



CamdenCAN

# Building Science Fundamentals

The Science Behind Comfort, Durability, and Indoor Air Quality

*November 13, 2025*

# Presenter:

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# What is **building science**?



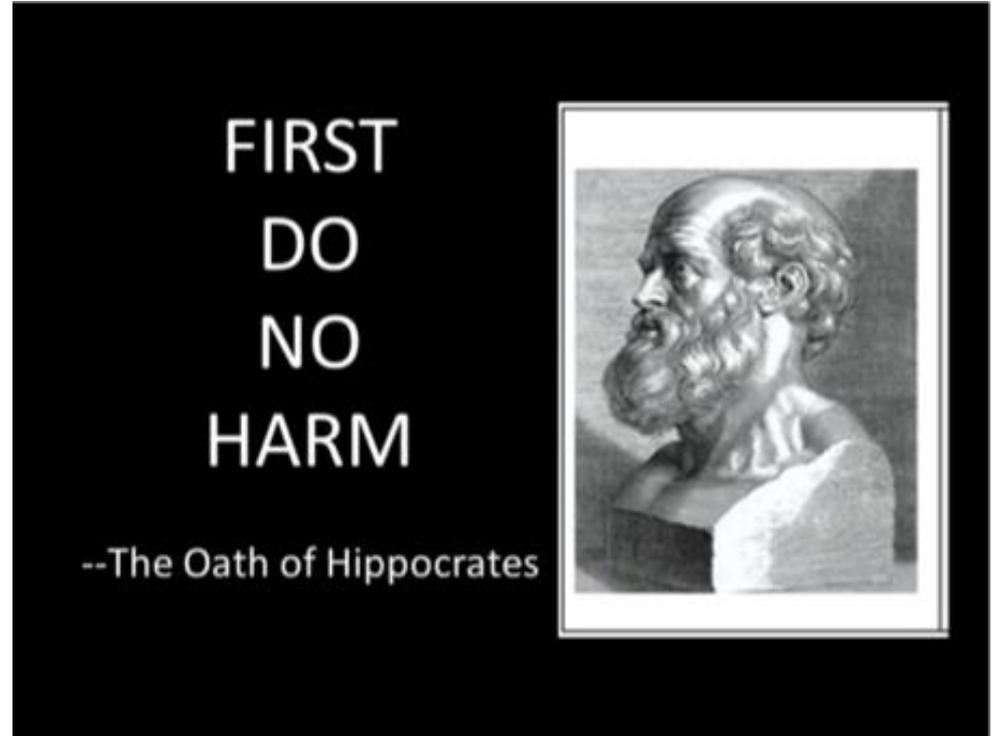
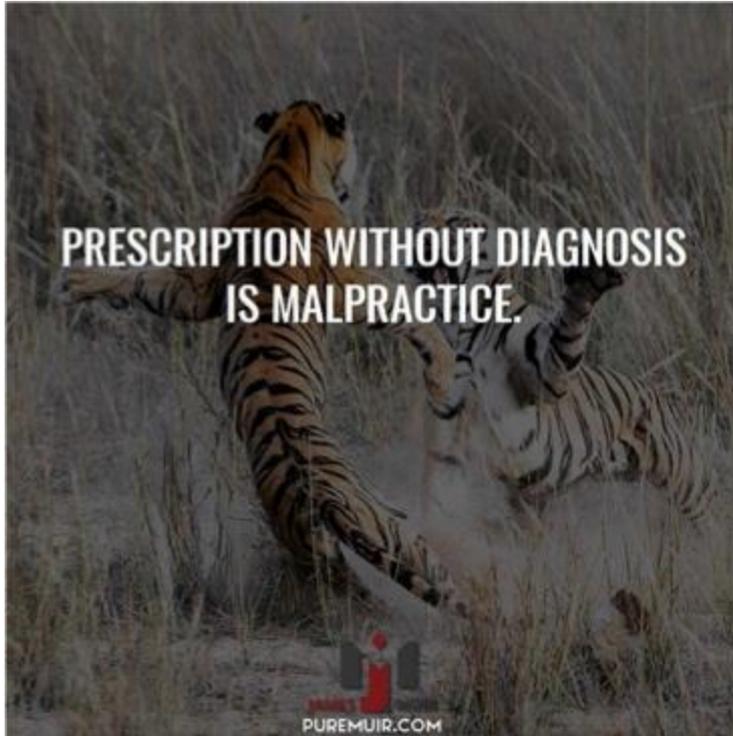
**Building science** is the study of how a building's components and systems interact with each other and the environment to create a high-performance, energy-efficient, durable, and healthy structure

Let's also define **Home Performance**:

A systematic approach to modifying a home's building components and mechanical appliances to achieve a **healthy** and **safe, comfortable** and **durable** indoor living environment.



# Why is **building science** so important?





## Building science says:

- Slow down, be thoughtful
- Consider the house as a system
- Consider the consequences
- First, do no harm

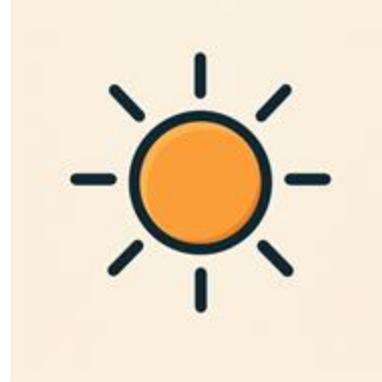
Let's start with the 4 control layers:



**Water**



**Air**



**Heat**



**Moisture**



## **Water:** essential for life, but destructive for buildings

How do we keep water out of our buildings?

- Weather Resistant Barriers
- Drainage Planes
- Gutters & Exterior Drainage
- Foundation Waterproofing



# Health Effects of Mold

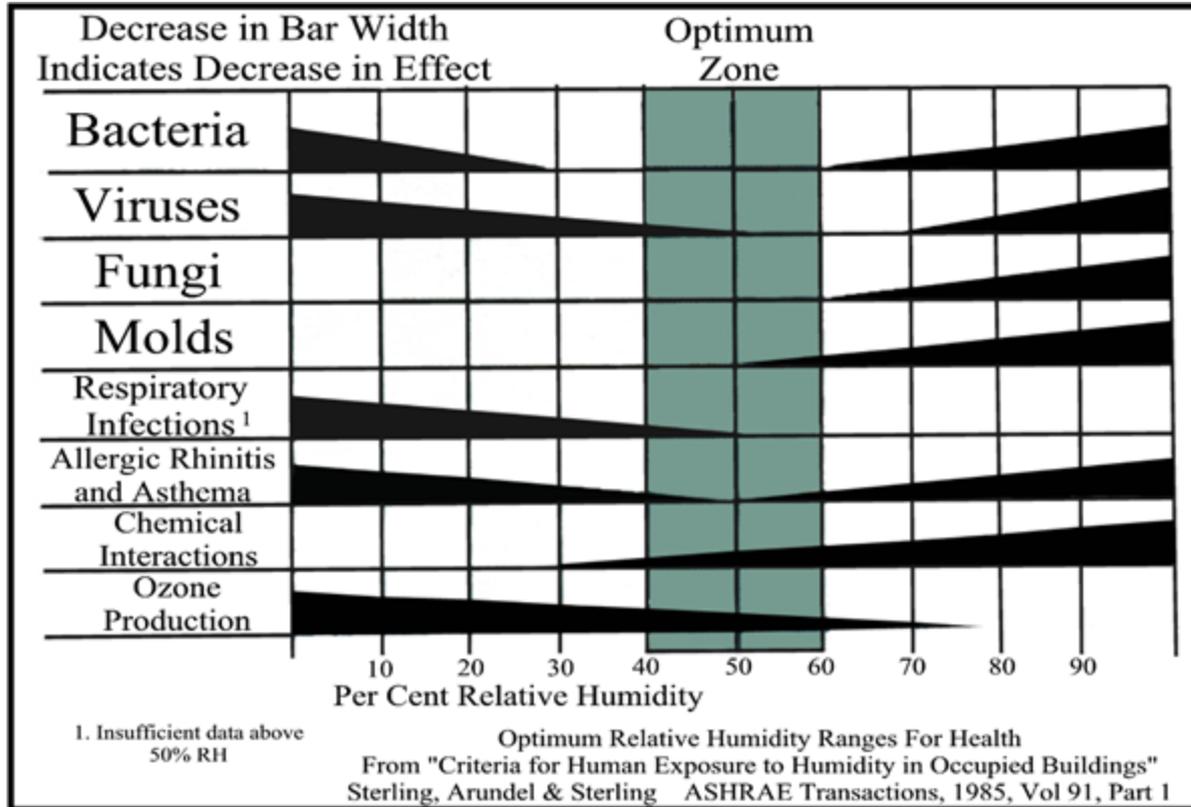
Typically, inhalation of mold spores irritates the lungs and causes an allergic reaction. It can trigger asthma and lung tissue inflammation, respiratory issues and COPD. Other reactions include rashes, eye irritation. Mold can be categorized as allergenic, pathogenic, or toxigenic.

