Joseph Lstiburek, Ph.D., P.Eng, ASHRAE Fellow

Building Science

Frame Walls

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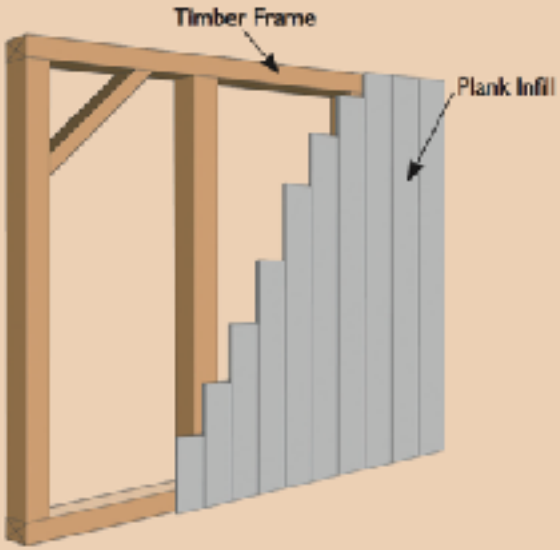
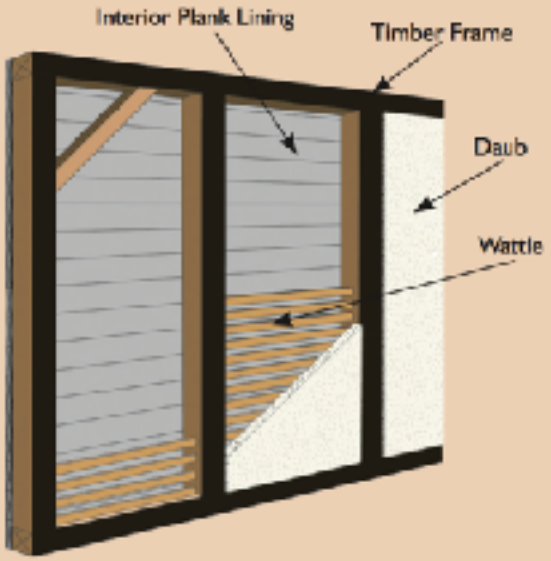
One Thousand Years of Evolution: A Timeline

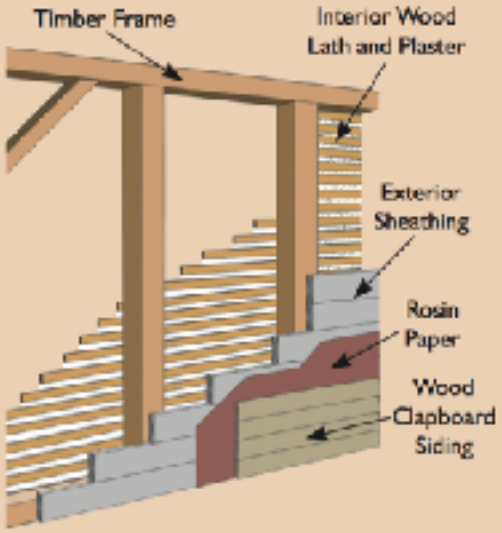




900 C.E.
Palisade wall: Closely spaced posts embedded in the ground.

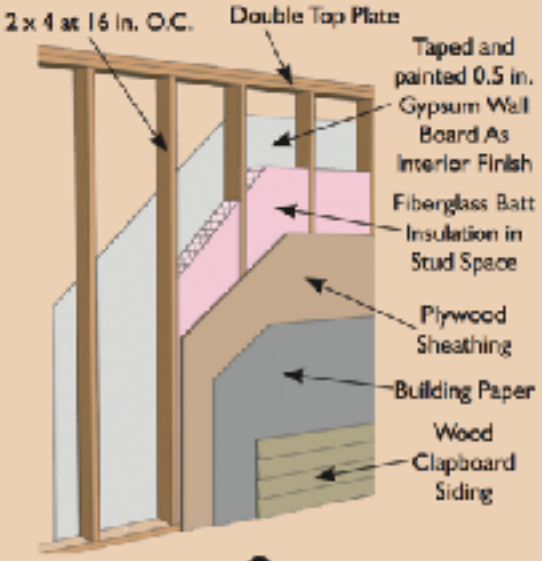
1200
Timber frame: Stave construction, timber four-sided frame with vertical exterior weatherboards.

1600
Wattle and daub: Tar coated exposed frame with an early pre-evolutionary version of exterior stucco—Neanderthal Stucco. Board sheathing inner lining.



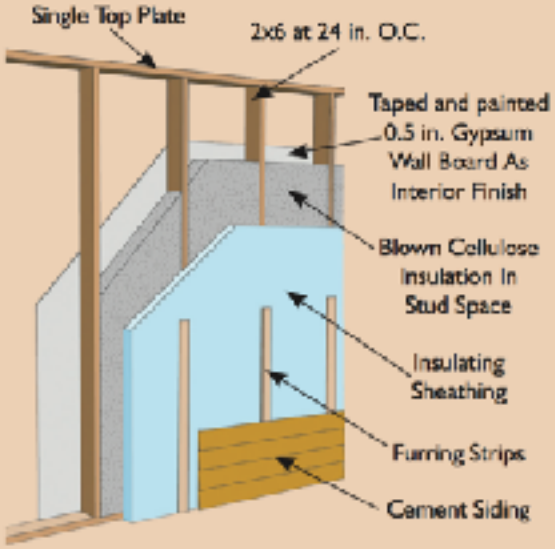
1900

Clapboard timber frame: Typical 1900 New England timber frame with plaster and lath interior lining and exterior board sheathing, rosin paper and clapboards.



1950

Platform frame: Typical 1950 American wood frame assembly with plywood sheathing and an interior gypsum board lining.



1990

Advanced frame: Insulating sheathing over 2x6 advanced frame.

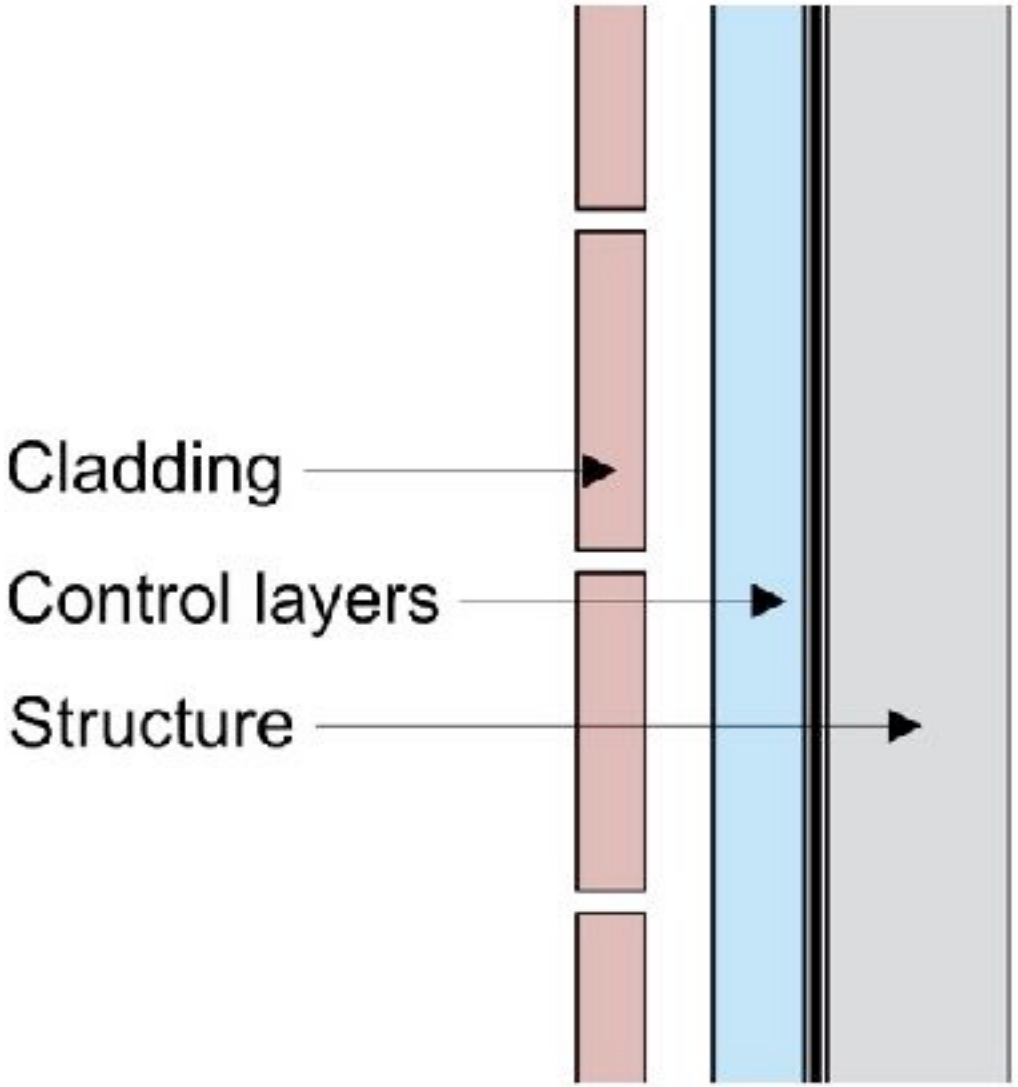
Control Layers

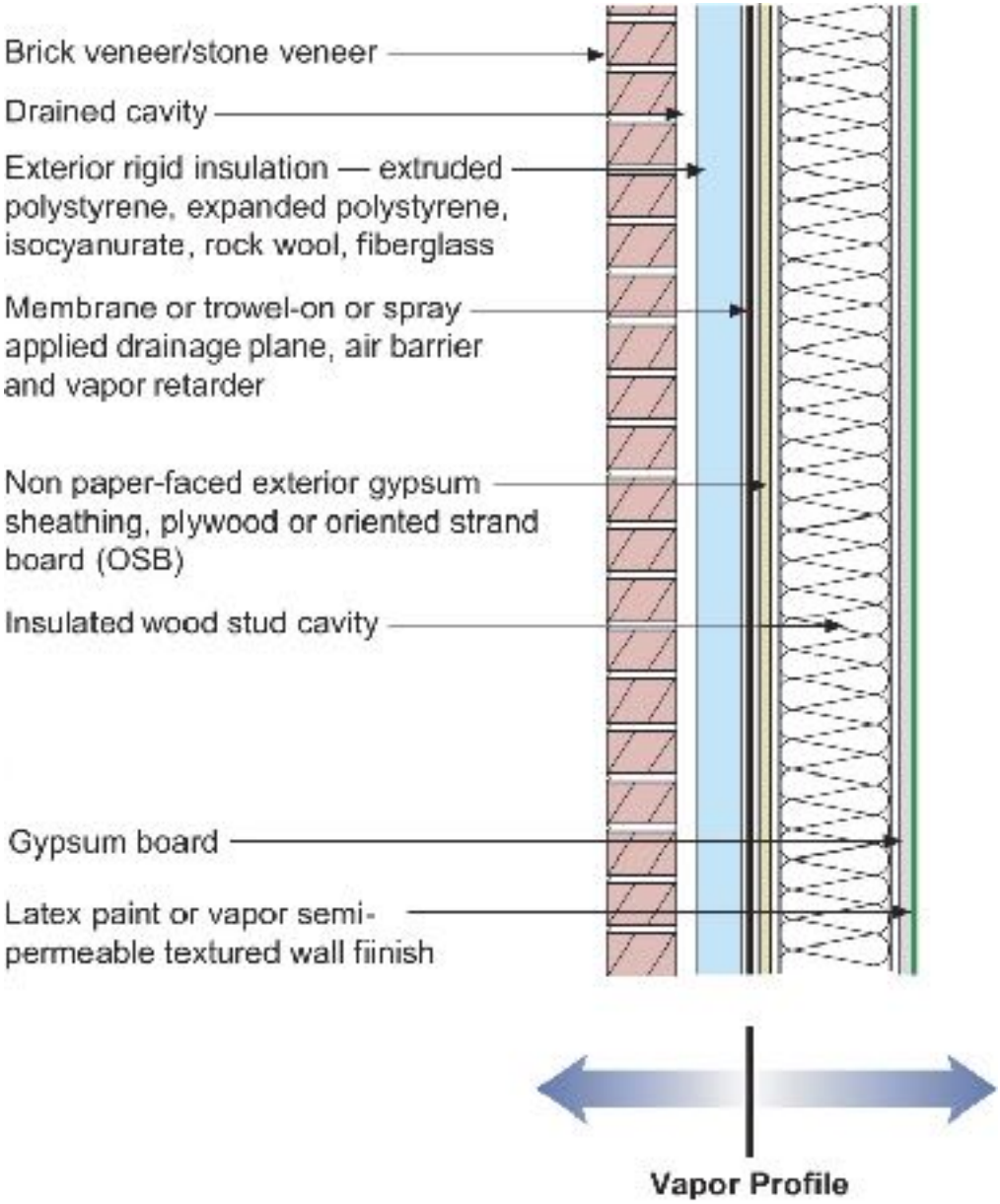
Water Control Layer

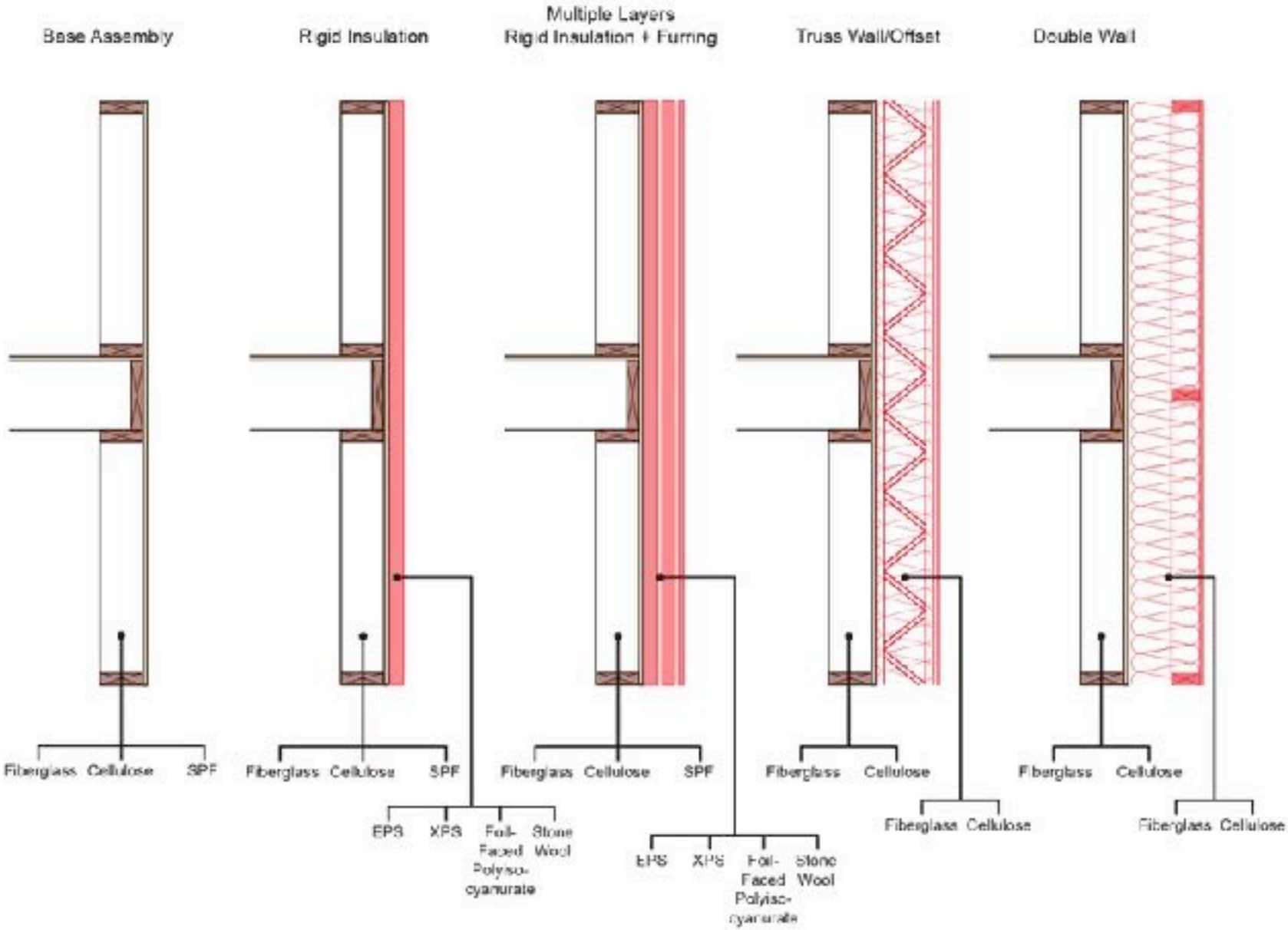
Air Control Layer

Vapor Control Layer

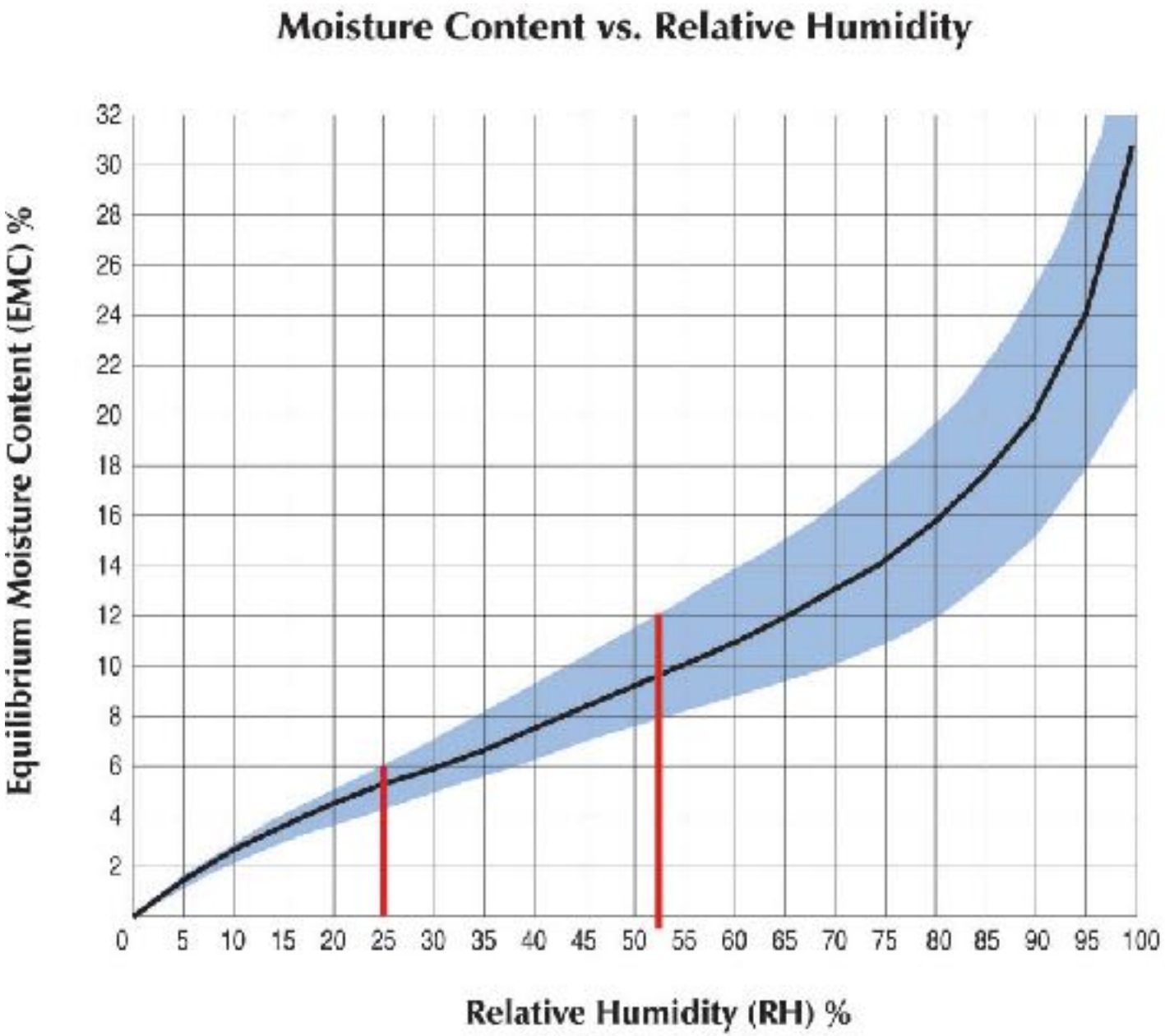
Thermal Control Layer

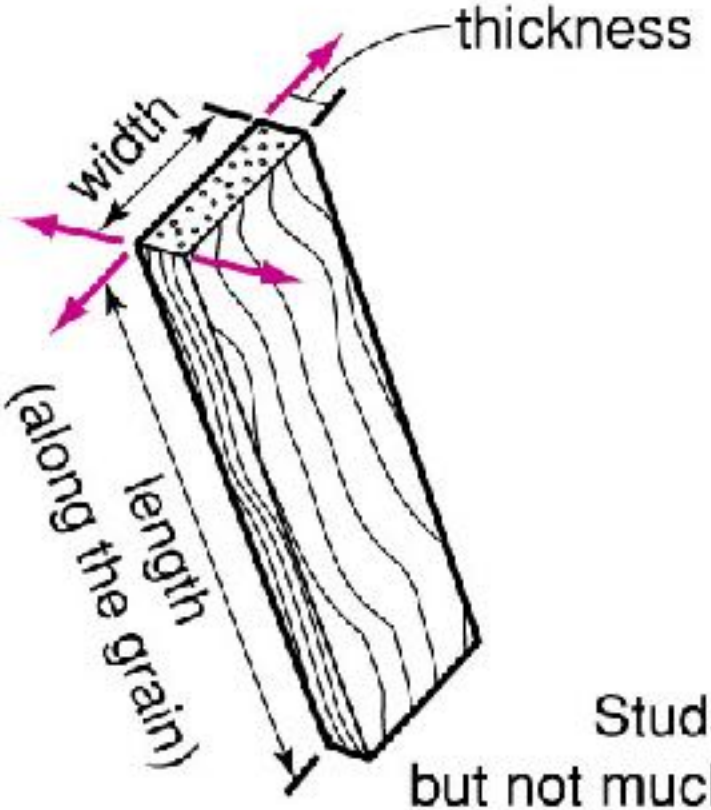

Cladding
Control layers
Structure

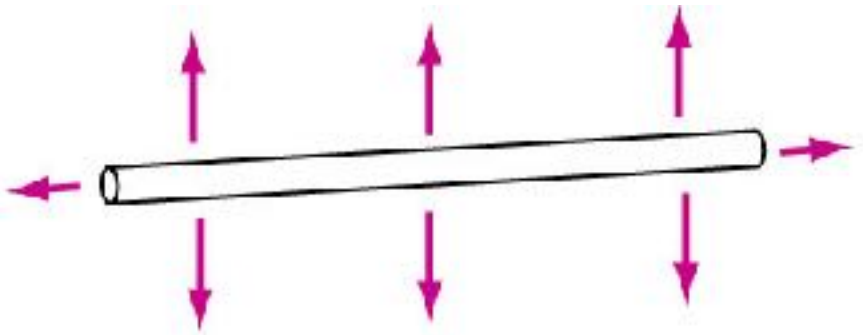

Brick veneer/stone veneer
Drained cavity
Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass
Membrane or trowel-on or spray applied drainage plane, air barrier and vapor retarder
Non paper-faced exterior gypsum sheathing, plywood or oriented strand board (OSB)
Insulated wood stud cavity
Gypsum board
Latex paint or vapor semi-permeable textured wall fiinish
Vapor Profile


