

# CAE 331/513

## Building Science

### Fall 2018



**August 23, 2018**

Review of pre-requisites

Energy concepts and unit conversions

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# Today's topics

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- Review of fundamentals from prerequisite courses
  - Energy concepts and unit conversions
- Assign HW #1 (due Thursday, August 30)

# **REVIEW OF PREREQUISITES**

# Review of prerequisite topics

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- CAE 208: Thermal-fluids engineering I
  - Basic laws of thermodynamics
    1. Conservation of energy
    2. Entropy increases
      - Heat energy goes from hot to cold
      - Fluids go from high pressure to low pressure
  - Energy and mass flows and balances
  - Introduction to fluid mechanics
- CAE 209: Thermal-fluids engineering II
  - Finish fluid mechanics
  - Heat and mass transfer
  - Energy and momentum equations
  - Convection, conduction, and radiation

# Some very important definitions: **Energy**

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## Energy

- **Energy** is the capacity of a system to do work
  - We use this term a lot
  - Primary units: Joules, kWh or BTU (or MMBTU =  $10^6$  BTU)
- Different forms of energy:
  - Thermal, radiative, solar, nuclear, geothermal, hydrocarbon
  - **Energy efficiency**
    - Energy that is **utilized** versus energy that is **not utilized**
  - **Embodied** or embedded energy
    - The energy required to extract resources, manufacture, and transport a product
- Energy use depends on the rate of energy use and the time/duration of operation
  - Rate of energy use = **Power**

# Some very important definitions: **Power**

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## Power

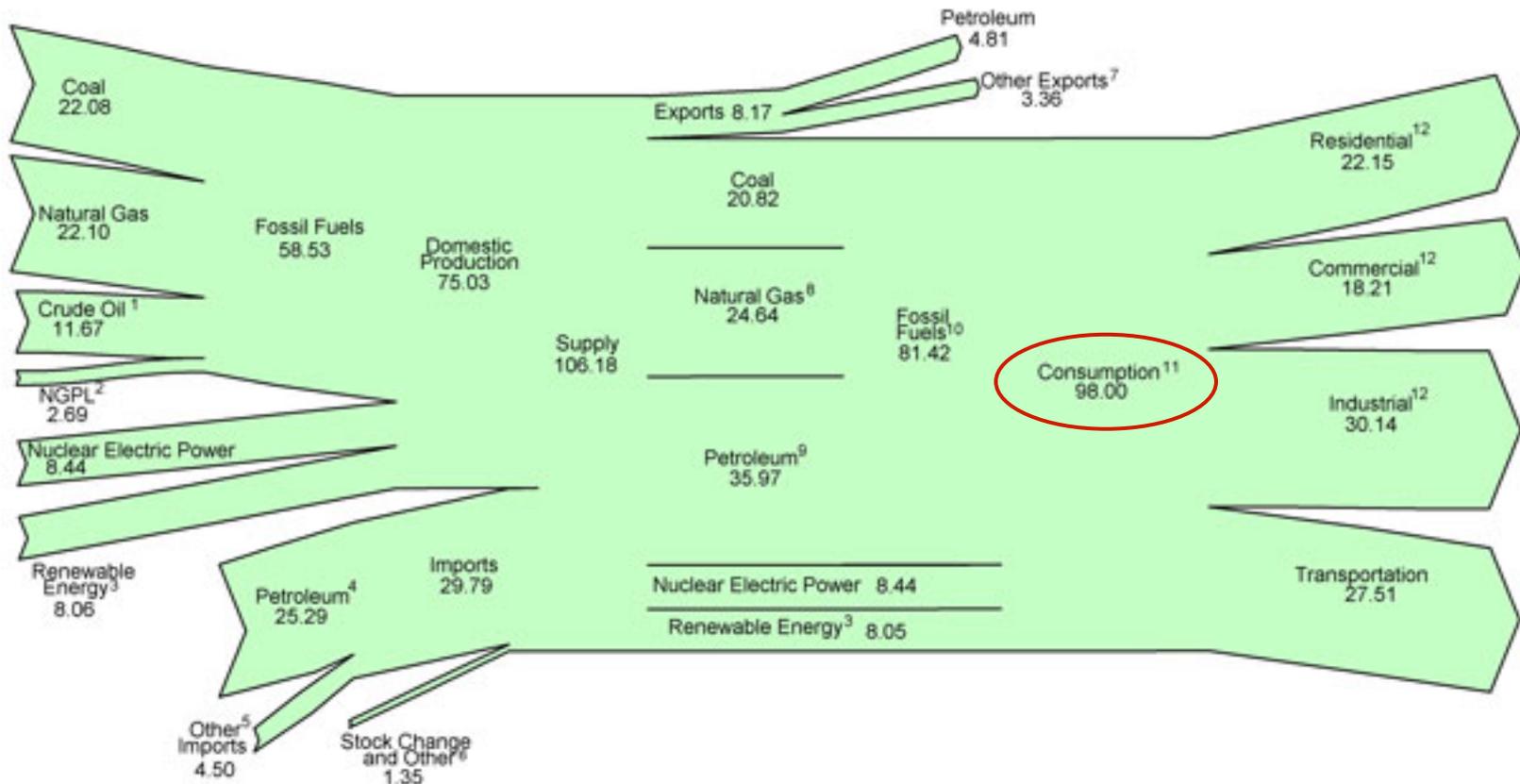
- **Power** is the **rate** at which energy is produced or consumed
  - Units are energy per time
  - IP: BTU per hour (BTU/hr) or kBTU per hour (1000 BTU/hr)
  - SI: Watt ( $W = J/s$ ) or kilowatt ( $kW = kJ/s$ ) or megawatt ( $MW = MJ/s$ )
- Be careful when using units associated with energy and power
  - People often confuse these
- Example: Batteries don't store power; they store energy
  - They release that energy (Watt-hours) at a rate determined by the equipment's power draw (Watts, or amperage)

# How much energy does the US use?

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# Energy and units

As we just heard, the U.S. uses about **100 Quads** of energy per year



- Q1: What is the US annual energy consumption in SI units? (J and kWh)  
 Q2: What is the average power draw per person in the US?

# Building energy use

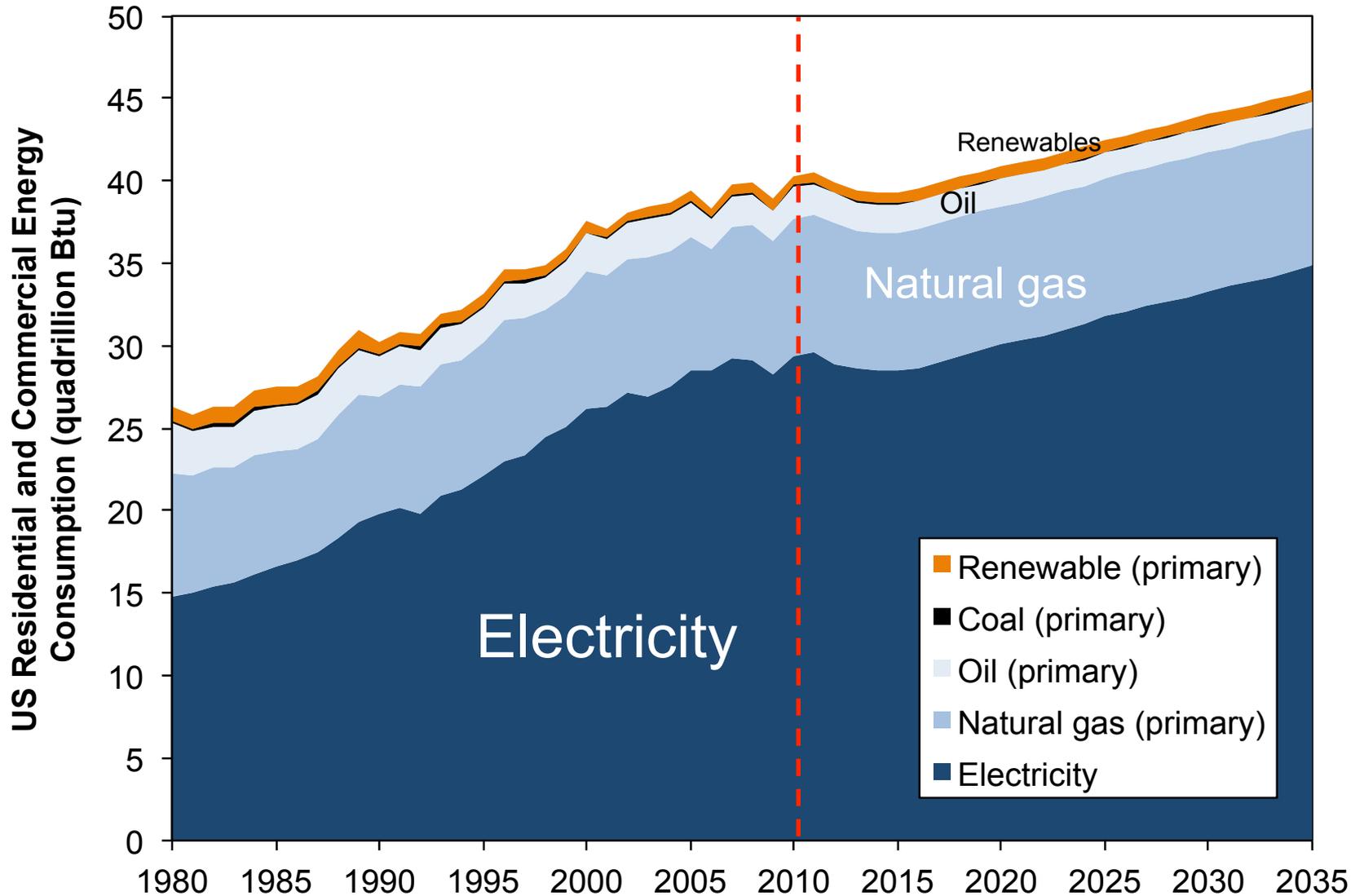
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- How do we utilize energy in buildings?
- We burn some fuels directly
  - Natural gas (mostly), oil (much less)
- We burn other fuels to generate electricity
  - Natural gas, coal, nuclear
    - Electric conversion efficiency is not 100%
    - There are also distribution and transmission losses (a few %)
- Renewable sources directly generate electricity as well
- Great resource: Energy Information Administration
  - <https://www.eia.gov/consumption/>

