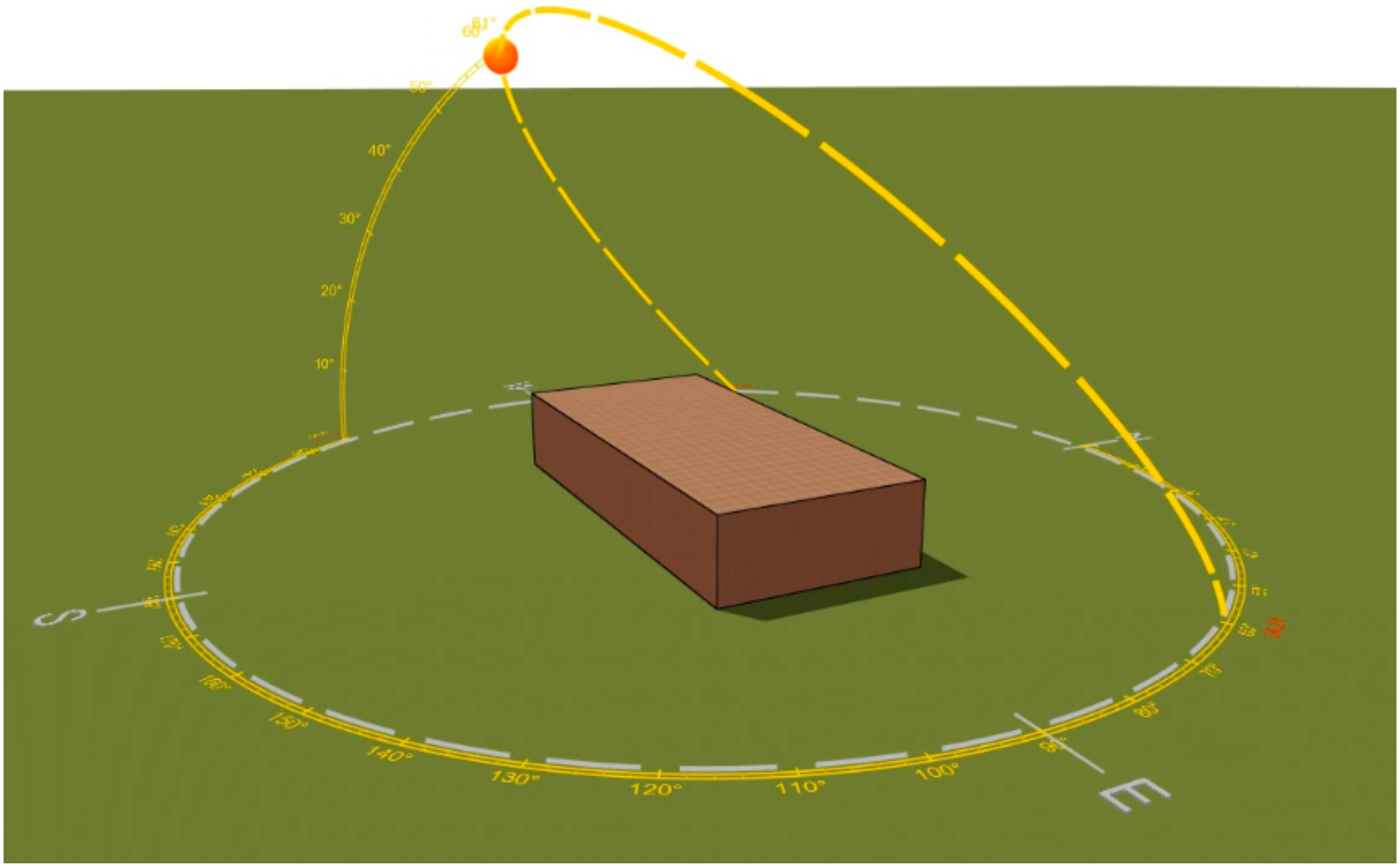
Solar radiation striking an exterior surface

- The amount of solar radiation received by a surface depends on the **incidence angle**, θ
- This is a function of:
  - Solar geometry (I_{DN})
    - Location
    - Time
  - Surface geometry
  - Shading/obstacles



$$I_D = I_{DN} \cos\theta$$

Visualizing solar relationships



http://energy.concord.org/energy3d/

Downloading solar data

- For hourly sun positions, you can build a calculator or use one from the internet
  - http://www.susdesign.com/sunposition/index.php
  - http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html

