CAE 463/524
Building Enclosure Design
Fall 2013

Lecture 3: September 4, 2013 - CORRECTED
Energy balances
Solar orientation
Conduction in building enclosures

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Last time

- Review of building science
  - Psychrometrics
  - Modes of heat transfer

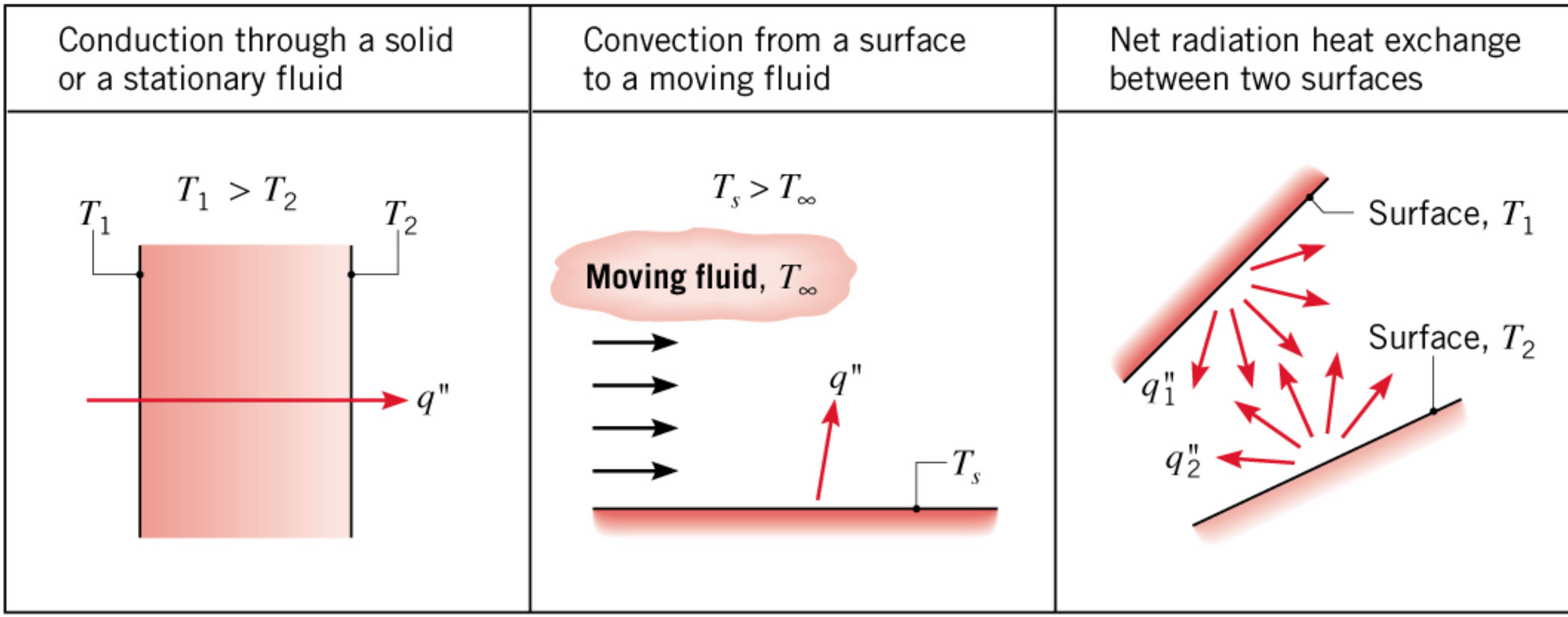
Today's objectives

- Example calculations for single-mode heat transfer
- Bring all the heat transfer modes together
- Solar orientation and enclosures

- Assign HW #1

Single-mode heat transfer examples

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



Conduction | **Convection** | **Radiation**

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 HOF (2005 Ch. 25):

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^{2}K
  - R = 1/U = 1/0.66 = ~1.5 m^{2}K/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)	Thickness** (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

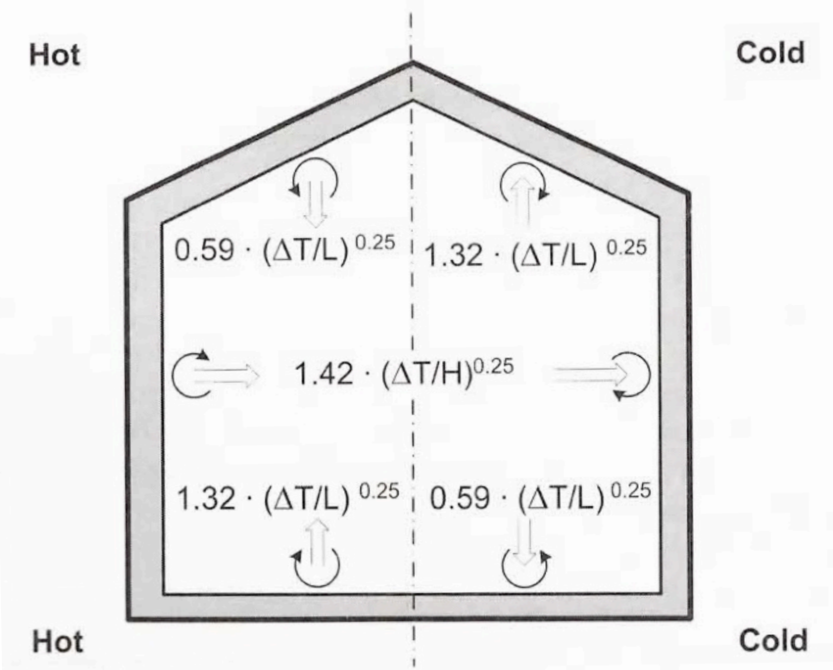


Figure 5.4: Natural convection coefficients for laminar flow

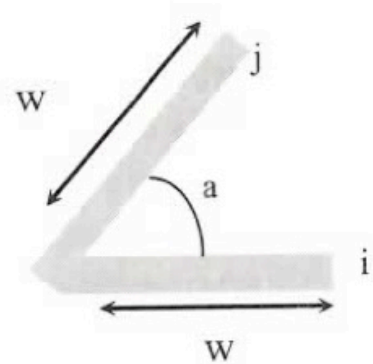
Example 2.3: Bulk convection

- 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?