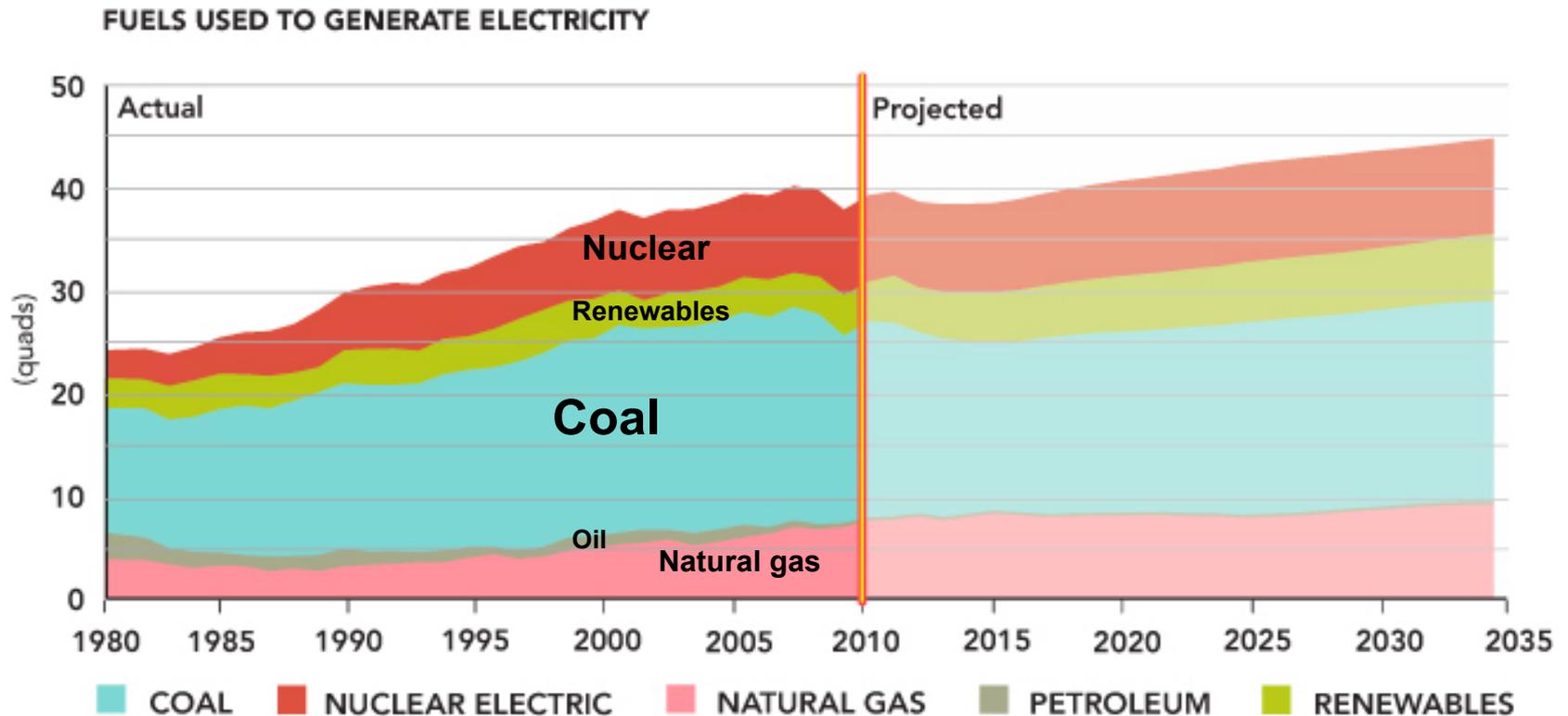
# How do we use energy at **home**?

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# US building energy consumption (by fuel)



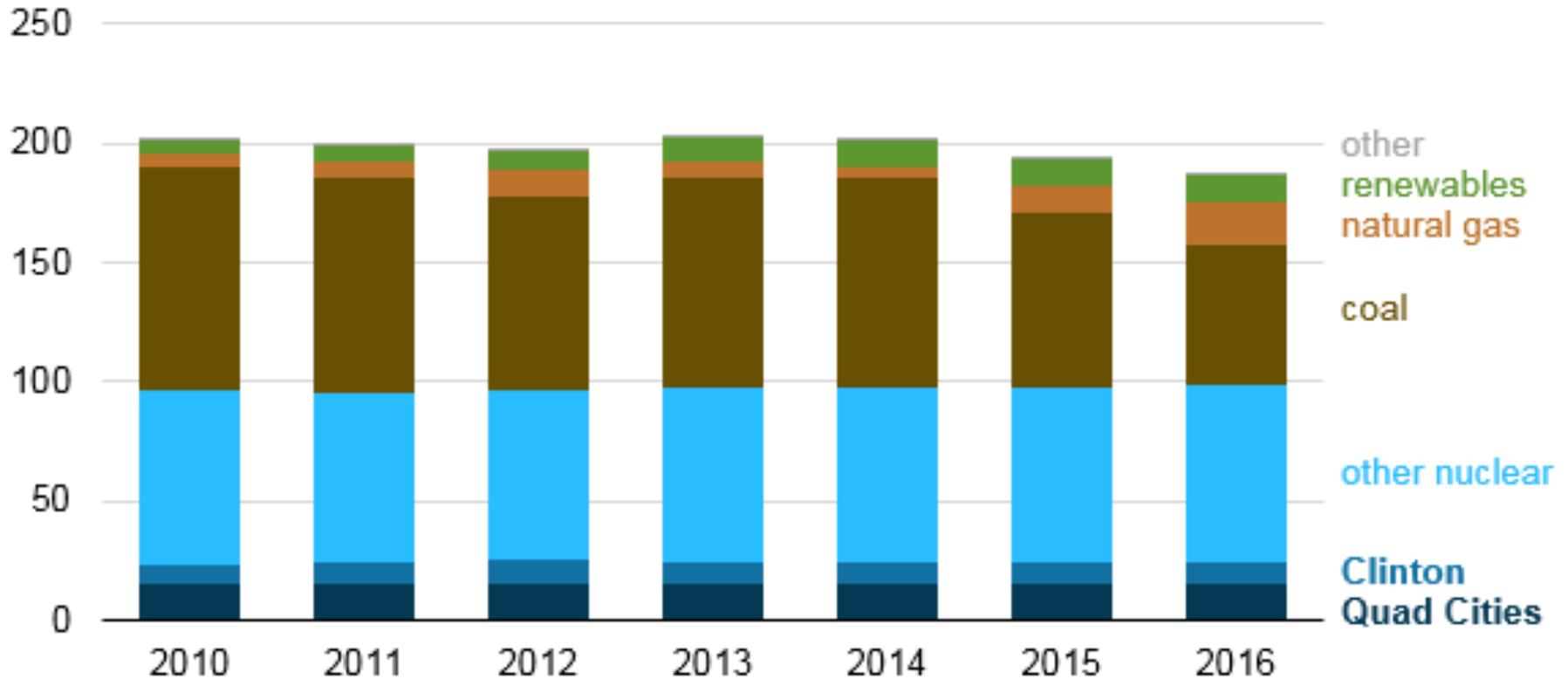
# Where do we get our **electricity** in the U.S.?



# How does **Illinois** get its electricity?

Illinois net electricity generation (2010-2016)

