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Building Science Education for Solar Decathlon

First Law of Thermodynamics

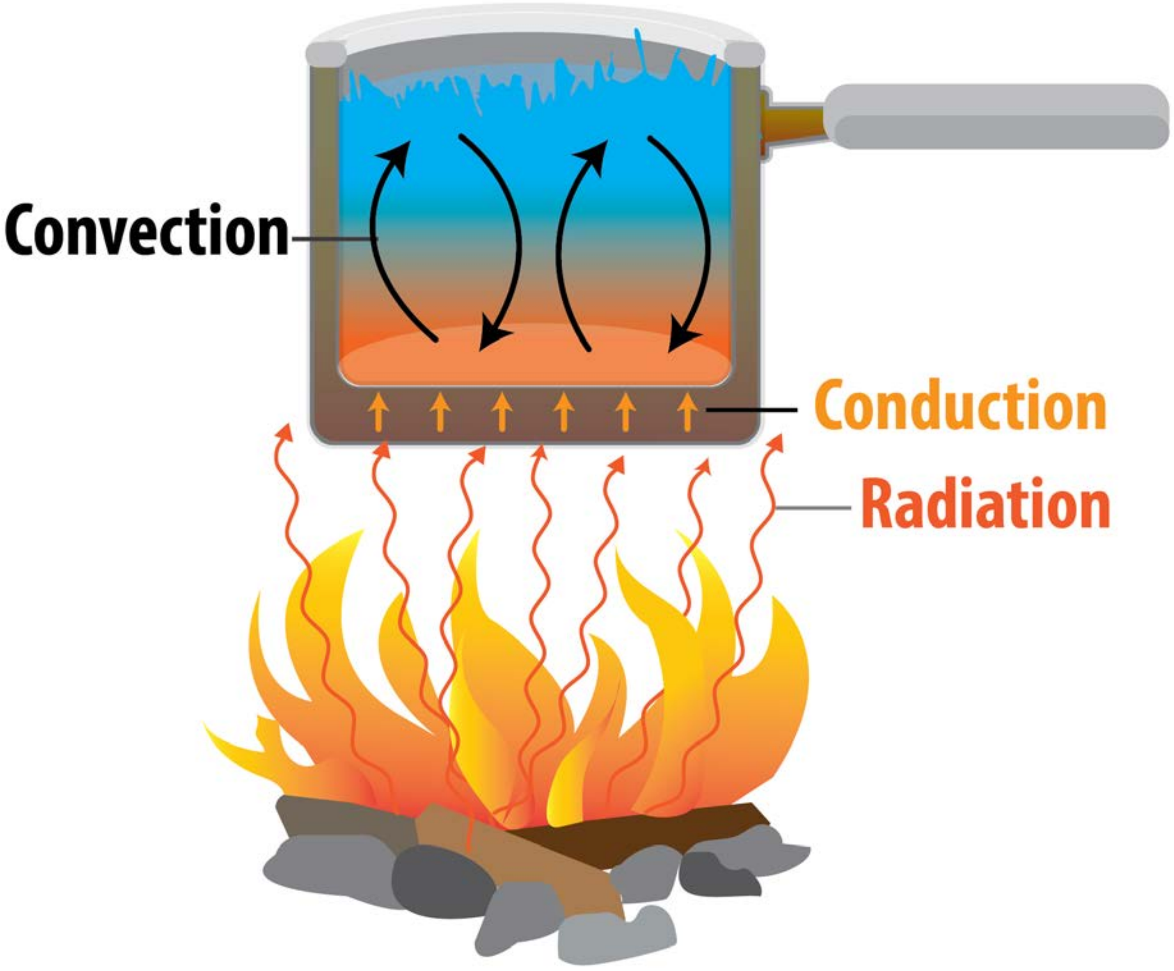

Photo by Marjorie Schott, NREL

NREL/PR-5500-83073

Episode ID: 0301-201105

First Law of Thermodynamics

"Thermo-" comes from the Greek word *thermos* meaning "hot" or "warm"

"Dynamics" comes from the Greek word *dynamis* meaning "force" or "power"

Law of Conservation of Energy:
"Energy cannot be created nor destroyed"

The first step of any thermodynamic problem is to define a system boundary.

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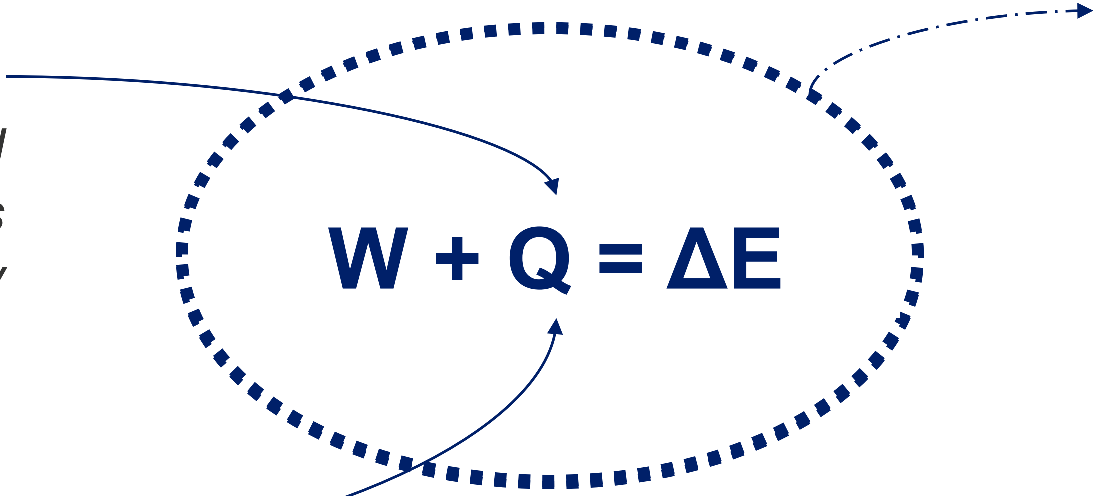
Measuring Energy Flows Across a Boundary

Theoretical energy boundary of a system

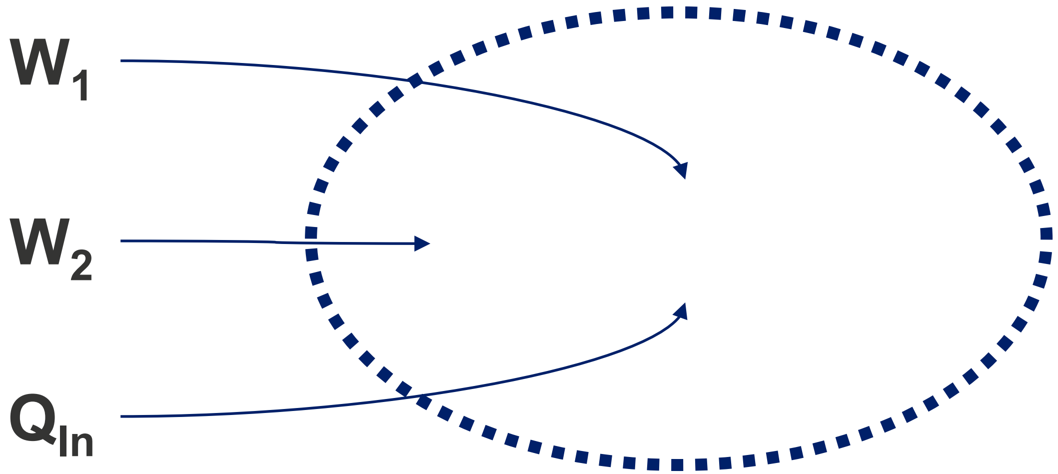
Work (W):
The transfer of mechanical or electrical energy across the boundary



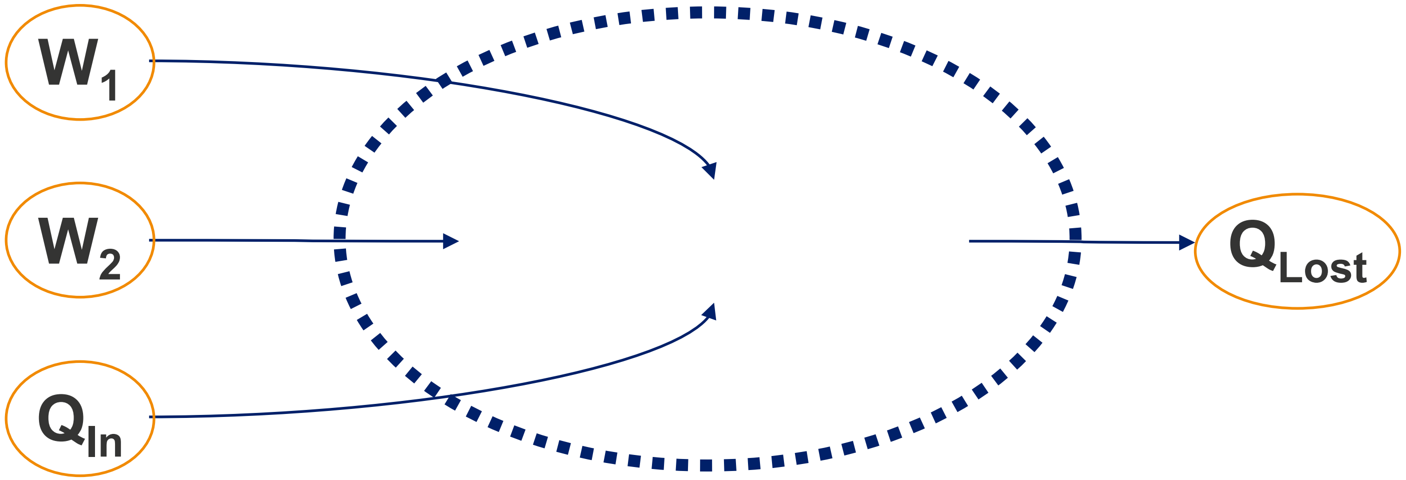
Heat (Q):
The transfer of thermal energy across the boundary due to a temperature difference at the boundary.

Energy associated with mass crossing the boundary is described as "heat equivalent" (e.g., natural gas)

Direction of Energy Flow is Important



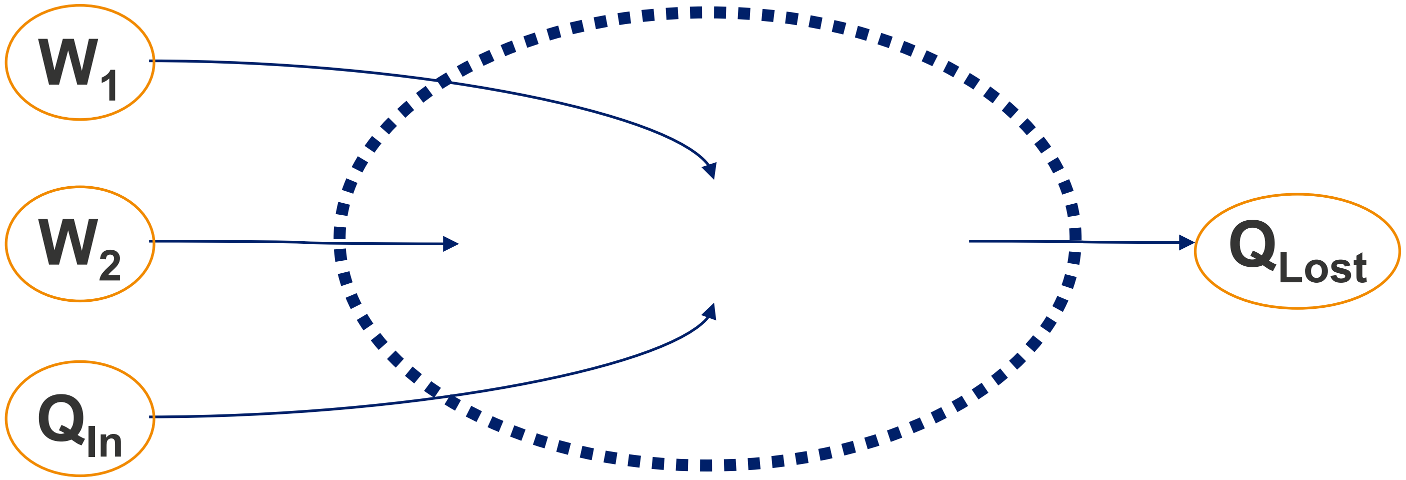
Direction of Energy Flow is Important



Caution: Units of Work (W) and Heat (Q) must be the same in order to add them together!

$$W_1 + W_2 + Q_{In} + (-Q_{Lost}) = \Delta E$$

Direction of Energy Flow is Important



Caution: Units of Work (W) and Heat (Q) must be the same in order to add them together!

$$W_1 + W_2 + Q_{In} - Q_{Lost} = \Delta E$$

Over time, $\Delta E = 0$

Therefore, $Energy_{in} = Energy_{out}$

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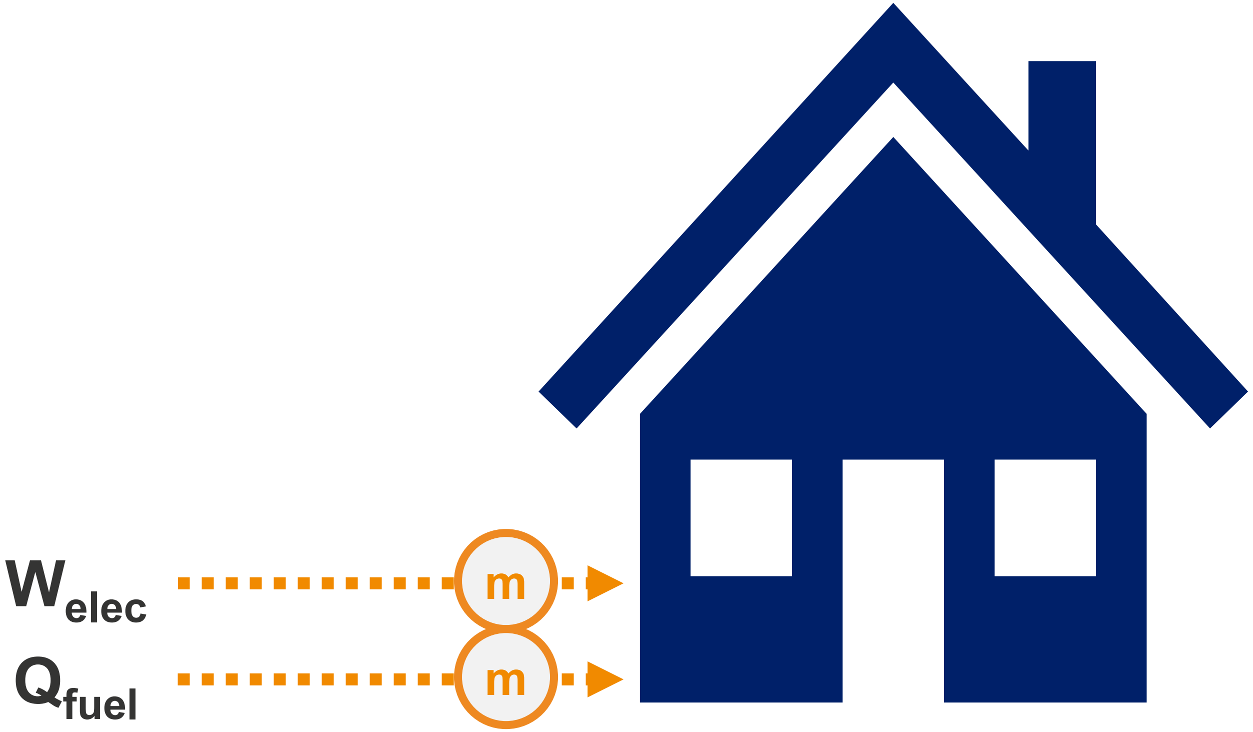
$Energy_{in} = Energy_{out}$



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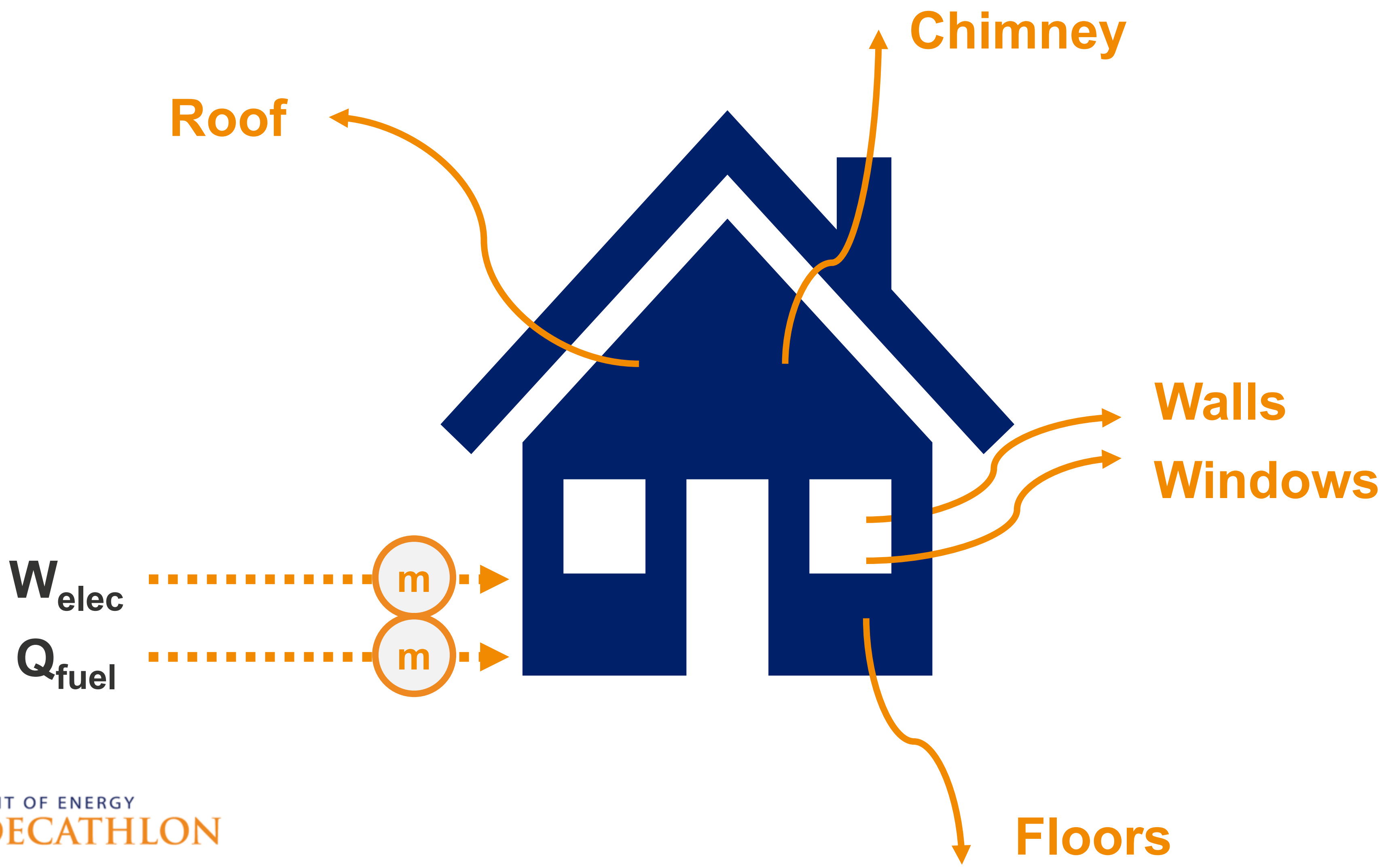
$Energy_{in} = Energy_{out}$



Coming up in the Building Envelope module…

Look at the concept of $Energy_{in}$ = $Energy_{out}$

Study how energy flows through the building envelope (e.g., walls, windows, doors)

Use that information to determine how much energy a building needs

Questions or comments?

Please email SolarDecathlon@nrel.gov

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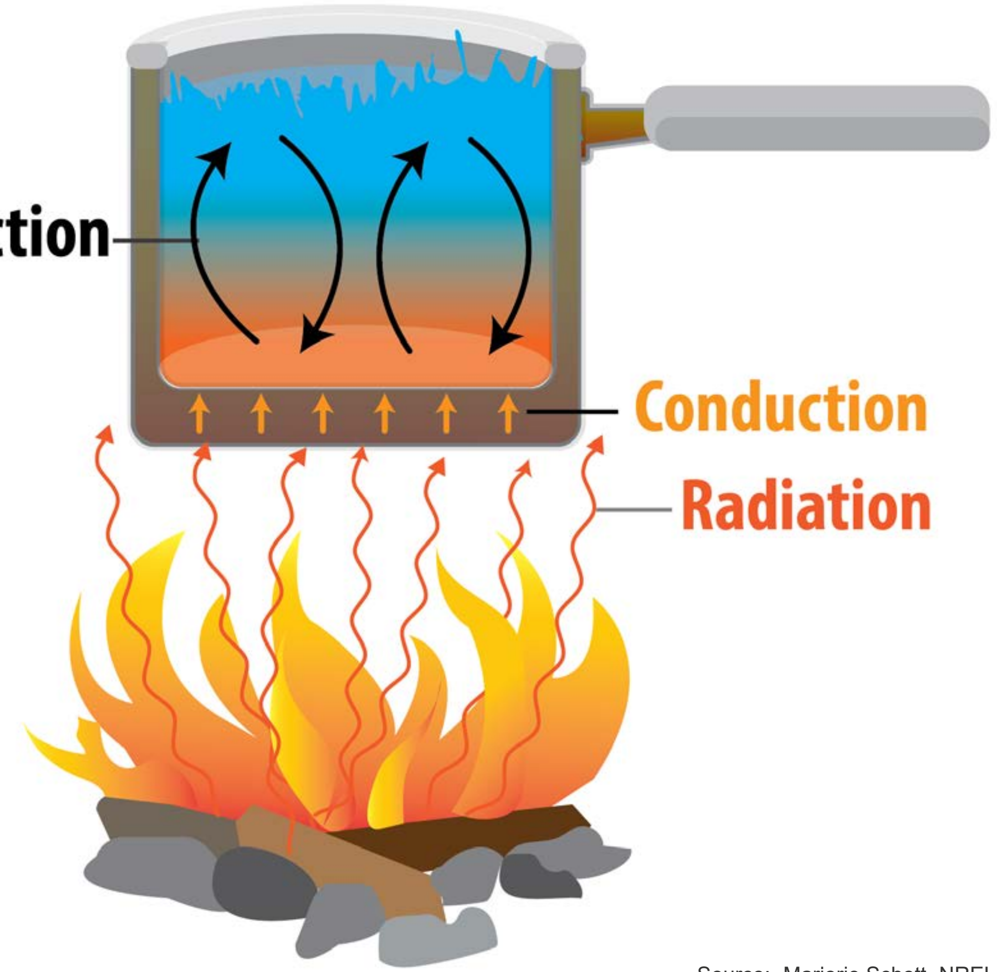
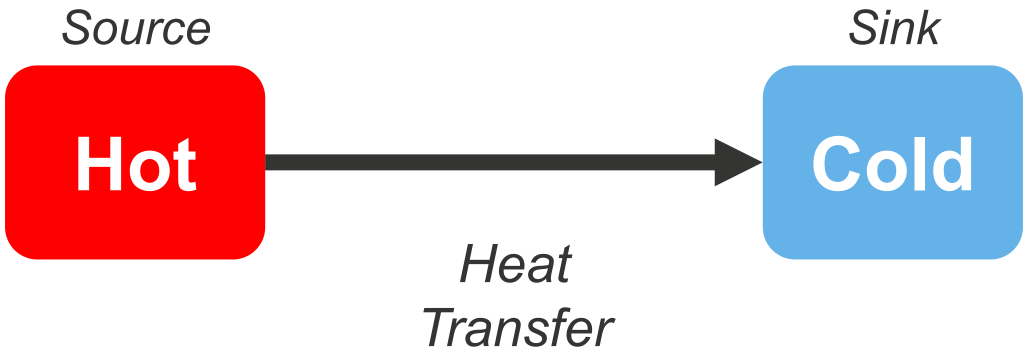
Fourier's Law of Heat Transfer

(Part 1)



Source: Marjorie Schott, NREL

Heat always flows from hot to cold



$$Q = thermal\ energy\ transferred\ (i.e., \text{heat})$$

Units: Btu, J, Wh

$$\dot{Q} = rate\ of\ thermal\ energy\ transfer\ (i.e., \text{heat transfer rate})$$

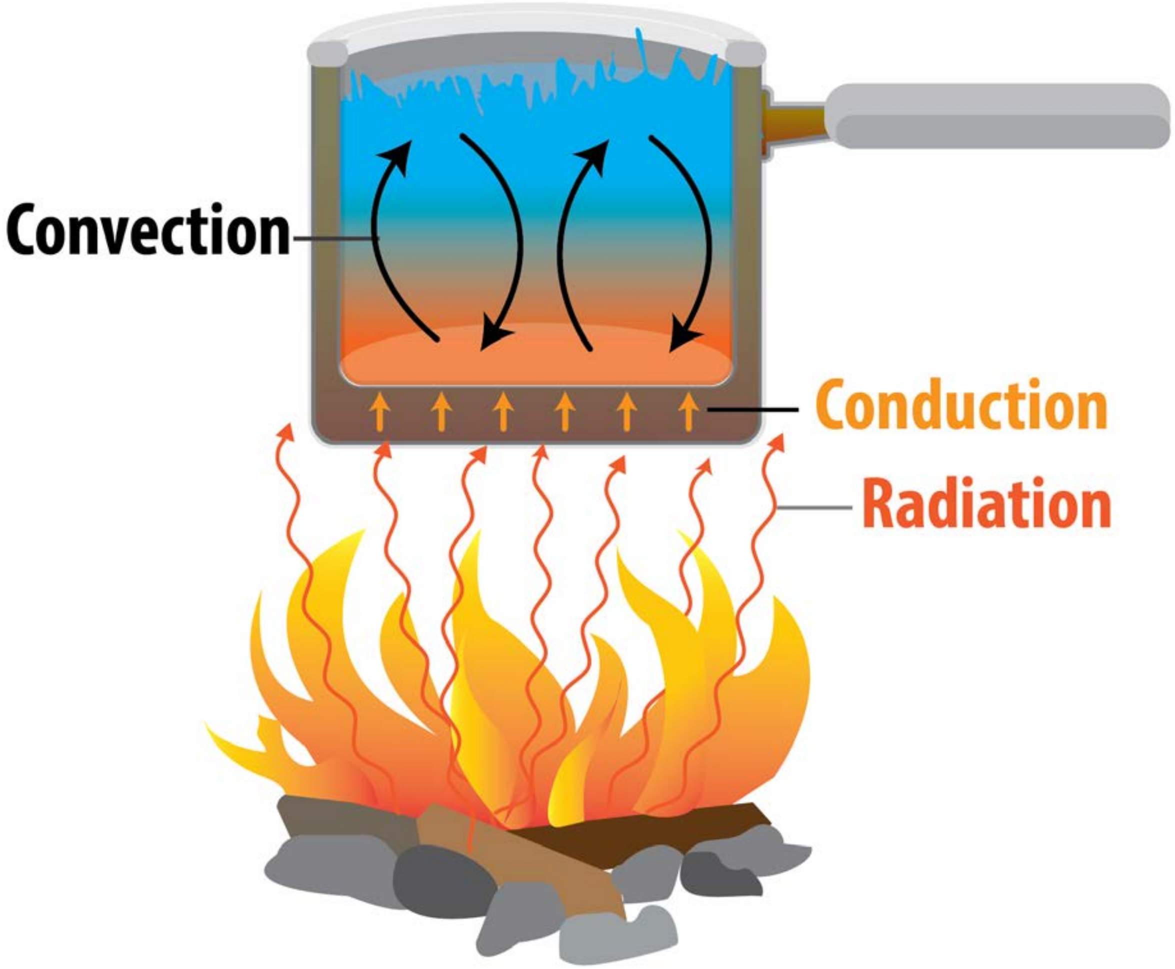
Units: Btu/hr, J/s = W

Modes of Heat Transfer

Conduction

Convection

Radiation



Source: Marjorie Schott, NREL

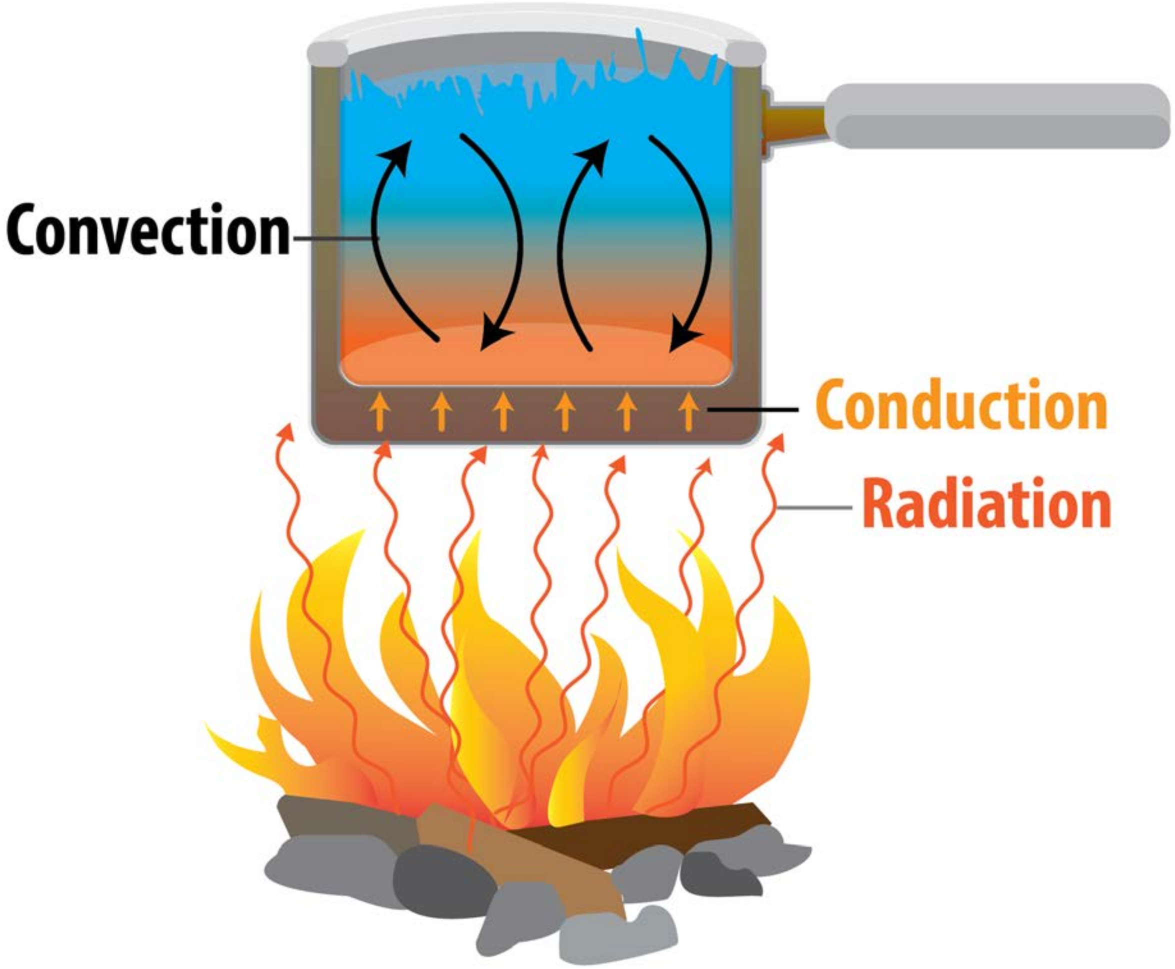
Modes of Heat Transfer

Conduction

- Exchange of kinetic energy between molecules, without any macroscopic movement of the molecules

Convection

Radiation



Source: Marjorie Schott, NREL

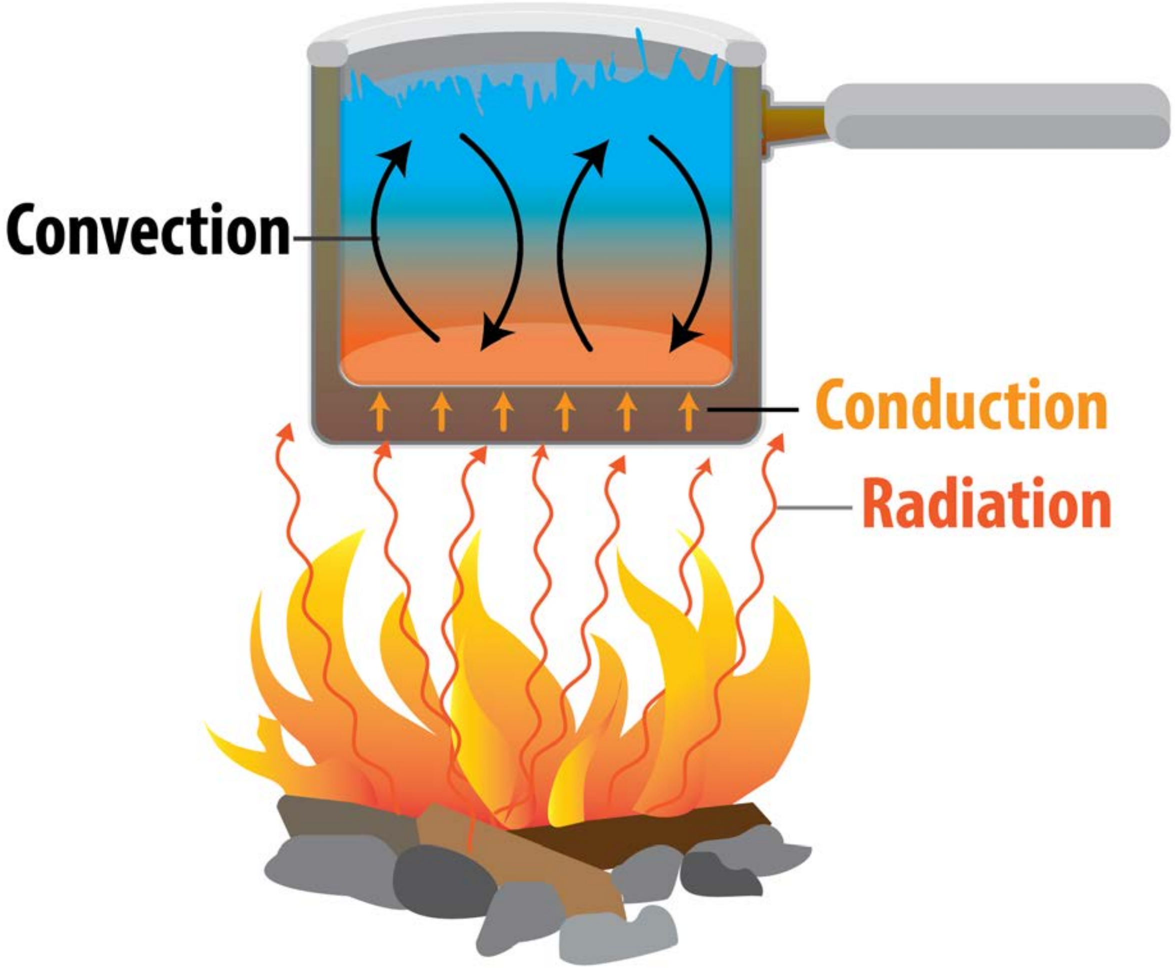
Modes of Heat Transfer

Conduction

Convection

- Motion of molecules in a fluid (i.e., liquid or gas) resulting from density gradient

Radiation



Source: Marjorie Schott, NREL

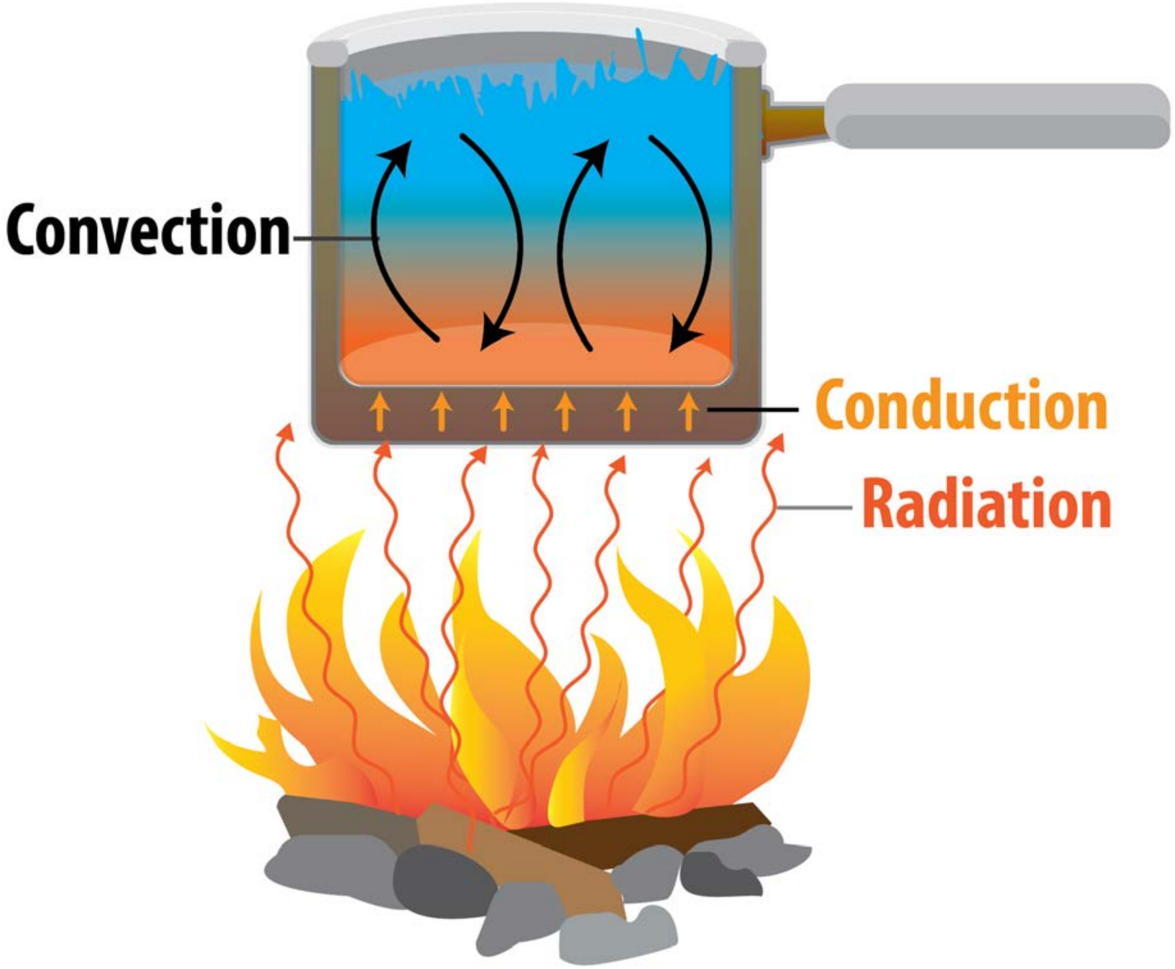
Modes of Heat Transfer

Conduction

Convection

Radiation

- Transfer of thermal energy through electromagnetic waves. No physical contact is required.



Source: Marjorie Schott, NREL

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Coming up in Part 2…

Application of heat transfer law to building science

Definition of each term of the heat transfer equation

$$\dot{Q} = U \cdot A \cdot \Delta T$$

Questions or comments?

Please email SolarDecathlon@nrel.gov

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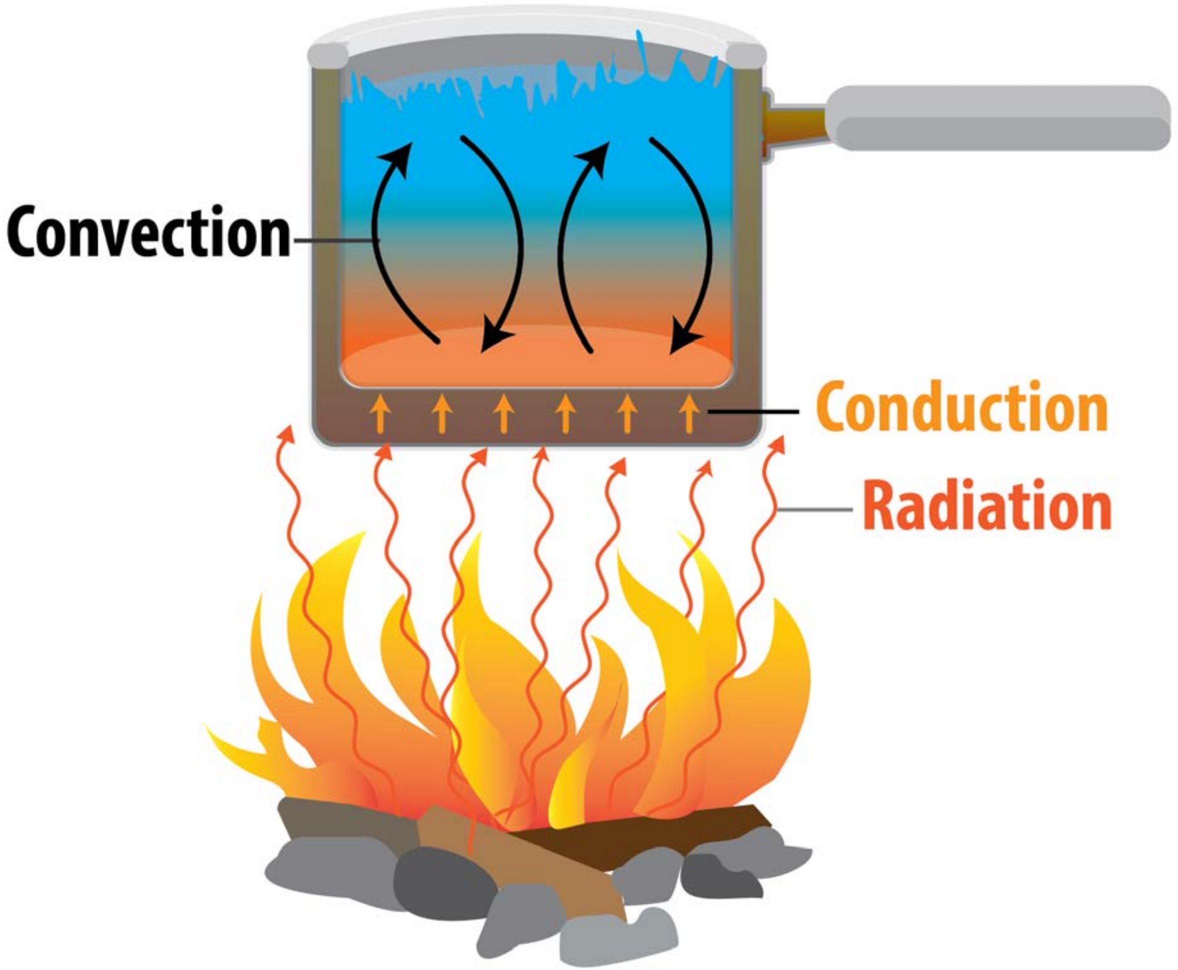
Fourier's Law of Heat Transfer

(Part 2)



Source: Marjorie Schott, NREL

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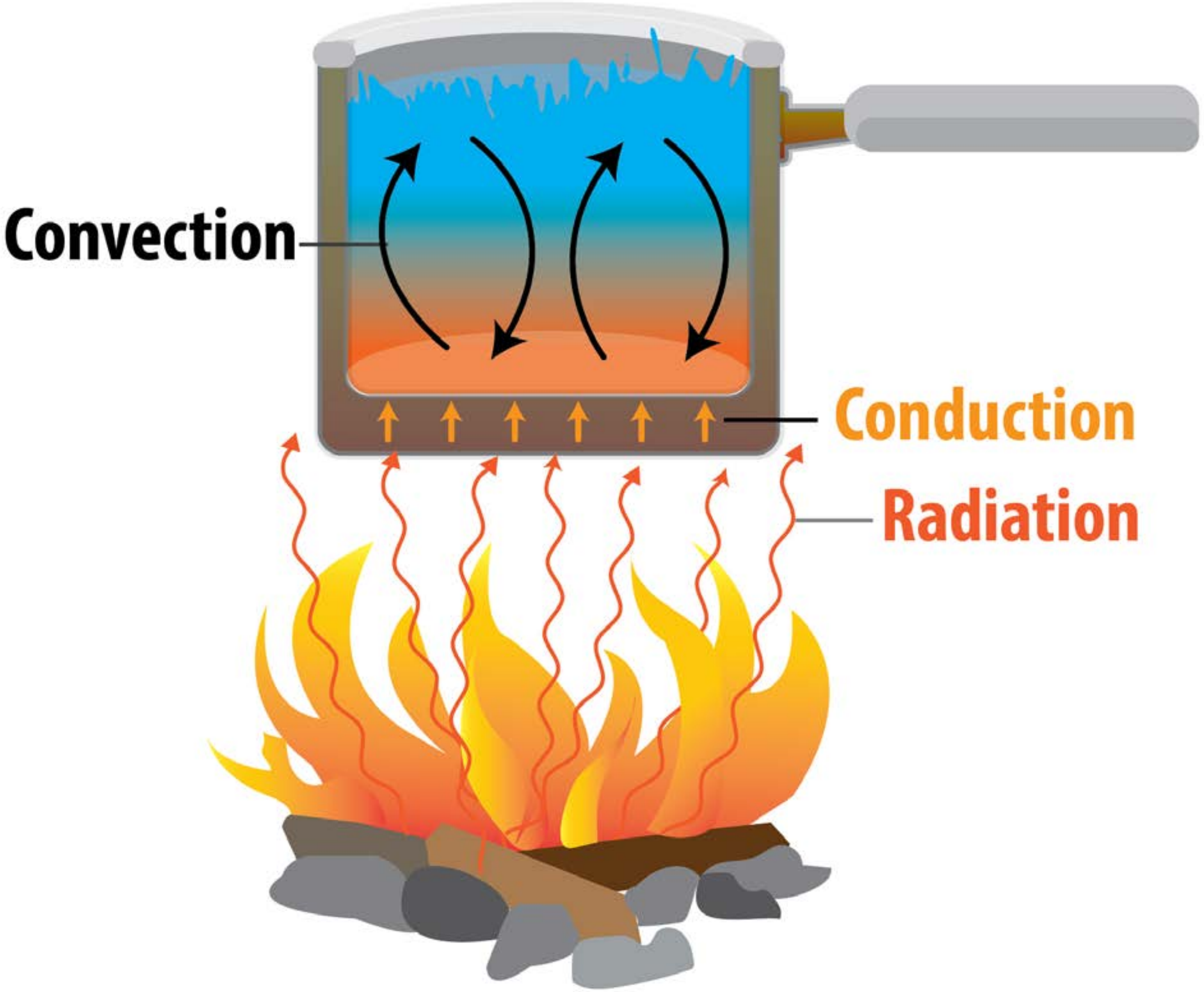
Modes of Heat Transfer



Source: Marjorie Schott, NREL

How does this apply to building science?

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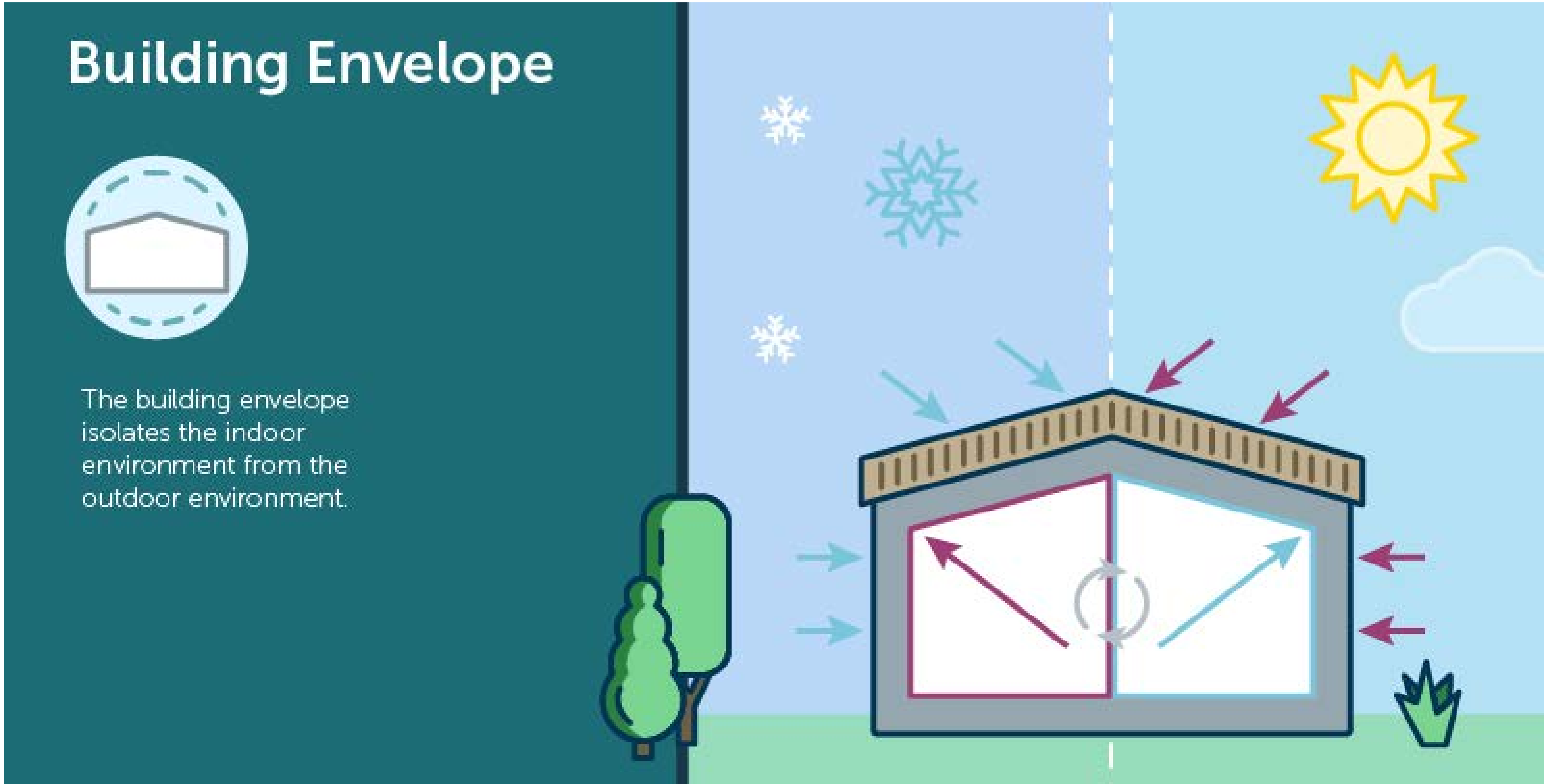
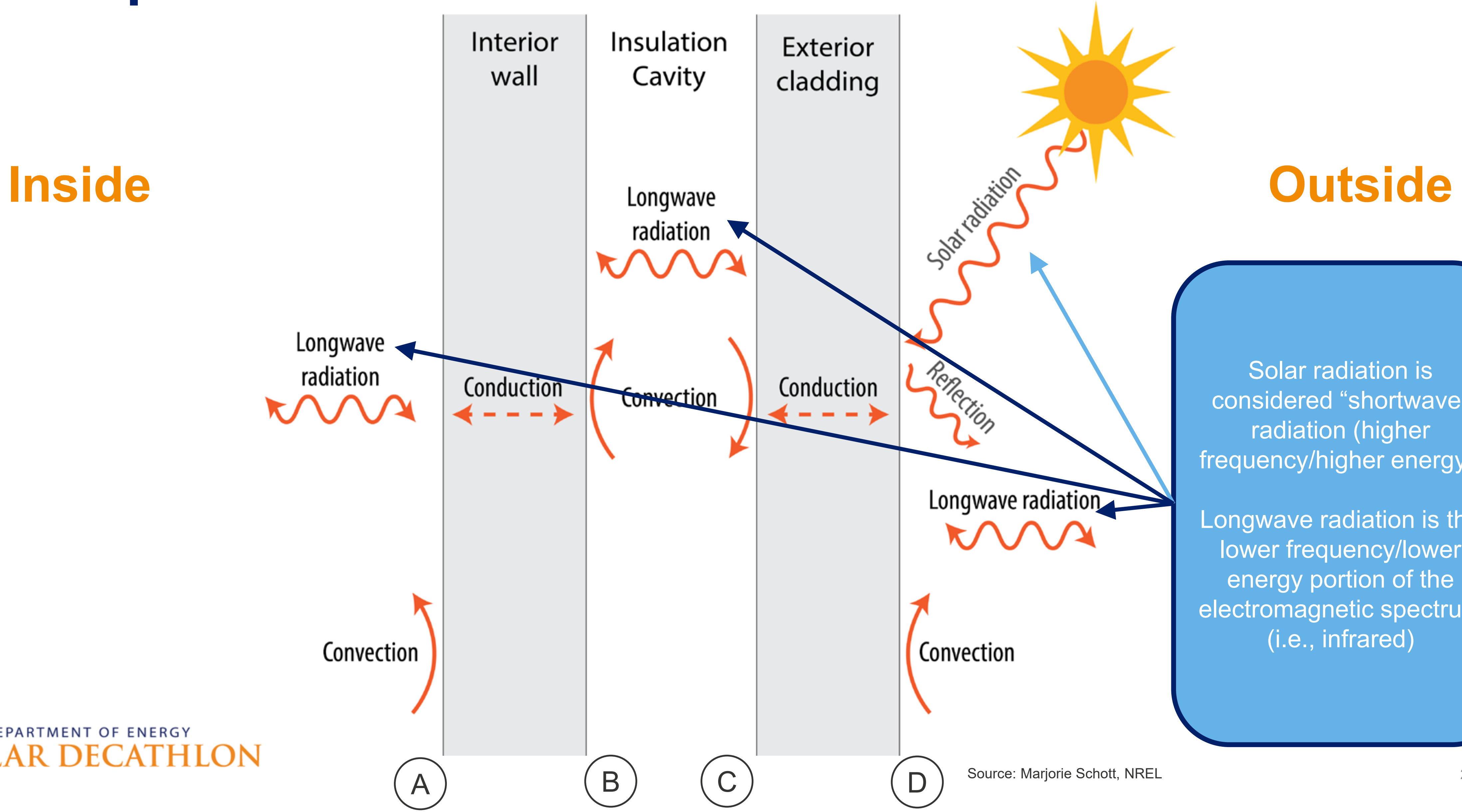
Heat Transfer Through the Building Envelope



Source: secondnature.org/solutions-center/building-envelope/

Heat transfer through the building envelope is actually very complex…



Solar radiation is considered "shortwave" radiation (higher frequency/higher energy).