Base Assembly
Rigid Insulation
Multiple Layers
Rigid Insulation + Furring
Truss Wall/Offset
Double Wall
Fiberglass
Cellulose
SPF
EPS
XPS
Foil-Faced Polyiso-cyanurate
Stone Wool

Wood is Weird


Moisture Content vs. Relative Humidity
Equilibrium Moisture Content (EMC) %
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
Relative Humidity (RH) %

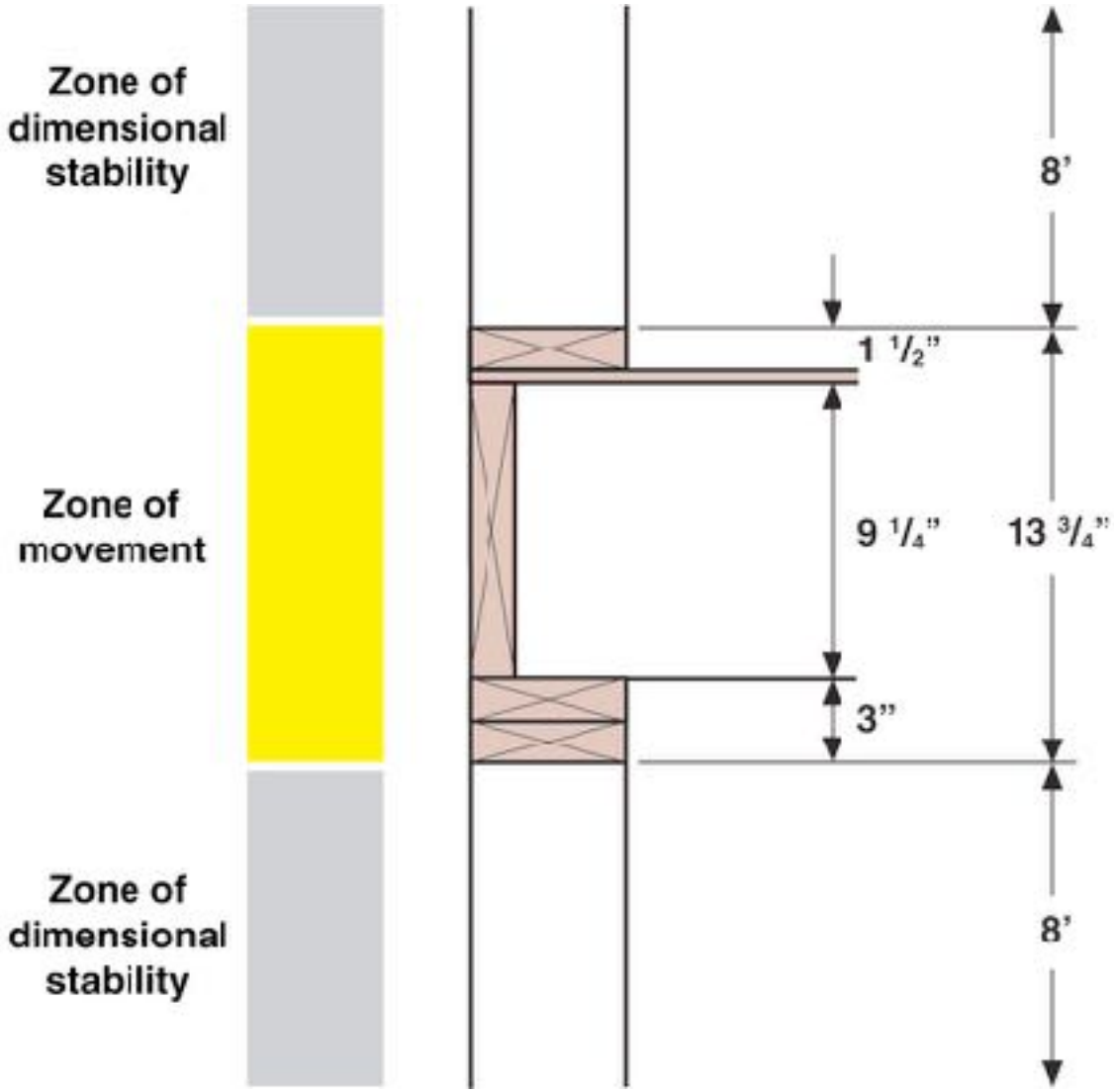


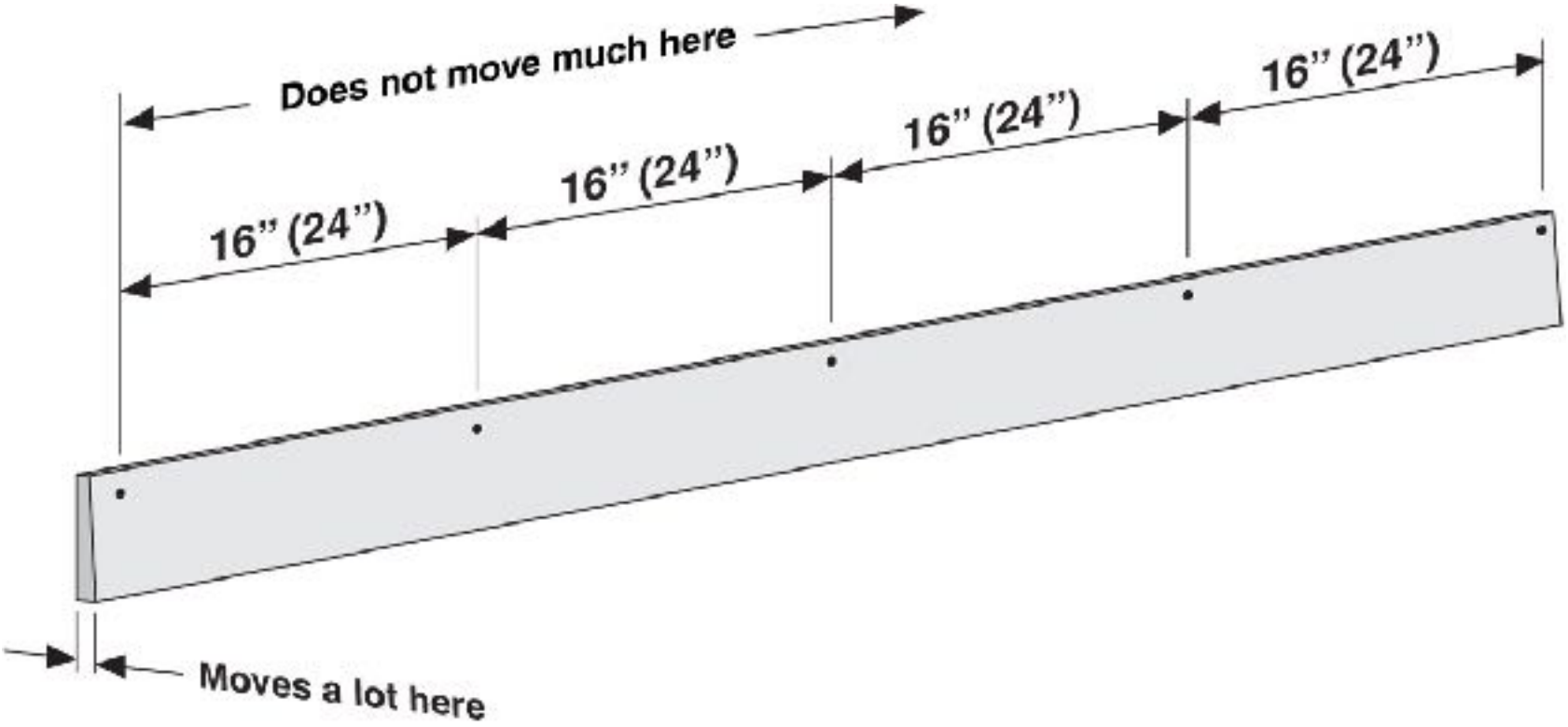


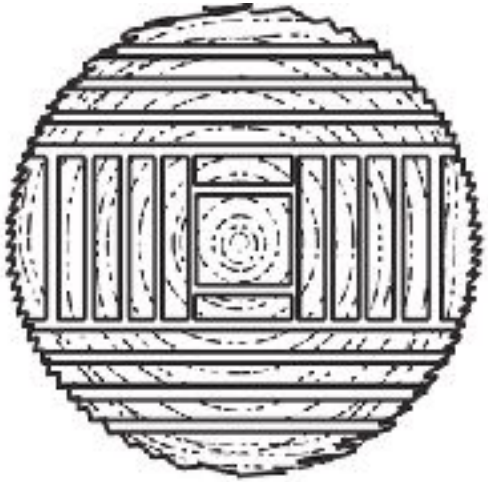
Wood Fiber

Fibers get much thicker than longer when they pick up moisture

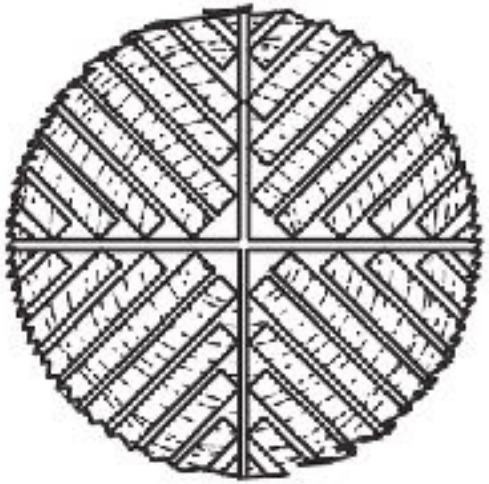
Studs get much wider and thicker, but not much longer, when they pick up moisture


Zone of dimensional stability
Zone of movement
Zone of dimensional stability
8'
1 1/2"
9 1/4"
13 3/4"
3"
8'