billion kilowatthours

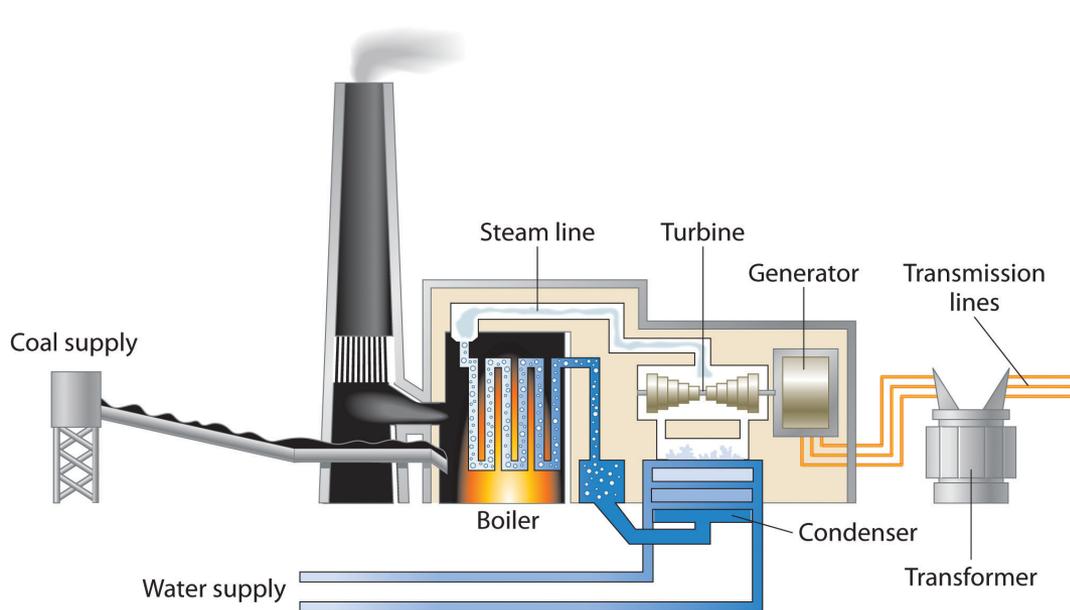


Source: U.S. Energy Information Administration, *Electric Power Monthly*

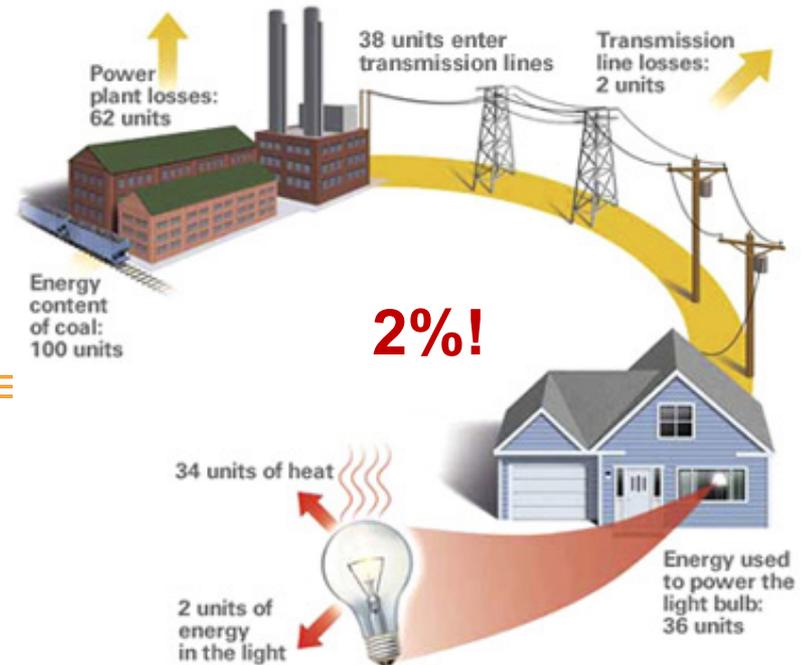
# Conversion efficiency for electric generators

**1<sup>st</sup> law of thermodynamics:** Energy can be transformed from one form to another, but cannot be created or destroyed

- **Q:** What is a typical electric power plant efficiency? **30-45%**
- **Q:** What is the “round trip” efficiency for an incandescent light bulb?

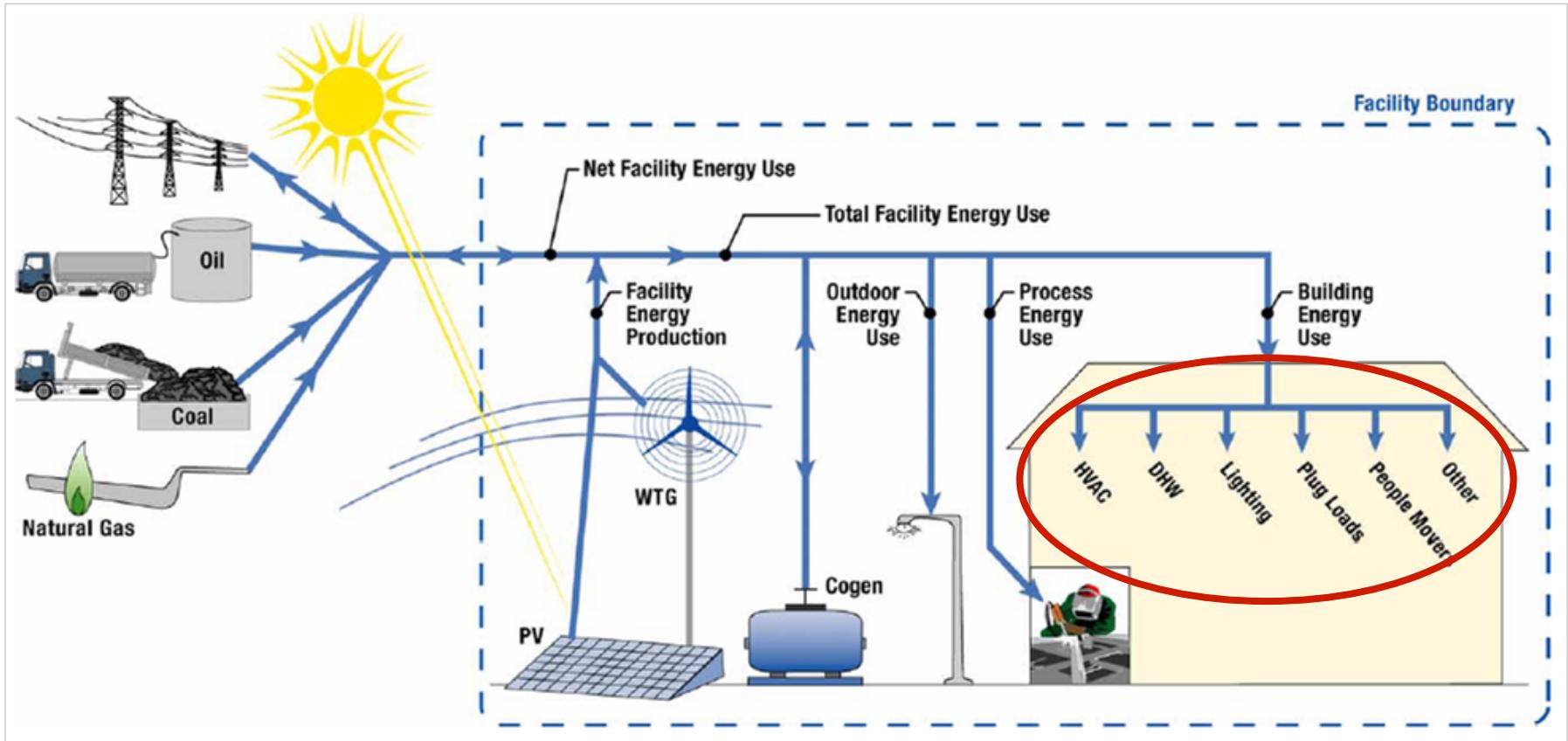


**Typical power plant schematic**



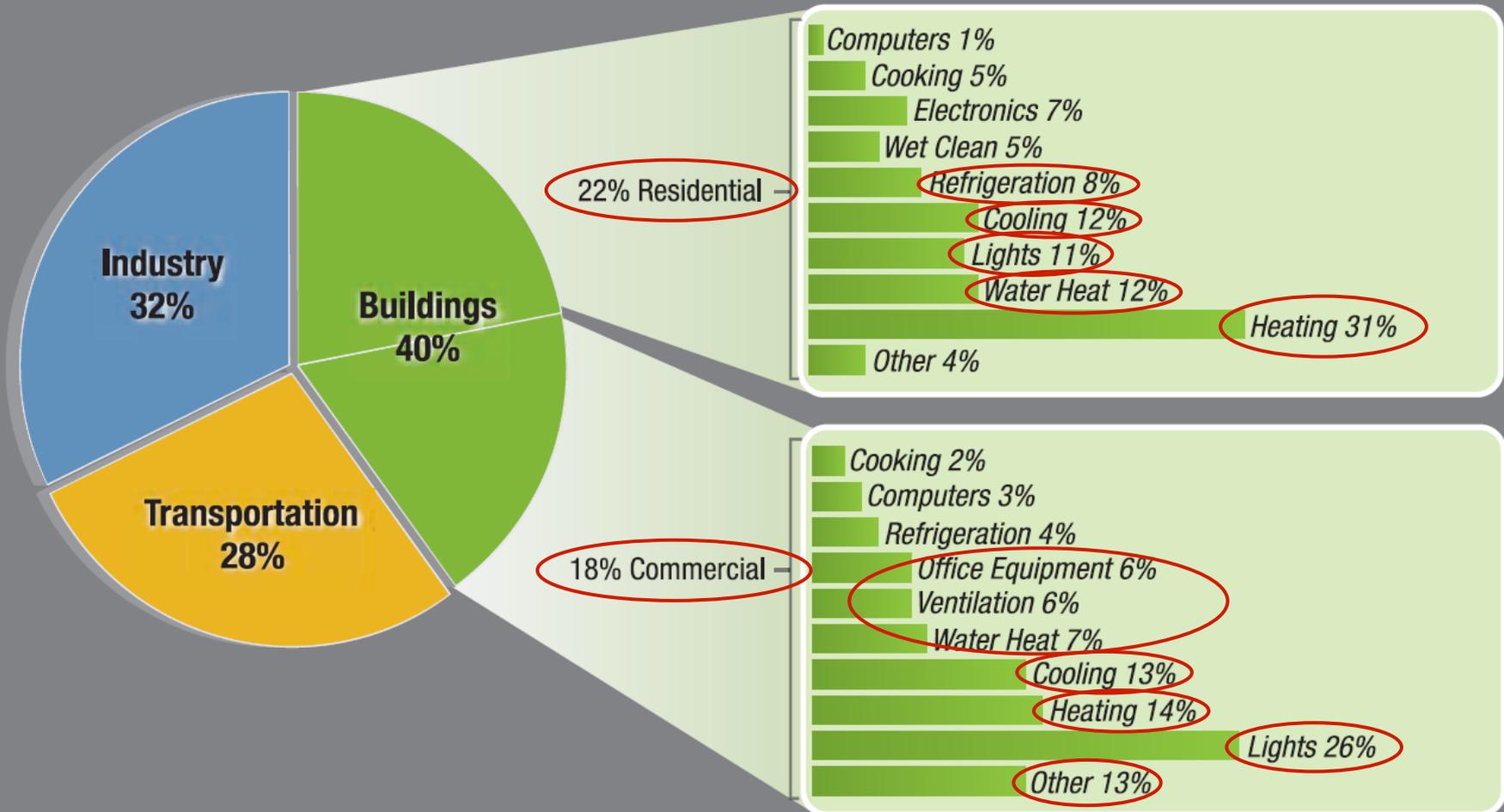
Natural gas used directly in buildings is typically **80-90%** efficient or more