Longwave radiation is the lower frequency/lower energy portion of the electromagnetic spectrum (i.e., infrared)

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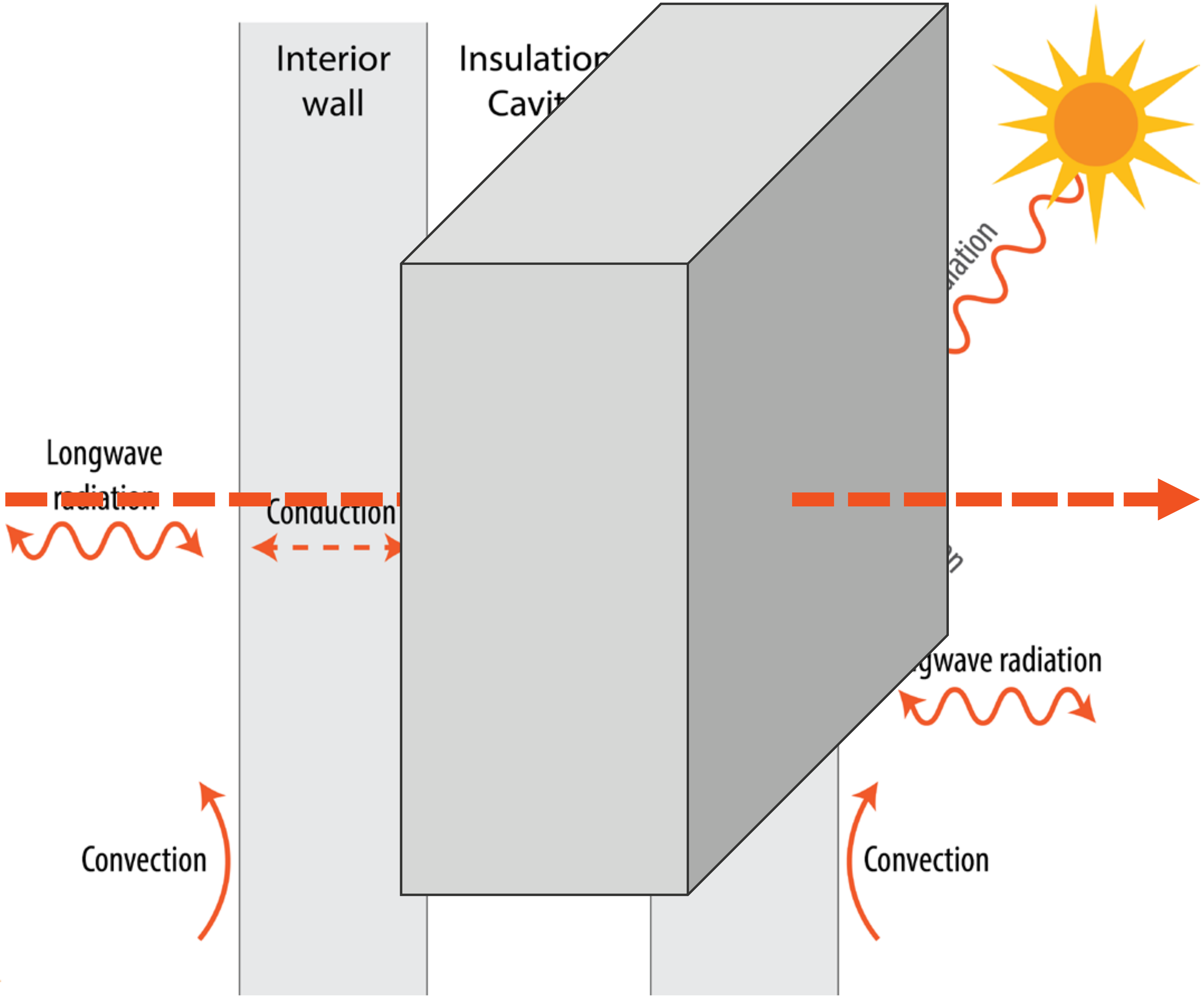
Source: Marjorie Schott, NREL

Heat transfer through the building envelope is actually very complex…



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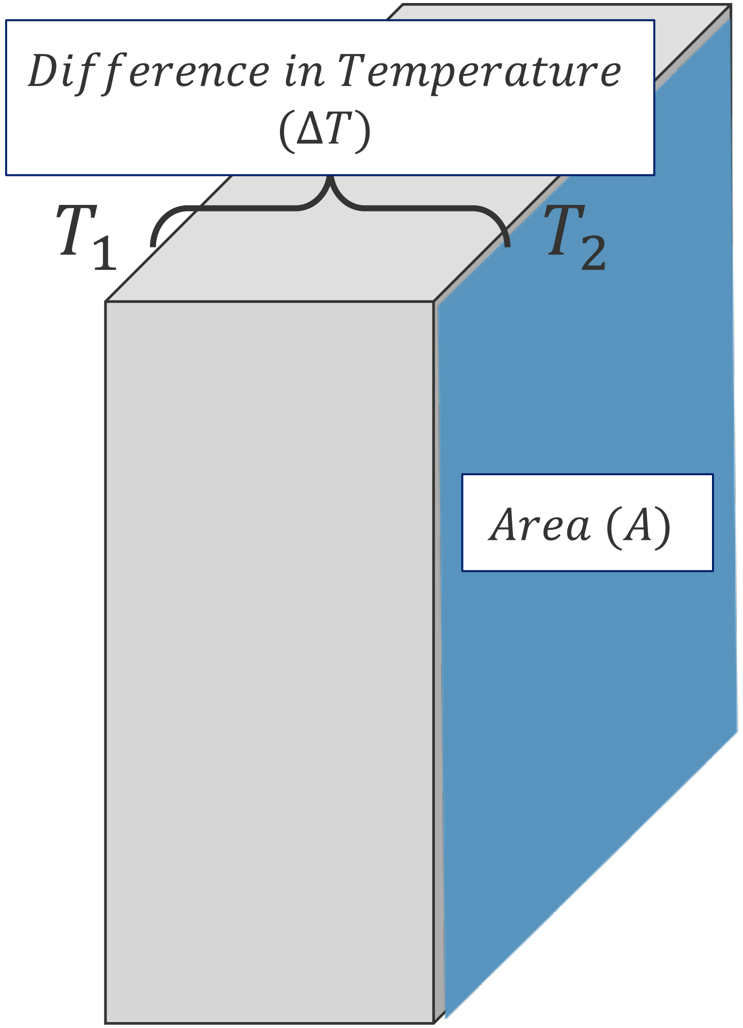
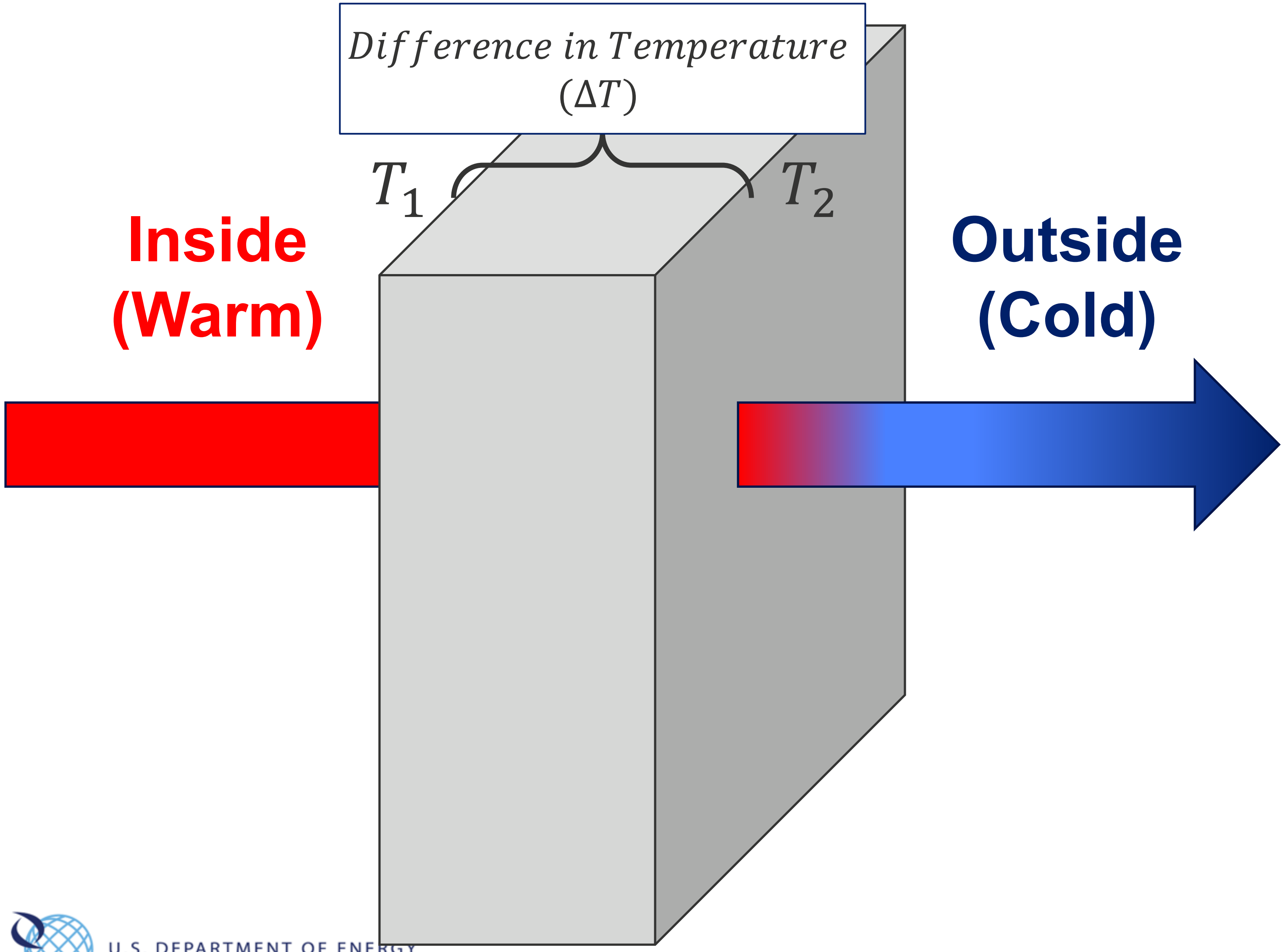
Heat Transfer Through the Building Envelope



$$Heat\ Transfer \propto Area\ (A) \cdot Difference\ in\ Temp.\ (\Delta T)$$

$$Proportionality\ constant = ?$$

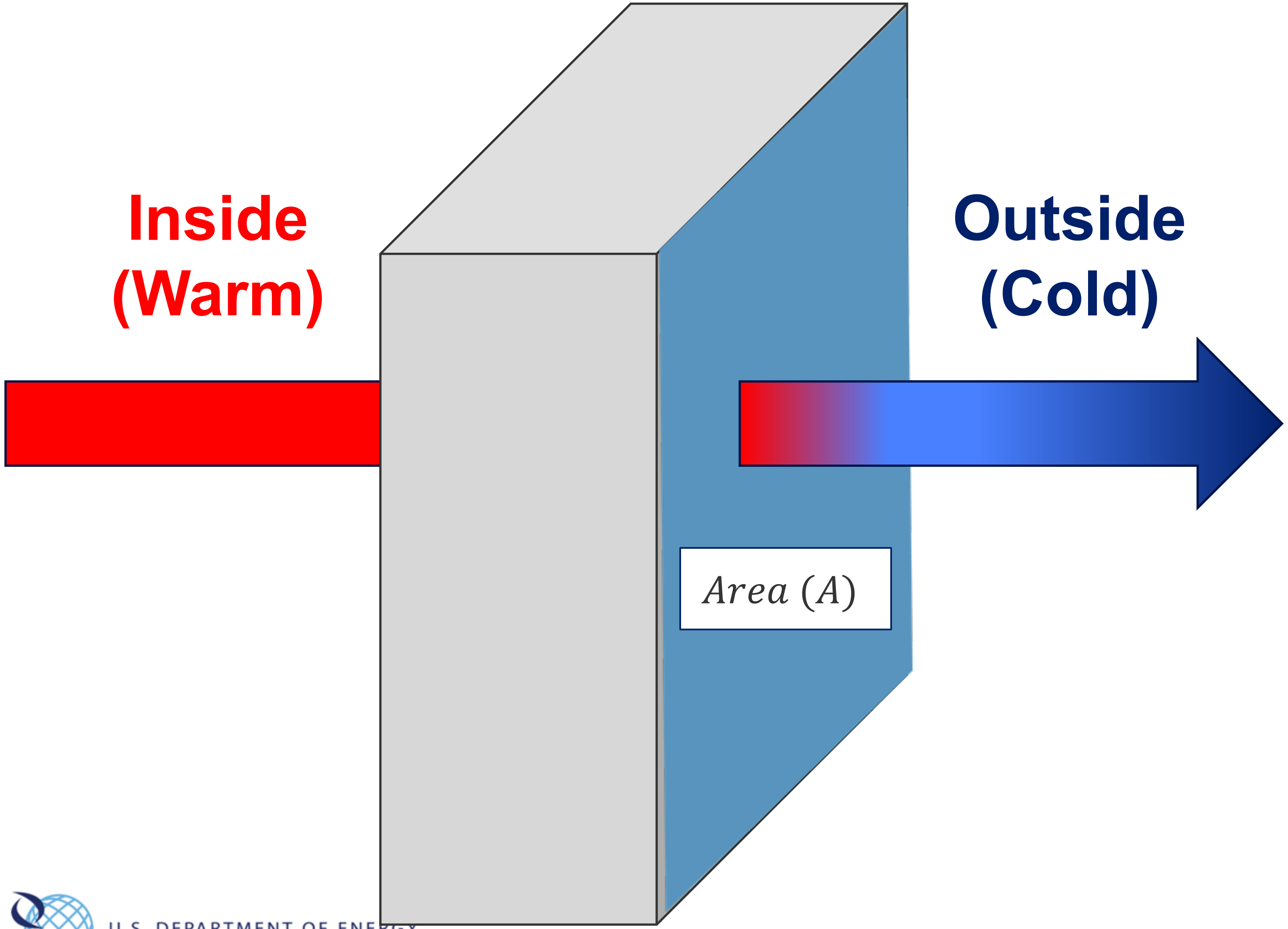
Heat Transfer Through the Building Envelope



Heat transfer is dependent upon:

Difference in temperature from inside to outside (ΔT). Larger ΔT results in a higher rate of heat transfer.

Heat Transfer Through the Building Envelope



Heat transfer is dependent upon:

Difference in temperature from inside to outside (ΔT). Larger ΔT results in a higher rate of heat transfer.

Cross-sectional area of the wall (A). Larger A results in a higher rate of heat transfer.

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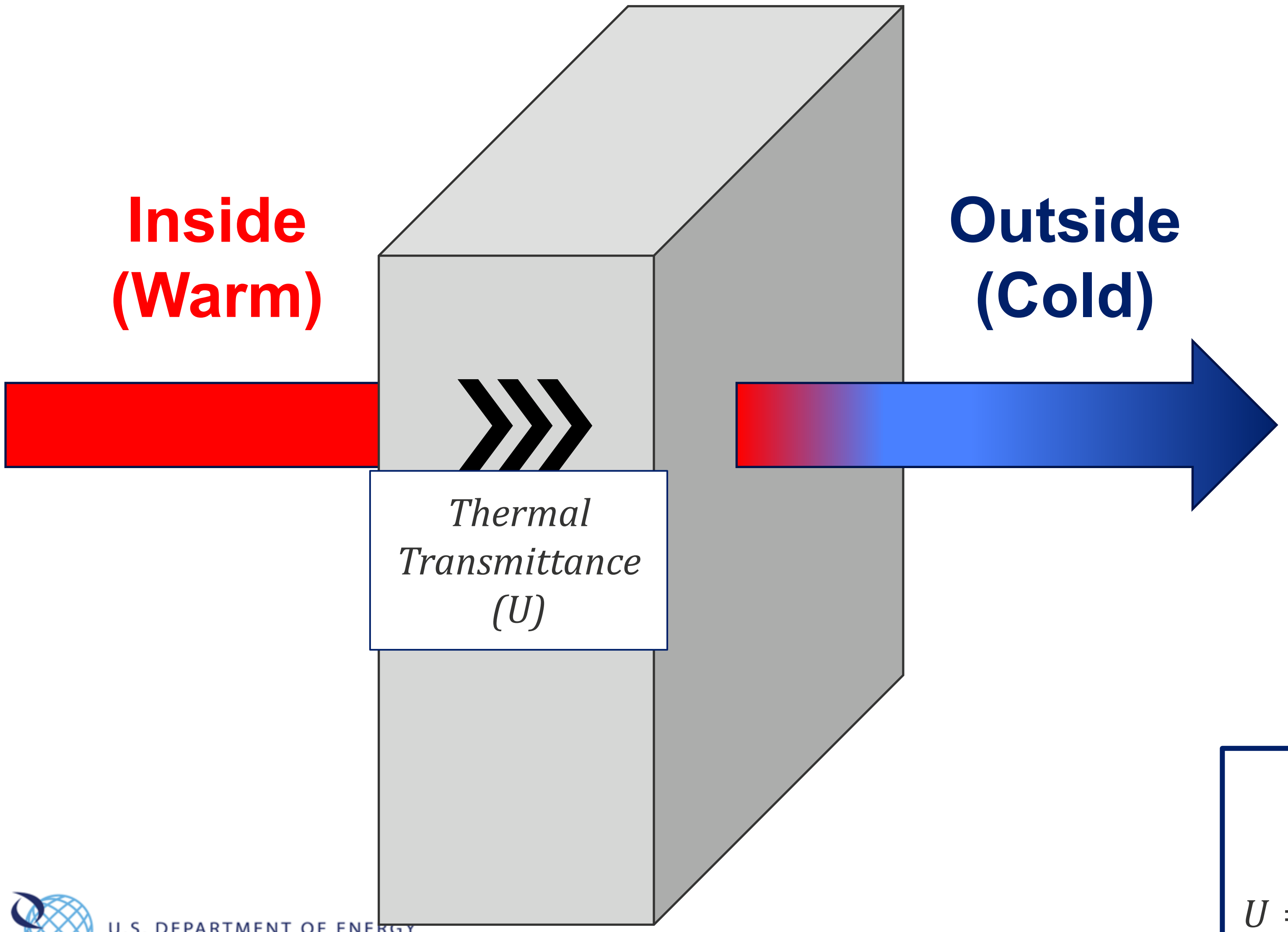
Heat Transfer Through the Building Envelope



Heat transfer is dependent upon:

Difference in temperature from inside to outside (ΔT). Larger ΔT results in a higher rate of heat transfer.

Cross-sectional area of the wall (A). Larger A results in a higher rate of heat transfer.

Thermal transmittance of the materials in the wall. Larger U-factor results in a higher rate of heat transfer.

In a homogeneous material:

$$U = \frac{Thermal\ Conductivity\ of\ the\ Material\ (k)}{Thickness\ of\ the\ Material\ (x)}$$

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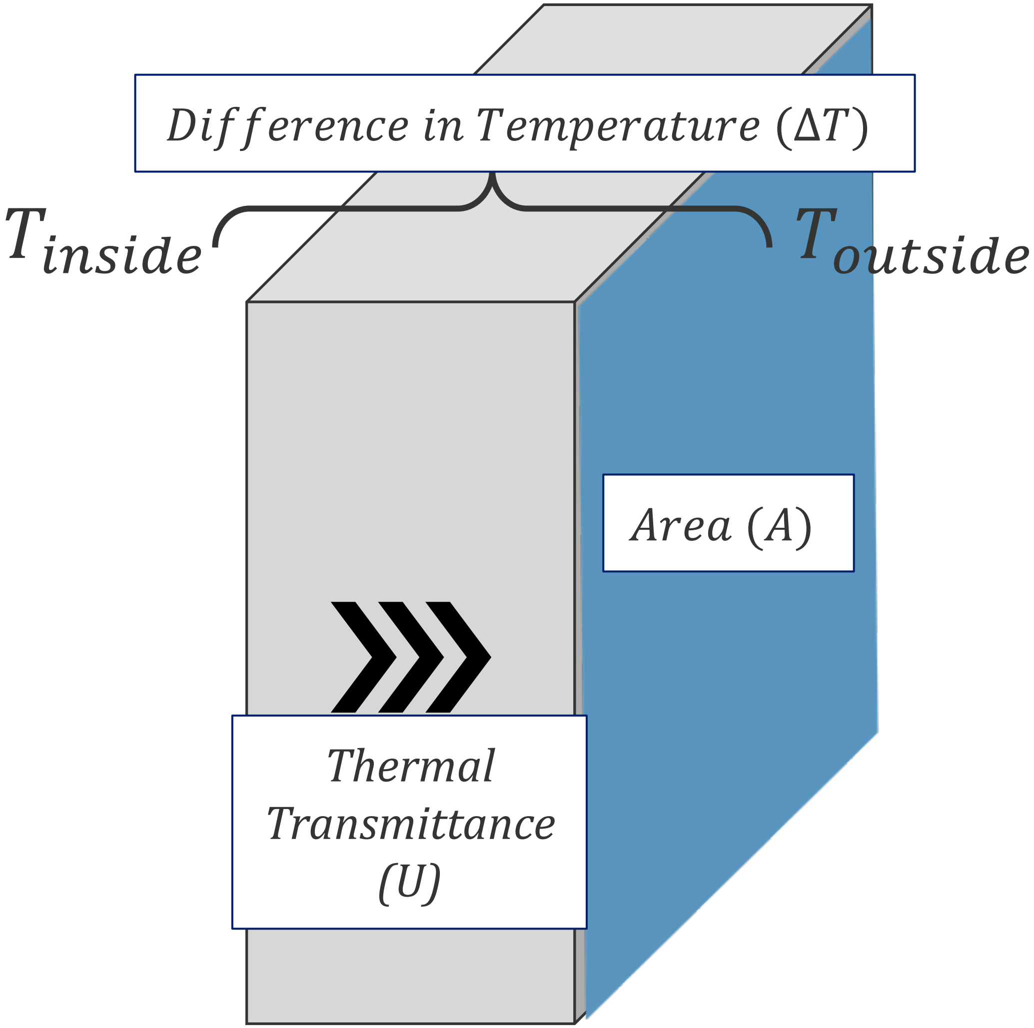
Heat Transfer Through the Building Envelope



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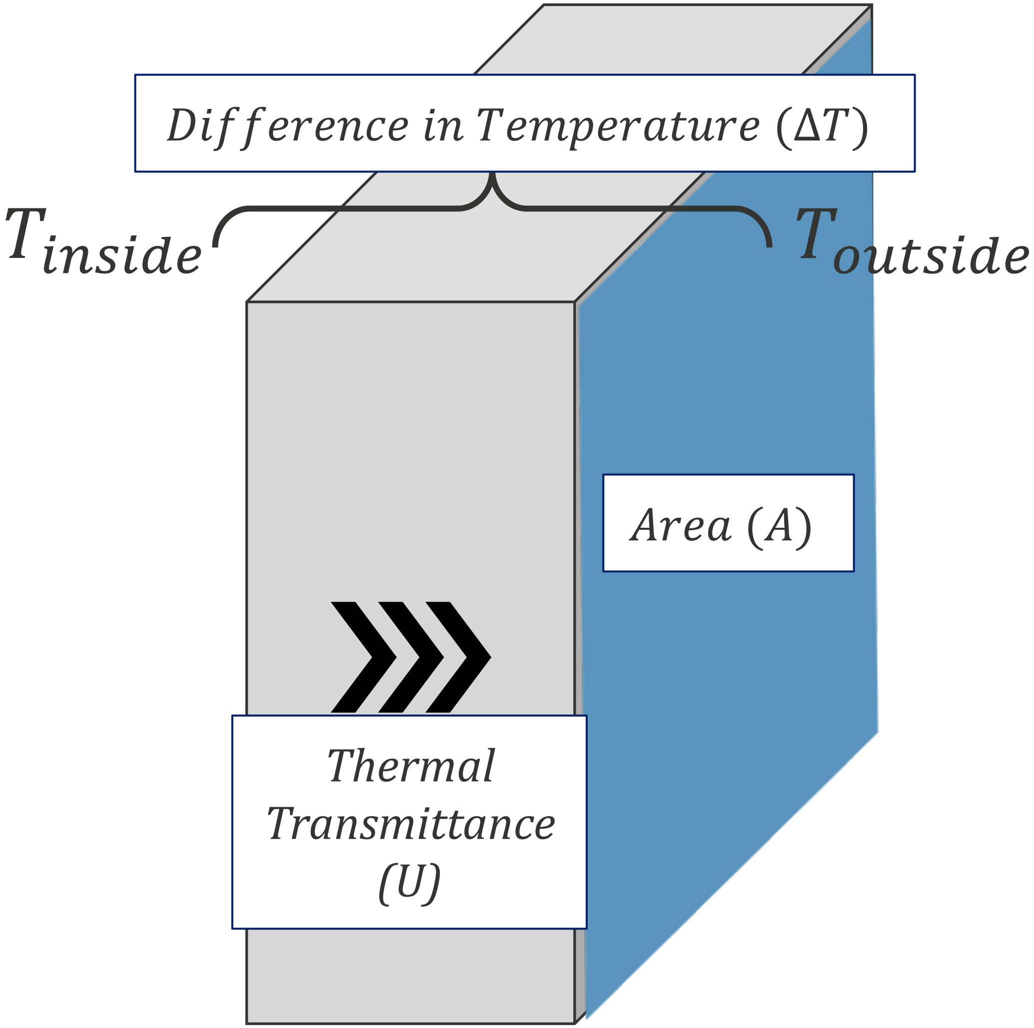
Heat Transfer Through the Building Envelope



$$Heat\ Transfer \propto Area\ (A) \cdot Difference\ in\ Temp\ (\Delta T)$$

$$Proportionality\ constant = U$$

$$\dot{Q} = U \cdot A \cdot \Delta T$$

$$\frac{Btu}{hr} = U \cdot ft^2 \cdot °F$$

$$\dot{Q} = \frac{Btu}{hr \cdot ft^2 \cdot °F} \cdot ft^2 \cdot °F$$

U-Factor vs. R-Value

Thermal Transmittance

Thermal Resistance

	$U-Factor$
English System	$\frac{Btu}{hr \cdot ft^2 \cdot °F}$

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Questions or comments?

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References

1. 2017 ASHRAE Handbook – Fundamentals: https://www.ashrae.org/technical-resources/ashrae-handbook/description-2017-ashrae-handbook-fundamentals
    a. Chapter 26: Material Properties
    b. Chapter 27: Calculate U-Factor

Commonly Used Units for the Heat Transfer Law

English System

$$\dot{Q} \propto \frac{Btu}{hr}$$

$$T \propto °\mathrm{F}$$

$$A \propto ft^2$$

$$U \propto \frac{Btu}{ft^2 \cdot hr \cdot °\mathrm{F}}$$

$$R \propto \frac{1}{U} \propto \frac{ft^2 \cdot hr \cdot °\mathrm{F}}{Btu}$$

Metric System

$$\dot{Q} \propto W$$

$$T \propto °\mathrm{C}$$

$$A \propto m^2$$

$$U \propto \frac{W}{m^2 \cdot °\mathrm{C}}$$

$$R_{SI} \propto \frac{1}{U} \propto \frac{m^2 \cdot °\mathrm{C}}{W}$$

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R-values and Insulation

Photo by Paul Norton, NREL

Episode ID: 0304-201105

U-Factor vs. R-Value

English System

$$U \propto \frac{Btu}{hr \cdot ft^2 \cdot {}^\circ\mathrm{F}}$$

$$R \propto \frac{1}{U} \propto \frac{hr \cdot ft^2 \cdot {}^\circ\mathrm{F}}{Btu}$$

Metric System

$$U \propto \frac{W}{m^2 \cdot {}^\circ\mathrm{C}}$$

$$R_{SI} \propto \frac{1}{U} \propto \frac{m^2 \cdot {}^\circ\mathrm{C}}{W}$$

R-Value is Printed on Insulation Product Labels

Higher R-Value =
Higher Resistance to Heat Flow

Photos by Paul Torcellini, NREL

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Marcus Bianchi, Ph.D. - Senior Engineer, NREL

Photo credit: NREL

Dr. Bianchi is a senior research engineer with NREL's Building Energy Science Group. He is a thermal energy expert and employs his background to conduct research in thermal sciences modeling, analysis, and testing of advanced building envelope components and systems to improve the energy performance of buildings. He conducts business development for the Buildings and Thermal Sciences Center in collaborations and partnerships with external organizations to support their common objectives in energy efficiency and generation.

R-values and Insulation

Marcus Bianchi, Ph.D.
Senior Engineer, NREL

Photo credit: NREL

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R-values are used to compare insulation products.

Insulation products are tested under standardized conditions to evaluate R-value (e.g., fixed ΔT, fixed thickness).

It's important to consider R-value for the entire insulation ***assembly***, not the individual materials.

Insulation behaves differently at different temperatures. As ΔT increases, thermal resistance decreases; as ΔT decreases, thermal resistance increases.

R-values incorporate all modes of heat transfer, even though we typically model it as primarily conduction.

Once known for a given insulation assembly, R-values can be used as inputs to building simulation tools to calculate annual heat loss.

It's important to understand that R-values have units. It is assumed that insulation products in the US display R-values in English Units, while insulation products in other countries display R_{SI}-values in Metric Units.

R-values and Insulation

What does it mean that insulation behaves differently at different temperatures?

- The R-value that is noted on the insulation label has been tabulated through a standardized testing process to indicate performance at typical building temperatures.
- This value works well as a constant value to calculate heat transfer through a wall.

What is the insulation “assembly”? And how is that R-value determined?

- More on this in another episode.
- The wall assembly consists of the various layers of materials in the wall.

Different types of insulation

- More on this in another episode.
- R-value is not the only consideration when selecting a type of insulation.

Questions or comments?

Please email SolarDecathlon@nrel.gov

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References

1. Bianchi, Marcus. "So You Think You Know How Insulation Works," BuildingEnergy Magazine, vol. 32, number 1, page 14 (Spring 2014).
    a. https://nesea.org/sites/default/files/Spring14_BE-MagFINAL.pdf

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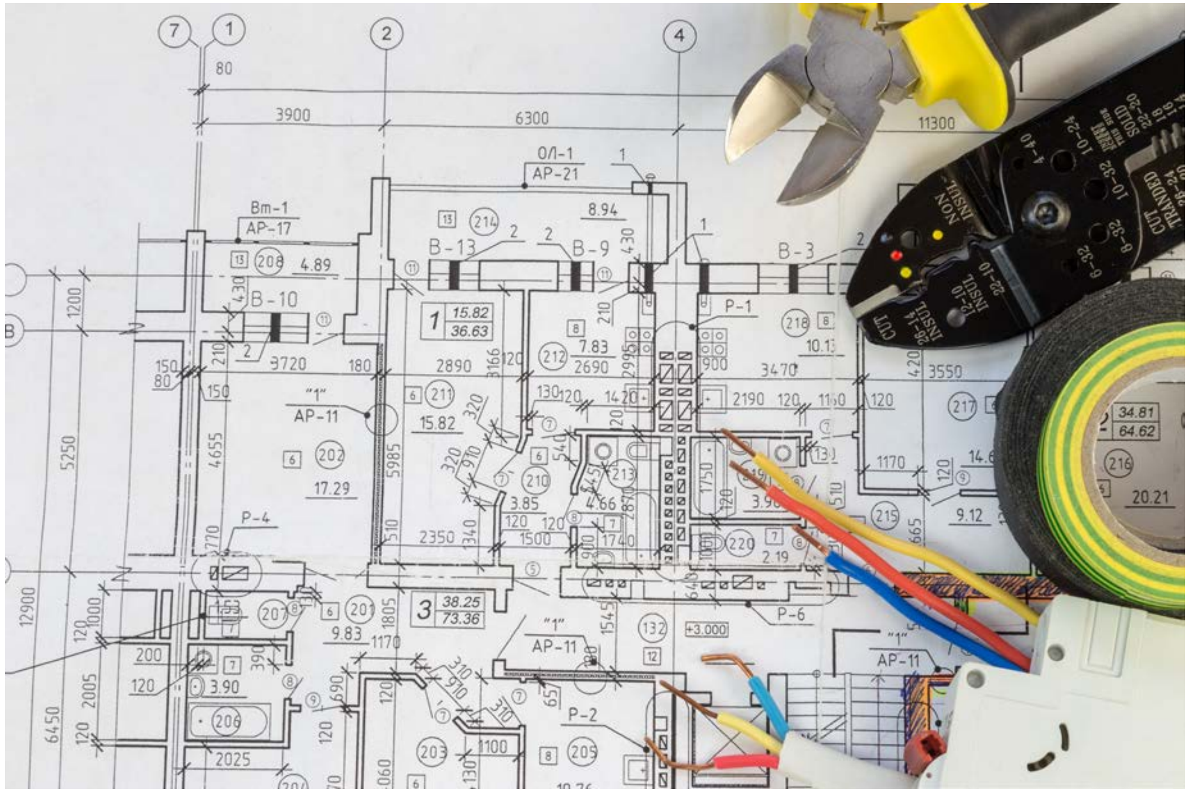
Calculating Area



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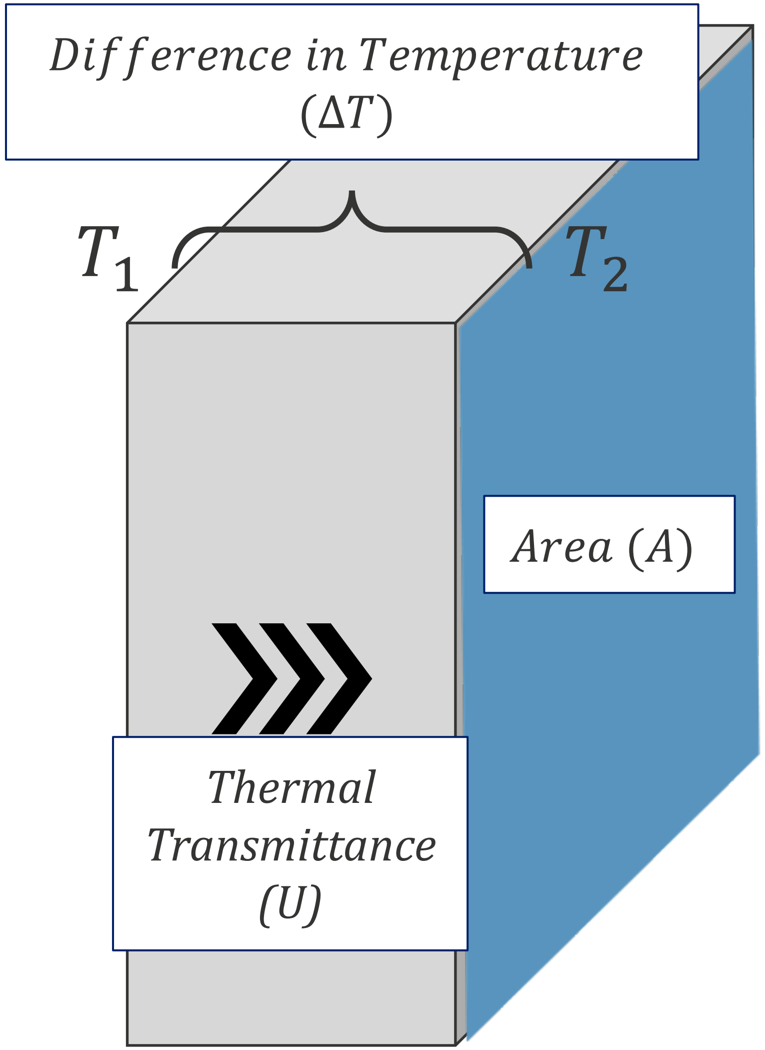
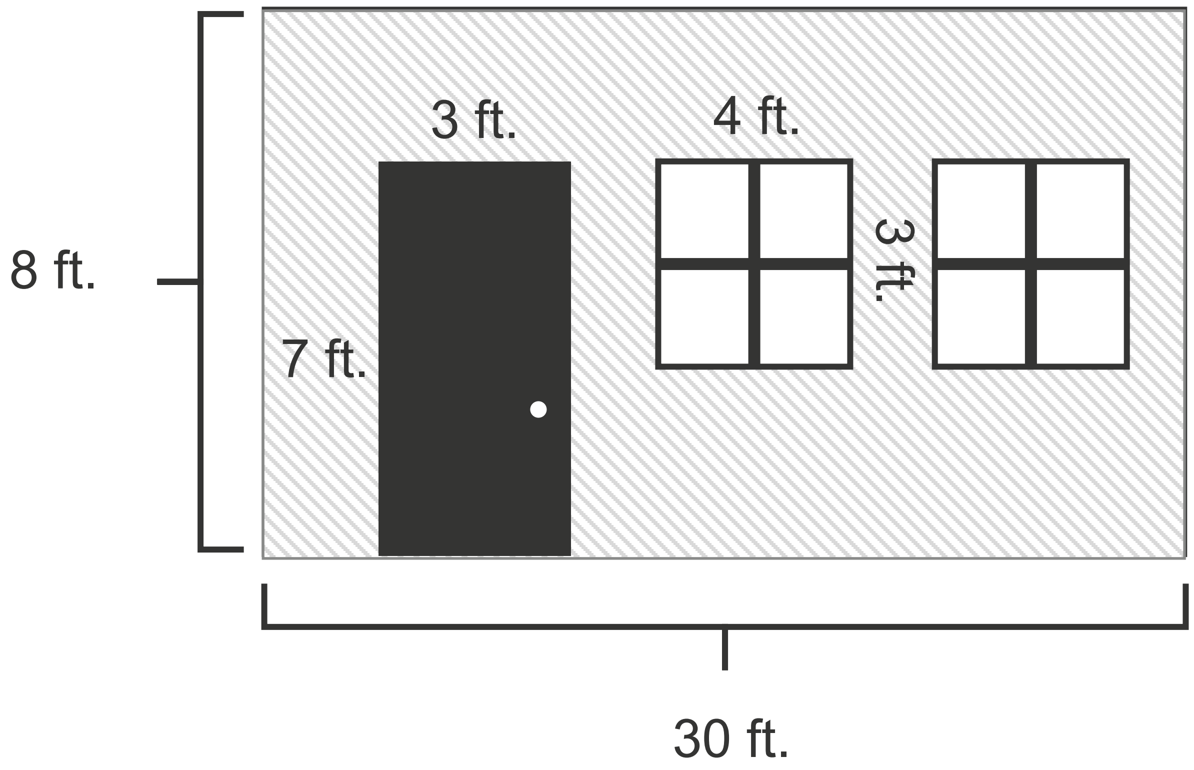
Fourier's Law of Heat Transfer

$$\dot{Q} = U \cdot A \cdot \Delta T$$

Cross-Sectional Area





Not to Scale

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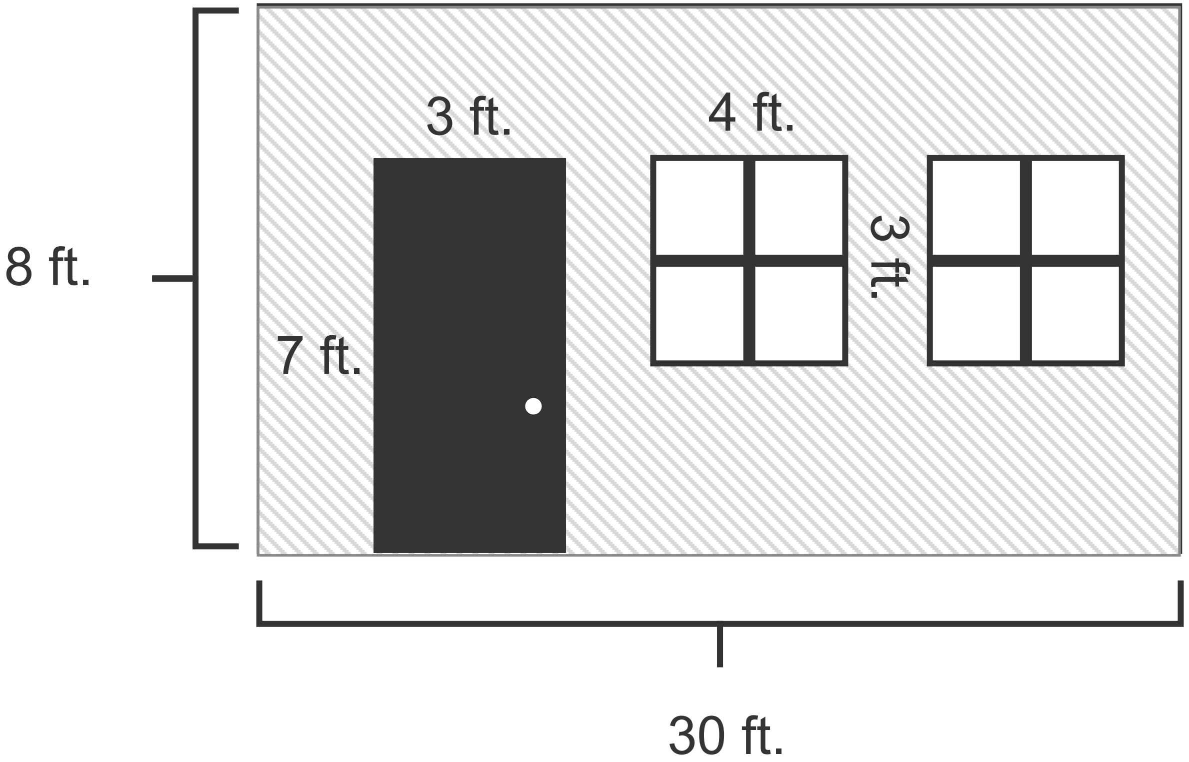
Different components of the building envelope have different U-factors, so we need to consider them separately.

Total Area of Wall | Area of 2 Windows | Area of 1 Door

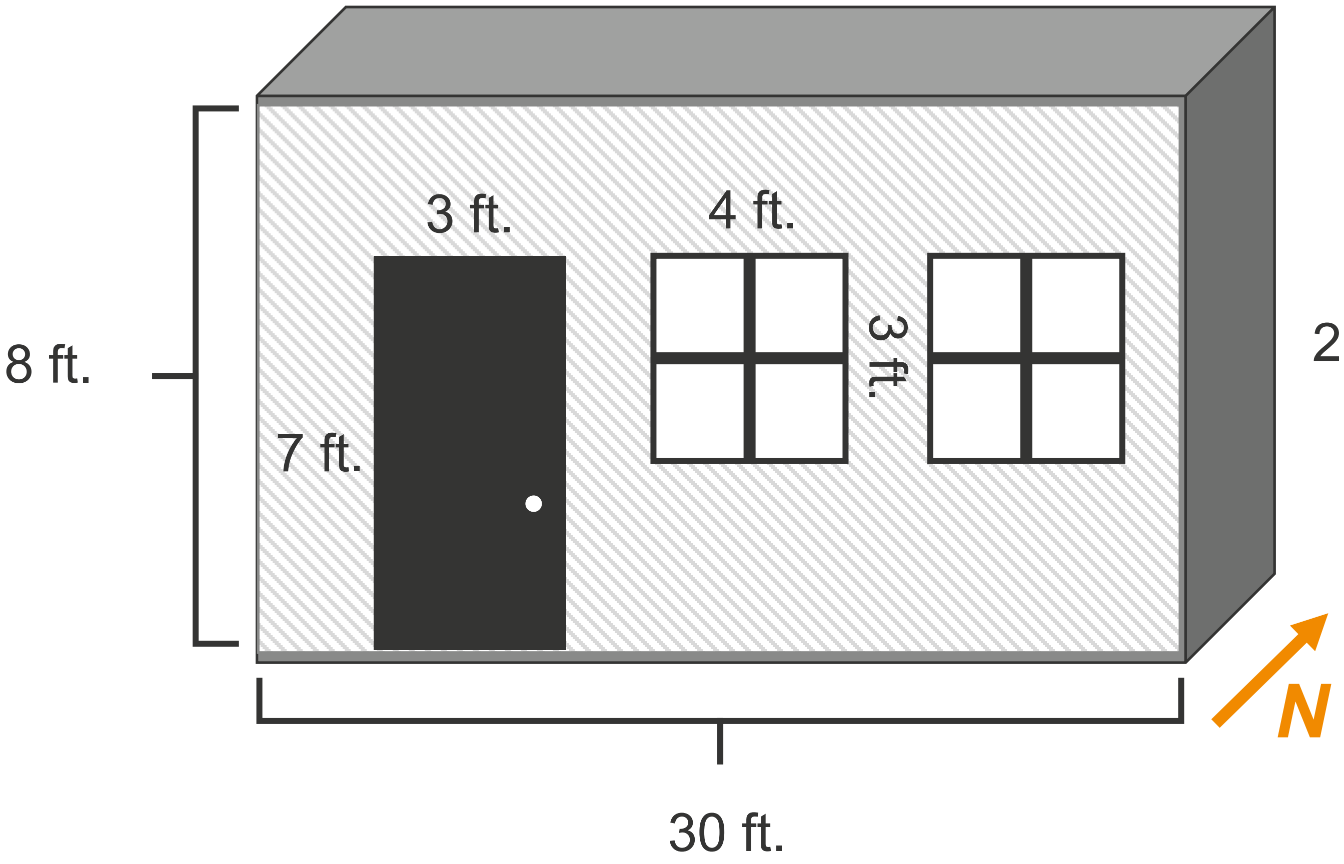


$$A_{Front\ Wall} = (30\ ft \cdot 8\ ft) - 2(3\ ft \cdot 4\ ft) - (3\ ft \cdot 7ft)$$

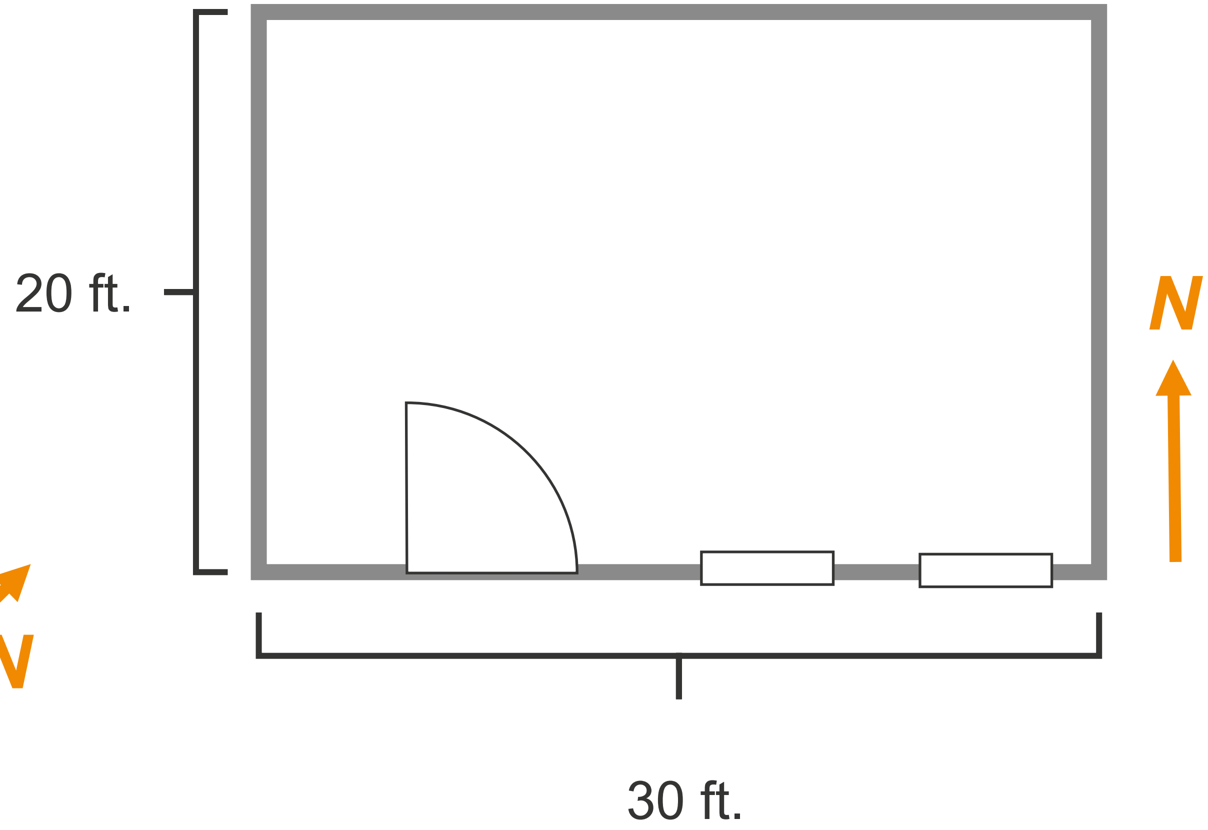
$$A_{Front\ Wall} = 240\ ft^2 - 2(12\ ft^2) - 21\ ft^2$$

$$A_{Front\ Wall} = 195\ ft^2$$

Not to Scale



Floor Plan



Not to Scale

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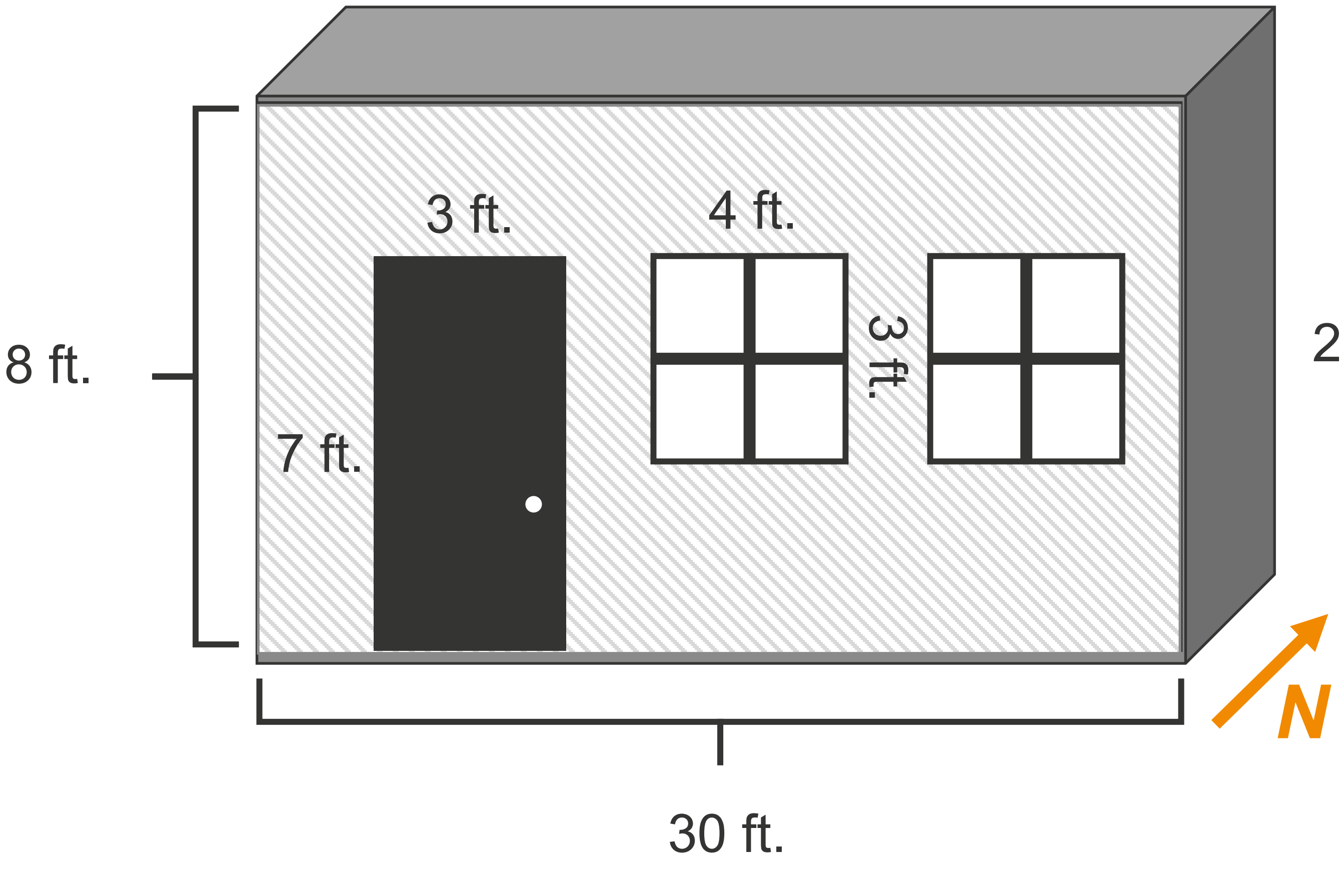
$$A_{Front\ Wall} = \mathbf{195\ ft^2}$$

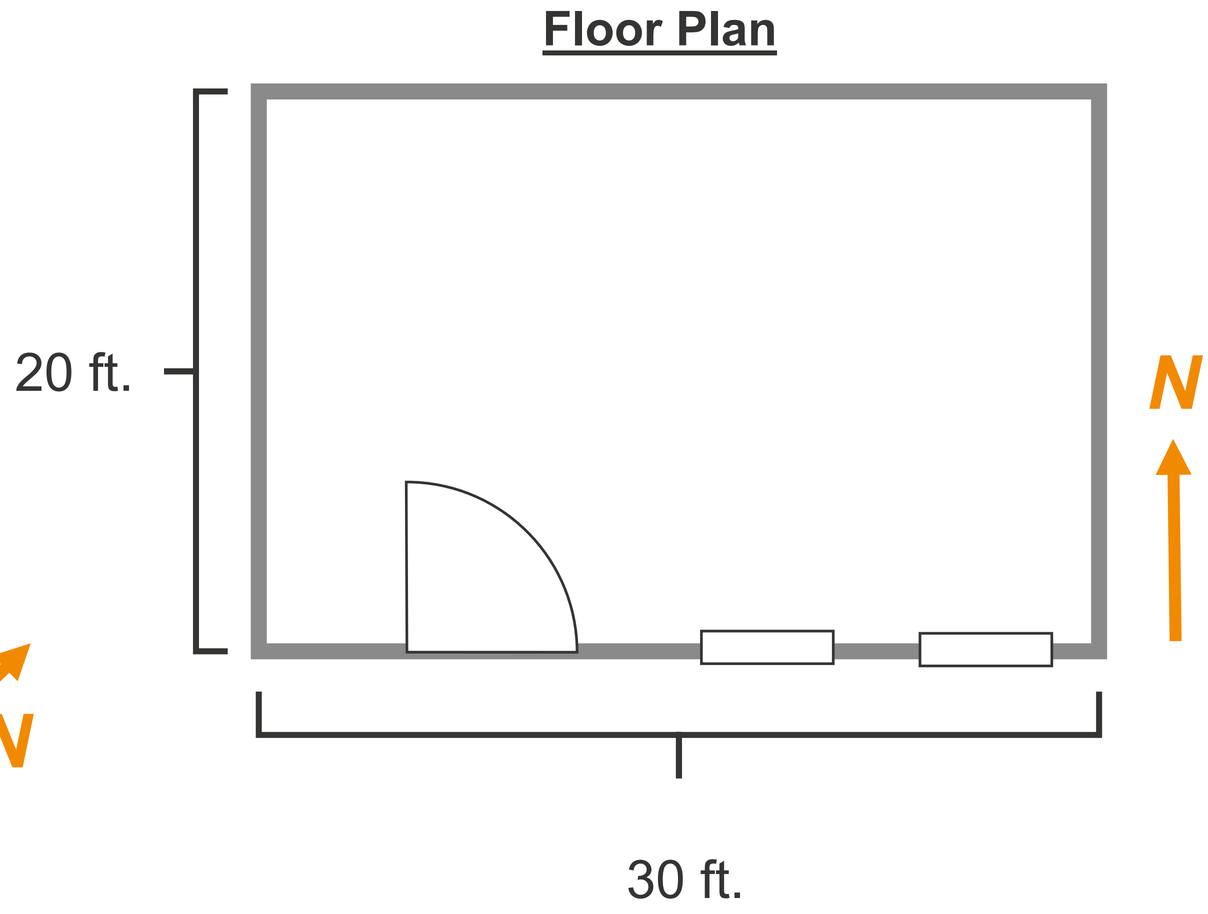
$$A_{Side\ Walls} = 2(20\ ft \cdot 8\ ft)$$

$$A_{Side\ Walls} = \mathbf{320\ ft^2}$$

$$A_{Back\ Wall} = (30\ ft \cdot 8\ ft)$$

$$A_{Back\ Wall} = \mathbf{240\ ft^2}$$





Not to Scale

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$A_{Front\ Wall} = \mathbf{195\ ft^2}$ **+**

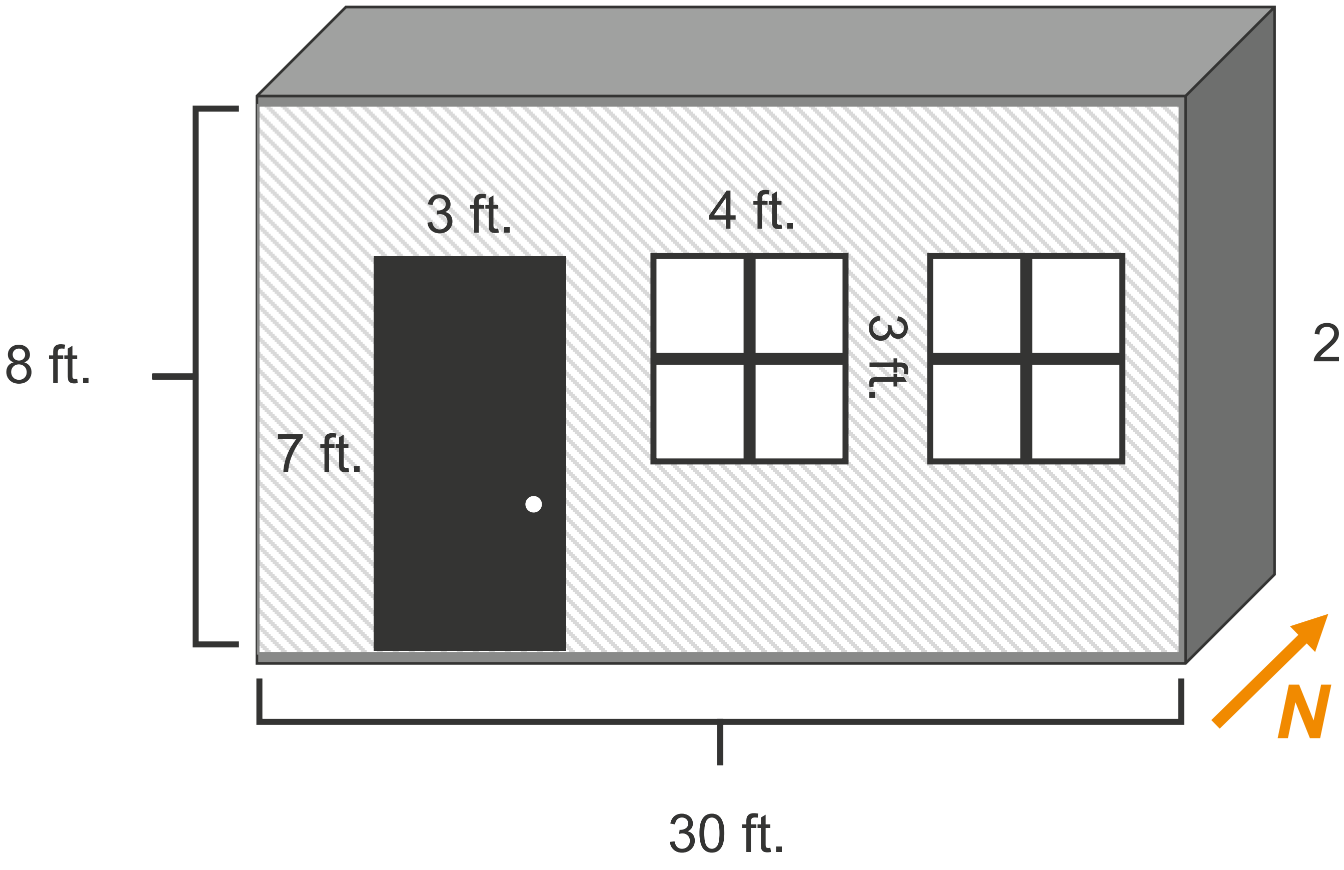
$A_{Side\ Walls} = 2(20\ ft \cdot 8\ ft)$

