BUILDING SCIENCE BASICS

How Heat Flows and How to Stop It

The three mechanisms of heat flow work together at all times. Under different circumstances, each takes turns being the dominant force.

by Justin Wilson, Construction Instruction, inc.

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CONTENTS

The physical Laws of Thermodynamics govern how energy behaves. When discussing insulation, the form of energy to focus on is heat.

Infrared cameras show where heat is flowing out of a house. Cool colors, such as blue are cold surfaces. Warm colors, red and yellow, pinpoint the heat leaks. Windows are colder than walls, but there are some big leaks at rooflines in this traditional craftsman bungalow.

BUILDING SCIENCE CONCEPTS

To understand how insulation works in a building, you must know the two most basic laws of physics: The First Law of Thermodynamics states that energy cannot be created nor destroyed, only transformed from one form to another. Potential energy in a stick of firewood it transformed into heat energy when it is burned.

The Second Law of Thermodynamics pertains more to building performance, and so it's the most important one to understand: "Heat moves from high temperature regions to lower temperature regions, and never the reverse." In order to reverse this process energy must be added to the system. An example of this would be an air conditioner: It moves energy from cold to hot using a electrically-driven compressor and refrigerant to "reverse this process".

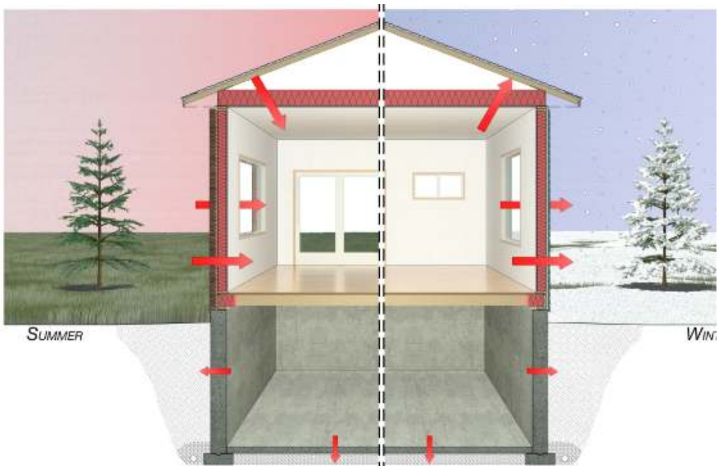
It is doing work.

Heat flows through conduction, convection, and radiation.

THEORETICAL BUILDING SCIENCE

Conduction: The main driver through walls, floors, and roofs

Conduction represents the most familiar form of heat flow. It's what happens between objects that touch each other, such as your hand and a hot frying pan handle: the heat flows from the pan to your hand and burns it. An oven mitt acts as an insulator — it is a material that slows the heat transfer so that you can handle the pan without burning your hand.

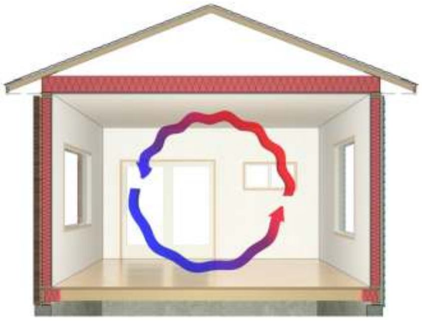


Conduction is the most familiar mechanism. In summer, heat pushes its way inside through assemblies. In winter, it pushes its way out - one molecule at a time.

Conduction occurs through walls, floors and ceilings moving heat from the higher temperature to the lower temperature side. This means that in winter indoor heat moves toward the cold outside and in summer outdoor heat flows in. Insulation slows this process down, but it cannot stop it. The higher the R-value, or resistance, the slower the heat transfer through conduction.

Convection: heat-driven loops occurring in air

Convection represents heat transfer through a moving liquid or gas, such as water or air. Heat moves in response to temperature and density differences in a fluid; warmer fluids with lower densities tend to rise, while cooler fluids with higher density tend to fall.