# Building boundaries and energy flows



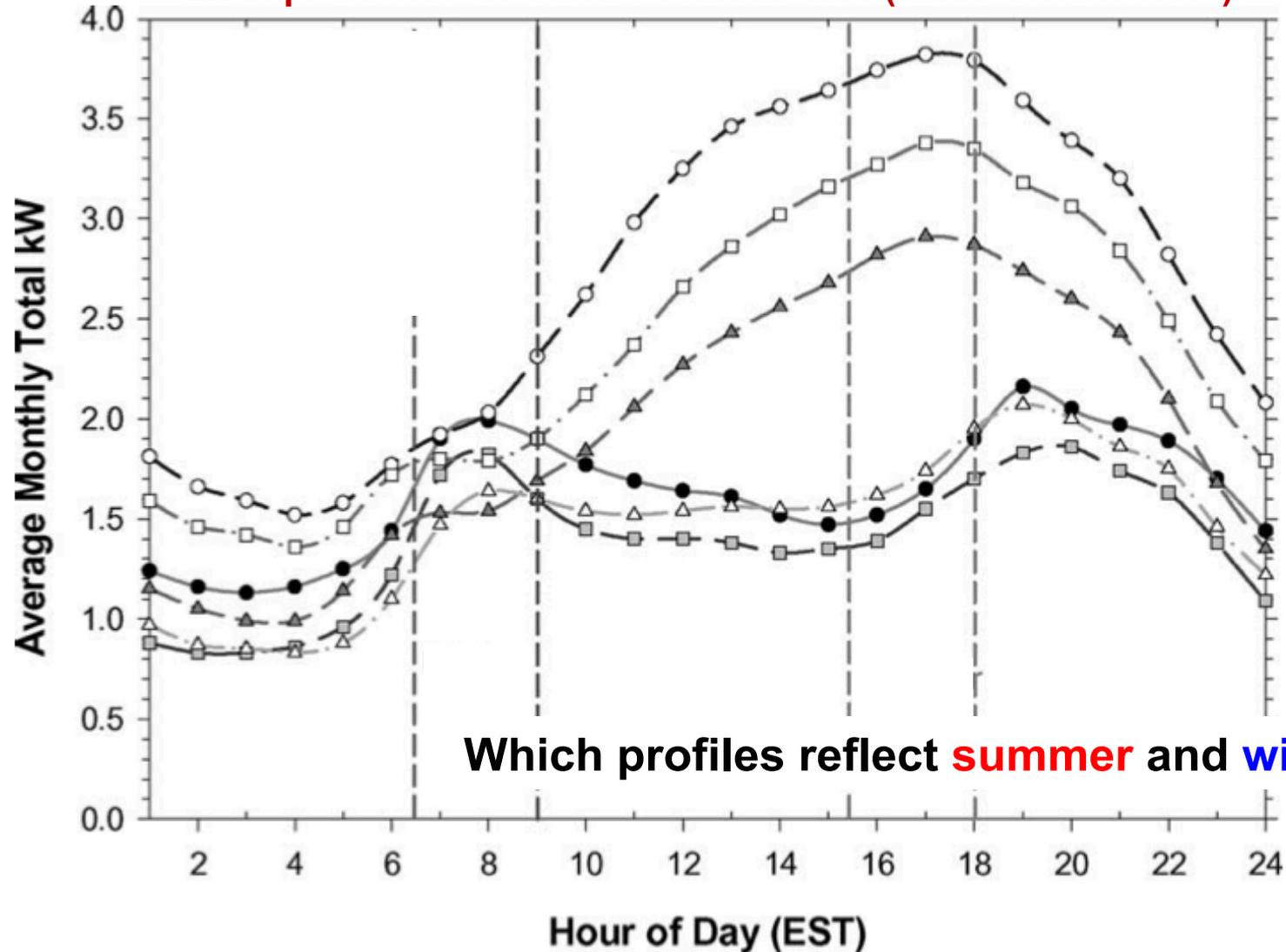
# How do buildings use energy?

Figure 1-1 U.S. Primary Energy Consumption, 2005<sup>2</sup>

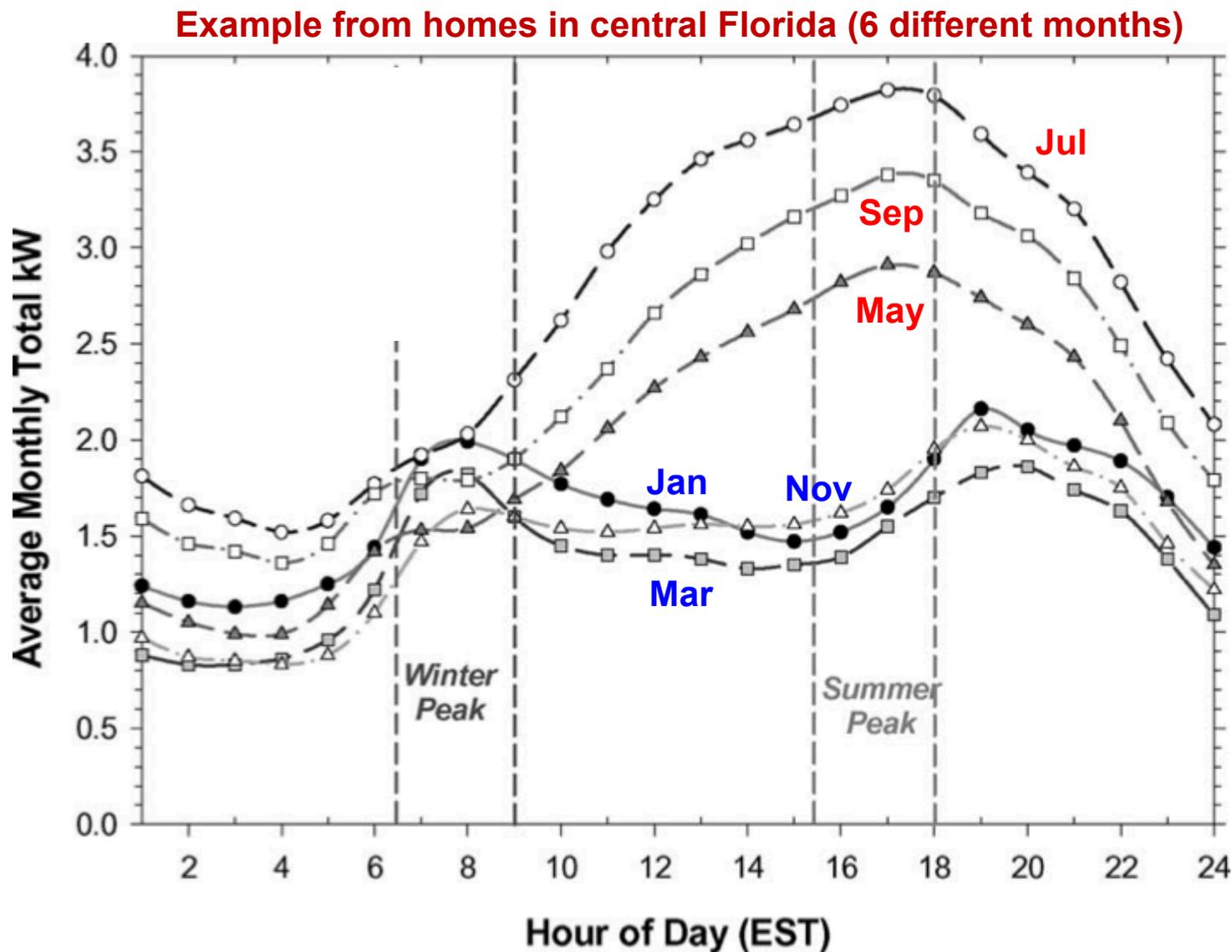


# Understanding building energy use: Electricity profiles

Example from homes in central Florida (6 different months)