$A_{Side\ Walls} = \mathbf{320\ ft^2}$ **+**

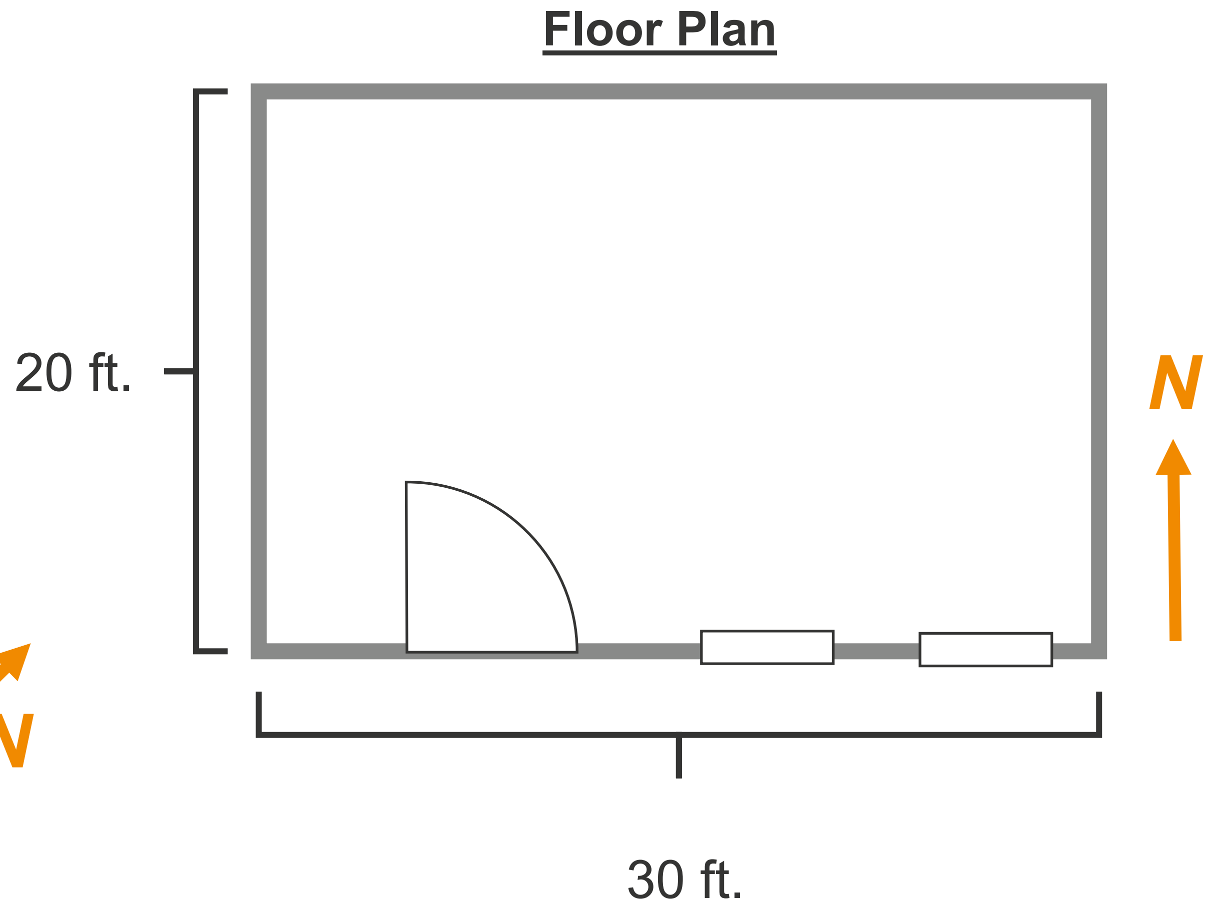
$A_{Back\ Wall} = (30\ ft \cdot 8\ ft)$

$A_{Back\ Wall} = \mathbf{240\ ft^2}$ →

$A_{Net\ Wall} = \mathbf{755\ ft^2}$

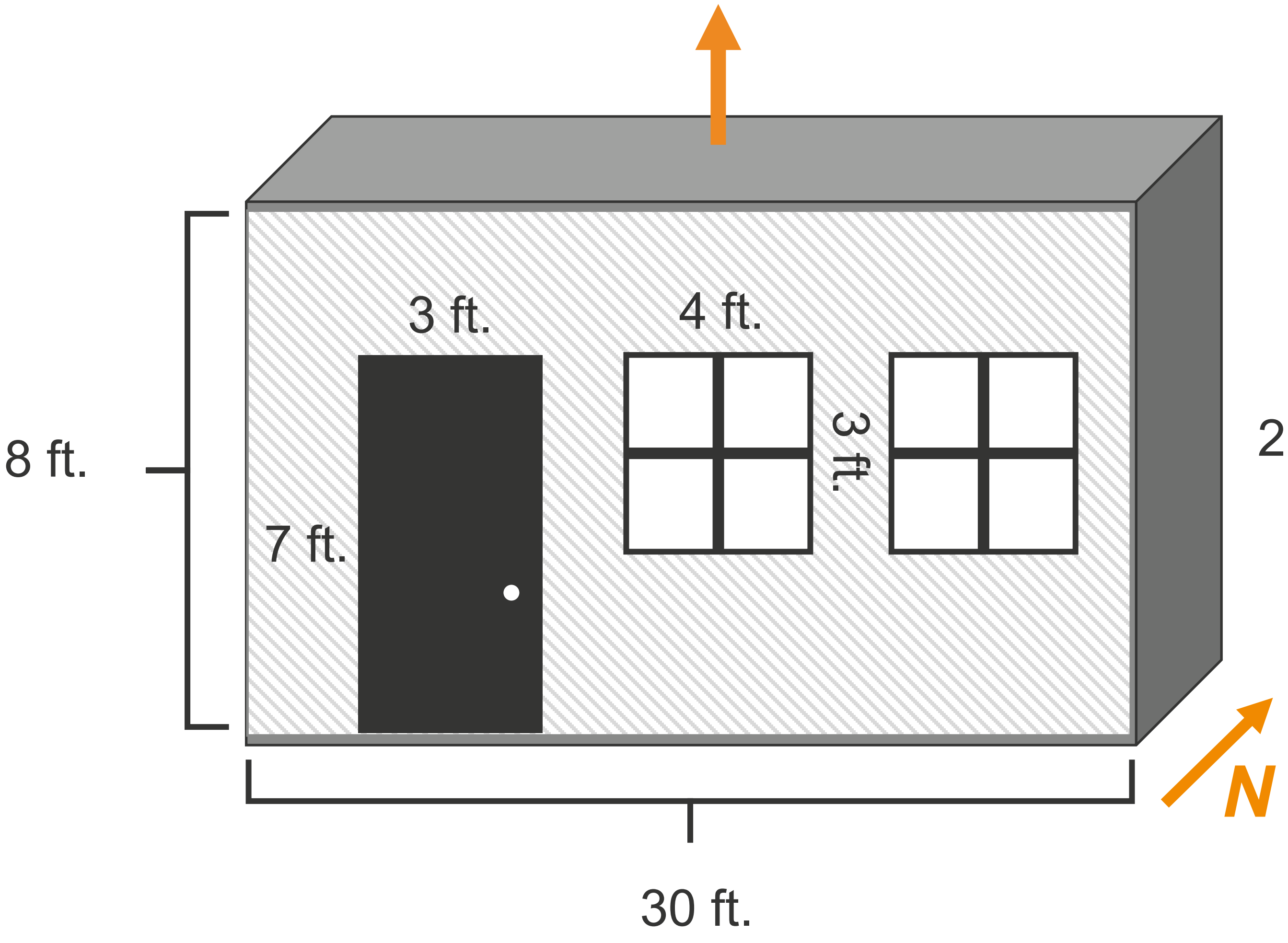


Not to Scale



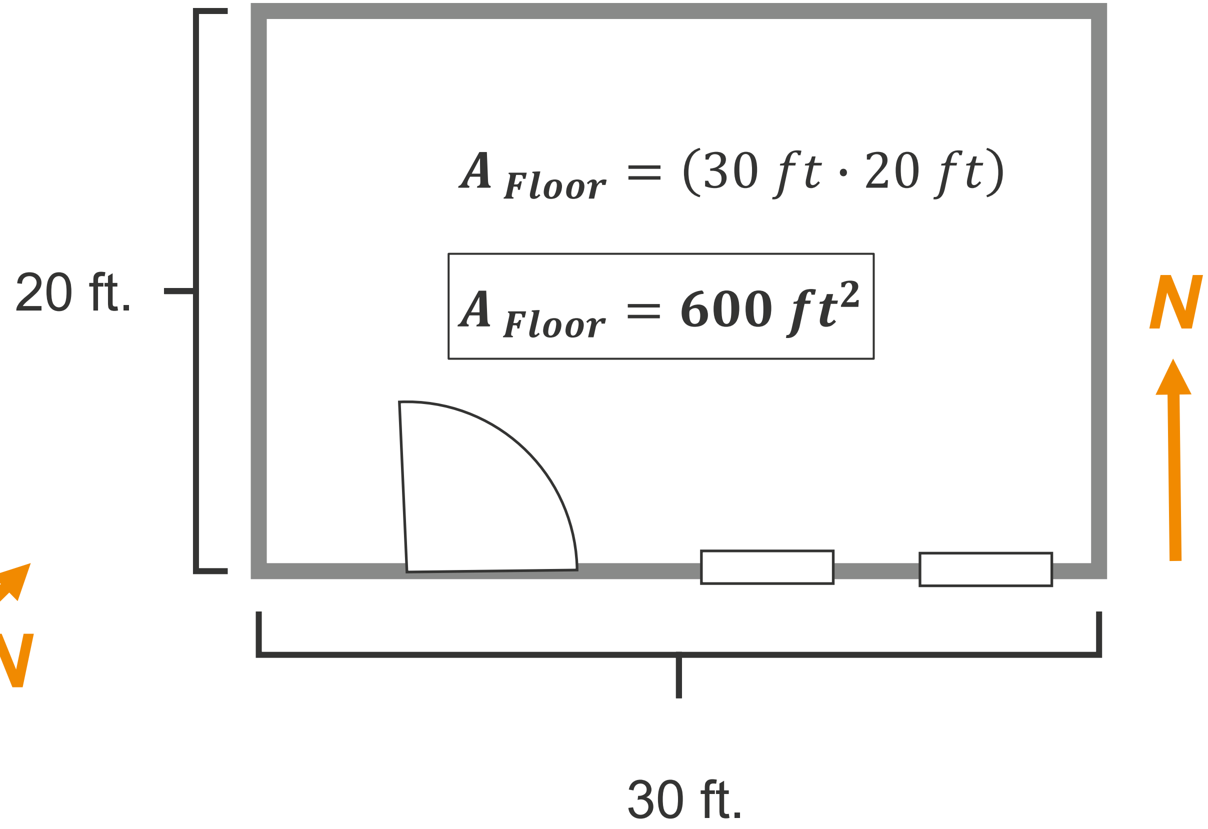
$$A_{Ceiling} = 600\ ft^2$$

$$A_{Net\,Wall} = 755\ ft^2$$

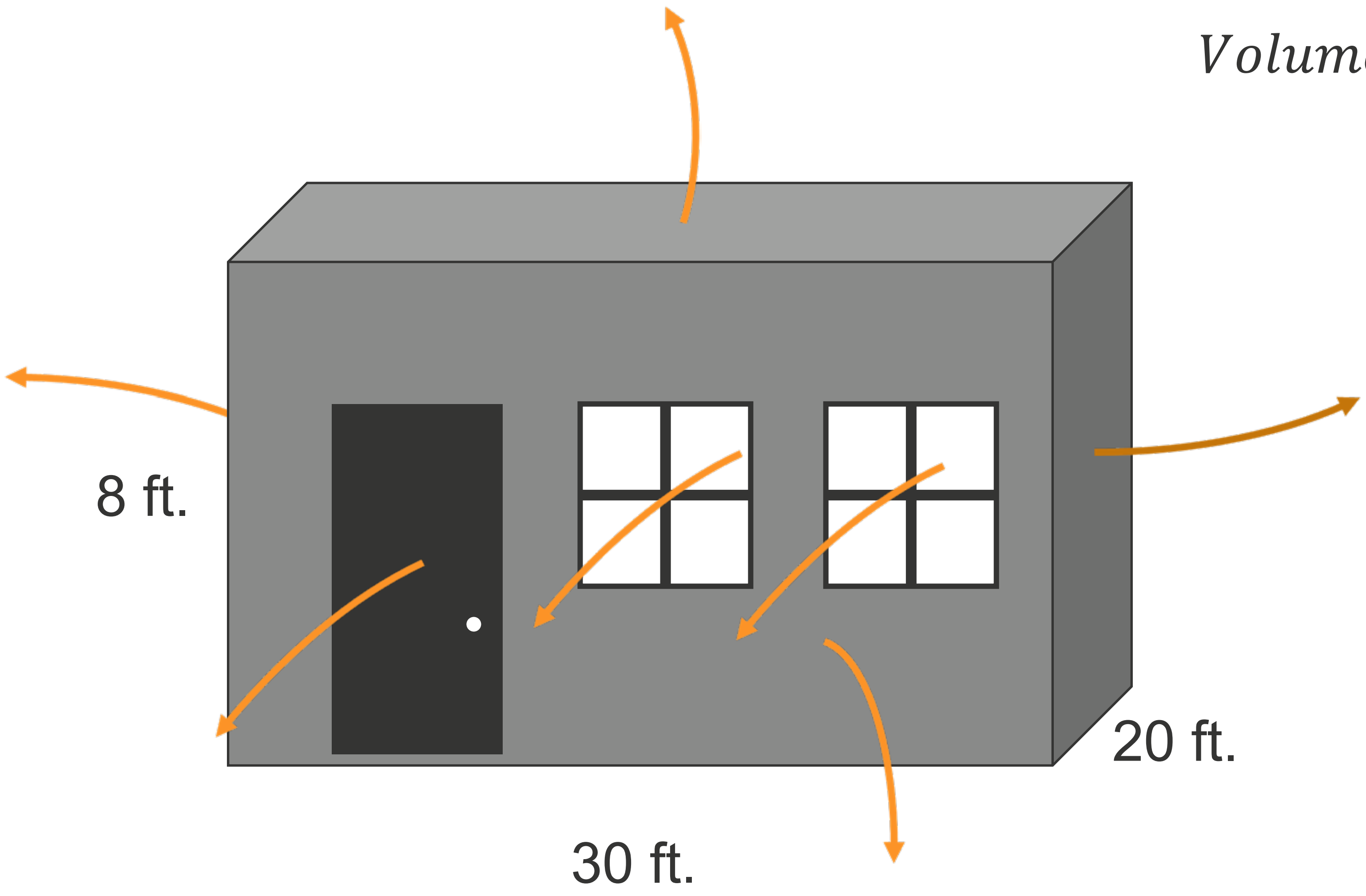


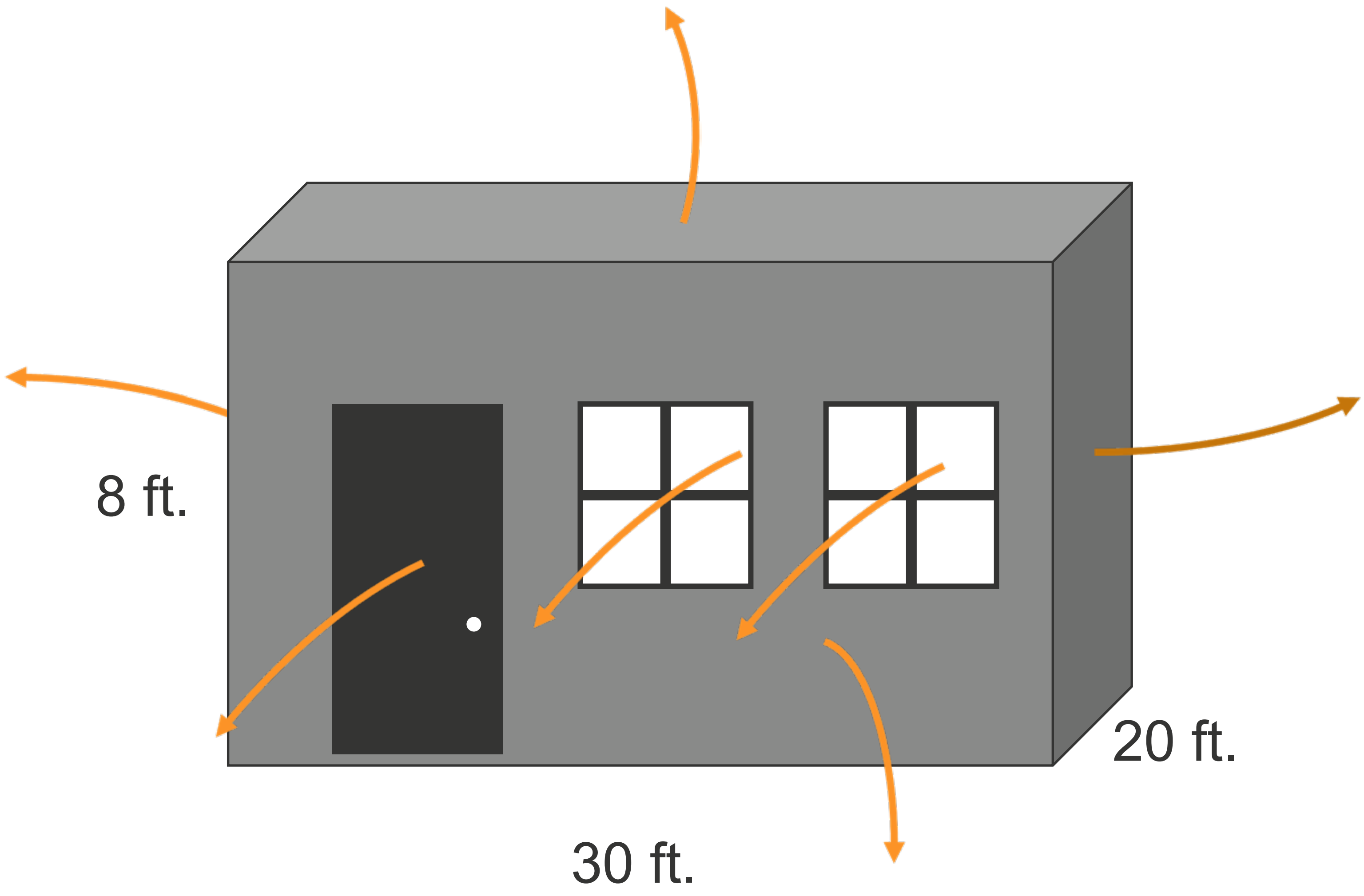
Not to Scale

Floor Plan



$$Volume = 30\ ft \cdot 20\ ft \cdot 8\ ft = 4800\ ft^3$$





Key Consideration

Walls, floors, roof, doors, windows must be considered separately when calculating heat loss.

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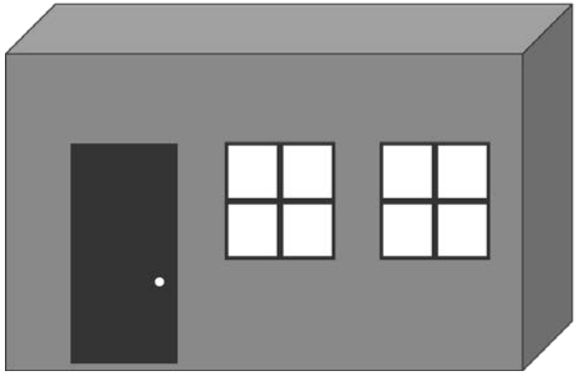
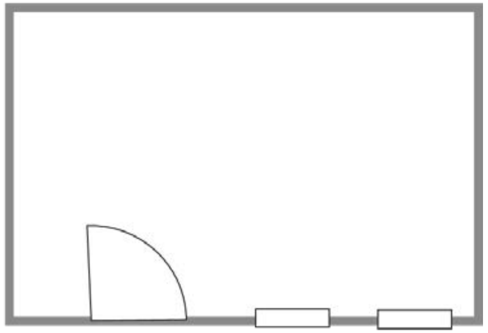


Floor Plan



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1									Climate Data:			Temperature (F)			
2		Geometry Inputs								HDD	CDD	Design	Inside		
3		length	30	ft		volume	4,800	ft3		6000		-2	65		
4		width	20	ft		area	600	ft2		6000					
5		height	8	ft											
6															
7							window	window	window	window		net area	Window to Wall Ratio		
8			area	length	height	area	width	height	number	area	door (ft2)	(ft2)	(%)		
9			wall1	30	8	240	3	4	2	24	21	195	10.00		
10			wall2	20	8	160			0	0		160	0.00		
11			wall3	30	8	240			0	0		240	0.00		
12			wall4	20	8	160			0	0		160	0.00		
13			**total wall area**							**24**	**21**	**755**	**3.00**		
14															
15															

Sheet1

Questions or comments?

Please email SolarDecathlon@nrel.gov

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National Renewable Energy Laboratory

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Building the Next Generation

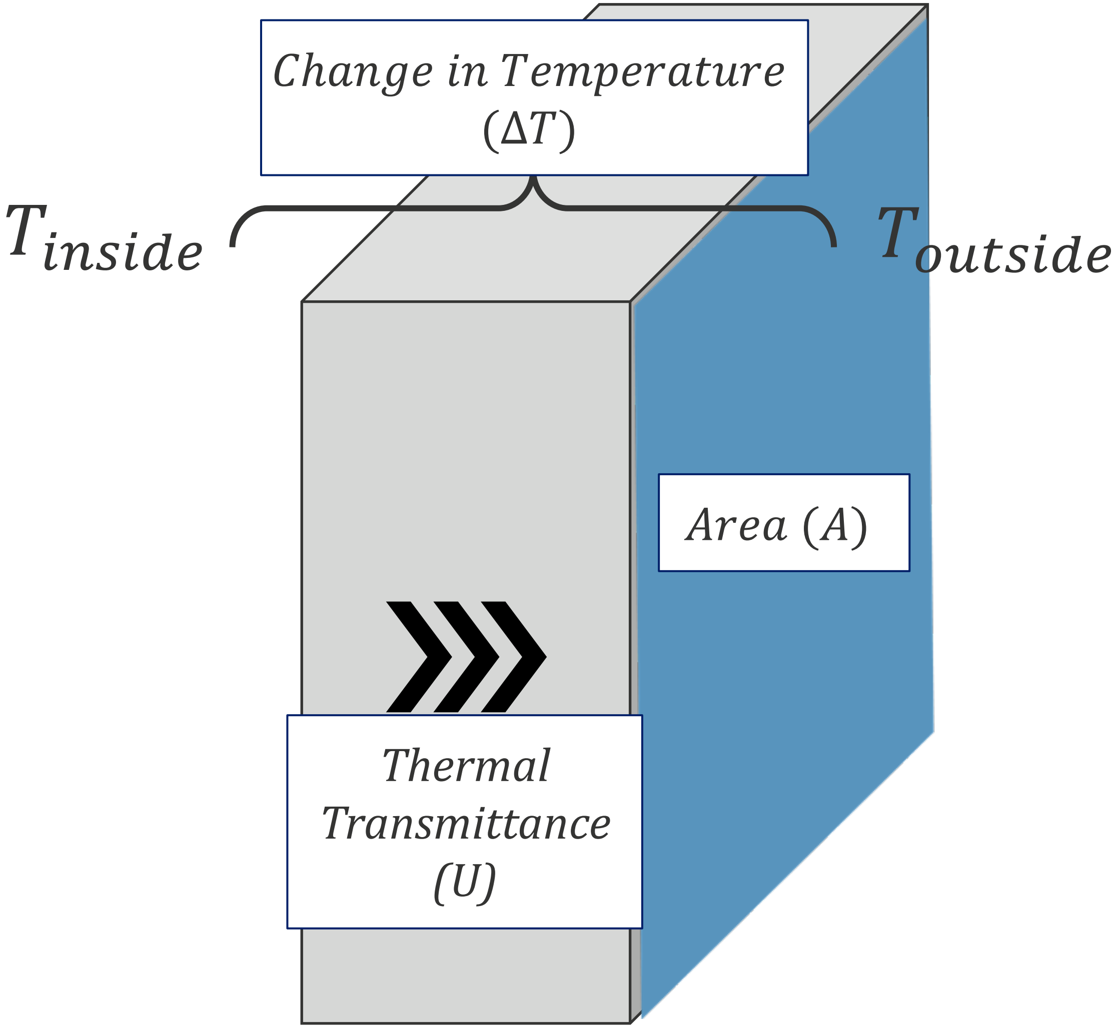
Building Science Education for Solar Decathlon

Temperature and Weather Data

Photo by Warren Gretz, NREL

Episode ID: 0306-220829

Heat Transfer Through the Building Envelope



$$\dot{Q} = U \cdot A \cdot \Delta T$$

$$\Delta T = T_{outside} - T_{inside}$$

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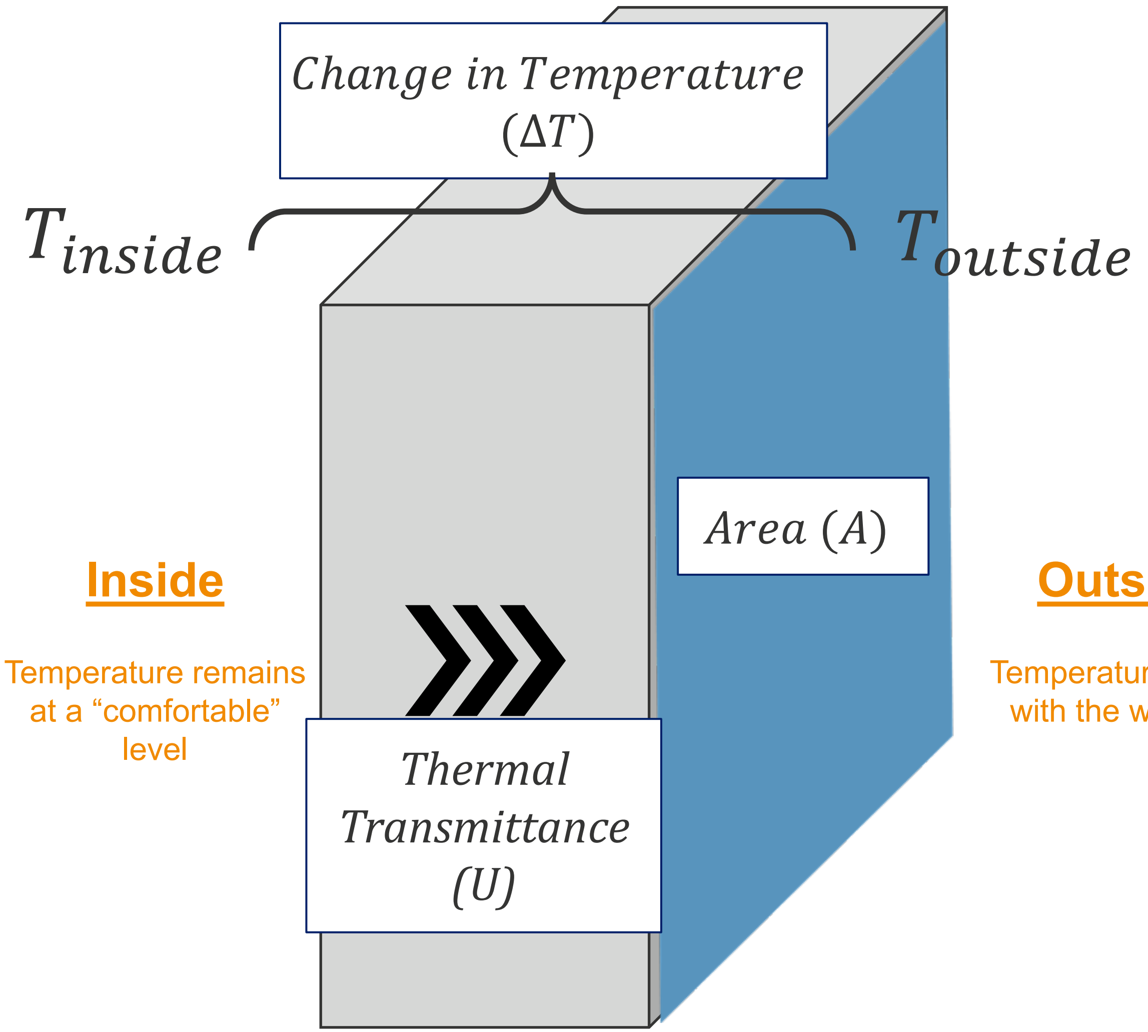
Heat Transfer Through the Building Envelope



Inside

Temperature remains at a “comfortable” level

Outside

Temperature varies with the weather

$$\dot{Q} = U \cdot A \cdot \Delta T$$

$$If \;\; T_{inside} = T_{outside}$$

$$\Delta T = 0$$

$$\dot{Q} = U \cdot A \cdot 0$$

$$\dot{Q} = 0$$

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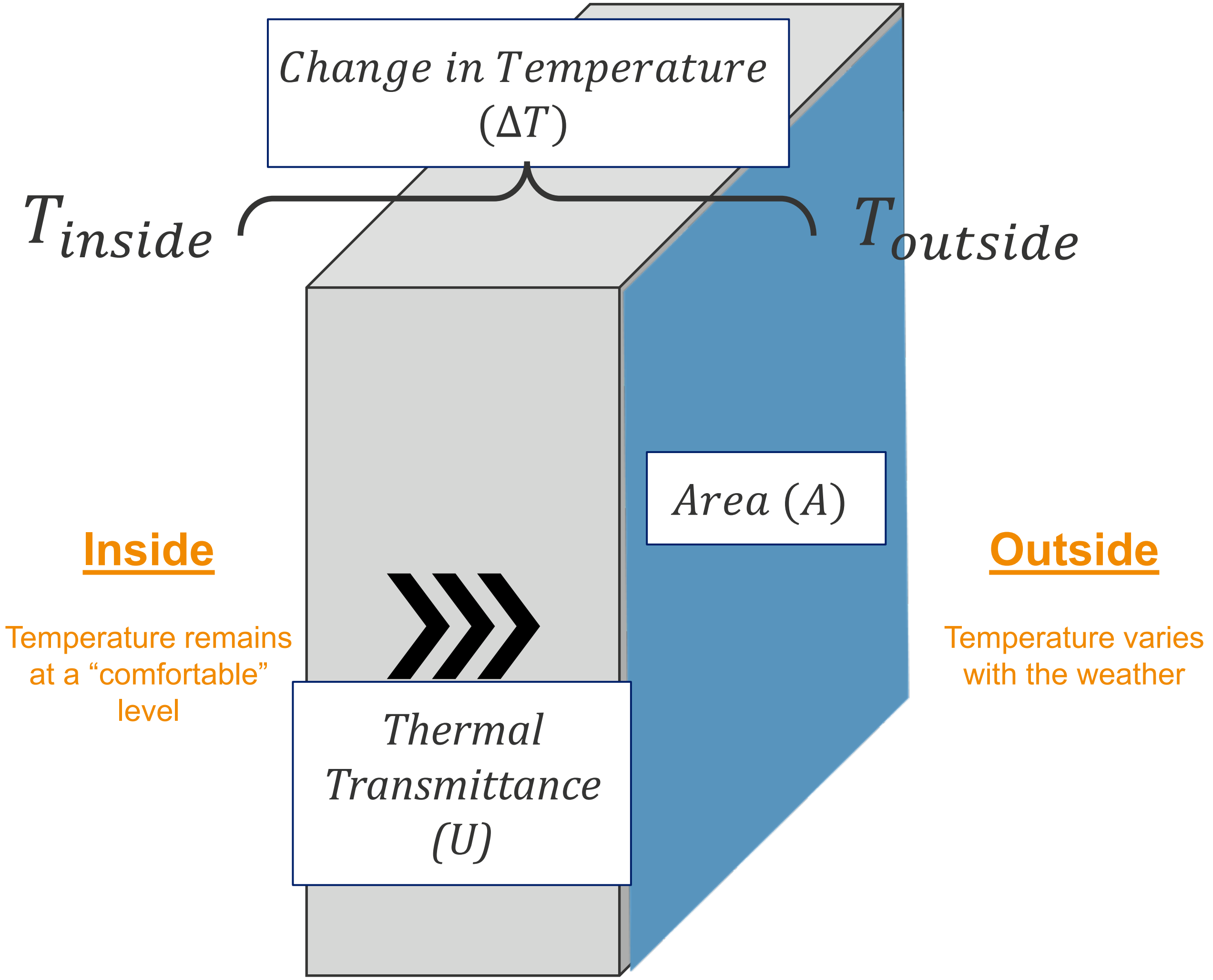
Heat Transfer Through the Building Envelope



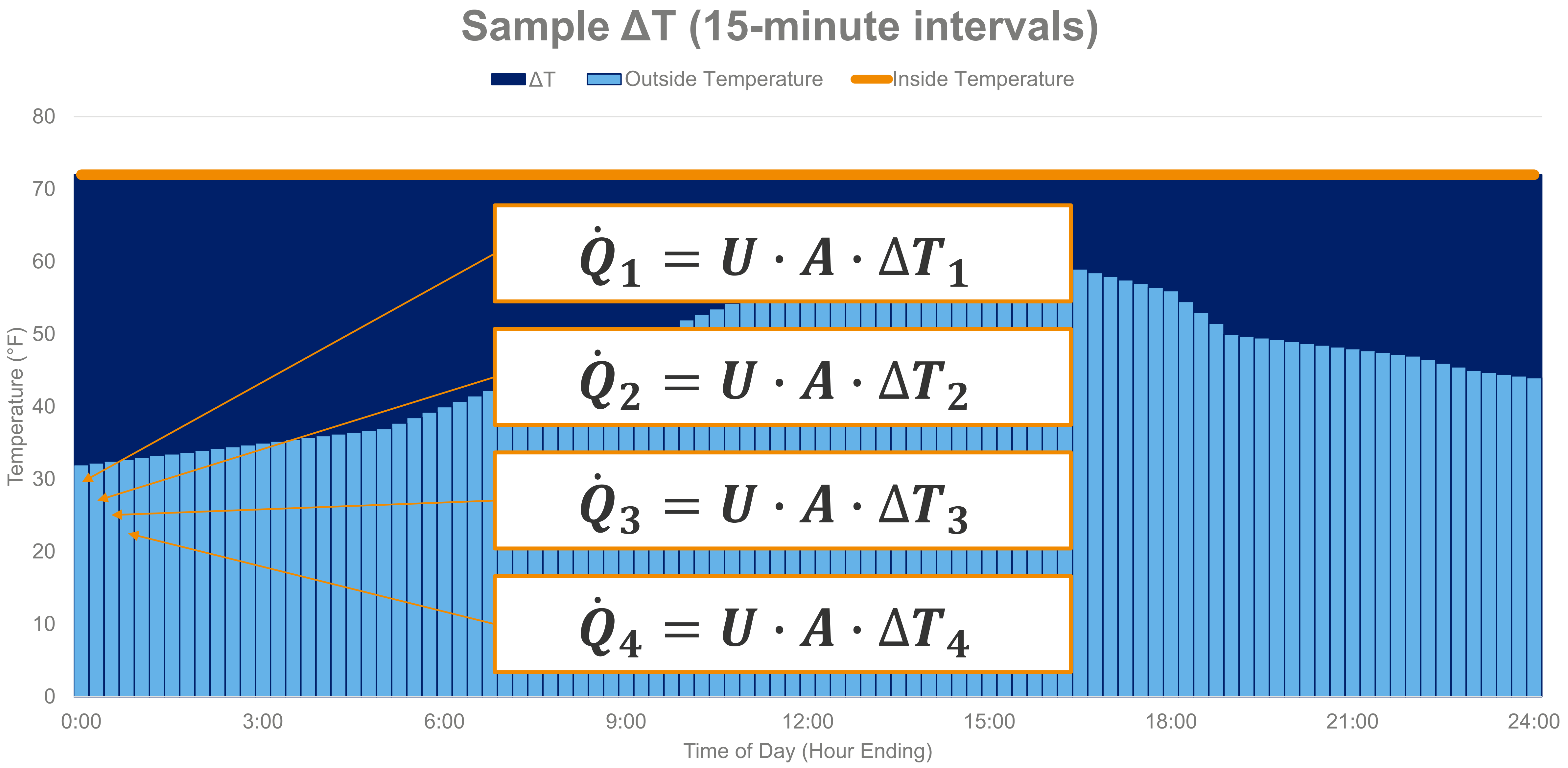
$$\dot{Q} = U \cdot A \cdot \Delta T$$

If $T_{inside} \gg T_{outside}$

ΔT ***increases,***
so $\dot{Q}$ ***also increases***

Temperature setback:

Reduce T_{inside} ***in order to reduce*** ΔT



$$\dot{Q}_1 = U \cdot A \cdot \Delta T_1$$

$$\dot{Q}_2 = U \cdot A \cdot \Delta T_2$$

$$\dot{Q}_3 = U \cdot A \cdot \Delta T_3$$

$$\dot{Q}_4 = U \cdot A \cdot \Delta T_4$$

$$\dot{Q}_n = U \cdot A \cdot \Delta T_n$$

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Weather Data

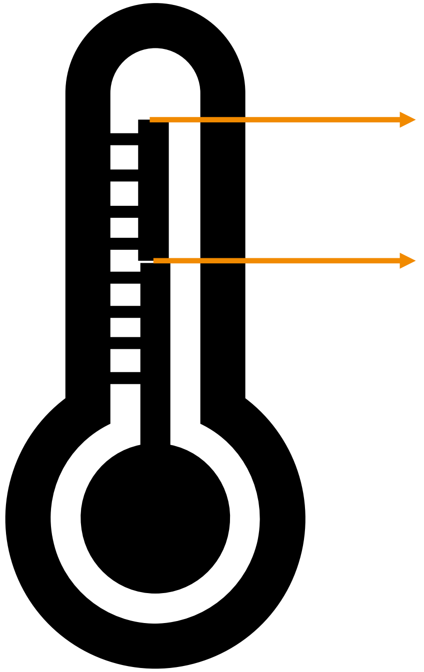
	Outside Temperature (°F)	Inside Temperature (°F)	Delta T (ΔT) (°F)
12:00 AM – 01:00 AM	35	72	37

Hourly weather data is collected at many locations and is available from numerous sources.

This data is called Typical Meteorological Year, or "TMY" data.

TMY data represents a typical year of weather based on actual data in that location for a 30-year period.

This is not the same as the 30-year average.



$$\frac{\textit{Daily High Temp.} + \textit{Daily Low Temp.}}{2} \cong \textit{Daily Average Temp.}$$

$$\dot{Q} = U \cdot A \cdot \Delta T$$

ΔT can be represented as the average inside temperature minus the average outside temperature

Assume U and A are constant for a given wall

$$\dot{Q} \cdot t = Q$$

The rate of heat transfer ($\dot{Q}$), times a period of time (t) equals the amount of heat transferred during that time (Q)

$$Q = U \cdot A \cdot \Delta T \cdot t$$

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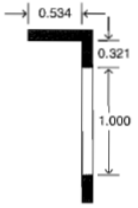
Boulder, CO

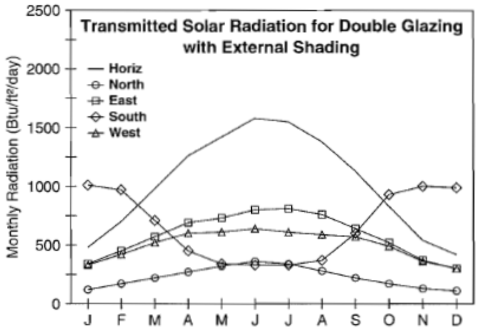
WBAN NO. 94018

LATITUDE: 40.02° N
LONGITUDE: 105.25° W
ELEVATION: 5361 feet
MEAN PRESSURE: 12.1 psia

STATION TYPE: Primary



Shading Geometry (Not to Scale)



Average Incident Solar Radiation (Btu/ft²/day), Uncertainty ±9%

Orientation		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Horizontal	Global	750	1030	1390	1750	1960	2160	2120	1890	1580	1200	830	670	1450
	Std.Dev.	52	51	96	115	152	164	116	115	119	95	46	41	54
	Minimum	660	880	1170	1510	1530	1810	1780	1590	1250	990	730	610	1340
	Maximum	850	1110	1570	1940	2270	2460	2350	2100	1760	1340	900	740	1520
	Diffuse	280	380	520	630	710	670	650	580	450	340	290	250	480
	Clear-Day Global	950	1310	1830	2330	2650	2770	2680	2390	1950	1440	1020	840	1850
North	Global	200	260	350	440	550	630	580	460	350	270	210	180	370
	Diffuse	200	260	350	420	480	490	480	430	350	270	210	180	340
	Clear-Day Global	170	230	310	410	590	720	650	460	320	250	190	160	370
East	Global	550	710	910	1110	1200	1320	1340	1220	1020	820	590	490	940
	Diffuse	250	330	430	520	570	570	570	520	420	340	270	220	420
	Clear-Day Global	750	960	1240	1460	1570	1590	1560	1460	1270	1020	780	680	1190
South	Global	1370	1410	1300	1110	890	810	850	1020	1270	1460	1370	1330	1180
	Diffuse	360	430	500	540	540	520	520	510	460	410	370	330	460
	Clear-Day Global	2060	2100	1920	1470	1080	920	980	1270	1690	2000	2050	2010	1630
West	Global	520	680	840	980	1020	1070	1010	970	920	780	570	480	820
	Diffuse	250	330	440	530	580	590	570	520	430	340	270	220	420
	Clear-Day Global	750	960	1240	1460	1570	1590	1560	1460	1270	1020	780	680	1190

Average Transmitted Solar Radiation (Btu/ft²/day) for Double Glazing, Uncertainty ±9%

Orientation		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Horizontal	Unshaded	480	700	980	1260	1420	1580	1550	1380	1130	830	540	420	1020
North	Unshaded	140	180	240	300	360	400	370	310	240	190	150	120	250
	Shaded	120	170	220	270	320	360	340	280	220	170	130	110	230
East	Unshaded	370	500	650	790	860	950	960	880	730	580	410	330	670
	Shaded	340	450	570	690	730	800	810	760	640	520	370	300	580
South	Unshaded	1030	1040	900	710	540	470	500	640	850	1050	1030	1010	810
	Shaded	1010	970	710	450	340	330	330	370	600	930	1000	990	670
West	Unshaded	360	470	590	690	720	760	710	690	650	550	390	330	580
	Shaded	330	420	520	600	610	640	610	590	570	490	360	300	500

Average Climatic Conditions

Element	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Temperature (°F)	29.7	33.4	39.0	48.2	57.2								
Daily Minimum Temp	16.1	20.2	25.8	34.5	43.6								
Daily Maximum Temp	43.2	46.6	52.2	61.8	70.8								
Record Minimum Temp	-25.0	-30.0	-11.0	-2.0	22.0								
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]								
HDD, Base 65°F	1094	885	806	504	253	71	0	0	144	429	780	1054	6020
CDD, Base 65°F	0	0	0	0	11	128	267	203	63	7	0	0	679
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Wind Speed (mph)	8.3	8.5	9.2	9.8	9.2	8.6	8.1	7.8	7.7	7.6	7.8	8.0	8.4
Clearness Index, Kt	0.55	0.56	0.56	0.57	0.56	0.59	0.59	0.58	0.58	0.58	0.55	0.54	0.57

Average Incident Illuminance (klux-hr) for Mostly Clear/Mostly Cloudy Conditions, Uncertainty ±9%

Orientation	March					June					September					December				
	9am	11am	1pm	3pm	5pm	9am	11am	1pm	3pm	5pm	9am	11am	1pm	3pm	5pm	9am	11am	1pm	3pm	5pm
Horizontal	42/28	73/51	82/59	65/44	27/18	51/34	84/63	101/78	95/67	68/46	31/18	69/45	84/60	77/52	47/31	16/10	43/29	48/34	29/20	2/2
North	10/10	13/15	15/17	13/14	8/7	18/14	14/16	16/17	16/17	14/14	8/7	13/14	14/16	14/15	10/11	5/5	10/10	10/11	8/8	1/1
East	81/38	56/37	15/17	13/14	8/7	86/46	70/51	29/26	16/17	14/14	77/28	71/41	26/23	14/15	10/11	47/18	41/24	10/11	8/8	1/1
South	44/24	74/46	85/55	67/39	28/14	11/11	31/27	46/38	41/32	20/17	24/12	59/35	75/50	69/42	39/23	44/17	87/44	94/50	67/31	5/2
West	10/10	13/15	24/21	68/40	70/29	11/11	14/16	16/17	52/38	79/47	8/7	13/14	14/16	54/35	77/39	5/5	10/10	23/17	52/25	8/3
M. Clr (%hrs)	38	38	32	30	29	59	60	51	36	28	57	58	57	50	44	41	44	44	42	43

Cooling Degree Days

$\textit{If } T_{outside\ avg} < 65°\text{F},$
$\textit{it's called a Heating Degree Day (HDD)}$ → $\textit{If } T_{outside\ avg} > 65°\text{F},$
$\textit{it's called a Cooling Degree Day (CDD)}$

$$\Delta T \cdot t = \left(65°\text{F} - \frac{T_{high} + T_{low}}{2}\right) \cdot t$$

***HDD's and CDD's cannot be converted from English Units (°F) to SI Units (°C).

In SI units, the Base Temperature is 18°C, so you must recalculate.

HDD and CDD with Different Base Temperatures

HDD65

CDD65

HDD50

CDD50

GDD50

HDD and CDD work best…

When there are large temperature differences from inside to outside

In buildings that have limited thermal mass

When there is low humidity

(CDD only)

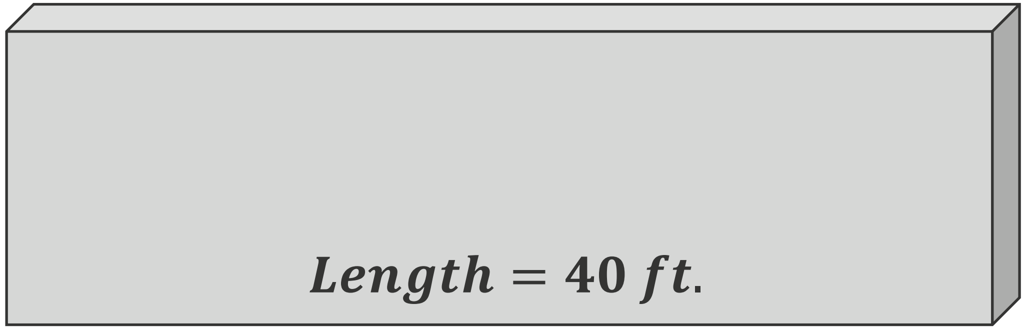
Degree Days are a way to model the Temperature term in Fourier's Law.

Models try to represent the physical phenomenon, but with assumptions that make them approximations.

Example

$Total\ Insulation = R12$

$HDD = 6100\ \frac{°F \cdot days}{year}$



$Height = 8\ ft.$

$$Q = U \cdot A \cdot \Delta T \cdot t$$

$$Q = U \cdot A \cdot HDD \longrightarrow A = 40\ ft \cdot 8\ ft = 320\ ft^2$$

$$Q = \frac{1}{R} \cdot A \cdot HDD$$

$$Q = \frac{320\ ft^2 \cdot 6100 \frac{°F \cdot days}{year}}{12 \frac{ft^2 \cdot °F \cdot hr}{Btu}}$$

How does this relate to Building Design?

If we want to reduce Q…

$$Q = U \cdot A \cdot \Delta T \cdot t \longrightarrow Q = \frac{1}{R} \cdot A \cdot \Delta T \cdot t \longrightarrow Q = \frac{1}{R} \cdot A \cdot HDD$$

Reduce A (i.e., build a smaller building)

Increase R (i.e., add more insulation)

Reduce HDD (i.e., move the building to another location – *NOT LIKELY*)

$$Q = \frac{320\ ft^2 \cdot 6100 \frac{°F \cdot days}{year} \cdot 24 \frac{hr}{day}}{24 \frac{ft^2 \cdot °F \cdot hr}{Btu}} = 1.95\ \frac{MMBtu}{year}$$

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Questions or comments?

Please email SolarDecathlon@nrel.gov

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National Renewable Energy Laboratory

David Brown

Accenture Federal Services

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Authors

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Paul Torcellini, Michael Young, and Marlena Praprost

National Renewable Energy Laboratory

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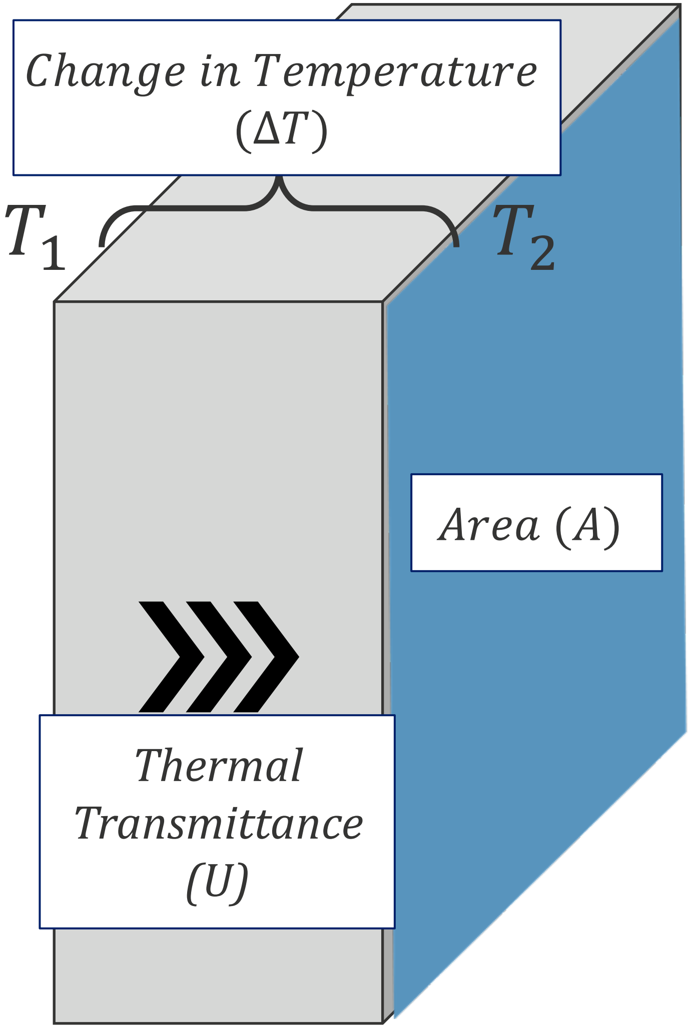
Building Science Education for Solar Decathlon

Calculating R-Value for a Wall (Part 1)

Photo by Dwight Stone

Episode ID: 0307-210202

Heat Transfer Through the Building Envelope



$$\dot{Q} = U \cdot A \cdot \Delta T$$

U-Factor: Thermal Transmittance

$$\frac{1}{U} = R$$

R-Value: Thermal Resistance

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Example: Concrete Wall with Foam Board Insulation

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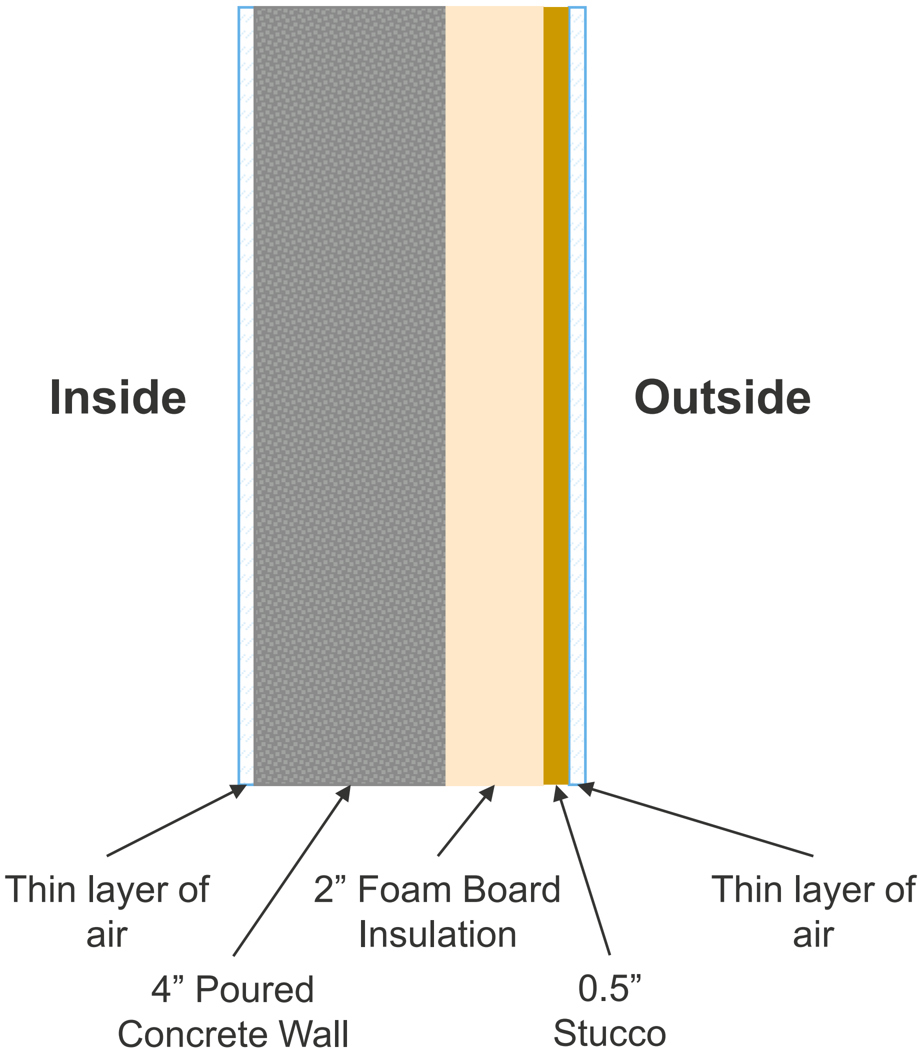
Example: Concrete Wall with Foam Board Insulation



- We want to determine the total R-value for the wall
- What are all the materials in the wall?
  - 4-inch poured concrete wall
  - 2-inch foam board insulation
  - ½-inch stucco exterior
  - Thin layers of air on the interior and exterior called the *Surface Films*

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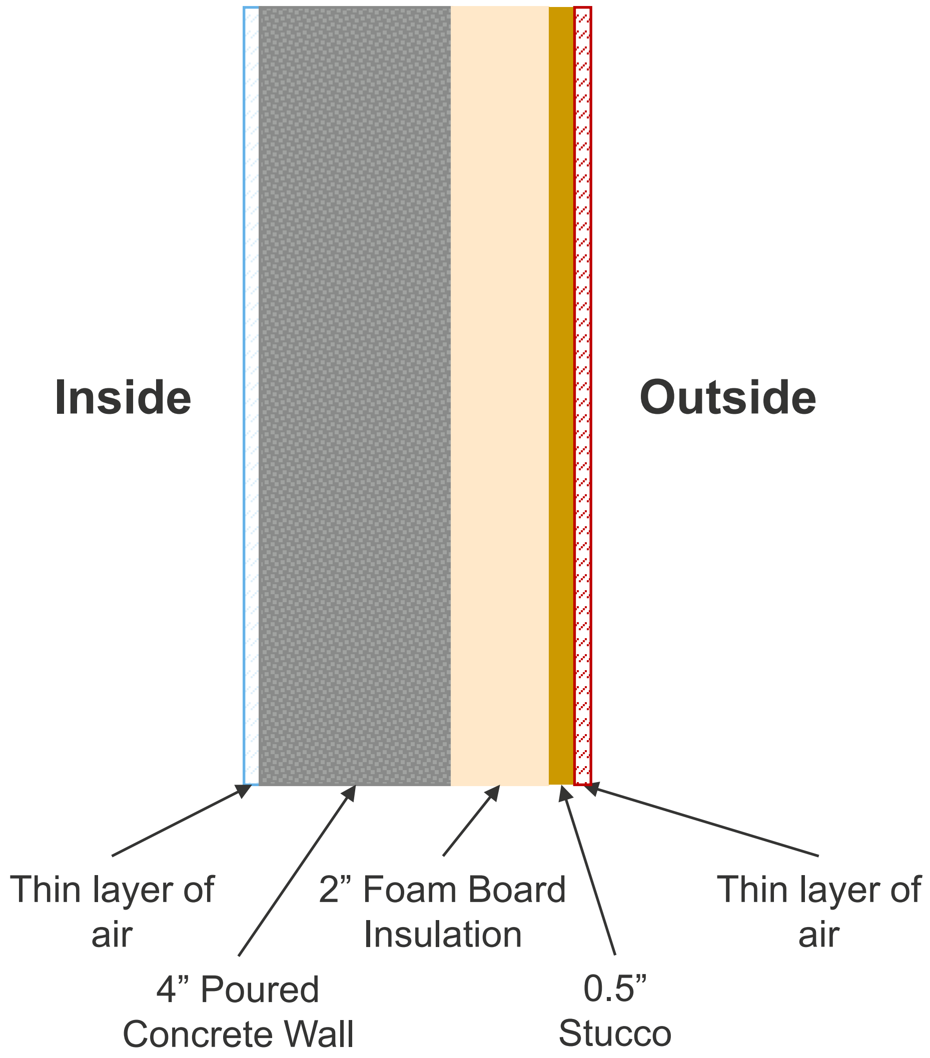
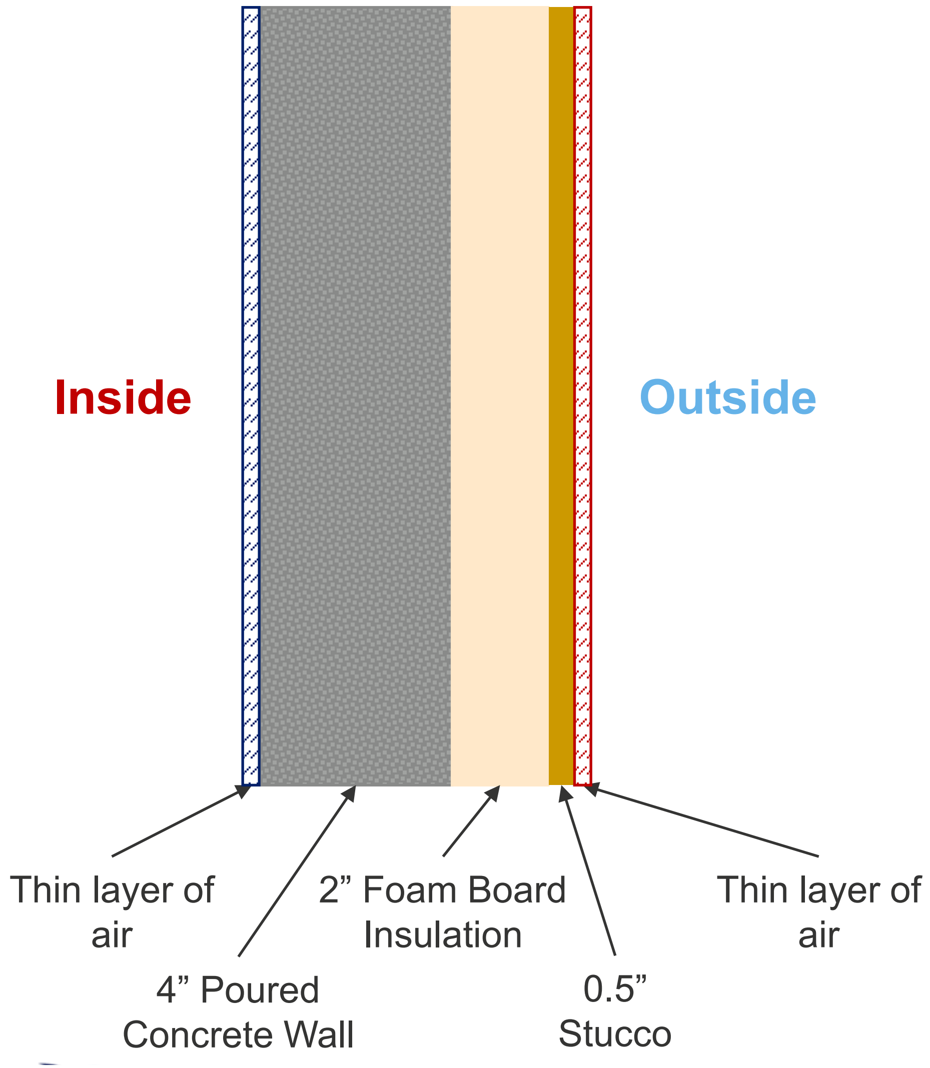
Example: Concrete Wall with Foam Board Insulation



- We want to determine the total R-value for the wall
- What are all the materials in the wall?
  - 4-inch poured concrete wall
  - 2-inch foam board insulation
  - ½-inch stucco exterior
  - Thin layers of air
    - Warmed up by the wall as heat transfers from inside to outside
    - Creates convection current in the air that creates a thin film of stagnant air
    - Exterior film coefficient[1] has an R-value* of $0.17\ \frac{ft^2 \cdot {}^\circ F \cdot hr}{Btu}$

** Surface film coefficients in ASHRAE Handbook of Fundamentals are specified for an average wind speed of 15mph. Part of the reason for this assumption is so that we underestimate the thermal resistance, as we do not want to undersize the heating and cooling system for the building.*