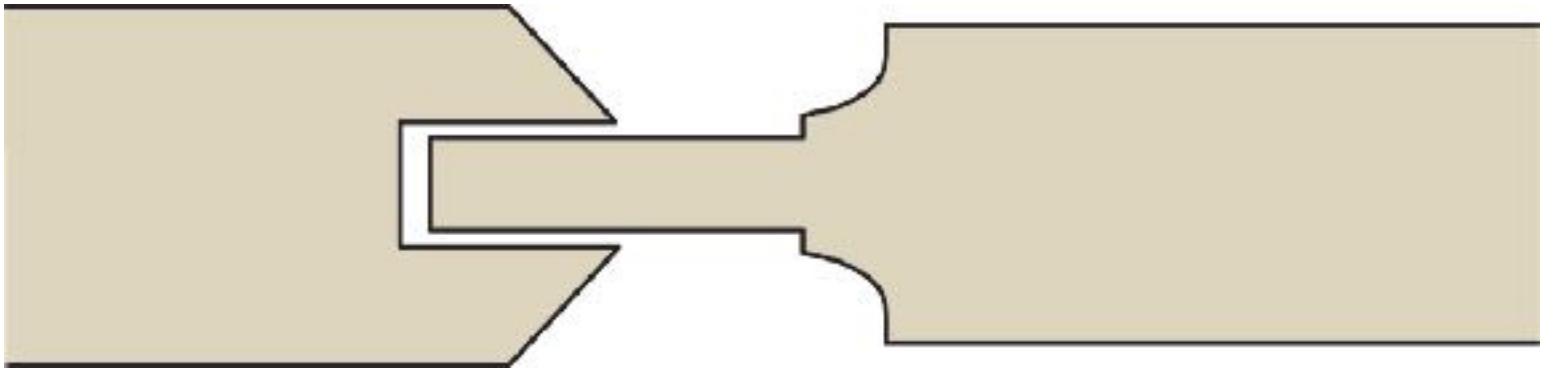

Does not move much here
16" (24")
16" (24")
16" (24")
16" (24")
Moves a lot here

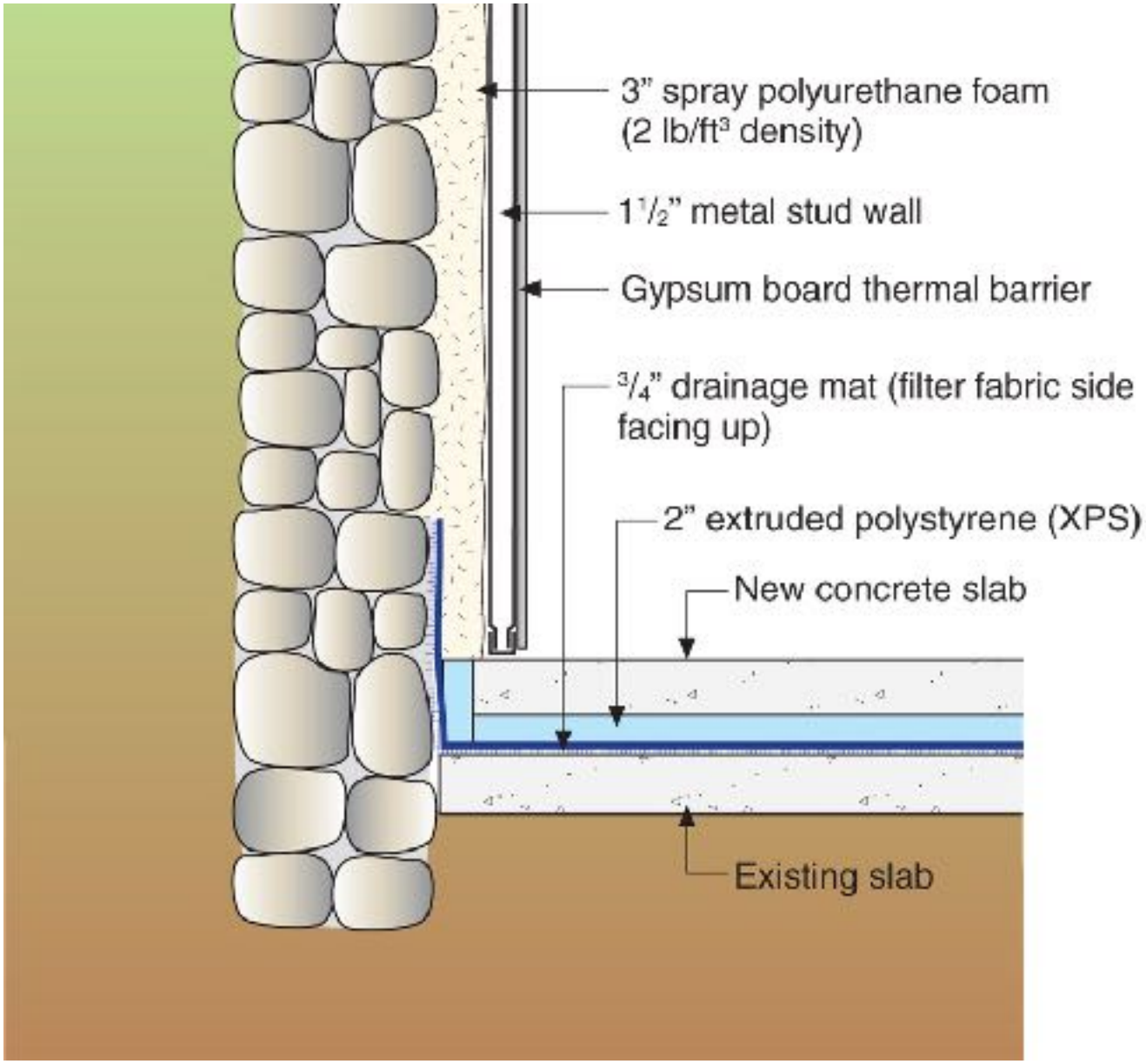


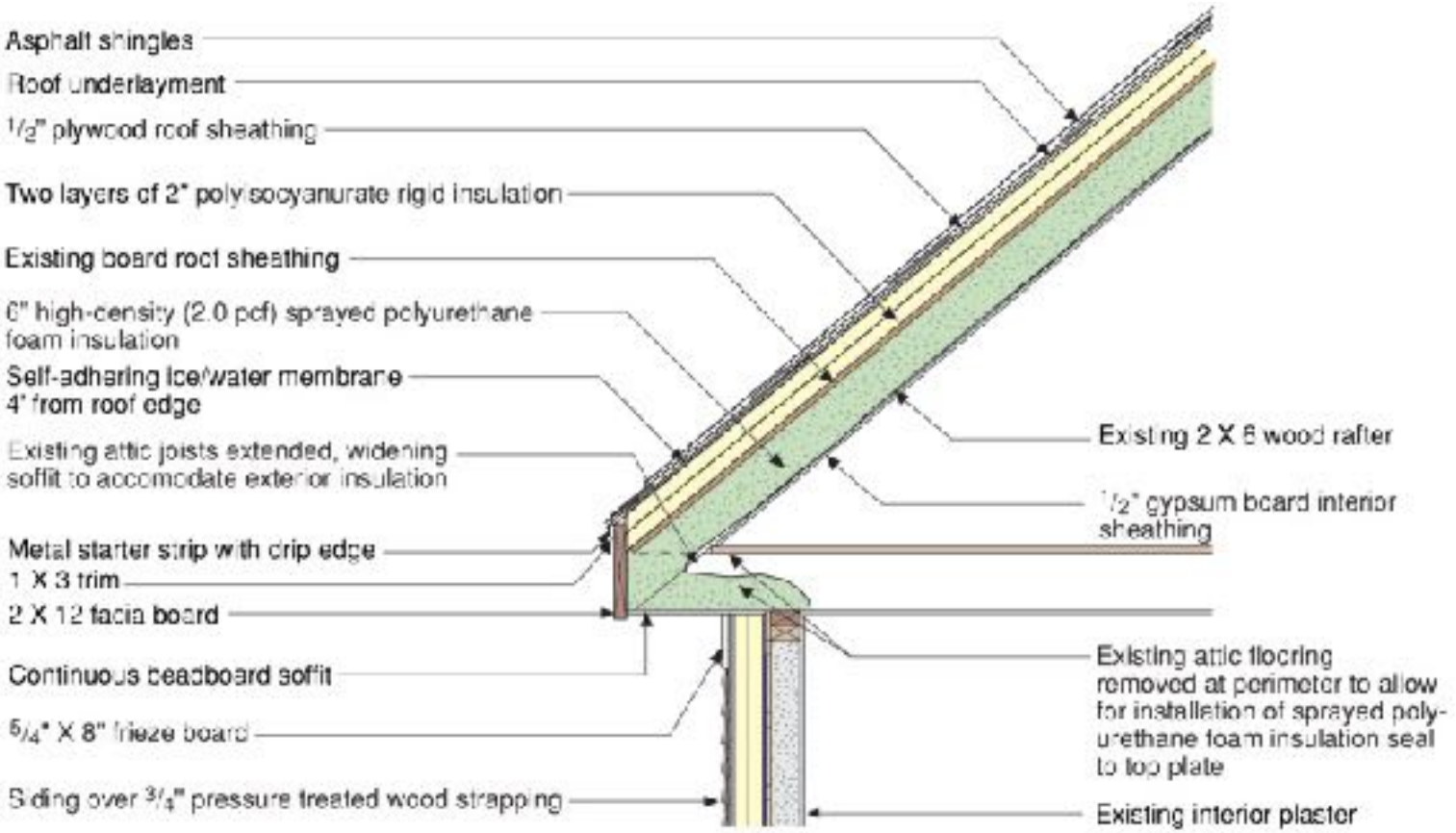
Plain sawn log



Quarter sawn log

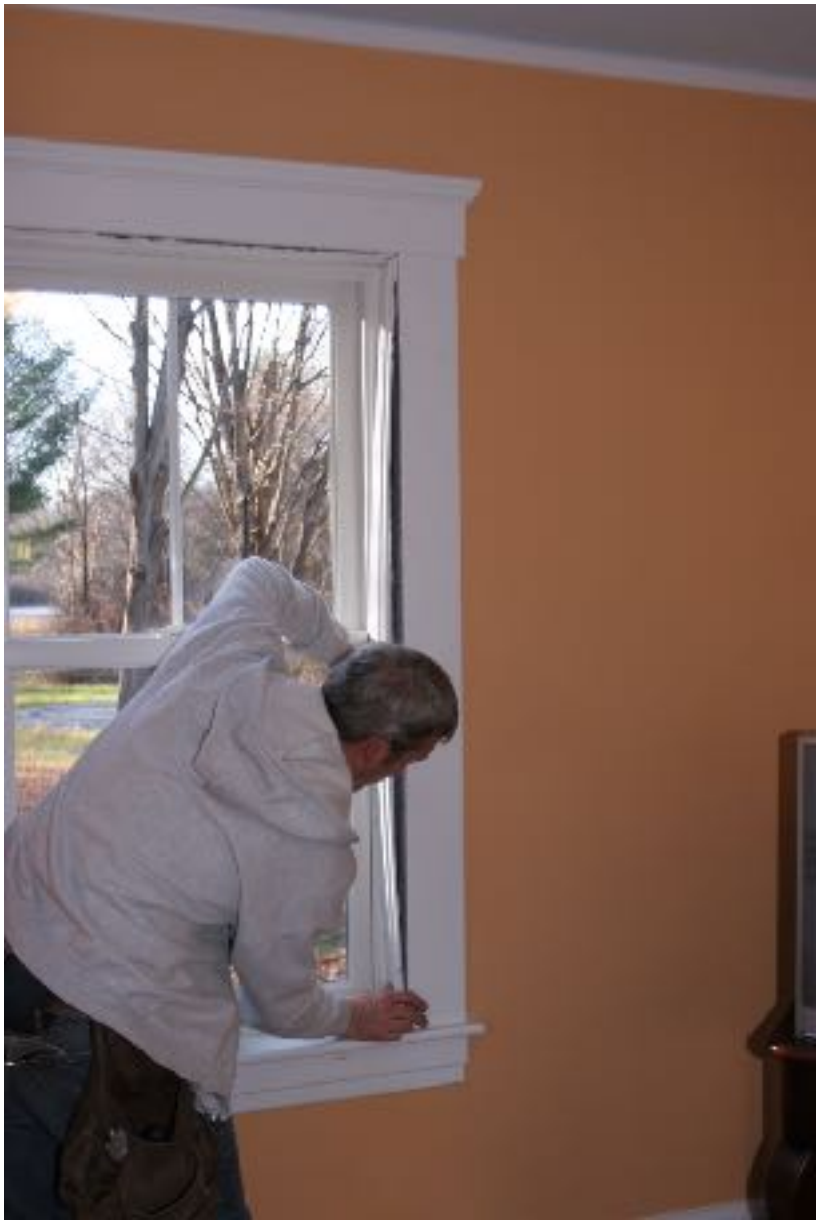



3" spray polyurethane foam
(2 lb/ft³ density)
1½" metal stud wall
Gypsum board thermal barrier
¾" drainage mat (filter fabric side facing up)
2" extruded polystyrene (XPS)
New concrete slab
Existing slab

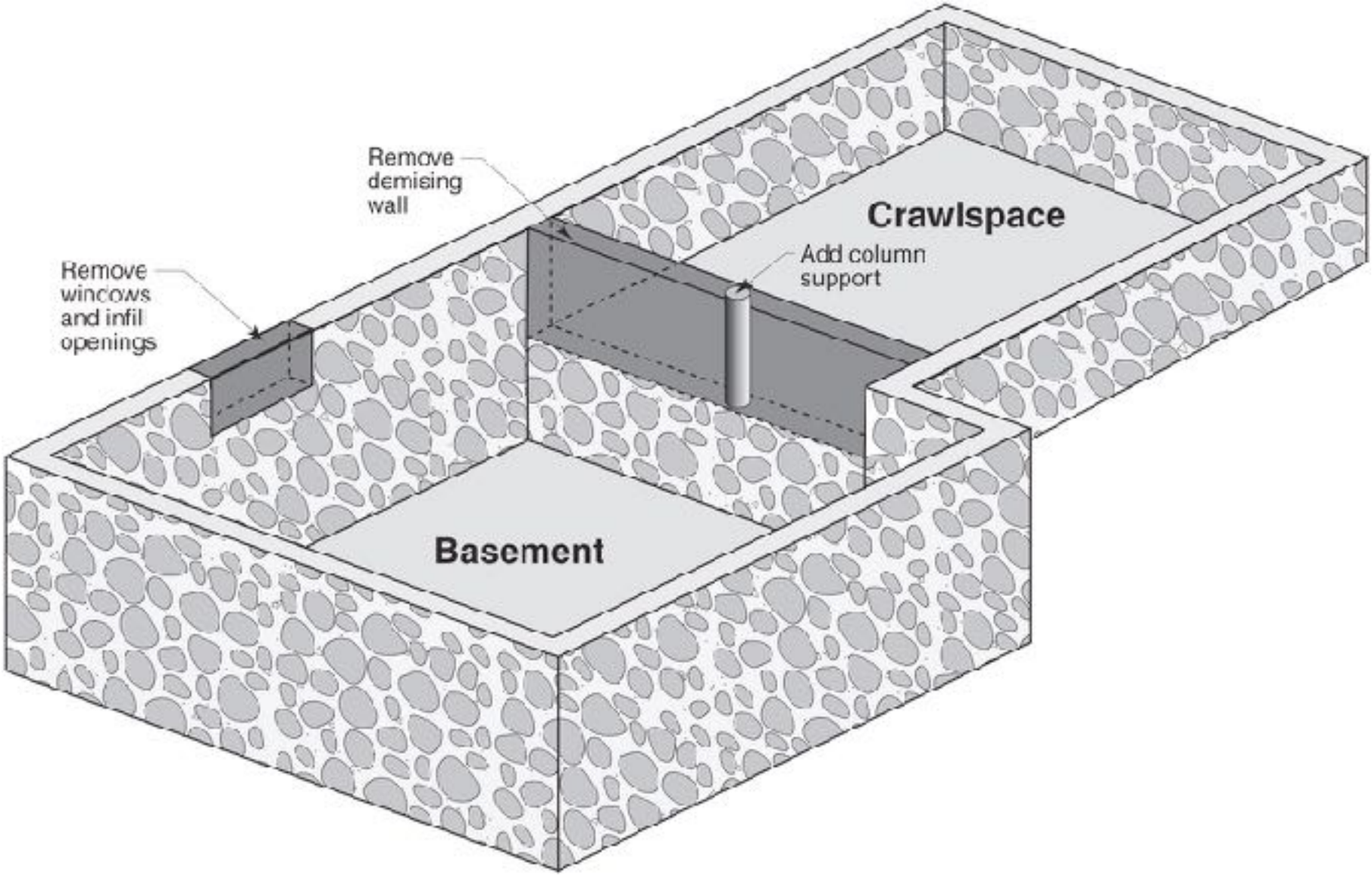

Asphalt shingles
Roof underlayment
1/2" plywood roof sheathing
Two layers of 2" polyisocyanurate rigid insulation
Existing board roof sheathing
6" high-density (2.0 pcf) sprayed polyurethane foam insulation
Self-adhering ice/water membrane 4' from roof edge
Existing attic joists extended, widening soffit to accomodate exterior insulation
Metal starter strip with drip edge
1 X 3 trim
2 X 12 fascia board
Continuous beadboard soffit
5/4" X 8" frieze board
Siding over 3/4" pressure treated wood strapping
Existing 2 X 6 wood rafter
1/2" gypsum board interior sheathing
Existing attic flooring removed at perimeter to allow for installation of sprayed polyurethane foam insulation seal to top plate
Existing interior plaster

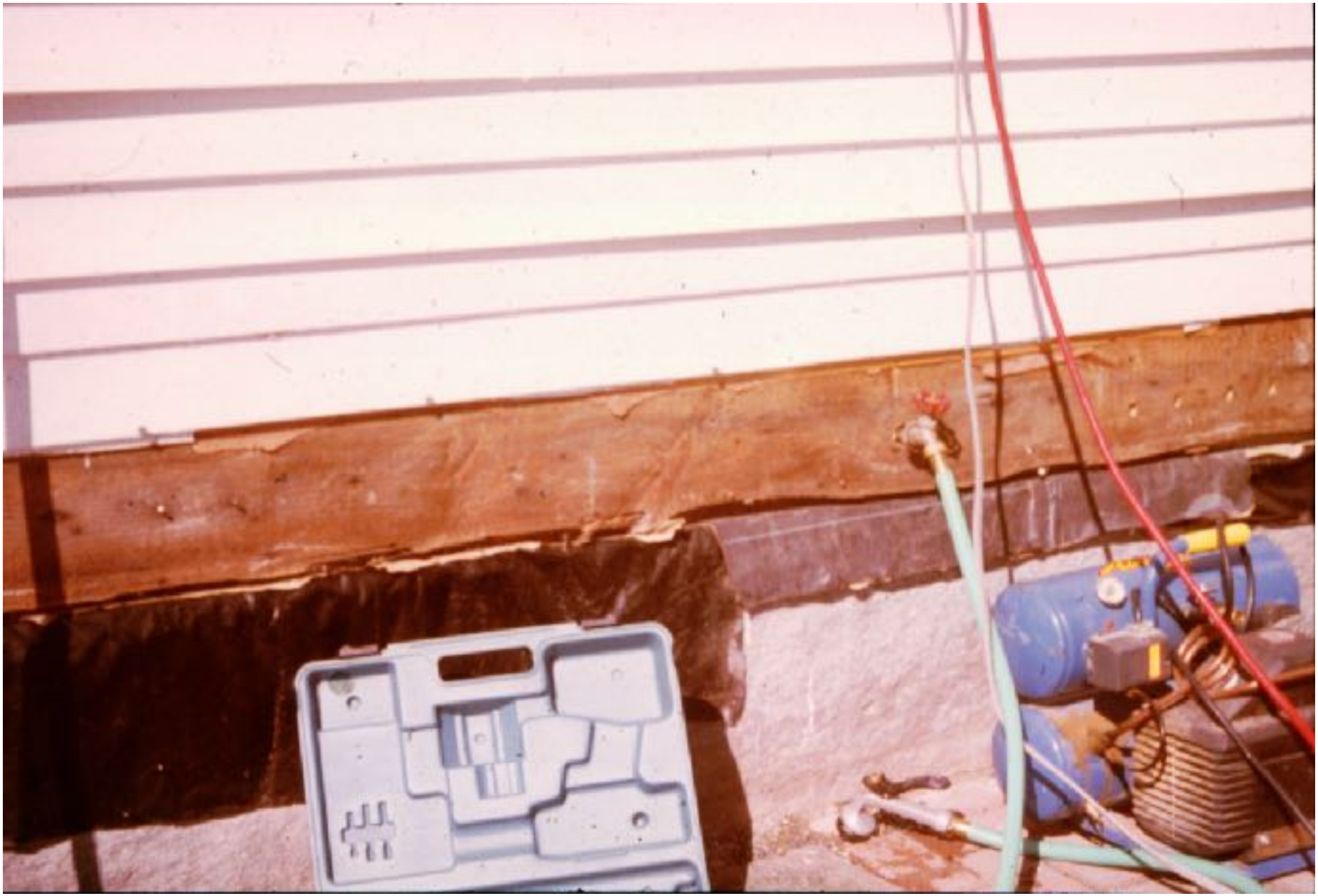

GRACE VYCOR® PLUS
GRACE VYCOR® PLUS


0.32
0.33
0.54
DP25




DU PONT


Remove
demising
wall
Crawlspace
Add column
support
Remove
windows
and infil
openings
Basement