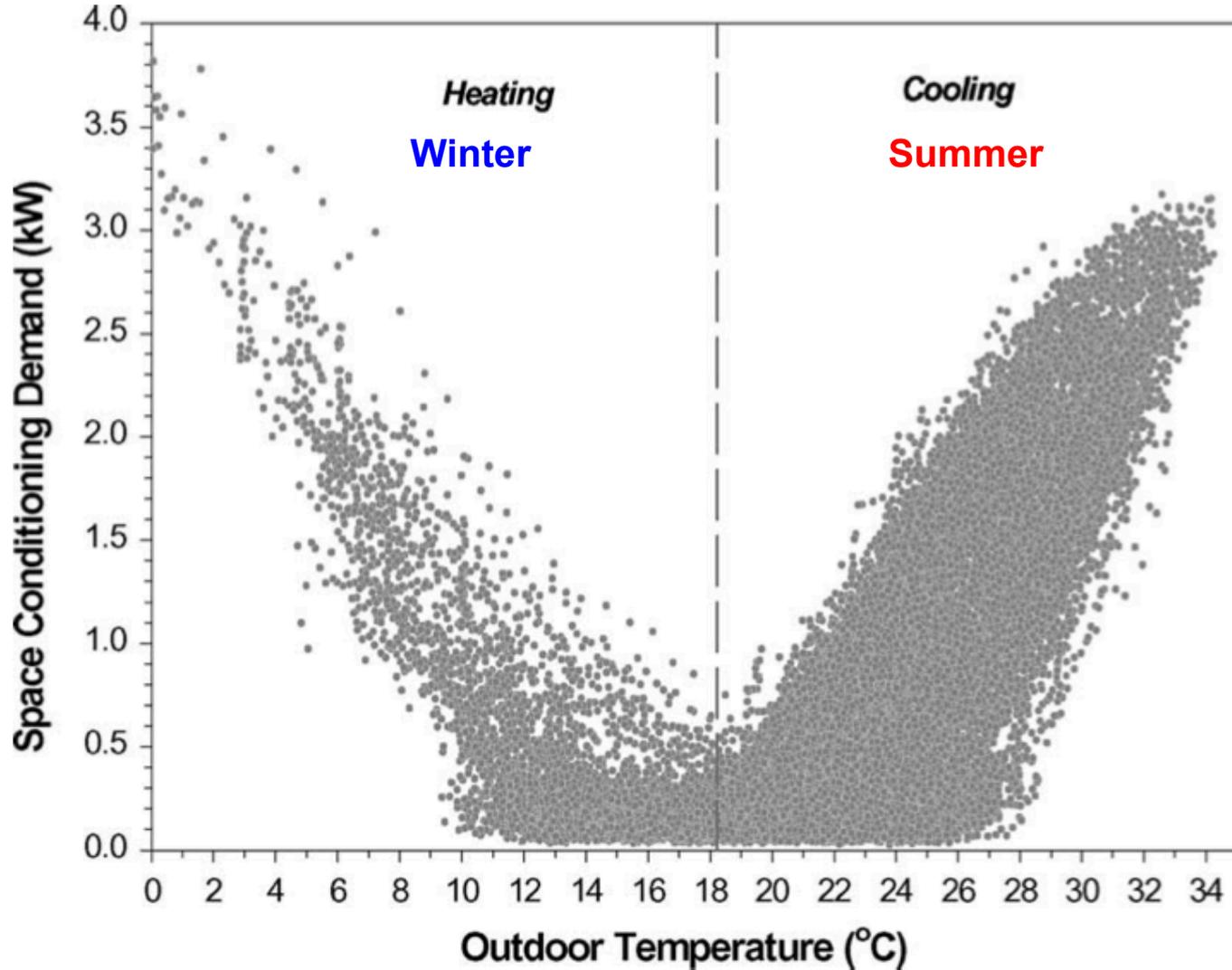


# Understanding building energy use: Electricity profiles



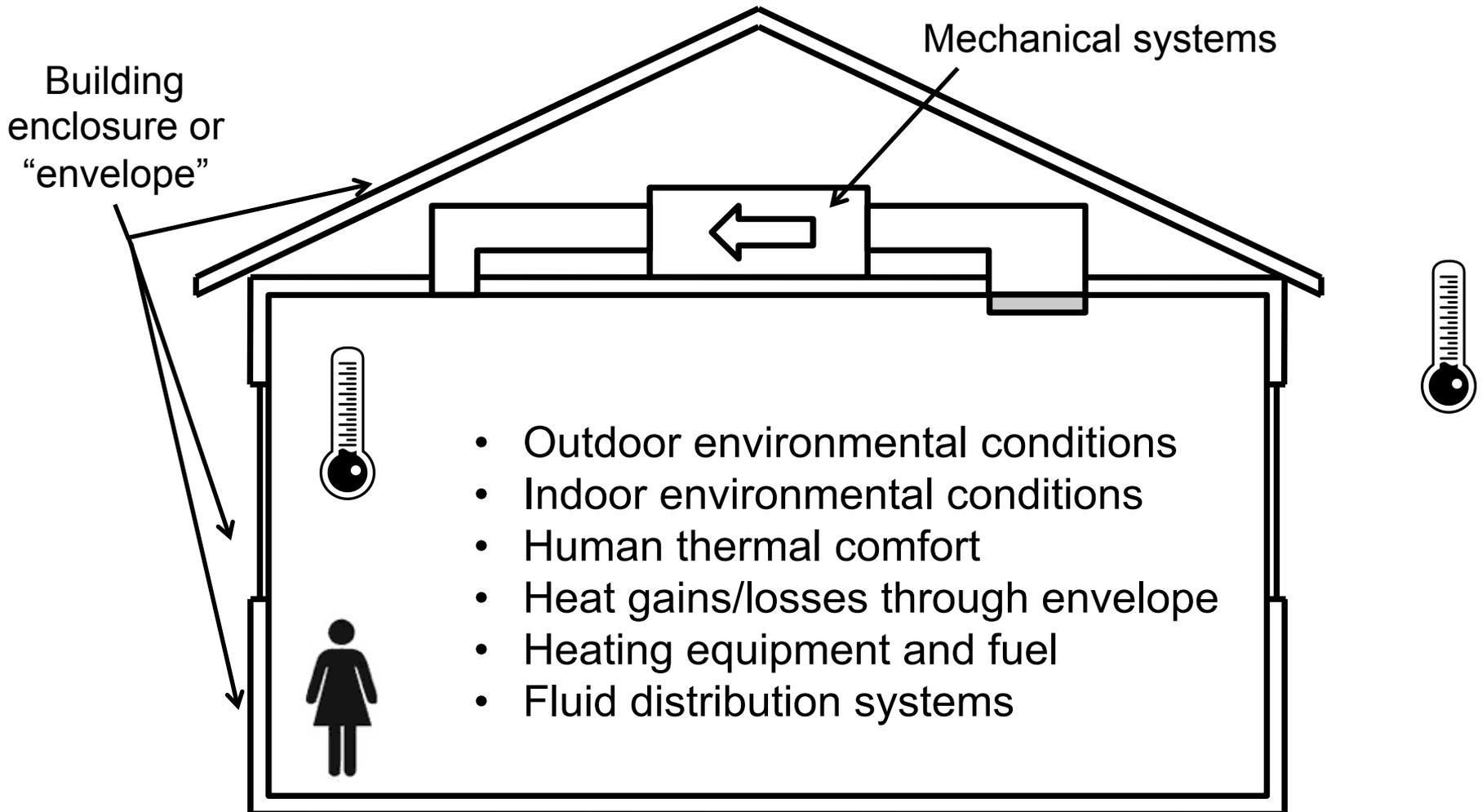
# Understanding building energy use: Electricity profiles

Example from homes in central Florida



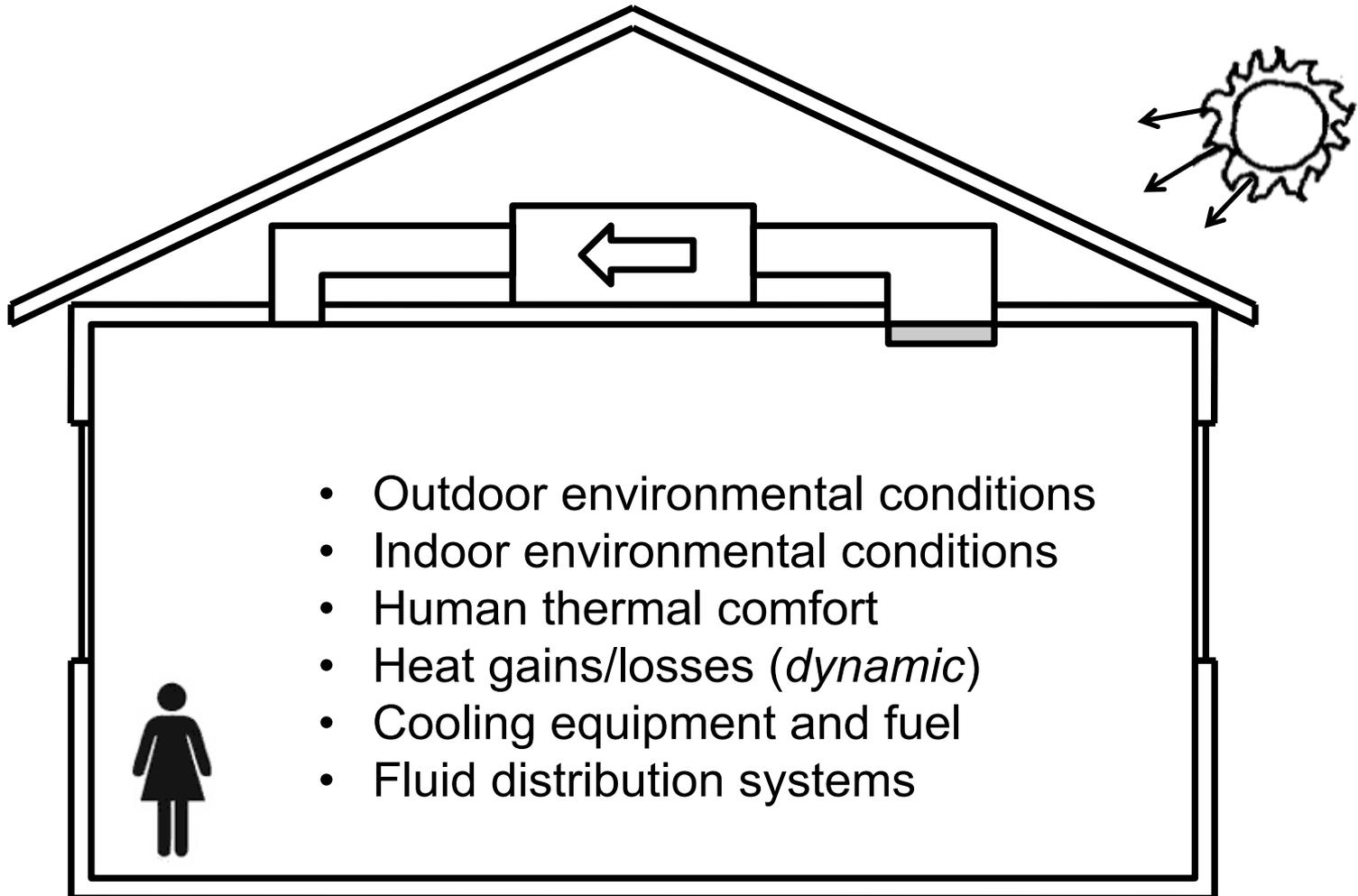
# Building energy use: Heating

What do we need to know to understand how buildings heat?