Mold requires:

- Moisture
- Suitable temperature
- Organic food source



# The Relative Humidity Sweet Spot: 40%-60% RH





## Air Barriers minimize the air coming into and moving out of our houses

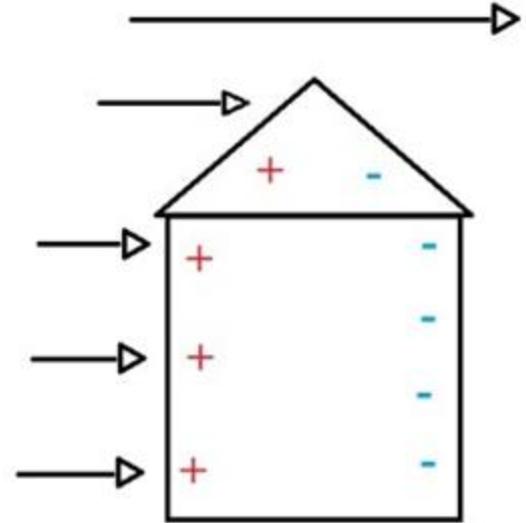
- In a typical house, 40% of the heat loss is due to air leakage
- Air barriers work a lot like a windbreaker for air leakage, like house wrap on our exterior walls to block the wind from pushing into our house



# Why do we have air leakage in our houses?

## Wind-driven:

- For every CFM (cubic feet per minute) of air that pushes into the house, it pushes 1 CFM of air out of the house
- Negative air pressure pulls air out of the house



# Why do we have air leakage in our houses?



**Stack Effect:** as air picks up heat and becomes more buoyant, it rises up and pushes warmer air out, while pulling in cooler air lower in the building

# Why do we have air leakage in our houses?

## Mechanicals:

- Bathroom exhaust fans
- Kitchen exhaust fans
- Clothes dryers
- Atmospheric draft boilers, furnaces, fireplaces
- Forced hot air ductwork pressure imbalances



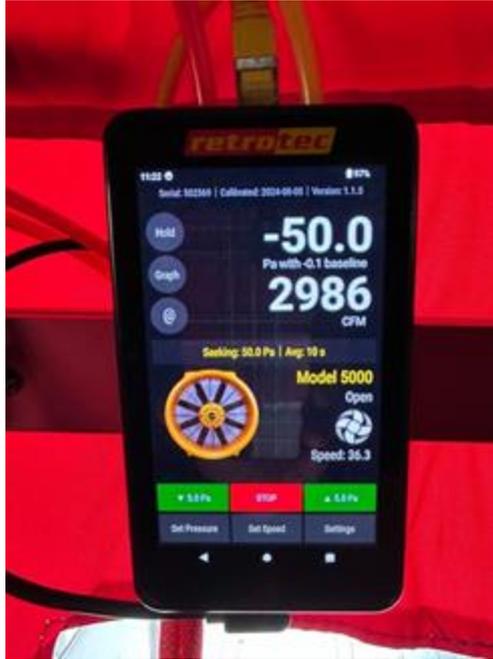
# Testing your air barriers: using a blower door



- Measures air leakage in buildings in CFM50
- Creates conditions to use additional diagnostic testing to find air leakage



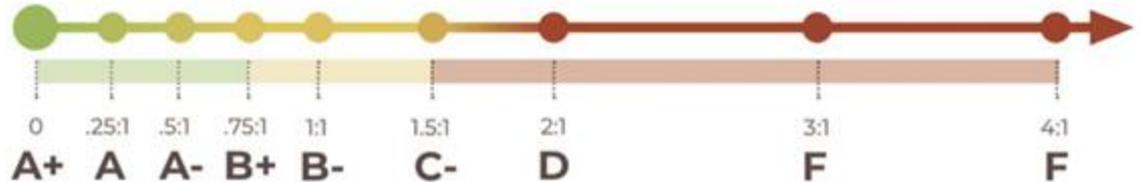
# Blower doors: what do the numbers mean?



## Blower Door Ratio A Good Heuristic

HOW LEAKY IS YOUR HOUSE?

Leakage to square foot ratio (cfm50)



## Other blower door metrics:

**Air changes per hour (ACH):** how many times the conditioned volume of air escapes each hour ( $\text{CFM}_{50} \times 60 / \text{volume} = \text{ACH}$ )

- 3 air changes per hour or less required in Maine for new construction OR
- 0.2 CFM per square foot of building envelope (houses less than 1,500 ft sq
- Can only be measured with a blower door

**Equivalent Leakage Area (ELA):** the equivalent hole size of all the air leakage in the building combined ( $\text{CFM}_{50} / 10 = \text{ELA}$  in square inches)

# Consider a blower door **pre-test** in new construction

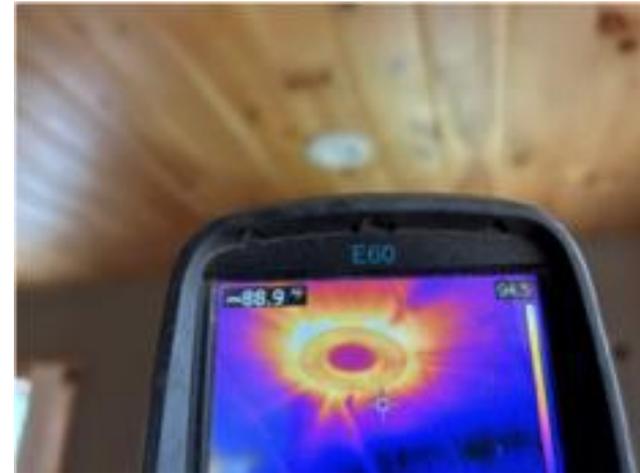
- All windows & doors are installed.
- Most Mechanical, Electrical, and Plumbing systems have been installed.
- Air barrier components are visible & accessible.
- No insulation or siding yet.