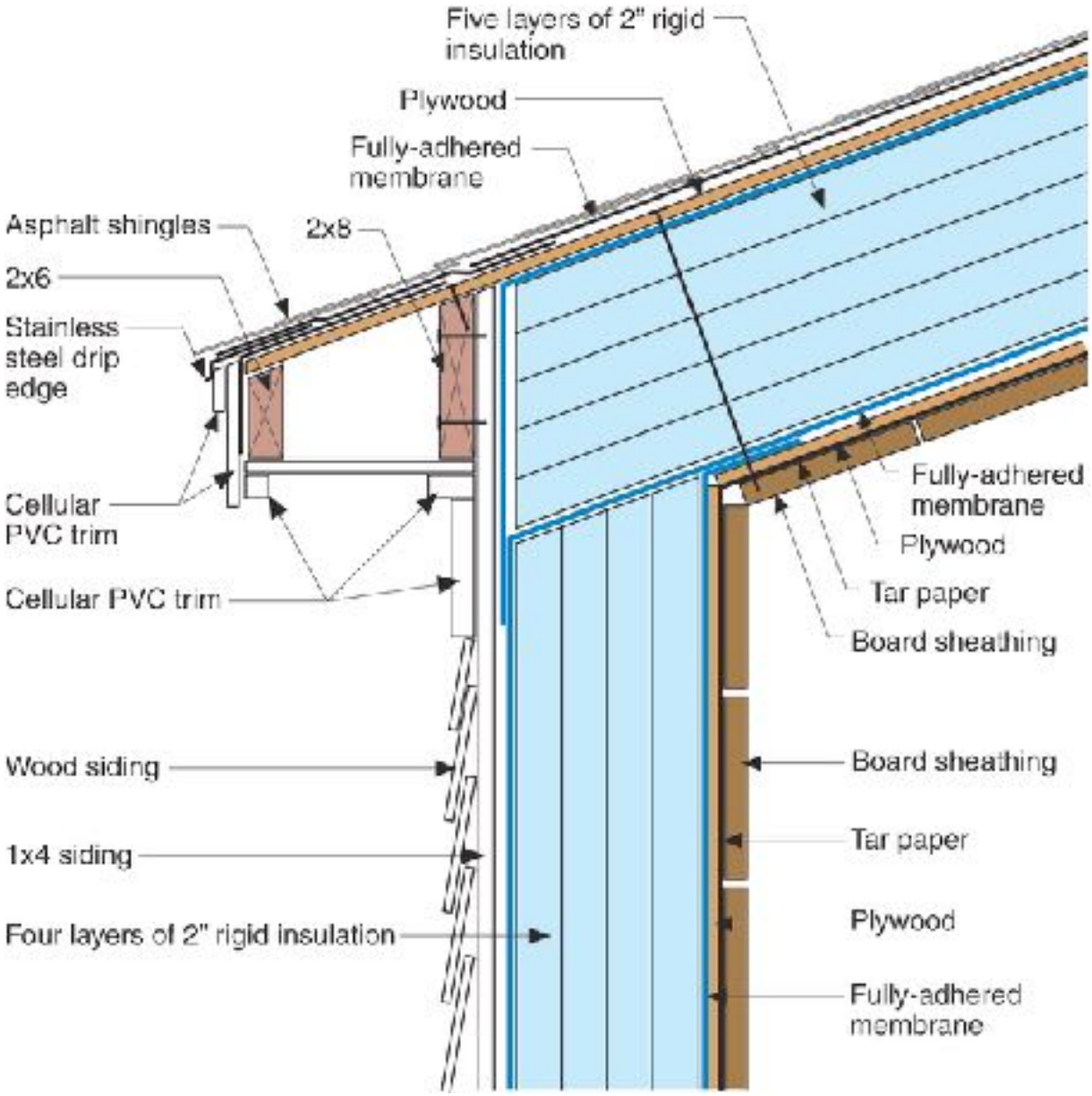

GRACE
Ice & Water Shield

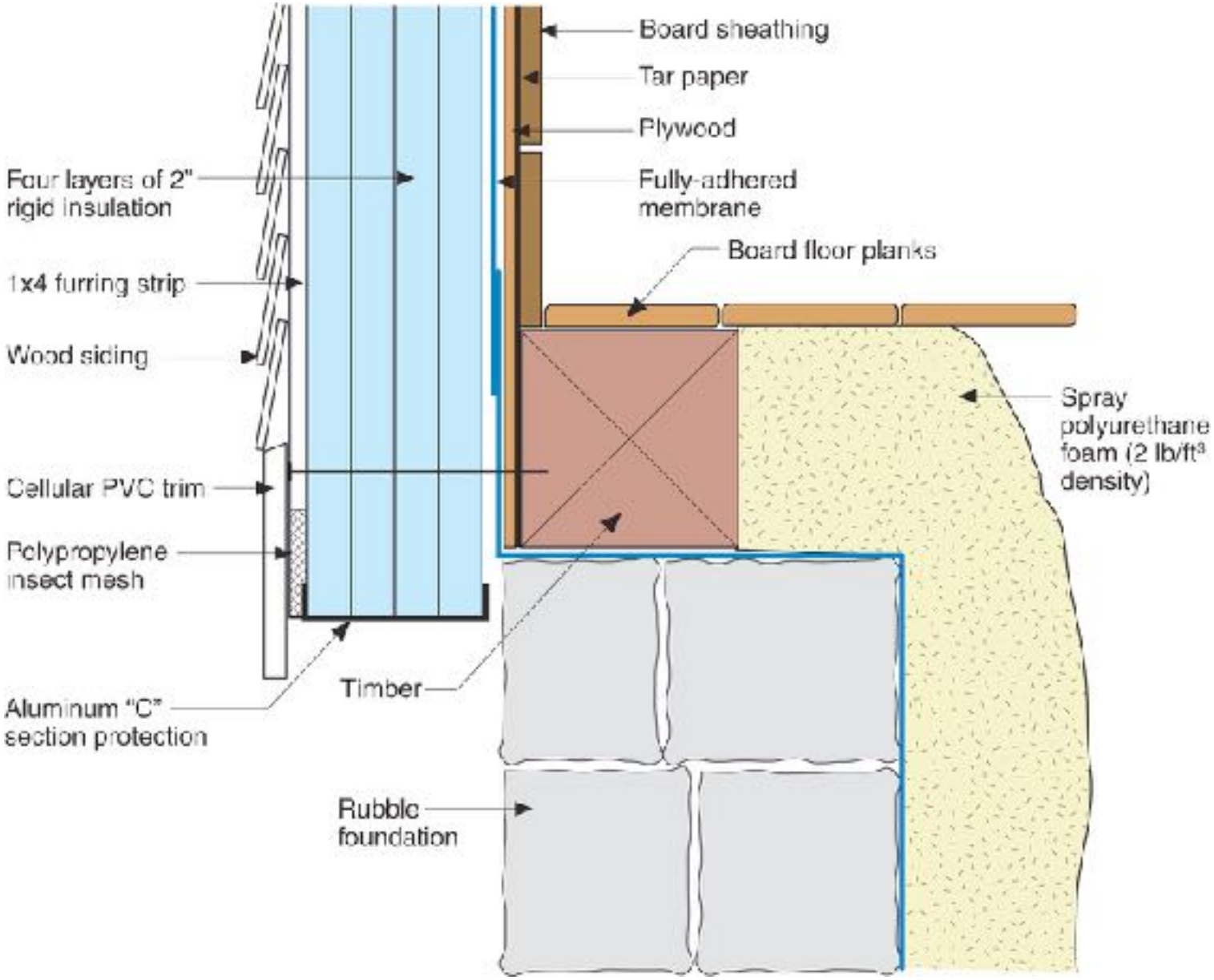

Tyvek
DUPONT
Tyve
DUPONT
Tyve

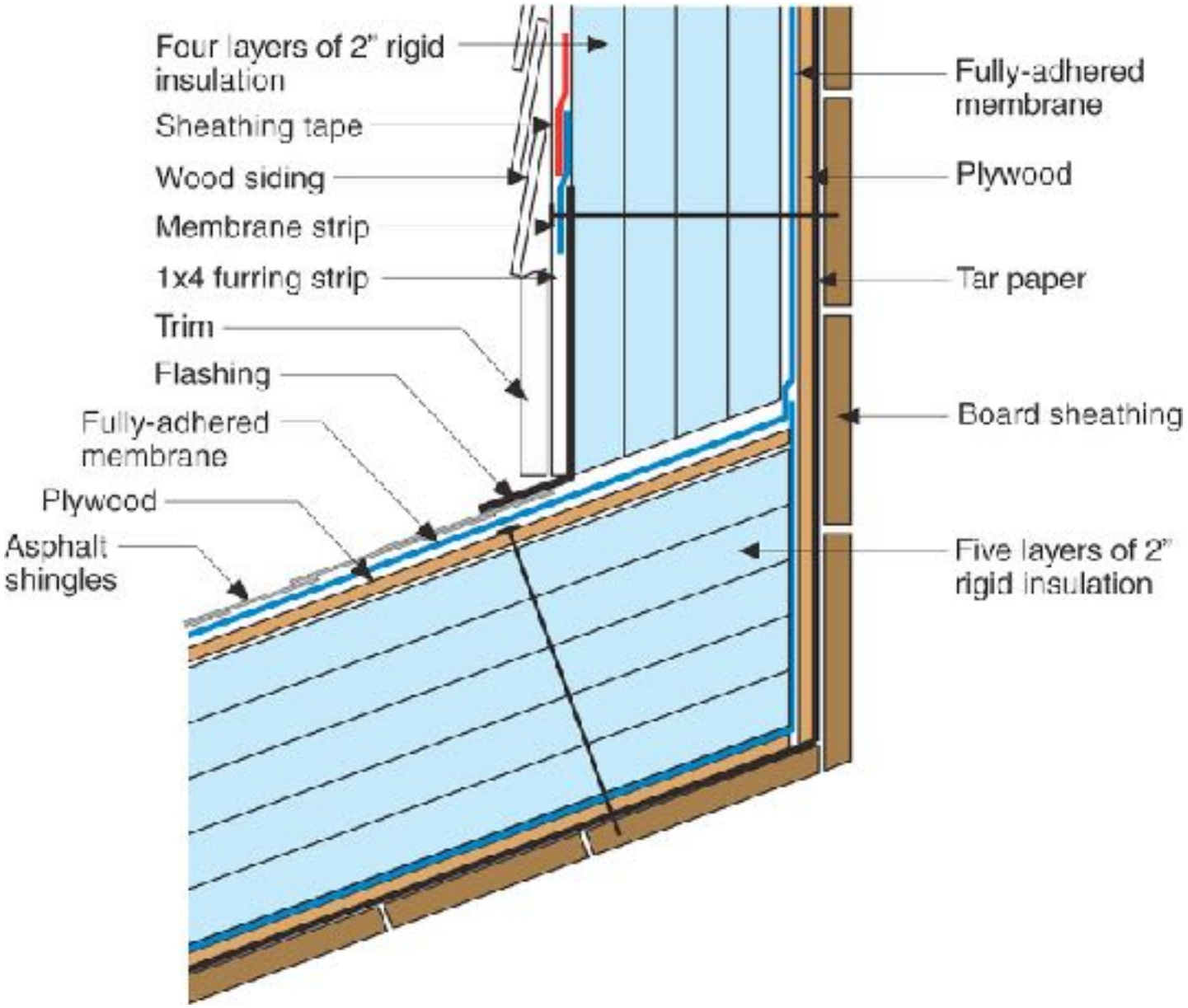

DOW
Styrofoam
BRAND
TONGUE &
GROOVE
DOW
TONGUE &
GROOVE
EXTRUDED
POLYSTYRENE

rene Insulatio
Thickness, Inche
R-Value @ 75° F M
Lowes Item Numb


778
778


Five layers of 2" rigid insulation
Plywood
Fully-adhered membrane
Asphalt shingles
2x8
2x6
Stainless steel drip edge
Cellular PVC trim
Cellular PVC trim
Wood siding
1x4 siding
Four layers of 2" rigid insulation
Fully-adhered membrane
Plywood
Tar paper
Board sheathing
Board sheathing
Tar paper
Plywood
Fully-adhered membrane

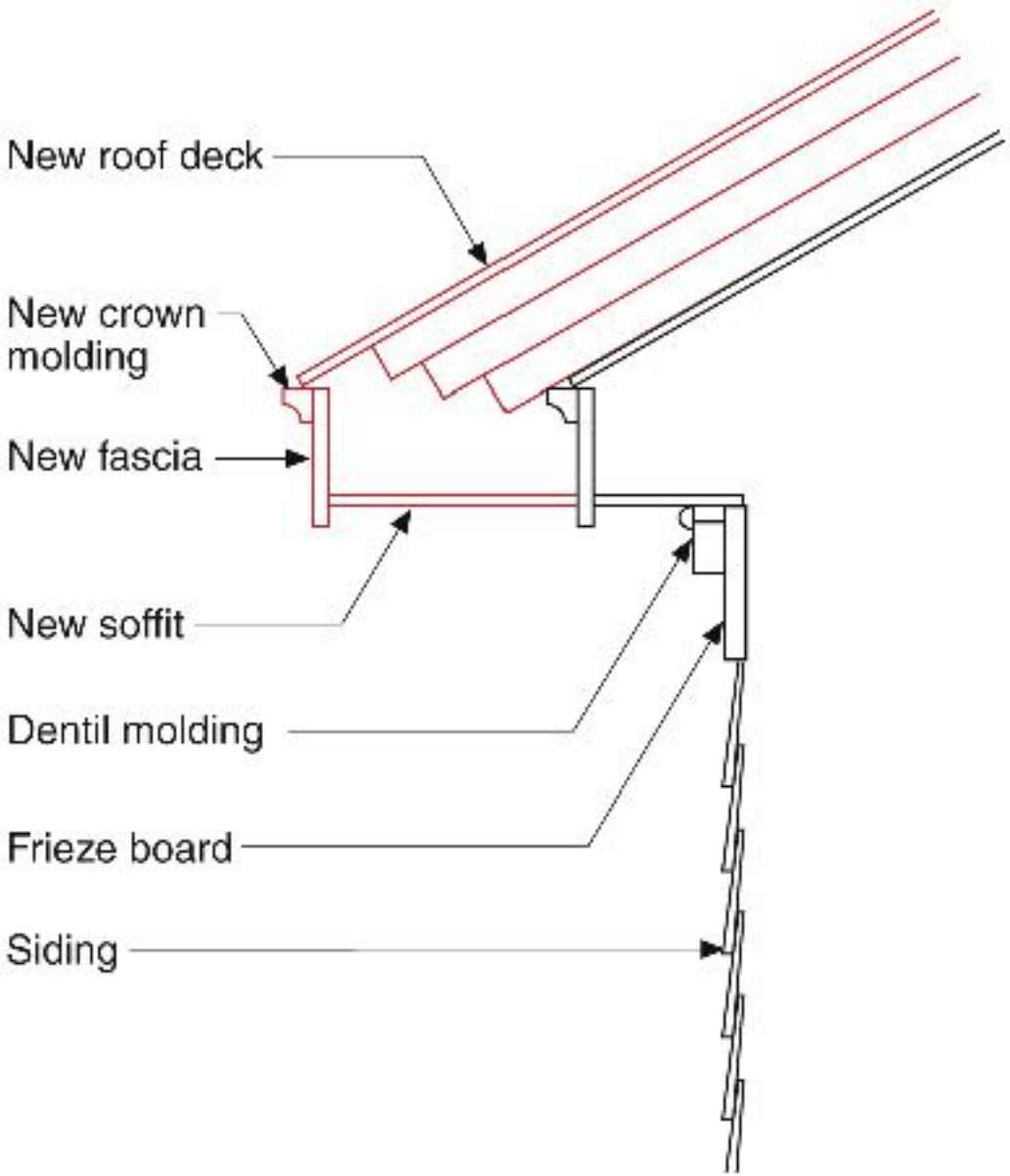

Board sheathing
Tar paper
Plywood
Four layers of 2" rigid insulation
Fully-adhered membrane
Board floor planks
1x4 furring strip
Wood siding
Spray polyurethane foam (2 lb/ft³ density)
Cellular PVC trim
Polypropylene insect mesh
Timber
Aluminum "C" section protection
Rubble foundation

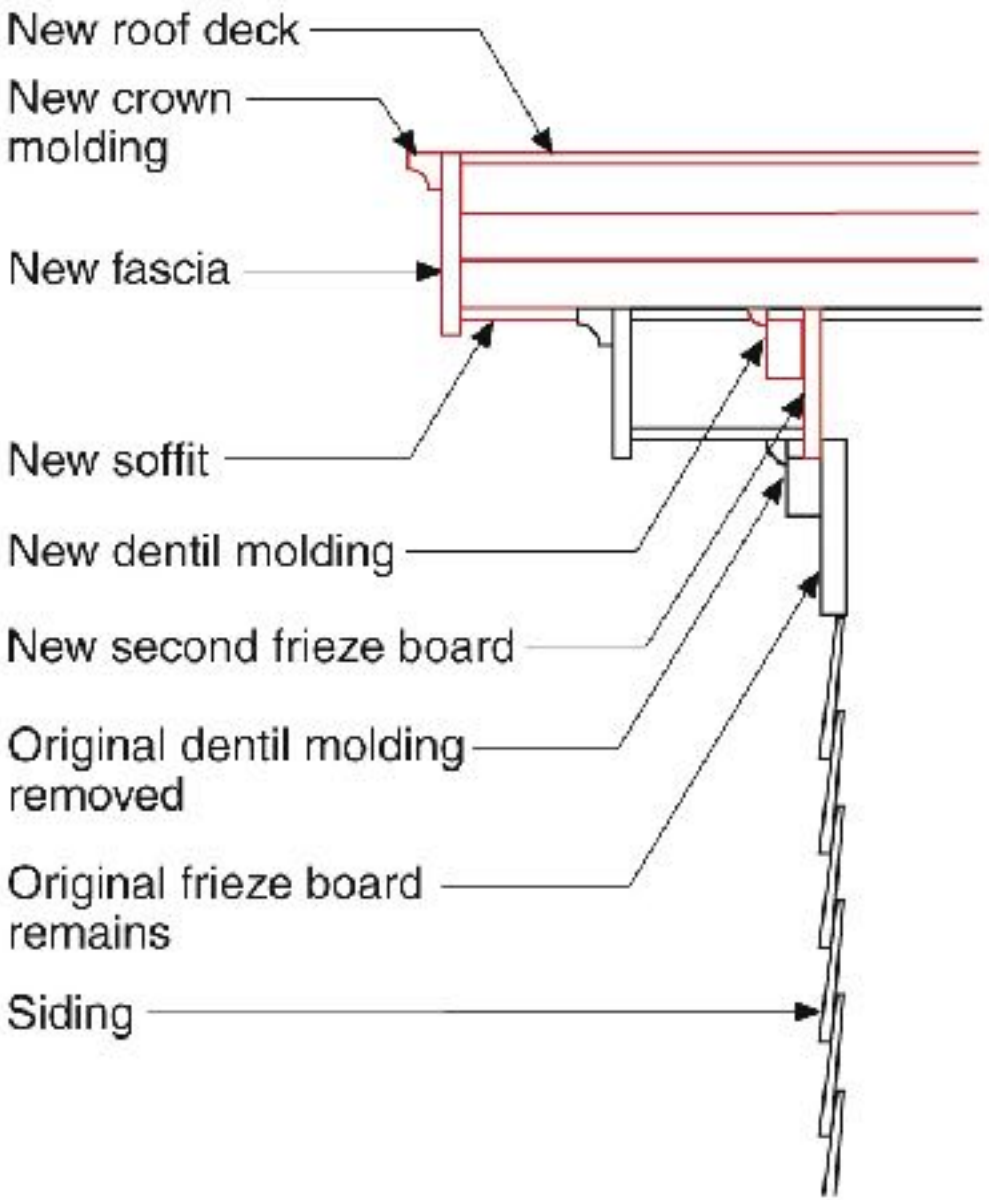

Four layers of 2" rigid insulation
Sheathing tape
Wood siding
Membrane strip
1x4 furring strip
Trim
Flashing
Fully-adhered membrane
Plywood
Asphalt shingles
Fully-adhered membrane
Plywood
Tar paper
Board sheathing
Five layers of 2" rigid insulation


DOW
Super TUFF-R
Sup
Comm


GRACE
Ice & Water Shield®
RIPCORD™


DOW
Super TUFF-R
Commercial Insulation


New roof deck
New crown molding
New fascia
New soffit
Dentil molding
Frieze board
Siding


New roof deck
New crown molding
New fascia
New soffit
New dentil molding
New second frieze board
Original dentil molding removed
Original frieze board remains
Siding


DOW
BRAND

Crawl Spaces

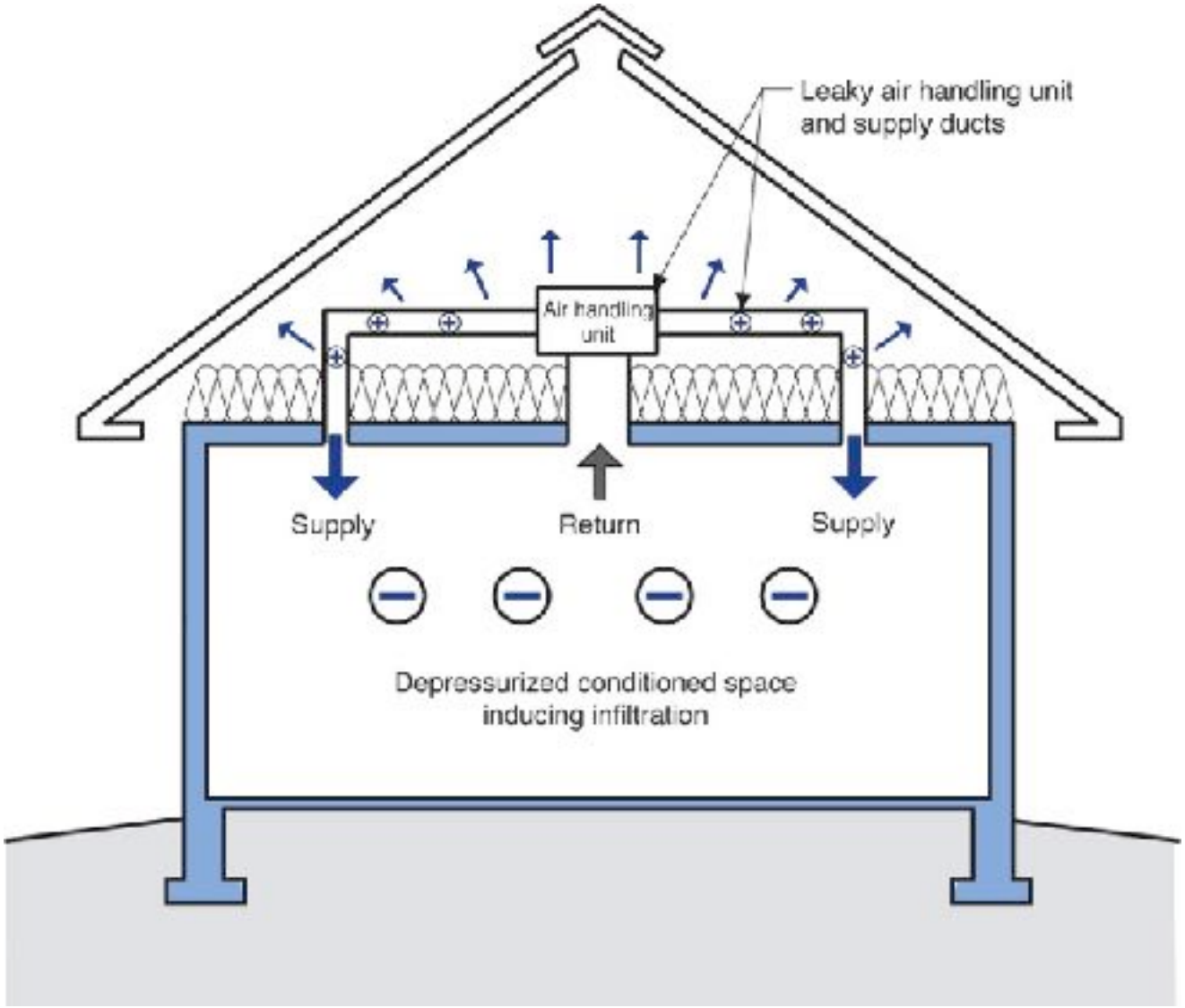
Crawl spaces must be completely connected to either the outside or the inside