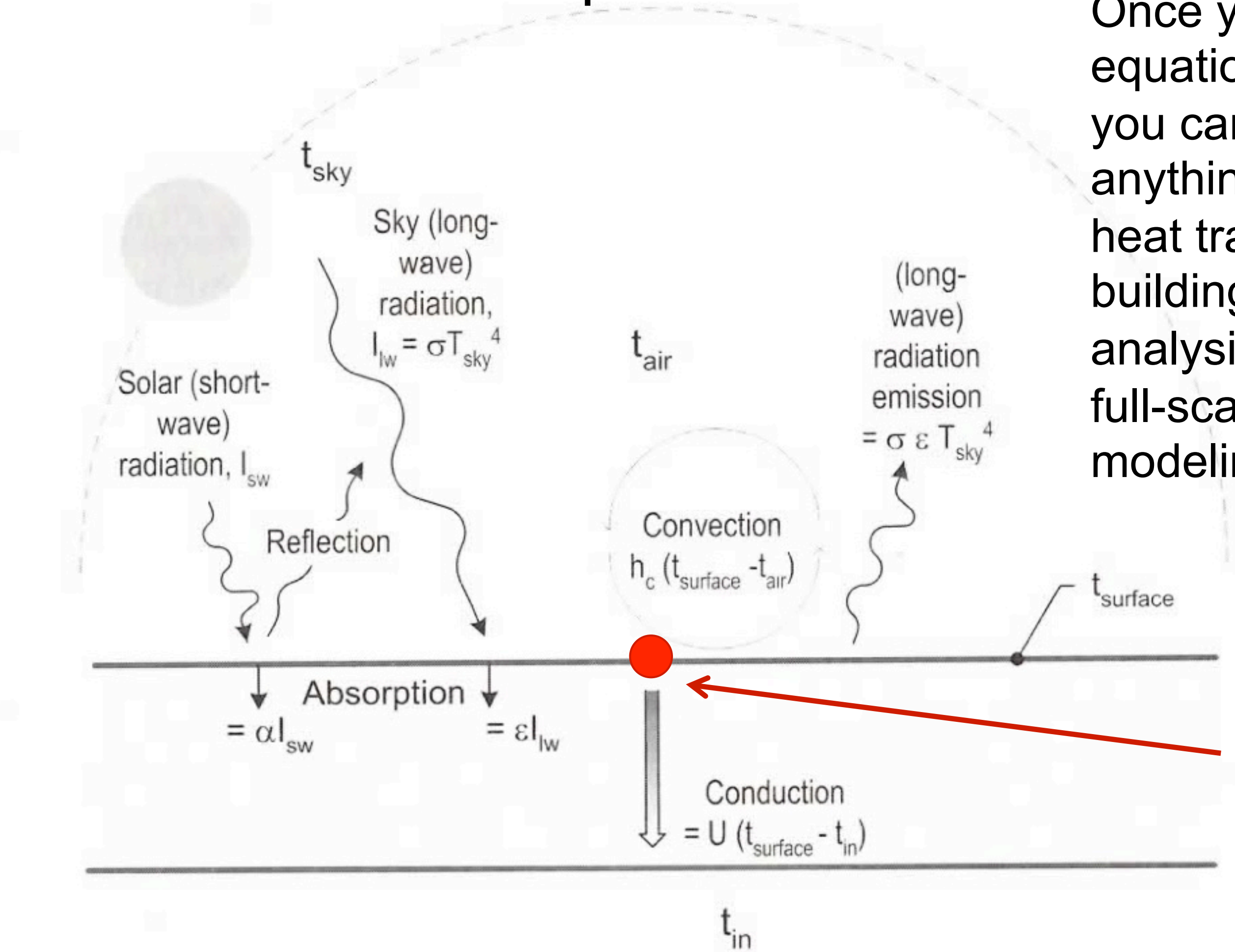
$$F_{ij} = 1 - \sin(\frac{a}{2})$$

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

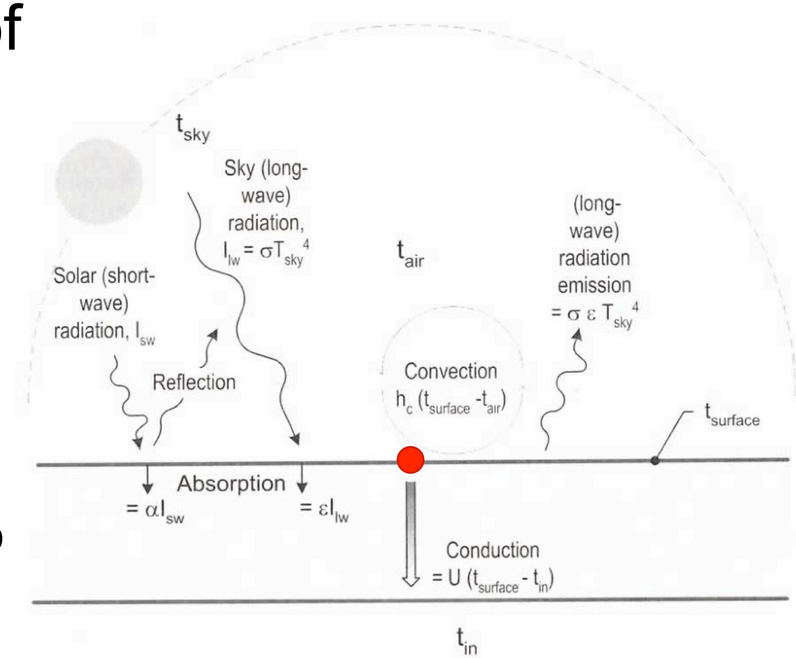
Steady-state energy balance at this exterior surface:
What enters must also leave (no storage)

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

Bringing all the modes together

- Exterior surface example: roof

$$\boxed{\sum q = 0}$$



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	$+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surf}^4)$	$+q_{lw,surface-sky}$
Surface-air radiation	$+\varepsilon_{surface}\sigma F_{air}(T_{air}^4 - T_{surface}^4)$	$+q_{lw,surface-air}$
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!

Correction: Accounting for *air* and *sky* LWR separately

- For a more detailed description of a discussion we had about whether or not to account for sky and air temperatures separately in long-wave radiation exchanges, please see the document I put on Blackboard and on my website

- I should note that some energy simulation programs deal only with surface-to-sky interactions, where sky temperatures are estimated from air temperatures and adjusted based on level of cloudiness and/or presence of water vapor (which absorb infrared radiation)
- Others, like EnergyPlus, which I've referenced in these slides, treat surface-air and surface-sky interactions separately
- Other disciplines don't even work with "sky" temperatures, but use air temperatures alone, although they are still adjusted for cloudiness and presence of water vapor
  - To-may-to vs. to-mah-to

Correction: Accounting for *air* and *sky* LWR separately

- For our purposes, I suggest we follow the EnergyPlus manual, with the following important changes that I failed to mention previously:
  - We should account for differences in surface-sky and surface-air long-wave radiation exchange simply by adjusting their respective view factors

Longwave Radiant View Factors, F_{sky} and F_g

Longwave radiant view factors are also somewhat case-dependent. Perhaps the simplest estimation of these parameters is to base them on the surface tilt, such that

$$F_{sky} = \left[\frac{(1+\cos\Sigma)}{2}\right]\cdot\cos\left(\frac{\Sigma}{2}\right) \quad (29)$$

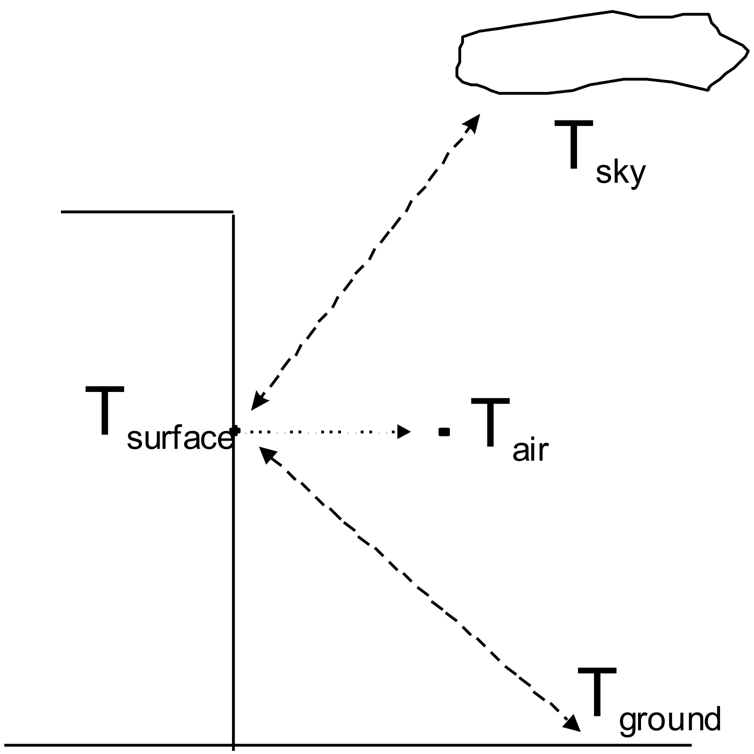
$$F_g = (1-\cos\Sigma)/2$$
$$(F_a = 1 - F_{sky} - F_g). \quad (30)$$

This is the formulation used in the BLAST program (Walton 1983). However, if the building is part of an urban environment, other buildings may dominate the surface's radiant view. Therefore, view factors should also be approximated based on the building's surroundings.

Source: McClellan, T.M., Pedersen, C.O. (1997). Investigation of outside heat balance models for use in heat balance cooling load calculation procedure. *ASHRAE Transactions* 103:469-484.