Convection is a fluid's response to heat gradients. Warmer fluids and gasses rise cooler ones sink. When one rises or sinks, it displaces oth fluid, causing a convective current.

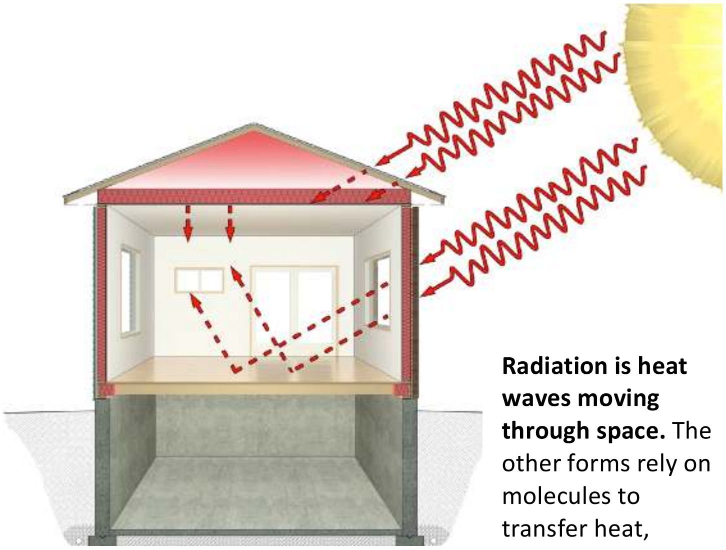
Heat does not rise, it moves to colder temperatures regardless of position, up or down, but hot air does rise, just as smoke rises in a chimney, moving from higher, heavier densities to lower, lighter densities. In winter it is typically warmer upstairs than downstairs; the warm air rises up — through convection. If you stand by a window, you can feel cool air falling to the floor; this is not a draft, it is the warm air losing energy at the cool window, becoming denser and sinking down — through convection.

Another example is when you boil water in a pot; you see the warmer, lighter fluids bubble to the top, the colder fluid falls to the bottom, creating a churning motion — more convection.

Radiation: Heat Flow From Surface to Surface

Radiation is heat passing through space, such as when sun warms your face on a cool day. Or when the sun heats up a south-facing room with a lot of windows. Solar heat gain through windows may be an asset in winter, but becomes the heaviest energy toll (30-50%) in summer.

Radiation also pulls warmth from your body in winter. Cold walls, glass or other surfaces draw body heat from people, compromising comfort. The area of greatest concern for radiation heat loss is the building's thermal enclosure. This is the reason we insulate walls, ceilings and floors, to keep these surfaces from radiating inward in summer and creating cold spots in winter.



Radiation is heat waves moving through space. The other forms rely on molecules to transfer heat, radiation does it direct.

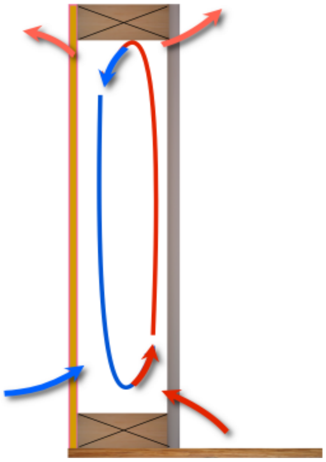
Products that have a reflective coating and face an air space such as low-E windows or light-colored roofing material help reduce radiant gain. Radiant heat can also be rejected with overhangs or trees that create shade.

Insulation slows the flow of heat through building assemblies

APPLIED BUILDING SCIENCE

Convection inside a wall

Air has little insulating value if not contained in small cells. If a framing cavity, such as between two studs in a wall, is sealed and the air inside is still, the insulation value is slightly better. If the wall cavity not sealed it will be greatly effected by convection. In walls, air gaps allow convection to occur, which speeds heat transfer and effectively lowers the R-value of the assembly. This is why high performance builders devote so much time and attention to properly sealing building assemblies.