- For solar position and intensity (from time and place)
  - http://www.nrel.gov/midc/solpos/solpos.html
  - Output of interest = “global irradiance on a tilted surface”

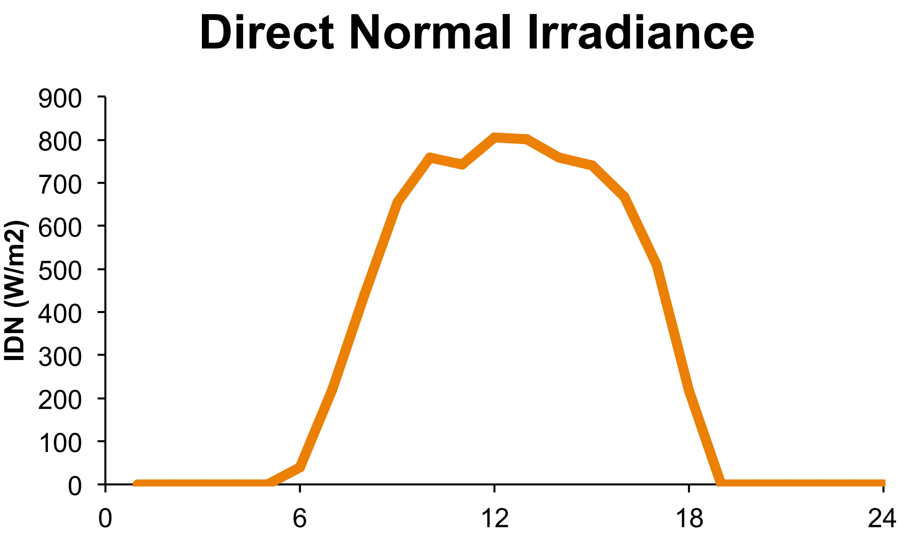
- For *actual* hourly solar data (direct + diffuse in W/m^2)
  - http://rredc.nrel.gov/solar/old_data/nsrdb/
  - Output of interest = “direct normal radiation” → adjust using cosθ
    - Note: “typical meteorological years”

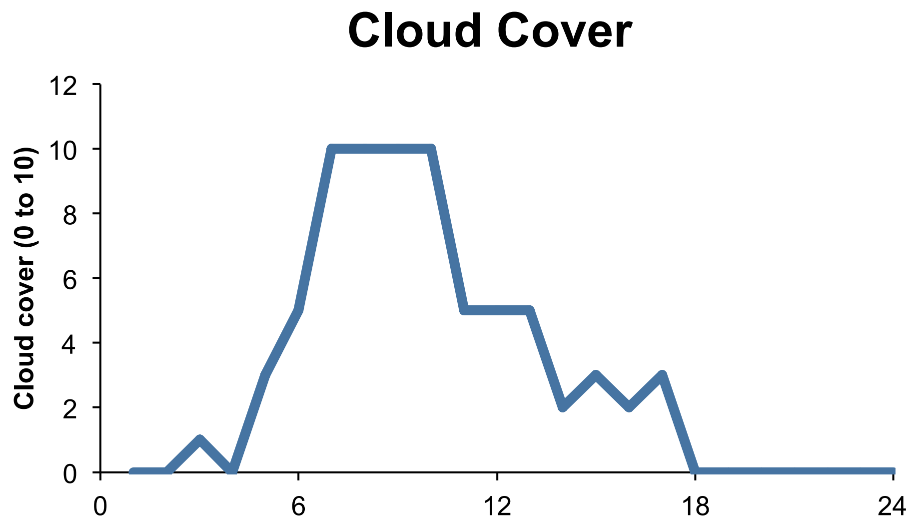
Typical meteorological year (TMY)