# Building energy use: **Cooling**

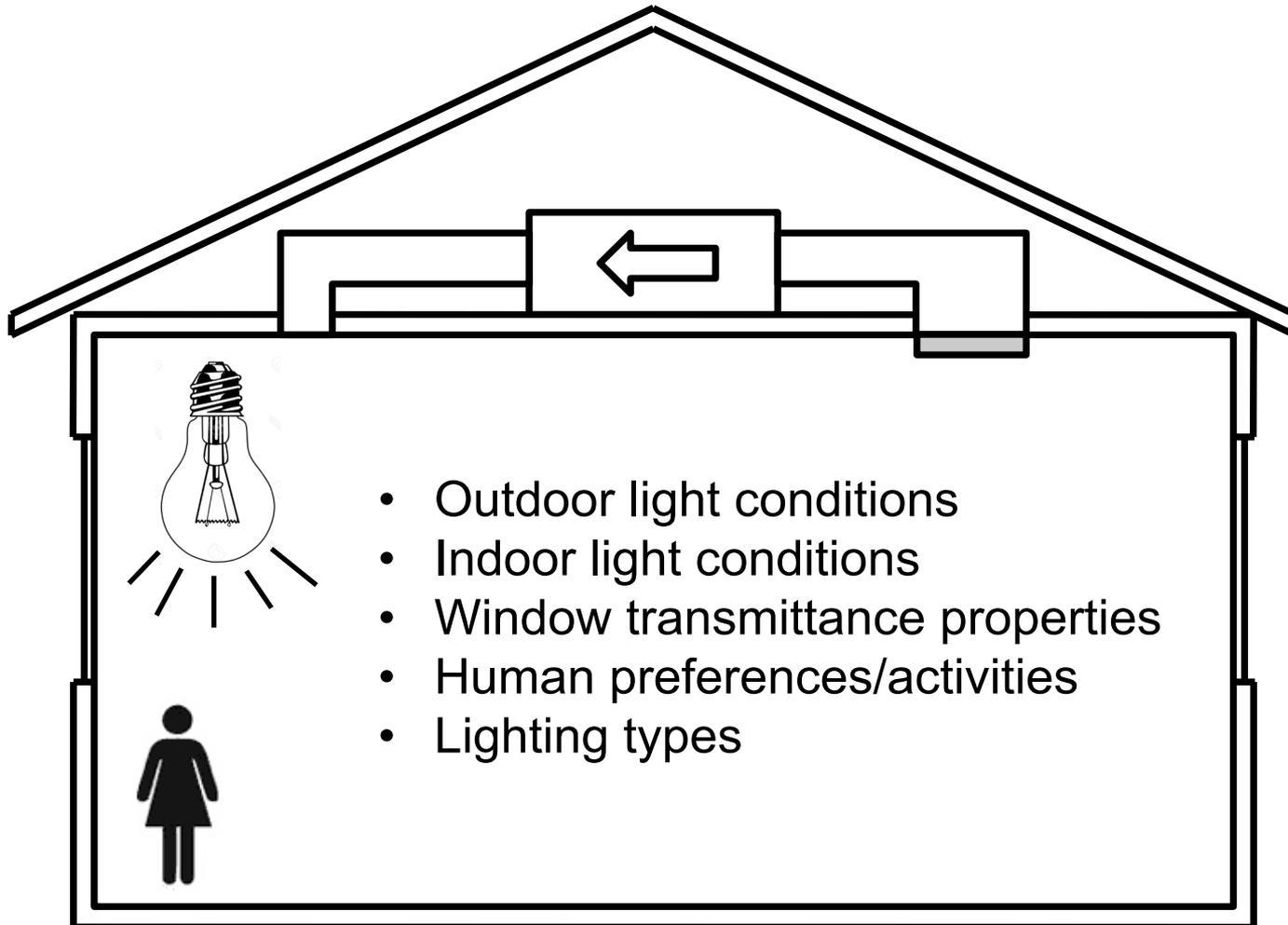
What do we need to know to understand how buildings cool?



# Building energy use: **Lighting**

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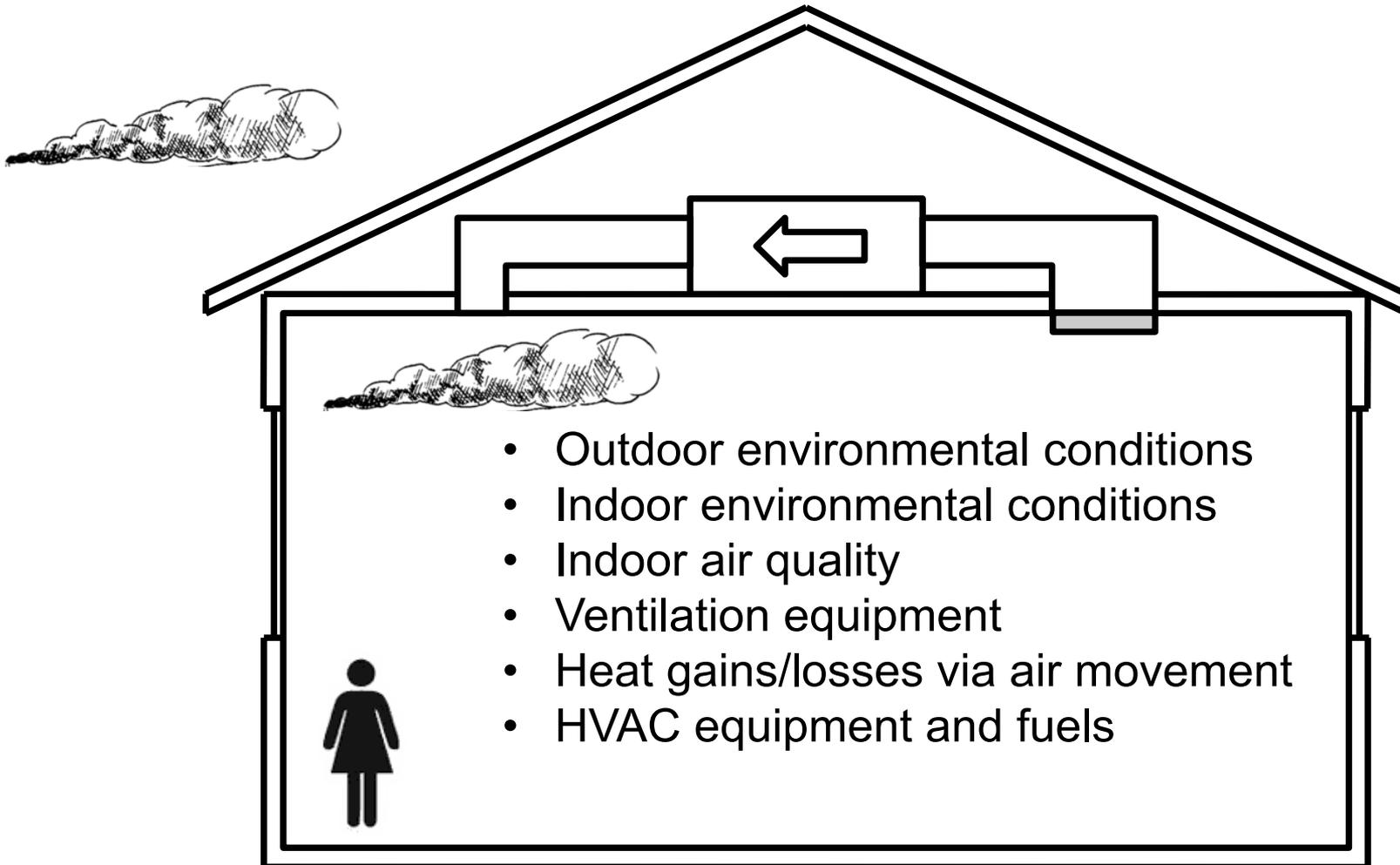
What do we need to know to understand lighting?