Convection can happen inside a wall cavity. When the drywall is warmed, air directly adjacent to it rises, which displaces slightly cooler air. Air adjacent to the exterior sheathing sinks, and the loop begins.

The speed of air movement depends on the temperature difference, the size of the airspace, and height of the air chamber. The greater the difference in these factors, the faster the convection.

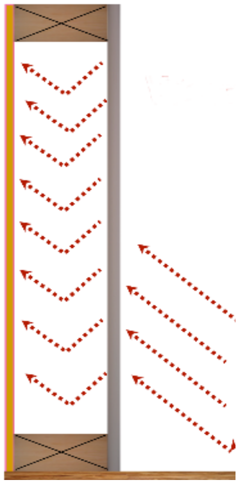
Convection has a greater effect in taller spaces due to stack effect. Attic insulation is effected, but not as much as a wall cavity because attic insulation is only a couple of feet tall whereas a wall is usually eight to ten feet tall. If the enclosed space is 70 degrees and the attic is colder, a convective loop will form in the attic, reducing the insulation's effective R-value.

To stop convective heat loss, air flow must be controlled with an air barrier on both sides of the assembly. The inside and outside air barriers are collectively called an air barrier system.

Radiation in a wall cavity

A warm body next to a cold body will emit radiation as warm surfaces always emit energy toward cold ones. As the drywall on the inside of the assembly warms up, heat radiates toward the colder exterior side. The air space, temperature difference, and material properties are the key factors determining how fast this happens.

Illustrating these principles graphically, the uninsulated wall transmits heat through it primarily by radiation, but also through convection. Remember, heat conducts through materials and then radiates through to space to another material. Conduction is what insulation combats, but in an uninsulated wall cavity, it is not much of a factor.

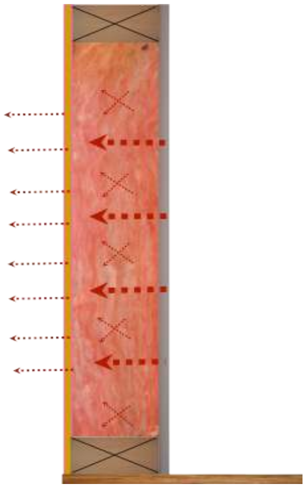


Radiation can happen inside a wall cavity too. Because most wall cavities are insulated, radiant heat gain is less of a problem through walls.

How insulation interrupts heat flow

Sealing a wall cavity and filling it with insulation virtually eliminates convection and radiation. Instead, heat must conduct its way through a maze of tiny, disconnected air pockets trapped within the insulation matrix. This slows heat flow considerably. But remember, convection is only eliminated by a good air-sealing job.

There are many types of wall cavity insulation, and they all provide similar benefits: they slow the transfer of heat through conduction and secondary radiation (which occurs within the material matrix), and they reduce or eliminate heat transfer through convection within the insulation. Some work more effectively than others and there are wild price ranges for different insulation types.



Insulation's job is to slow conduction and radiant heat gain. Poo installed insulation will not stop convection, s the R value is lowered.

Insulation is only as good as the install job

Defects in the installation, and gaps in the insulation (such as those caused by studs, joists, and rafters), lower the overall performance of the assembly. Energy efficient construction focuses on excellent air sealing, reducing the number of framing members, and adding of exterior insulation to provide a continuous layer of thermal resistance.

Insulation slows heat flow three ways:

- By using materials that are poor conductors of heat.
- By using materials that trap air within small pockets to slow heat flow.
- By restricting air circulation within the materials.

A microscopic view of fiberglass insulation shows how the fiber matrix creates a maze of air pockets through which heat must travel. Fiberglass as a material is a poor conductor because its strands are discontinuous. The air pockets between the fibers further reduce conductivity. The overall mesh of glass fiber and air provides an excellent, fire resistive insulation material.