# Let's put it to the test: additional testing with a blower door



**Infrared cameras** show air leakage through surfaces, the blower door allows infrared to be used year-round



# Let's put it to the test: additional testing with a blower door



**Smoke testing:** quickly finds sources of air leakage visually

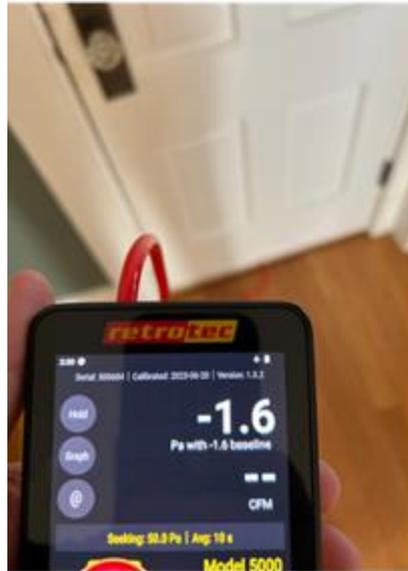
- A blower door can depressurize or pressurize a building

**Use your senses:** you can use your body and feel and hear air leakage



# Let's put it to the test: additional testing with a blower door

**Zone Pressure Diagnostics** measure pressure differences in rooms, zones, attics, basements, additions, etc.



## Thermal Barriers: keeping the heat in

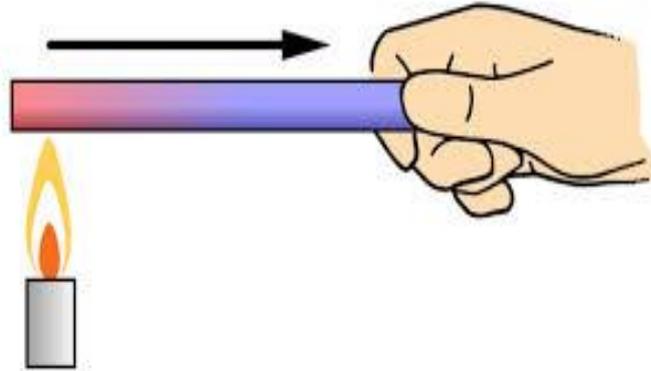


- Insulation acts like a sweater for your house to slow down the transfer of heat
- In a typical house, 60% of heat loss is through materials (not enough insulation)
- 2nd Law of Thermodynamics: heat moves from high concentration to low concentration
- All insulation works by trapping heat in small pockets of air

# Three methods of heat transfer:

## Conduction:

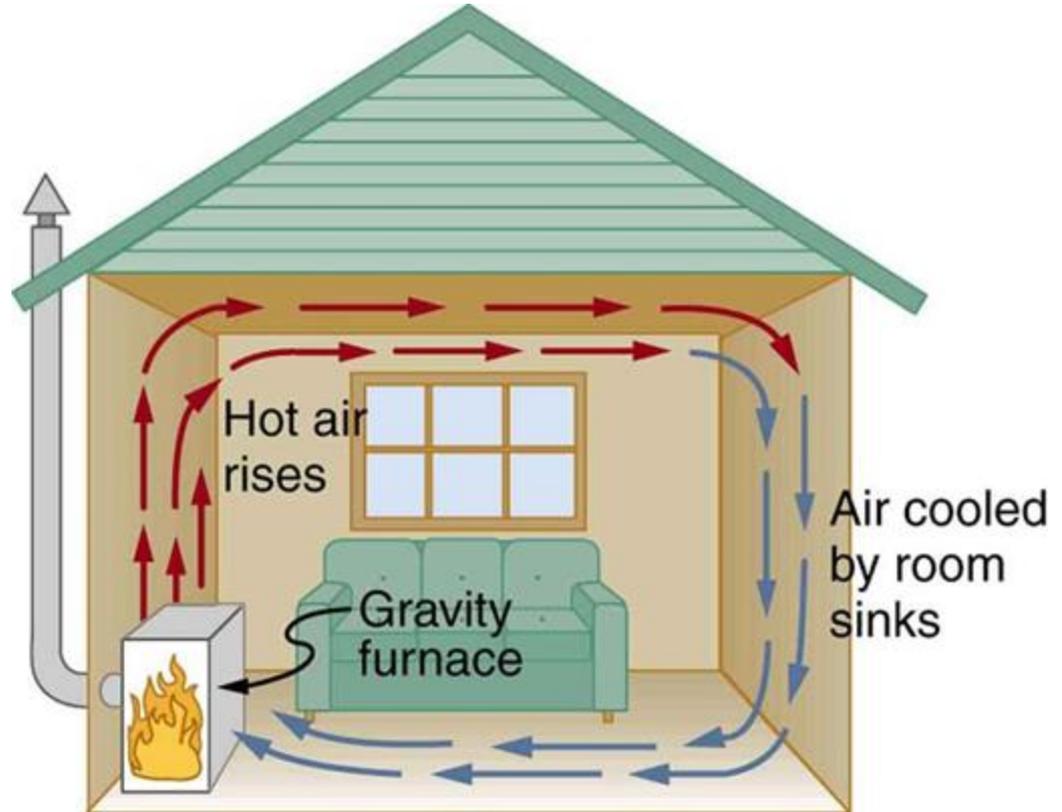
- Heat conducts through solid objects and between objects touching one another
- Most familiar and predictable type of heat flow



# Three methods of heat transfer:

## Convection:

- Heat transferred by a moving fluid like air or water
- Convective Loops

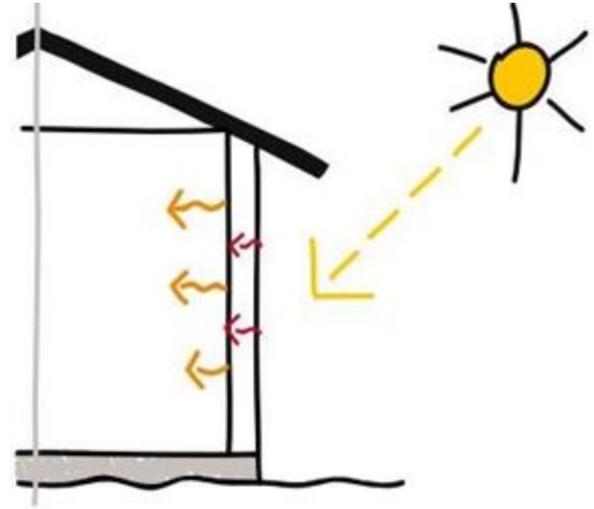




# Three methods of heat transfer:

## Radiation:

- Heat moves through space from one object to another
- Solar Energy
- Infrared Radiation - from objects on earth, emitted at different wavelengths



# How much difference does insulation make?

Conductive heat loss formula:  $\text{Area} \times \Delta T / R\text{-value} = \text{BTUs/hour}$

Square footage of  
a surface

Difference in temperature  
difference

Resistance to  
conductive heat  
transfer

## Heat Loss Formula: New construction, fully insulated



16" of cellulose in the attic = 800 ft sq surface area, on a cold day it's 20 degrees F outside and 70 degrees F inside

800 ft sq x 50 degrees / R60 (R-value) = 666 BTUs heat loss per hour

## Heat Loss Formula: Colonial built in 2000, standard construction



9" of fiberglass batts in the attic = 800 ft sq surface area, on a cold day it's 20 degrees F outside and 70 degrees F inside

$800 \text{ ft sq} \times 50 \text{ degrees} / R17 \text{ (de-rated R-value)} = 2,352 \text{ BTUs heat loss per hour}$

## Heat Loss Formula: 1850's farmhouse, no insulation in the attic



Uninsulated attic = 800 ft sq surface area, on a cold day it's 20 degrees F outside and 70 degrees F inside

$800 \text{ ft sq} \times 50 \text{ degrees} / R1 \text{ (R-value)} = 40,000 \text{ BTUs heat loss per hour}$

Knowing the BTU heat loss per hour through a surface, we can use energy modeling software to predict:

- Heat loss over the heating season
- Cost to heat (ex: 100,000 BTUs/hour from one gallon of propane)
- Annual savings from adding insulation, installing more efficient heating, etc.