Crawl spaces must be completely connected to either the outside or the inside

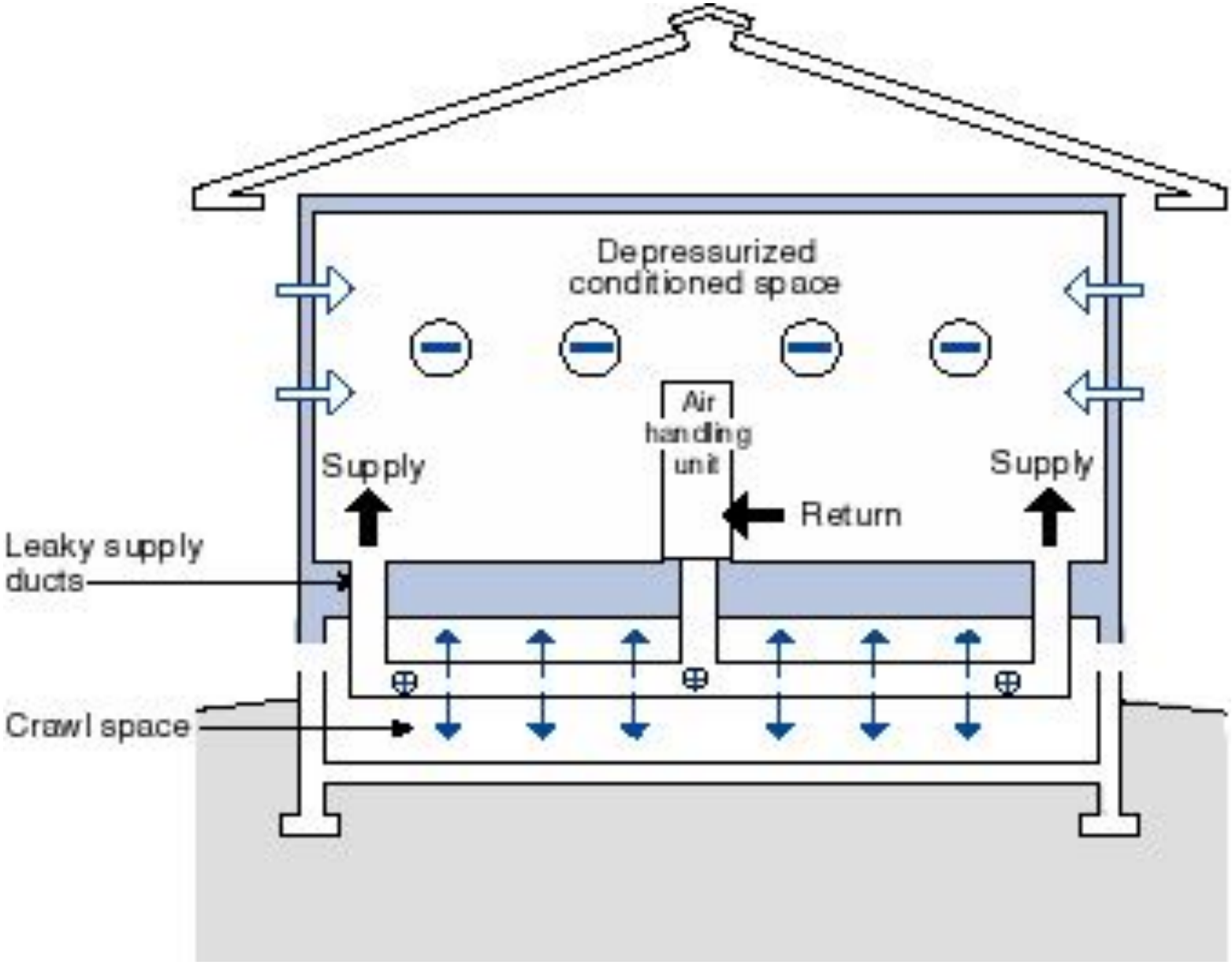
Vented crawl spaces work

Unvented conditioned crawl spaces work

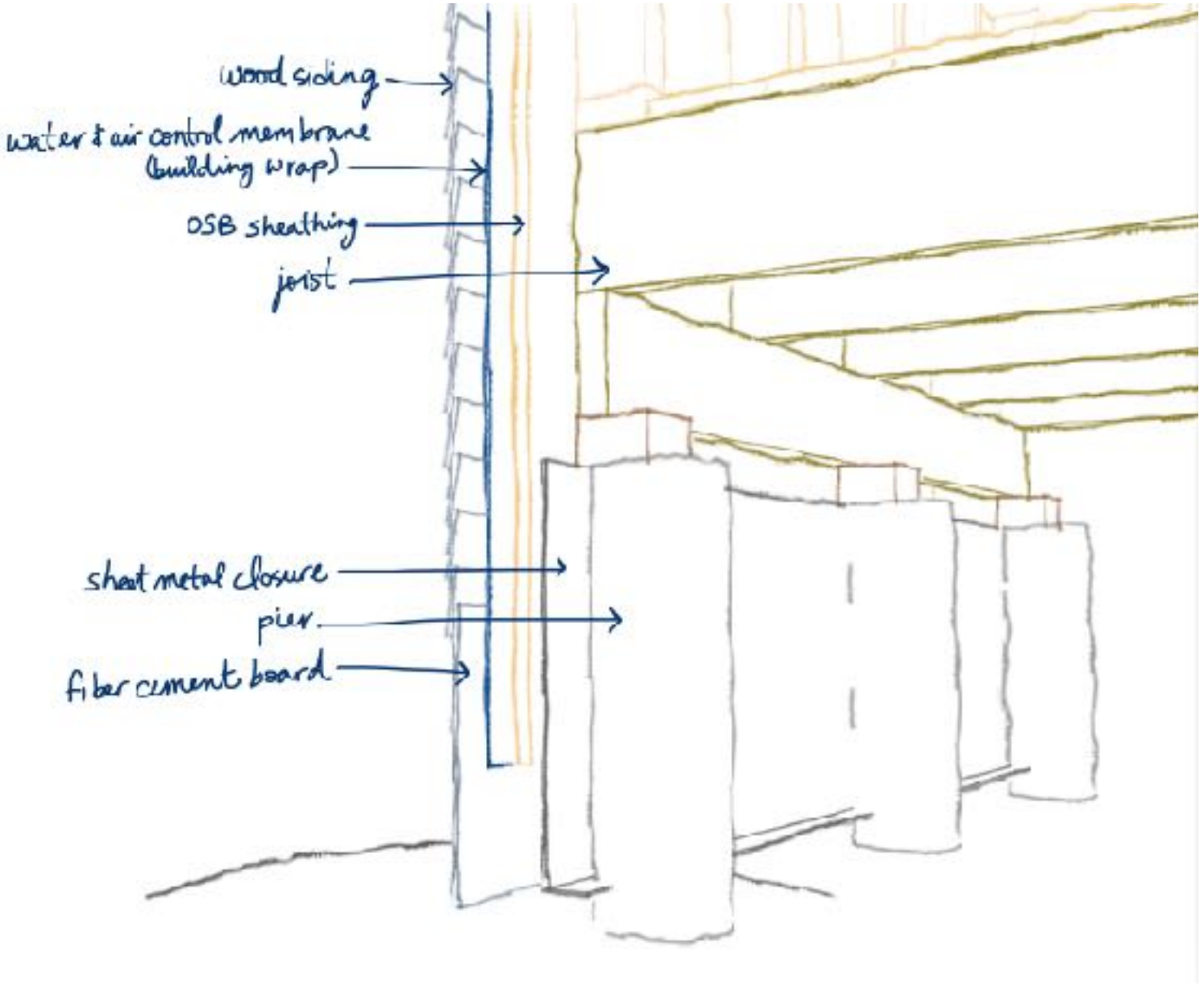
Don’t Do Stupid Things

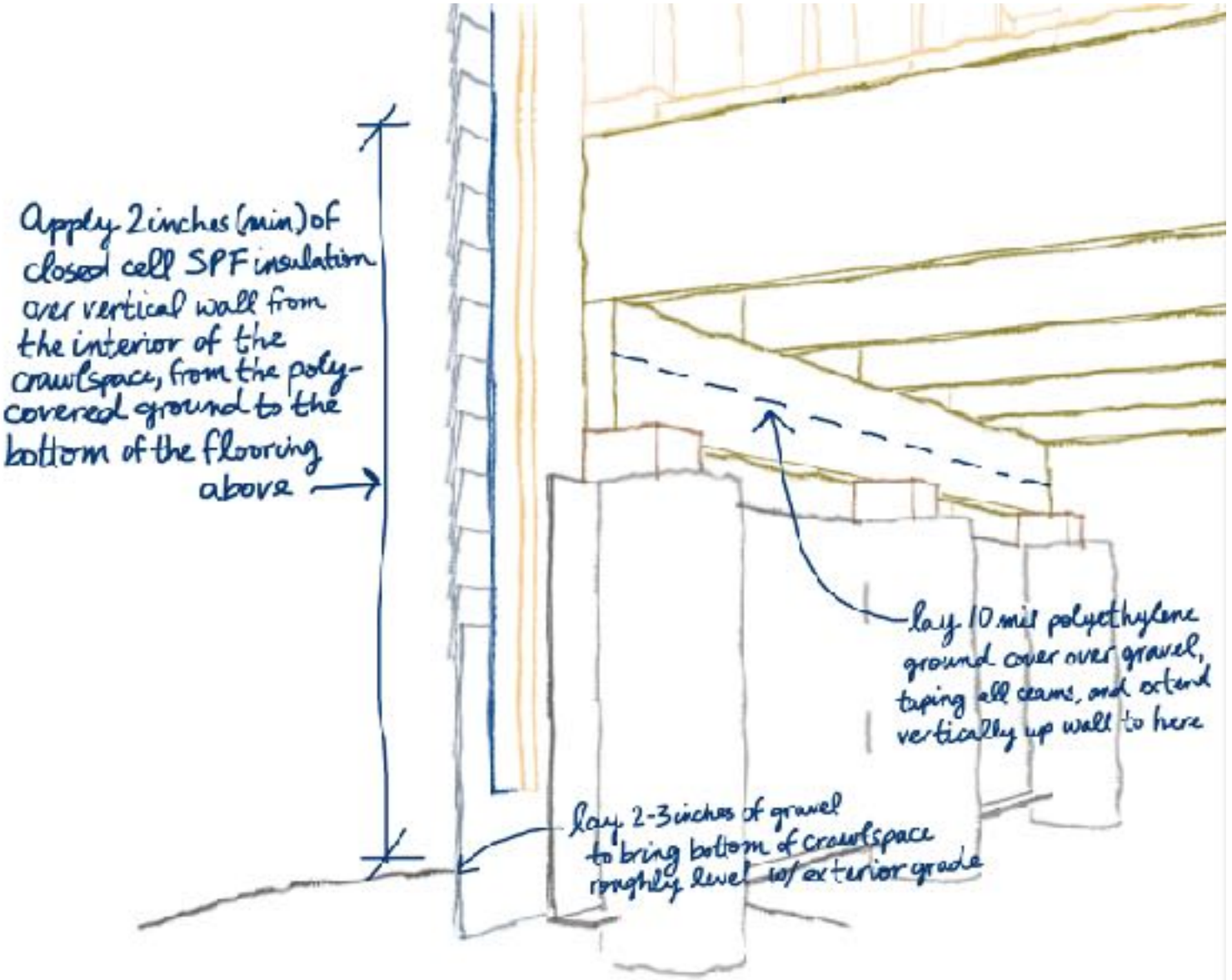

Leaky air handling unit
and supply ducts
Air handling unit
Supply
Return
Supply
Depressurized conditioned space
inducing infiltration

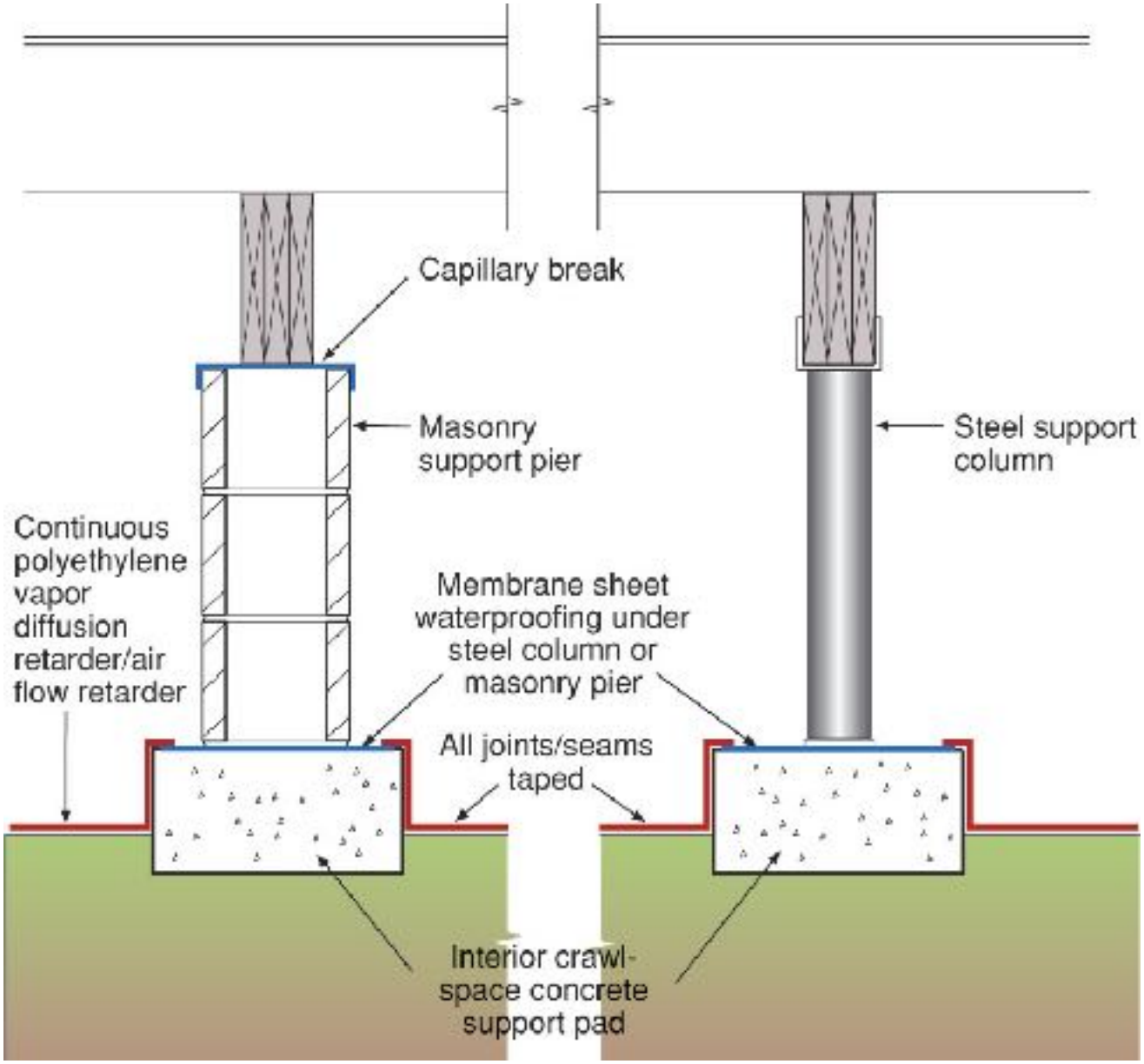
Depressurized conditioned space
inducing infiltration
Supply
Return
Supply
Air handling
unit
Leaky air handling unit
and supply ducts


Depressurized conditioned space
Air handling unit
Supply
Supply
Return
Leaky supply ducts
Crawl space

Smart Thing


wood siding
water & air control membrane
(building wrap)
OSB sheathing
joist
sheet metal closure
pier
fiber cement board


Apply 2 inches (min) of closed cell SPF insulation over vertical wall from the interior of the crawlspace, from the poly-covered ground to the bottom of the flooring above
lay 10 mil polyethylene ground cover over gravel, taping all seams, and extend vertically up wall to here
lay 2-3 inches of gravel to bring bottom of crawlspace roughly level w/ exterior grade


Capillary break
Masonry support pier
Steel support column
Continuous polyethylene vapor diffusion retarder/air flow retarder
Membrane sheet waterproofing under steel column or masonry pier
All joints/seams taped
Interior crawl-space concrete support pad

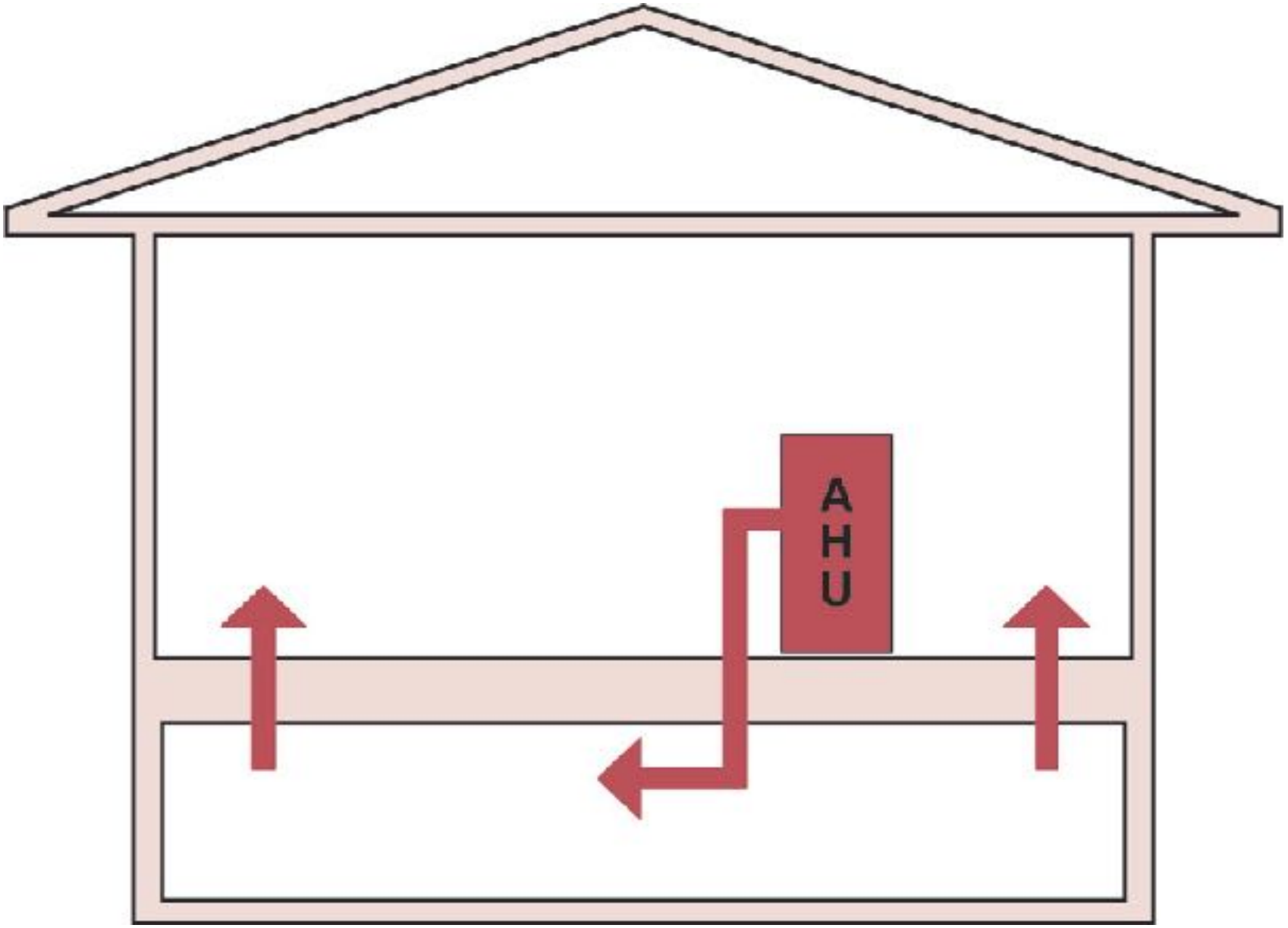
Conditioned Crawlspaces Not Unvented Crawlspaces