Tiny pockets of insulation
Scanning electron micrograph of fiberglass shows the many fibers, which mat together to create insulating air pockets.

Heat loss (and preventing it) is not as linear as R-value suggests

BUILDING SCIENCE CALCULATIONS

R, U, and $

R-value stands for resistance value. It is a way of quantifying the resistance to energy flow through a material. The higher the R-value, the better the insulating properties of a material.

U-value represents the actual energy flow through a material. The lower the U-value the better the insulating properties of the material or assembly.

R-values are primarily used for labeling and marketing building insulation materials. If we know the R value of a material we can determine the U-value and vice versa because U-value is the inverse of R-value.

R=1/U

For example:
If a wall assembly has a U-value of 0.10, then
R = 1/0.1
R = 10

R value is important but it does not tell the whole story about insulation. Foam and fiberglass have similar R-values per inch, but this doesn't mean that they perform the same in a real-world scenario. Other factors, such as air movement caused by wind, stack effect, and mechanical equipment, are important to consider when comparing insulations.

Quality of installation and continuity of the air barrier are nearly as important as the insulation material itself.

Measuring conductive heat loss is fairly simple

Energy loss and gain can be calculated if the R-values of the assembly, the area of the assembly and the temperature difference across the assembly are known.

The equations at right explore a couple of examples of heat loss from a house that is 70-degrees on the inside and 30-degrees outside. In the first example, the R-40 ceiling insulation helps reduce heat loss considerably — the heat loss is 1,000 btu per

Calculating Heat Loss

HL = A x ΔT / R-Value

Heat loss through 1,000 sq. ft. of ceiling:
1,000 x (70-30) / 40 = 1,000 BTUs/Hour

Heat loss through 1,000 sq. ft. of R-10 wall:
1,000 x (70-30) / 10 = 4,000 BTUs/Hour

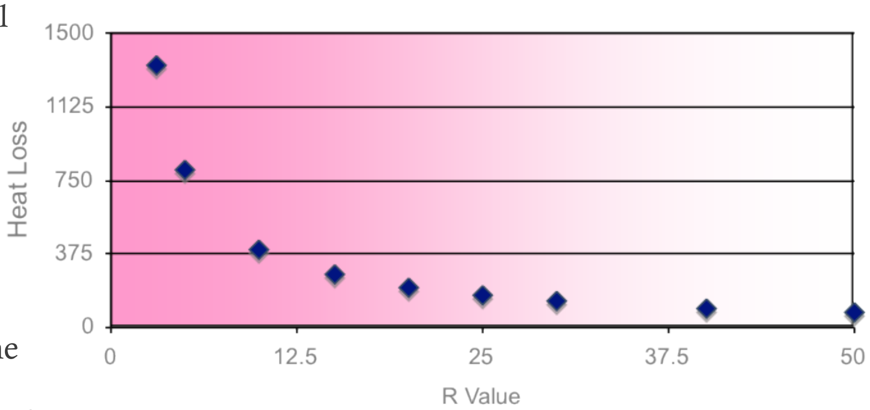
HL: Heat loss
EA: Exposed area
ΔT: Temperature difference (assume 30°F outside, 70°F inside).

hour. The second example, with only an R-10 ceiling spanning the same area, has 4 times the heat loss — 4,000 btu per hour. One fourth of the resistance to heat flow, four times the losses. But this can be a little misleading.

The law of diminishing returns applies heat flow

When insulation is doubled, heat flow is always cut in half. At some point, the heat flow has been reduced enough that cutting it in half again is no longer practical or cost effective.

To double an R-10 wall to R-20 will cut the BTUs from 4,000 to 2,000 resulting in significant energy savings. Bringing that same wall to R-40 would cut the BTUs to 1,000. In most climates it would take a long time to recoup the extra investment, so this is a poor investment at today's energy prices. If energy prices go up, the investment looks better.