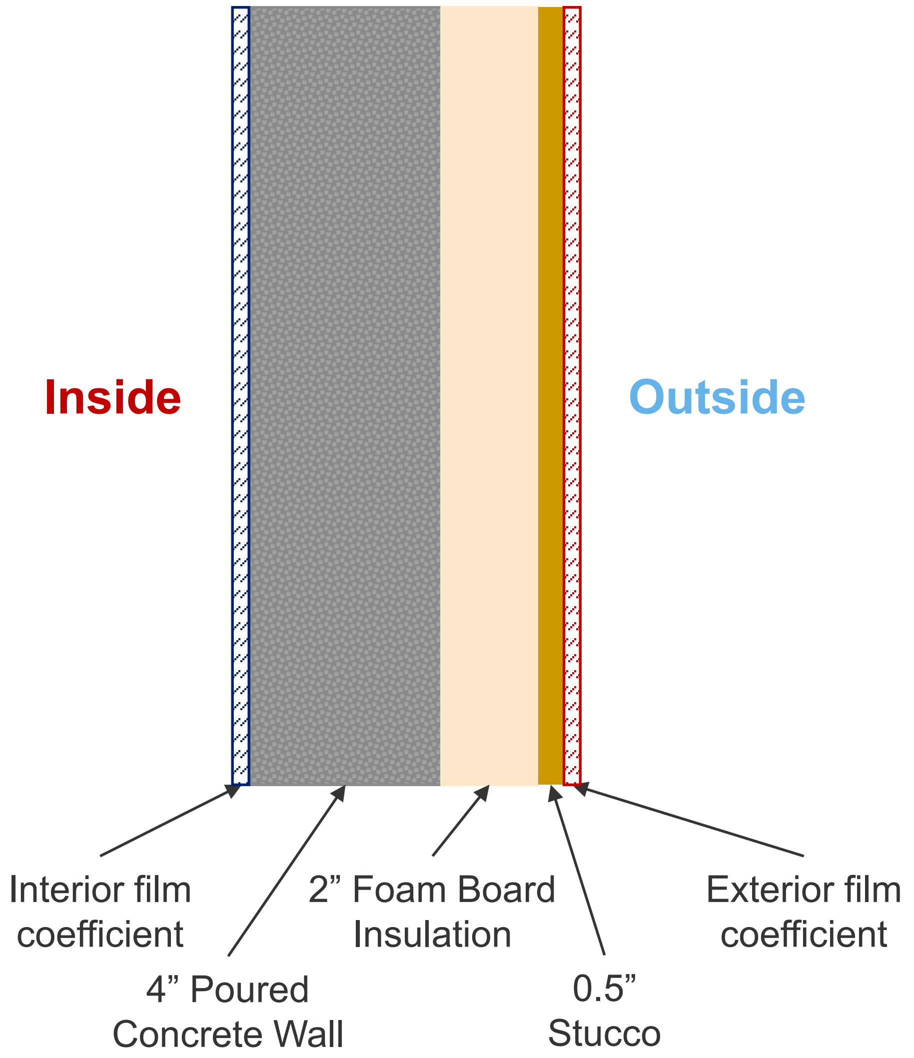
Example: Concrete Wall with Foam Board Insulation



** Surface film coefficients in ASHRAE Handbook of Fundamentals are specified for an average wind speed of 15mph. Part of the reason for this assumption is so that we underestimate the thermal resistance, as we do not want to undersize the heating and cooling system for the building.*

- We want to determine the total R-value for the wall
- What are all the materials in the wall?
  - 4-inch poured concrete wall
  - 2-inch foam board insulation
  - ½-inch stucco exterior
  - Thin layers of air
    - Warmed up by the wall as heat transfers from inside to outside
    - Creates convection current in the air that creates a thin film of stagnant air
    - Exterior film coefficient[1] has an R-value* of $0.17\ \frac{ft^2 \cdot {}^\circ F \cdot hr}{Btu}$
    - Interior film coefficient[1] has an R-value* of $0.68\ \frac{ft^2 \cdot {}^\circ F \cdot hr}{Btu}$

Example: Concrete Wall with Foam Board Insulation



R-values of wall components:

0.17 Exterior film coefficient[1]

0.10 Stucco[2]

10.00 Foam board[1]

0.52 Concrete[1]

0.68 Interior film coefficient[1]

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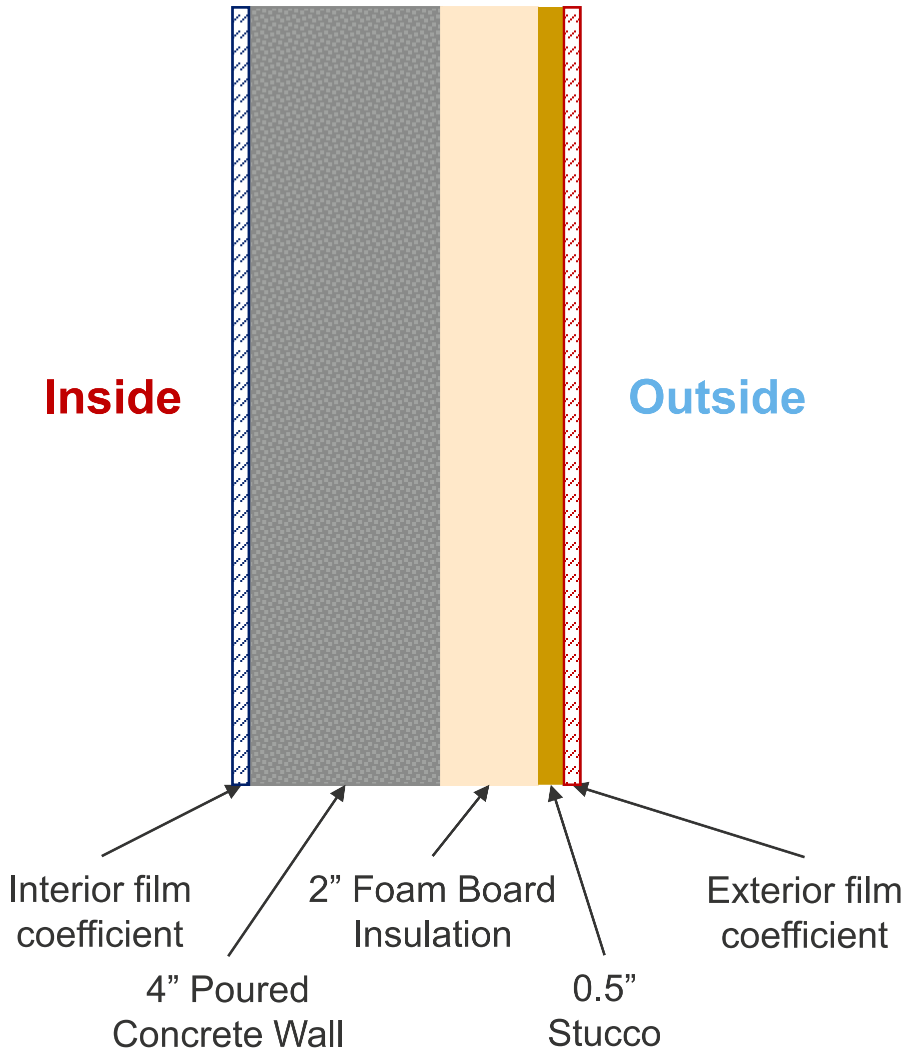
Example: Concrete Wall with Foam Board Insulation



R-values of wall components:

0.17 Exterior film coefficient[1]

0.10 Stucco[2]

10.00 Foam board[1]

0.52 Concrete[1]

+ 0.68 Interior film coefficient[1]

$$11.47 \frac{ft^2 \cdot {}^\circ F \cdot hr}{Btu}$$

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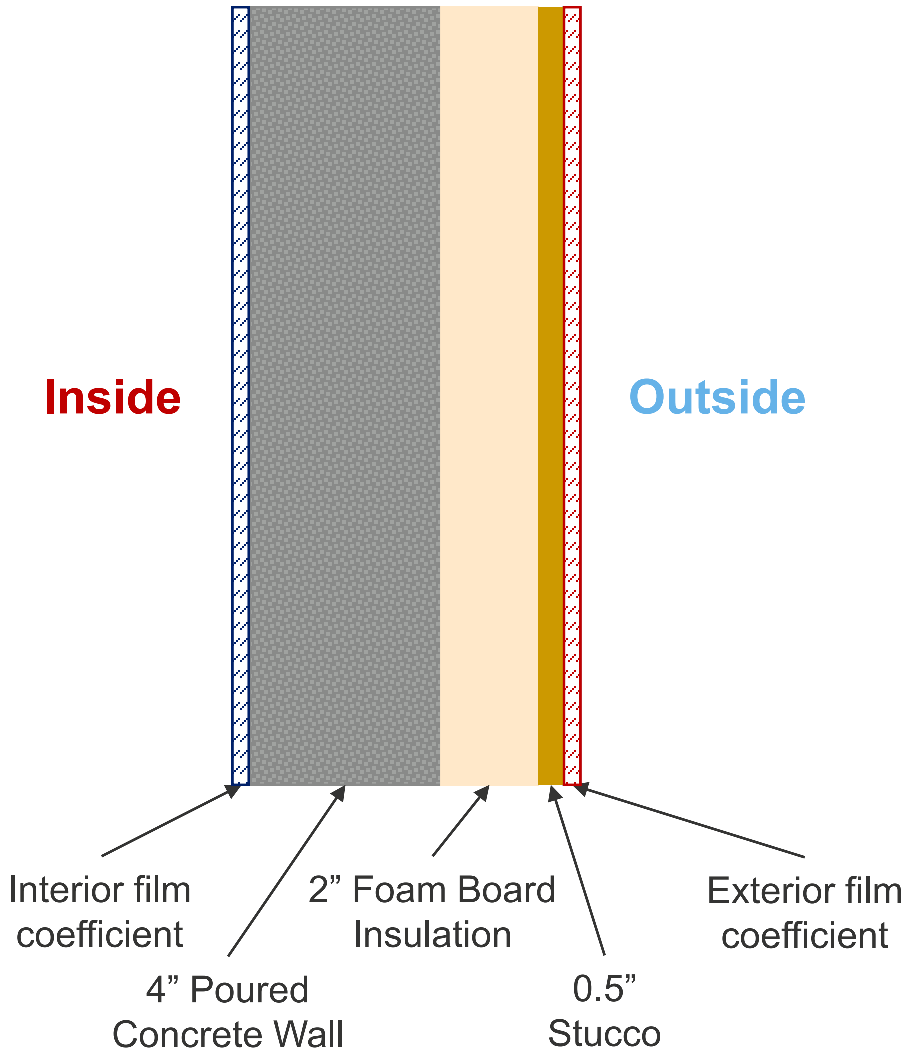
Example: Concrete Wall with Foam Board Insulation



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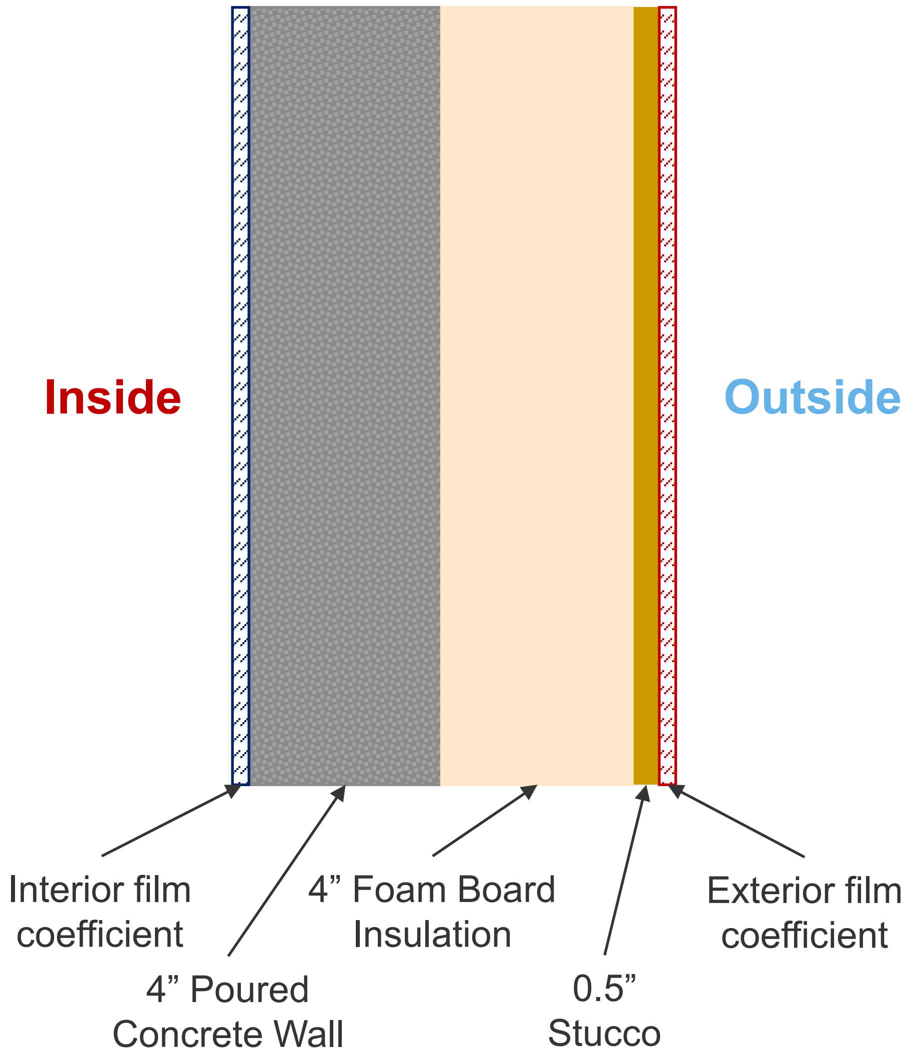

R-values of wall components:

0.17 Exterior film coefficient[1]

0.10 Stucco[2]

20.00 Foam board[1]

0.52 Concrete[1]

+ 0.68 Interior film coefficient[1]

$$21.47 \ \frac{ft^2 \cdot {}^\circ F \cdot hr}{Btu}$$

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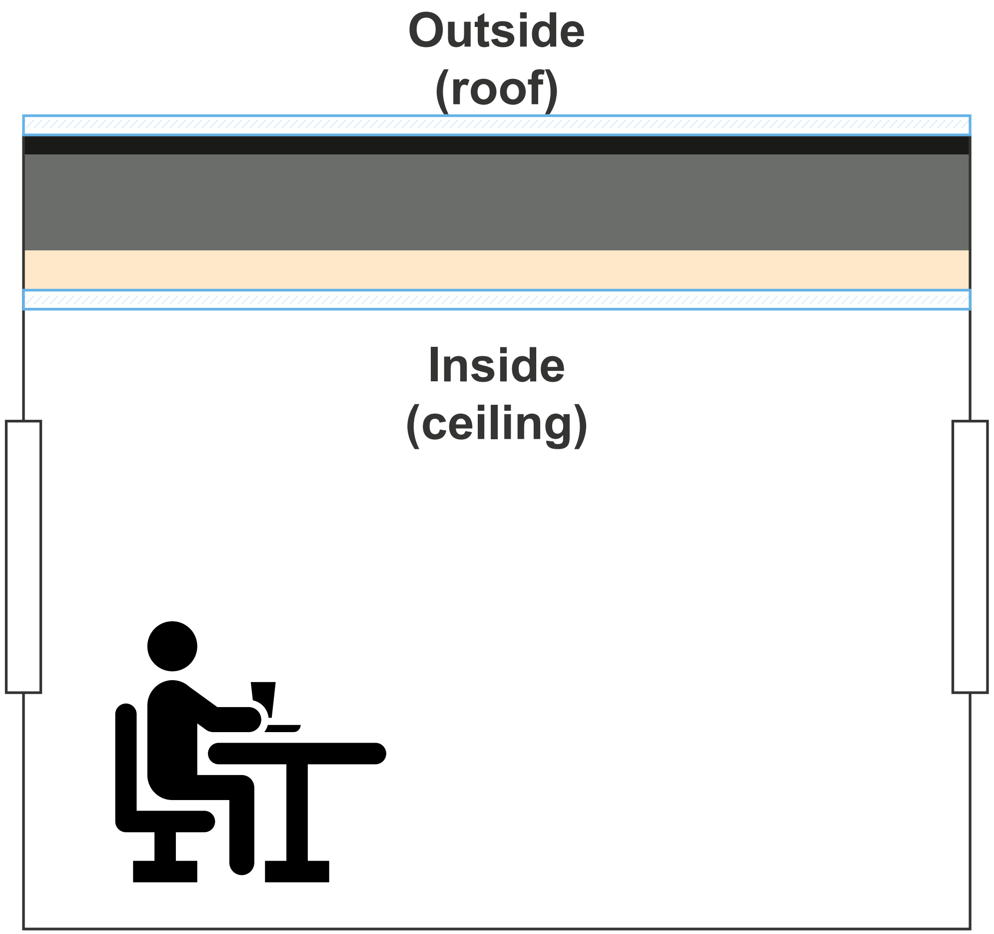
Surface Film Coefficients for Horizontal Surfaces

- Previous example focused on vertical wall surfaces and introduced the concept of Interior and Exterior film coefficients
- Horizontal surfaces, like a flat roof, also have Interior and Exterior film coefficients
  - Interior (i.e., air at the ceiling)[3]
    - $R = 0.61 \frac{ft^2 \cdot °F \cdot hr}{Btu}$
  - Exterior (i.e., air adjacent to roof surface)[3]
    - $R = 0.17 \frac{ft^2 \cdot °F \cdot hr}{Btu}$
- Exceptions exist, such as unconditioned attics



Questions or comments?

Please email SolarDecathlon@nrel.gov

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National Renewable Energy Laboratory

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3. 2017 ASHRAE Handbook of Fundamentals. Chapter 26, Table 10. https://www.ashrae.org/technical-resources/ashrae-handbook/description-2017-ashrae-handbook-fundamentals

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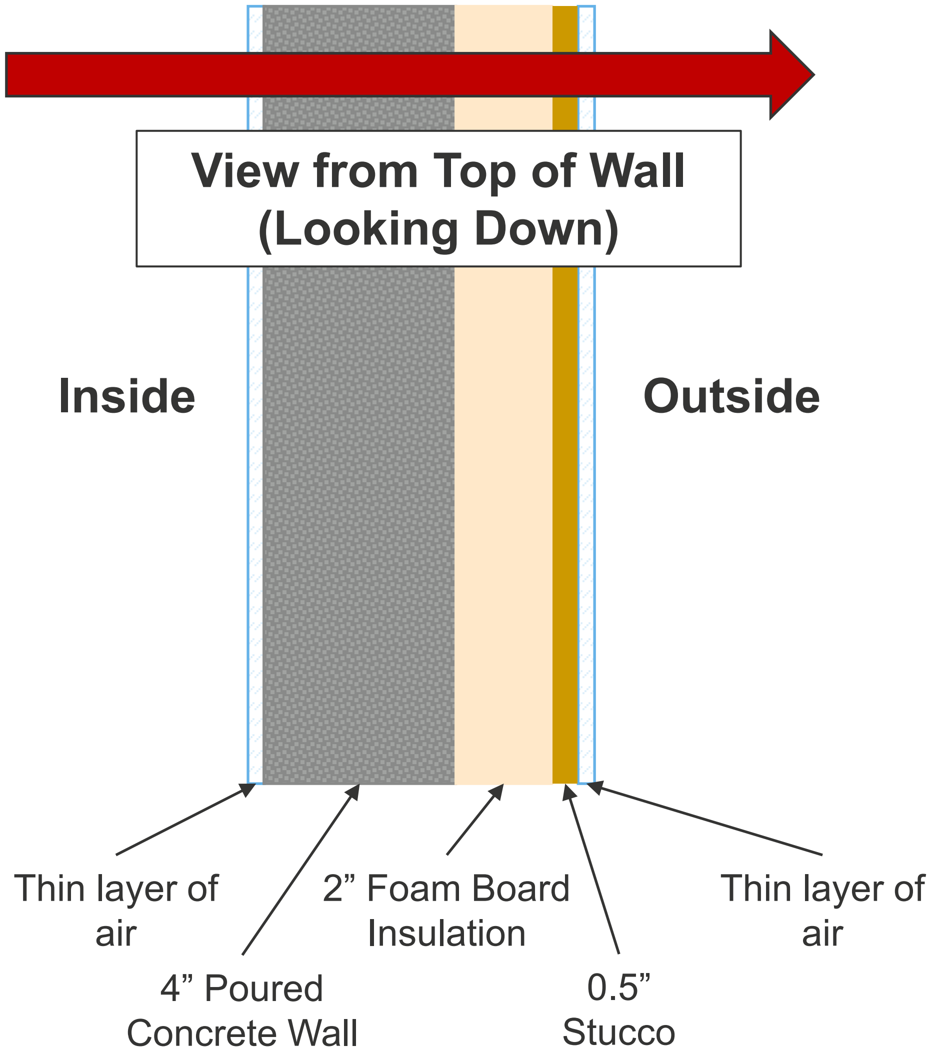
Calculating R-Value for a Wall (Part 2)

Photo by Paul Norton, NREL

Episode ID: 0308-210202

Homogeneous Layers vs. Heterogeneous Layers

- In our concrete wall example, the materials and thickness of each layer are the same everywhere on the wall
- Thermal resistance is consistent for all heat transfer pathways
- Not all walls are constructed this way
    - Some have multiple components within the same layer
    - Thermal resistance differs depending on the location of the heat transfer pathway



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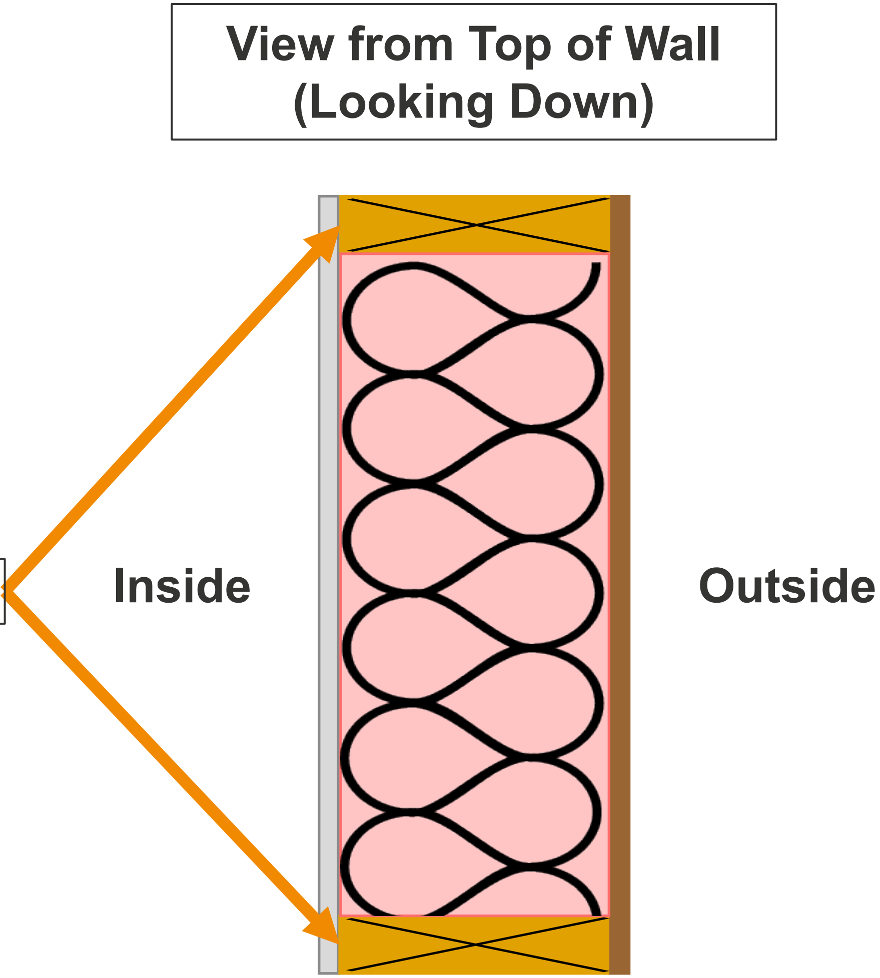
Example: Stud Frame Wall

Photo by Michael Young, NREL



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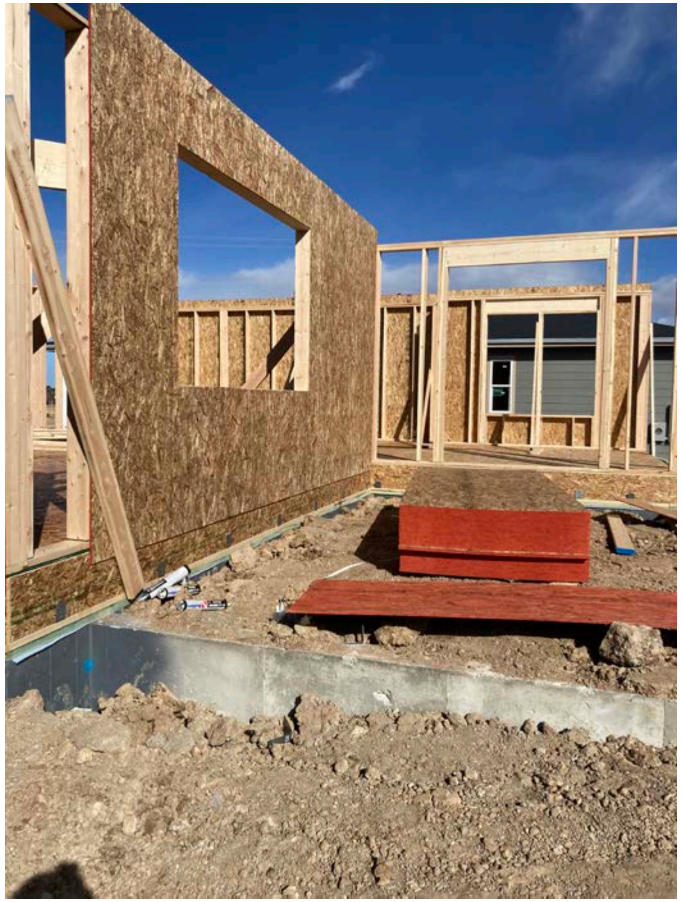
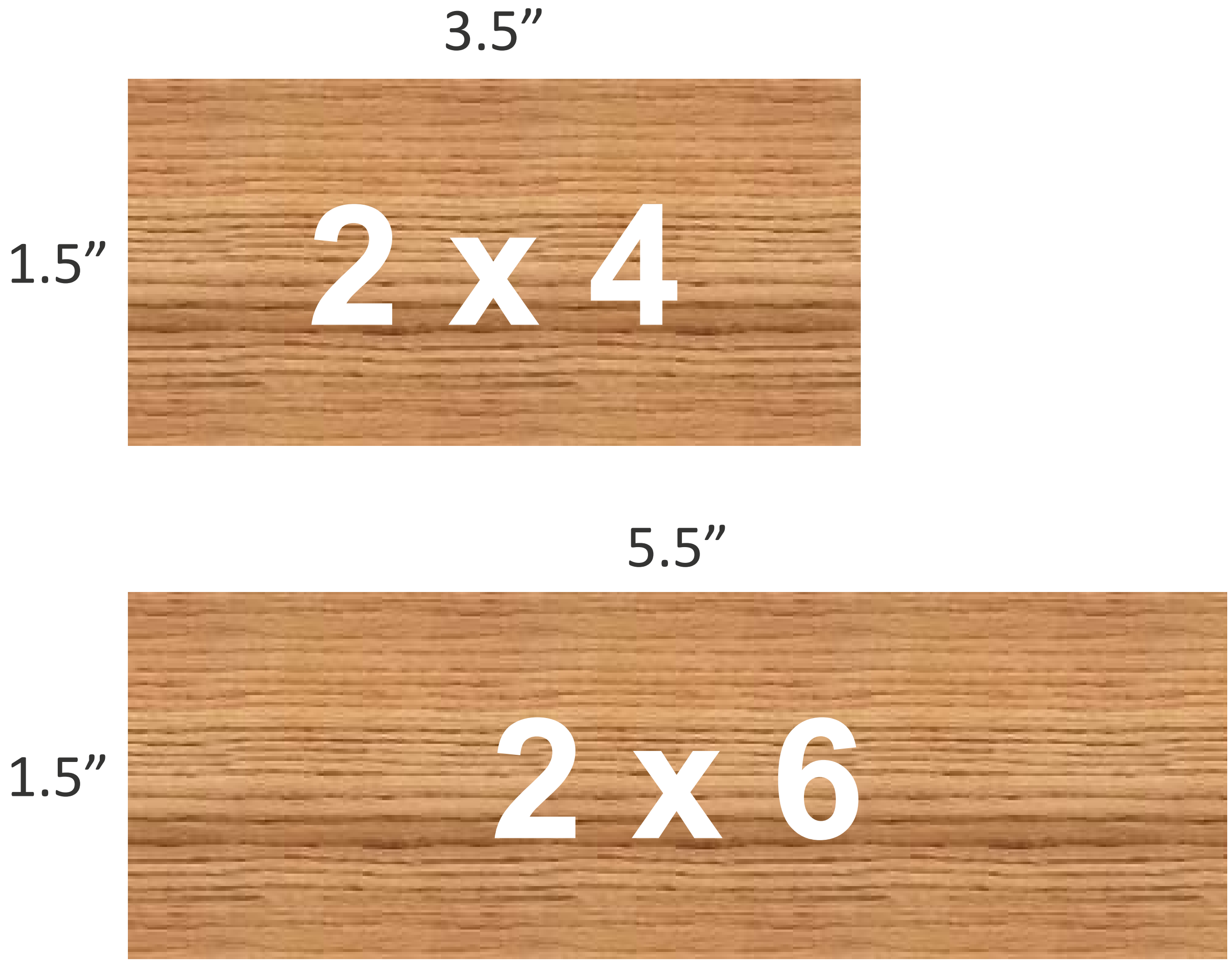


Photos by Michael Young, NREL

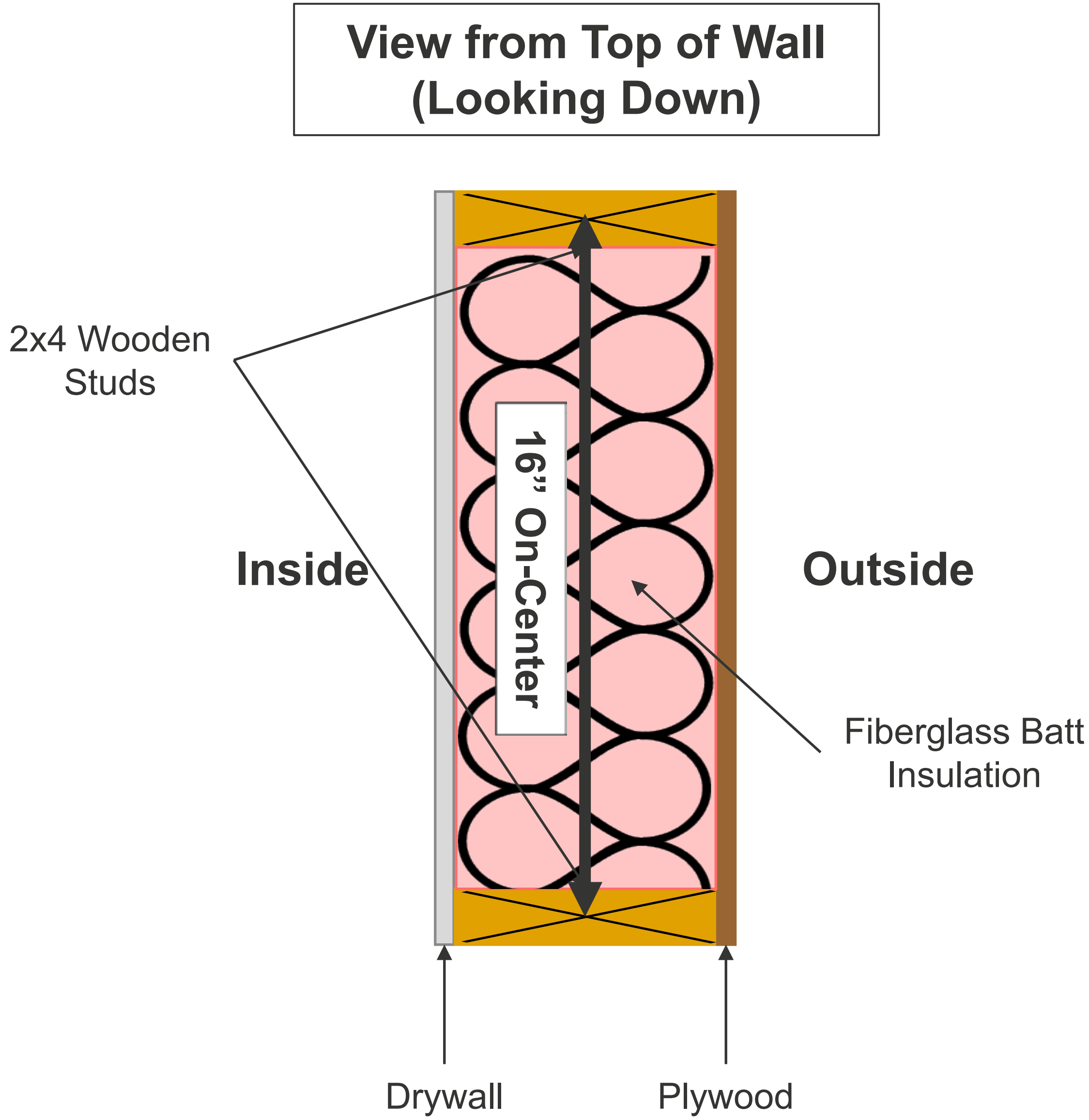
Example: Stud Frame Wall

Naming Convention for Stud Dimensions	Actual Dimensions
2” x 4”	1.5” x 3.5”
2” x 6”	1.5” x 5.5”
2” x 8”	1.5” x 7.25”
2” x 10”	1.5” x 9.25”
2” x 12”	1.5” x 11.25”

Source: https://www.fpl.fs.fed.us/documnts/misc/miscpub_6409.pdf

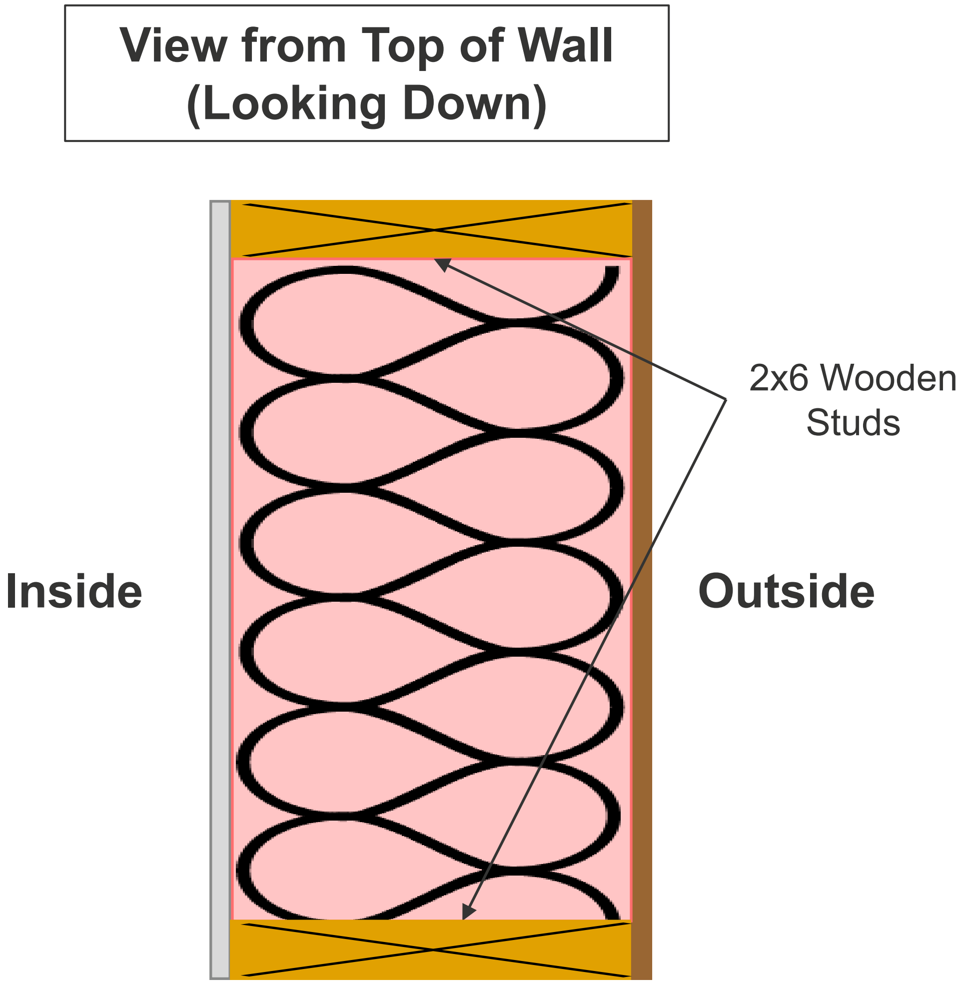


Example: Stud Frame Wall with Fiberglass Insulation



Example: Stud Frame Wall with Fiberglass Insulation

- Before the 1970's, wall cavities were often empty
- As interest in energy efficiency and indoor environmental comfort grew…
  - Wall cavities were filled with insulation
  - 2"x6" studs were used to increase thickness of the cavity and allow for more insulation



Example: Stud Frame Wall with Fiberglass Insulation

Heat transfer rates are additive

$$\dot{Q} = U \cdot A \cdot \Delta T$$

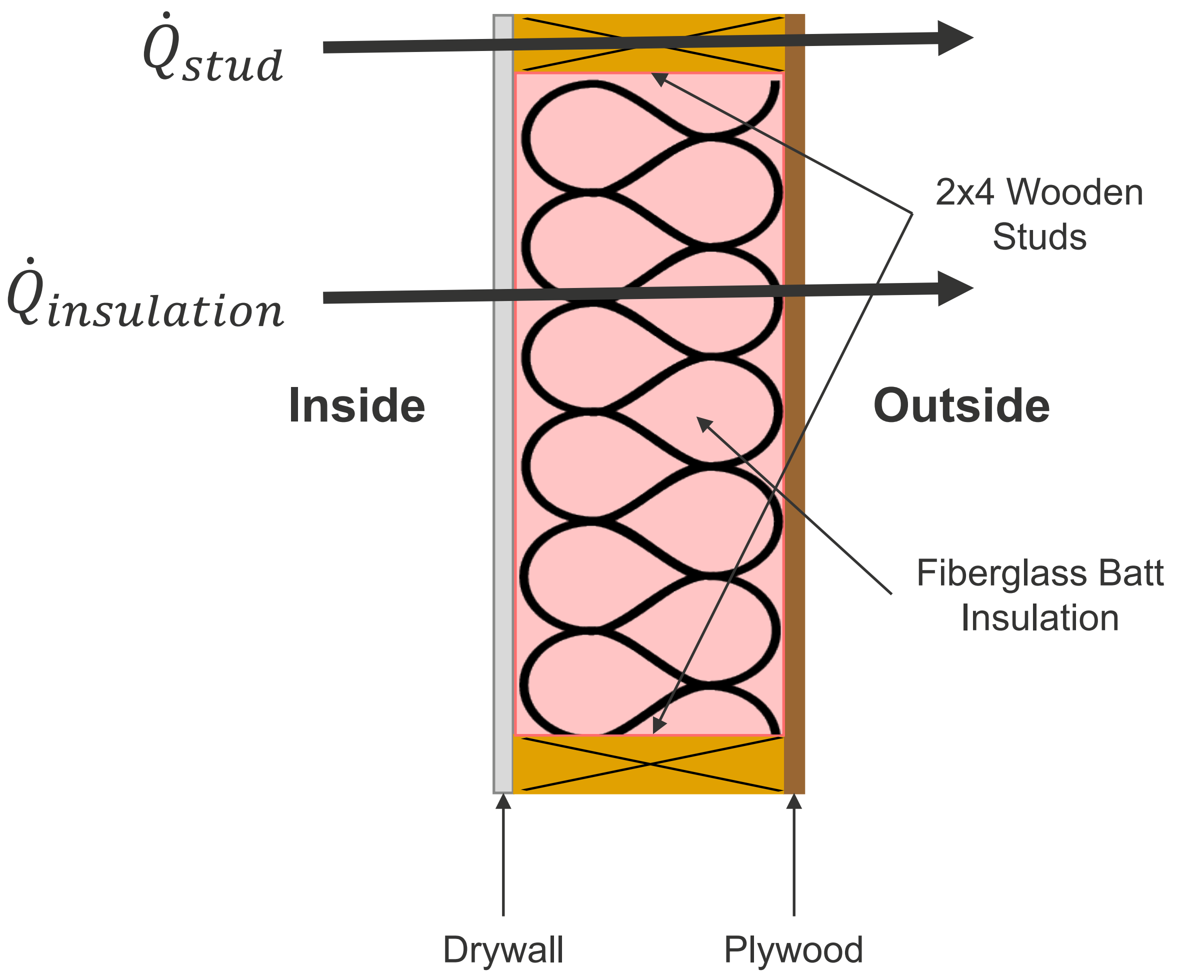
$$\dot{Q}_{total} = \dot{Q}_{stud} + \dot{Q}_{insulation}$$

$$U_t A_t \cancel{\Delta T} = U_s A_s \cancel{\Delta T_s} + U_i A_i \cancel{\Delta T_i}$$

$$U_t = \frac{U_s A_s + U_i A_i}{A_t}$$

$$U_t = U_s \frac{A_s}{A_t} + U_i \frac{A_i}{A_t}$$

View from Top of Wall (Looking Down)



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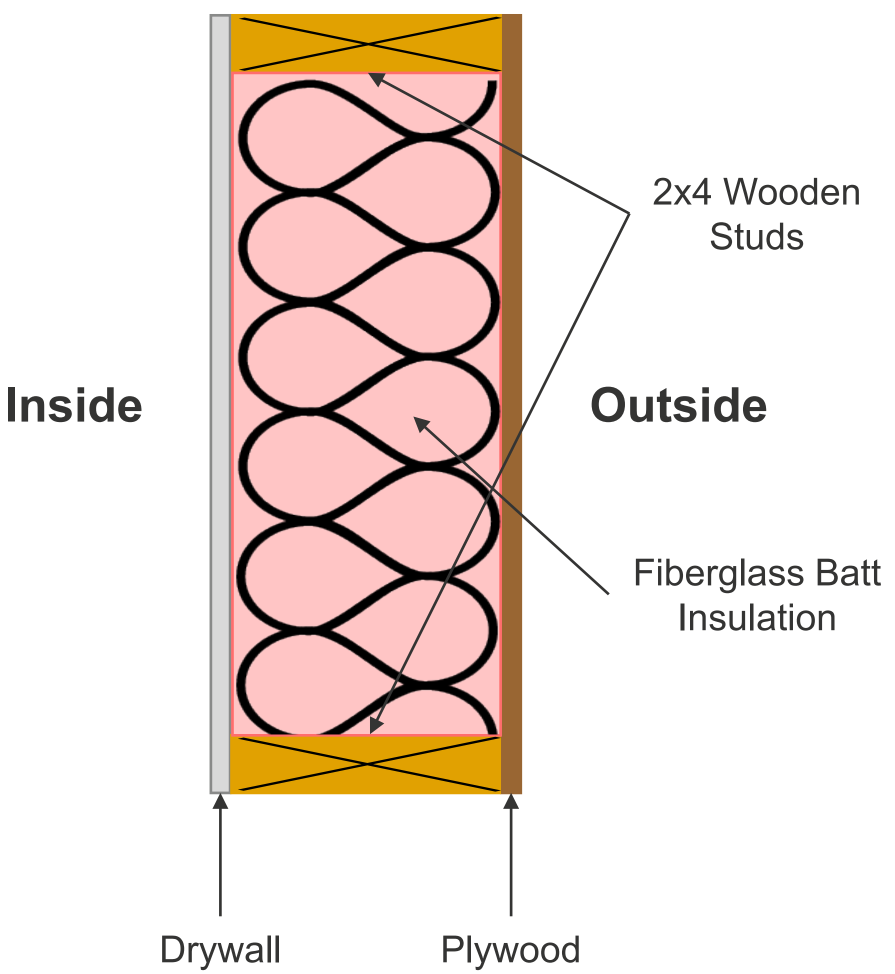
$$U_t = \frac{U_s A_s + U_i A_i}{A_t} = \frac{U_s A_s + U_i A_i}{A_s + A_i}$$

$$U_t = U_s \frac{A_s}{A_t} + U_i \frac{A_i}{A_t}$$

$$\frac{A_s}{A_t} = \text{"Framing Factor"}$$

View from Top of Wall (Looking Down)



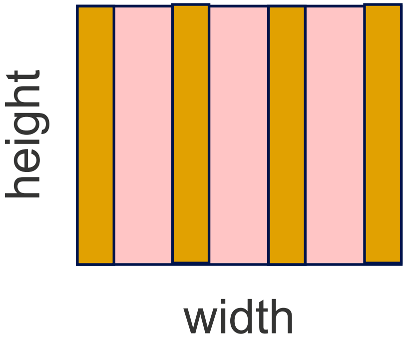
Example: Stud Frame Wall with Fiberglass Insulation

$$\frac{A_s}{A_t} = \text{"}Framing\ Factor\text{"}$$

- *Amount of frame compared to total area of insulated wall*
- *Not uncommon to assume* 15%

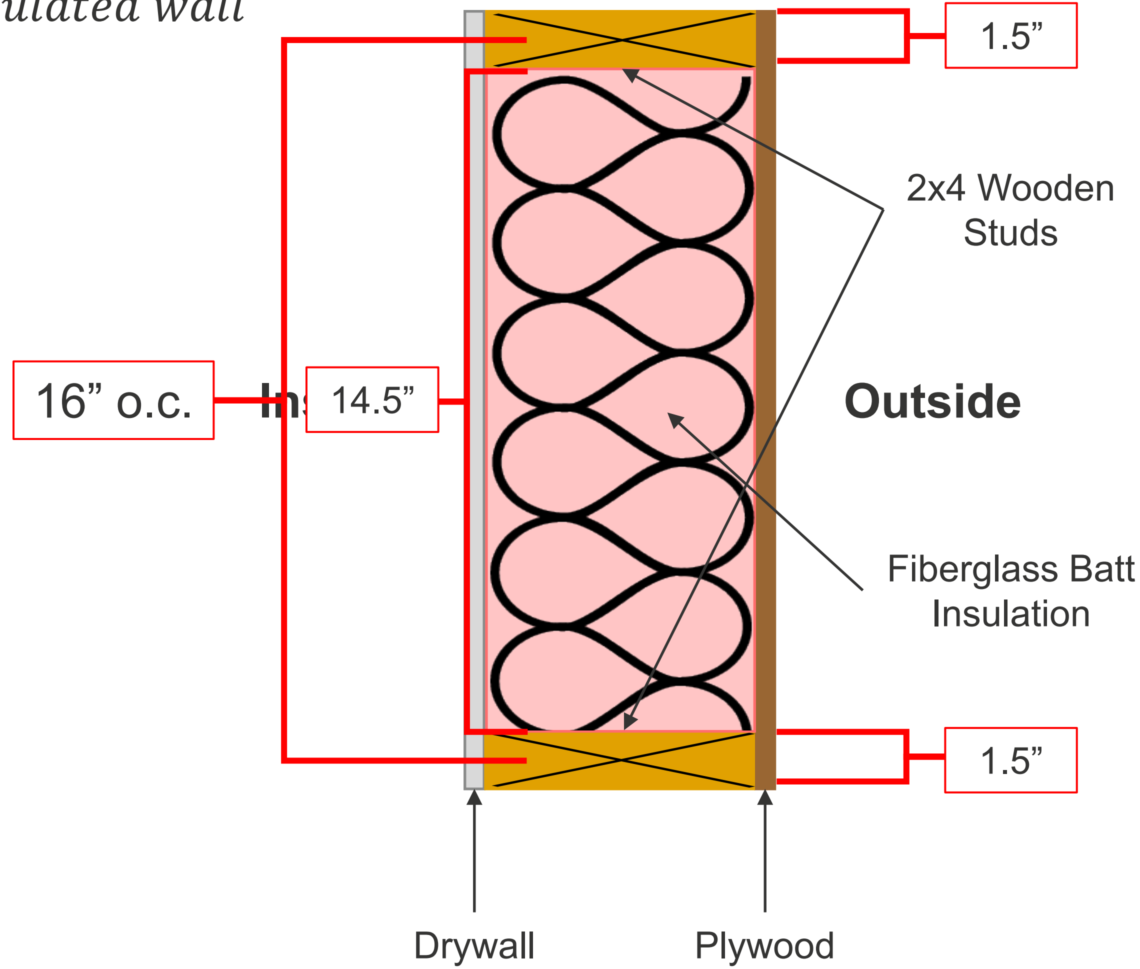
$$A = w \cdot h$$

$$\frac{A_s}{A_t} = \frac{w_s \cdot \cancel{h_s}}{w_t \cdot \cancel{h_t}} = \frac{w_s}{w_s + w_i}$$



$$\frac{A_s}{A_t} = \frac{w_s}{w_s + w_i}$$

View from Top of Wall (Looking Down)



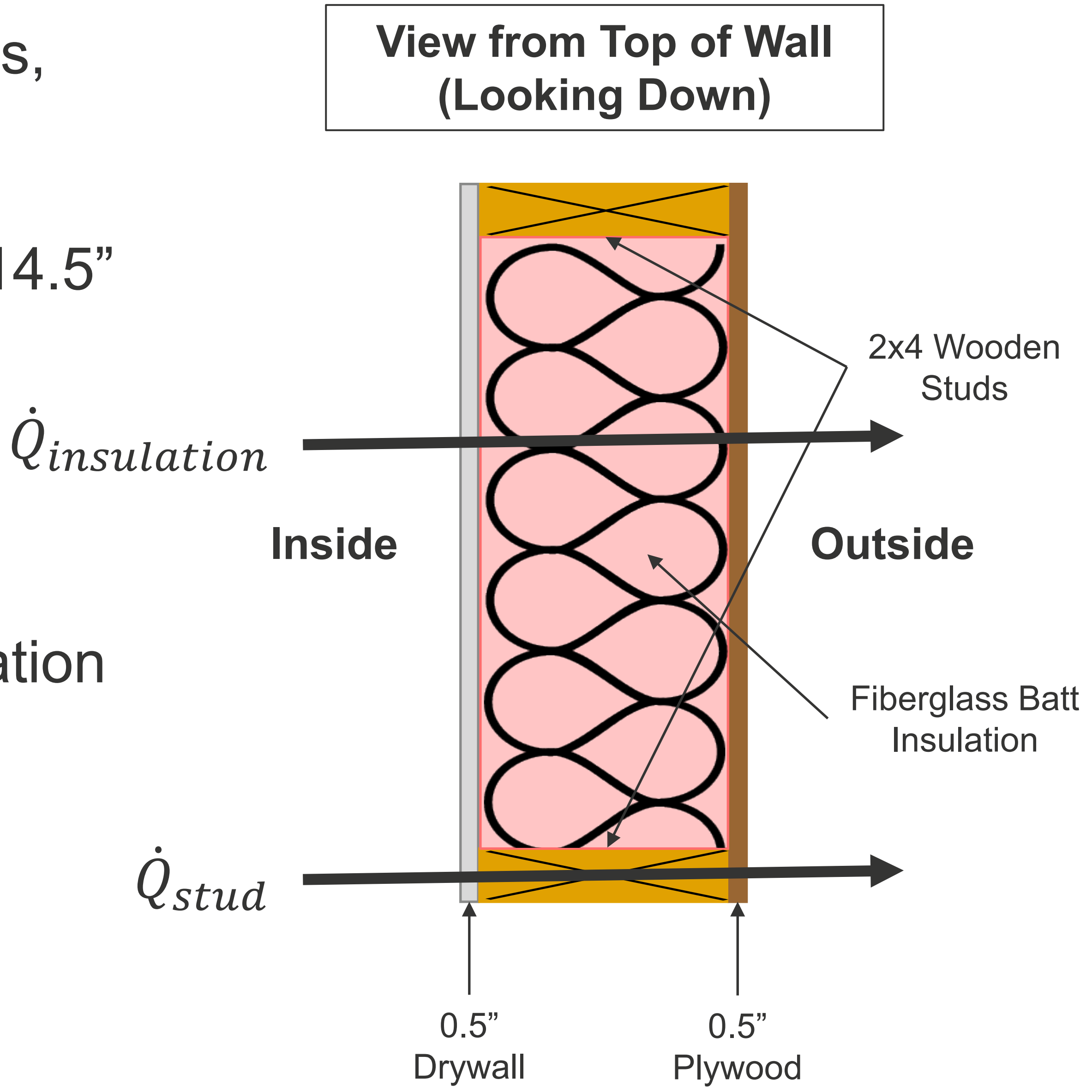
Example: Stud Frame Wall with Fiberglass Insulation

Assume wall is constructed with 2x4 studs, spaced 16” o.c. (on-center)

- Studs are 3.5” wide
- Fiberglass insulation fills wall cavity 14.5” wide

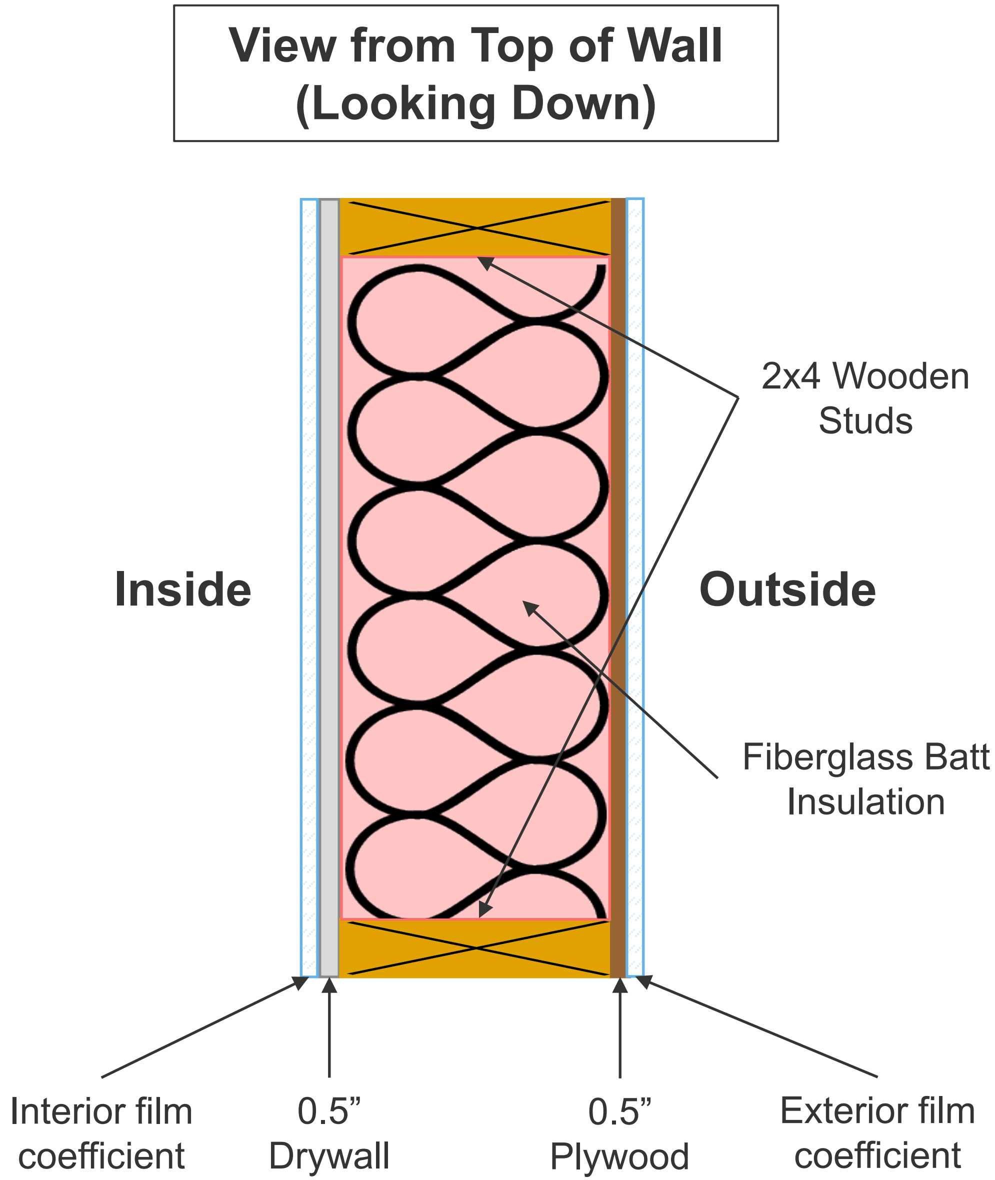
From inside to outside:

- 0.5” Drywall
- 3.5” Stud / 3.5” Fiberglass Batt Insulation
- 0.5” Plywood



Example: Stud Frame Wall with Fiberglass Insulation

Material	R-value/inch	R-value: Path 1
Interior film coefficient		0.68
Drywall (0.5”)	1.10	0.55
Stud (3.5”)	0.94	3.29
Insulation (3.5”)	3.14	
Plywood (0.5”)	1.56	0.78
Exterior film coefficient		0.17
Total		***5.47***



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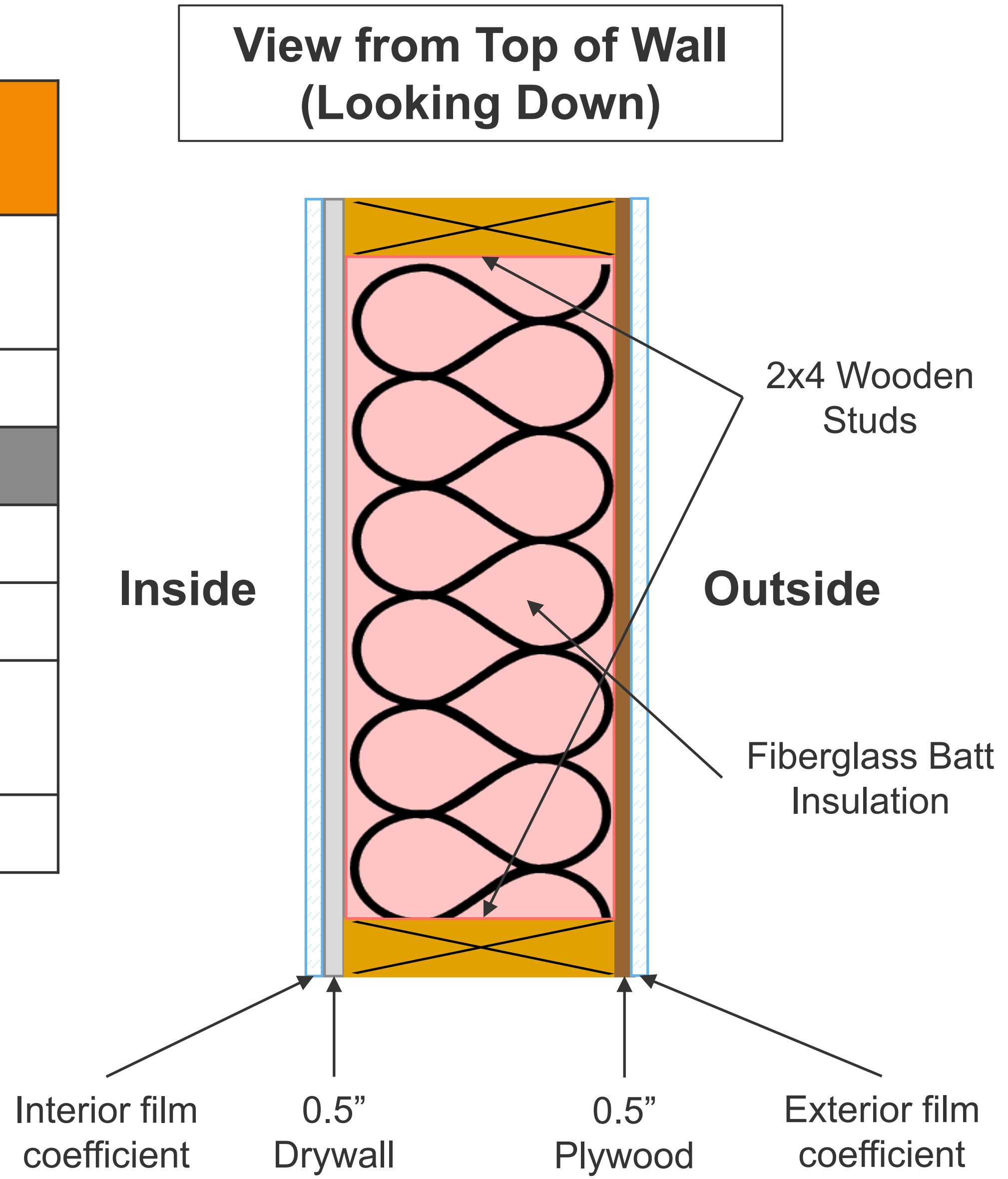
Example: Stud Frame Wall with Fiberglass Insulation

Material	R-value/inch	R-value: Path 1	R-value: Path 2
Interior film coefficient		0.68	0.68
Drywall (0.5")	1.10	0.55	0.55
Stud (3.5")	0.94	3.29	
Insulation (3.5")	3.14		10.99
Plywood (0.5")	1.56	0.78	0.78
Exterior film coefficient		0.17	0.17
Total		***5.47***	***13.17***



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Total		***5.47***	***13.17***

$$U_t = U_s \frac{w_s}{w_t} + U_i \frac{w_i}{w_t}$$

$$U_t = \frac{1}{5.47} \cdot \frac{w_s}{w_t} + \frac{1}{13.17} \cdot \frac{w_i}{w_t}$$

$$U_t = \frac{1}{5.47} \cdot \frac{1.5}{16} + \frac{1}{13.17} \cdot \frac{14.5}{16}$$

$$U_{total\,wall} = 0.086$$

$$R_{total\,wall} = \frac{1}{0.086} = 11.63$$

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Questions or comments?