Some free energy modeling software: (sort of)



# Types of insulation: fiberglass



- Most common type of insulation, fairly inexpensive and DIY-friendly
- Rated R-value and effective, real-world R-value is often very different (9" R30 fiberglass batt can be only R6 real-world)



**Challenge question:** do we need to use fiberglass insulation in houses?

# Types of insulation: cellulose & wood fiber

- Lower carbon footprint, using recycled materials
- Can be loose-blown or dense-packed
- Typically requires professional installation



# Types of insulation: rockwool



- Batts and rigid board
- Is vapor-open, can be used in basements and as continuous exterior insulation
- Great for sound insulation, does not burn

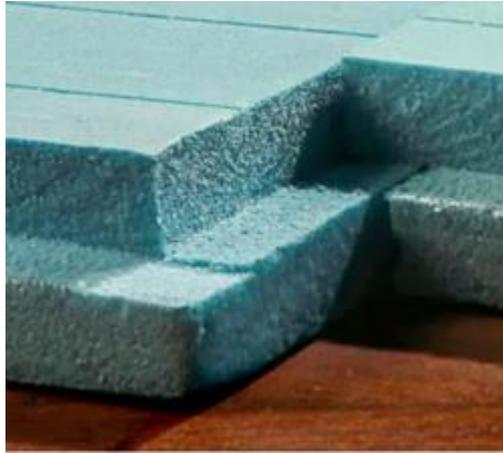


# Types of insulation: 2-part spray foam

- Highest R-value per inch (sort of)
- Also air seals for a tighter house (sort of)
- Environmental & climate issues
- Effectiveness highly dependent on installation, is a controversial product that can cause damage over time
- Can be several times more expensive than other insulation products
- When is it most practical to use?
- There is usually very limited (or no) quality assurance testing for spray foam after installation
- Requires an ignition barrier



# Types of insulation: rigid foam board



- High R-value per inch (sort of)
- Foam insulation is a plastic product
- Can be used for exterior continuous insulation, basements
- Polyisocyanurate (polyiso), extruded polystyrene (XPS), expanded polystyrene (EPS)
- Alternatives: Timber HP TimberBoard and Rockwool ComfortBoard

## Typical Insulation R-values

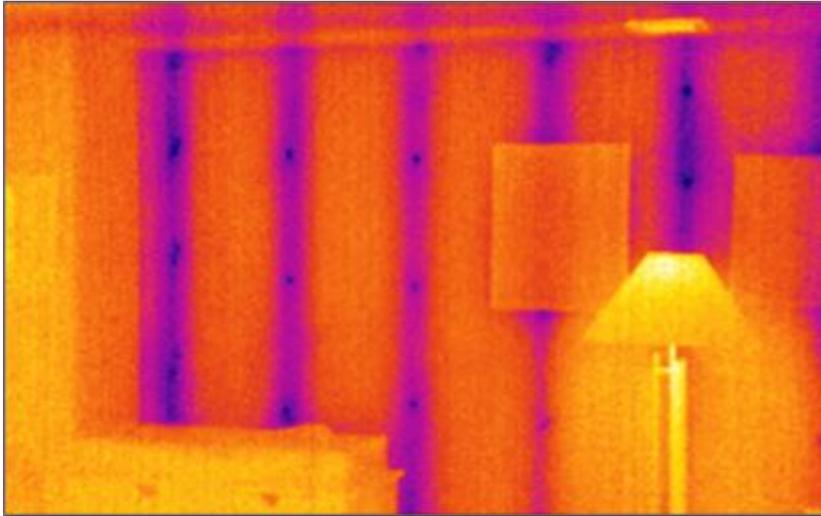
Insulation Type	R-value per inch	Typical Applications
Cellulose, loose fill	3.7	Attic Floor
Cellulose, high density	3.2	Walls, Enclosed Cavities, Framing Transitions
Fiberglass, batts	3.0*	Basement Ceiling, Open Stud Walls, Attic Floor*
Fiberglass, loose fill	2.8	Attic Floor, Walls (existing)
Fiberglass, loose fill, fluffed below manufacturer's standards	uncertain	Do not install, or correct by blowing over with higher density
Rockwool	3.0	Attic Floor, Walls, Basement Ceiling (may be loose or batts)
Vermiculite	2.7	Attic Floor
Poly-isocyanurate, rigid board	7.0	Foundation Walls, Attic Access Doors
Polystyrene, expanded rigid board	4.0	Foundation Walls, Sill Plate
Polystyrene, extruded rigid board	5.0	Foundation Walls, Sub-Slab, Sill Plate
Low Density Urethane, sprayed foam	3.7	Attics, Walls (new construction); Sill Plate, Band Joist, Framing Transitions
Urethane, sprayed foam	6.0	Attics, Walls (new construction); Sill Plate, Band Joist, Framing Transitions
Urea Formaldehyde Foam	4.0	Attics, Walls (existing)

*\*see chart below for existing fiberglass batt evaluation*

# Thermal bridging



# Thermal bridging: why we use continuous insulation



15% - 30% of heat loss through exterior walls is typically due to thermal bridging



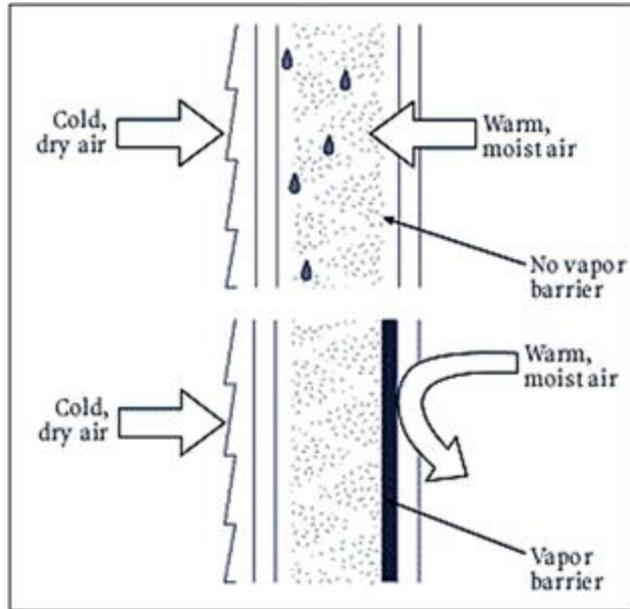
# Thermal bridging: why we use continuous insulation



Source: TimberHP



# Vapor Control Layer: slows moisture diffusion (moisture transfer through solid materials)



- Not a true barrier, there are different levels of permeability allowing some moisture diffusion
- In Maine, we use a vapor control layer on the inside surfaces of our exterior walls to reduce moisture diffusion into the wall cavities
- Another example is plastic sheeting over a dirt floor in a basement or crawl space

# Condensation inside exterior wall cavities

On a hot, humid day, why does water form on a cold soda can?

Let's say it's a cold winter day, 20 degrees F outside, 70 degrees F inside, you just cooked pasta on the stove - where does all that moisture go?