Correction: A note on typical view factors, $F_{1\text{-}2}$

- Some typical view factors from surfaces to ground or sky
  - $\cancel{F_{surface\text{-}air}\text{ typically 1.0}}$ $F_{surface\text{-}air}$ ranges from 0 to 0.15 depending on tilt



Typically assume: $T_{ground} = T_{air}$

View ("shape") factors for:

Vertical surfaces:

- To sky ($F_{surface\text{-}sky}$) 0.35
- To ground ($F_{surface\text{-}ground}$) 0.5
- To air ($F_{surface\text{-}air}$) 0.15

Horizontal surfaces:

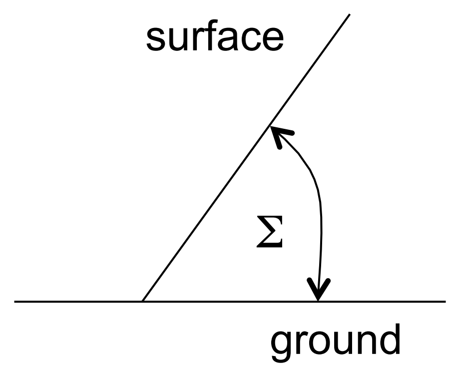
- To sky ($F_{surface\text{-}sky}$) 1
- To ground ($F_{surface\text{-}ground}$) 0
- To air ($F_{surface\text{-}air}$) 0

Tilted surfaces:

$$F_{sky} = \left[\frac{(1+\cos\Sigma)}{2}\right] \cdot \cos\left(\frac{\Sigma}{2}\right)$$

$$F_g = (1-\cos\Sigma)/2$$

$$(F_a = 1 - F_{sky} - F_g).$$



*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

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)

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 and RH = 30%
  - Indoor surface temperature is 22°C

Example 2.5: Solution (original, incorrect)

Surface energy balance		***Add***	***Subtract***
		W/m^2	W/m^2
Solar (short-wave)		900	
Surface-sky long-wave radiation		-364	
Surface-air long-wave radiation		-286	
Convection on roof		-239	
Conduction through roof			12
	SUM	0	

Given	alpha	0.9	bituminous membrane		
Given	Itotal, W/m2	1000			
Assume	Fsurface-sky	1			
Assume	Fsurface-air	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**	**337.55**	**64.4**	**degC**	
Given	Tsurf,in, K	295.15	22.0	degC	
Constant	stef-boltz, W/(m2K4)	5.6704E-08			
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 (corrected)

Surface energy balance		***Add***	***Subtract***
		W/m^2	W/m^2
Solar (short-wave)		900	
Surface-sky long-wave radiation		-512	
Surface-air long-wave radiation		0	
Convection on roof		-372	
Conduction through roof			17
	SUM	-1	

Given	alpha	0.9	bituminous membrane		
Given	Itotal, W/m2	1000			
Assume	Fsurface-sky	1			
Assume	Fsurface-air	0			
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**	**355.05**	**81.9**	**degC**	
Given	Tsurf,in, K	295.15	22.0	degC	
Constant	stef-boltz, W/(m2K4)	5.6704E-08			
Given	R-value IP, h-ft2-F/Btu	20			
Given	R-value, SI	3.52			
Given	U-value, W/m2K	0.28			

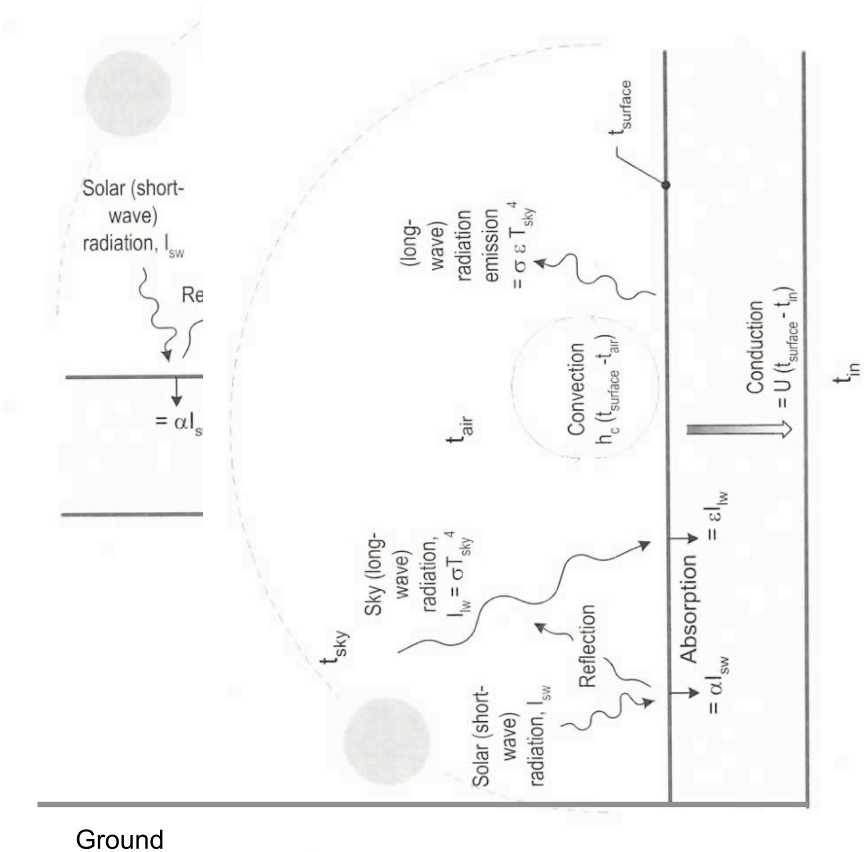
Adjust $T_{surface}$ until sum of all heat transfer modes equals zero

Note that there is no assumed surface-to-air radiation for this horizontal surface
The roof surface is expected to be about 17 degrees C warmer than before!

Bringing all the modes together

- Similarly, for a vertical surface:

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



$$
\begin{aligned}
&\alpha I_{solar} \\
&+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surf}^4) \\
&+\varepsilon_{surface}\sigma F_{air}(T_{air}^4 - T_{surface}^4) \\
&\boxed{+\varepsilon_{surface}\sigma F_{ground}(T_{air}^4 - T_{ground}^4)} \\
&+h_{conv}(T_{air} - T_{surface}) \\
&-U(T_{surface} - T_{surface,interior}) = 0
\end{aligned}
$$