Please email SolarDecathlon@nrel.gov

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Insulation Materials

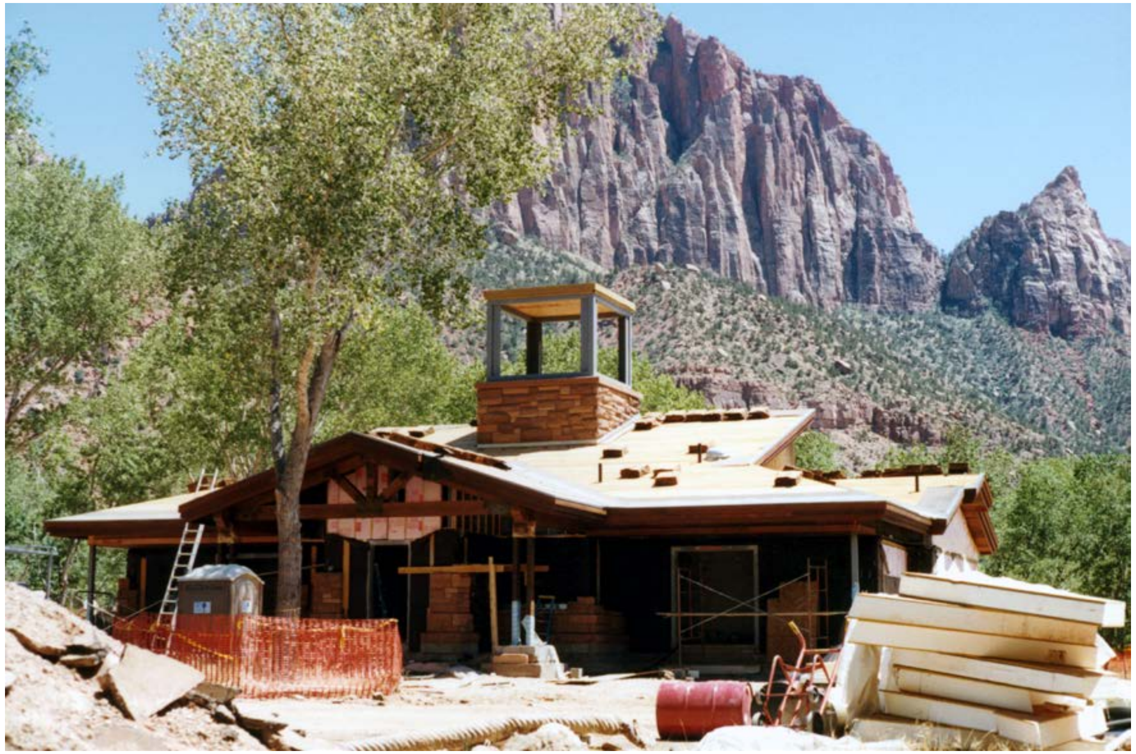
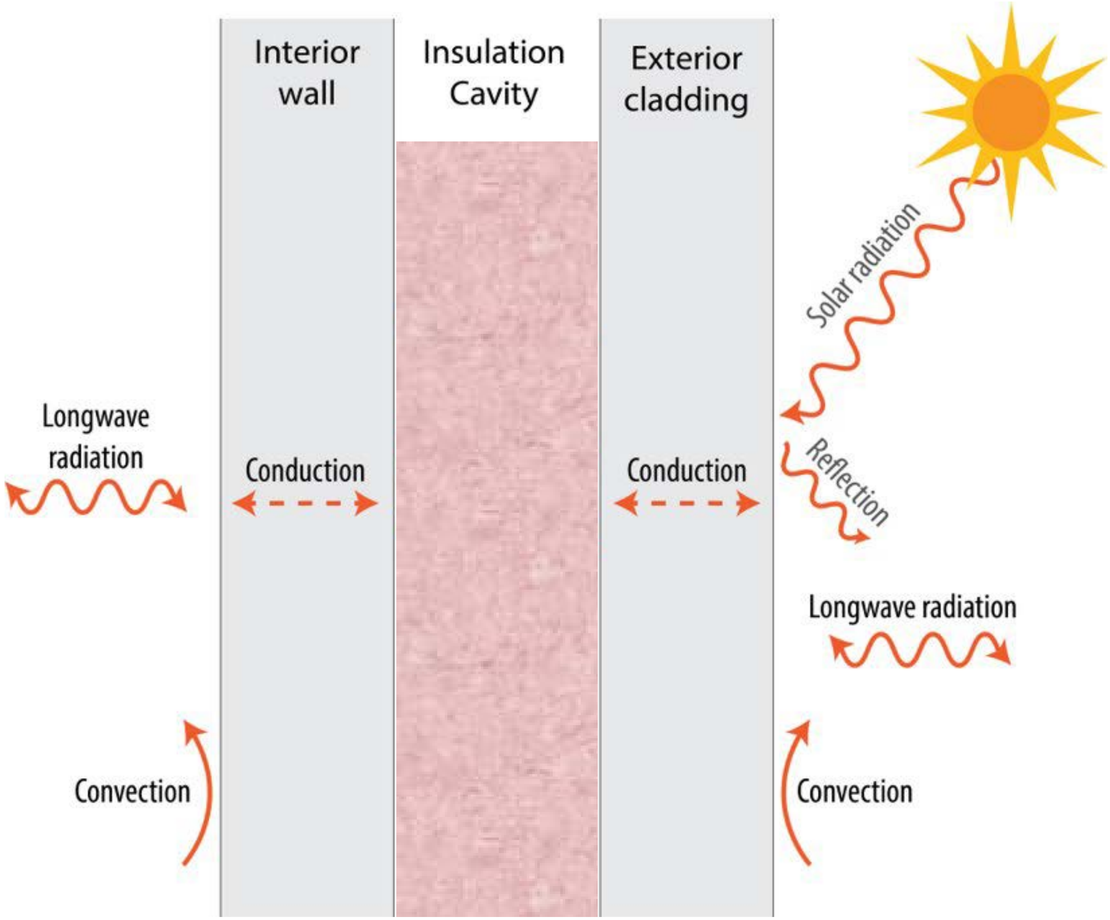


Photo by Paul Torcellini, NREL

Insulation Materials



Source: Marjorie Schott, NREL

Fiberglass

Photo by Paul Torcellini, NREL

Cellulose

Source: David Springer, NREL

Mineral wool

Photo by Paul Torcellini, NREL

Foams/Thermoplastics

Source: Paul Norton, NREL

Natural Fibers

Fiberglass

Source: Amanda Kirkeby, NREL

Composition

- Molten glass blown into fibers

Recycled Material Content

- 40-60% recycled glass

Other information

- One of the most common insulation materials

Mineral Wool

Source: Paul Torcellini, NREL

Composition

- Rock wool: man-made from natural minerals, such as basalt
- Slag wool: man-made from blast furnace slag, the waste matter that forms on surface of molten metal

Recycled Material Content

- 75% post-industrial material

Other information

- Fire-resistant

Cellulose

Source: David Springer, NREL

Composition

- Recycled paper products, such as newsprint

Recycled Material Content

- 82-85% recycled paper product

Other information

- Additives such as mineral borate ensure fire and insect resistance
- Requires no moisture barrier

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Natural Fibers

Cotton

Sheep wool

Straw

Source: Evelyn Simak

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Cotton

Composition

- 85% recycled cotton and 15% plastic fibers treated with borate

Recycled Material Content

- 85% (some use recycled blue jean trim waste)

Other information

- Additives such as mineral borate ensure fire and insect resistance
- Minimal energy to manufacture

Sheep wool

Composition

- Sheep wool

Recycled Material Content

- Natural material

Other information

- Treated with mineral borate ensure fire, insect, and mold resistance
- Can hold large quantities of water
- 2” x 4” wall (R-13)
- 2” x 6” wall (R-19)

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Straw

Source: Straw Bale House, Philipp, flikr

Composition

- Straw Bales finished with stucco
- Straw boards

Recycled Material Content

- Natural material

Other

- Popular 150 years ago in Great Plains of United States
- Inexpensive
- R-25 walls

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Polystyrene Insulation Materials

R-Value is dependent on density: Loose-fill/bead has lower R-Value than foam board

Molded Expanded Polystyrene (MEPS)

Source: Amanda Kirkeby, NREL

- Foam board
  or Small foam beads

***Expanded* Polystyrene (EPS)**

- Small, thermoplastic beads fused together

***Extruded* Polystyrene (XPS)**

Source: Amanda Kirkeby, NREL

- Molten thermoplastic pressed into rigid boards
- R-value can drop over time – "Thermal drift"

Polyisocyanurate Insulation Materials

✓ Low-conductivity ✓ Hydrochlorofluorocarbon-free ✗ Subject to Thermal Drift

Liquid, Sprayed Foam

Source: Paul Norton, NREL

- Molds itself to all surfaces, leading to better performance
- Cheaper than foam board installation

Rigid Foam Board

Source: Amanda Kirkeby, NREL

- Can be laminated with a variety of facings

Polyurethane Insulation Materials

Spray-in foam insulation with different density options.

Open-cell Foam

Source: Rodney Diaz

- Low density
- Lower R-Value
- Spongy texture that can absorb water
- Little thermal drift

Close-cell Foam

Source: Rodney Diaz

- High-density
- Higher R value
- Expand to space around it
- Expensive
- Thermal drift

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Cementitious Foam Insulation Materials

Source: Dennis Schroeder, NREL

Composition

- Cement-based foam minerals such as magnesium silicate and magnesium oxide (found in seawater)

Other

- Pumped into closed cavities
- Fire-resistant
- Non-toxic

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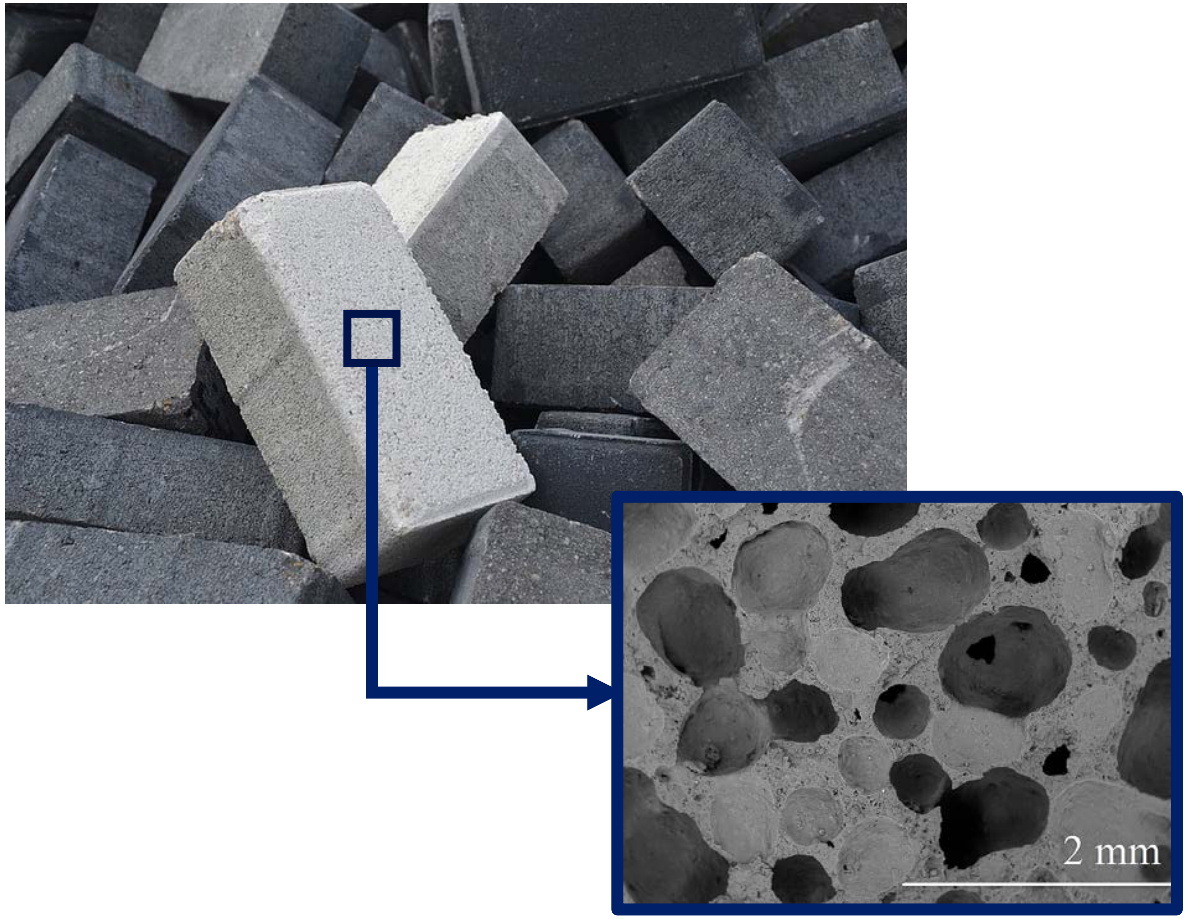
Autoclaved Concrete



Source: Tarmo Tamm

Composition

- Solid, precast autoclaved, lightweight concrete masonry
- Autoclaved *Aerated* Concrete (AAC) – High-Silica Sand
- Aerated *Cellular* Concrete (ACC) – Fly ash, a waste product of coal-burning power plants

Other

- 80% air by volume
- 10 times the insulating value of conventional concrete

Insulation Facings

Source: Amanda Kirkeby, NREL

Common Facing Materials

- Kraft paper
- Vinyl sheeting
- Aluminum foil (radiant barrier)

Other

- Protects insulation surface
- Some facings provide air, radiant, and/or vapor barrier
- Can provide flame and insect resistance

Note: Radiant barriers only work if there is a non-solid/non-liquid space between the radiant barrier and the next space

Key Points

Many different types of insulation materials

- Each type has its benefits and different applications.

Insulation materials mitigate heat transfer in building envelope

Up next…

- Applications of different insulation materials

Questions or comments?

Please email SolarDecathlon@nrel.gov

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2. US Department of Energy. *Insulation Materials*. https://www.energy.gov/energysaver/weatherize/insulation/insulation-materials

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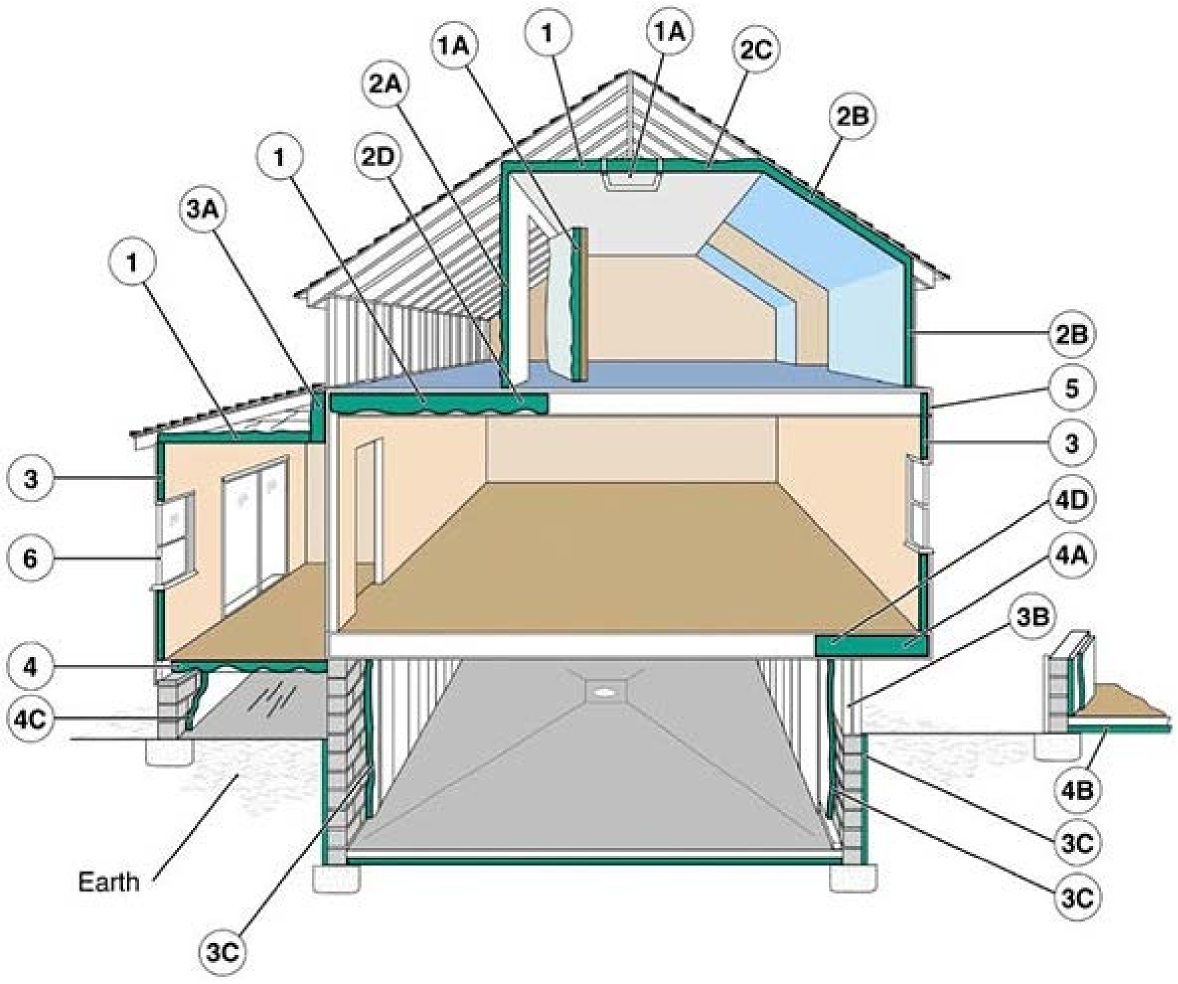
Insulation Types

Photo by Paul Norton / NREL

Episode ID: 0310-201229

How to Choose the Right Insulation Type

- **Where will you install the insulation?**
  1. Unfinished attic spaces
  2. Finished attic rooms
  3. All exterior walls
  4. Floors above cold spaces
  5. Band joists
  6. Windows
- **What R-Value do you want to achieve?**
- **Impact of insulation type on:**
  - Indoor air quality
  - Life cycle costs
  - Embodied environmental impact
  - Ease/cost of installation



Source: DOE/ORNL https://www.energy.gov/energysaver/weatherize/insulation/where-insulate-home

Note: Moisture management and condensation control are critical elements of insulation selection, placement, and design.

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Blanket – Batt and Roll Insulation

Types

- Fiberglass (most common)
- Mineral wool
- Cotton
- Sheep Wool

Applications

- Attic trusses, rafters, walls, and floor joists
- Higher R-values in thicker spaces

Source: US Department of Energy

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Fiberglass Batt Insulation Characteristics

Photos by Amanda Kirkeby, NREL

Thickness (inches)	R-Value
3 1/2	11
3 5/8	13
3 1/2 (high density)	15
6 to 6 1/4	19
5 1/4 (high density)	21
8 to 8 1/2	25
8 (high density)	30
9 1/2 (standard)	30
12	38

Source: https://www.energy.gov/energysaver/weatherize/insulation/types-insulation#271890-tab-1

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Foam Board

Types

- Polystyrene
- Polyisocyanurate
- Polyurethane

Applications

- Exterior wall sheathing
- Interior sheathing in basement walls
- Special applications, such as attic hatches

Photo by Amanda Kirkeby, NREL

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Loose Fill and Blown-In Insulation

Types

- Cellulose
- Fiberglass
- Rock wool

Applications

- Retrofits
- Small, unusually shaped spaces where other insulation is difficult to install

Photo by Dennis Schroeder, NREL

Recommended Specifications by Loose-Fill Insulation Material	Cellulose	Fiberglass	Rock Wool
Density in lb/ft³ (kg/m³)	1.5–2.0 (24–36)	0.5–1.0 (10–14)	1.7 (27)
Weight at R-38 in lb/ft² (kg/m²)	1.25–2.0 (6–10)	0.5–1.2 (3–6)	1.6–1.8 (8–9)

Source: https://www.energy.gov/energysaver/weatherize/insulation/types-insulation#271890-tab-1

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Loose Fill and Blown-In Insulation

Loose-Fill

Photo by Robert Hendron

Blown-in

Photo by Dennis Schroeder, NREL

Spray-Foam and Foamed-In-Place Insulation

Types

- Polyisocyanurate
- Polyurethane
- Cementitious Foam

Applications

- Injected into closed wall cavities
- Sprayed or foamed-in-place to fill wall cavities or small spaces
- Conforms to shape of cavity

Photo by Paul Norton, NREL

Photo by Dennis Schroeder, NREL

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Spray-Foam and Foamed-In-Place Insulation

Types

- Polyisocyanurate
- Polyurethane
- Cementitious Foam

Applications

- Reduce air leakage
- Injected into closed wall cavities
- Sprayed or foamed-in-place to fill wall cavities or small spaces
- Conforms to shape of cavity

Photo by Paul Norton, NREL

Photo by Dennis Schroeder, NREL

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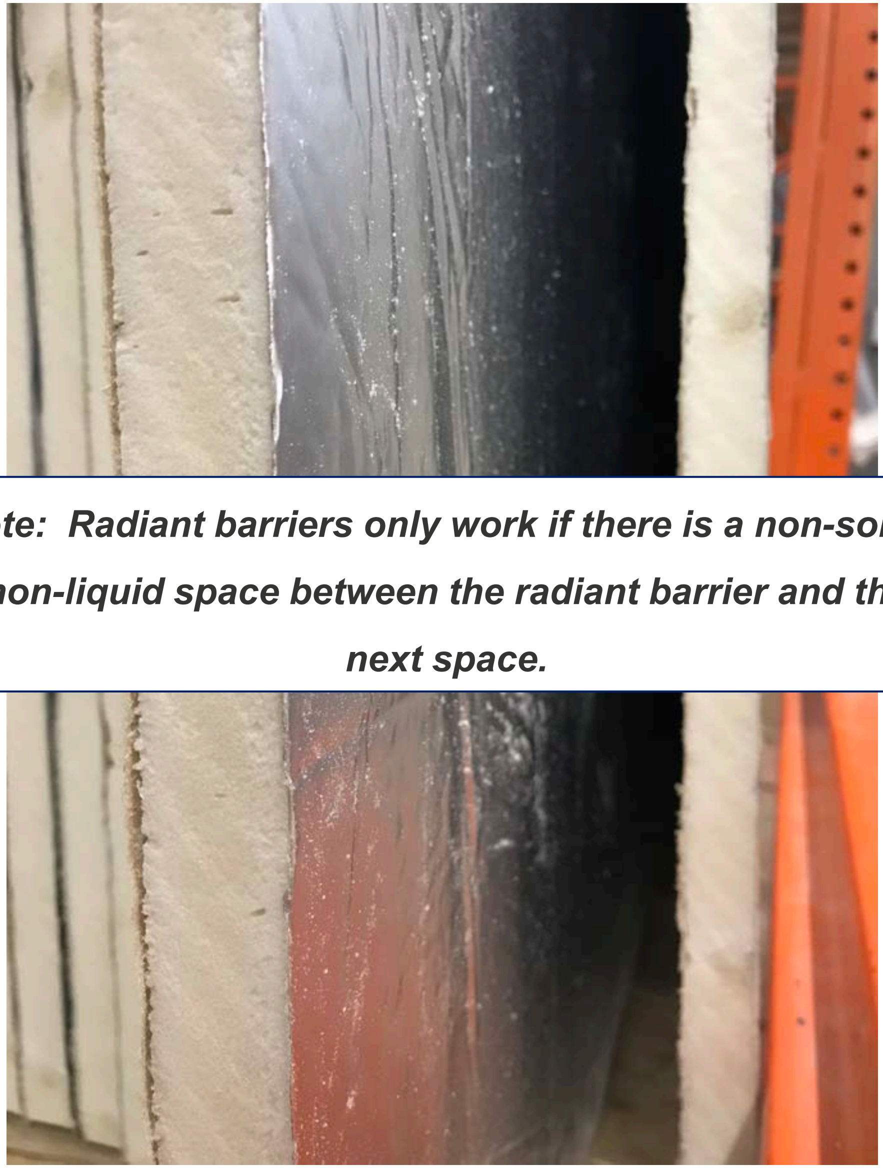
Radiant Barriers and Reflective Insulation Systems

Types

- Highly-reflective aluminum foil
- Kraft paper
- Plastic film
- Polyethylene bubbles
- Cardboard
- Thermal insulation materials

Applications

- Reduce summer heat gain through a radiant heat transfer barrier



Note: Radiant barriers only work if there is a non-solid / non-liquid space between the radiant barrier and the next space.

Photo by Amanda Kirkeby, NREL

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Concrete Block Insulation

Types

- Core filling
- Exterior insulation
- Polystyrene beads incorporated into concrete
- Rigid foam inserts

Applications

- Insulate concrete foundation and wall constructions

Credit: FESC/IBACOS

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Concrete Block Insulation (cont.)

Types

- Core filling
- Exterior insulation
- Polystyrene beads incorporated into concrete
- Rigid foam inserts

Applications

- Insulate concrete foundation and wall constructions


Credit: FESC/IBACOS

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Insulating Concrete Forms (ICFs)

Description

- Insulated forms for poured concrete walls that remain part of the wall assembly

Applications

- Walls
- Look like stick-built construction


Credit: Weber State University

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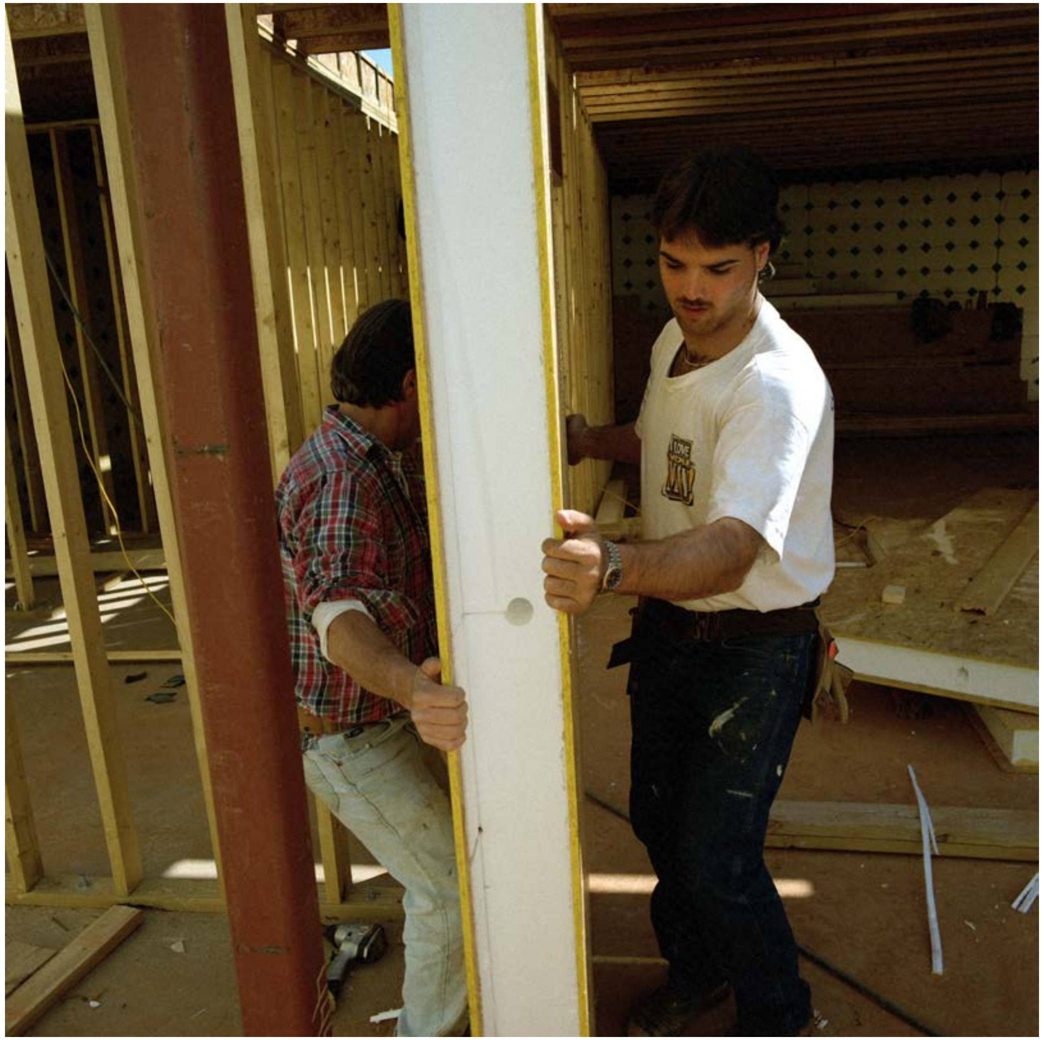
Structural Insulated Panels (SIPs)

Description

- Pre-fabricated insulated structural elements

Applications

- Building walls
- ceilings
- floors
- Roofs
- High R-value
- High strength-to-weight ratio

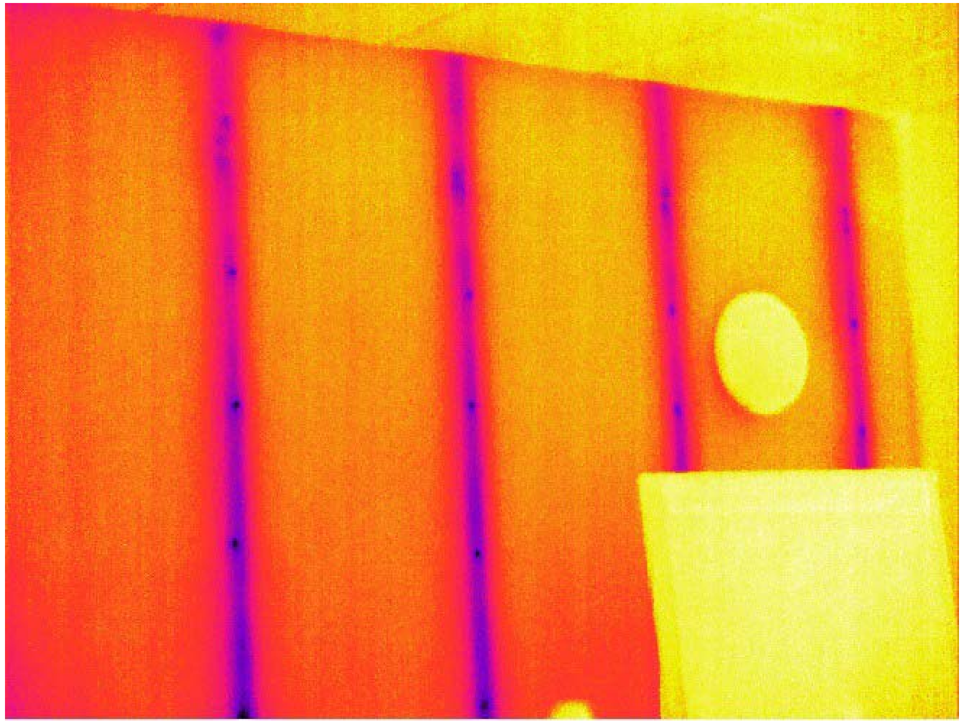


Source: Craig Miller Productions, DOE

Installation: Quality matters

Source: Craig Miller Productions, DOE

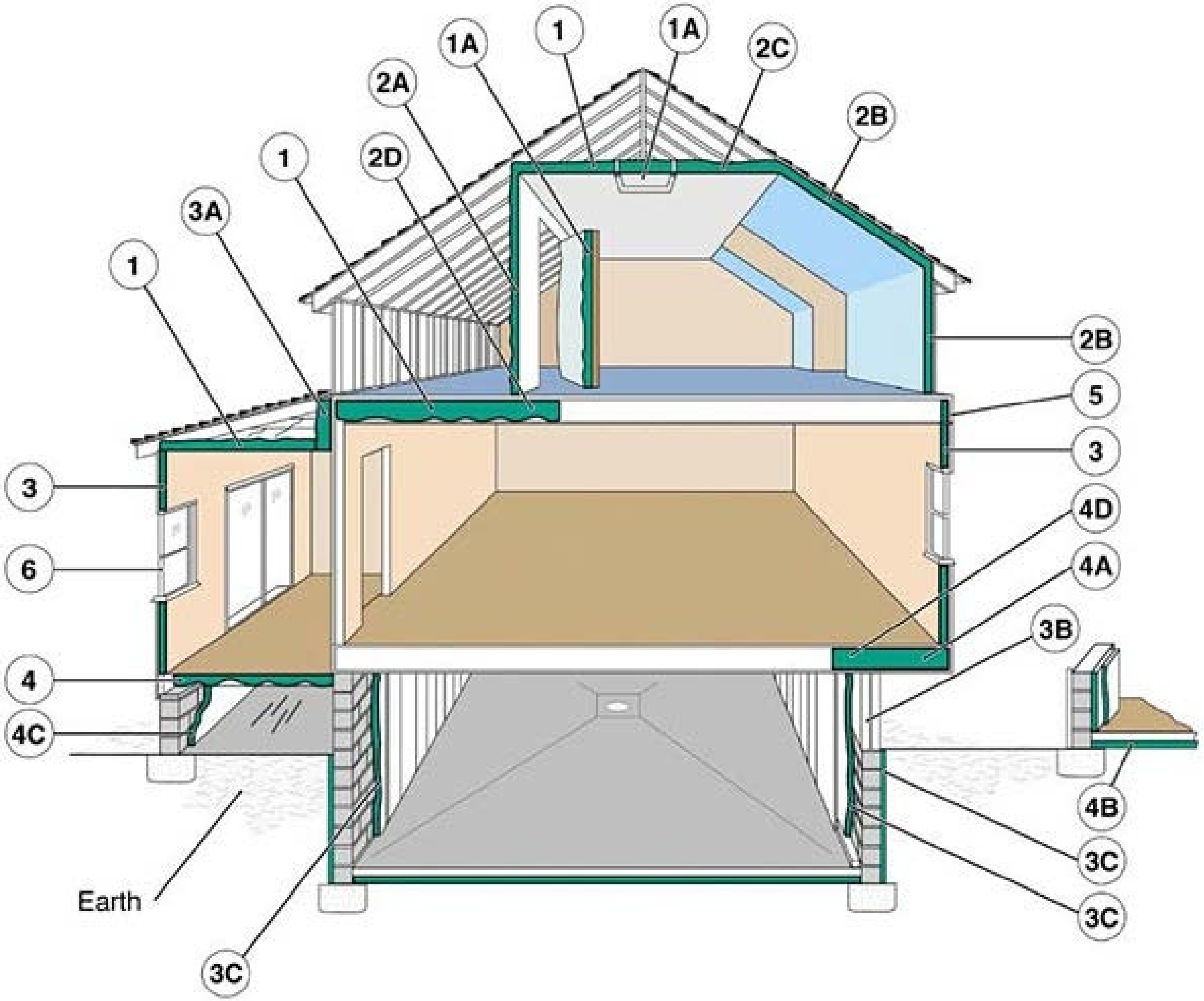
Quality of installation impacts R-value



Source: Dane Christensen, NREL

How much and where

1. Unfinished attic spaces
2. Finished attic rooms
3. All exterior walls
4. Floors above cold spaces
5. Band joists
6. Windows



Source: DOE/ORNL https://www.energy.gov/energysaver/weatherize/insulation/where-insulate-home

Key Points

Strive to go beyond the minimum requirements of the building code

Make an informed decision

- Know ***where*** you are going to install the insulation
- Understand impact of insulation type on all aspects of design, including embodied environmental impact, life cycle cost, indoor air quality, and energy use.

Questions or comments?

Please email SolarDecathlon@nrel.gov

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Authors

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National Renewable Energy Laboratory

References

1. US Department of Energy. *Types of Insulation.* https://www.energy.gov/energysaver/weatherize/insulation/types-insulation
2. US Department of Energy. *Insulation Materials*. https://www.energy.gov/energysaver/weatherize/insulation/insulation-materials

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Building the Next Generation

Building Science Education for Solar Decathlon

Intro to Windows and Fenestration

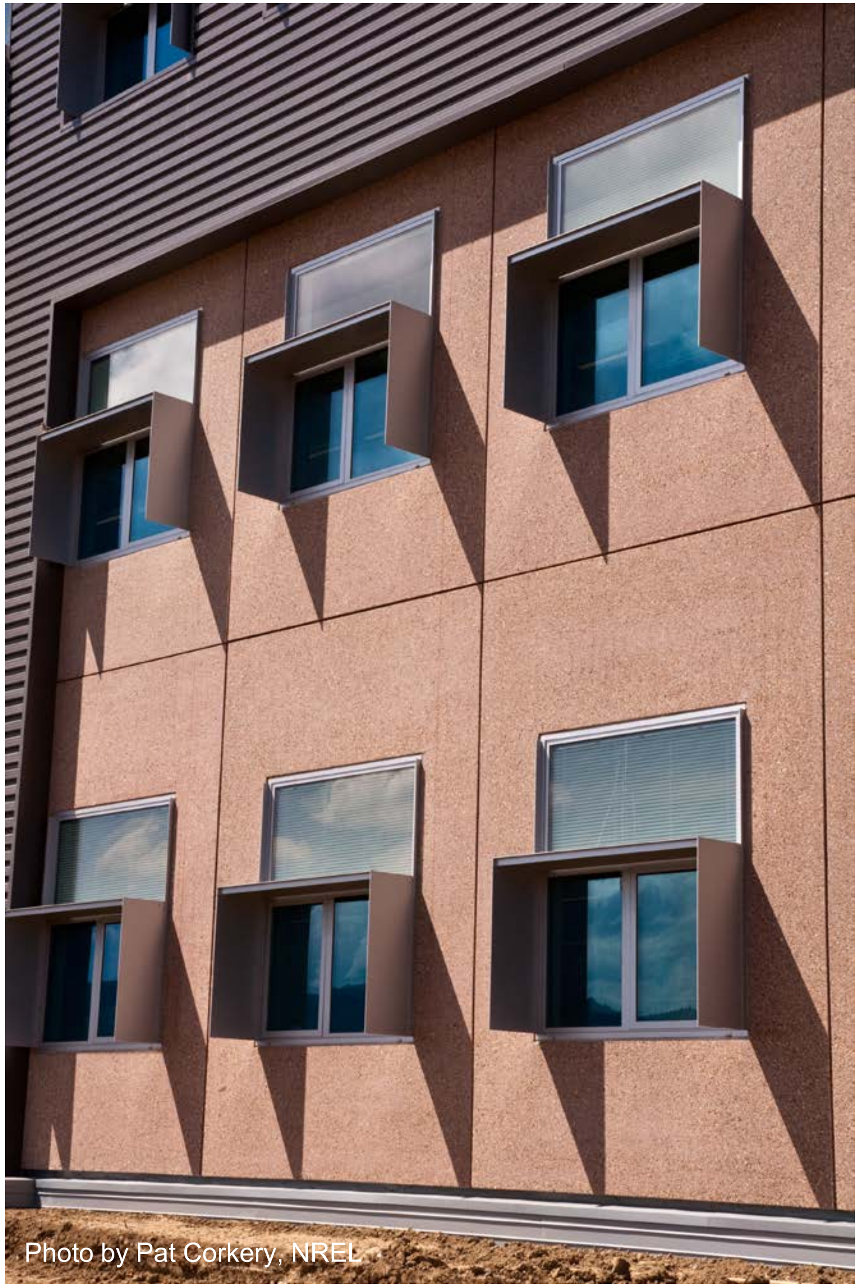
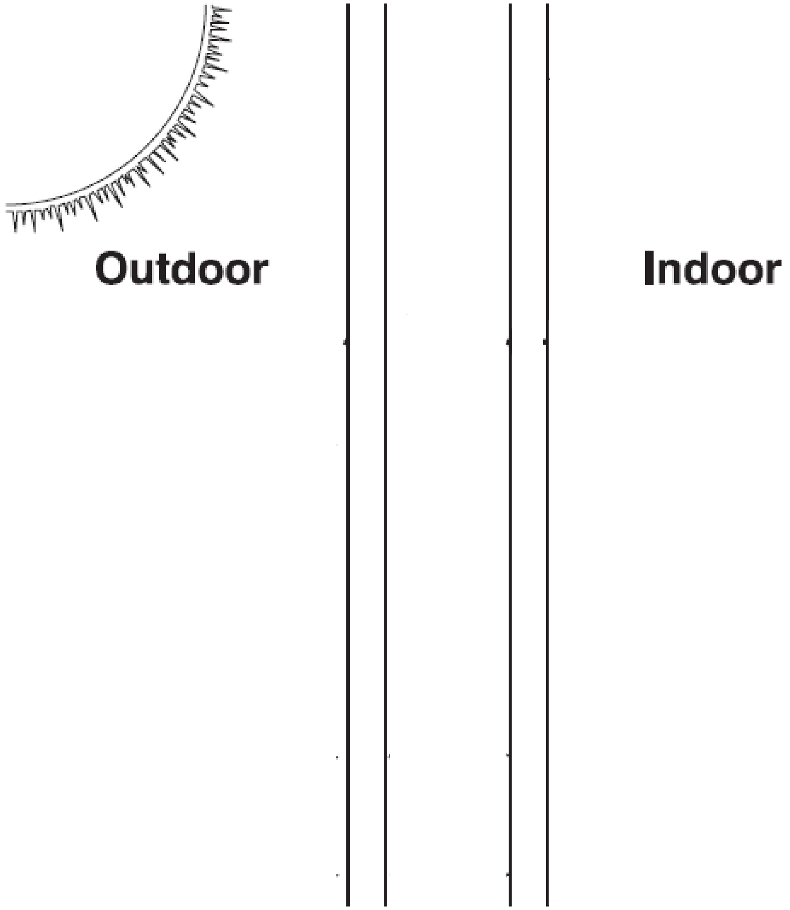
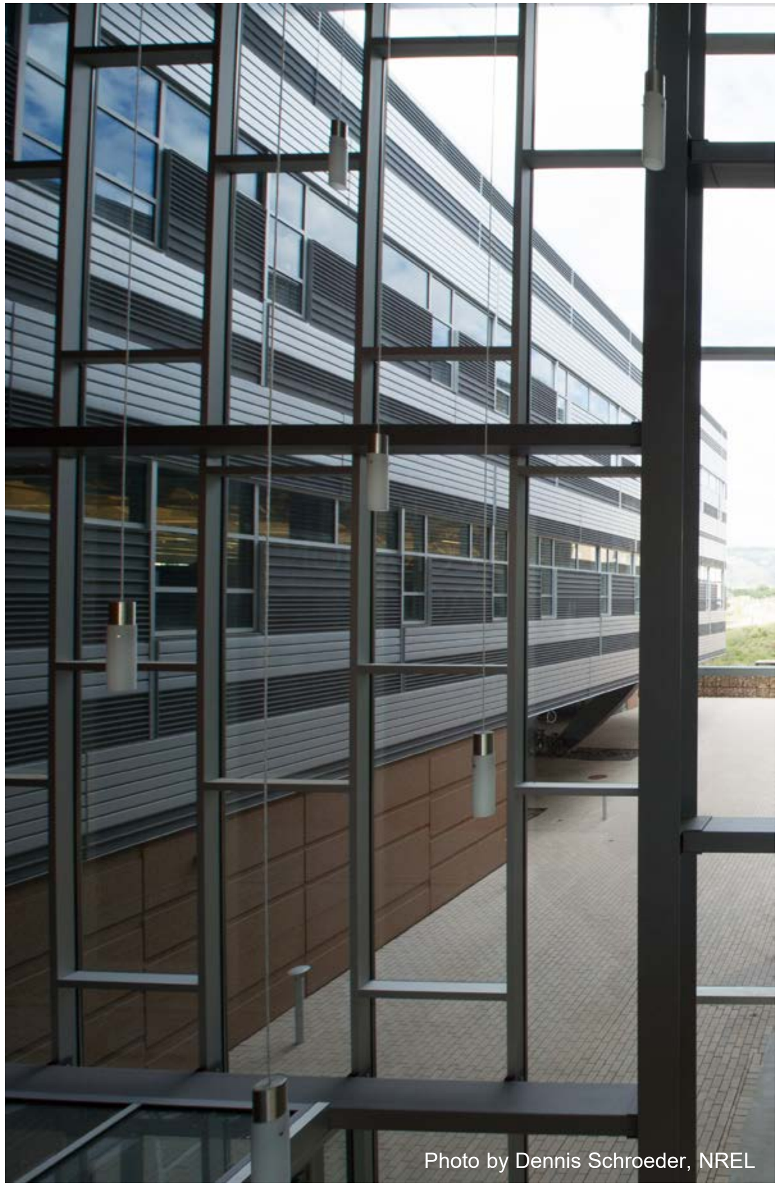


Photo by Pat Corkery, NREL

Windows



Source: Efficient Windows Collaborative[1]



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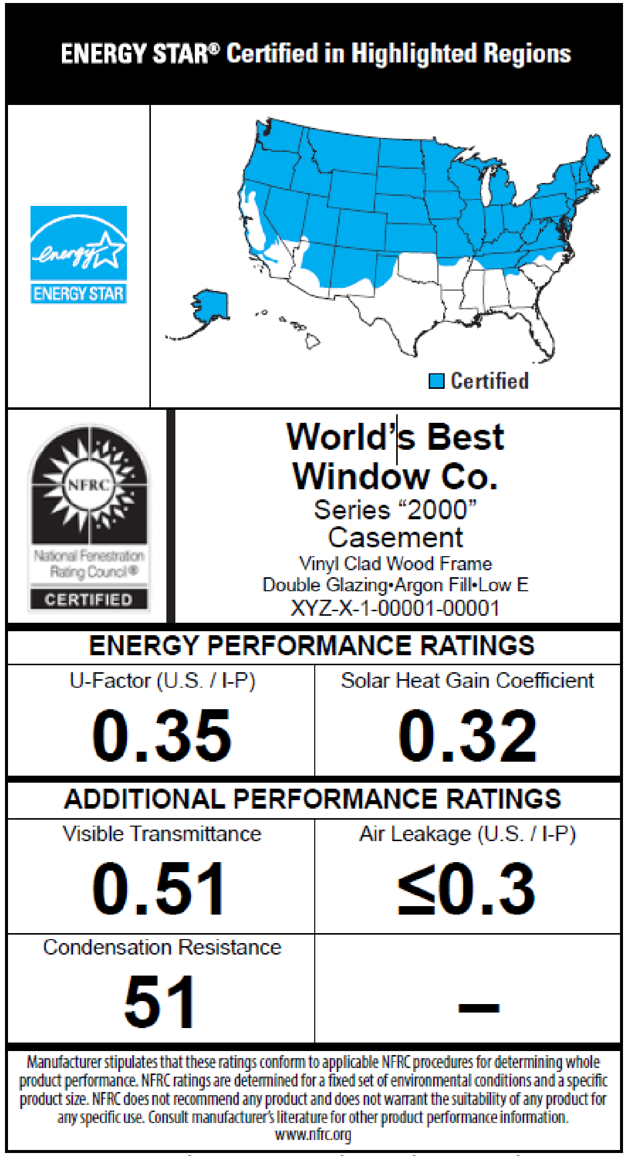
Key Terms

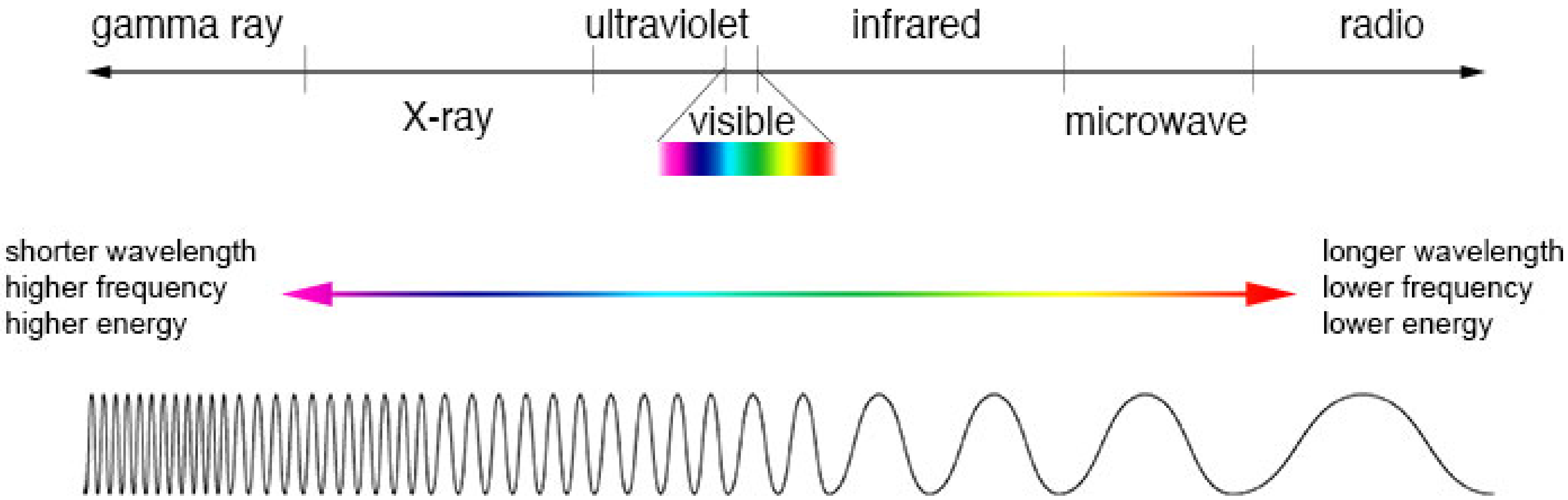
- ✓ U-Factor
- Visible Transmittance (VT)
- Solar Heat Gain Coefficient (SHGC)
- Air Leakage (AL)



NFRC labels on window units give ratings for U-factor, SHGC, visible light transmittance (VT), and (optionally) air leakage (AL) and condensation resistance (CR) ratings.

Credit: DOE[3]

The Electromagnetic Spectrum

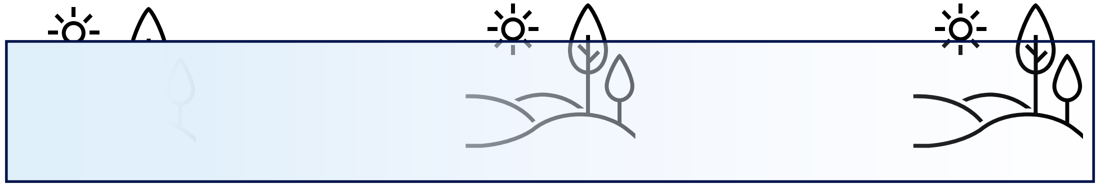


Source: NASA's Imagine the Universe[2]

Key Terms

Visible Transmittance (VT)

the fraction of the *visible* spectrum of sunlight that is transmitted through the glazing of a window, door, or skylight.



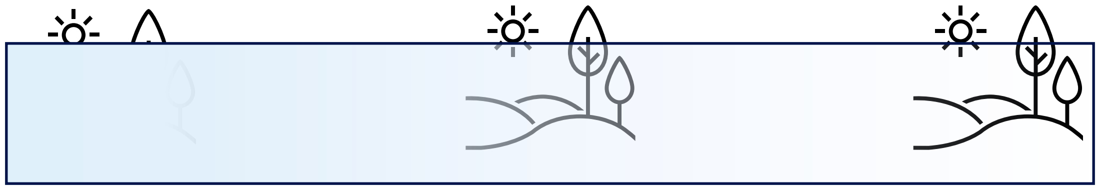
0%
Opaque

100%
Transparent

Key Terms

Visible Transmittance (VT)

the fraction of the *visible* spectrum of sunlight that is transmitted through the glazing of a window, door, or skylight.

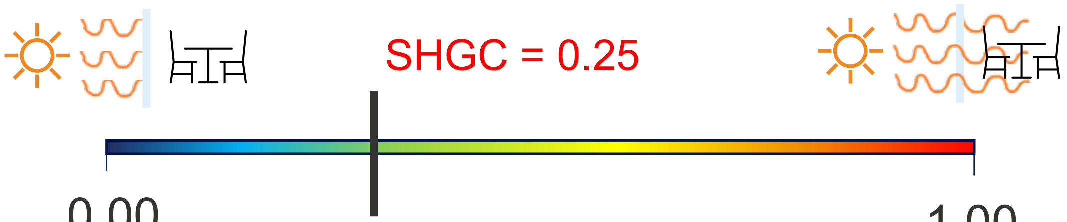


0%
Opaque

100%
Transparent

Solar heat gain coefficient (SHGC)

the fraction of solar radiation admitted through a window, door, or skylight -- either transmitted directly and/or absorbed, and subsequently released as heat inside a home.



0.00
No solar energy transmitted

Allows ¼ of the solar energy through the window

1.00
All solar energy transmitted

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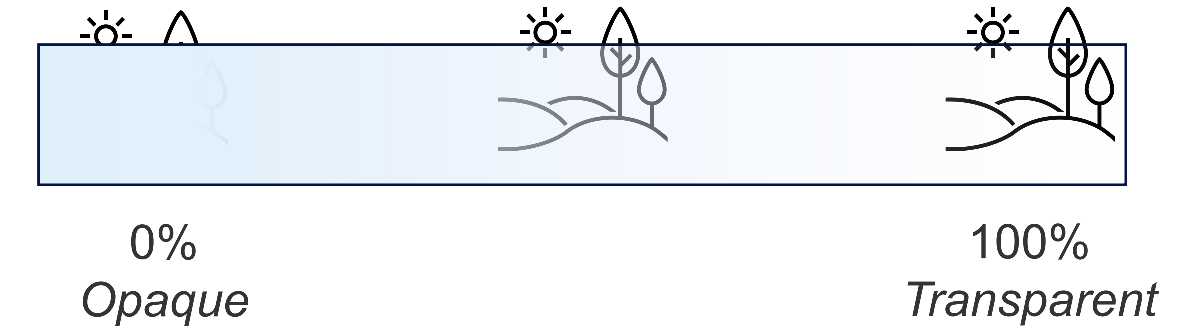
Key Terms

Visible Transmittance (VT)

the fraction of the *visible* spectrum of sunlight that is transmitted through the glazing of a window, door, or skylight.



Solar heat gain coefficient (SHGC)

the fraction of solar radiation admitted through a window, door, or skylight -- either transmitted directly and/or absorbed, and subsequently released as heat inside a home.

Air Leakage (AL)

the rate of air movement around a window, door, or skylight in the presence of a specific pressure difference across it. (Units - cfm/ft^2)

0.30 cfm/ft^2 is required by most codes and standards

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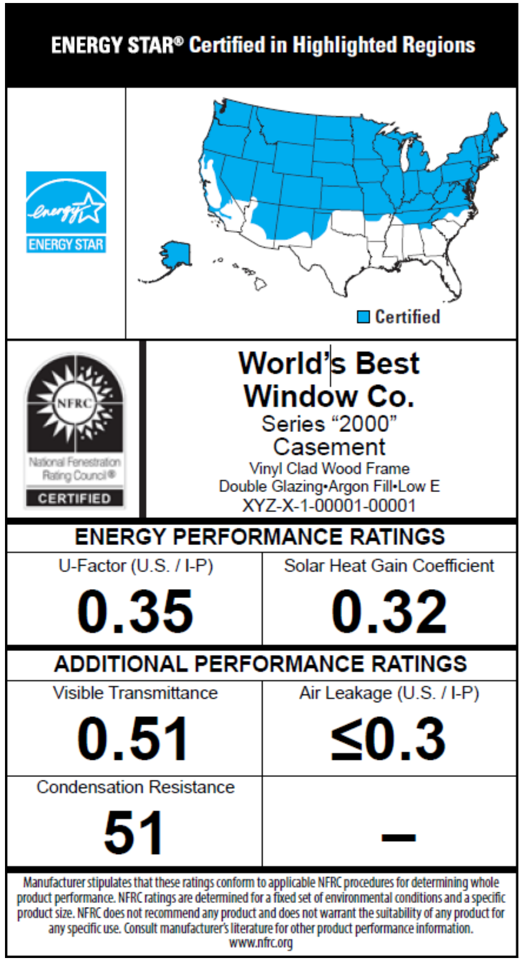
National Fenestration Rating Council

- ✓ U-Factor
- ✓ Visible Transmittance (VT)
- ✓ Solar Heat Gain Coefficient (SHGC)
- ✓ Air Leakage (AL)



NFRC labels on window units give ratings for U-factor, SHGC, visible light transmittance (VT), and (optionally) air leakage (AL) and condensation resistance (CR) ratings.