**Vapor Control Layer:** slows moisture diffusion (moisture transfer through solid materials)



# Rain Screen

Cheap insurance for  
vapor and bulk water  
control



# The 4 Control Layers

One surface can perform more than one layer's function



# The 4 Control Layers



# The 4 Control Layers



# The 4 Control Layers

Continuity of layer important

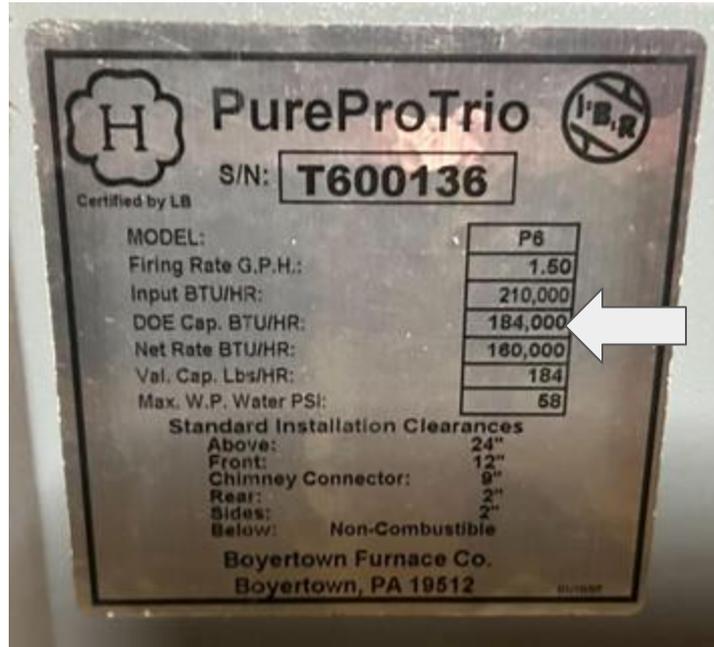


# The 4 Control Layers

Continuity of layer important



# Mechanical Systems: Heating & Cooling



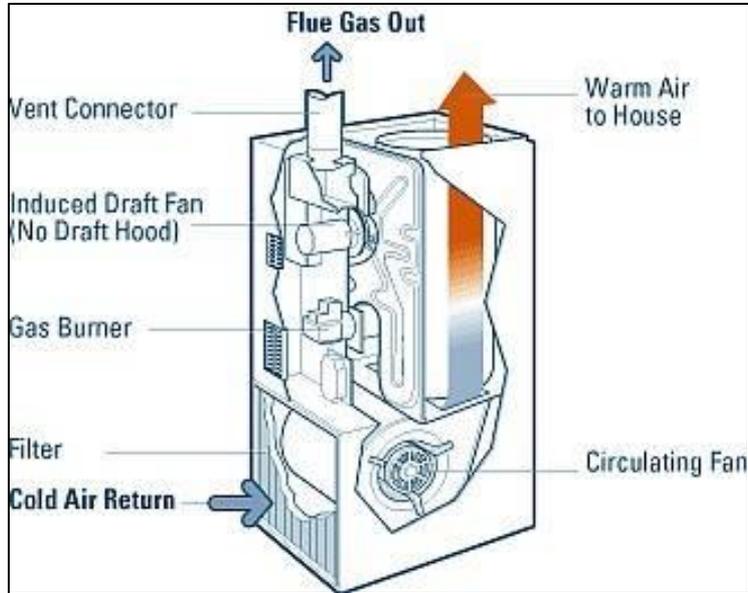
- BTUs/hour (British Thermal Units)
- Heating load is calculated to replace heat loss
- 184,000 BTUs is brute force heating capacity

# Heating System Types



- Forced Air
- Hydronic (Hot Water)
- Steam Radiant
- Heat Pumps (air)
- Geothermal (ground source heat pump)

# Forced Air System



Source: About, <http://homerepair.about.com/od/heatingcoolingrepair/tp/Top-Furnace-Troubleshooting-And-Repair-Tutorials.htm>

## Distribution -

Air Heated in a furnace

## Fuel Sources -

Natural Gas, Propane, Oil  
Electricity

## Advantages -

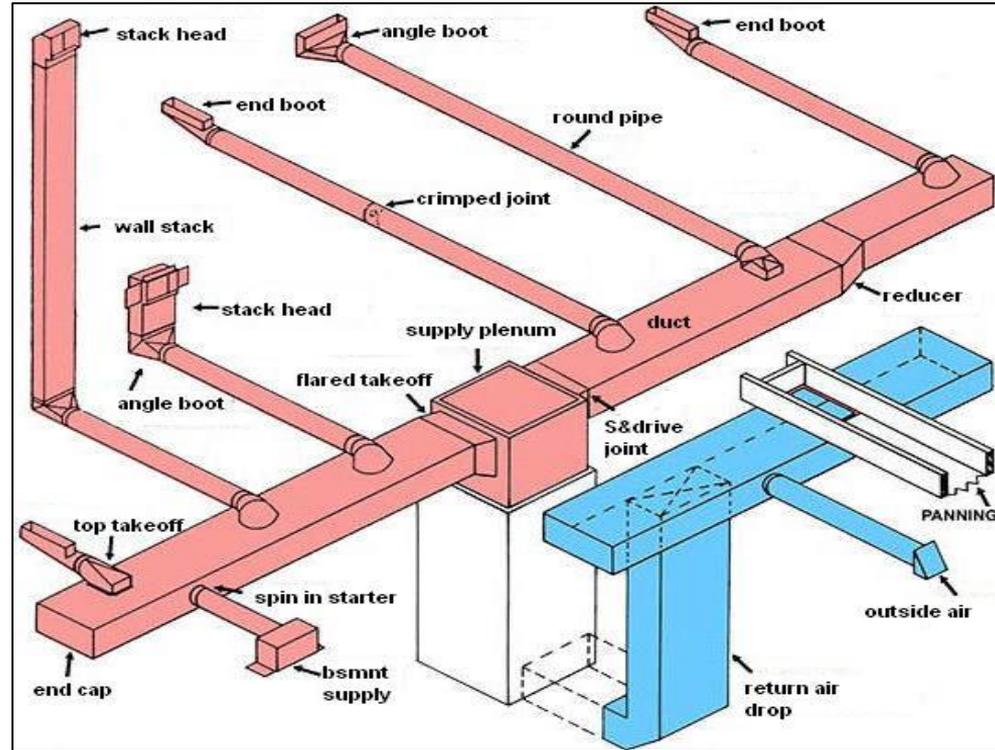
The only distribution system  
that can be used for cooling

## Disadvantages -

Requires Ductwork

Air requires filtration

# Duct System Layout



# Hydronic Systems

55



## **Distribution -**

Hot water heated by a boiler piped to fin tube baseboards or radiators

## **Fuel Sources -**

Natural Gas, Propane, Oil,  
Electricity Coal, Wood

## **Advantages -**

Energy efficient – Quiet  
Close temperature control

## **Disadvantages -**

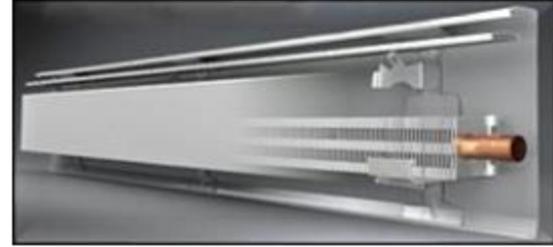
Slow temperature increase  
Radiation units must remain unobstructed  
A/C requires separate Ductwork

# Hydronic / Radiant Systems

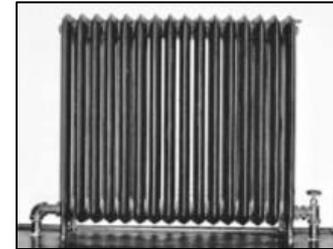
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Source: Radiant Floor,  
<http://radiantfloor.org/author/admin/page/53/>



Source: Northern Tool and Equipment,  
[http://www.northerntool.com/shop/tools/category\\_heaters-stoves-fireplaces+wood-stoves](http://www.northerntool.com/shop/tools/category_heaters-stoves-fireplaces+wood-stoves)