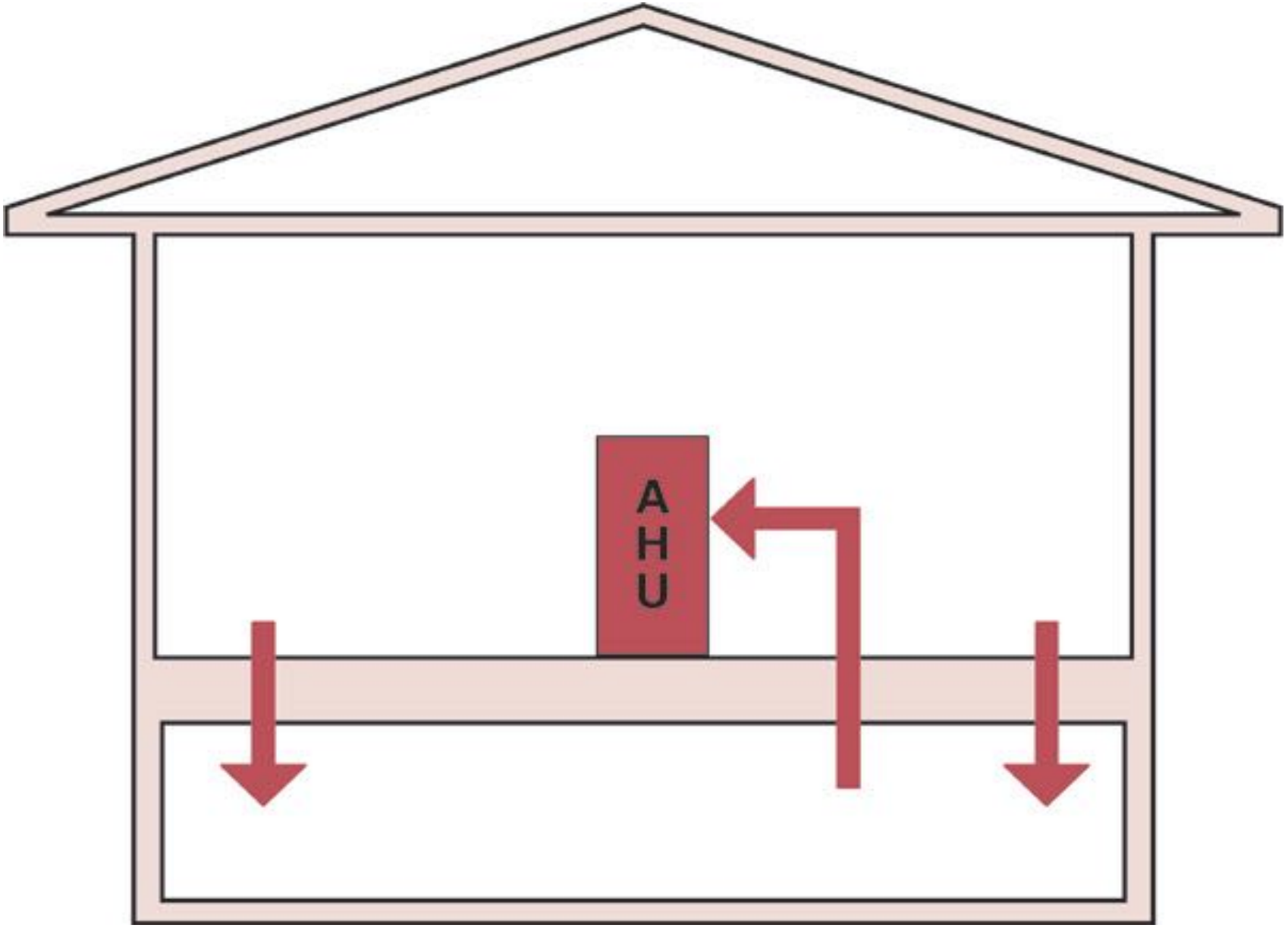
Need Supply Air

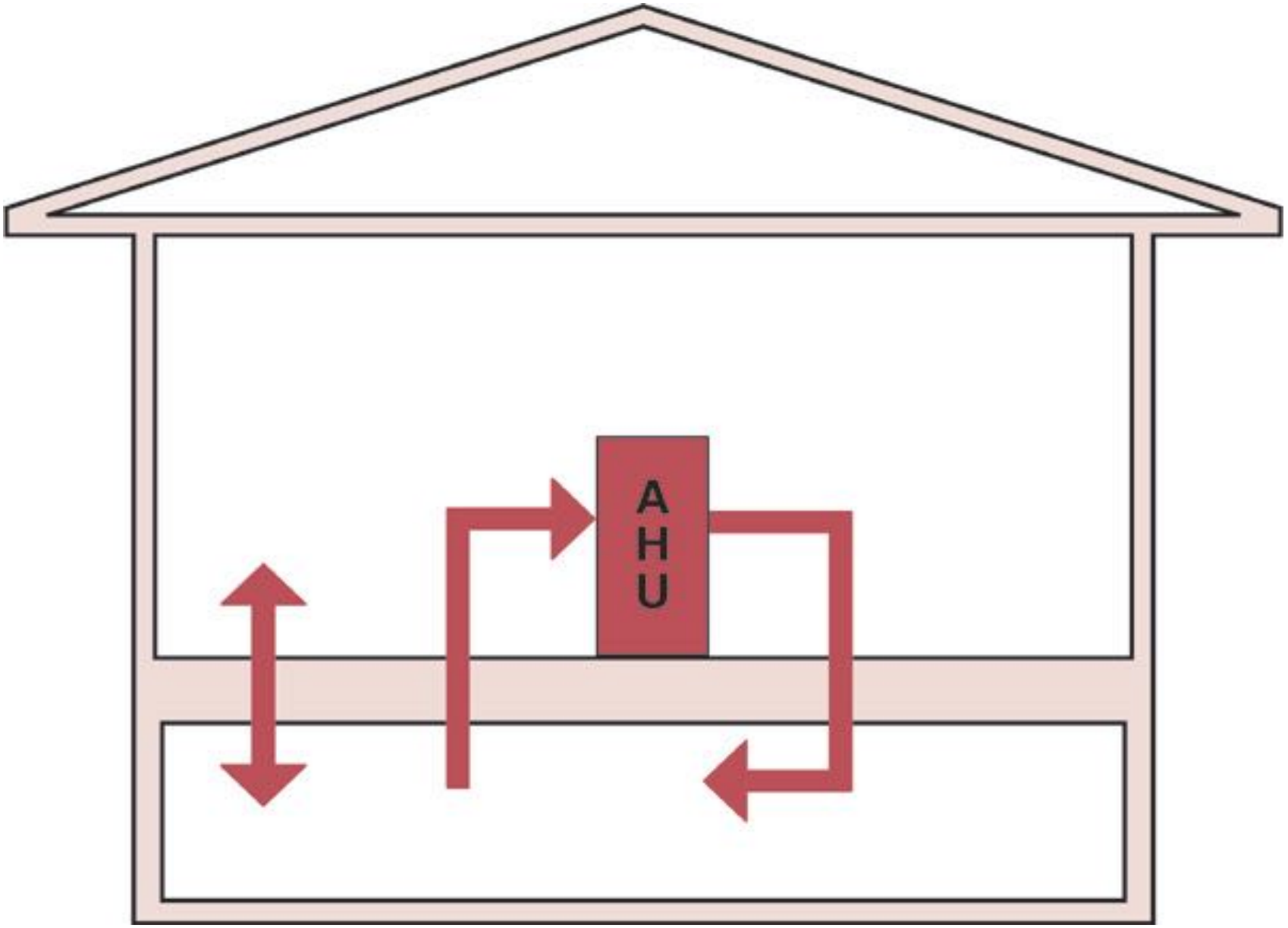
50 cfm/1000 ft2 of Crawlspace Area

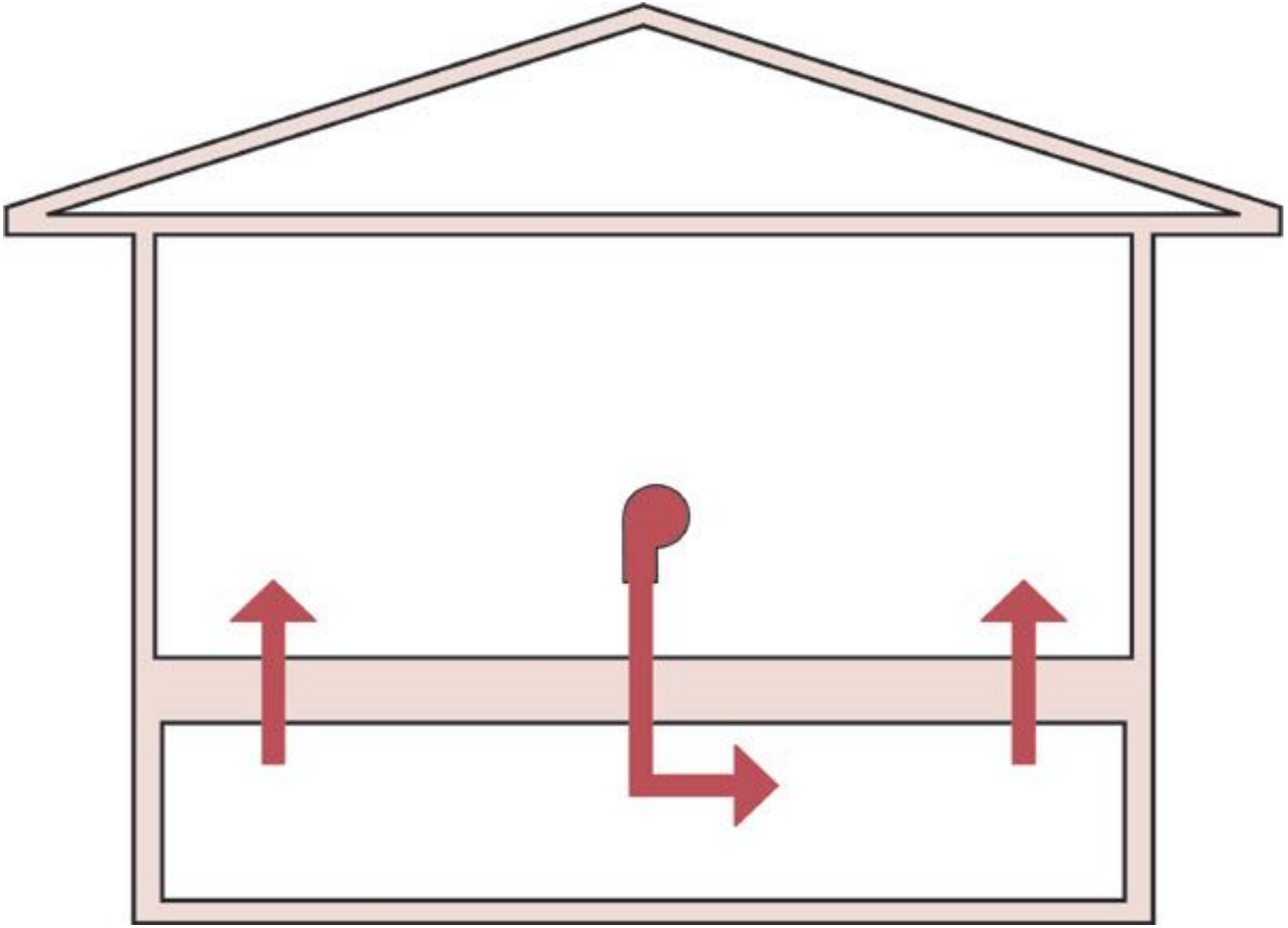
Or

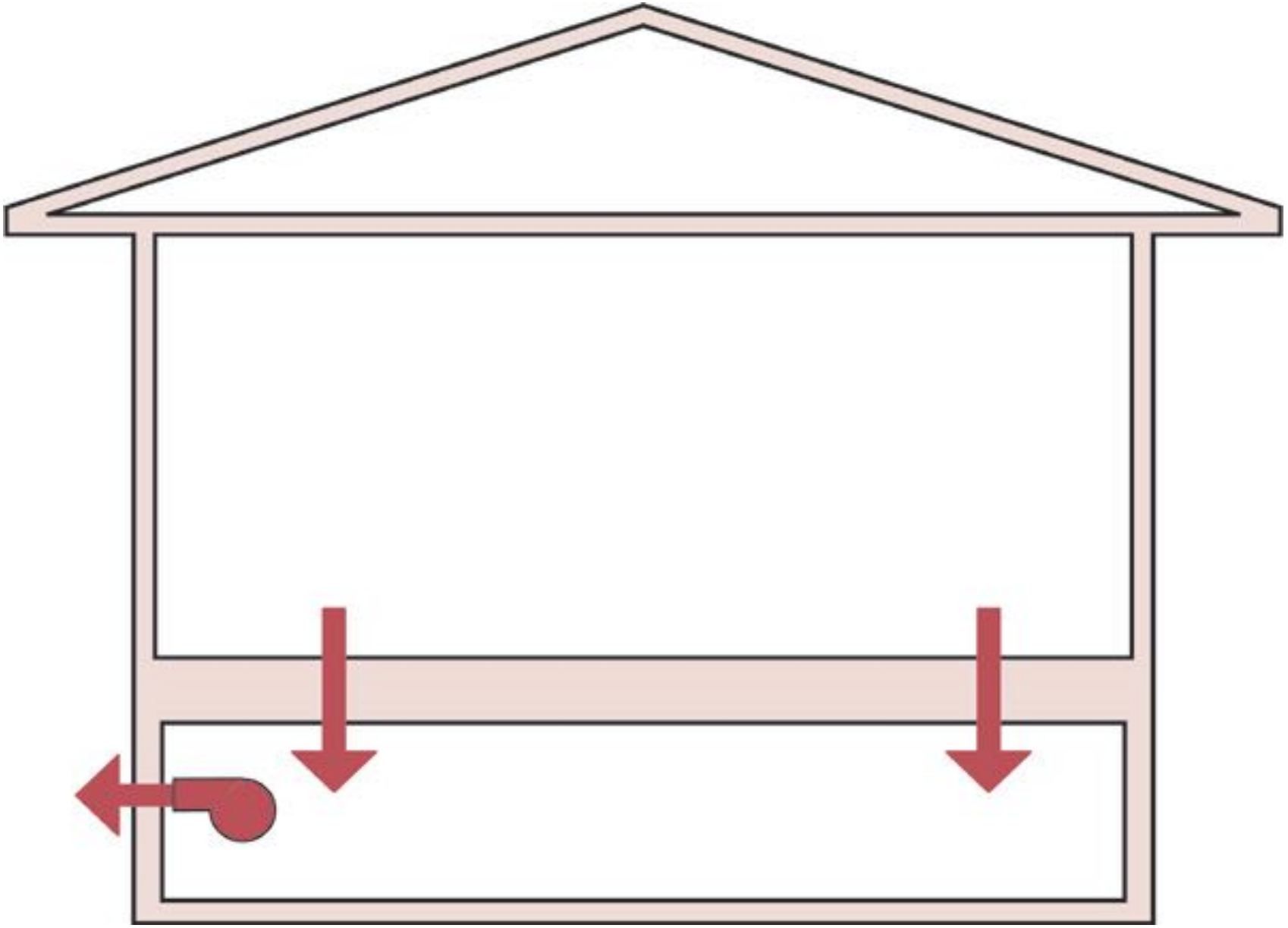
Dehumidification

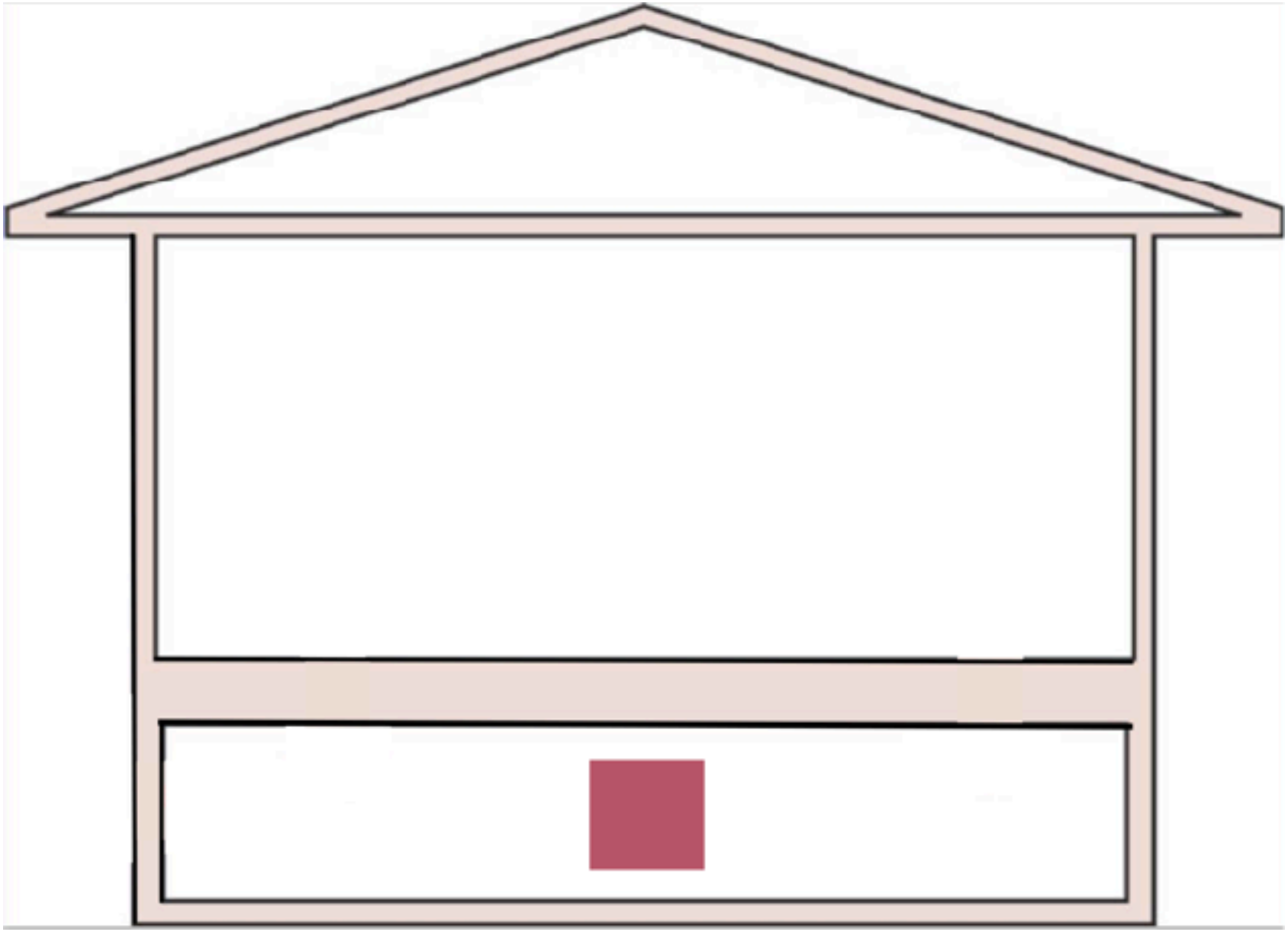

AHU

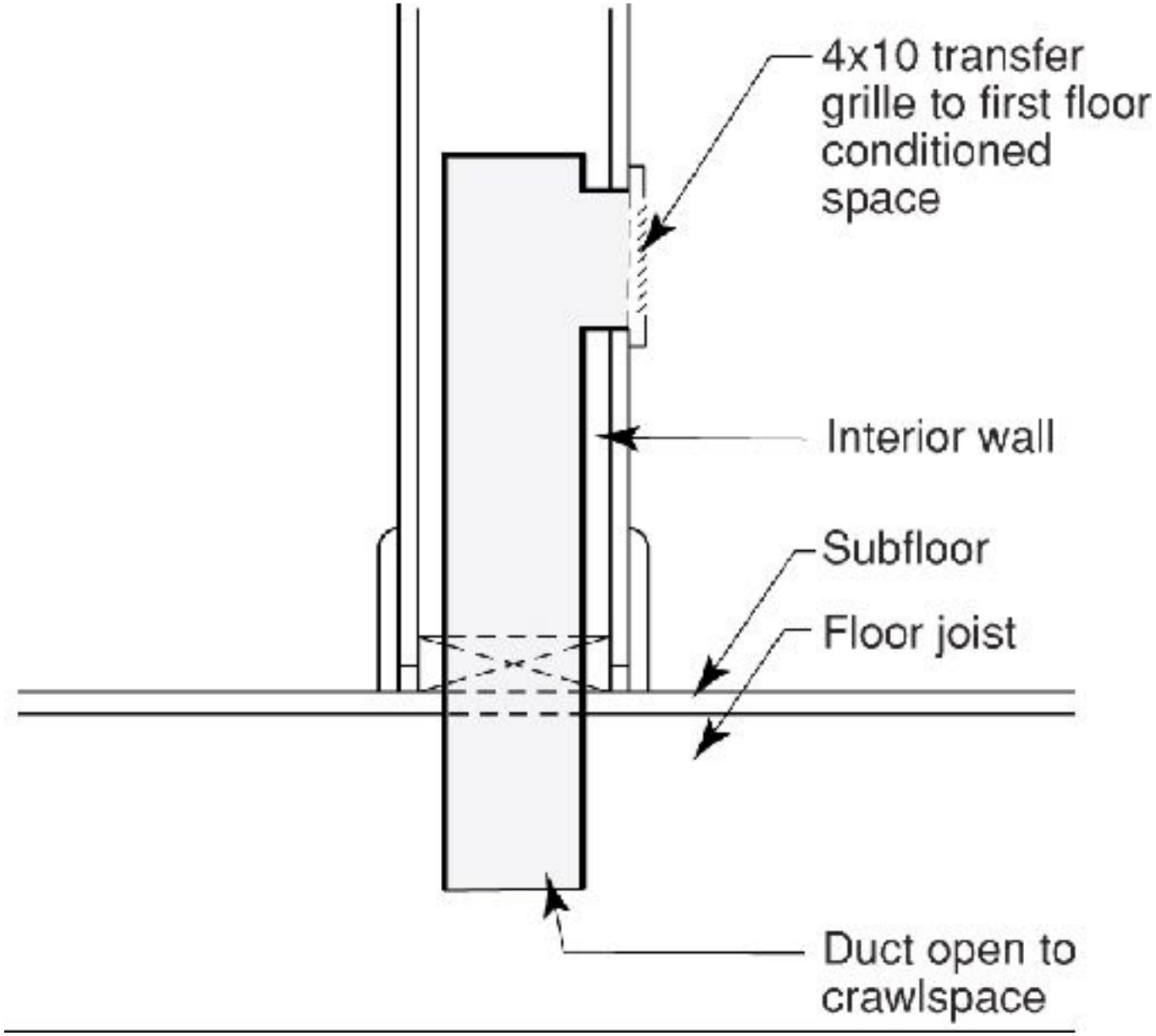

AHU

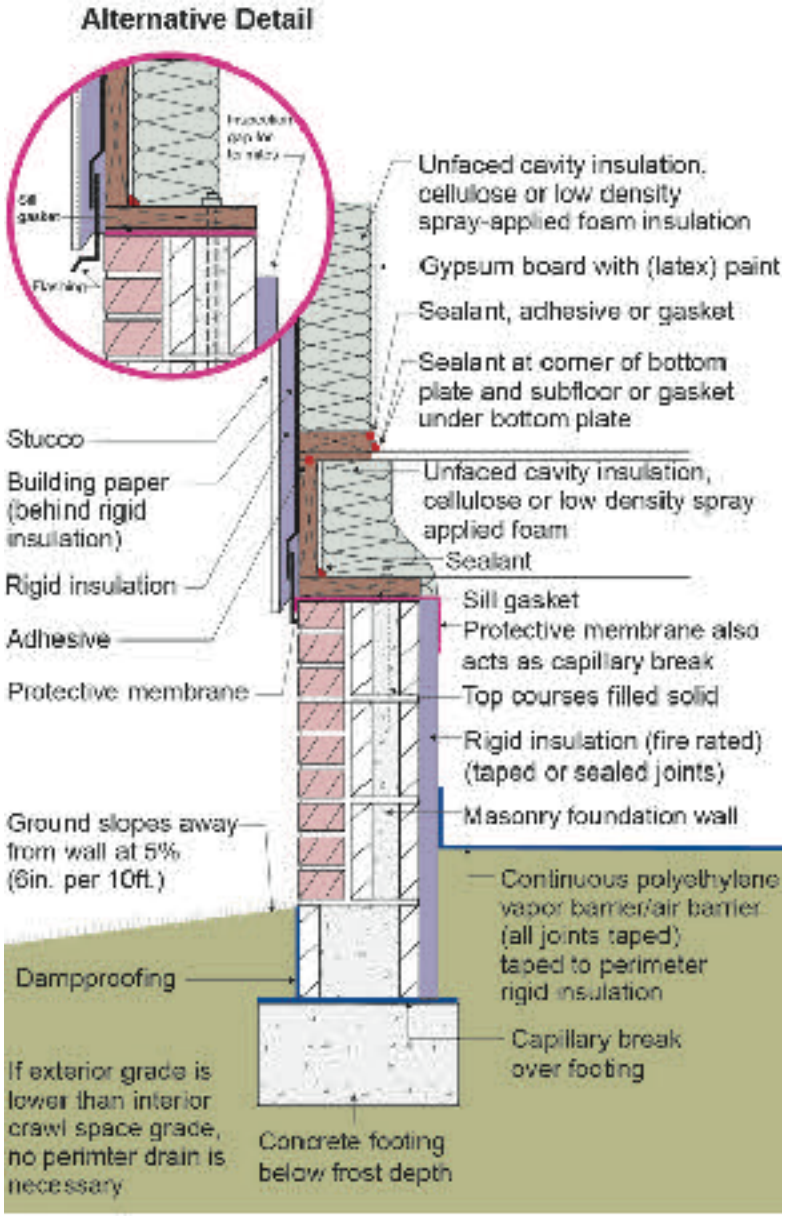

AHU



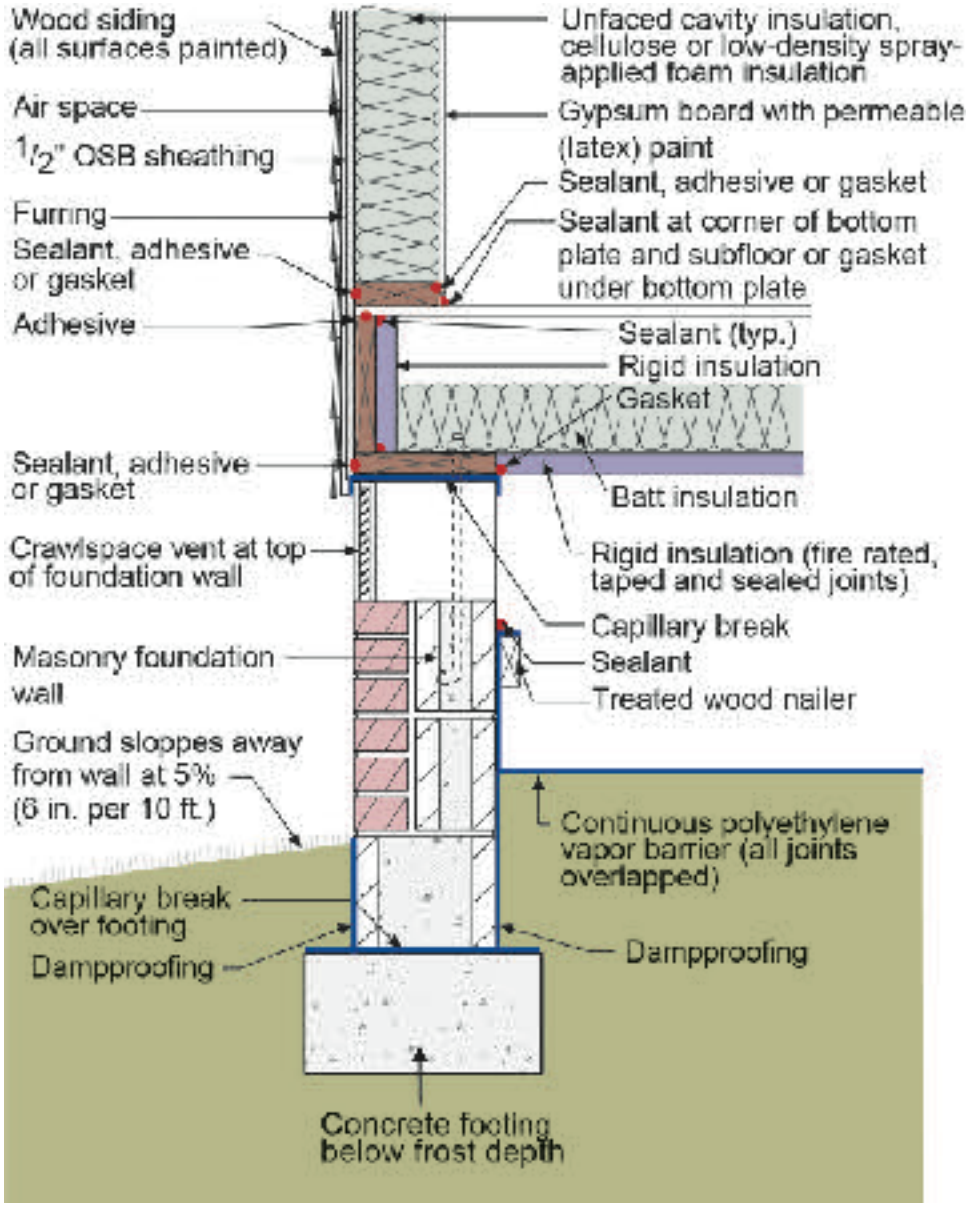


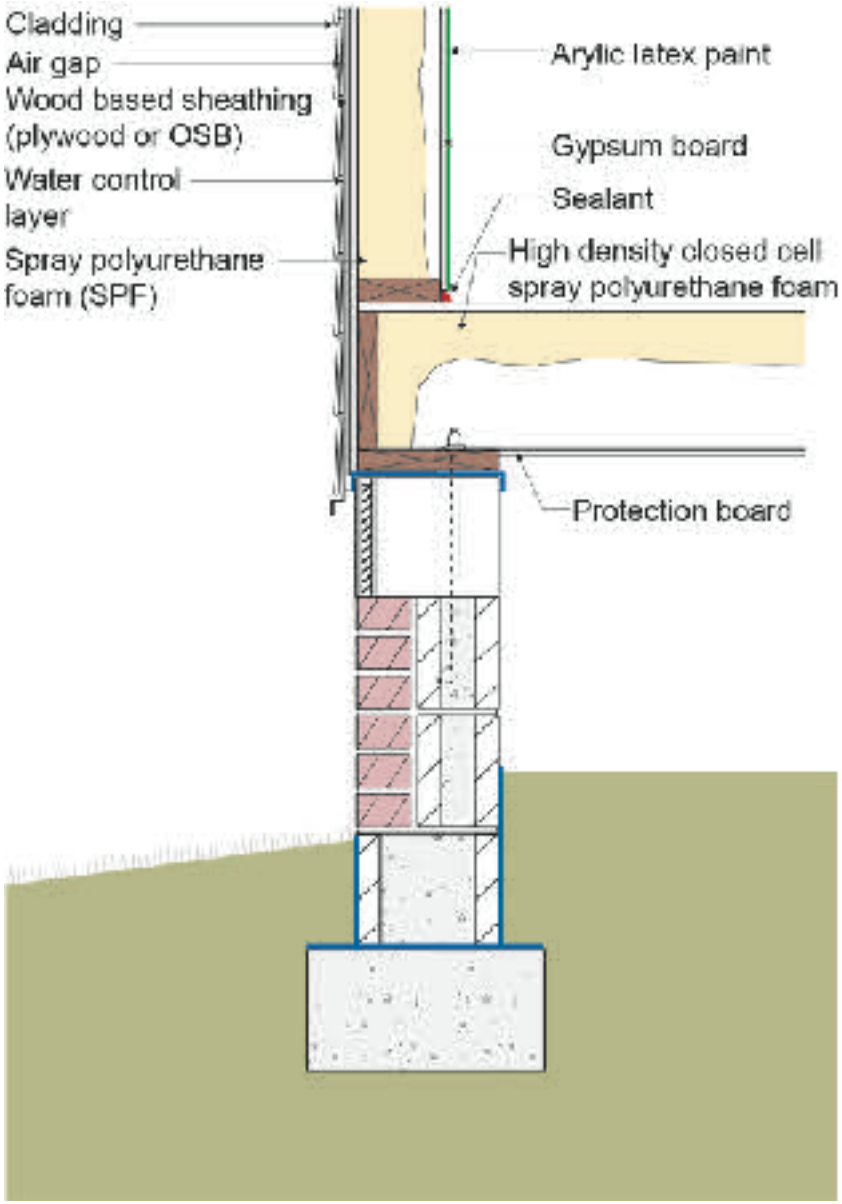


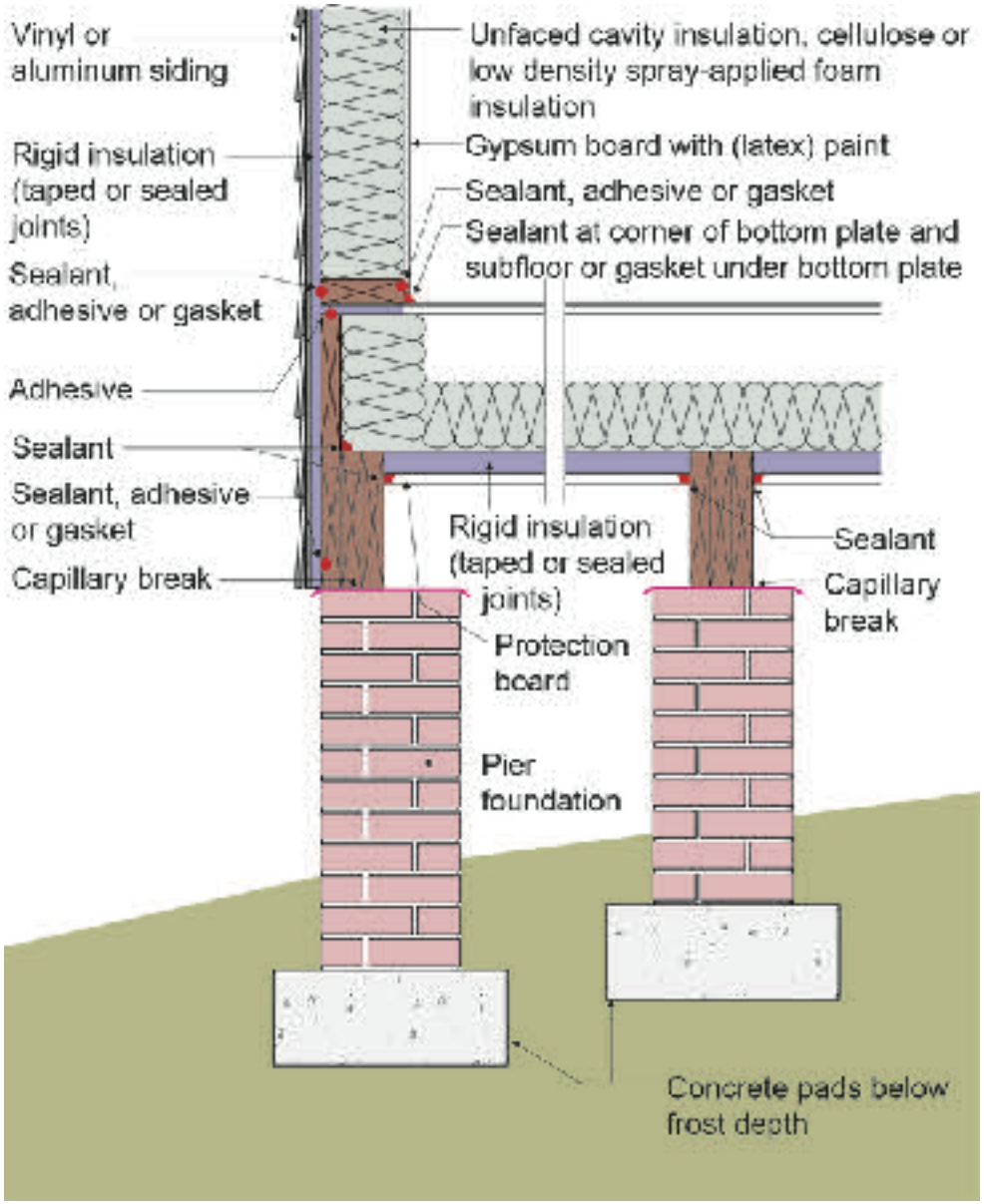

4x10 transfer grille to first floor conditioned space
Interior wall
Subfloor
Floor joist
Duct open to crawlspace

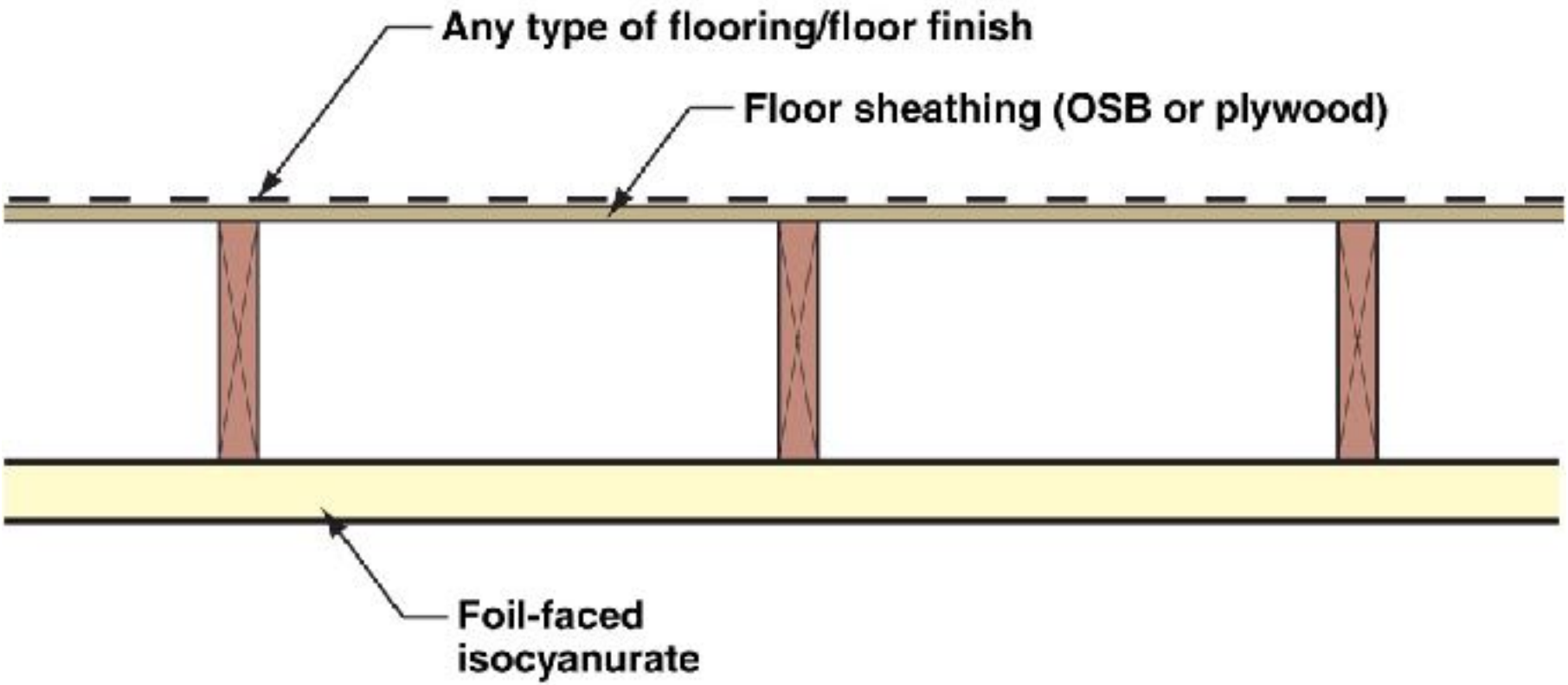

Alternative Detail
Unfaced cavity insulation, cellulose or low density spray-applied foam insulation
Gypsum board with (latex) paint
Sealant, adhesive or gasket
Sealant at corner of bottom plate and subfloor or gasket under bottom plate
Stucco
Building paper (behind rigid insulation)
Rigid insulation
Adhesive
Protective membrane
Unfaced cavity insulation, cellulose or low density spray applied foam
Sealant
Sill gasket
Protective membrane also acts as capillary break
Top courses filled solid
Rigid insulation (fire rated) (taped or sealed joints)