Credit: DOE[3]

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Reducing U-Factor

3 Modes of Heat Transfer

Conduction

Convection

Radiation

Photo by Dennis Schroeder, NREL

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Single Glazed Window

- Single pane of glass is highly conductive
- Substantial portion of window's resistance to heat transfer comes from convection layer and radiative exchange

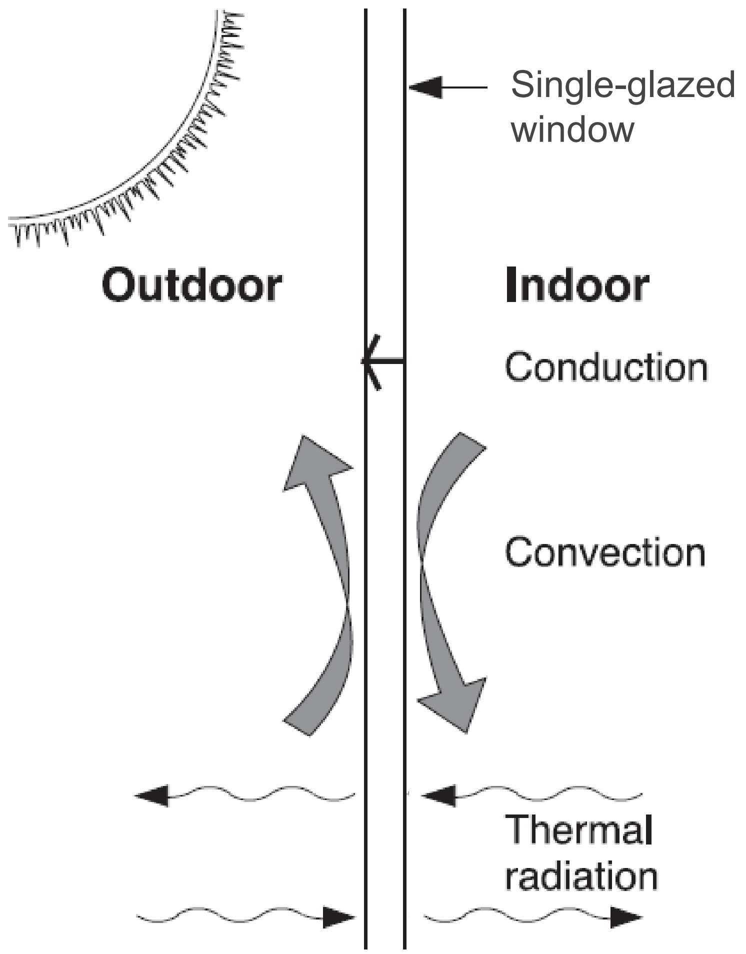

Illustration adapted from Efficient Windows Collaborative

Double Glazed Window

- Conduction is reduced

- Spacing between layers of glazing provide additional thermal resistance
    - Convection can occur in the air gap
    - Spacing is fine-tuned to optimize insulative properties

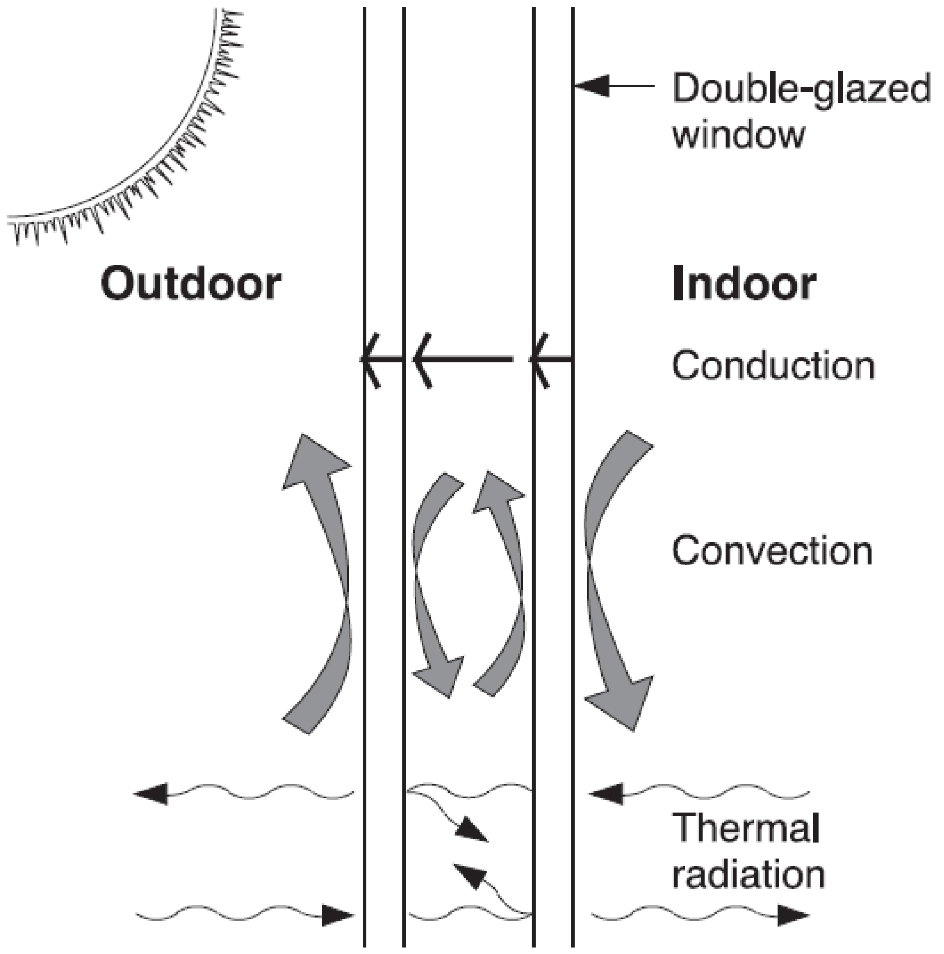

Illustration adapted from Efficient Windows Collaborative

Other Strategies to Reduce Window U-Factor

- Noble-gases (ex. argon)
  - Less dense than air, so less heat transfer
- Aero-gel
  - Encapsulates tiny pockets of air into a clear structure
  - Inhibits convection by separating the air pockets
- Third glazing
  - Third layer of glass
  - Creates two air gaps

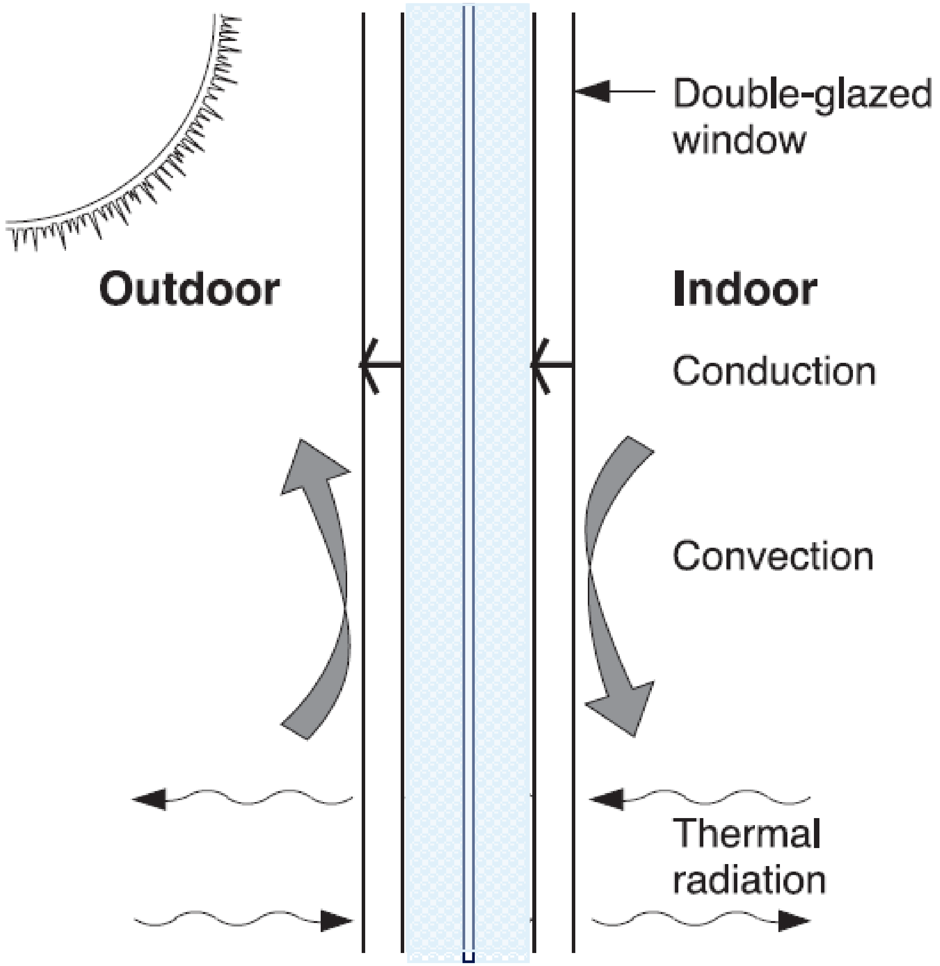

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Illustration adapted from Efficient Windows Collaborative

Low-e Coatings to Reduce Radiative Heat Transfer

- Radiative heat transfer caused by
  - Temperature difference between panes of glass
  - Temperature difference between controlled interior environment and outside
- Low-emissivity (Low-e) coating applied to Surfaces 2 and 3

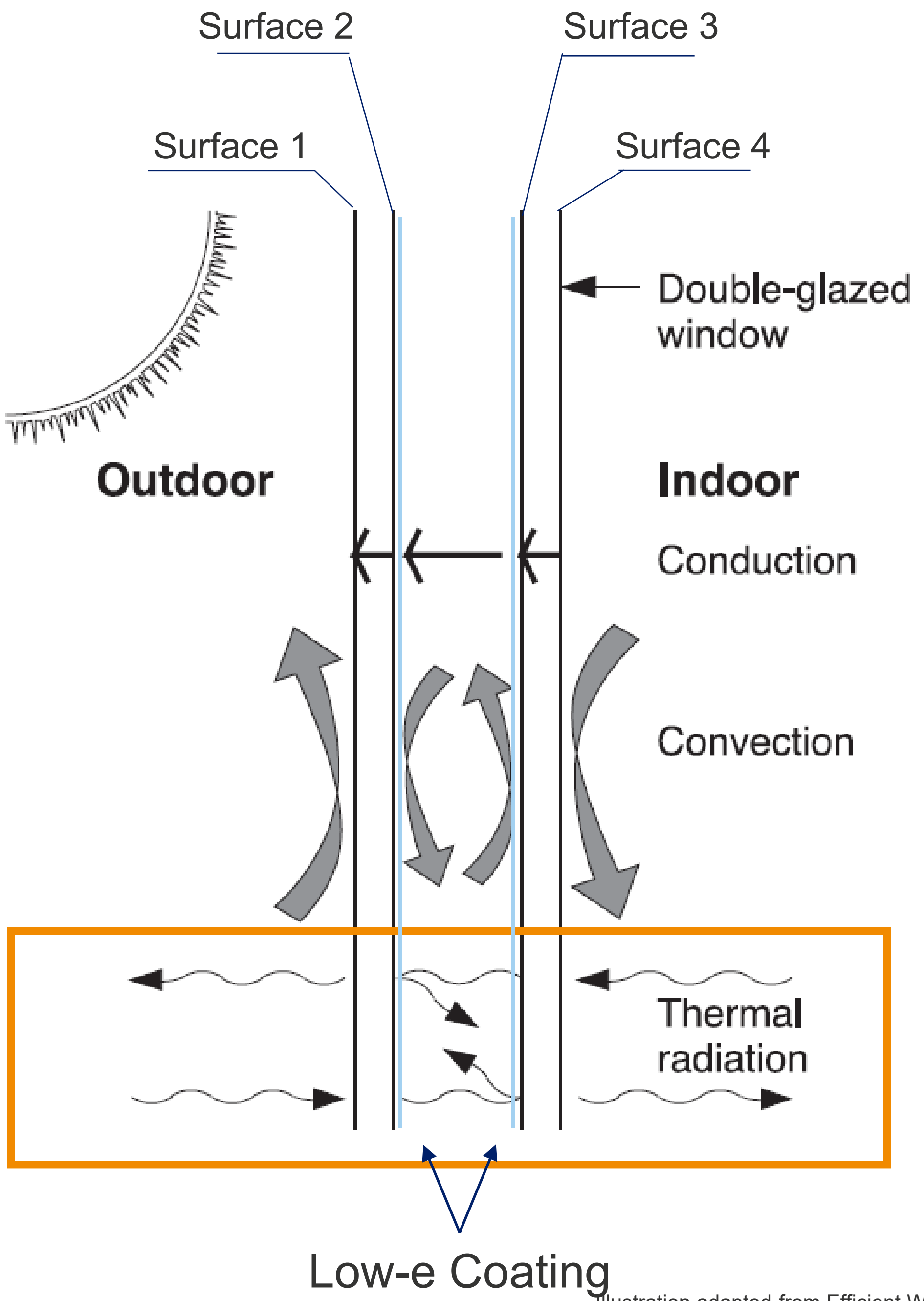

Illustration adapted from Efficient Windows Collaborative

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Low-e Coatings to Reduce Radiative Heat Transfer

- Low-e coating on Surface 2 helps to reflect radiant energy before it can enter the indoor space
- Low-e coating on Surface 3 allows the inner pane of glass to warm up and transfer the sun's thermal energy to the indoor space via conduction

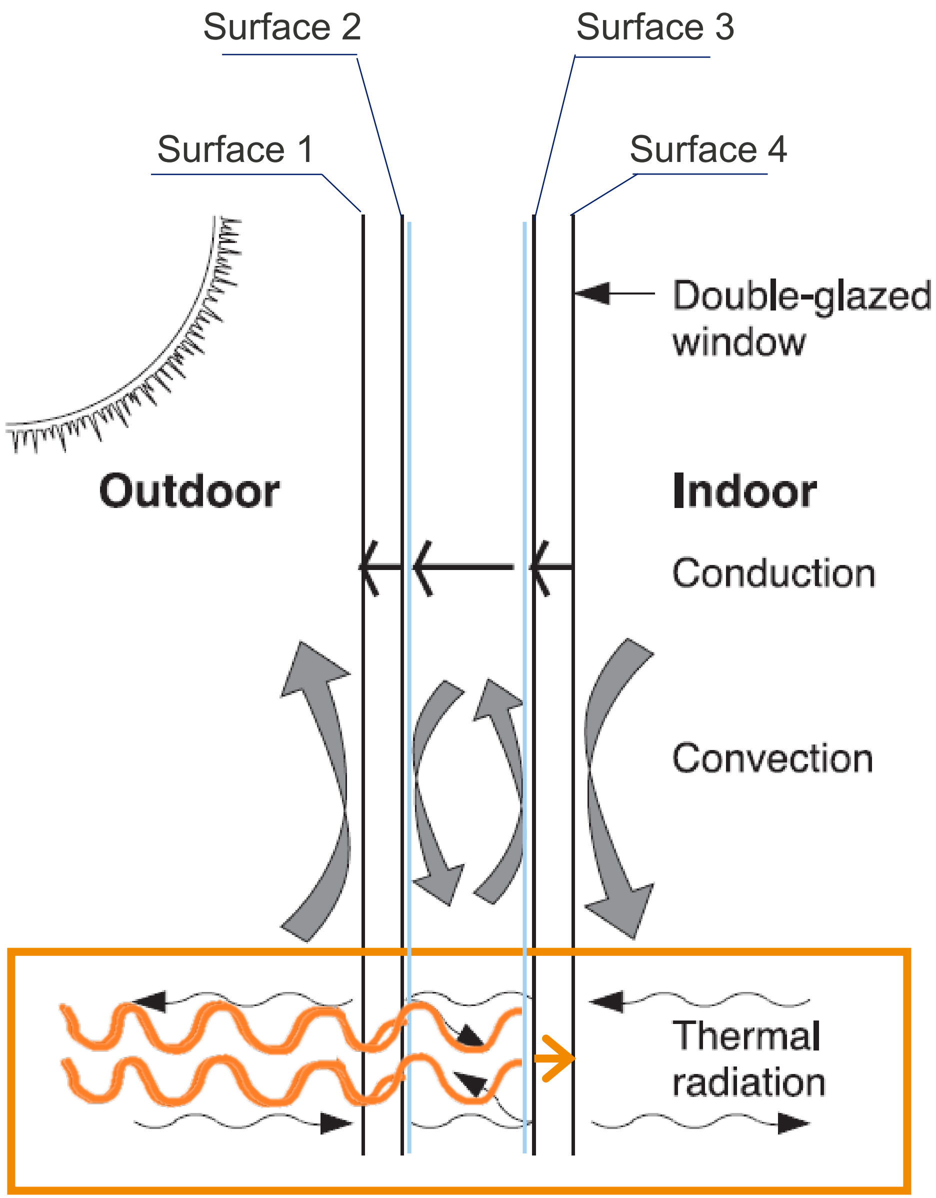

Illustration adapted from Efficient Windows Collaborative

Low-e Coatings to Reduce Radiative Heat Transfer

- Low-e coating on Surface 2 helps to reflect radiant energy before it can enter the indoor space
- Low-e coating on Surface 3 allows the inner pane of glass to warm up and transfer the sun's thermal energy to the indoor space via conduction
    - Also reduces heat loss from the building at night
    - Ideal for beneficial solar heating on south-facing windows (Northern Hemisphere)

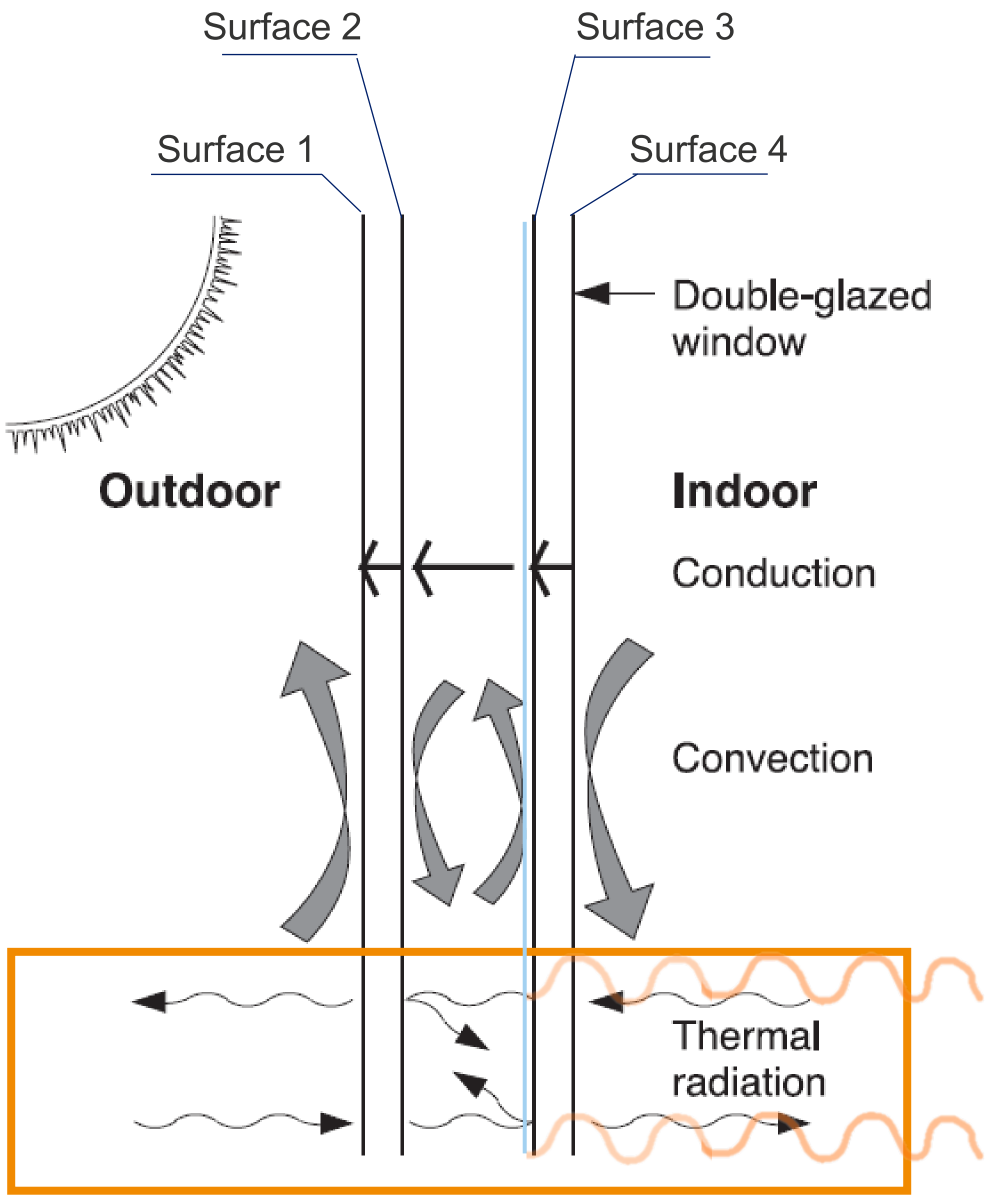

Illustration adapted from Efficient Windows Collaborative

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Building Design Example

If you want free heat from the sun during wintertime…

- You need a window with a high Solar Heat Gain Coefficient (SHGC)
- You also need a low U-factor to limit heat loss
- This is typically achieved by using a Low-e coating on Surface 3 for south-facing windows (in the Northern Hemisphere)

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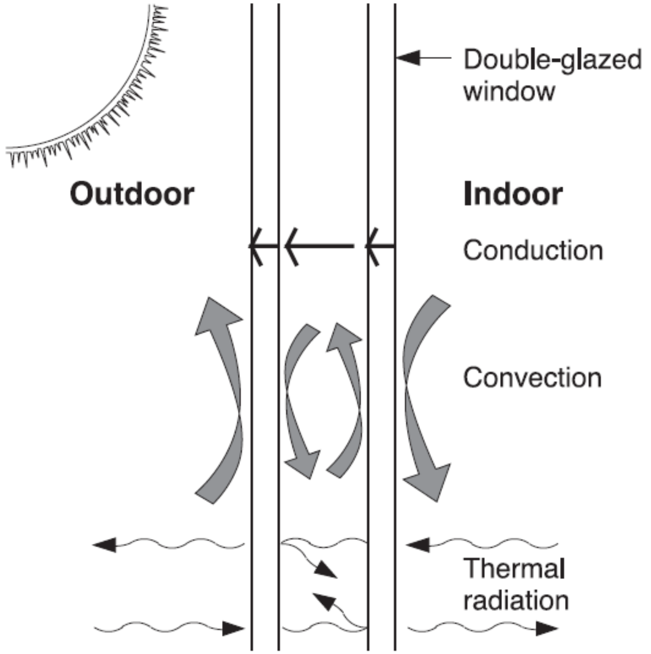
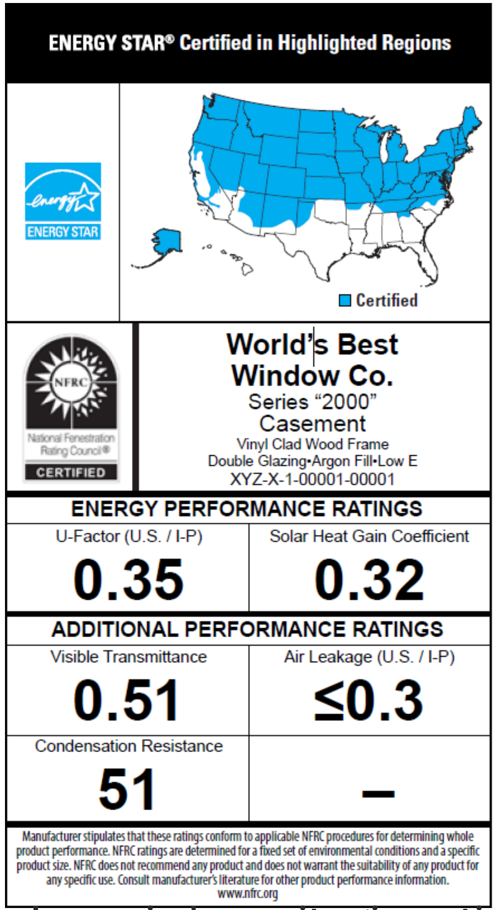
Summary

U-Factor already includes surface film coefficients

- U-Factor
- Visible Transmittance (VT)
- Solar heat gain coefficient (SHGC)
- Air Leakage (AL)





NFRC labels on window units give ratings for U-factor, SHGC, visible light transmittance (VT), and (optionally) air leakage (AL) and condensation resistance (CR) ratings.

Credit: DOE[3]

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Illustration adapted from Efficient Windows Collaborative

Questions or comments?

Please email SolarDecathlon@nrel.gov

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References

1. Efficient Windows Collaborative. *Windows for High Performance Commercial Buildings, Window Technologies: Glass*. https://www.commercialwindows.org/ufactor.php
2. NASA Imagine the Universe. *The Electromagnetic Spectrum*. https://imagine.gsfc.nasa.gov/science/toolbox/emspectrum1.html
3. US Department of Energy. Energy Performance Ratings for Windows, Doors, and Skylights: https://www.energy.gov/energysaver/design/windows-doors-and-skylights/energy-performance-ratings-windows-doors-and#:~:text=Visible%20transmittance%20(VT)%20is%20a,VT%20transmits%20more%20visible%20light

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Building Science Education for Solar Decathlon

The Importance and Opportunity for Advanced Window Technologies

The Importance and Opportunity for Advanced Window Technologies

Presented by Marc LaFrance

Windows Technology Manager

U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy

Photo Source: US Department of Energy, https://www.energy.gov/eere/buildings/contributors/p-marc-lafrance

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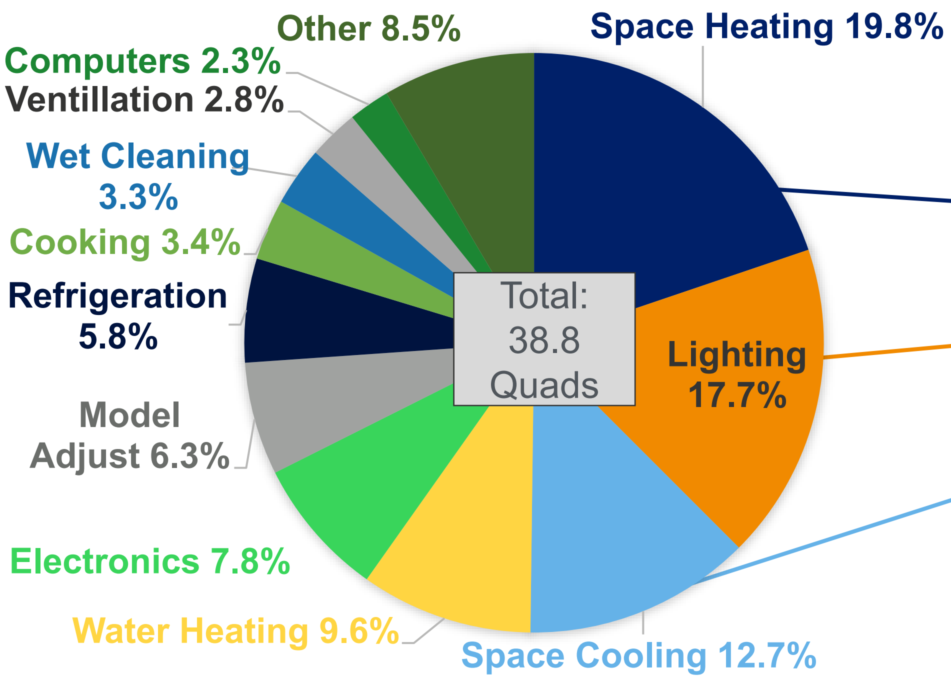
Topics

- General background on windows
  - Opportunity and market perspectives
  - Major energy flows
- Design software and ratings
- ENERGY STAR Criteria
- Technology development goals and targets
- Latest advancements and technologies
  - Highly insulating windows
  - Dynamic solar control
  - Innovative research

U.S. Building's Energy Consumption and Expenditures

Building Energy Use



Envelope & Windows Impact Over 50% of Loads

Windows can have large thermal losses in the winter, as well as beneficial heating through solar gains

Windows can bring in light to reduce electric lighting loads

Windows can adversely add heat in the summer because of solar gains

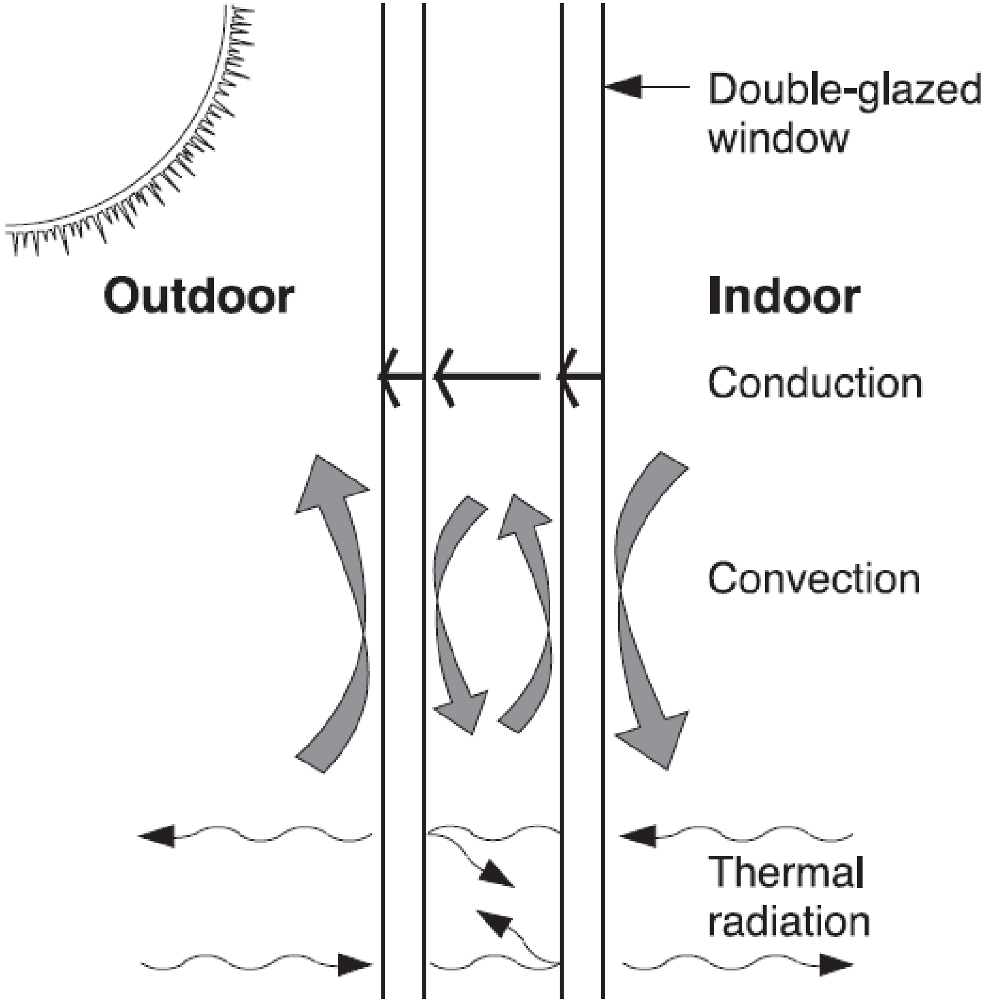
Buildings Natural Gas Use: 60% of U.S. total

Buildings Electricity Use: 75% of U.S. total

U.S. Building Energy Bill: $380 billion per year

Data Source: US Energy Information Administration

Heat and Light Transfer through Windows



More detailed information:

Lawrence Berkeley National Laboratory (LBNL)

Windows and Daylighting, Outreach

https://windows.lbl.gov/outreach

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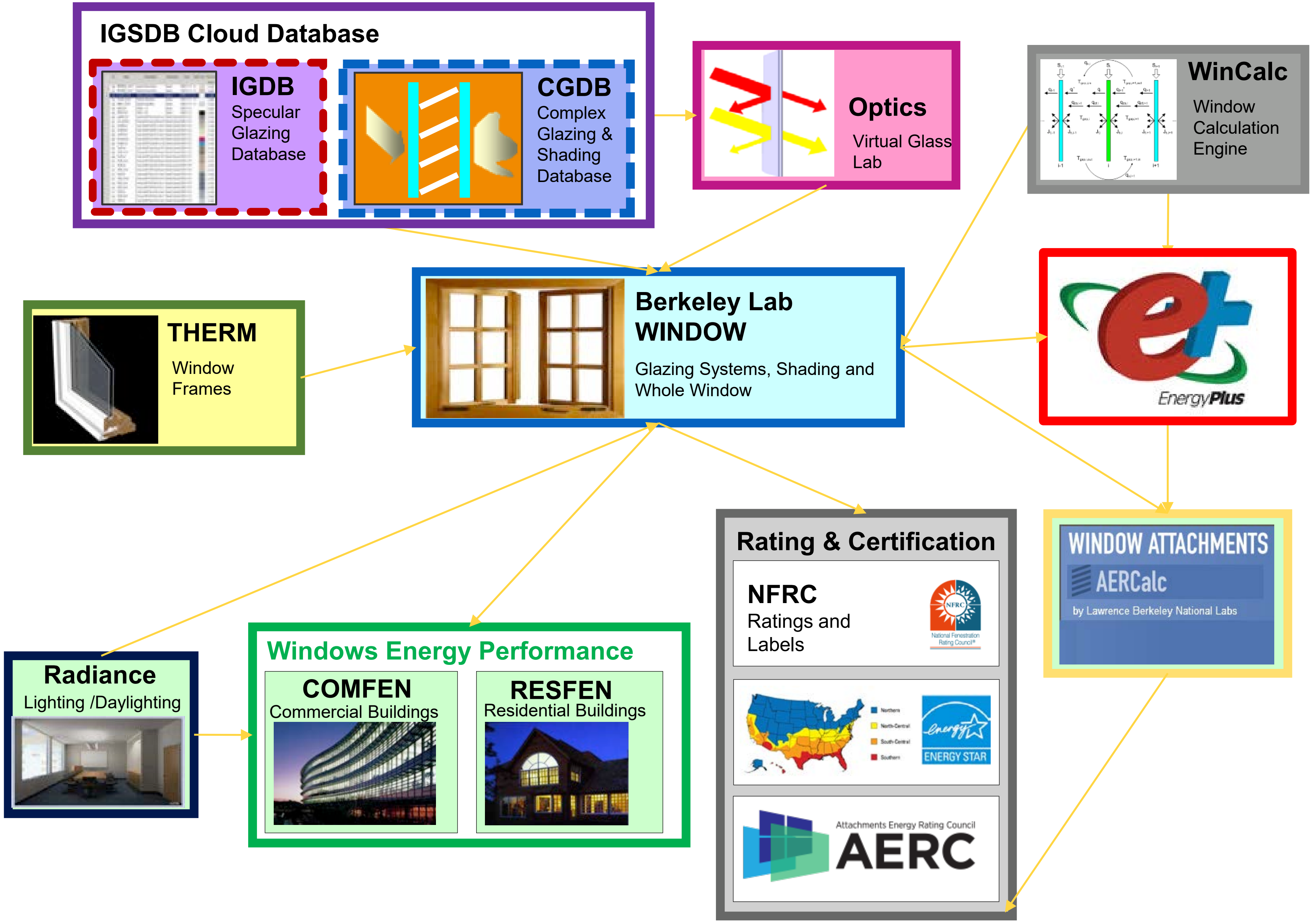
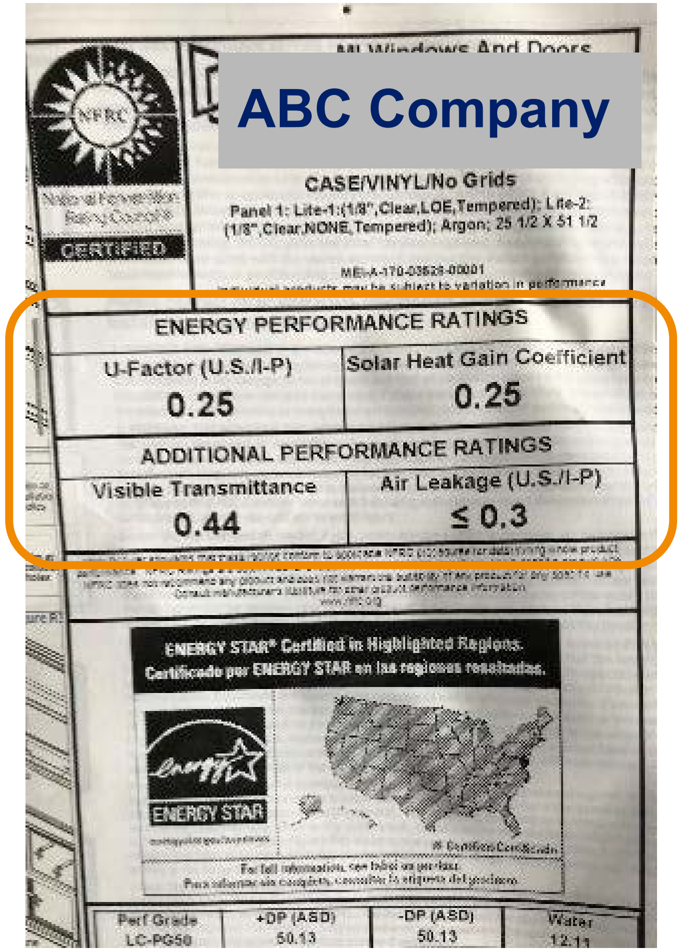
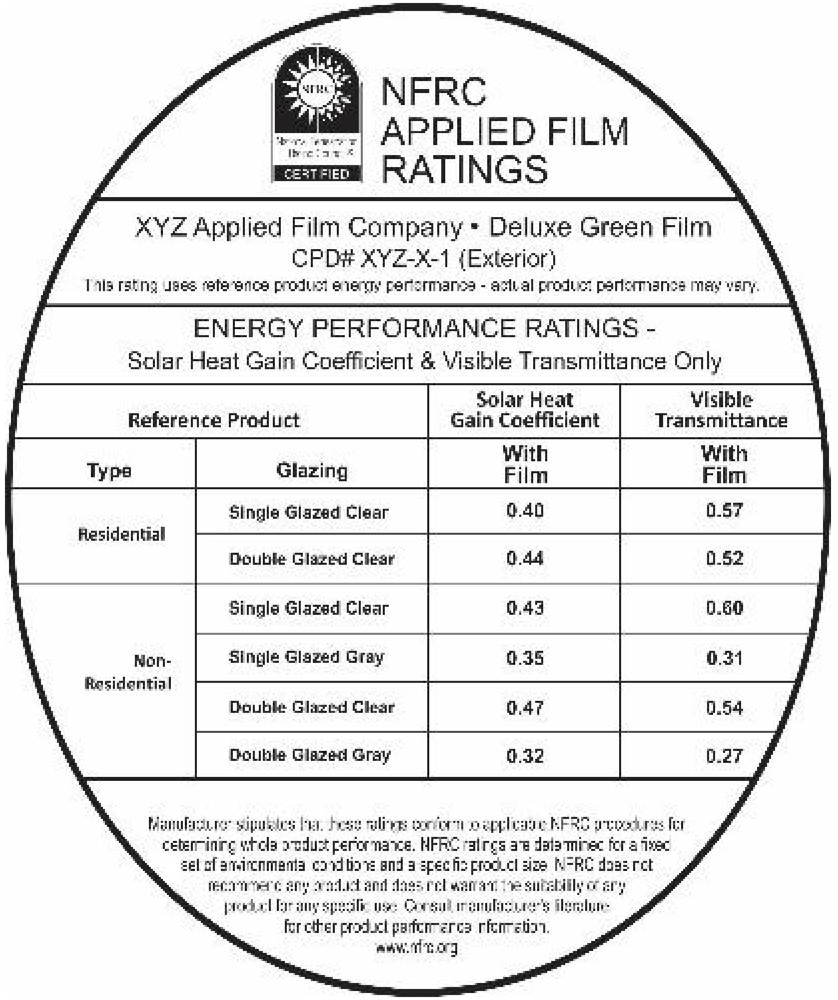
Fenestration Software Tools Eco System



Energy Performance Labels



National Fenestration Rating Council (NFRC)


NFRC APPLIED FILM RATINGS

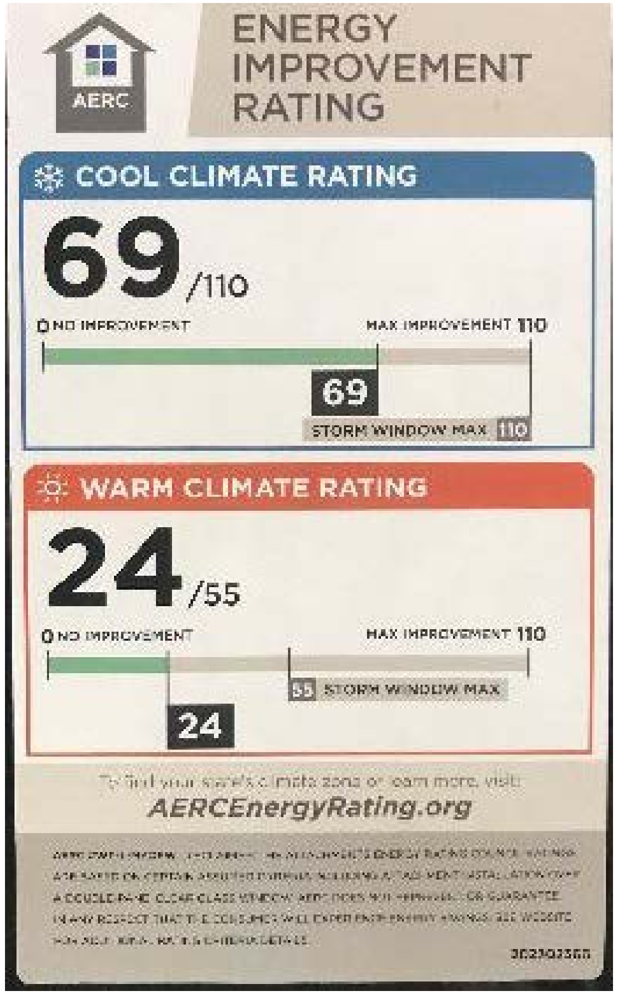
CERTIFIED

XYZ Applied Film Company • Deluxe Green Film
CPD# XYZ-X-1 (Exterior)
This rating uses reference product energy performance - actual product performance may vary.

ENERGY PERFORMANCE RATINGS - Solar Heat Gain Coefficient & Visible Transmittance Only

Reference Product		Solar Heat Gain Coefficient	Visible Transmittance
Type	Glazing	With Film	With Film
Residential	Single Glazed Clear	0.40	0.57
	Double Glazed Clear	0.44	0.52
Non-Residential	Single Glazed Clear	0.43	0.60
	Single Glazed Gray	0.35	0.31
	Double Glazed Clear	0.47	0.54
	Double Glazed Gray	0.32	0.27

Manufacturer stipulates that these ratings conform to applicable NFRC procedures for determining whole product performance. NFRC ratings are determined for a fixed set of environmental conditions and a specific product size. NFRC does not recommend any product and does not warrant the suitability of any product for any specific use. Consult manufacturer's literature for other product performance information.
www.nfrc.org



Attachment Energy Rating Council (AERC)

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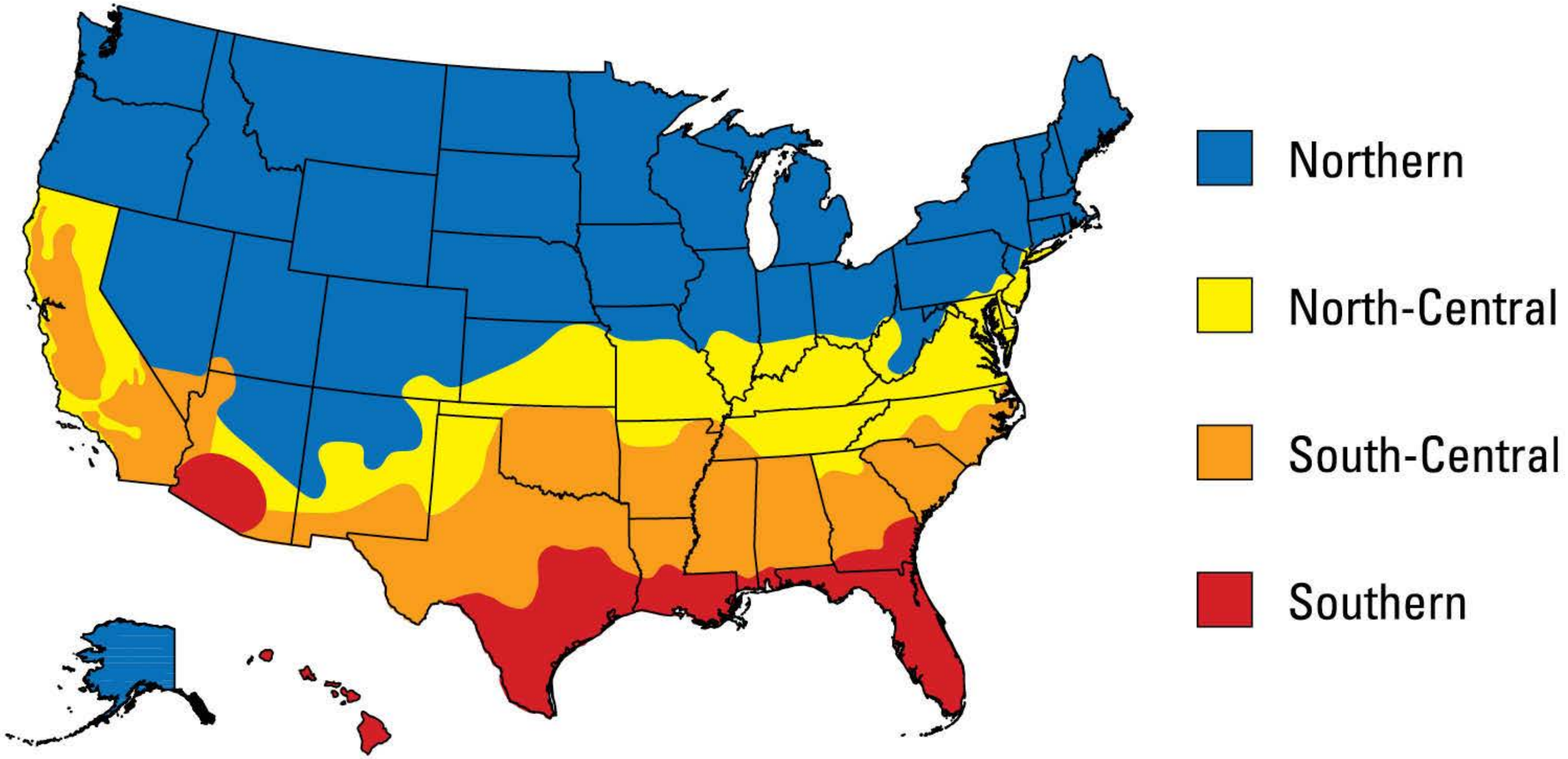
Source: Marc LaFrance

LEARN MORE AT
energystar.gov

ENERGY STAR® for Windows, Doors, and Skylights

CLIMATE ZONE MAP



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Source: https://www.energystar.gov/products/residential_windows_doors_and_skylights/key_product_criteria

ENERGY STAR Final Version 6.0 Specification

Windows

Climate Zone	U-Factor[1]	SHGC[2]	
Northern*	≤ 0.27	Any	Prescriptive
	= 0.28	≥ 0.32	Equivalent Energy Performance
	= 0.29	≥ 0.37	
	= 0.30	≥ 0.42	
North-Central	≤ 0.30	≤ 0.40	
South-Central	≤ 0.30	≤ 0.25	
Southern	≤ 0.40	≤ 0.25	

Air Leakage ≤ 0.3 cfm/ft^2

[1] Btu/h ft^2·°F
[2] Solar Heat Gain Coefficient

* The effective date for the Northern Zone prescriptive and equivalent energy performance criteria for windows is January 1, 2016.

Doors

Glazing Level	U-Factor[1]	SHGC[2]	
Opaque	≤ 0.17	No Rating	
≤ ½-Lite	≤ 0.25	≤ 0.25	
> ½-Lite	≤ 0.30	Northern North-Central	≤ 0.40
		Southern South-Central	≤ 0.25

Air Leakage for Sliding Doors ≤ 0.3 cfm/ft^2
Air Leakage for Swinging Doors ≤ 0.5 cfm/ft^2

Skylights

Climate Zone	U-Factor[1]	SHGC[2]
Northern	≤ 0.50	Any
North-Central	≤ 0.53	≤ 0.35
South-Central	≤ 0.53	≤ 0.28
Southern	≤ 0.60	≤ 0.28

Air Leakage ≤ 0.3 cfm/ft^2

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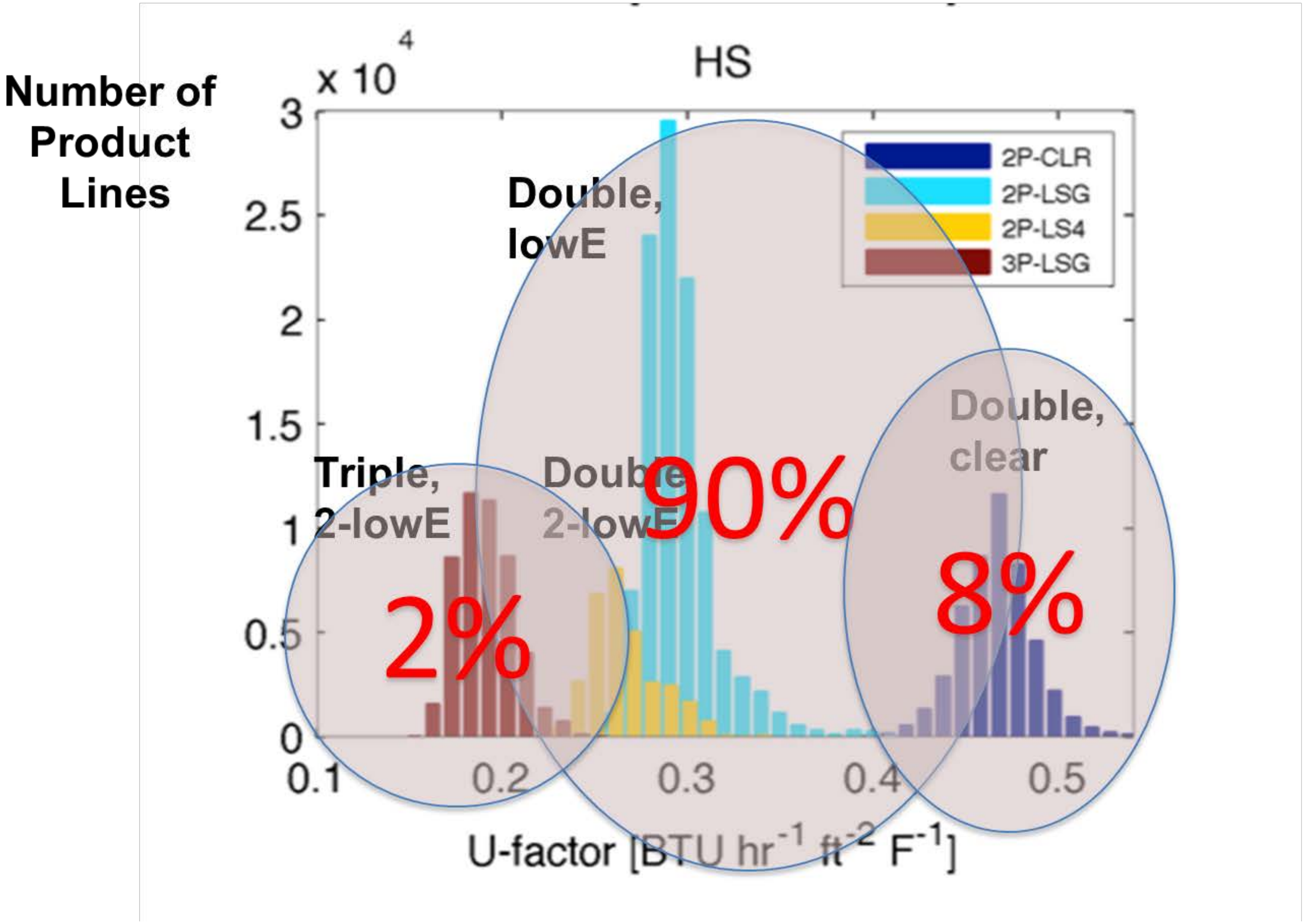
Market Snapshot

Source: EPA ENERGYSTAR analysis, Horiz. sliding windows



Window Metrics and Targets by Technology

	Building Sector	Performance		Installed Price Premium		Primary Energy Savings (quads)	
						2030	2050
Highly Insulating Windows	Residential	13	R-value	2.9	\$/ft^2 window area	1.28	1.07
	Commercial	10		8.5		0.93	0.72
Dynamic Windows	Residential	0.05/0.65	SHGC (active/inactive)	2.9	\$/ft^2 window area	1.35	1.5
	Commercial			15		1.56	1.64
Daylighting	Commercial	40%	Lighting energy savings	13	\$/ft^2 window area	0.26	0.17

Windows Research and Development Opportunities Report (DRAFT)

https://www.energy.gov/eere/buildings/downloads/research-and-development-opportunities-report-windows

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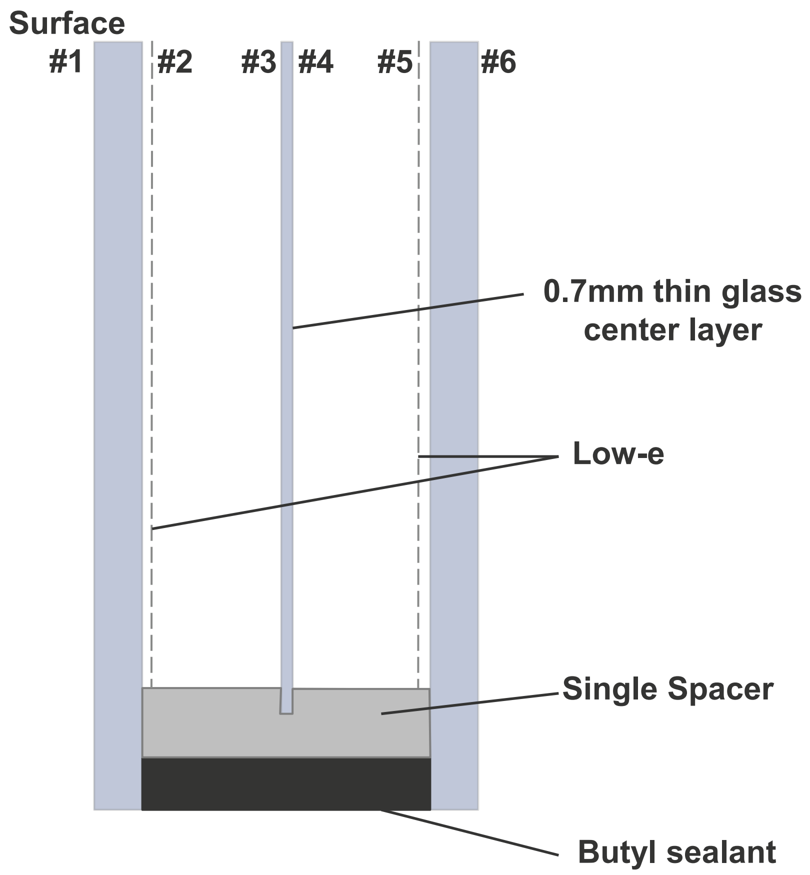
Latest Breakthrough – Thin Triple Pane Glazings



- Thin float glass
  - 0.7 - 1.6 mm
- Multiple suppliers
- 2 Low-E coatings
- Krypton gas fill
- Non-structural center
  - 2 seals, not 4
- Infrastructure exists
- “Affordable”

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Field Studies of Thin Triples

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Source: Marc LaFrance

Variable Solar Control and Daylighting

Electrochromic Windows

Electrochromic windows can tint to reduce solar gain. They can be controlled manually or automated to respond to a control signal

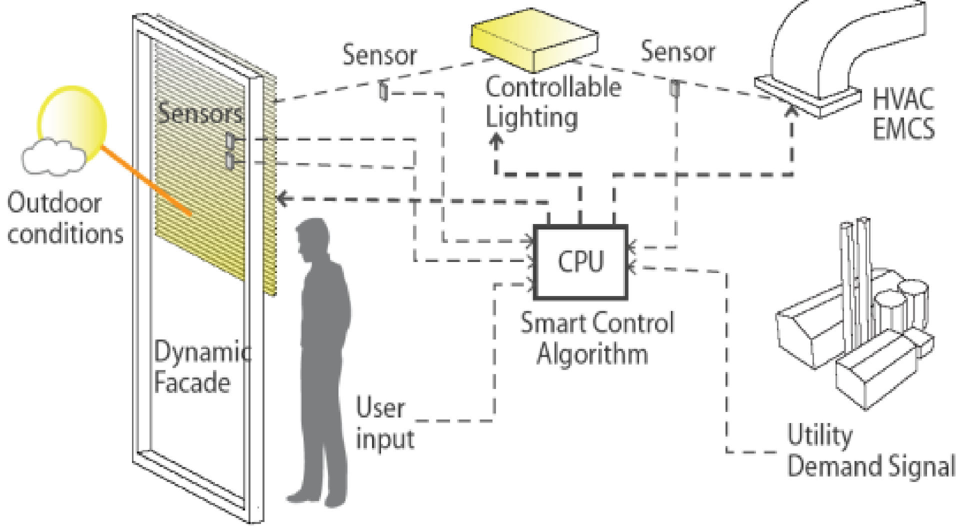
Source: sageglass.com

Automated Shading

Automated (motorized) shading can reduce solar gains and modulate light levels. Exterior shading is particularly effective for reducing cooling

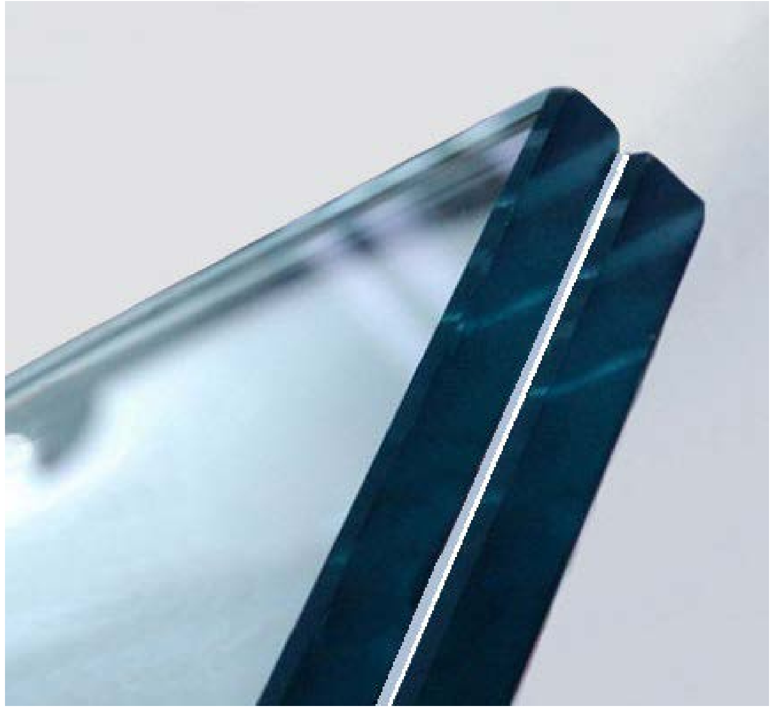
Dynamic – Integrated Facades

- Dynamic solar control - automated shades and dynamic glass
- Validated large peak electricity reduction and lighting savings at US Government buildings and other locations
- R&D on core technology and integration (natural daylight, controls, and grid responsive)



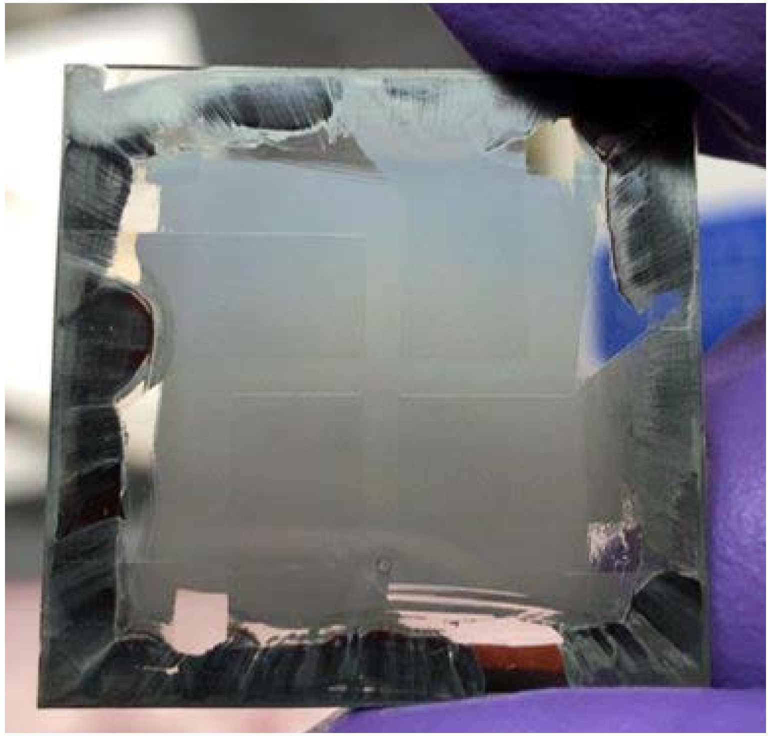
Source: https://eta-intranet.lbl.gov/sites/default/files/lightingsystemsintegration_scoping_study_draft_20200714.pdf

Innovative and Exploratory Technologies



Vacuum Glazing

Aerogel



Thermochromic Photovoltaic

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source: https://www.energy.gov/sites/default/files/2019/05/f62/bto-peer%E2%80%932019-vacuum-glass-r-10-windows.pdf , https://innovationgateway.vcu.edu/technologies/engineering/energy-efficient-windows.html

Summary

High performance windows are critical to save energy and to achieve zero energy buildings

Triple pane windows with dynamic solar control are market ready, but improvements are still needed to reduce market barriers and to become affordable

Many new opportunities for windows exist that can become net energy providers in mixed and cold climate - a home with R10 highly insulating dynamic windows, will use less energy than a home without windows

Extensive tools available for the design of windows and the impact in buildings through whole building modeling – system level benefits allows for lower capacity HVAC system and elimination of ducts near the perimeter

Questions or comments?