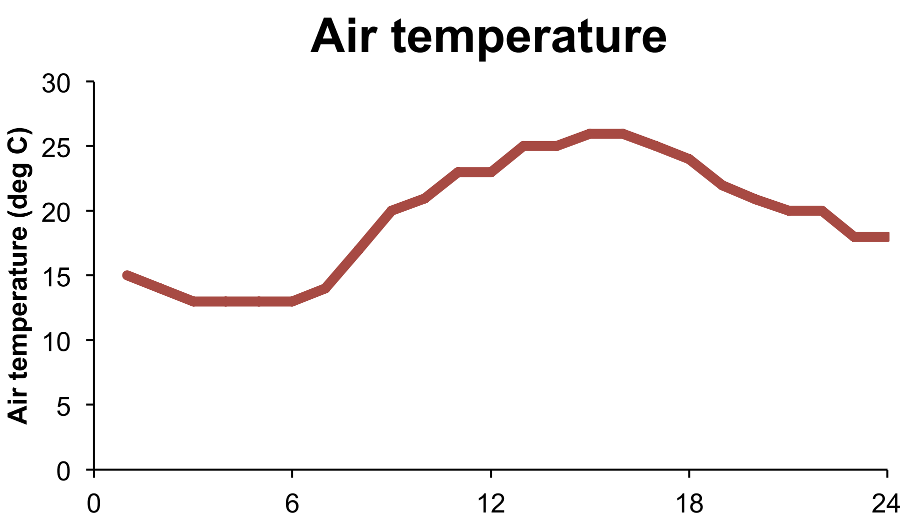
- For heating and cooling load calculations and for hourly building energy simulations, we often rely on a collection of weather data for a specific location
- We generate this data to be representative of more than just the previous year
  - Represents a wide range of weather phenomena for our location
  - TMY3: Data for 1020 locations from 1960 to 2005
    - Composed of 12 typical meteorological months
    - Each month is pulled from a random year in the range
    - Actual time-series climate data
    - Mixture of measured and modeled solar values
    - http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/
  - Variables include: outdoor temperature, direct normal radiation, wind speed, wind direction, outdoor RH, cloud cover, and more

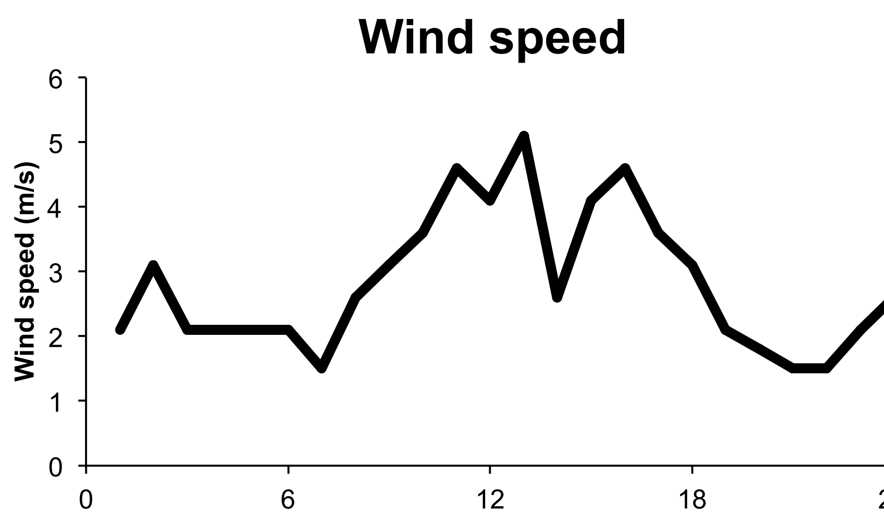
Typical meteorological year (TMY): Solar data