Masonry foundation wall
Ground slopes away from wall at 5% (6in. per 10ft.)
Continuous polyethylene vapor barrier/air barrier (all joints taped) taped to perimeter rigid insulation
Dampproofing
Capillary break over footing
If exterior grade is lower than interior crawl space grade, no perimter drain is necessary
Concrete footing below frost depth

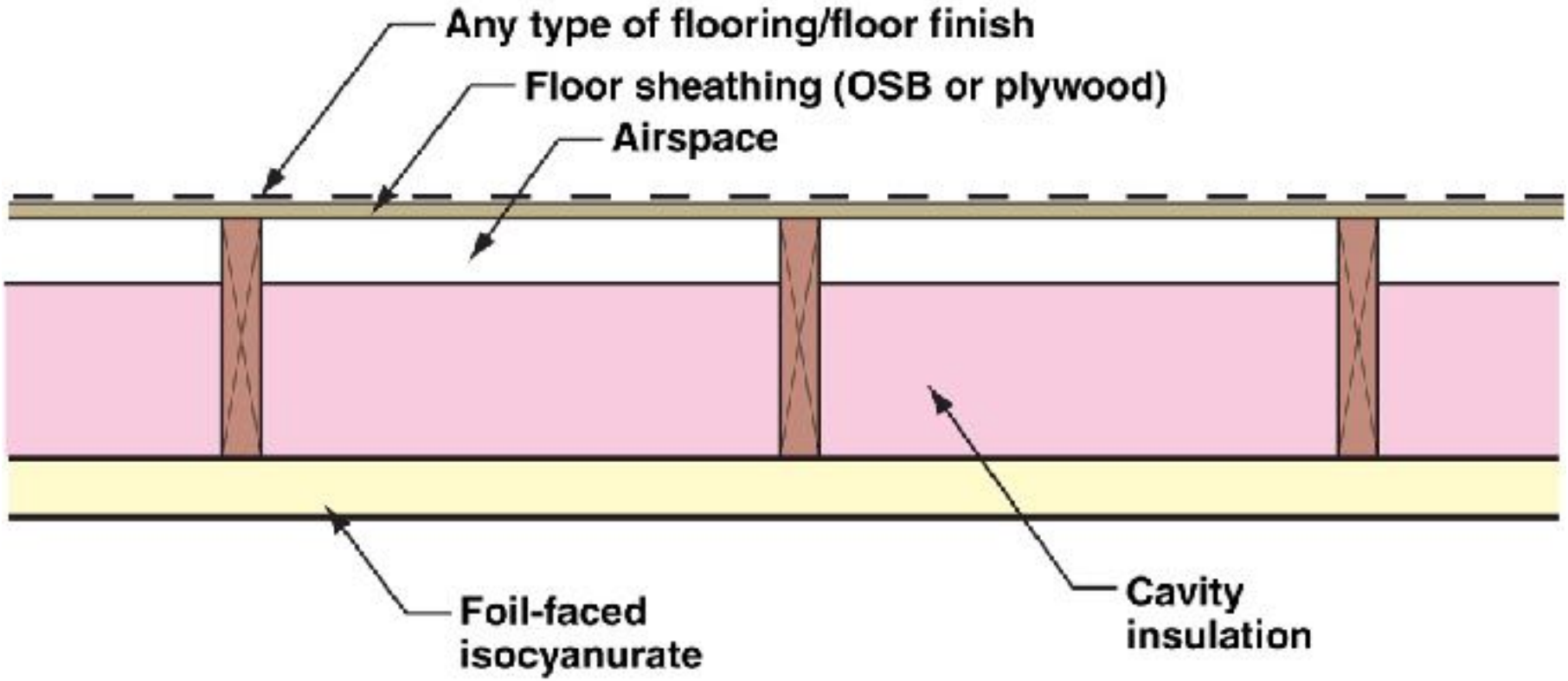
Smart Thing

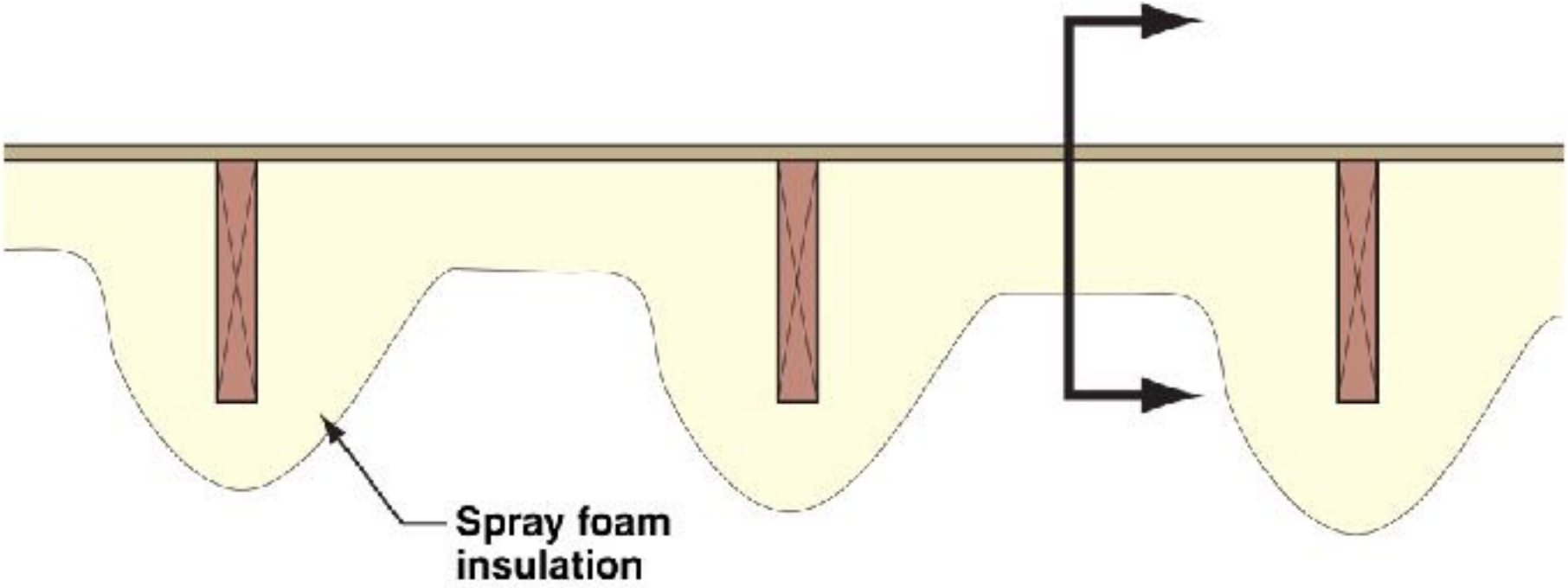

Wood siding
(all surfaces painted)
Air space
1/2" OSB sheathing
Furring
Sealant, adhesive
or gasket
Adhesive
Sealant, adhesive
or gasket
Crawlspace vent at top
of foundation wall
Masonry foundation
wall
Ground sloppes away
from wall at 5%
(6 in. per 10 ft.)
Capillary break
over footing
Dampproofing
Concrete footing
below frost depth
Unfaced cavity insulation,
cellulose or low-density spray-
applied foam insulation
Gypsum board with permeable
(latex) paint
Sealant, adhesive or gasket
Sealant at corner of bottom
plate and subfloor or gasket
under bottom plate
Sealant (typ.)
Rigid insulation
Gasket
Batt insulation
Rigid insulation (fire rated,
taped and sealed joints)
Capillary break
Sealant
Treated wood nailer
Continuous polyethylene
vapor barrier (all joints
overlapped)
Dampproofing