Please email SolarDecathlon@nrel.gov

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Accenture Federal Services

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National Renewable Energy Laboratory

Links and References

1. Building Technology Office, Emerging Technologies, Windows and Envelope, https://www.energy.gov/eere/buildings/windows-and-building-envelope
2. Window Research and Development Opportunity Report (Draft), https://www.energy.gov/eere/buildings/downloads/research-and-development-opportunities-report-windows
3. LBNL Windows and Daylighting; resources, software, research studies, https://windows.lbl.gov/
4. National Fenestration Rating Council, https://www.nfrc.org/
5. Attachment Energy Rating Council, https://aercnet.org/
6. EPA ENERGY STAR Windows Program, https://www.energystar.gov/products/building_products/residential_windows_doors_and_skylights

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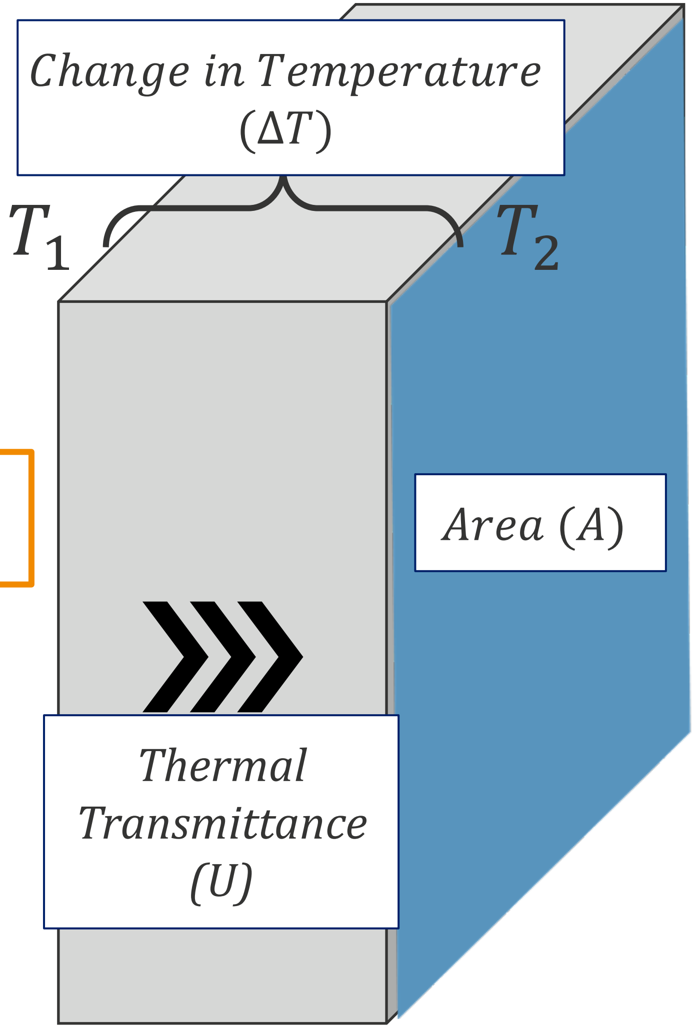
Infiltration


Photo by Dennis Schroeder, NREL

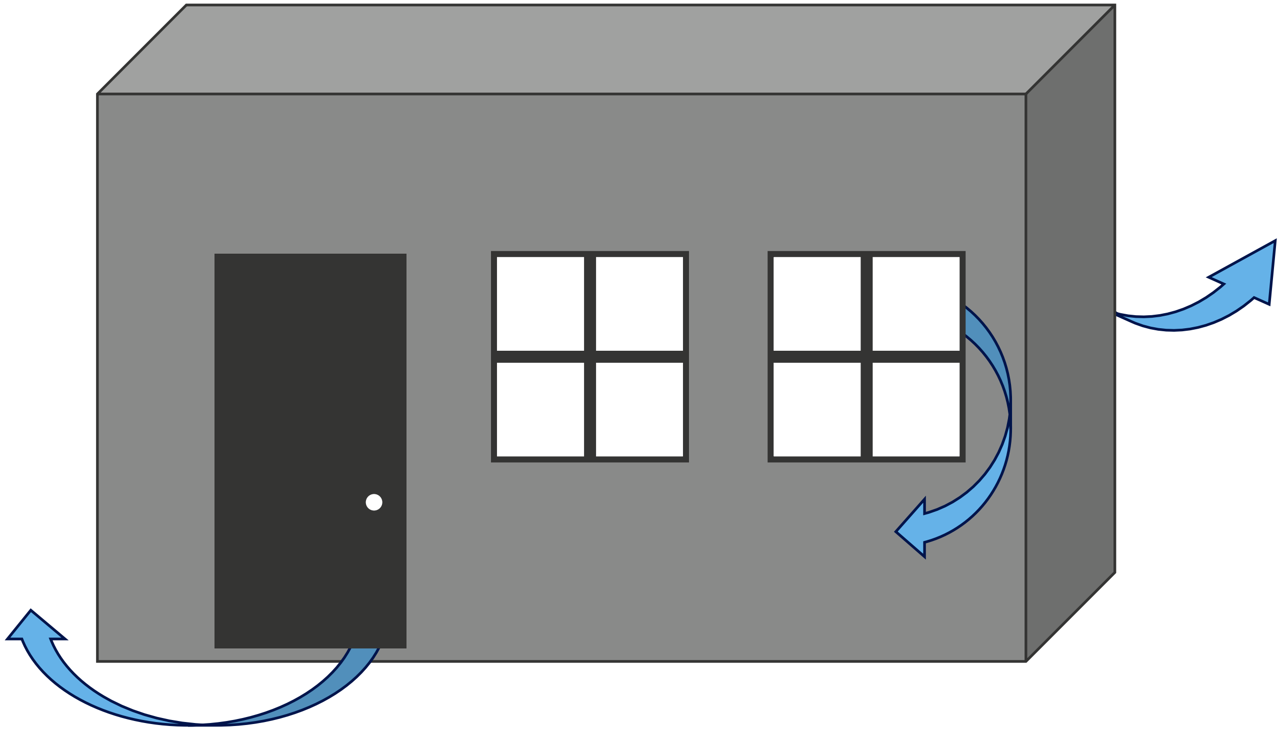
Fourier's Law of Heat Transfer

$$\dot{Q} = U \cdot A \cdot \Delta T$$



Heat Transfer via Air Infiltration

"Infiltration" describes air that comes **into** the building. If air is moving in, then that air must also be leaving or exfiltrating.



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Heat Transfer via Air Infiltration

$$Q = m \cdot c_p \cdot \Delta T$$

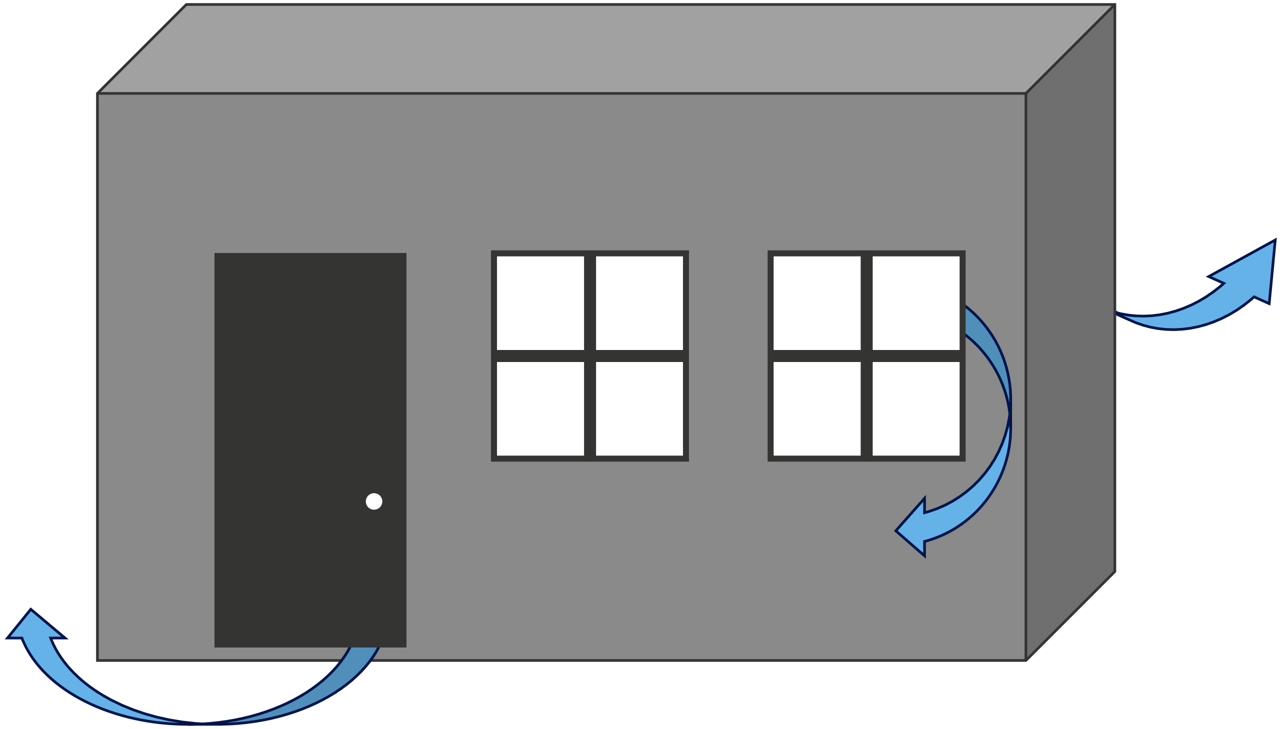
- Q: Amount of energy required to heat the air
- m: Air mass
- c_p: Air's specific heat (constant)
- ΔT: Change in temperature of the air (constant)

$$\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T$$

- $\dot{Q}$: Heat transfer rate
- $\dot{m}$: Mass flow rate

Air that leaves the structure represents energy that is lost from the building and cannot be recovered. Replacement air brought in from the outside must be heated or cooled to maintain a comfortable indoor environment.

Because the mass of the air in the building at any given time does not change, then the amount of air entering the building must equal the amount of air that is escaping the building.



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However, mass flow rate is not a common way to measure air movement through the building envelope…

A more common measurement is the Volumetric Flow Rate, measured in cubic feet per minute

$$\dot{V} \propto \frac{ft^3}{min} \text{ or "cfm"}$$

$$\dot{V} = \frac{\dot{m}}{\rho_{air}} \left[\frac{lb/min}{lb/ft^3}\right]$$

$$\dot{Q} = \dot{V} \cdot \rho_{air} \cdot c_p \cdot \Delta T$$

$$\dot{Q} = \dot{V} \cdot 0.07298 \cdot 0.4299 \cdot \Delta T$$

$$\dot{Q} = 0.018 \left[\frac{Btu}{ft^3 \cdot °F}\right] \cdot \dot{V} \left[\frac{ft^3}{min}\right] \cdot \Delta T[°F]$$

At room temperature: $\rho_{air} = 0.07298\, lb/ft^3$, $c_p = 0.4299\, Btu/lb \cdot °F$

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Volumetric Flow Rate of Air

Changes based on several parameters…

ΔT (difference in temperature from inside to outside)	Pressure gradient from a “stack effect”	Wind

Ultimately, we want a simple metric to account for many of these parameters, so infiltration rate is typically expressed in terms of Air Changes per Hour (ACH).

ACH indicates how many times the total volume of air in the building is exchanged with the outdoor air each hour.

Infiltration Rate | Air Changes per Hour (ACH)

1 ACH → **All of the air inside the building is replaced by fresh outdoor air every hour**

Today, it is common for buildings to have an infiltration rate of 0.2 ACH, meaning the air in the building is exchanged with outdoor air once every five hours.

Example

Assume:

- Infiltration Rate = 0.2 ACH
- Outside Temperature = 20°F
- Inside Temperature = 70°F
- Building Volume = 10,000 ft^3

Find the heat lost by infiltration.

$$\dot{Q} = 0.018 \cdot \dot{V} \cdot \Delta T$$

$$\dot{V} = 0.2\,ACH \cdot 10{,}000\,ft^3 = 2{,}000\,\frac{ft^3}{hr}$$

$$\Delta T = 70°F - 20°F = 50°F$$

$$\dot{Q} = 0.018\left[\frac{Btu}{\cancel{ft^3} \cdot \cancel{°F}}\right] \cdot 2{,}000\left[\frac{\cancel{ft^3}}{hr}\right] \cdot 50[\cancel{°F}]$$

$$\dot{Q} = 1{,}800\left[\frac{Btu}{hr}\right]$$

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Example

Assume:

- Building Volume = 10,000 ft^3
- Infiltration Rate = 0.2 ACH
- Outside Temperature = 20°F
- Inside Temperature = 70°F
- Annual HDD = 6,000 °F·days

Find the heat lost by infiltration.

$$\dot{Q} = 0.018 \cdot \dot{V} \cdot \Delta T$$

$$\dot{Q} \cdot t = 0.018 \cdot \dot{V} \cdot \Delta T \cdot t$$

$$Q = 0.018 \cdot \dot{V} \cdot HDD$$

$$Q = 0.018 \left[\frac{Btu}{ft^3 \cdot {}^\circ F}\right] \cdot 2{,}000 \left[\frac{ft^3}{hr}\right] \cdot 6{,}000 \left[\frac{{}^\circ F \cdot days}{season}\right] \cdot 24 \left[\frac{hr}{day}\right]$$

$$Q = 5{,}184{,}000 \left[\frac{Btu}{season}\right] = 5.184 \left[\frac{MMBtu}{season}\right]$$

Heat lost through infiltration (Does not include heat lost by conduction through the building envelope)

Questions or comments?

Please email SolarDecathlon@nrel.gov

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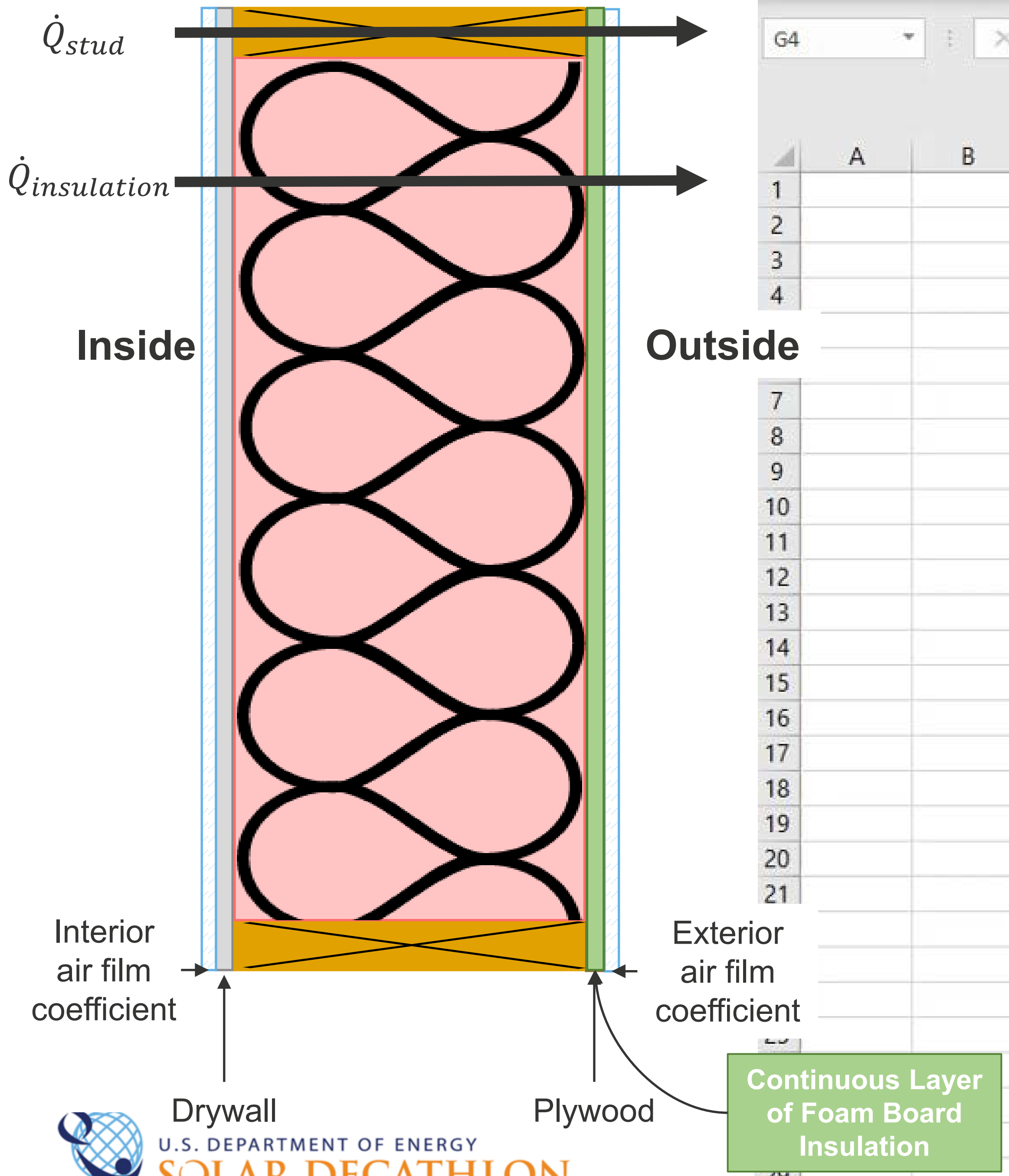
Calculating R-Value for a Wall (Part 3)

Photo by Thomas Kelsey, US DOE Solar Decathlon

Episode ID: 0314-201223



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G4 | 1.5

	D	E	F	G	H
1					
2	Calculating Overall R-values		Stud spacing	16.00	inches
3	for walls with different		Stud cavity thickness	3.50	inches
4	heat transfer paths		Stud Width	1.50	inches
			or Framing Factor		%
7			[IP Units]	R-value	R-value
8	**Wall Layers (inside to outside)**	**Thickness (inches)**	**R-value/inch**	**Path1**	**Path 2**
9					
10	Interior Air Film Coefficient			0.68	0.68
11	Drywall	0.50	1.10	0.55	0.55
12					
13	<beginning path1>				
14	Wooden Stud	3.50	0.94	3.29	
15		3.50		0.00	
16	>beginning path2>				
17	Fiberglass Insulation	3.50	3.14		10.99
18		3.50			0.00
19					
20	<end path>				
21				0.00	0.00
	Plywood	0.50	1.56	0.78	0.78
	Exterior Air Film Coefficient			0.17	0.17
			R-Value Totals/Path	**5.47**	**13.17**
			Framing Factor	0.0938	
			U-factor	0.0860	
30			**Overall R-Value**	**11.63**	
31					

Questions or comments?

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Building Envelope Control Layers


Photo by US Department of Commerce, National Institute of Standards and Technology (NIST)

Episode ID: 0315-220719

The Purpose of a Building

- Shelter – a basic human need
- Building envelope – separates the inside of the building from outside elements





Photos by US Department of Commerce, National Institute of Standards and Technology (NIST)

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Exterior Cladding

- Outermost layer of a building - often made of brick or siding
  - Other types as well

- Exterior cladding can prevent some water from penetrating, but is not a perfect vapor barrier

- The invention of insulation saved lots of energy in buildings, but also introduced challenges with moisture penetration

https://basc.pnnl.gov/resource-guides/drainage-plane-behind-exterior-wall-cladding#edit-group-training

https://www.nps.gov/places/building-4-at-thomas-edison-s-laboratory-complex.htm

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Building Envelope

- Provides structure for the building
- Controls heat flow, air flow, water flow, and vapor flow

Movement of Heat, Liquid Water, Water Vapor, and Air:

Heat	Hot	Cold
Liquid Water	Higher Elevation	Lower Elevation
Water Vapor	Higher Concentration	Lower Concentration
Air	Higher Pressure	Lower Pressure

Building Envelope Control Layers

1
- **Water Control Layer**
- Leaking water = big problem

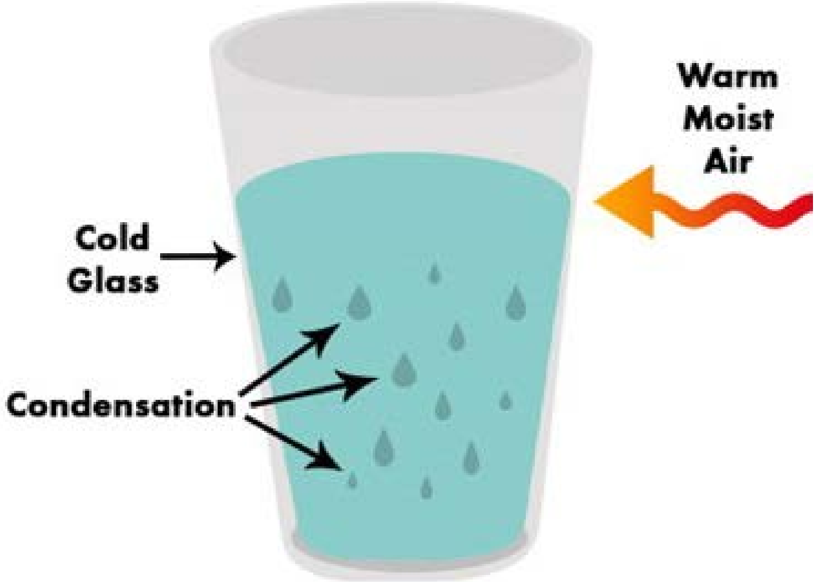
2
- **Air Control Layer**
- Can result in drafty buildings

3
- **Vapor Control Layer**
- Can lead to mold growth and/or structural damage

4
- **Thermal Control Layer**
- Reduces energy use and maintains comfortable indoor temperature

Water Vapor

- Warm air holds more moisture than cold air
- **Dew point:** temperature air needs to be cooled to in order for water droplets to condense and form dew
- In cold climates, this phenomenon results in condensation inside the building envelope
  - Need a vapor control layer located ***inside*** of the insulation (the thermal barrier)

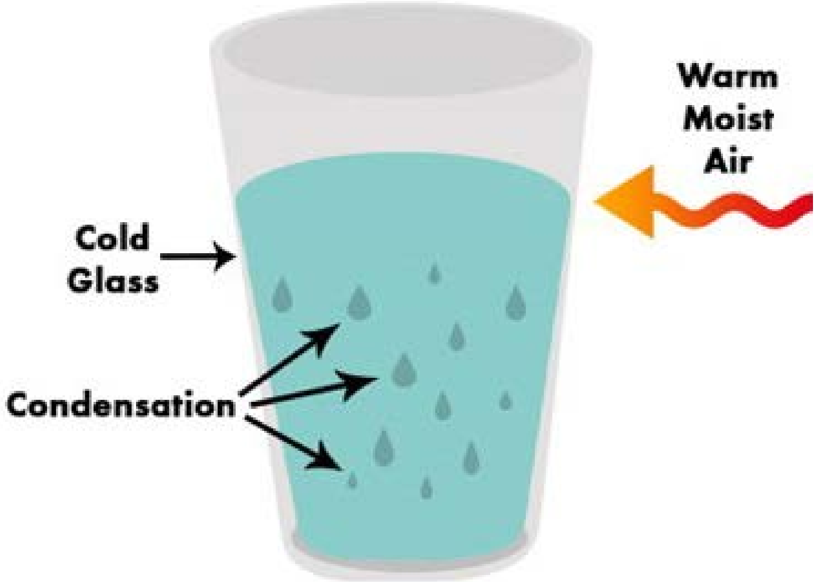


https://www.ashfield.gov.uk/housing/repairs-improvements/tenant-repair-responsibilities/damp-mould-condensation/

https://www.energy.gov/energysaver/moisture-control

Water Vapor

- Warm air holds more moisture than cold air
- **Dew point:** temperature air needs to be cooled to in order for water droplets to condense and form dew
- In cold climates, this phenomenon results in condensation inside the building envelope
    - Need a vapor control layer located ***<u>inside</u>*** of the insulation (the thermal barrier)
- In warm climates, the opposite is true
    - Vapor control layer can be located on the outside of the insulation



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https://www.ashfield.gov.uk/housing/repairs-improvements/tenant-repair-responsibilities/damp-mould-condensation/

https://www.energy.gov/energysaver/moisture-control

Liquid Water

- Don’t let water enter the building!
- Achieved through a strong water control layer

- Can cause wood rot and mold growth, which have dangerous structural and health consequences

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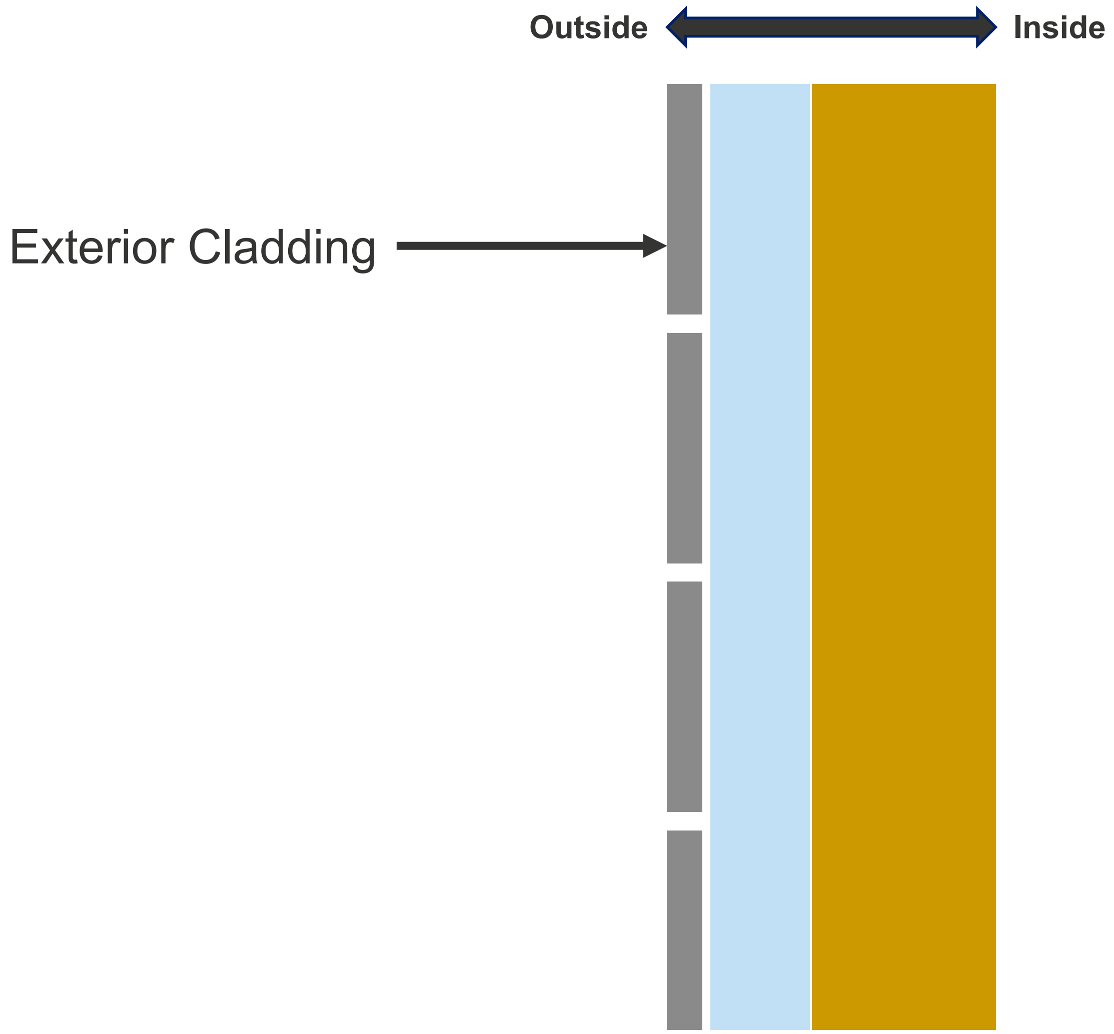
https://www.epa.gov/mold/mold-remediation-schools-and-commercial-buildings-guide-chapter-1

https://www.cdc.gov/niosh/topics/indoorenv/moldtesting.html

Exterior Cladding

- Outermost layer
- Protects the envelope from damage
- Prevents some moisture penetration but we cannot rely on it as the vapor control barrier
- Design feature (It is the part of the building we see!)



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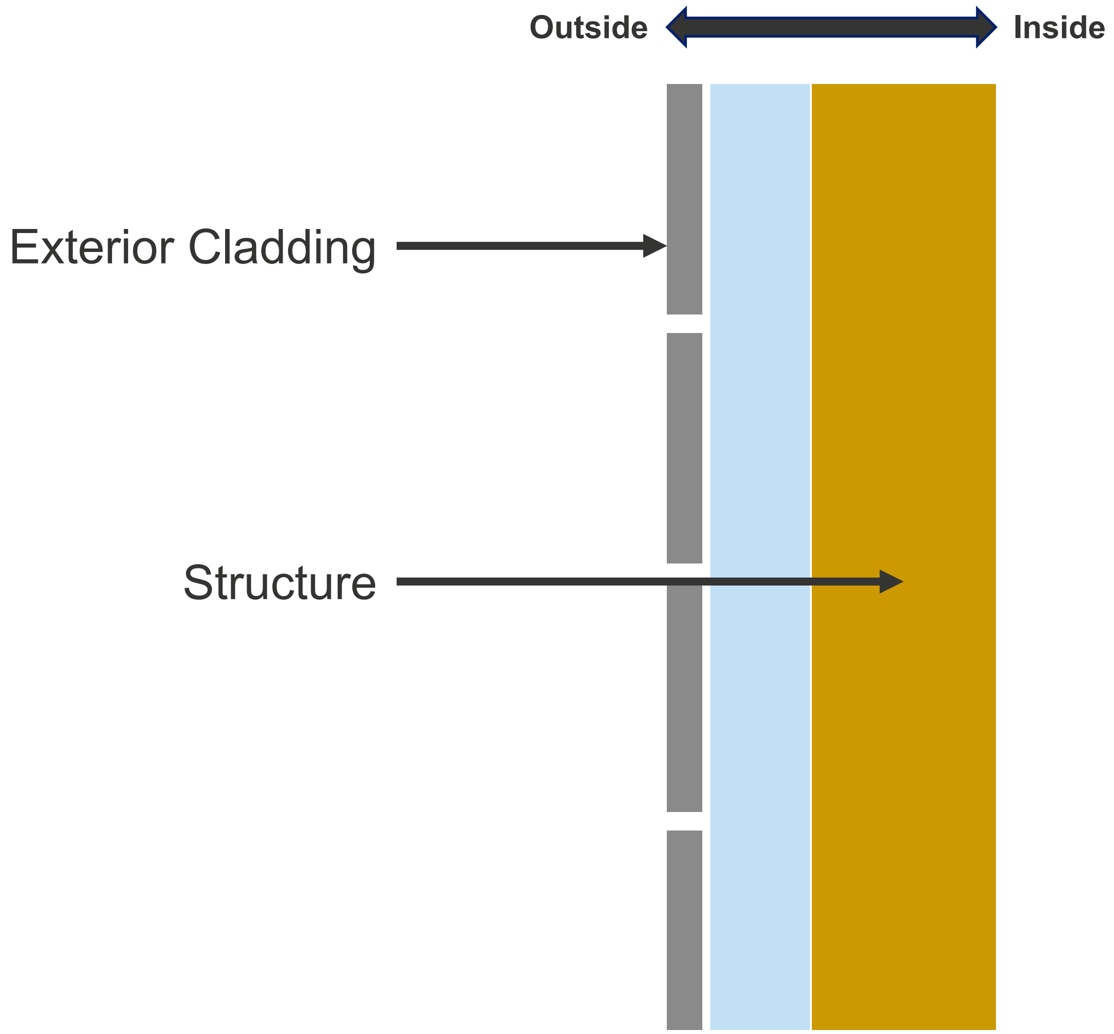
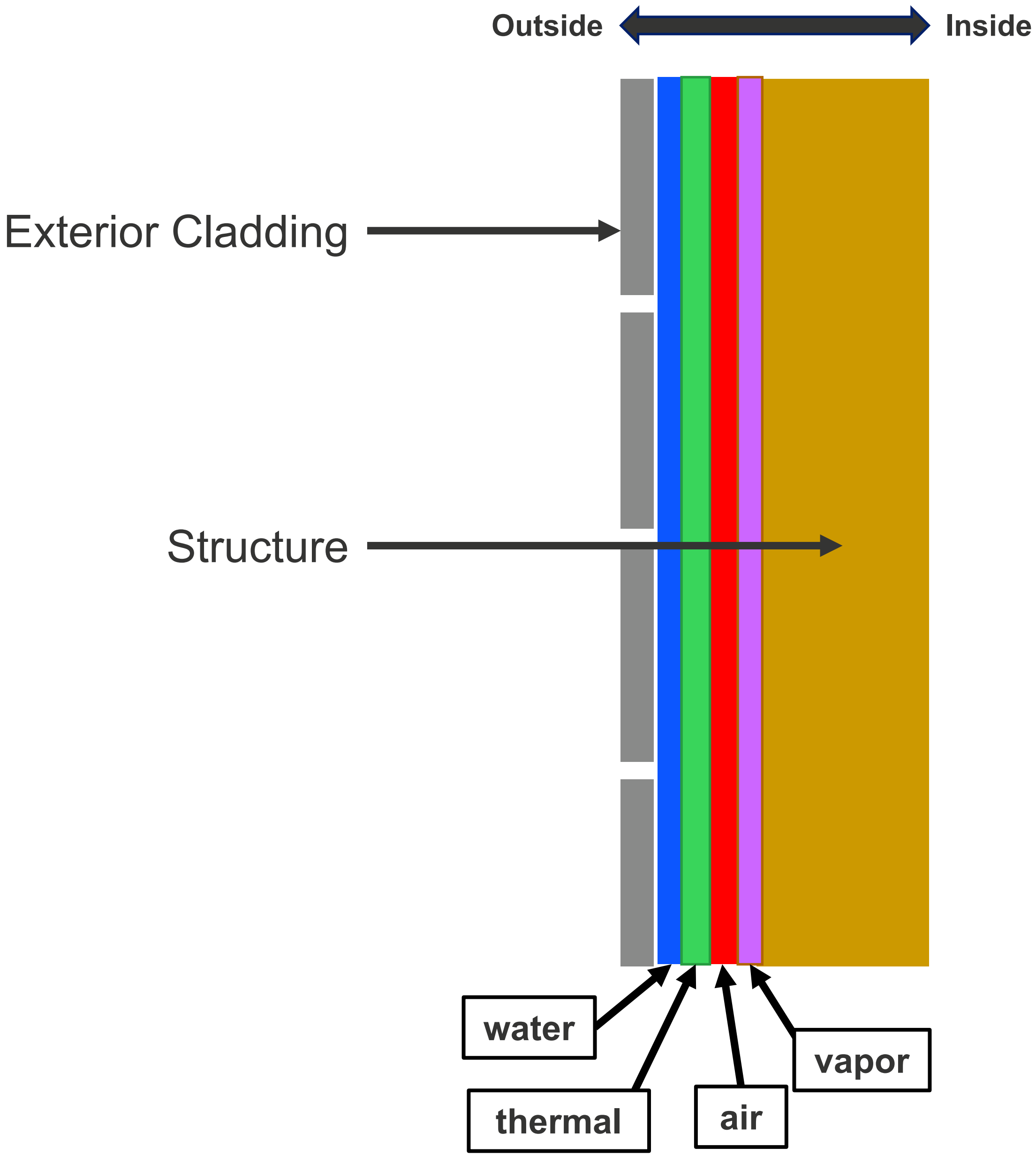
Structure

- Provides structure for the building
- Can be compromised by moisture penetration
- WE DO NOT WANT THE STRUCTURE TO GET WET!



Location of Layers

- Blue line = water control layer
  - Outermost control layer
- Green line = thermal control layer
  - Can go anywhere
- Red line = air control layer
  - Can go anywhere
- Purple = vapor control layer
  - The most complicated control layer



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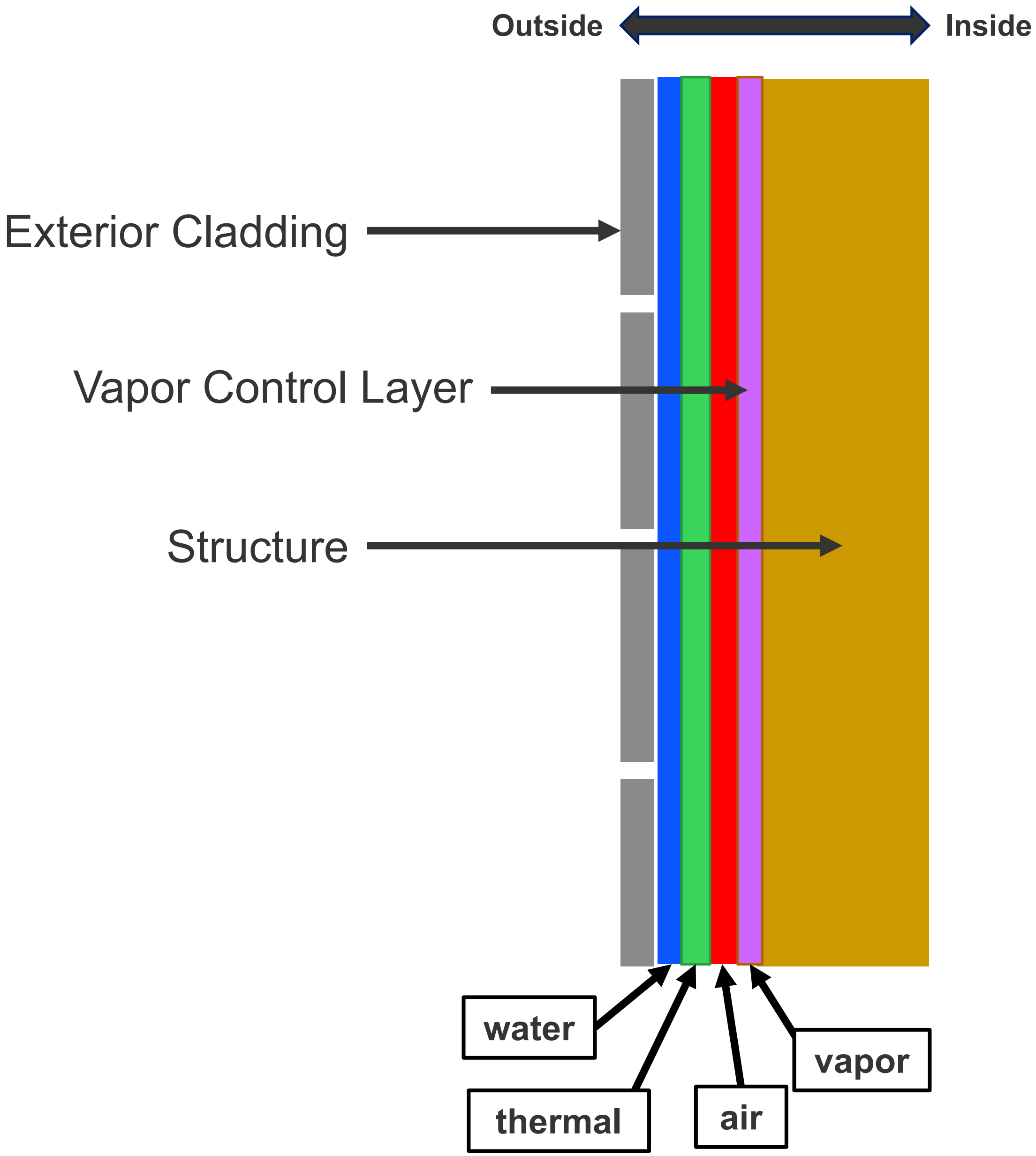
Vapor Control Layer – Cold Climates

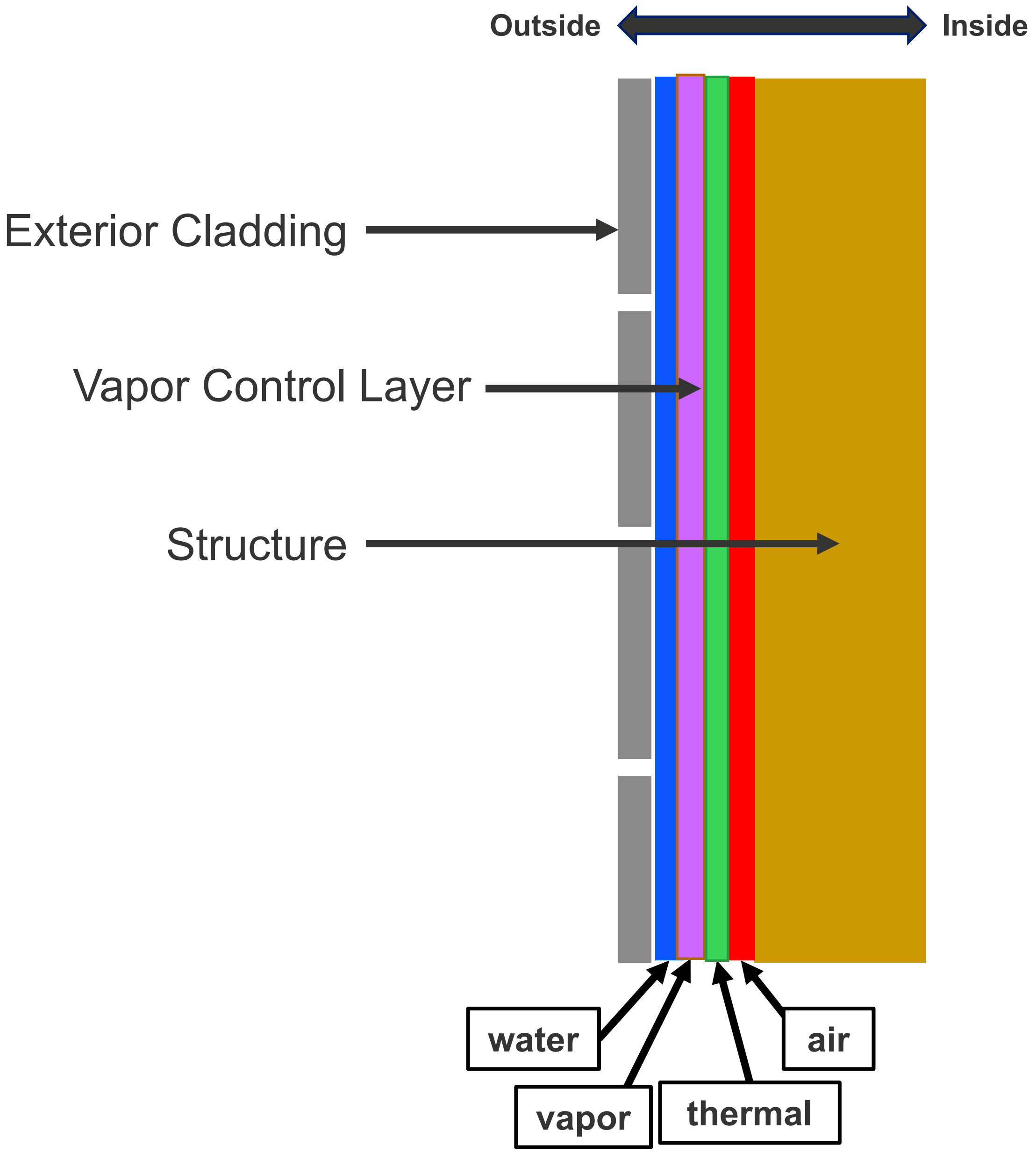
- In cold climates, this layer needs to be kept warm (above the dew point of the air)

- Typically, this is near the inside of the wall
  - Keeps moist air from leaving the building and condensing



Vapor Control Layer – Hot Humid Climates

- In hot climates, the vapor control layer has to be outside the thermal layer



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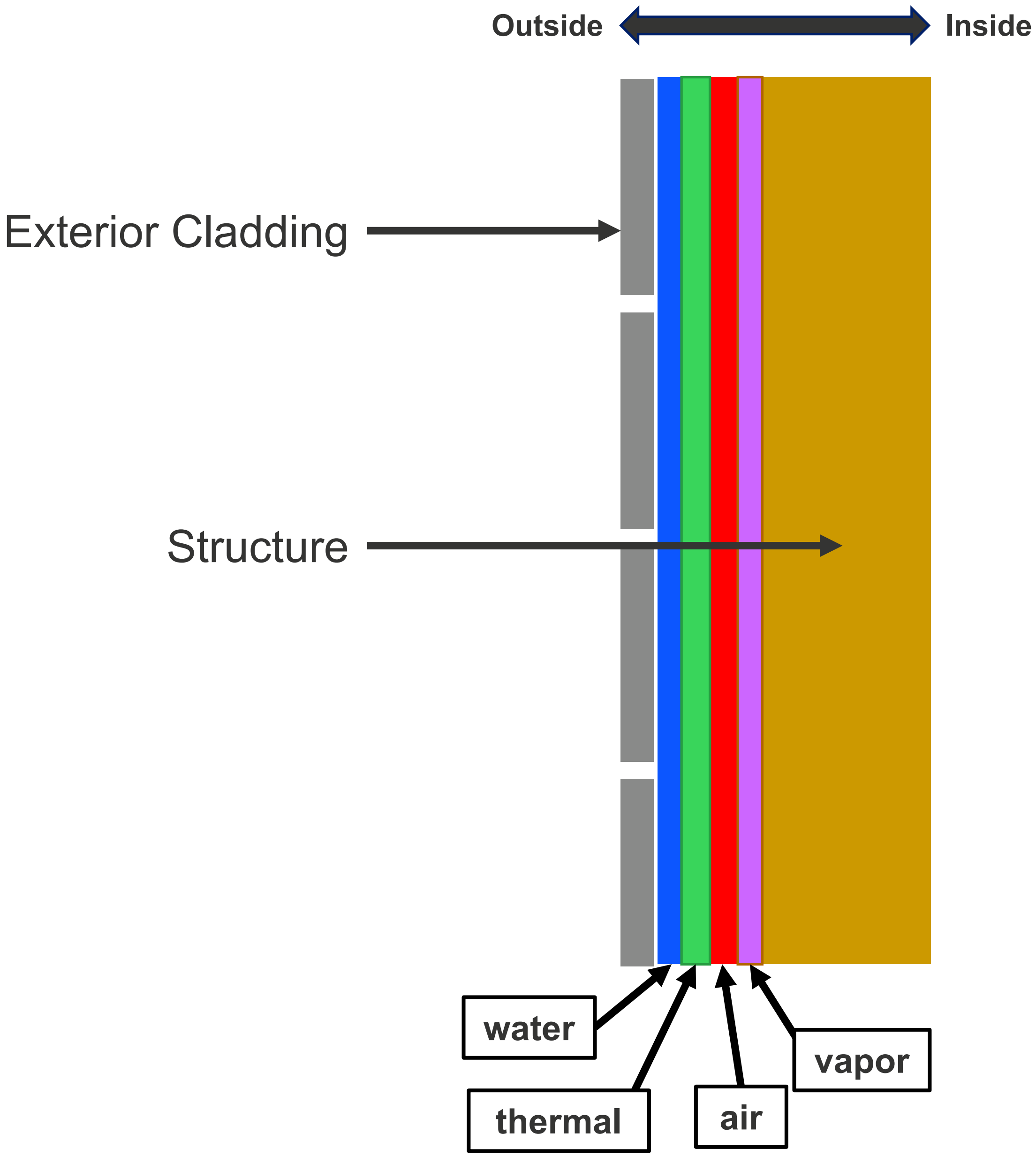
Water Penetration is Inevitable

- Some water will inevitably enter the wall assembly

- Must design wall to allow it to dry if it gets wet
  - All layers inside the vapor barrier must be breathable
  - Thermal control layer must be able to get wet



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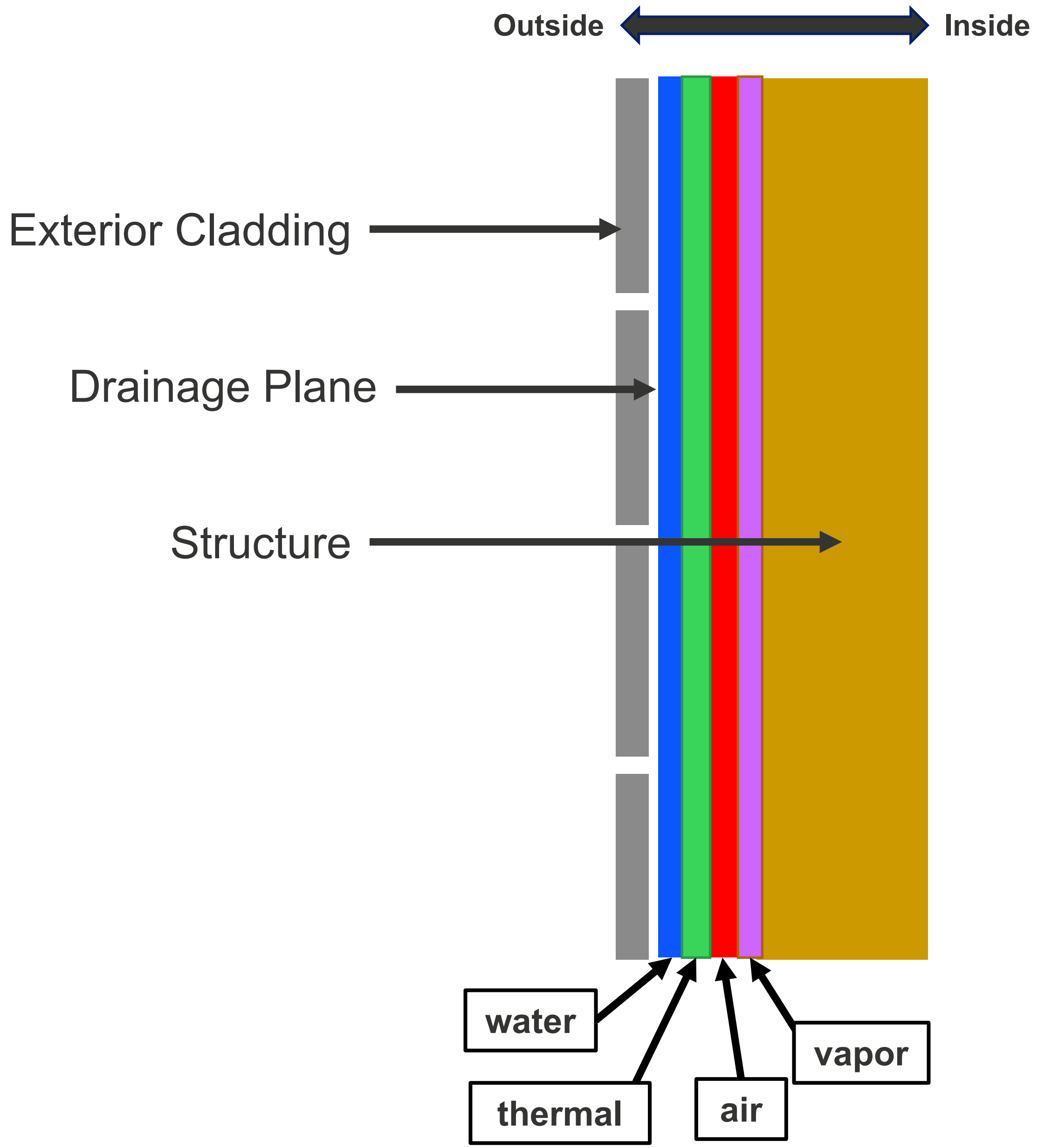
Drainage Plane

- Drainage plane – somewhere for moisture to wick to the bottom of the wall outside the thermal layer.