<u>Data for typical September 10th at Midway, Chicago, IL</u>







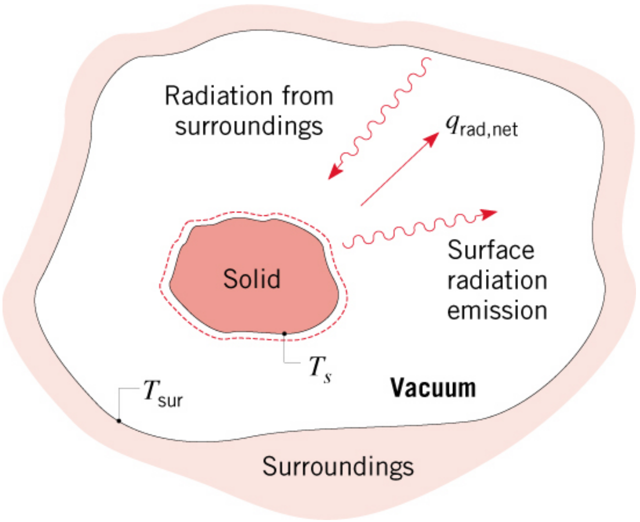


SURFACE (LONG-WAVE) RADIATION

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

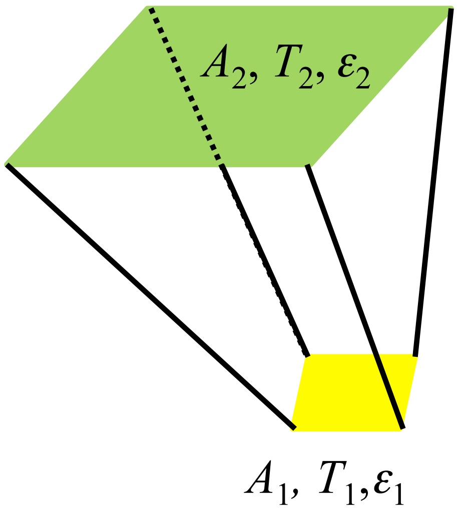
T = Absolute temperature [K]

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

Radiation heat transfer (surface-to-surface)

- We can write the net thermal radiation heat transfer between surfaces 1 and 2 as:

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



where ε_1 and ε_2 are the surface emittances,

A_1 and A_2 are the surface areas

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

$F_{1\to 2}$ is a function of geometry only

Emissivity (“gray bodies”)

- Real surfaces emit less radiation than ideal “black” ones
  - The ratio of energy radiated by a given body to a perfect black body at the same temperature is called the emissivity: ε
- ε is dependent on wavelength, but for most common building materials (e.g. brick, concrete, wood…), $\varepsilon = 0.9$ at most wavelengths

Emissivity (ε) of common materials

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

Emissivity (ε) of common building materials

TABLE 2.11

Emissivities of Some Common Building Materials at Specified Temperatures

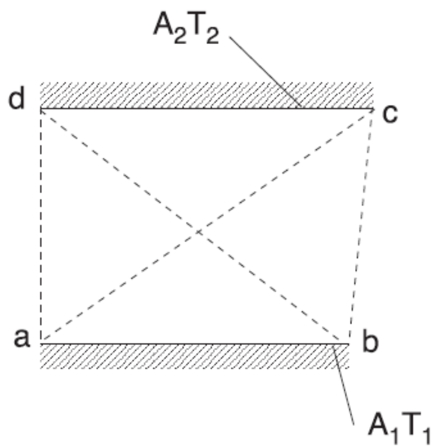
Surface	Temperature, °C	Temperature, °F	ϵ
Brick			
Red, rough	40	100	0.93
Concrete			
Rough	40	100	0.94
Glass			
Smooth	40	100	0.94
Ice			
Smooth	0	32	0.97
Marble			
White	40	100	0.95
Paints			
Black gloss	40	100	0.90
White	40	100	0.89–0.97
Various oil paints	40	100	0.92–0.96
Paper			
White	40	100	0.95
Sandstone	40–250	100–500	0.83–0.90
Snow	−12–−6	10–20	0.82
Water			
0.1 mm or more thick	40	100	0.96
Wood			
Oak, planed	40	100	0.90
Walnut, sanded	40	100	0.83
Spruce, sanded	40	100	0.82
Beech	40	100	0.94

Source: Courtesy of Sparrow, E.M. and Cess, R.D., *Radiation Heat Transfer*, augmented edn, Hemisphere, New York, 1978. With permission.

View factors, F_{12}

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

Some common view factors:



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

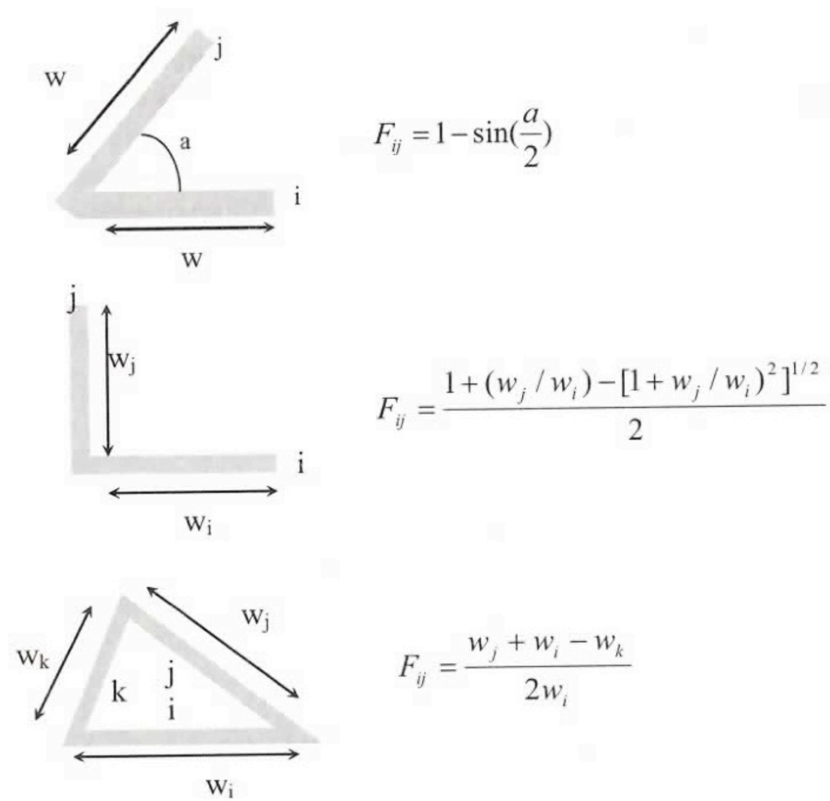
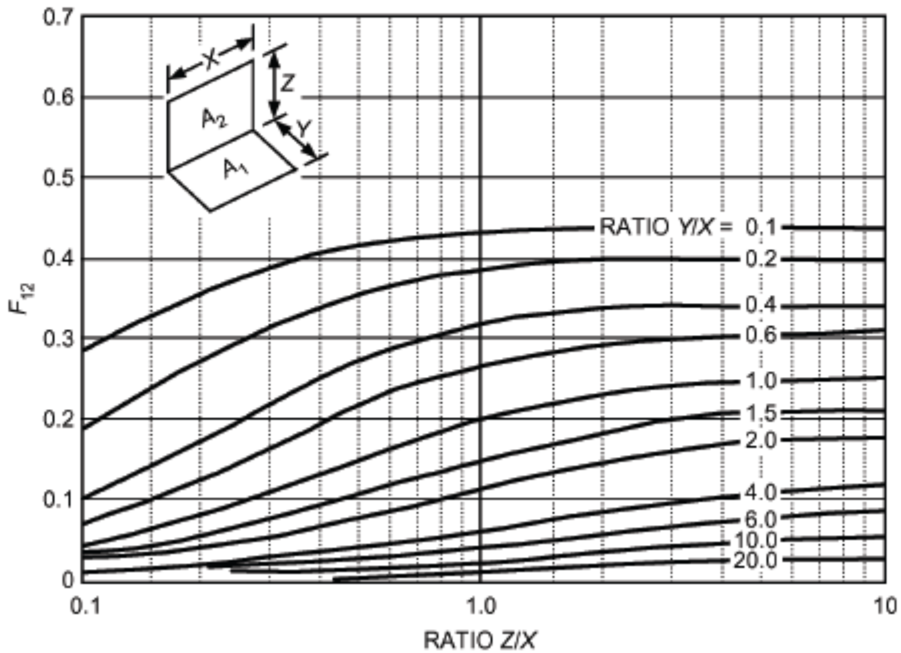