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

Heat Xfer @ external surfaces:
Radiation and convection

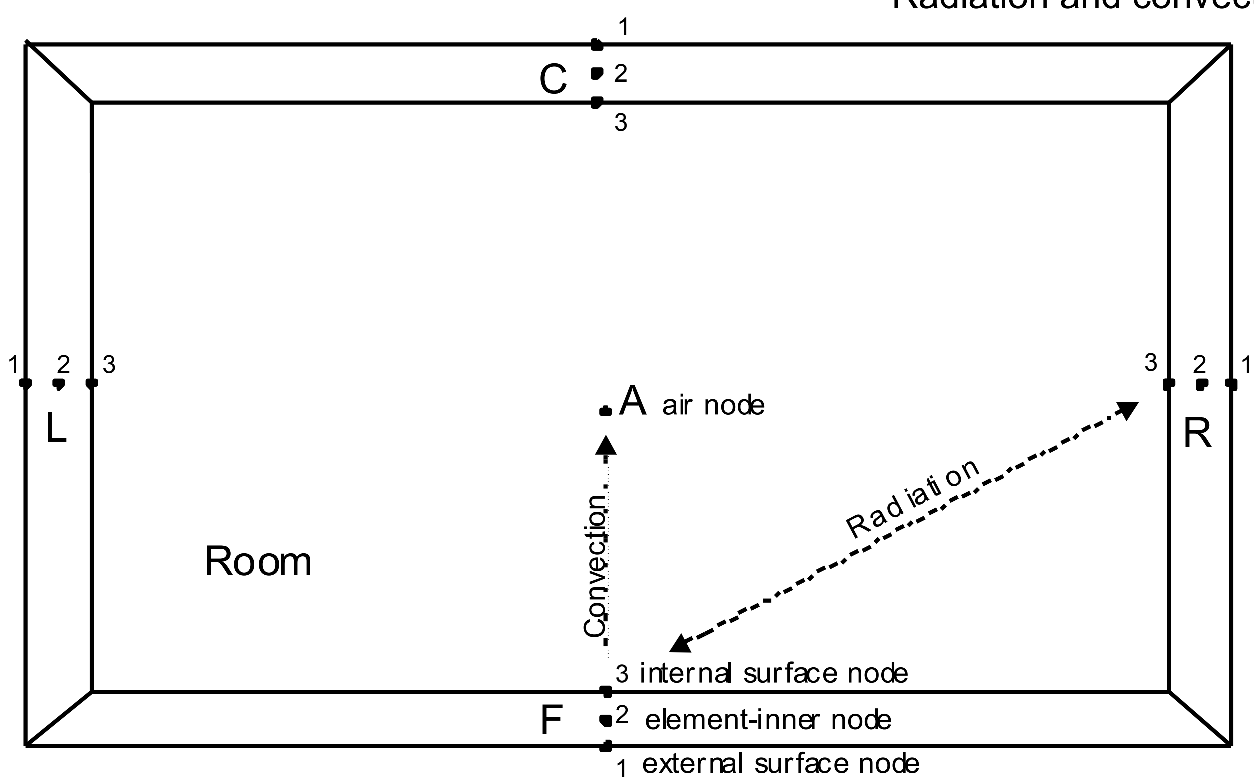
At surface nodes:

$$\sum q = 0$$

At nodes inside materials:

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

Based on density and heat capacity of material…

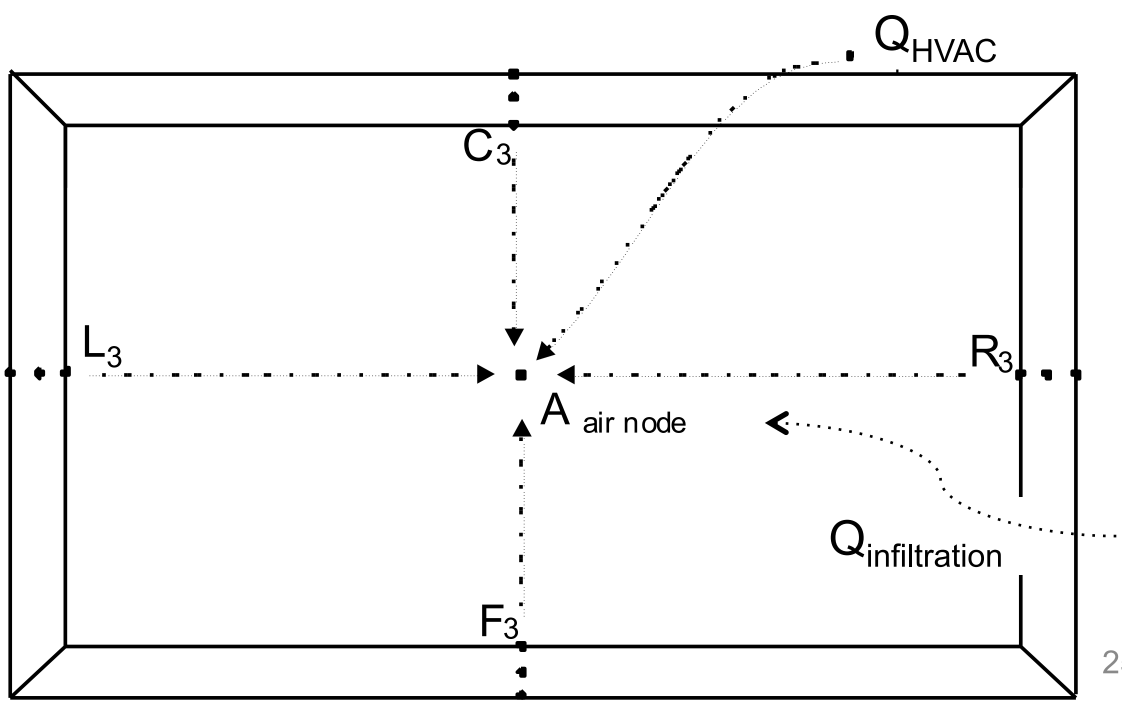


Bringing all modes (and nodes) together

- 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



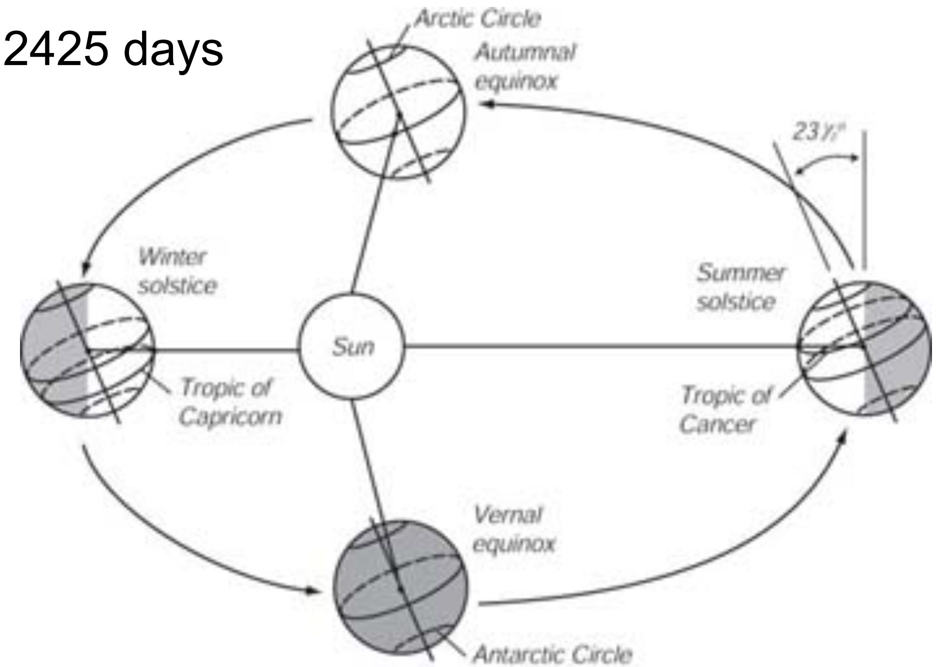
SOLAR ORIENTATION

Solar radiation

- The sun is the source of most energy on the earth
- Need to have a working knowledge of earth's relationship to the sun
- Should be able to estimate solar radiation intensity
  - Understand thermal effects of solar radiation and how to control or utilize them
  - Need to estimate solar gains on a building
  - Need to predict intensity of solar radiation and the direction at which it strikes building surfaces
    - Start with relationships between the sun and the earth

Solar radiation: earth-sun relationship

- Earth rotates about its axis every 24 hours
- Earth revolves around sun every 365.2425 days
- Earth is titled at an angle of 23°27’



- Therefore, different locations on earth receive different levels of solar radiation during different times of the year (and different times of the day)
  - The greatest amount of solar radiation is delivered to northern hemisphere on **June 21**
  - Least amount of solar energy delivered on **December 21**
- There are methods of determining the amount of flux of solar radiation to surfaces on the earth

Earth-sun relationships

- The position of a point *P* on the earth's surface w/r/t the sun's rays can be calculated if we know:
  - Latitude of point on earth, *l* (degrees)
  - Hour angle of the point on earth, *h* (degrees)
  - Sun's declination, *d* (degrees)