# Building energy use: **Ventilation**

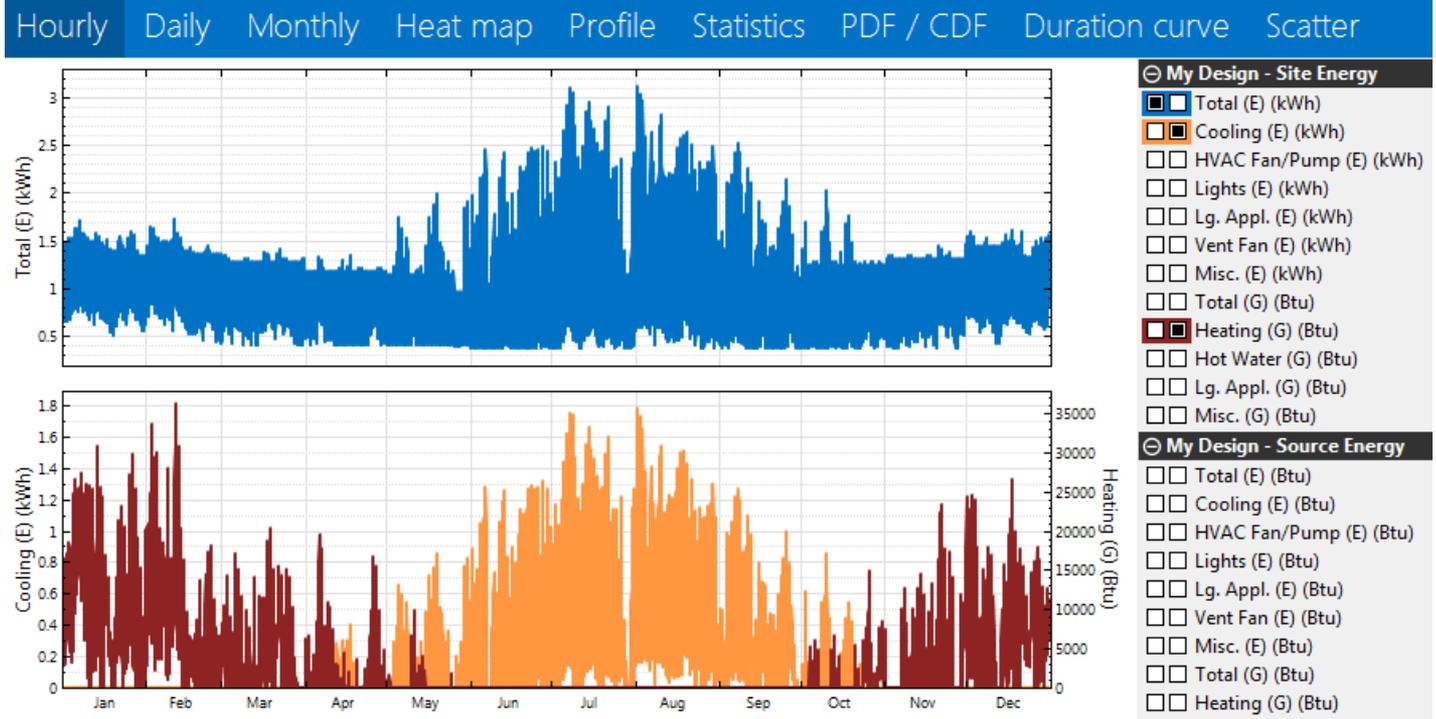
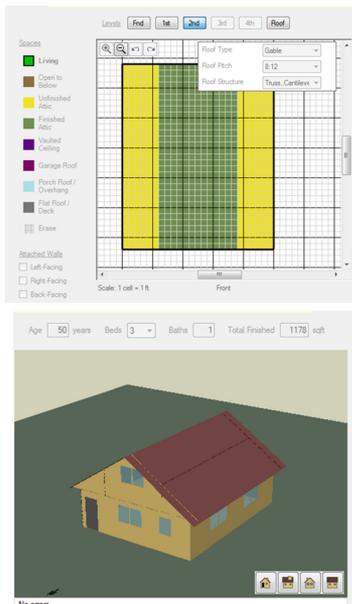
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What do we need to know to understand **ventilation**?



# Understanding building energy use

It all starts with understanding building and material properties and heat and mass transfer processes



If we want to model this building....

# Understanding building energy use

It all starts with understanding building and material properties and heat and mass transfer processes

<u>Building</u>					
Orientation	1	5	\$0	East	
Neighbors	1	3	\$0	at 15ft	
<u>Operation</u>					
Heating Set Point		4	\$0	71 F	
Cooling Set Point		4	\$0	76 F	
Humidity Set Point		4	\$0	60% RH	
Misc Electric Loads		4	\$0	1.00	
Misc Gas Loads	2		\$0	1.00	
Misc Hot Water Loads	2		\$0	1.00	
Natural Ventilation	2		\$0	Benchmark	
Interior Shading	2		\$0	Benchmark	
<u>Walls</u>					
Wood Stud			\$3,560	R-19 Fiberglass Batt, Gr-1, 2x6, 24 in o.c.	12 18
Double Wood Stud	1		\$0	None	
CMU	1		\$0	None	
SIP	1		\$0	None	
ICF	1		\$0	None	
Other	1		\$0	None	
Wall Sheathing	2		\$3,190	OSB, R-10 XPS	8 9
Exterior Finish	1		\$15,973	Stucco, Medium/Dark	
Interzonal Walls			\$759	R-19 Fiberglass Batt, Gr 1, 2x6, 24 in o.c.,	11 17 23 29
<u>Ceilings/Roofs</u>					
Unfinished Attic			\$959	Ceiling R-60 Fiberglass, Vented	6 7 9 10 16
Roof Material	1 2		\$3,911	Asphalt Shingles, Dark	
Radiant Barrier	1		\$0	None	
<u>Foundation/Floors</u>					
Unfinished Basement			\$1,852	Whole Wall R-10 XPS	7 8 9
Interzonal Floor			\$146	R-38 Fiberglass Batt	2 3 4 5
			\$126,884	Total Present Value	

# Understanding building energy-related properties

It all starts with understanding building and material properties and heat and mass transfer processes

My Design

- Orientation: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
- Neighbors: 1 2 3 4
- Operation**
  - Heating Set Point: 1 2 3 4 5 6 7 8 9 10
  - Cooling Set Point: 1 2 3 4 5 6 7 8 9 10
  - Misc Electric Loads: 1 2 3 4 5 6 7 8
  - Misc Gas Loads: 1 2 3 4
  - Misc Hot Water Loads: 1 2 3 4
  - Natural Ventilation: 1 2 3 4
  - Interior Shading: 1 2 3 4 5 6
- Walls**
  - Wood Stud**: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23:
  - Double Wood Stud: 1 2 3 4 5 6 7
  - CMU: 1 2 3 4 5 6
  - SIP: 1 2 3 4 5 6 7 8 9
  - ICF: 1 2 3 4
  - Other: 1 2 3 4
  - Wall Sheathing: 1 2 3 4 5 6 7 8 9 10 11 12
  - Exterior Finish: 1 2 3 4 5 6 7 8 9 10 11
  - Interzonal Walls: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23:
- Ceilings/Roofs**
  - Unfinished Attic: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23:
  - Roof Material: 1 2 3 4 5 6 7 8 9 10 11 12 13
  - Radiant Barrier: 1 2
- Foundation/Floors**
  - Slab: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
  - Carpet: 1 2 3 4 5 6
- Thermal Mass**
  - Exterior Wall Mass: 1 2 3 4 5

Option	R-Assembly [h-ft <sup>2</sup> -R/Btu]	Framing Factor [frac]	Cost [\$ /ft <sup>2</sup> Exterior Wall]
1) None			
2) Uninsulated, 2x4, 16 in o.c.	3.6	0.25	\$1.84
3) Uninsulated, 2x6, 24 in o.c.	3.7	0.22	\$1.76
4) R-7 Fiberglass Batt, Gr-3, 2x4, 16 in o.c.	8.3	0.25	\$2.41
5) R-7 Fiberglass Batt, Gr-2, 2x4, 16 in o.c.	8.7	0.25	\$2.43
6) R-7 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	8.9	0.25	\$2.46
7) R-11 Fiberglass Batt, Gr-3, 2x4, 16 in o.c.	9.6	0.25	\$2.49
8) R-11 Fiberglass Batt, Gr-2, 2x4, 16 in o.c.	10.1	0.25	\$2.51
9) R-11 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	10.5	0.25	\$2.54
10) R-13 Fiberglass Batt, Gr-3, 2x4, 16 in o.c.	10.3	0.25	\$2.53
11) R-13 Fiberglass Batt, Gr-2, 2x4, 16 in o.c.	10.9	0.25	\$2.55
<b>12) R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.</b>	<b>11.4</b>	<b>0.25</b>	<b>\$2.58</b>
13) R-15 Fiberglass Batt, Gr-3, 2x4, 16 in o.c.	10.9	0.25	\$2.57
14) R-15 Fiberglass Batt, Gr-2, 2x4, 16 in o.c.	11.7	0.25	\$2.59
15) R-15 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	12.2	0.25	\$2.62
16) R-19 Fiberglass Batt, Gr-3, 2x6, 24 in o.c.	13.4	0.22	\$2.58
17) R-19 Fiberglass Batt, Gr-2, 2x6, 24 in o.c.	14.6	0.22	\$2.60
18) R-19 Fiberglass Batt, Gr-1, 2x6, 24 in o.c.	15.5	0.22	\$2.62
19) R-21 Fiberglass Batt, Gr-3, 2x6, 24 in o.c.	14.6	0.22	\$2.61
20) R-21 Fiberglass Batt, Gr-2, 2x6, 24 in o.c.	16.1	0.22	\$2.64
21) R-21 Fiberglass Batt, Gr-1, 2x6, 24 in o.c.	17.2	0.22	\$2.66
22) R-13 Cellulose, Gr-3, 2x4, 16 in o.c.	10.3	0.25	\$2.55
23) R-13 Cellulose, Gr-2, 2x4, 16 in o.c.	10.9	0.25	\$2.57
24) R-13 Cellulose, Gr-1, 2x4, 16 in o.c.	11.4	0.25	\$2.60
25) R-19 Cellulose, Gr-3, 2x6, 24 in o.c.	14.0	0.22	\$2.64

Standard wood stud framed walls with cavity insulation. When batt insulation must be compressed to fit within the cavity (e.g. R19 in a 5.5' 2x6 cavity), R-values reflect this effect.