# Steam Systems

57



Source: Steam Radiators,  
<http://steamradiators.com/cust-gallery.html>



Source: Steam Radiators,  
<http://steamradiators.com/cust-gallery.html>

## **Distribution** -

Steam piping and radiators

## **Fuel Sources** -

Natural Gas, Propane, Oil      Electricity –

Coal / Wood

## **Advantages** -

Efficient – Warms space quickly

New, modern convection units

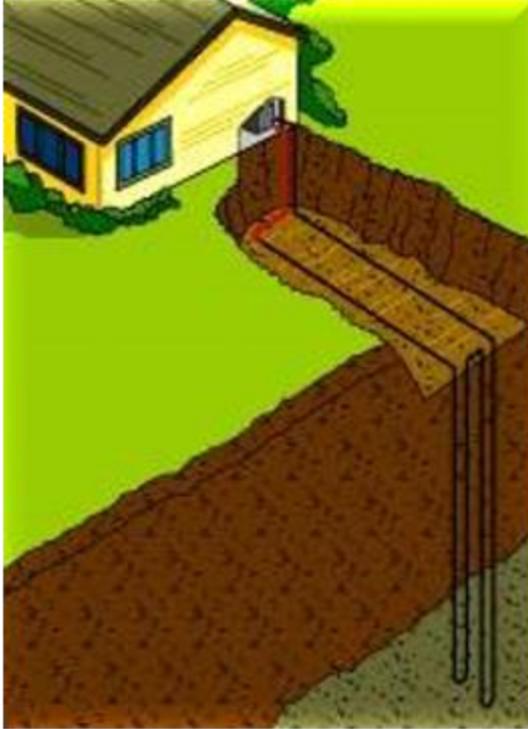
## **Disadvantages** -

Old radiators are unsightly

Radiation units must remain unobstructed

Operating Pressures and System Leakage

# Geothermal Systems



Source, Oakland University, <http://www.oakland.edu/cerc/geo>

## Distribution -

Heat Pump Hydronic

## Fuel Sources -

Electricity

Earth Heat Sink

## Advantages -

COPs 3-4

Eco-Friendly

## Disadvantages -

Expensive - May need a back-up systems at periods

Limited range w/o oversizing

# Mechanical Systems: Heating Pumps

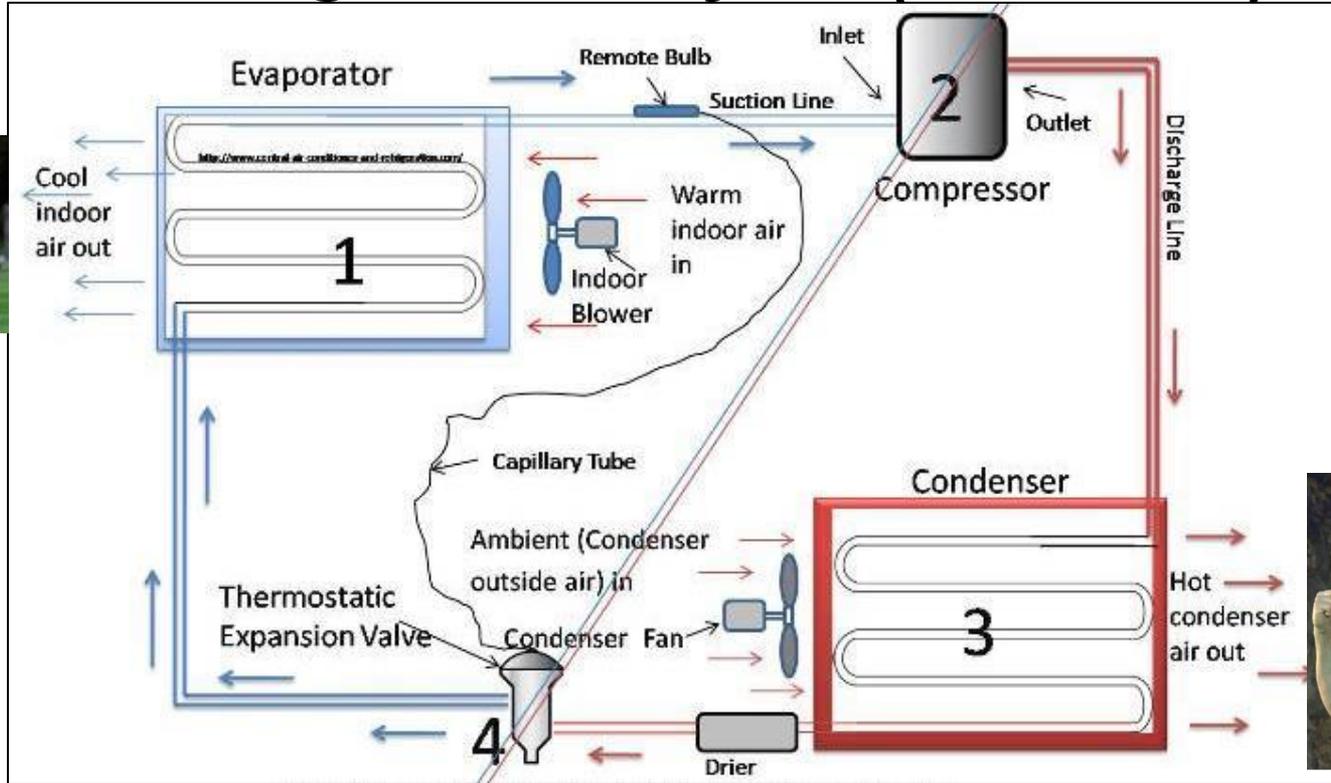
- Much more energy efficient than fuel oil (300%-400% efficient)
- Variable speed (more precise)
- Heating & air conditioning
- You can generate your own heat using solar PV panels
- Different configurations including outside and interior units



**Challenge question:** why install fuel-based heating systems at all in new construction?

# The Refrigeration Cycle (The Hulk)

High to Low -  
Coolant wants  
to be low  
temperature



R410A boils at  
55 degrees F



Source: Central Air Conditioner and Refrigeration, <http://www.central-air-conditioner-and-refrigeration.com/basic-refrigeration-cycle.html>

# Heat Pumps: Easy Opportunities



Central A/C replacements



Existing furnace / ductwork

# How to Accurately Size Heating Equipment?

- **Manual J:** determines heating and cooling load of the building, taking into account existing insulation, air leakage (blower door reading), and volume of the spaces
- **Manual S:** determines the size of the heating and cooling system equipment to be installed
- **Manual D and T:** guidance for designing ductwork for forced hot air systems, locating registers and grilles
- **Manual H:** guidance for system design for heat pumps
- At 3 air changes per hour, there probably isn't sufficient combustion air for natural-draft heating systems and water heaters, or fireplaces

# Domestic Hot Water Heating:

Typically 18% of annual household energy use



Tankless coil on boiler



Atmospheric-draft gas storage tank



Indirect storage off boiler

# Domestic Hot Water Heating: more efficient options



Heat pump water heater



On-demand



Electric, sometimes the most practical, depending on space

# Domestic Hot Water Heating: installation options



Point-of-source



Foam pipe wrap insulation  
(easy DIY option)

- Plan for the shortest runs between water heater and sinks / showers
- Set water temp to 120 degrees F

# Ventilation: “A house needs to breathe!”

*(no, it doesn't)*



Where your  
'fresh' air  
actually comes  
from:



# Mechanical Ventilation: how much fresh air do you need?

**RED ASHRAE 62.2-2016 Ventilation** Reset Print

New or existing construction: Existing  
Dwelling unit is: Detached  
Use infiltration credit: Yes

Closest weather station: United States  
Weather and shielding factor [1/hr] =

Floor area [ft<sup>2</sup>] =  
Number of occupants =  
Dwelling height [ft] =  
Measured leakage @ 50Pa [CFM] =

Use Advanced Blower Door Inputs

Use Local Ventilation Alternative Compliance

**Dwelling-Unit Ventilation Results**

Effective annual avg infiltration rate [CFM] =  
Total required ventilation rate,  $Q_{tot}$  [CFM] =  
Infiltration credit,  $Q_{inf}$  [CFM] =  
Required mechanical ventilation rate,  $Q_{req}$  [CFM] =

**Dwelling-Unit Ventilation Run-Time Solver**

Fan capacity [CFM] =  
Fan run-time per hour [min] =

**Dwelling-Unit Leakage Rate Solver**

Target mechanical ventilation rate [CFM] =  
Corresponding measured leakage @ 50Pa [CFM] =

Version 2016-07-06\_01:30 © 2016 Residential Energy Dynamics, LLC

<https://basc.pnnl.gov/redcalc>

- Exhausts stale air (we breathe in oxygen and breathe out carbon dioxide)
- Removes moisture/humidity
- Improves indoor air quality