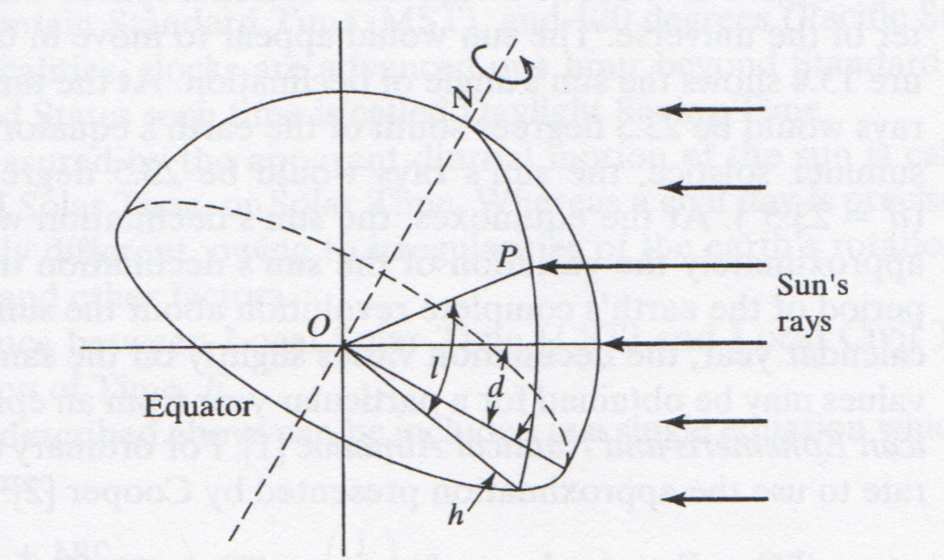


Figure 13.3 Latitude, hour angle, and sun's declination.

Earth-sun relationships

- Sun's declination, *d*, can be estimated by:

$$d = 23.45 \sin\left(360\,\frac{284 + n}{365}\right)$$

Where *n* is the day of the year, which you can determine by counting on your hands, looking up online, or using this table:

TABLE 13.1 Variation in *n* throughout the Year for Eq. (13.1)

Month	*n* for the Day of the Month, *D*	Month	*n* for the Day of the Month, *D*
January	*D*	July	181 + *D*
February	31 + *D*	August	212 + *D*
March	59 + *D*	September	243 + *D*
April	90 + *D*	October	273 + *D*
May	120 + *D*	November	304 + *D*
June	151 + *D*	December	334 + *D*

Where *D* is the day of the month

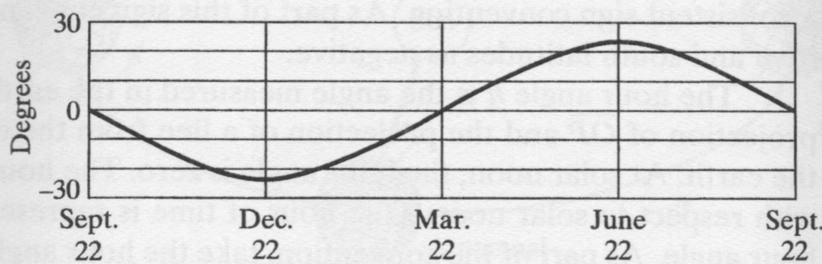


Figure 13.5 Variation of sun's declination.

d is **positive** when sun's rays are **north** of the equator

Earth-sun relationships

- Now we have latitude (*l*) and sun's declination (*d*)
  - Need hour angle (*h*)

It's all about **time:**

- Greenwich Civil Time = time at line of zero longitude
- Local Civil Time (CT) is governed by your longitude
  - 1/15th of an hour (4 mins) of time for each degree difference in longitude
    - Central Standard Time is 90 degrees from 0
    - 4 min per degree * 90 degrees = 360 minutes = 6 hours
- Time also measured by apparent diurnal motion of the sun
  - Apparent Solar Time (AST), Local Solar Time (LST), or Solar Time (ST)
    - Interchangeable
  - Slightly different than a civil day because of irregularities of the earth's rotation and shape of earth's orbit
  - The difference between solar time (LST) and civil time (CT) is called the **Equation of Time (E)**

Calculating solar time (LST)

- Local **solar** time:

$$LST = CT + \left(\frac{1}{15}\right)(L_{\text{std}} - L_{\text{loc}}) + E - DT$$

Where:
LST = local solar time (hour)
CT = clock time (hour)
L_{std} = standard meridian longitude for local time zone (degrees west)
L_{loc} = longitude of actual location (degrees west)
E = Equation of Time (hour)
DT = Daylight savings time correction (hour)
    *DT = 1 if on DST; otherwise 0

**Note that all times should be converted to decimal format from 0 to 24. For example, 3:45 PM = 15.75 hours

- Equation of Time: $$E = 0.165 \sin 2B - 0.126 \cos B - 0.025 \sin B$$

where $B = \dfrac{360(n - 81)}{364}$ and n is the day of the year. *B* is in degrees

Calculating solar time (LST)

- Finally, the solar hour angle, h, can be calculated:

$$h = 15(\mathrm{LST} - 12) \text{ degrees}$$

h is **positive *after*** solar noon and **negative *before***

LST is in 24 hour format

- Again, you can either calculate these values, use a website*, or look them up in a table like this:

TABLE 13.2 The Sun's Declination and Equation of Time, Calculated

	Day							
	7		*14*		*21*		*28*	
Month	*Declination, Degrees*	*Eq. of Time, Hours*	*Declination, Degrees*	*Eq. of Time, Hours*	*Declination, Degrees*	*Eq. of Time, Hours*	*Declination, Degrees*	*Eq. of Time, Hours*
January	−22.4	−0.10	−21.4	−0.15	−20.1	−0.19	−18.5	−0.22
February	−15.8	−0.24	−13.6	−0.24	−11.2	−0.24	−8.7	−0.22
March	−6.0	−0.20	−3.2	−0.17	−0.4	−0.13	2.4	−0.09
April	6.4	−0.04	9.0	−0.01	11.6	0.02	13.9	0.04
May	16.7	0.06	18.5	0.06	20.1	0.06	21.4	0.05
June	22.7	0.02	23.3	0.00	23.45	−0.03	23.3	−0.05
July	22.6	−0.08	21.7	−0.09	20.4	−0.10	18.9	−0.10
August	16.3	−0.09	14.1	−0.07	11.8	−0.04	9.2	−0.01
September	5.4	0.05	2.6	0.09	−0.2	0.13	−3.0	0.17
October	−6.6	0.22	−9.2	0.25	−11.8	0.27	−14.1	0.27
November	−17.1	0.27	−18.9	0.25	−20.4	0.22	−21.7	0.18
December	−22.8	0.12	−23.3	0.07	−23.45	0.02	−23.3	−0.04

*NOAA has website for this: http://www.esrl.noaa.gov/gmd/grad/solcalc/

Calculating solar time (*LST*) and hour angle (*h*)

- Example problem 2.6

- Determine the local solar time and sun's hour angle in Minneapolis, MN (L_{loc} = 93°W) at 2:25 PM Central Daylight Savings Time on July 21

Earth-sun relationships

- Once we have our local latitude *l*, the sun's declination angle *d*, and the hour angle *h*, we can move on to other important relationships:

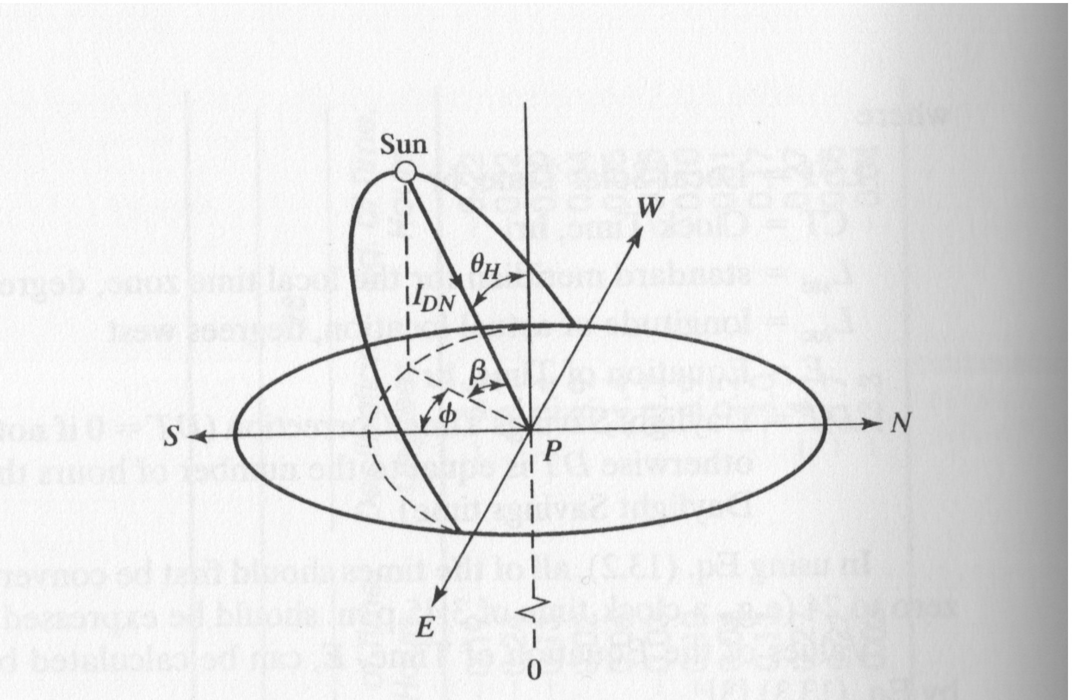


Figure 13.6 Definition of sun's zenith, altitude, and azimuth angles

<u>Three important angles (°)</u>

***θ_H* = sun's zenith angle**
angle between the sun's rays and the local vertical

***β* = altitude angle**
angle in a vertical plane between the sun's rays and the projection of the earth's horizontal plane

***ϕ* = solar azimuth angle**
angle in the horizontal plane measured from south to the horizontal projection of the sun's rays

*Note that I_{DN} represents the sun's rays

Earth-sun relationships

- Relationships between l, h, d, and θ_H, β, and ϕ can all be described in this figure:

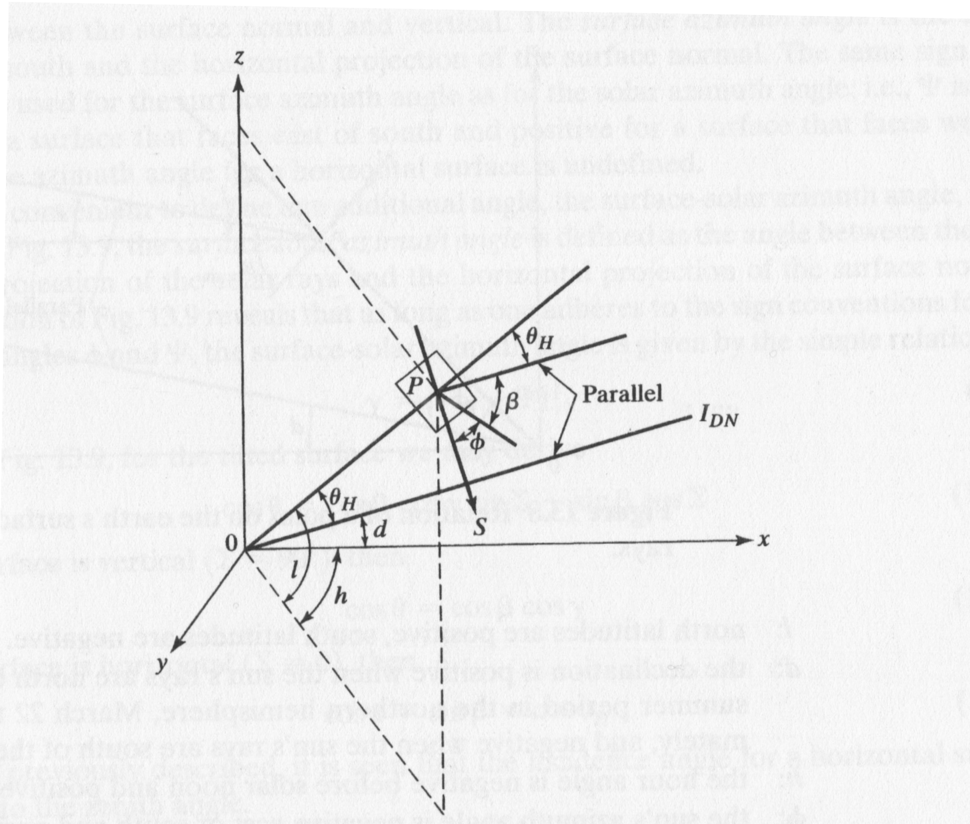


Figure 13.7 Relation of a point on the earth's surface to sun's rays.

*Don't worry if this doesn't all make sense; there are formulas!

Determining solar angles

- After a lot of complex geometry/trigonometry…

$$\cos \theta_H = \cos l \cos h \cos d + \sin l \sin d$$

$$\sin \beta = \cos l \cos h \cos d + \sin l \sin d$$

$$\cos \phi = (\cos d \sin l \cos h - \sin d \cos l) / \cos \beta$$

A note on sign conventions for all of these relationships:
North latitudes (*l*) are positive, south latitudes are negative
Declination (*d*) is positive when sun's rays are north of equator
Hour angle (*h*) is negative before solar noon, positive after
Azimuth angle (ϕ) is negative east of south and positive west of south

Note that β for solar noon = 90 degrees - | *l* - *d* |
Also note that $\beta + \theta_H$ = 90 degrees

**Keep units consistent

Earth-sun relationships

- Last but not least…
- The previous relationships identify a point on the earth's surface in relation to the sun
  - All valid for horizontal surfaces
  - Buildings are not horizontal surfaces!
- Surface-sun relationships:

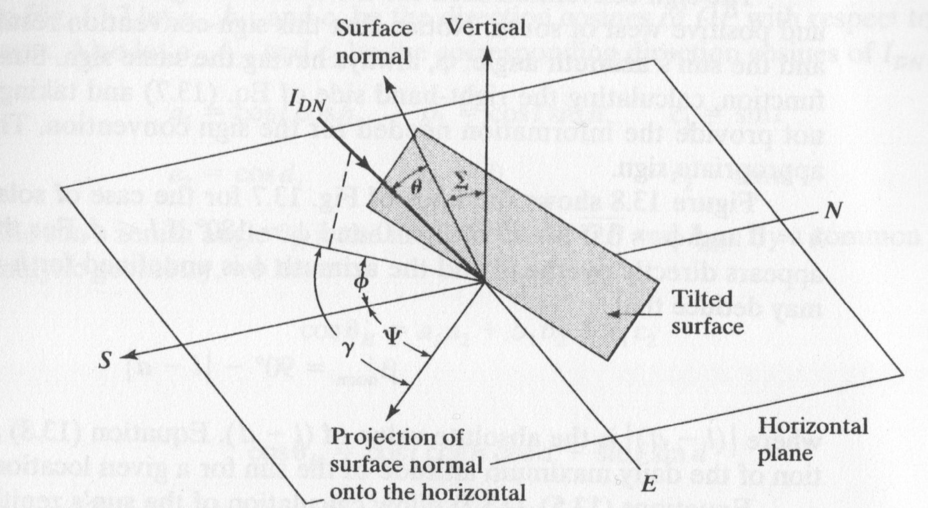


Figure 13.9 Definitions of surface azimuth, surface tilt, and surface-solar azimuth angles and the relation of sun's rays to a tilted surface.