The first R is the biggest. Each additional R after that has half the effect of the previous R. Adding piles and piles of insulation only makes sense in cold climates where big temperature differentials exist between inside and out.

The real world is more complicated than equations and models

BUILDING SCIENCE SUBTERFUGE

As temperature changes, so does R- value

So, some insulation materials work better than others in different applications. In an attic, two different densities of loose fill insulation (with the same R-value) can perform very differently.

They also are affected by the temperature differential placed across the insulation. In fact, for most insulation materials, R-value increases as the outdoor temperature decreases, down to about -20F, at which point it drops off. Put another way for people in hot climates, as temperature increases, your attic insulation loses R-value.

Different seasons (and climates) drive heat flow differently

In winter, heat loss is primarily through conduction across the building assembly. Convection through stack effect and air leakage play a secondary role and radiation accounts for a small percentage of heat loss. This is why people use much more insulation in foundations, attics and walls in cold climates.

Radiation is the primary form of heat gain in summer occurring through windows, skylights, and dark colored walls and roofs. Conduction is also important in a cooling season and as energy codes get more stringent, insulation levels will increase to slow conduction losses. The point of diminishing returns, however, is reached quicker in hot climates than it is in cold climates. Convection heat gain through air leakage has less effect in the summer because stack effect is reversed (cool air in the house is heavier than the lighter outside air).

For all of these reasons, it is important to focus not only on the type of insulation material, but on the work it is supposed to do, where it is supposed to do this work, and the quality of its installation. Stopping air with a well-defined air barrier system, and controlling radiant heat gain will go a long way toward making a house comfortable and energy efficient during winter and summer.

MORE ABOUT HEAT FLOW AND INSULATION:

Building America Solutions Center:
Thermal Enclosure Field Checklist
https://basc.pnnl.gov/resource-guides?f[0]=field_checklist_focus%3A121

Energy and Environmental Building Alliance (EEBA):
Houses that Work
(www.eeba.org/housesthatwork)

ConstructionInstruction.com
The R Factor
(www.constructioninstruction.com/articles/r-factor-mlaliberte)

Filling the Void
(www.constructioninstruction.com/articles/filling-void-insulation-fernando-pages)

Green Building Advisor:
The Building Envelope
(www.greenbuildingadvisor.com/green-basics/green-enclosures-do-four-things)

Building Science Corporation:
Thermal Control in Buildings
(www.buildingscience.com/documents/digests/bsd-011-thermal-control-in-buildings)

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Ci also teaches high performance building best-practices to thousands of building professionals each year at trade shows, industry conferences, and specialized accredited classes, such as Houses That Work, offered through the Energy and Environmental Building Alliance (EEBA).

Ci Productions is the media wing of the company. Ci Productions manages the Ci HD app, the website (ConstructionInstruction.com), and Ci's *VIP Newsletter*. The Ci HD app began as a leave-behind for big builders after we consulted on their job sites — an information safety-net that could help them continue to make sense of what we teach. The app has since grown in popularity into the most-downloaded construction mobile application in Apple's app store with more than 120,000 downloads and over 60,000 active users.

Ci's key players are former builders, remodelers, engineers, or designers.

THE Ci TEAM:

Mark LaLiberte, President
mark@ConstructionInstruction.com

Gord Cooke, Vice President,
gord@ConstructionInstruction.com

Justin Wilson, Vice President, Operations
justin@ConstructionInstruction.com

Daniel Morrison, Media Director
dan@ConstructionInstruction.com

Deirdre Damron, Project Manager
deirdre@ConstructionInstruction.com

Amy Pardee, Marketing Manager
amy@ConstructionInstruction.com

CONTACT Ci:

info@constructioninstruction.com
(719) 375-9300
P.O. Box 3009
Colorado Springs, CO 80934