# Understanding building energy-related properties

eQUEST Schematic Design Wizard

**Exterior Windows**

Window Area Specification Method:

Describe Up To 3 Window Types

	Glass Category	Glass Type	Frame Type	Frame Wd (in)
1:	<input type="text" value="Single Clr/Tint"/>	<input type="text" value="Single Clear 1/8in (1000)"/>	<input type="text" value="Wood/Vinyl, Operable"/>	<input type="text" value="1.50"/>
2:	<input type="text" value="- select another -"/>			

Window Dimensions, Positions and Quantities

	Typ Window Width (ft)*	Window Ht (ft)	Sill Ht (ft)	% Window (floor to ceiling, including frame):			
				North	South	East	West
1:	<input type="text" value="2.50"/> <input checked="" type="checkbox"/>	<input type="text" value="4.25"/>	<input type="text" value="3.00"/>	<input type="text" value="15.0"/>	<input type="text" value="20.0"/>	<input type="text" value="15.0"/>	<input type="text" value="18"/>

Estimated building-wide gross (flr-to-flr) % window is 15.2% and net (flr-to-ceiling) is 16.9%.

\* - A window width of 0 results in one long window per facet (check adjoining box if window width is to take precedence over % window)

Wizard Screen

# Understanding building energy-related properties

eQUEST DD Wizard: Shell Component -- Bldg Envelope & Loads 1

### Activity Areas Allocation

Area Type	Percent Area (%)	Design Max Occup (sf/person)	Design Ventilation (CFM/per)	Assign First To...		Zone(s):	
				Cor	Per	Cor	Per
1: Corridor	2.4	64	72.73	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
2: Lobby (Main Entry and Assembly)	40.2	276	276.73	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
3: Office (General)	14.2	388	492.22	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
4: Kitchen and Food Preparation	3.7	102	155.03	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
5: Storage (Conditioned)	39.5	1,082	1,687.73	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
6: - select another -							
Percent Area Sum:		100.0	41	1.276			

Show Zone Group Screen

### Occupancy Profiles by Season

Typical Use	Winter	Summer/Fall	
EL1 Occup Profile (S1)	EL1 Occup Profile (S2)	EL1 Occup Profile (S3)	...

Wizard Screen 13 of 25

Help Previous Screen Next Screen Return to Navigator

# **UNITS IN BUILDING SCIENCE AND ARCHITECTURAL ENGINEERING**

# Importance of units

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- Units are **extremely important** in architectural engineering and building science
- Your first HW (assigned today) will cover unit conversions and energy concepts
- If you can understand and convert units, and if you can get a sense of scale and magnitude associated with units, you will be well on your way to becoming a building scientist

# Building science units and dimensions

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- Within architectural engineering, both SI and IP (inch-pound) units are used
  - I am **very sorry** for that
- IP is dominant in US engineering
  - (But changing slowly)
- We will use both in this class (primarily IP)
  - So it will be useful to memorize the most commonly used constants and conversion factors between both units

# Building science units and dimensions

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- Lengths are usually in feet [ft] or meters [m]
- Volumes are usually in cubic feet [ft<sup>3</sup>] or cubic meters [m<sup>3</sup>]
- Volumetric flow rates are usually in [ft<sup>3</sup>/min] (CFM)
  - Sometimes [m<sup>3</sup>/hr], [m<sup>3</sup>/s], [L/s]
  - Water flows are often [L/min] (lpm) or [gal/min] (gpm)
- Temperatures are either Fahrenheit [°F] or Celsius [°C]
  - Sometimes Kelvin [K], rarely Rankine [R]
- Velocities are either [ft/s], [m/s], or sometimes [cm/s]
- Concentrations are parts per million [ppm], parts per billion [ppb], or micrograms per cubic meter [μg/m<sup>3</sup>]
- Mass is typically [lb<sub>m</sub>] or [kg]

# More building science units

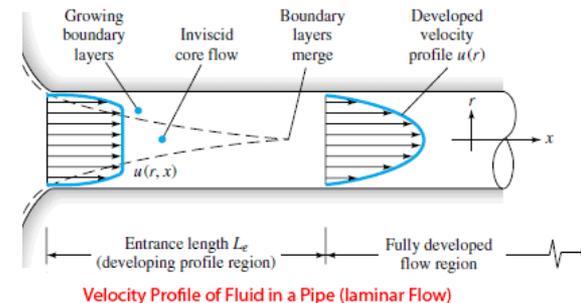
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- Energy is usually in [J] or [BTU]
  - Or [kWh] (for electric) or [therms] (for natural gas)
    - 1 kWh = 3412 BTU
    - 1 therm =  $10^5$  BTU
  - Or [MMBTU] = “million BTU” =  $10^6$  BTU
- Power is usually [W = J/s] or [BTU/hr]
  - Tons of refrigeration [1 ton = 12000 BTU/hr = 3412 W]
- Pressure is usually [Pa] or [in-wg or in w.c.] (inches of water)
  - Larger pressures are also [in-Hg] (inches of mercury)
    - Or [psi] (pounds per square inch) for very high pressures

# Unit conversion examples

## Unit conversion example problem:

- Water of density  $\rho = 62.44 \text{ lbm/ft}^3$  ( $1000 \text{ kg/m}^3$ ) flows at a rate of  $V = 10 \text{ gal/min}$  ( $0.6308 \times 10^{-3} \text{ m}^3/\text{s}$ ) through a pipe of interior diameter  $D = 1.0 \text{ inches}$  ( $2.54 \text{ cm}$ )



- Find the velocity pressure, given by the formula:

$$P = \frac{\rho v^2}{2}$$

- Provide answer in units of [Pa] and [in-WG]

# BB\ASHRAE Materials\ASHRAE IP-SI Unit Conversions

	A	B	C	D	E
1	Enter I-P Number	I-P Unit	SI Conversion	SI Unit	Conversion Factor
2		acre (43,560 ft <sup>2</sup> )	0	ha	0.4047
3		acre (43,560 ft <sup>2</sup> )	0	m <sup>2</sup>	4046.873
4		atmosphere (standard)	0	kPa	101.325
5		bar	0	kPa	100
6		barrel (42 U.S. gal, petroleum)	0	L	159
7		barrel (42 U.S. gal, petroleum)	0	m <sup>3</sup>	0.1580987
8		Btu (International Table)	0	J	1055.056
9		Btu (thermochemical)	0	J	1054.35
10		Btu/ft <sup>2</sup> (International Table)	0	J/m <sup>2</sup>	11,356.53
11		Btu/ft <sup>2</sup> (International Table)	0	J/m <sup>2</sup>	37,258.95
12		Btu/gal	0	J/m <sup>3</sup>	278,717.18
13		Btu·ft/h·ft <sup>2</sup> ·°F	0	W/(m·K)	1.730735
14		Btu·in/h·ft <sup>2</sup> ·°F (thermal conductivity $k$ )	0	W/(m·K)	0.1442279
15		Btu/h	0	W	0.2930711
16		Btu/h·ft <sup>2</sup>	0	W/m <sup>2</sup>	3.154591
17		Btu/h·ft <sup>2</sup> ·°F (overall heat transfer coefficient $U$ )	0	W/(m <sup>2</sup> ·K)	5.678263
18		Btu/lb	0	kJ/kg	2.326
19		Btu/lb·°F (specific heat $c_p$ )	0	kJ/(kg·K)	4.1868
20		bushel (dry, U.S.)	0	m <sup>3</sup>	0.0352394
21		calorie (thermochemical)	0	J	4.184
22		centipoise (dynamic viscosity $\mu$ )	0	mPa·s	1
23		centistokes (kinematic viscosity $\nu$ )	0	mm <sup>2</sup> /s	1
24		clo	0	(m <sup>2</sup> ·K)/W	0.155
25		dyne	0	N	1.00E-05
26		dyne/cm <sup>2</sup>	0	Pa	0.1
27		EDR hot water (150 Btu/h)	0	W	43.9606
28		EDR steam (240 Btu/h)	0	W	70.33706
29		EER	0	COP	0.293
30		ft	0	m	0.3048
31		ft	0	mm	304.8
32		ft/min, fpm	0	m/s	0.00508
33		ft/s, fps	0	m/s	0.3048
34		ft of water	0	Pa	2989
35		ft of water per 100 ft pipe	0	Pa/m	98.1
36		ft <sup>3</sup>	0	m <sup>3</sup>	0.092903
37		ft <sup>2</sup> ·h·°F/Btu (thermal resistance $R$ )	0	(m <sup>2</sup> ·K)/W	0.17611

# Unit conversion and energy concepts

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## Order of magnitude example problem:

- How long would you have to operate a 60 W light bulb immersed in a bathtub to warm up the water by 1 degree C (1.8 degree F), assuming there are no losses?
  - Do not try this at home

Internal energy:

$$E = mC_pT$$

$m$  = mass (kg)

$E$  = internal energy (J)

$C_p$  = heat capacity (J/kg/K)

$T$  = temperature (K)

# Unit conversion and energy concepts

---

## Order of magnitude example problem:

- From what height would you have to jump into the same bathtub to warm up the water the same amount, assuming that all of the kinetic energy from the jump goes into heating the water (again, there are no losses)?

Work = change in energy

Work = force x distance

Change in energy = gravitational force x height

$$\Delta E = mgh$$

**MOVING FORWARD**

# HW #1 due next week

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- HW 1 is now available on blackboard
- Due Thursday, August 30

# Next time

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- Beginning heat transfer applications in buildings