Surface-sun relationships

More important angles (°)

***θ* = incidence angle**
angle between the solar rays and the surface normal

***Σ* = surface tilt angle**
angle between surface normal and the vertical
 Vertical surface: $\Sigma = 90°$
 Horizontal surface: $\Sigma = 0°$

***Ψ* = surface azimuth angle**
angle between south and the horizontal projection of the surface normal

***γ* = surface-solar azimuth angle**
angle between horizontal projection of solar rays and the horizontal projection of the surface normal
 $\gamma = | \phi - \Psi |$

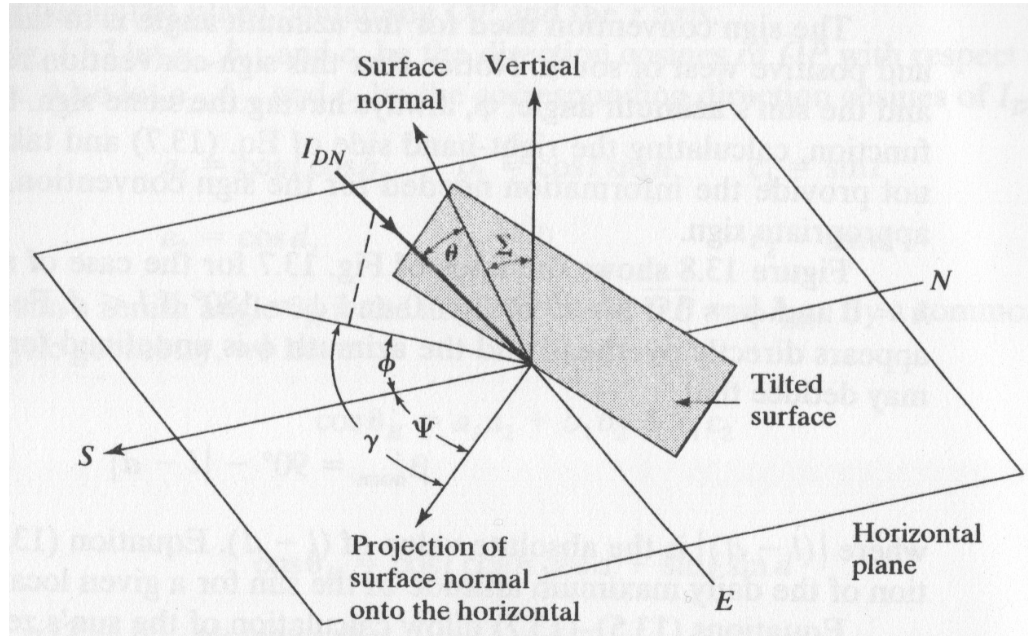


Figure 13.9 Definitions of surface azimuth, surface tilt, and surface-solar azimuth angles and the relation of sun's rays to a tilted surface.

*Sign convention: *Ψ* is negative for a surface that faces east of south and positive for a surface that faces west of south

Tilted surface:
$\cos\theta = \cos\beta \cos\gamma \sin\Sigma + \sin\beta \cos\Sigma$

Vertical surface (*Σ* = 90°):
$\cos\theta = \cos\beta \cos\gamma$

Surface-sun relationships

- Example problem 2.7
- Calculate sun's altitude (β) and azimuth (ϕ) angles at 7:30 am solar time on August 7 for a location at 40 degrees north latitude

Surface-sun relationships

- Example problem 2.8
- Calculate sun’s incidence angle for a vertical surface that faces 25 degrees east of south and has a tilt angle of 60 degrees at 3:00 pm solar time on June 7 for a location at 36 degrees north latitude

Translation:

Find θ

Given:
Ψ, Σ, l, h, β, ϕ

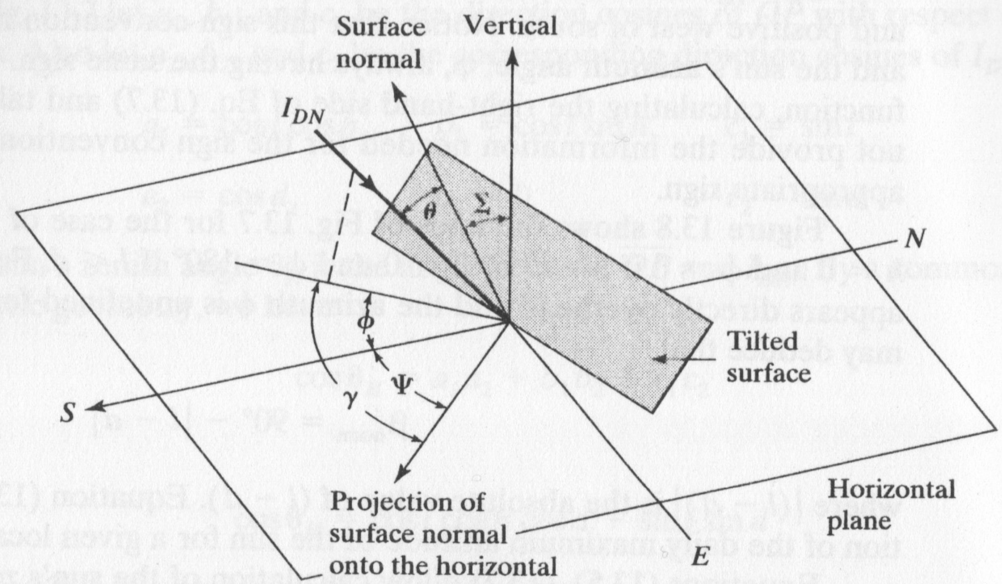


Figure 13.9 Definitions of surface azimuth, surface tilt, and surface-solar azimuth angles and the relation of sun’s rays to a tilted surface.

Solar flux

- Once we know earth-surface-sun relationships, we can eventually get to the effects of those relationships on actual solar radiation

- Solar radiation intensity is roughly constant at the outer layer of the atmosphere
  - 1367 W/m^2 – varying a few percent depending on time of year
- The earth's atmosphere depletes some direct solar radiation
  - Intercepted by other air molecules, water molecules, dust particles
  - Remaining reaches earth's surface unchanged in wavelength
    - Direct radiation
  - The deflected radiation turns aside from the direct beam
    - Diffuse radiation

Solar flux

- Estimating intensity of direct normal solar radiation
  - Many, *many* ways to estimate this
  - ASHRAE uses a relationship for "average clear days"

$$I_{DN} = Ae^{-B/\sin\beta}$$

Where:
I_{DN} = direct normal solar radiation (W/m^2)
A = apparent direct normal solar flux at outer edge of earth's atmosphere (W/m^2)
B = empirically determined atmospheric extinction coefficient (dimensionless)
β = altitude angle

- Estimating intensity of diffuse horizontal radiation

$$I_{dH} = CI_{DN}$$

Where:
I_{dH} = diffuse horizontal solar radiation (W/m^2)
C = empirically determined coefficient for typical "clear days" (dimensionless)

Typical clear day values for solar radiation

TABLE 13.3 Coefficients for Average Clear Day Solar Radiation Calculations for the Twenty-First Day of Each Month, Base Year 1964

	A		B	C		
	$\frac{Btu}{hr \cdot ft^2}$	$\frac{W}{m^2}$	Dimensionless Ratios		Declination, deg	Equation of Time, hr
January	390	1230	0.142	0.058	−20.0	−0.19
February	385	1215	0.144	0.060	−10.8	−0.23
March	376	1186	0.156	0.071	0.0	−0.13
April	360	1136	0.180	0.097	11.6	0.02
May	350	1104	0.196	0.121	20.0	0.06
June	345	1088	0.205	0.134	23.45	−0.02
July	344	1085	0.207	0.136	20.6	−0.10
August	351	1107	0.201	0.122	12.3	−0.04
September	365	1151	0.177	0.092	0	0.13
October	378	1192	0.160	0.073	−10.5	0.26
November	387	1221	0.149	0.063	−19.8	0.23
December	391	1233	0.142	0.057	−23.45	0.03

SOURCE: Adapted by permission from *ASHRAE Handbook, Fundamentals Edition*, 1993.

$$I_{DN} = Ae^{-B/\sin\beta}$$

Solar flux to building surfaces (finally!)