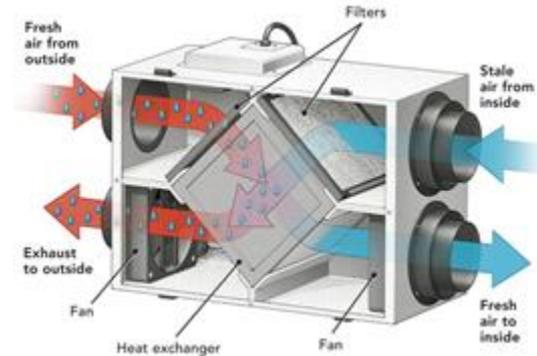
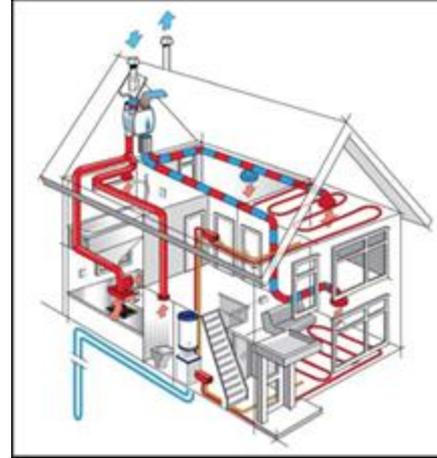
# Mechanical Ventilation options: local exhaust fans



- 'Bath fan on a timer'
- Low-cost option for mechanical ventilation
- Exhaust-only fans increase air leakage

# Mechanical Ventilation options: ERVs

- Provides filtered air from outside, exhausts stale air
- Will soon be required by MUBEC in all of Maine
- Can be a ducted system (most common) or ductless through-wall unit(s)

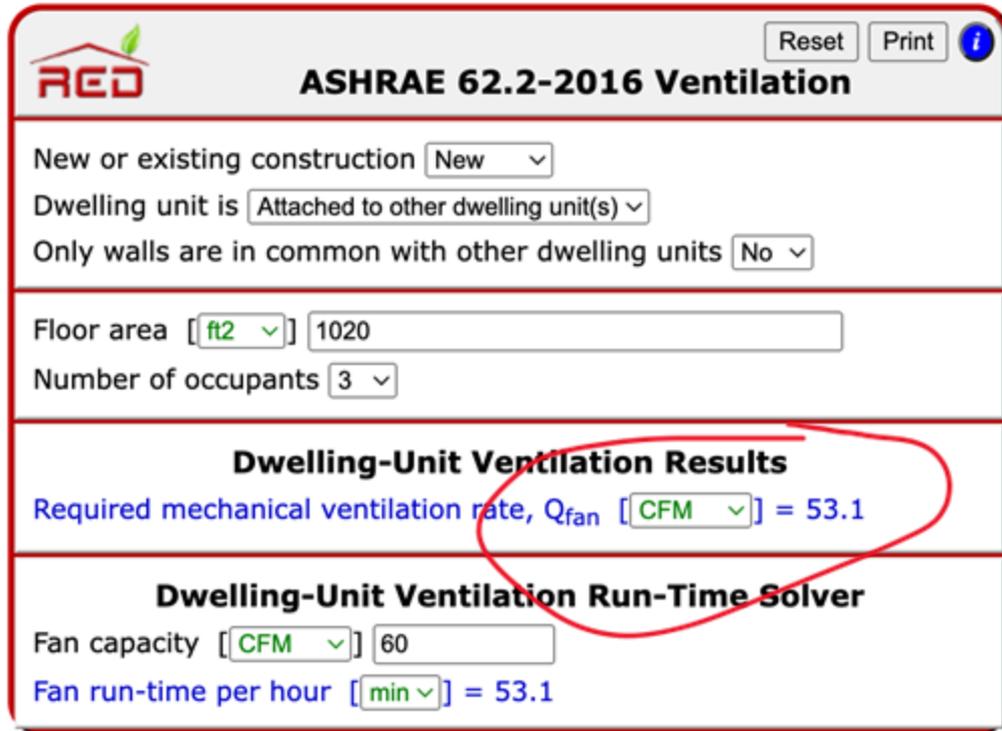


# Tell-tale signs of a tight, under-ventilated house:

- Black mildew in living space
- Back drafting wood stoves
- Doors pop open
- Sustained high humidity
- Mildew around windows
- Moldy furniture
- Lingering odors
- Occupant allergy-type symptoms
- Indoor pollutants, some of which are life threatening (CO)



# Tight Houses with No Mechanical Ventilation



The image shows a screenshot of the ASHRAE 62.2-2016 Ventilation software interface. The interface is titled "ASHRAE 62.2-2016 Ventilation" and includes a "Reset" button, a "Print" button, and an information icon. The form contains several input fields and dropdown menus. The "New or existing construction" dropdown is set to "New". The "Dwelling unit is" dropdown is set to "Attached to other dwelling unit(s)". The "Only walls are in common with other dwelling units" dropdown is set to "No". The "Floor area" input field is set to "1020" with a unit dropdown set to "ft2". The "Number of occupants" dropdown is set to "3". The "Dwelling-Unit Ventilation Results" section shows "Required mechanical ventilation rate,  $Q_{fan}$ " with a unit dropdown set to "CFM" and a value of "53.1". The "Dwelling-Unit Ventilation Run-Time Solver" section shows "Fan capacity" with a unit dropdown set to "CFM" and a value of "60", and "Fan run-time per hour" with a unit dropdown set to "min" and a value of "53.1". A red circle highlights the "Dwelling-Unit Ventilation Results" section.

- House built in 2023, 6" spray foam wall insulation, 16" cellulose in attic
- Moldy furniture after 1 month



- 1,200 ft<sup>2</sup>
- 4 ACH

## Other mechanical systems:

- Dehumidifiers (auto-drain, 55% RH)
- Sump pumps (cover sump holes)
- Radon mitigation systems (air, water)
- Smart indoor air quality monitors



Dehumidifier



Open sump hole



Radon system



Smart IAQ monitor

# Gas Ovens: let's move on



Gas oven/stovetop



Induction oven/stovetop

- Banned in some states for new construction
- Significant impact on indoor air quality
- Significant safety hazard
- Induction outperforms gas stovetops

# Let's talk windows: let the sun shine in

- Windows typically make up 15% of total wall space
- Windows are designed to allow some parts of the electromagnetic spectrum through while blocking others
- U-factor is the inverse of R-value (0.27 U is R3.7)



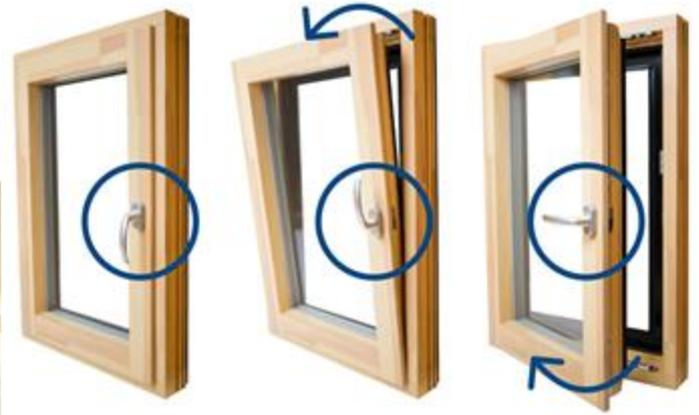
# Let's talk windows: types



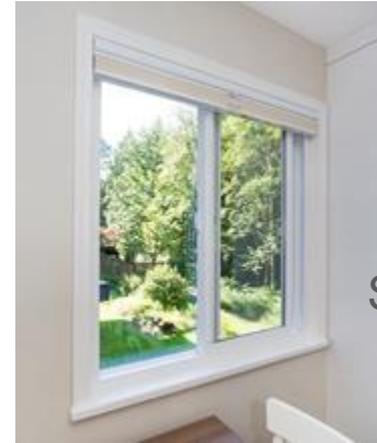
Double-hung



Casement



European tilt & turn



Sliding windows

- Consider window material types
- Double-paned vs triple-paned

# Let's talk windows: further efficiency improvements

- Air seal the rough openings
- Operable windows vs fixed windows
- Casement/tilt vs double-hung
- Interior window inserts / rigid foam inserts
- Shades & curtains - pros and cons
- Skylights - overheating