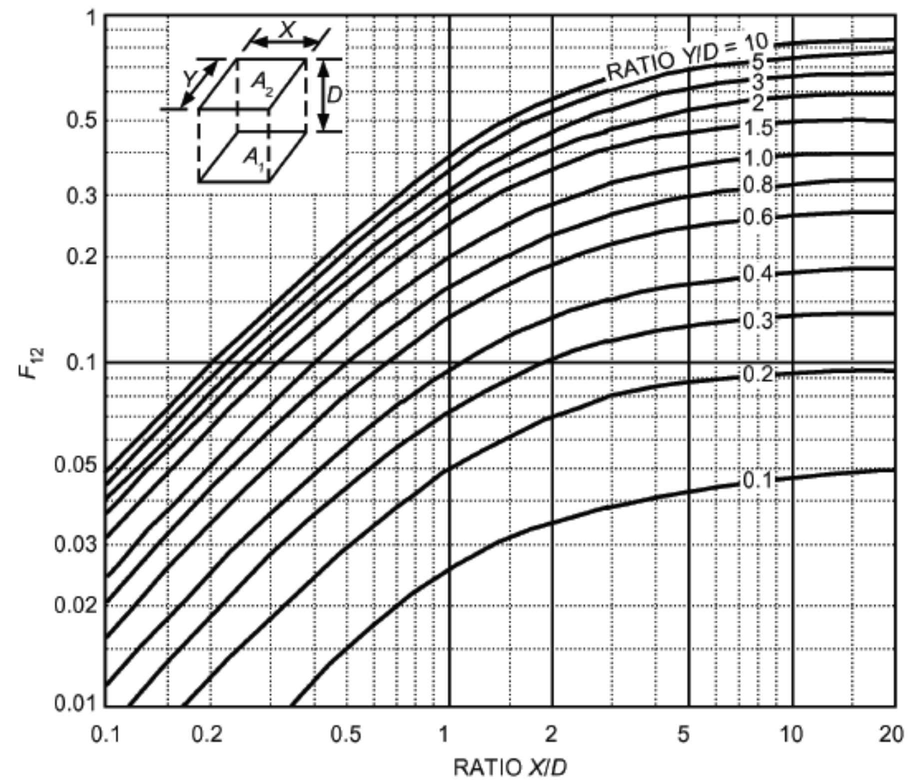
Figure 5.6: View factors for common situations in building enclosures [Hagentoft 2000]

Typical view factors

Other common view factors from the ASHRAE Handbook of Fundamentals:



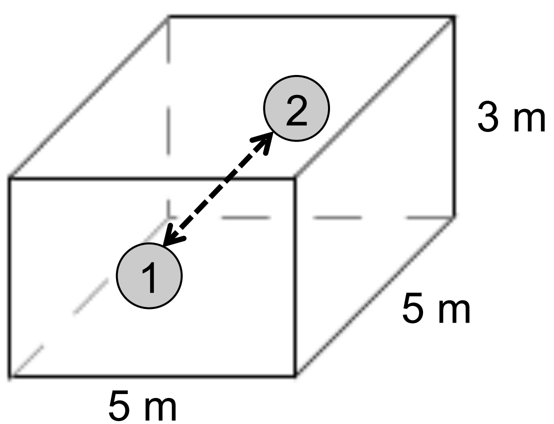
A. PERPENDICULAR RECTANGLES WITH COMMON EDGE

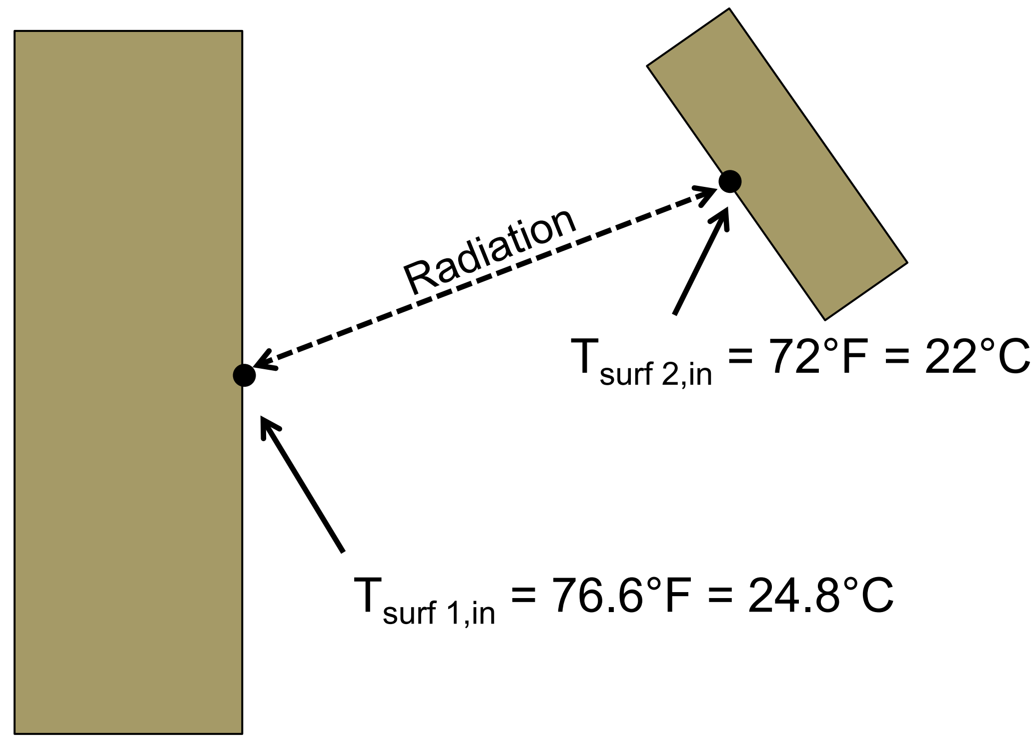


B. ALIGNED PARALLEL RECTANGLES

Long-wave radiation example

- What is the net radiative exchange between the two interior wall surfaces below if the room is 5 m x 5 m x 3 m?