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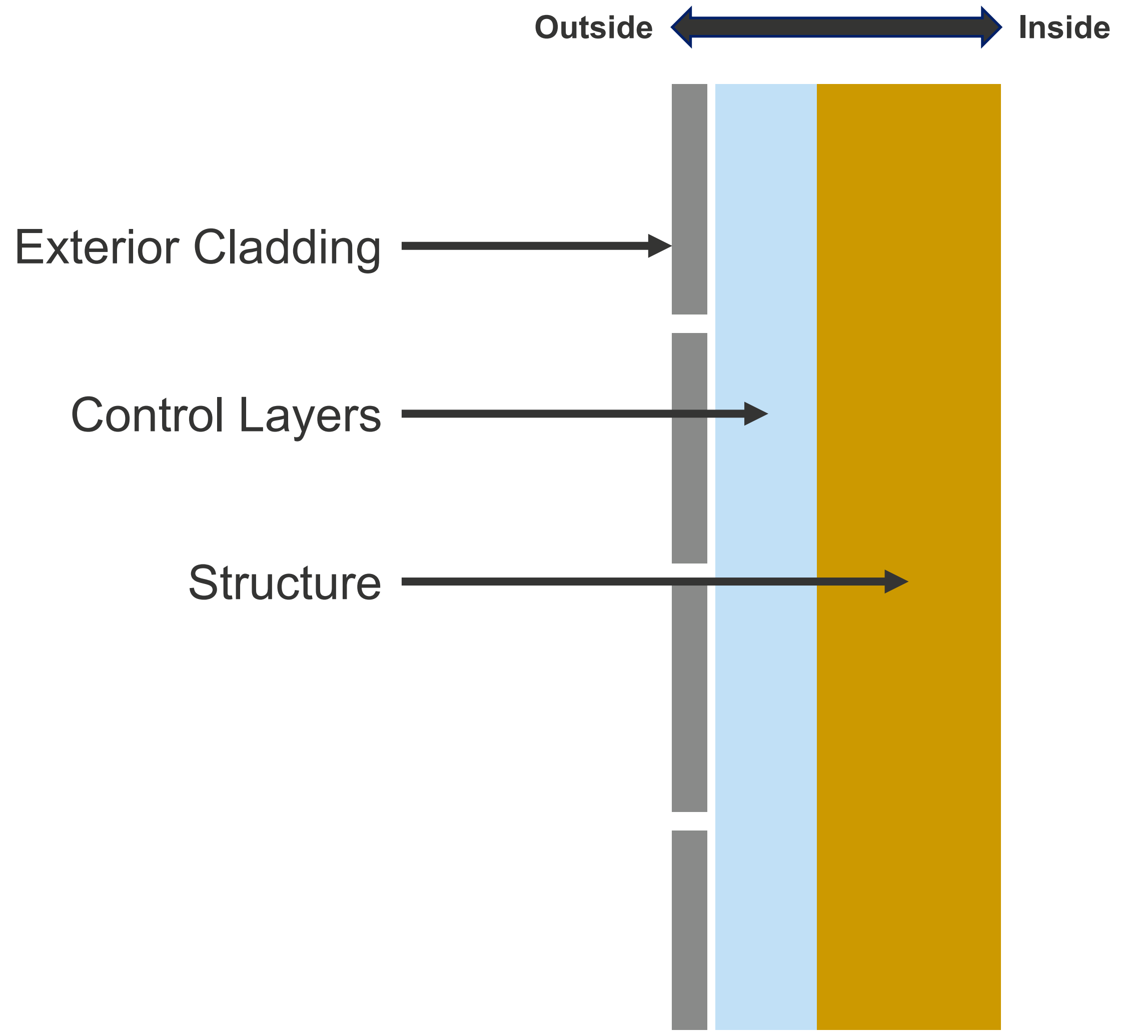
One Solution

- Some materials can function as all four building envelope control layers



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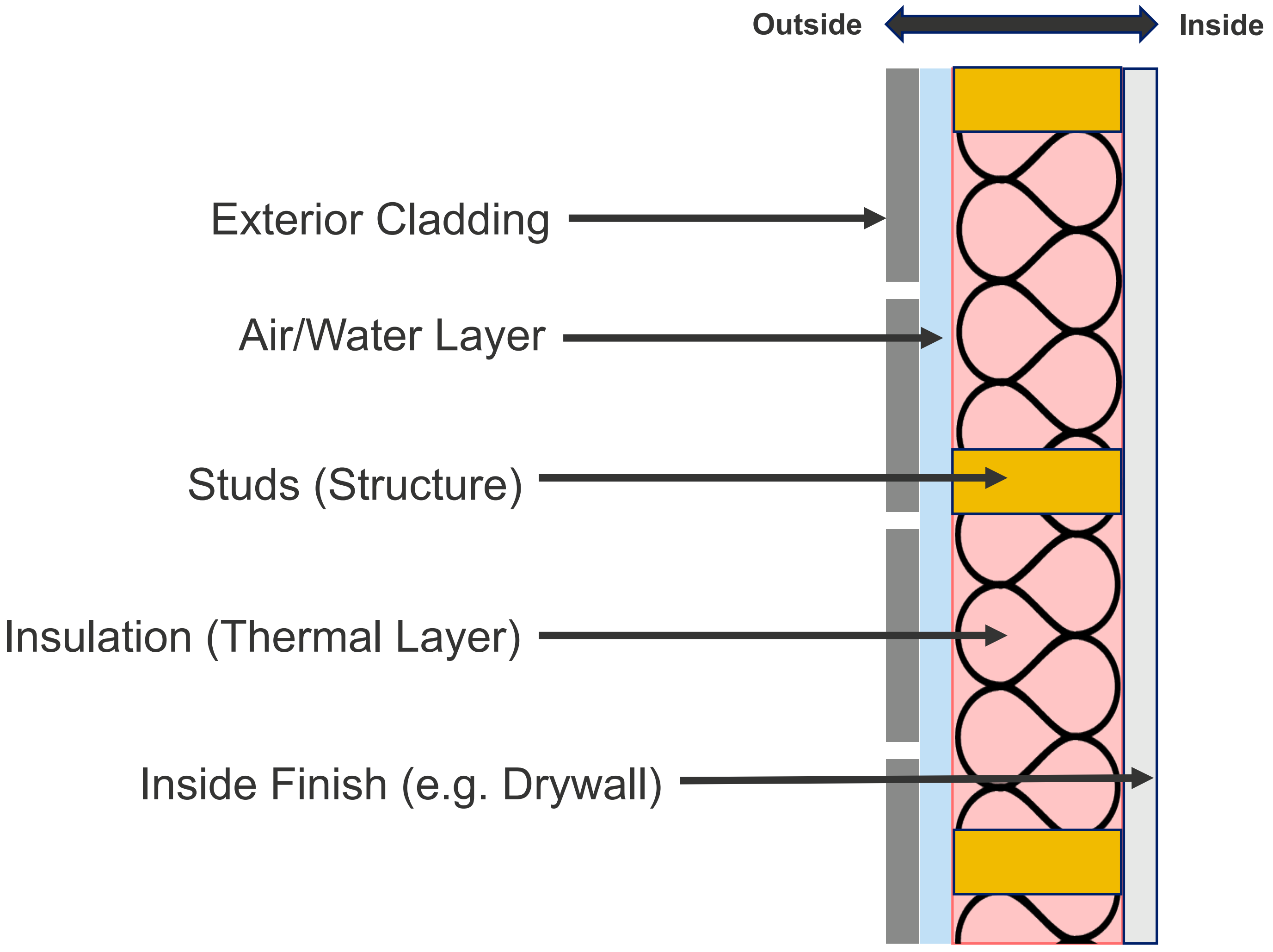
Traditional Wall Systems

- Historically, insulation is placed at the structure (i.e. inside the stud cavity)
- Need to make sure water does not get into the structure either as vapor or as liquid water



Top View

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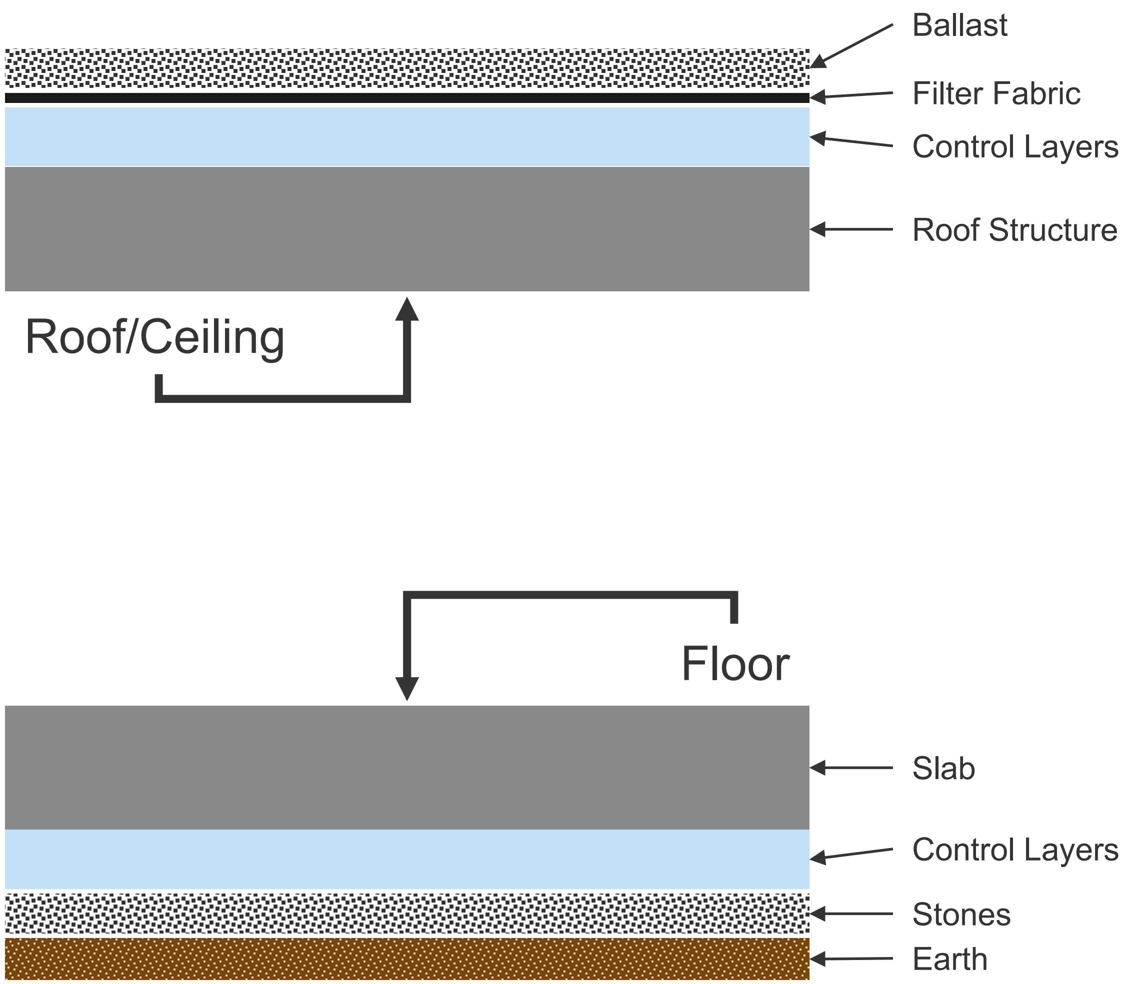
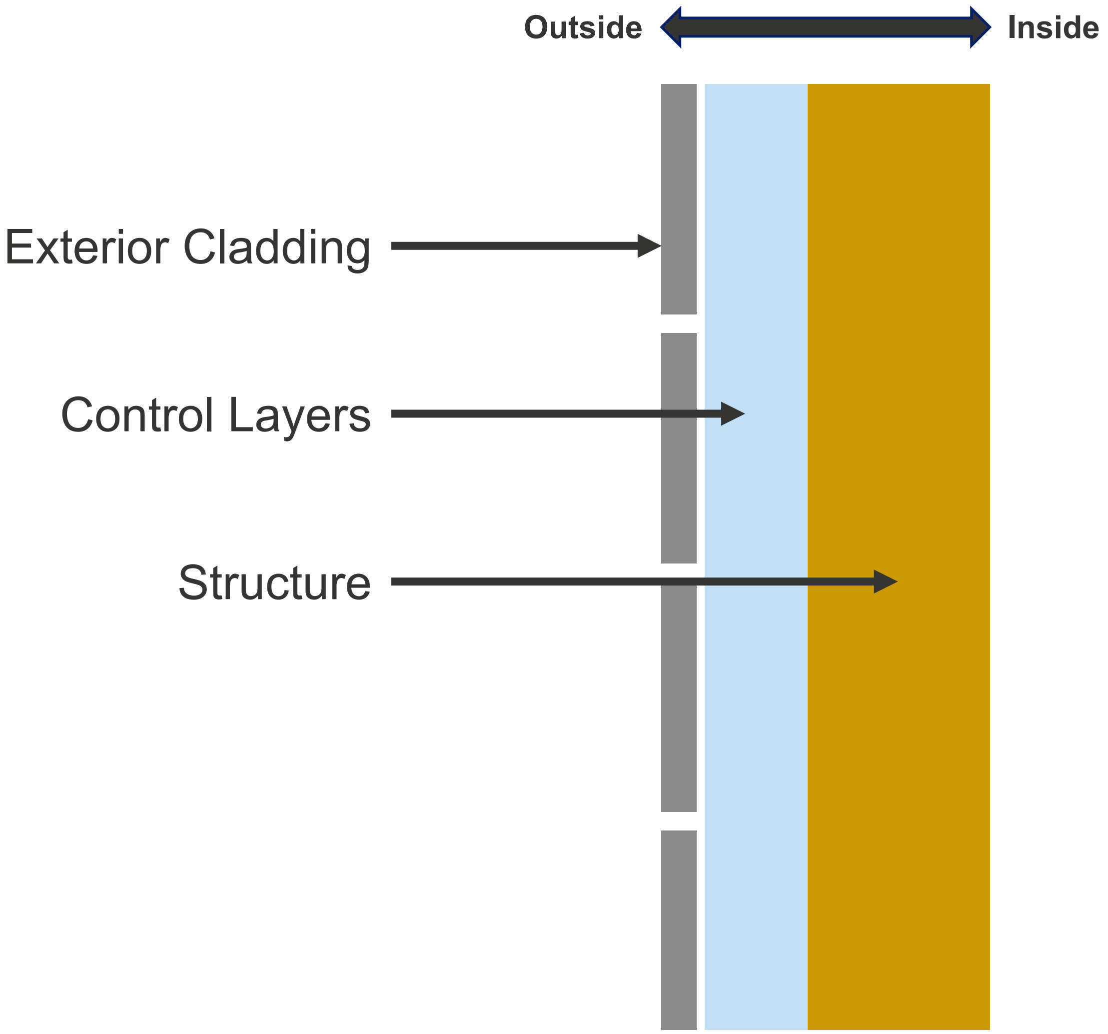
Ceilings and Floors





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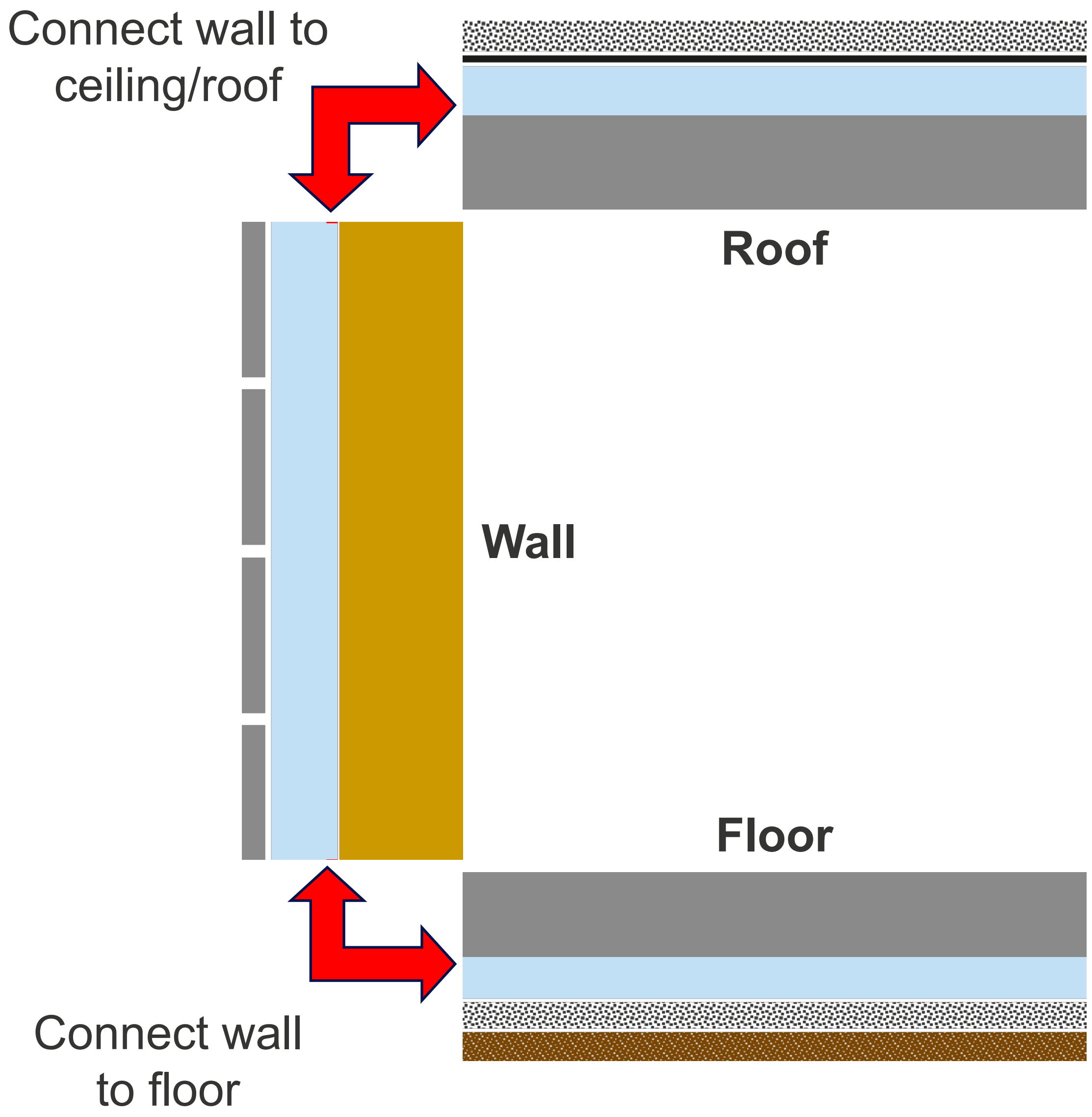
Connecting Walls, Ceilings, and Floors

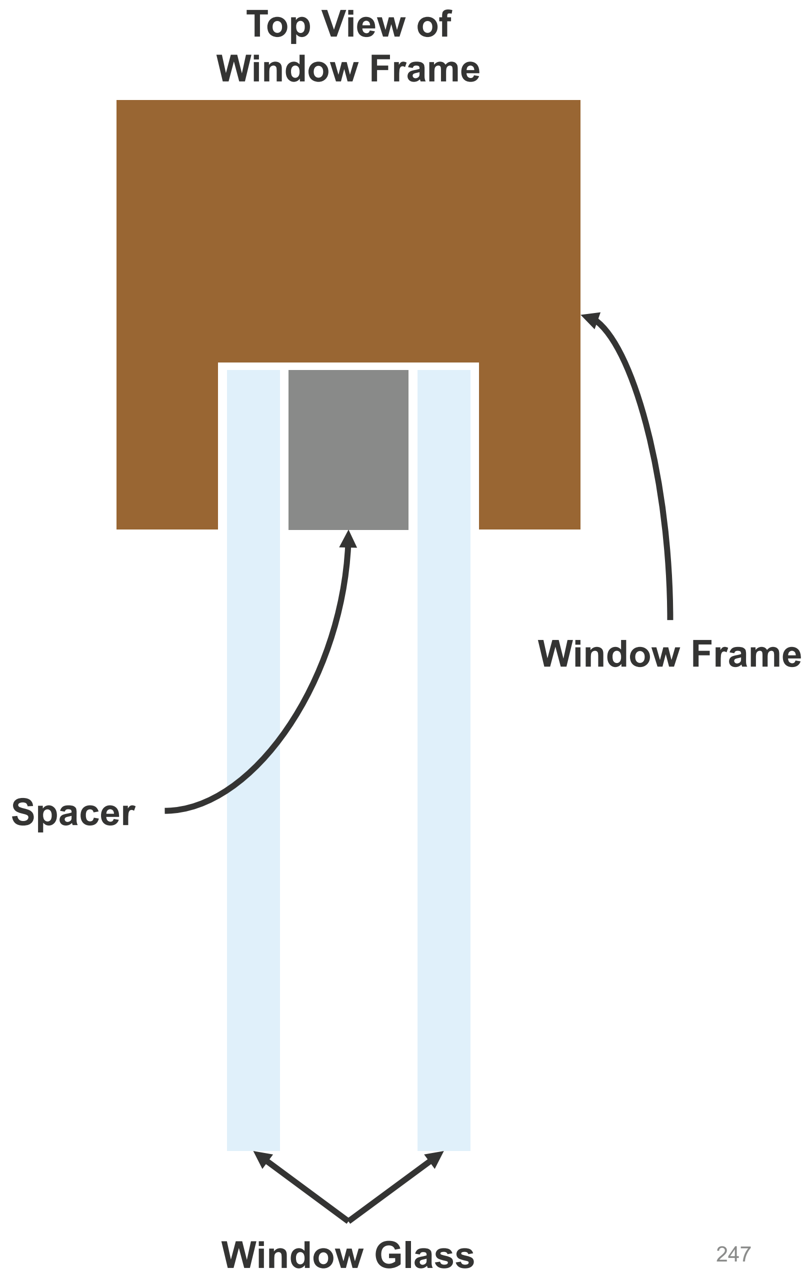
- Must maintain the barriers
- Continuous around corners, through doors, windows, etc.



Window Example

Photo by Thomas Kelsey, US Department of Energy Solar Decathlon

Photo by Paul Torcellini, NREL



Window Example

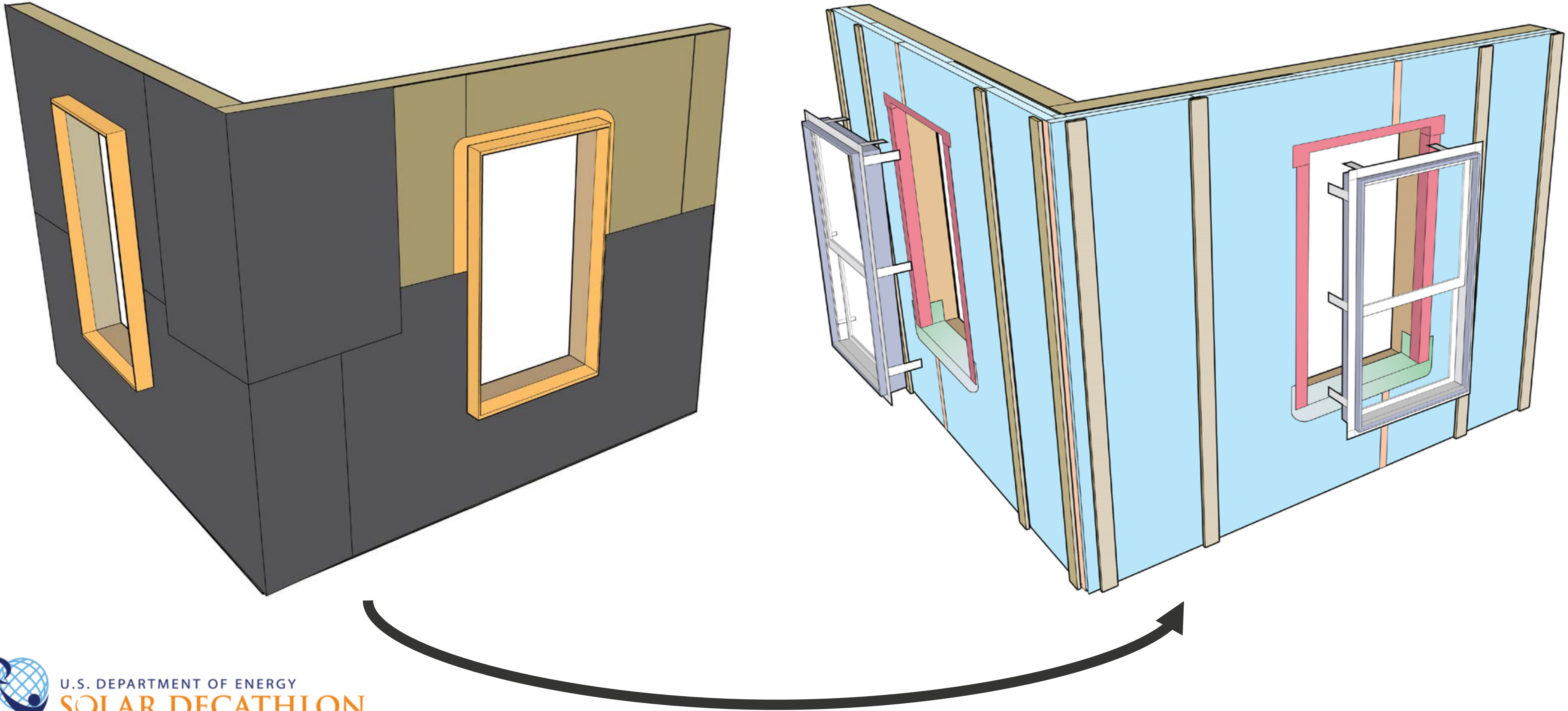
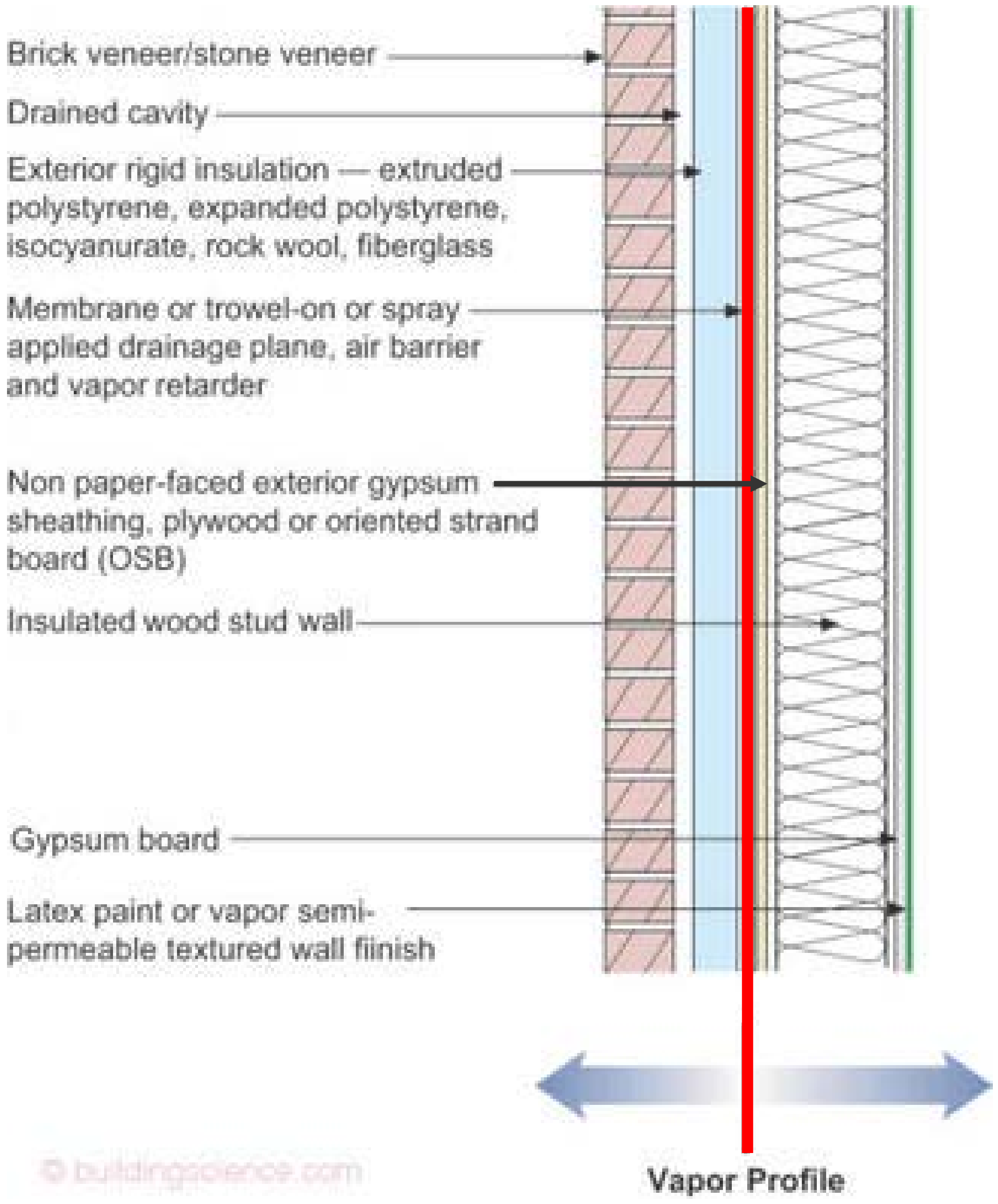


Image credit: Joe Lstiburek, Building Science Corporation

Maintain the Barrier

- ***<u>Do your homework on barriers</u>***
- If a barrier fails, make sure the wall will dry both to the inside and to the outside
- Want a durable, long-lasting structure that will not rot or decay with moisture – but still have good thermal integrity.



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Questions or comments?

Please email SolarDecathlon@nrel.gov

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2. https://www.buildingscience.com/documents/insights/bsi-056-leiningen-versus-the-ants-redux

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Building the Next Generation

Building Science Education for Solar Decathlon

Commissioning

Source: CMTA, Inc.

What is Commissioning?

- Process of ensuring that a building is operating as designed through verification and validation

- Often abbreviated as "Cx"

- Many commissioning procedures focus on the building envelope
  - **Major** cause of energy (and money) losses

What is Commissioning?

- Process of ensuring that a building is operating as designed through verification and validation
- Often abbreviated as "Cx"
- Many commissioning procedures focus on the building envelope
  - **Major** cause of energy (and money) losses
  - Leaky buildings create occupant comfort and safety issues
    - Temperature
    - Humidity
    - Condensation
    - Mold
    - Mildew

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Why is Commissioning Important?

- Verify that the building is operating at the level of energy efficiency to which it was designed
  - Informs HVAC sizing

Why is Commissioning Important?

- Verify that the building is operating at the level of energy efficiency to which it was designed
  - Informs HVAC sizing
- In existing buildings: identify problematic areas/systems; establish baseline to compare to after improvements are made
- Applying the commissioning process to existing buildings is called "retro-commissioning"

Why is Commissioning Important?

- New buildings: verify that the building is operating at the high performance standard to which it was designed
  - Informs HVAC sizing
- Existing buil… stablish baseline to c…
  - Called "re…

A building can be considered code compliant on paper, but there is no guarantee of high performance without commissioning procedures.

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Why do Building Envelopes Leak?

- Vintage
  - Gaps and cracks form over time

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https://architecture2030.org/why-the-building-sector/

Why do Building Envelopes Leak?

- Vintage
  - Gaps and cracks form over time
- Non-continuous envelope
  - Windows and doors break up the envelope and introduce more places for leaking

https://architecture2030.org/why-the-building-sector/

Why do Building Envelopes Leak?

- Vintage
  - Gaps and cracks form over time
- Non-continuous envelope
  - Windows and doors break up the envelope and introduce more places for leaking
- Bad insulation

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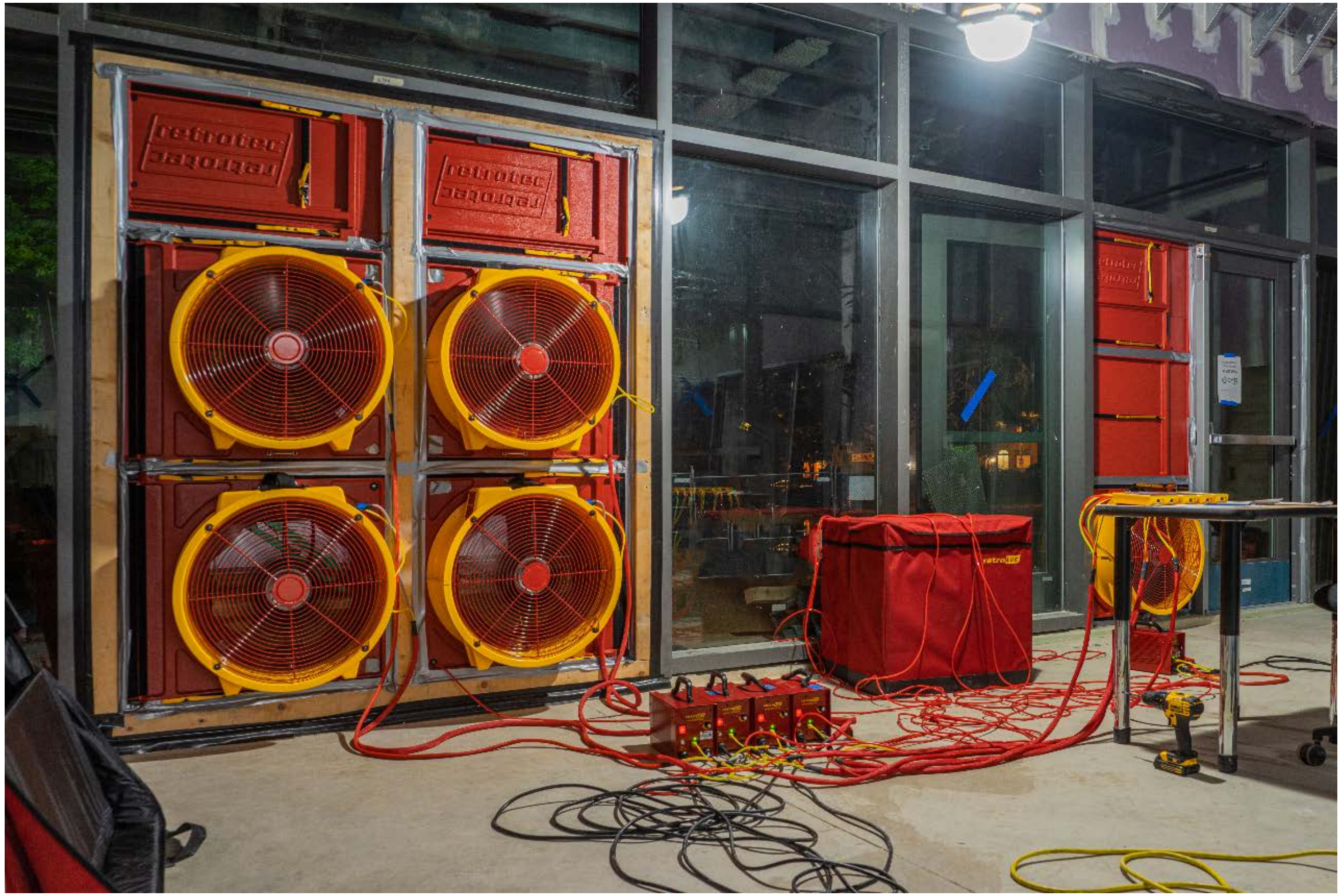
https://architecture2030.org/why-the-building-sector/

Blower Door Testing

- Blower door fans create positive or negative pressure differential between inside and outside of building
- Used to evaluate air tightness and identify air leakage sites
- Methods outlined in ASTM Standards E1827 and E779



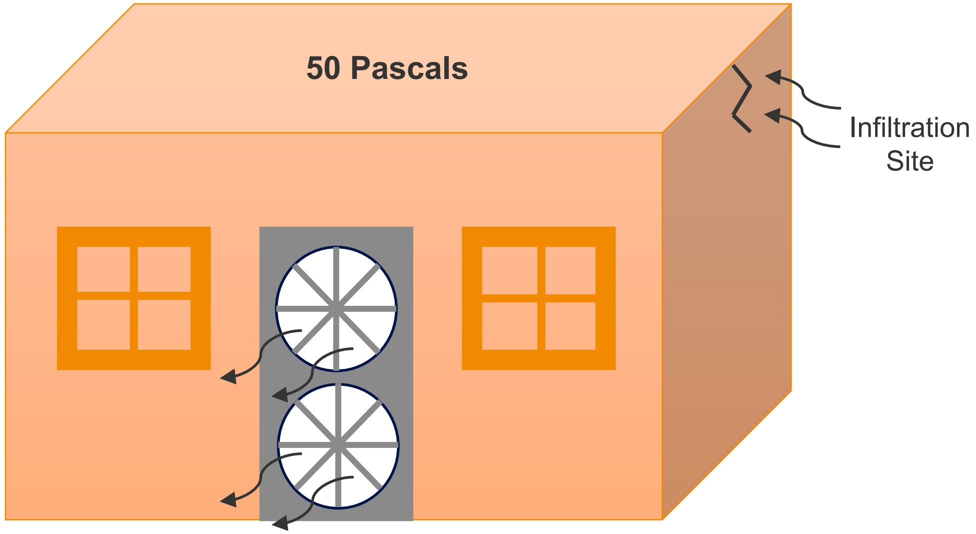
Source: CMTA, Inc.

Blower Door Testing

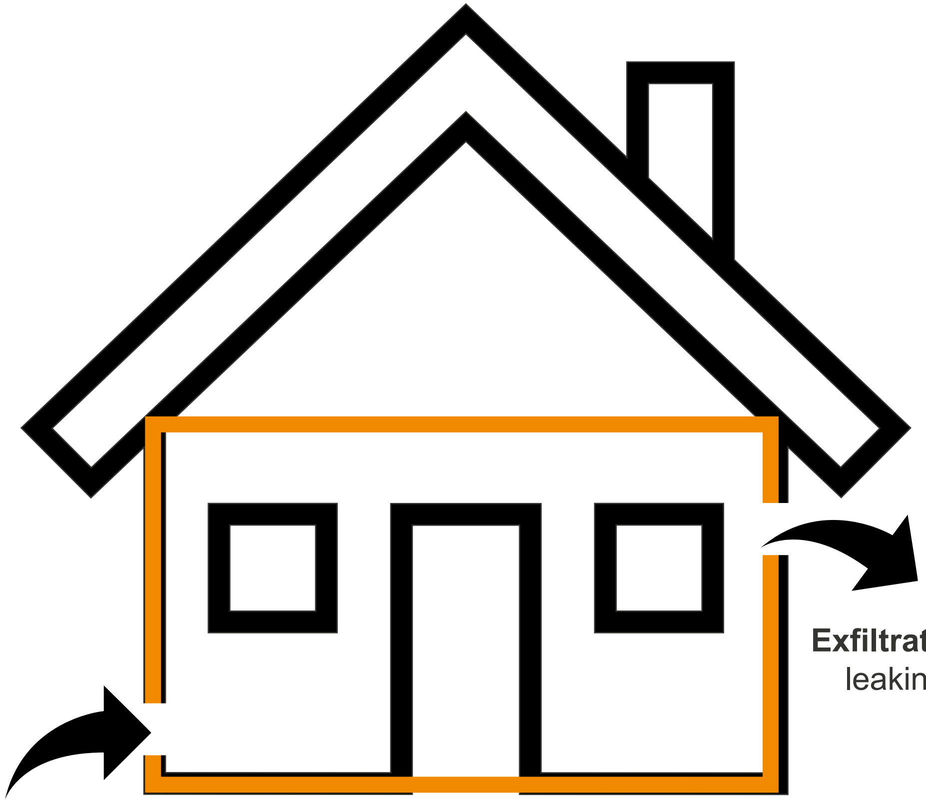
Source: CMTA, Inc.

Blower Door Testing

- Positive pressure test: evaluates exfiltration
- Negative pressure test: evaluates infiltration



Blower Fans Suck Air out of Building, Creating Negative Pressure Differential



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Blower Door Testing

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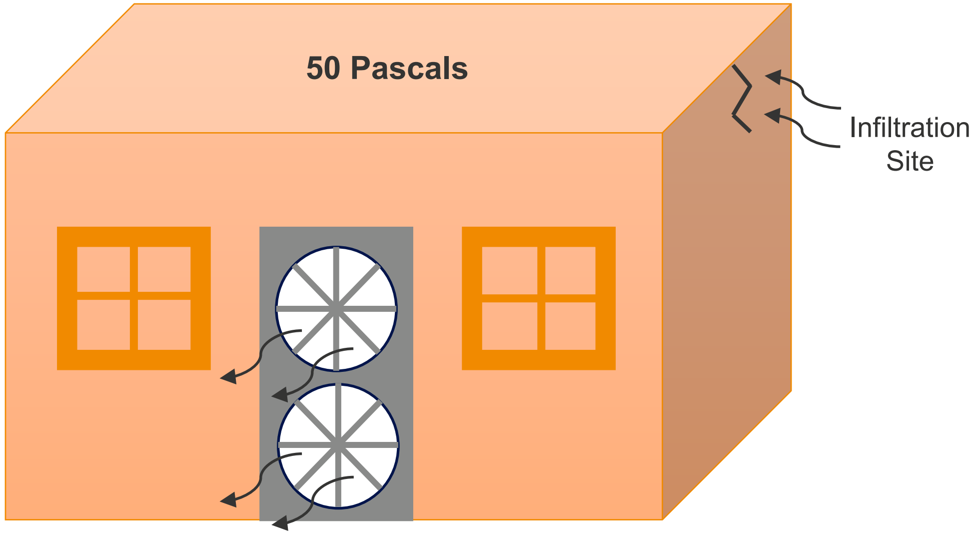

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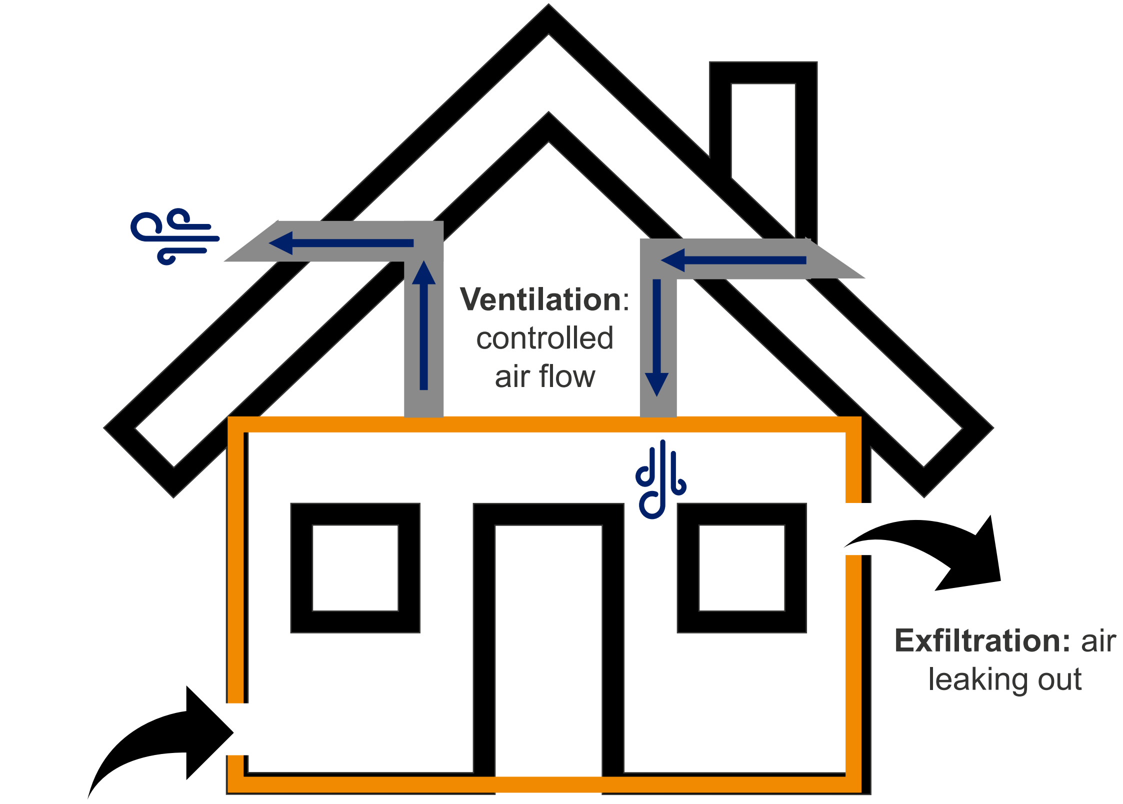

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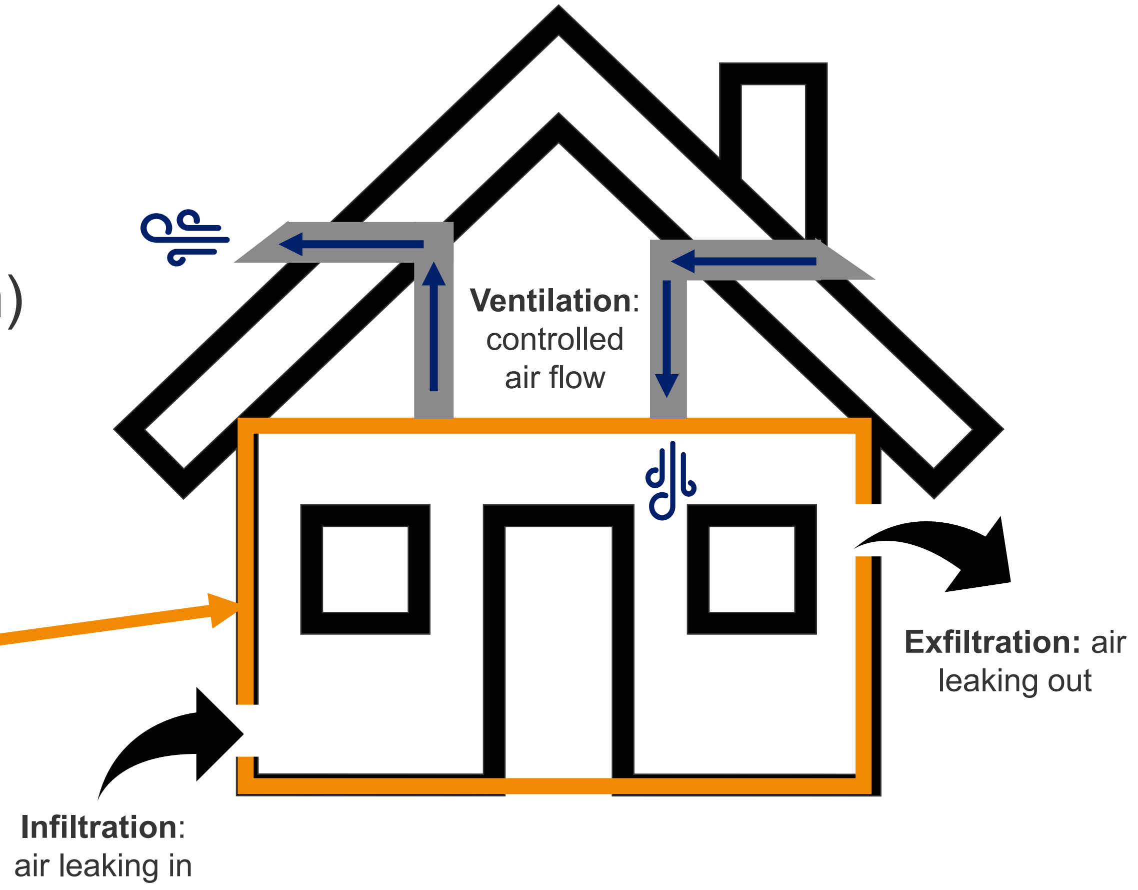
Blower Door Testing

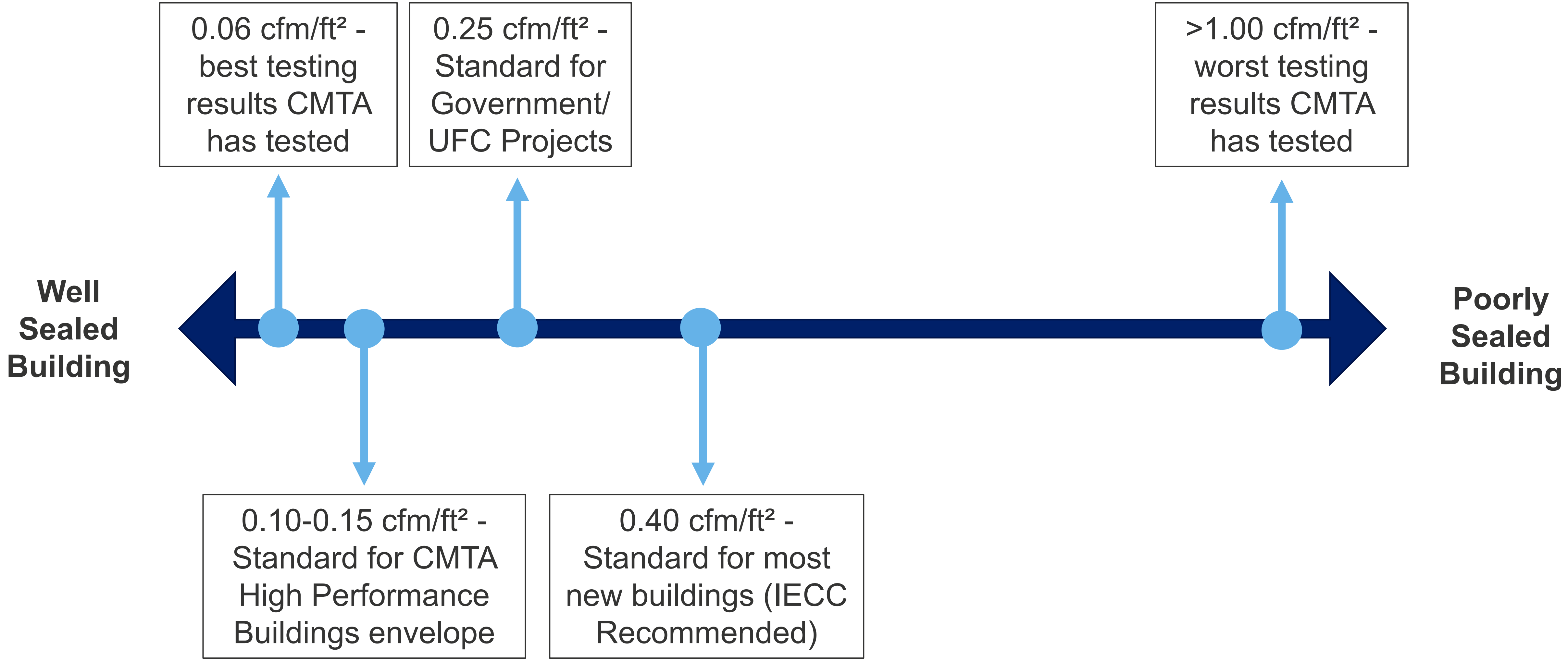
- Positive pressure test: evaluates exfiltration
- Negative pressure test: evaluates infiltration
- Leakage measured in cubic feet per minute (cfm) per square foot of **thermal boundary area**

The thermal boundary area is the entire area between the inside and outside.

It includes walls, floors, ceilings, windows, doors.



Blower Door Testing



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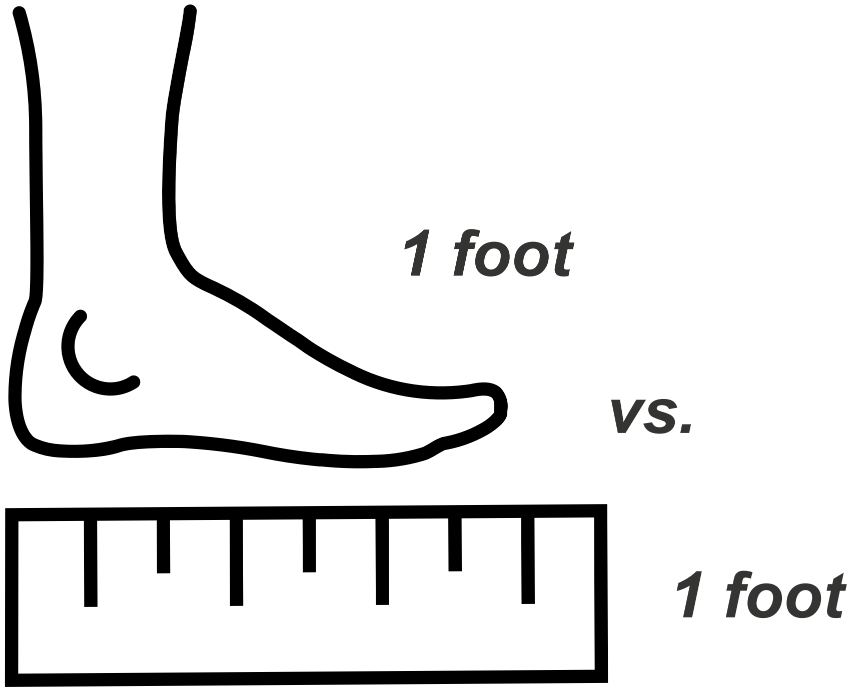
Importance of Testing Standards

- Standardize the way we measure things
- Everyone is on the same page
- Results can be directly compared
- ASTM Standards - American Society for Testing and Materials



Infrared Imaging (Thermography)

- Used to capture temperature differences on surfaces
- Methods outlined in ASTM Standard C1060
- Larger temperature delta results in best images
    - Condition spaces prior to thermography if possible
- Perform during pressure testing to identify exact air infiltration and exfiltration areas

Source: CMTA, Inc.

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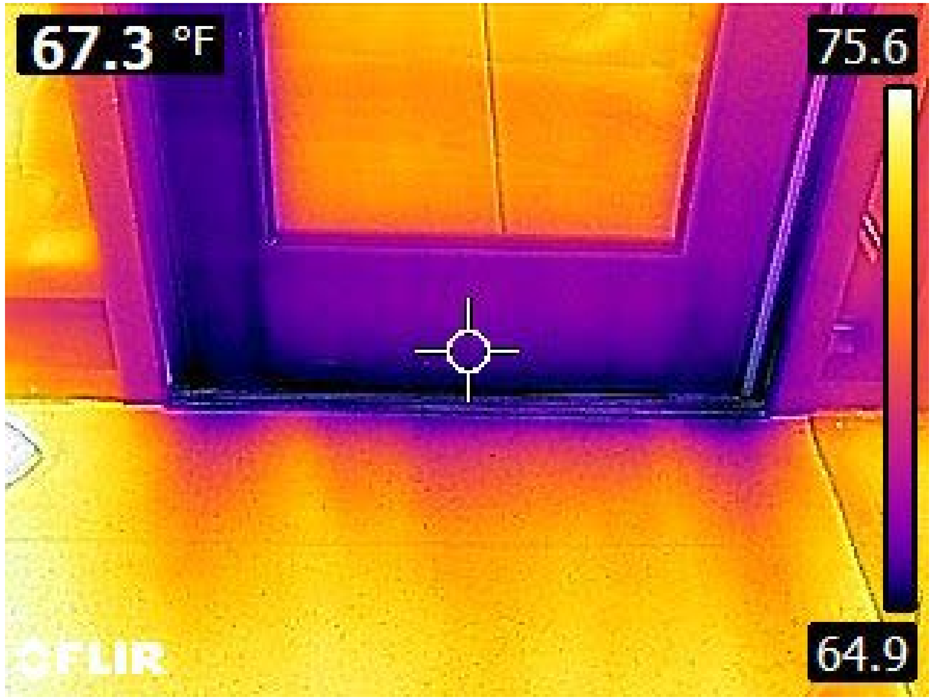
Infrared Imaging Examples



Thermal trails in a doorway during negative pressurization

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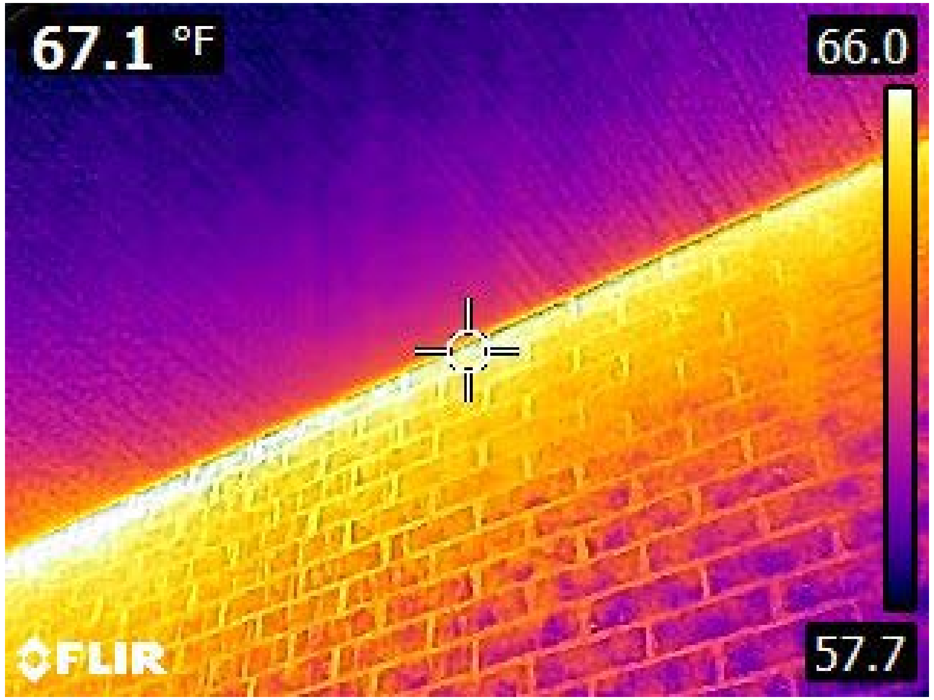
Source: CMTA, Inc.

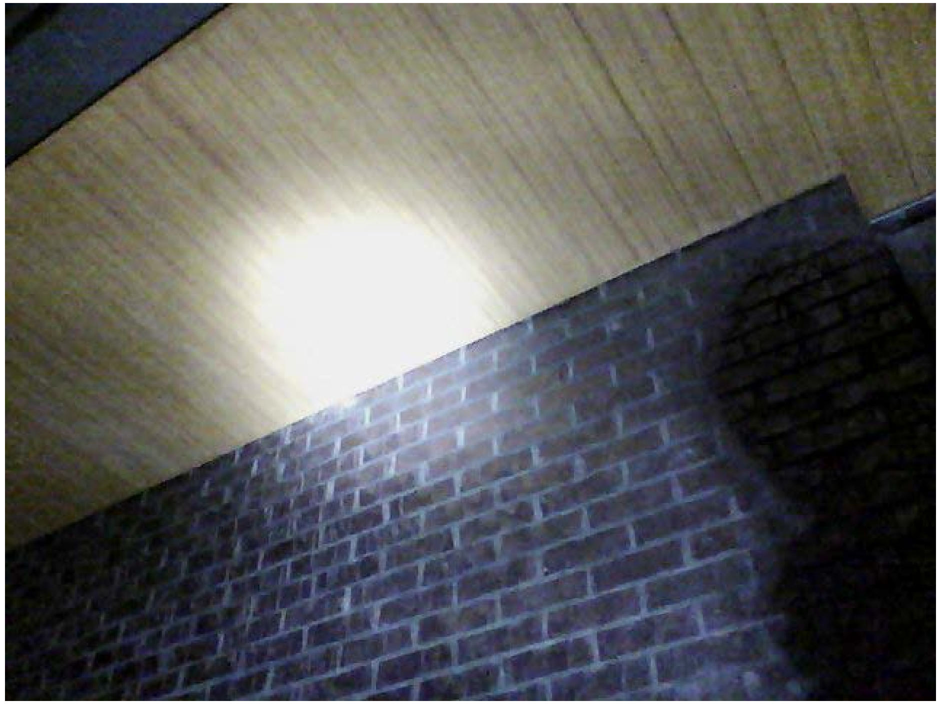
Infrared Imaging Examples

Leakage through a window (this is typical)

Source: CMTA, Inc.

Infrared Imaging Examples





Poor seal or thermal break at exterior roof line

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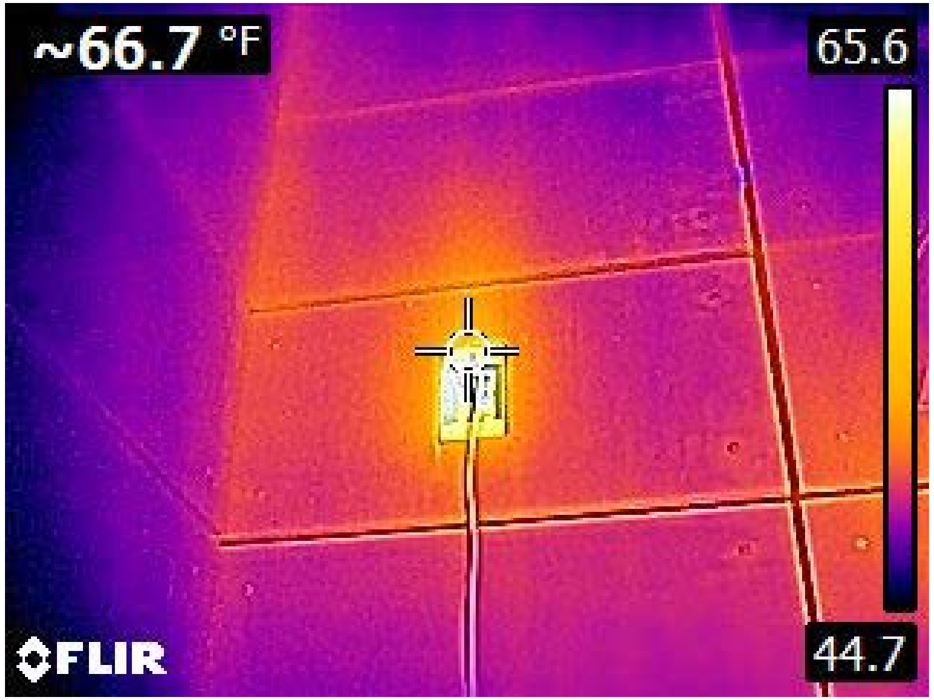
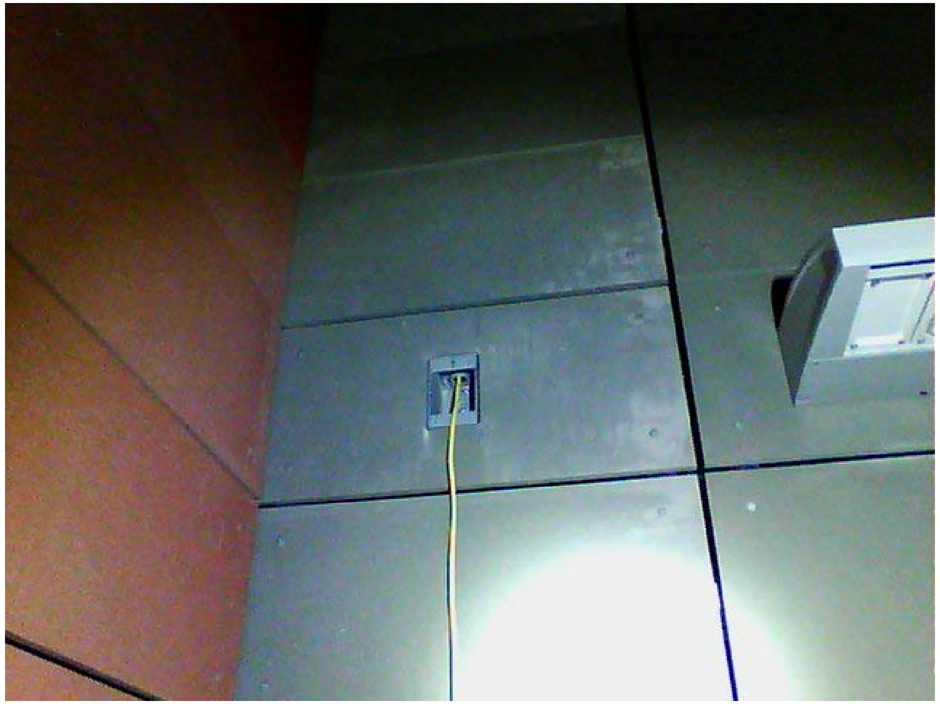
Source: CMTA, Inc.

Infrared Imaging Examples





Poor conduit seal at J-box installation

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Source: CMTA, Inc.

Commissioning of Other Building Systems

- HVAC
- Electrical
- Plumbing
- Protective systems
  - Fire
  - Security
  - Communication
  - Alarm

- Easier to detect performance issues with these systems compared to envelope
  - Manual testing or detection
  - Automated commissioning – integration with Building Automation System
    - Auto-commissioning (ACx) or Monitor-Based Commissioning (MBCx)

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https://www.automatedlogic.com/en/media/ADD-ACX_CS_tcm702-102089.pdf

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