# Weatherization & Energy Codes: reducing heat loss

- Pre-insulation (before 1940's = the Wild West, except....)
- Early insulation (1940's-1965, not at all serious)
- The 1970's experiments
- Early code (1975-2015, not serious)
- Current code (serious)
- Passive House (incredibly serious)

**Challenge question:** does new construction need to be 'affordable'?



# Importance of Building Science: some examples



- 1850's farmhouse, no insulation
- The house was not designed to be insulated, the system depends on natural air leakage
- Before we insulate and tighten the house, consider the consequences
- The basement never had mold, radon, or indoor air quality issues
- The old 200,000 BTU/hr furnace will be oversized and short-cycle

# Importance of Building Science: some examples



- 3,800 ft<sup>2</sup>
- 0.384 ACH

- 'Build tight, ventilate right'
- Effectively no natural air leakage at 0.384 ACH
- Balanced mechanical ventilation is essential
- Heating with wood not really an option
- With such little heat loss, the house could go without power for days

# Importance of Building Science: some examples



1950's ranch, minimal insulation

- Considering installing heat pumps as the primary heating/cooling system
- Will it be effective and efficient without insulating first?
- 130,000 BTU/hr oil boiler could drive the moisture out
- Heat pumps may be  $\frac{1}{5}$  of the heating capacity
- Will there be issues with frozen pipes in the basement and walls?
- Accurate heat load sizing is very important

# New construction vs renovations

## New

- Stay above grade
- Watch material contents
- Avoid combustion devices
- Install balanced ventilation
- Don't trap moisture
- Install a radon prevention system
- Monitor

## Reno

- Don't tighten house without dealing with moisture
- Start with bulk water
  - Roof
  - Flashing
  - Siding
  - Gutters
  - Grading
- Deal with basement
- Get toxic materials out
- Test for lead
- Test for radon/install a system

# Building Science & Indoor Air Quality

- Radon is a colorless, odorless, tasteless radioactive gas that comes up from the ground and gets trapped inside buildings.
- Exposure to radon causes lung cancer. Radon exposure can occur in any built environment: home, school, work, and more.
- Radon is the #1 cause of lung cancer in non-smokers. Only smoking causes more lung cancer than radon.
- The only way to detect radon is to test for it. EPA maximum safe threshold is 4 pCi/L.

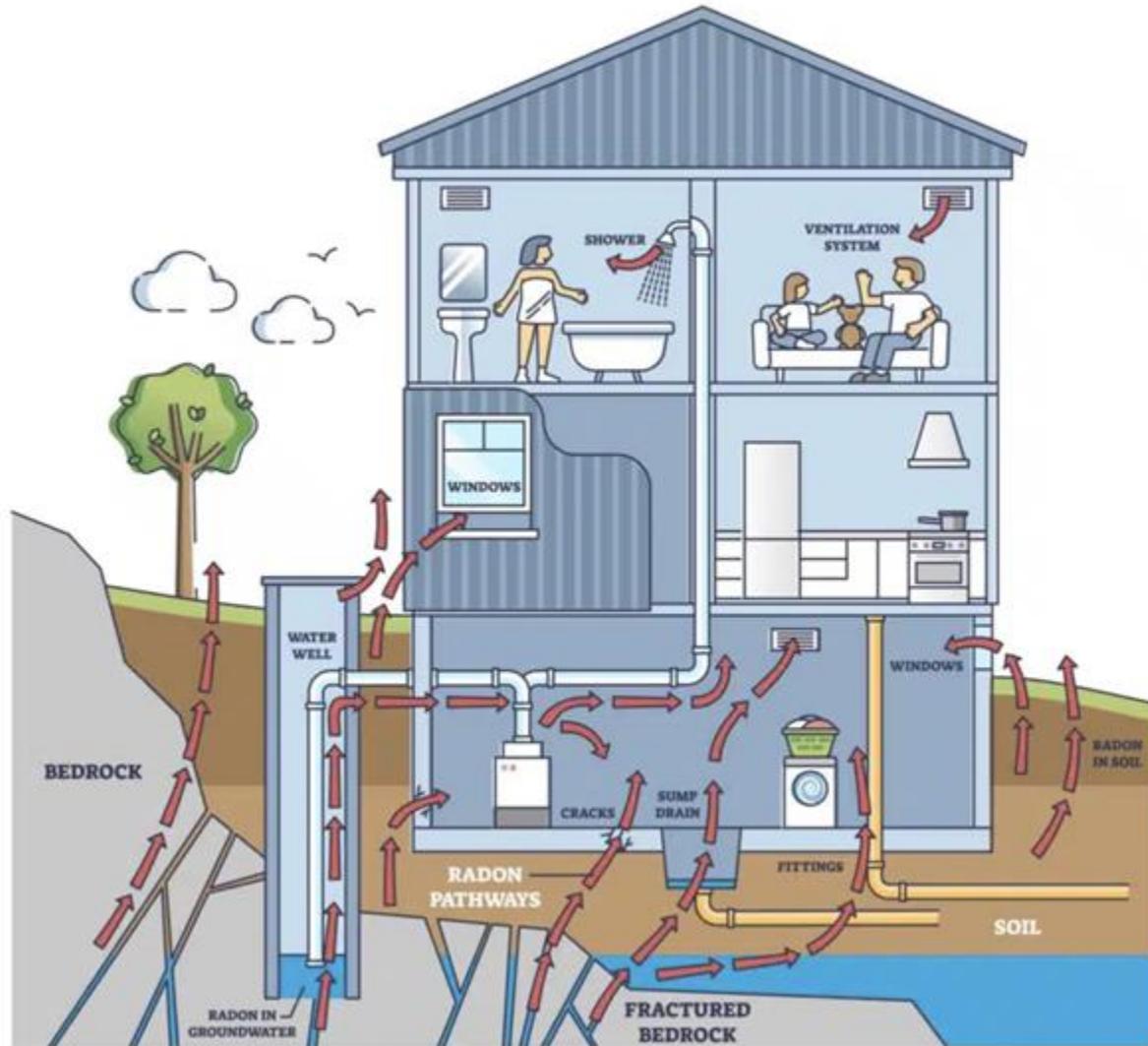


# Radon in Maine

- Maine is #3 in the country for having the highest rates of radon-induced lung cancer
- 1 in 3 Maine homes likely has a radon problem. 2 in 3 Maine homes in Cumberland County likely have radon problems.
- Maine's average radon level is 5.9 picocuries per liter, which is 392% higher than the nationwide average of 1.3 picocuries per liter, and 68% above U.S. EPA recommended action level of 4.0 picocuries per liter.
- Exposure to 4.0 picocuries per liter of radon is equivalent to smoking 8 cigarettes a day or getting 200 chest x-rays per year.
- 310 Mainers contract radon-induced lung cancer each year.
- 165 Mainers die each year from radon-induced lung cancer
- It doesn't matter if a building is new or old, what type of foundation it has, or what soil types/ground conditions it sits on: any building might have a radon problem.

# How does radon enter a house?

- Odorless
- Colorless
- Radioactive



# Remember the Stack Effect?

What happens in the basement, happens in the living space



# Monitors



# Radon

## KIT, SINGLE LS, MANUFACTURED

**SKU:** 25099

★★★★★ [1 Review](#) [Add Your Review](#)

Liquid Scintillation (LS) Radon in Air test includes a single test device, instructions, analysis from an accredited radon laboratory, and test report. Please call 800-767-3703 for best pricing on orders with large





CO<sub>2</sub>



# PM 2.5



# All in One

Air quality monitor

## View Plus

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Our most comprehensive radon & air quality monitor with 7 sensors, including radon, PM 2.5, CO2, and more — WiFi connected and cable-free.

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Thank You!

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