Q: What if $T_{surf1,in}$ dropped to 50°F (10°C)?

Simplifying surface radiation

- We can also often simplify radiation from:

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

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

Particularly when dealing with large differences in areas, such as sky-surface or ground-surface exchanges

Simplifying radiation

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

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

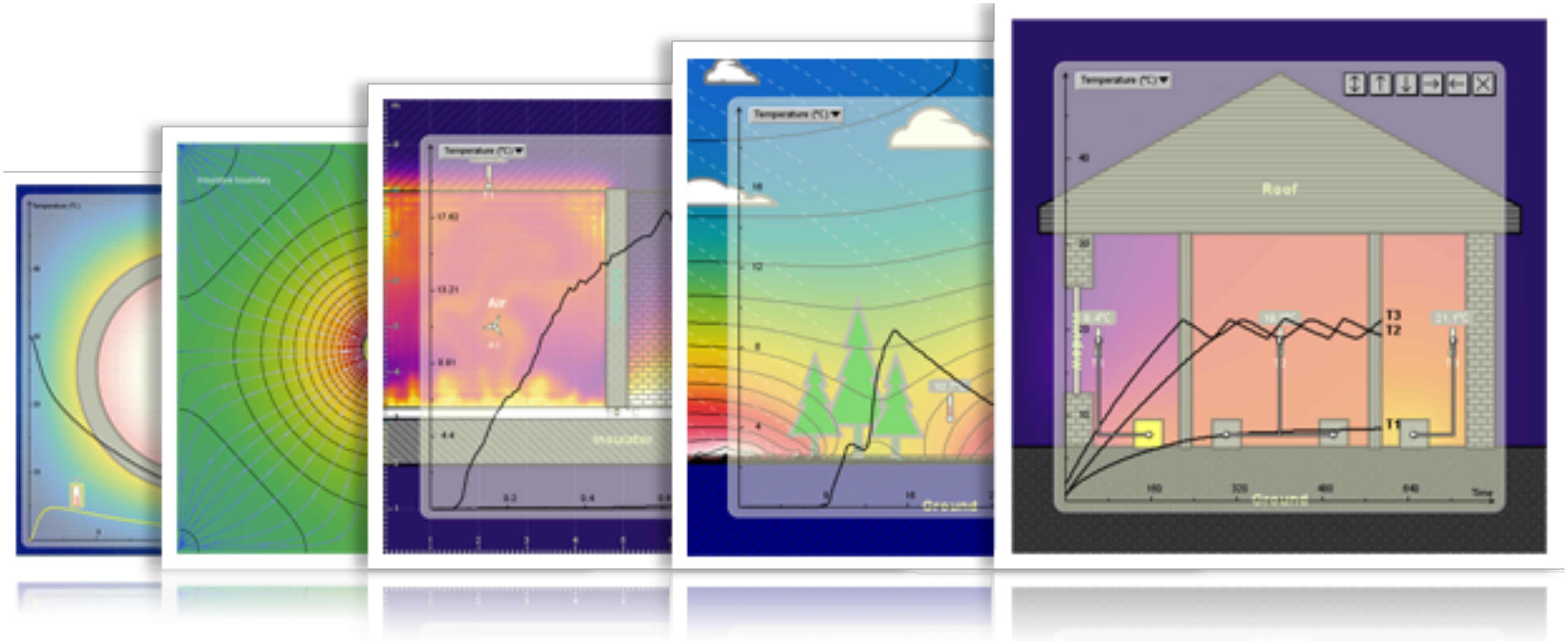
- When $A_1 = A_2$, and T_1 and T_2 are within ~50°F of each other, we can approximate h_{rad} with a simpler equation:

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

where

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

Radiation visualizations



Energy2D

Interactive Heat Transfer Simulations for Everyone