- Solar radiation striking a surface: $I_{solar} = I_D + I_d + I_R$
  - Direct + diffuse + reflected

- Direct (I_D): $I_D = I_{DN} \cos\theta$

Where:
θ = incidence angle, or the angle between the solar rays and the surface normal
I_{DN} = direct normal solar radiation (W/m^2)

- Diffuse (I_d): $I_d = I_{dH} \dfrac{1 + \cos\Sigma}{2}$

Where:
Σ = surface tilt angle, or the angle between surface normal and surface vertical
I_{dH} = diffuse horizontal solar radiation (W/m^2)

Solar flux to building surfaces (finally!)

- Reflected (I_R)
  - Radiation striking a surface after reflecting off surrounding surfaces
  - Similar to diffuse
  - Usually concerned with reflection from the ground

$$I_R = \frac{\rho_g I_H (1 - \cos\Sigma)}{2}$$

Where:
ρ_g = solar reflectance of the ground (depends on surface, usually 0.1-0.4)
I_H = total solar flux striking the horizontal ground (W/m^2)

$$\mathrm{I_H} = I_{DN} \cos\theta_H + I_{dH}$$

Solar flux to building surfaces

- Reflected (I_R)
  - Values of reflectance (ρ_g) for common ground surfaces

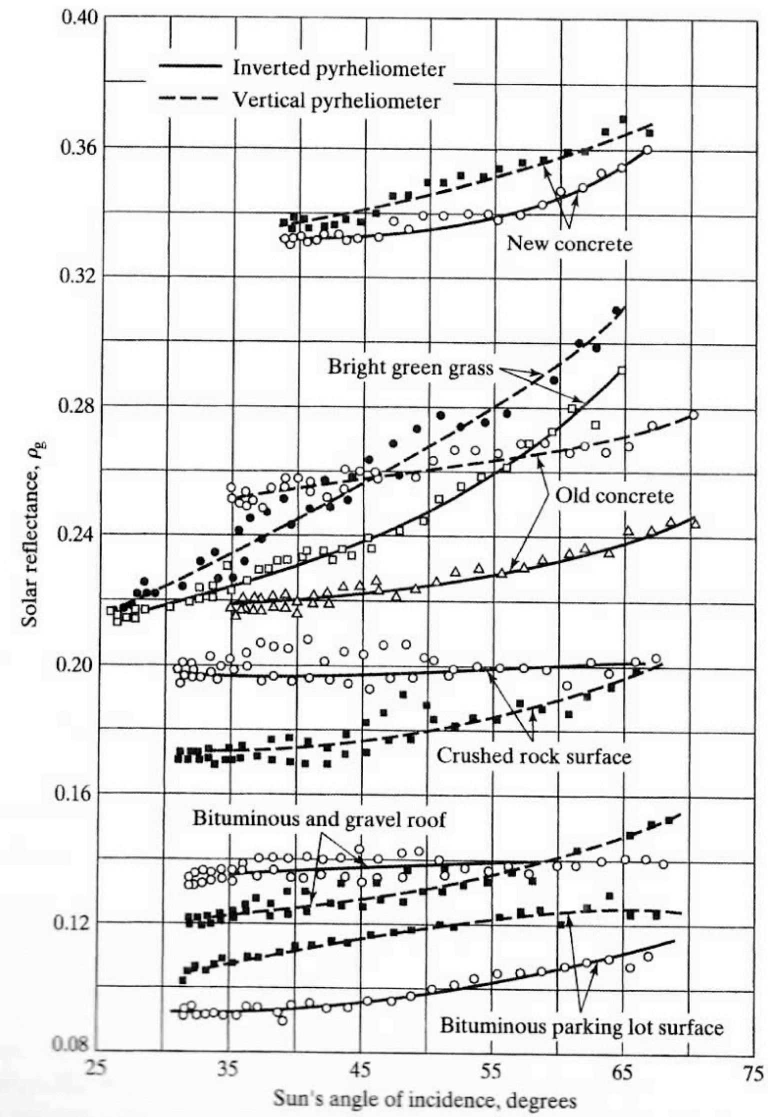


Figure 13.21 Solar reflectance for various ground surfaces. [Reprinted by permission from *ASHRAE Trans.*, 69 (1963), 31.]

Solar flux to building surfaces

- Example problem 2.9

- Find the solar flux incident on the tilted surface used in the previous problem
  - Assume a ground reflectance of 0.15

Refined solar data

- Now, you could make all of these calculations for every hour of the day…

OR

- You can build calculators or download data
- For hourly sun positions, you can build a calculator or use one from the internet
  - http://www.susdesign.com/sunposition/index.php
- For hourly solar data (direct + diffuse in W/m^2)
  - http://rredc.nrel.gov/solar/old_data/nsrdb/
  - You may be familiar with "typical meteorological years"
    - These data inform those databases
- For visualizing geometry, using something like IES-VE
  - Show videos (videos can be download on course website)

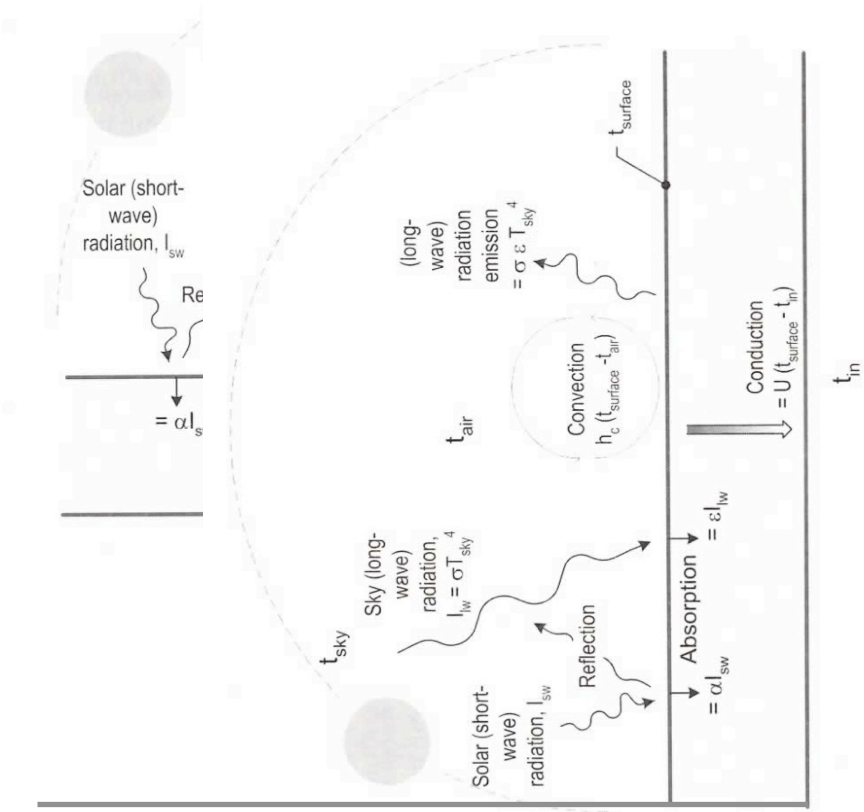
Solar orientation videos/software

- http://built-envi.com/courses/cae-463524-building-enclosure-design-fall-2013/

- http://built-envi.com/wp-content/uploads/2013/07/solar_position_ies.zip
  - 56 mb zip file of several videos

Bringing all the modes together

- Energy balance for a vertical surface:



Ground

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

$$\begin{aligned}
&\alpha I_{solar} \\
&+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surf}^4) \\
&+\varepsilon_{surface}\sigma F_{air}(T_{air}^4 - T_{surface}^4) \\
&+\varepsilon_{surface}\sigma F_{ground}(T_{air}^4 - T_{ground}^4) \\
&+h_{conv}(T_{air} - T_{surface}) \\
&-U(T_{surface} - T_{surface,interior}) = 0
\end{aligned}$$

We need to understand conduction through enclosures that are more complex than just single materials

Wrapping up

- HW #1 will be due Wed, September 11 in class (1 week)

Next series of topics:

- Heat transfer through layers of enclosure elements
  – Thermal networks
- Heat transfer through more complex enclosure assemblies
  – Various methods