Cladding
Air gap
Wood based sheathing (plywood or OSB)
Water control layer
Spray polyurethane foam (SPF)
Arylic latex paint
Gypsum board
Sealant
High density closed cell spray polyurethane foam
Protection board


Vinyl or aluminum siding
Rigid insulation (taped or sealed joints)
Sealant, adhesive or gasket
Adhesive
Sealant
Sealant, adhesive or gasket
Capillary break
Unfaced cavity insulation, cellulose or low density spray-applied foam insulation
Gypsum board with (latex) paint
Sealant, adhesive or gasket
Sealant at corner of bottom plate and subfloor or gasket under bottom plate
Rigid insulation (taped or sealed joints)
Protection board
Pier foundation
Sealant
Capillary break
Concrete pads below frost depth


Any type of flooring/floor finish
Floor sheathing (OSB or plywood)
Foil-faced
isocyanurate


Any type of flooring/floor finish
Floor sheathing (OSB or plywood)
Airspace
Foil-faced isocyanurate
Cavity insulation


Spray foam
insulation

Mechanical Systems

Mechanical Systems
Cooling System To Make It Cold

Mechanical Systems

Cooling System To Make It Cold

Dehumidification System To Make It Dry

Mechanical Systems

Cooling System To Make It Cold

Dehumidification System To Make It Dry

Heating System To Make It Warm

Mechanical Systems

Cooling System To Make It Cold

Dehumidification System To Make It Dry

Heating System To Make It Warm

Energy Recovery System To Keep It Cold and Dry and Warm and Comfortable

Mechanical Systems

Cooling System To Make It Cold

Dehumidification System To Make It Dry

Heating System To Make It Warm

Energy Recovery System To Keep It Cold and Dry and Warm and Comfortable

Distribution System To Make It Uniform

Mechanical Systems

Cooling System To Make It Cold

Dehumidification System To Make It Dry

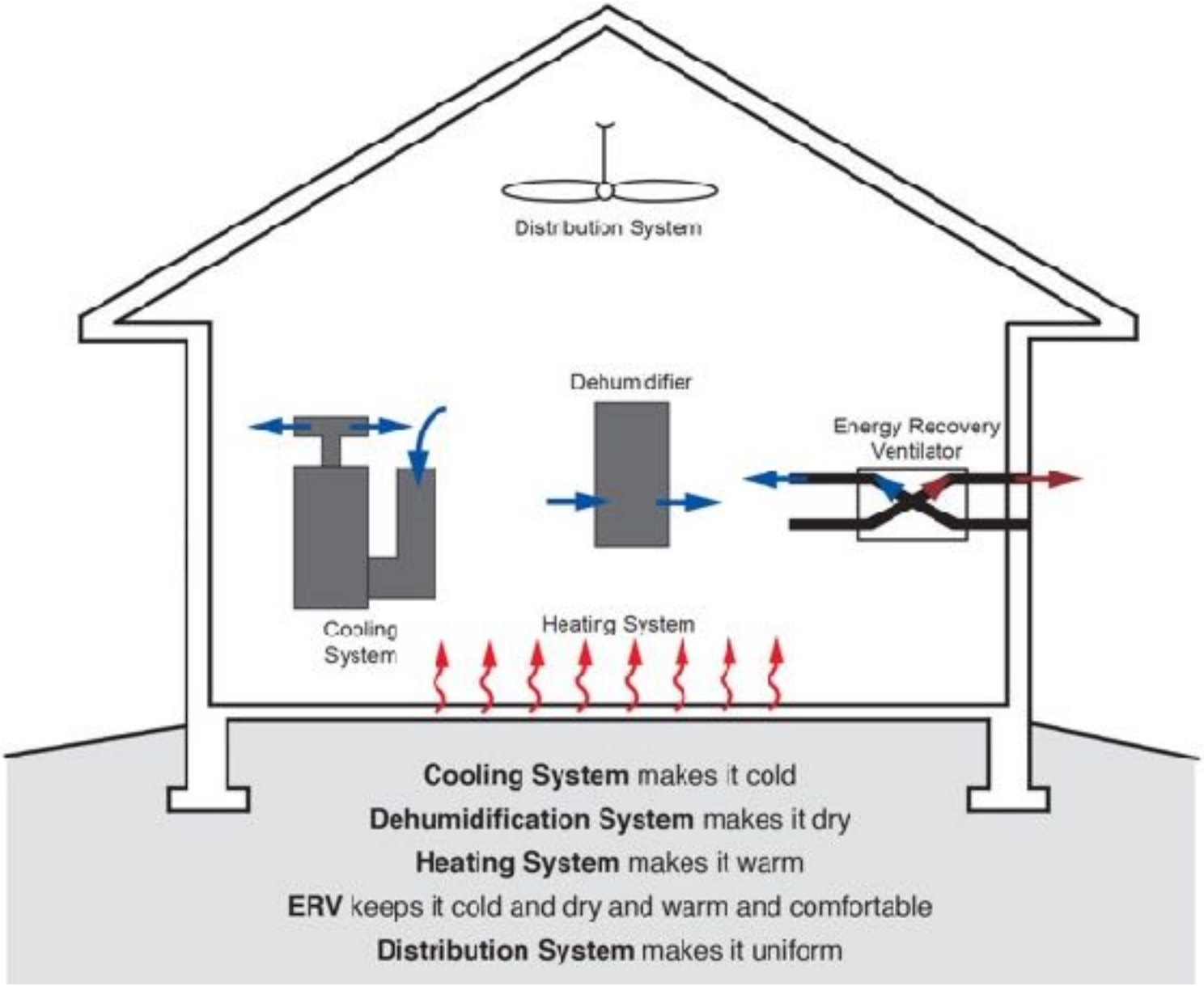
Heating System To Make It Warm

Energy Recovery System To Keep It Cold and Dry and Warm and Comfortable

Distribution System To Make It Uniform

Range Hoods Are A Special Kind of Hell

Don’t Try to Combine Them…...


Distribution System
Dehumidifier
Energy Recovery
Ventilator
Cooling
System
Heating System
Cooling System makes it cold
Dehumidification System makes it dry
Heating System makes it warm
ERV keeps it cold and dry and warm and comfortable
Distribution System makes it uniform

Build Tight - Ventilate Right

Build Tight - Ventilate Right

How Tight?

What's Right?

Air Barrier Metrics

Material	0.02 l/(s-m2) @ 75 Pa
Assembly	0.20 l/(s-m2) @ 75 Pa
Enclosure	2.00 l/(s-m2) @ 75 Pa
	0.25 cfm/ft2 @ 50 Pa

Getting rid of big holes	3 ach@50
Getting rid of smaller holes	1.5 ach@50
Getting German	0.6 ach@50

Best

As Tight as Possible - with -
Balanced Ventilation
Energy Recovery
Distribution and Mixing
Source Control - Spot exhaust ventilation
Filtration
Material selection

Worst

Leaky - with – Nothing

Spot Ventilation in Bathroom/Kitchen

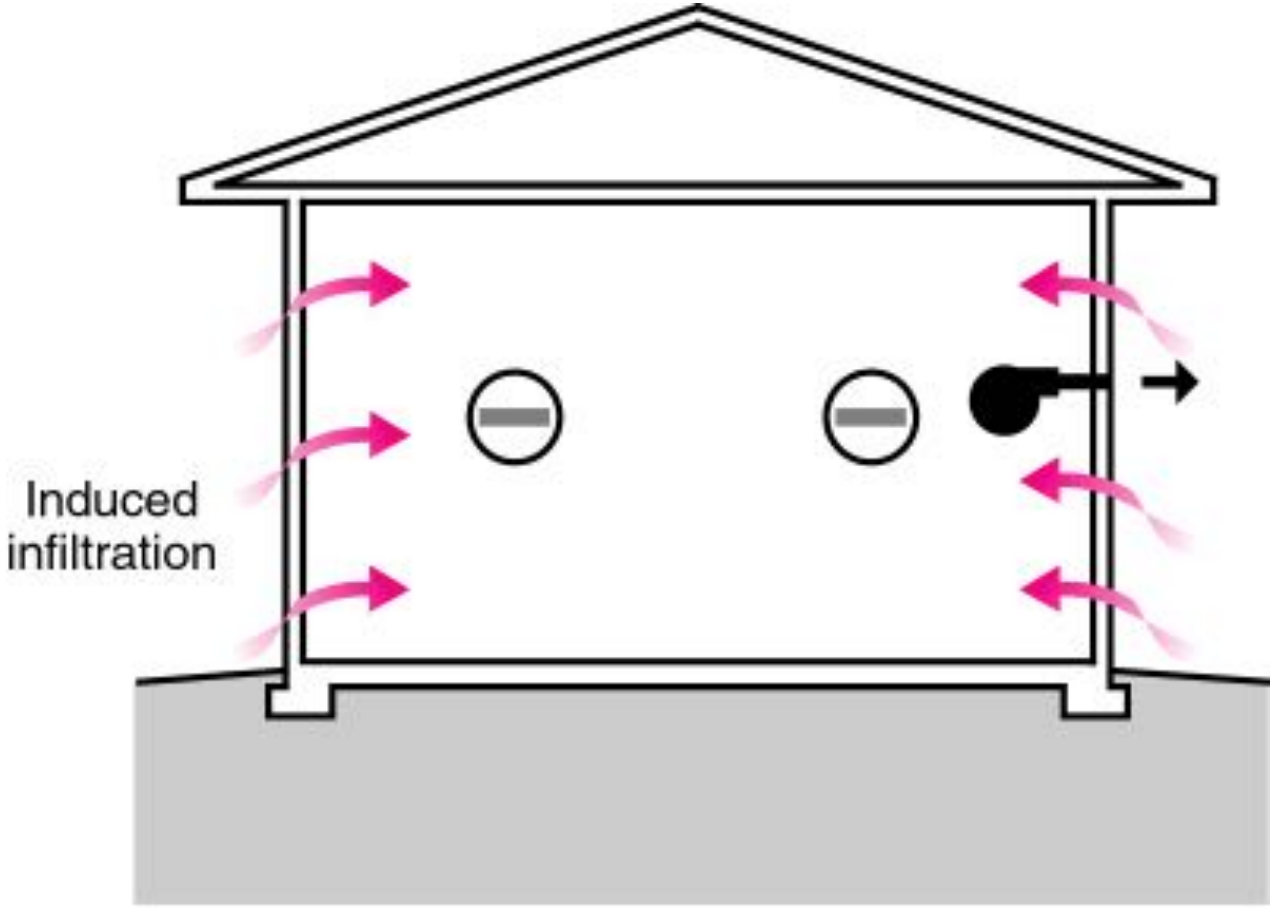
Exhaust Ventilation – with – No Distribution and No Mixing

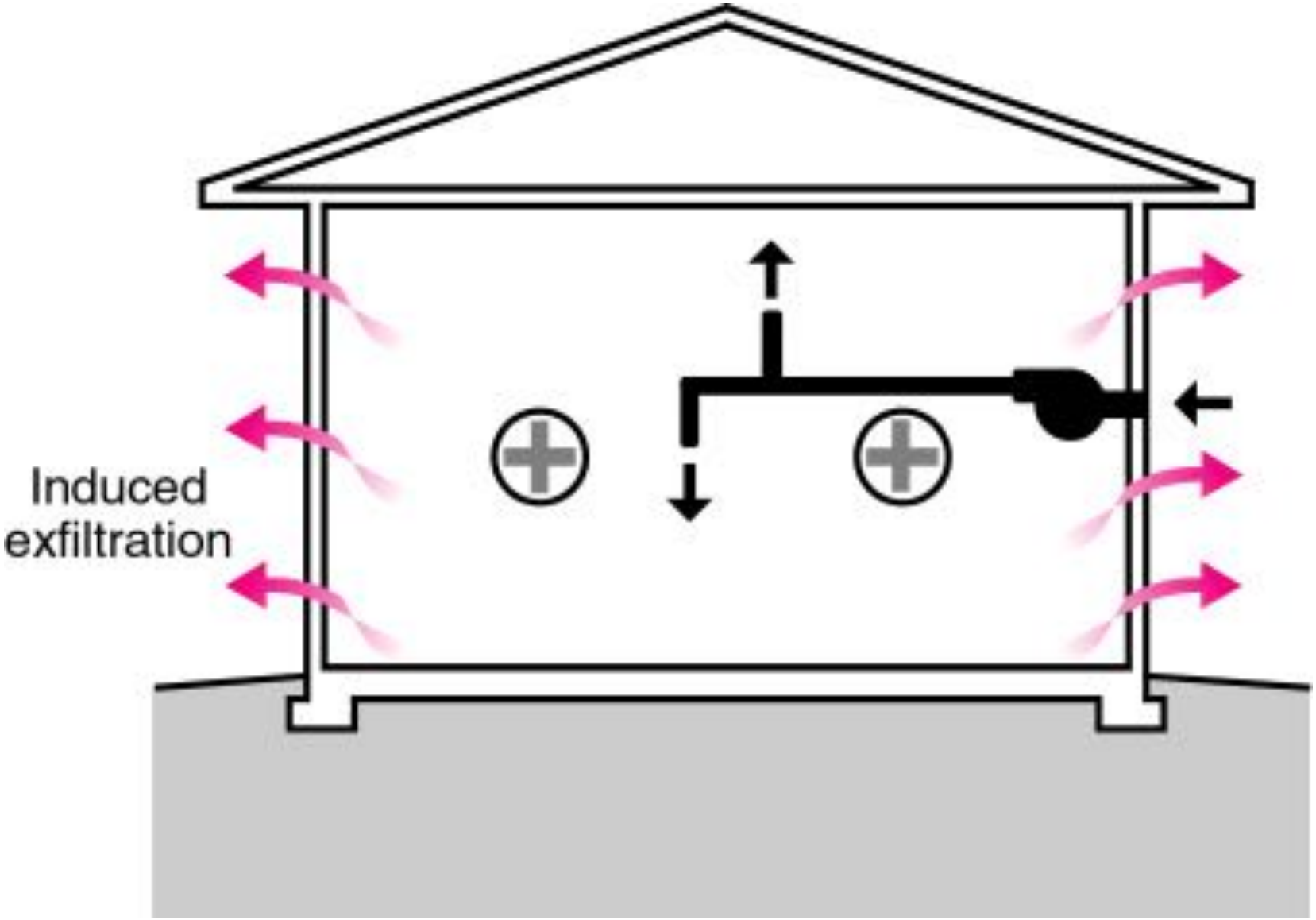
Three Types of Controlled Ventilation Systems

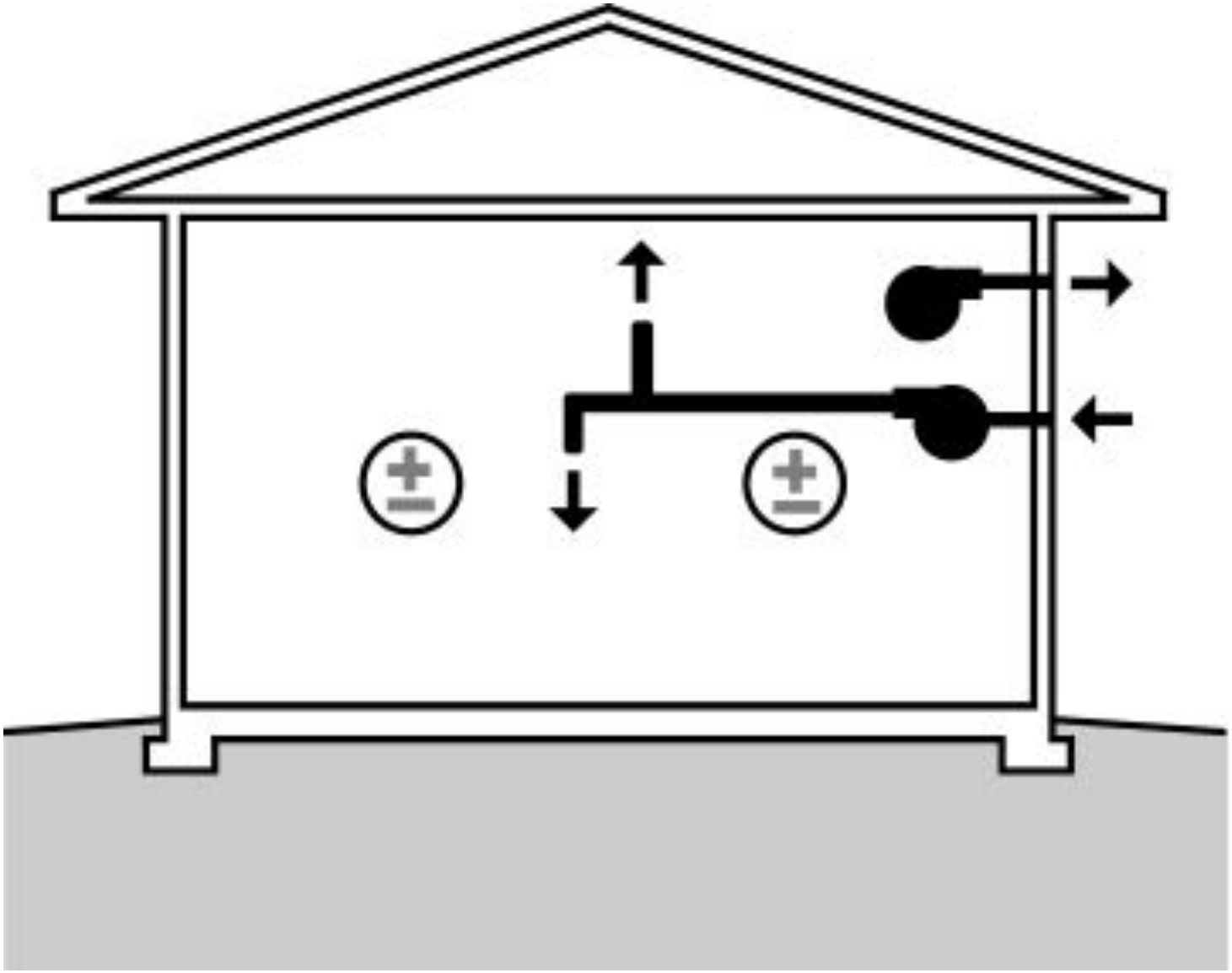
Exhaust Ventilation

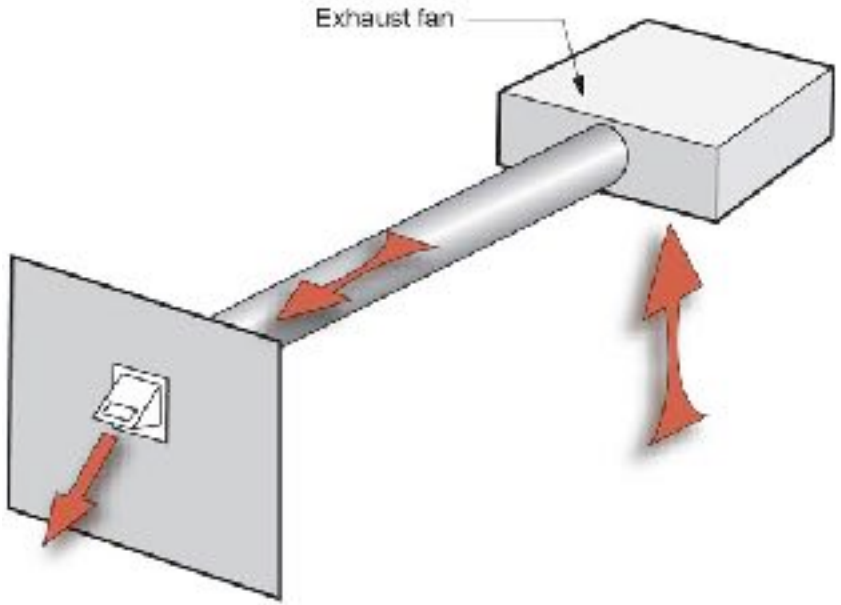
Supply Ventilation

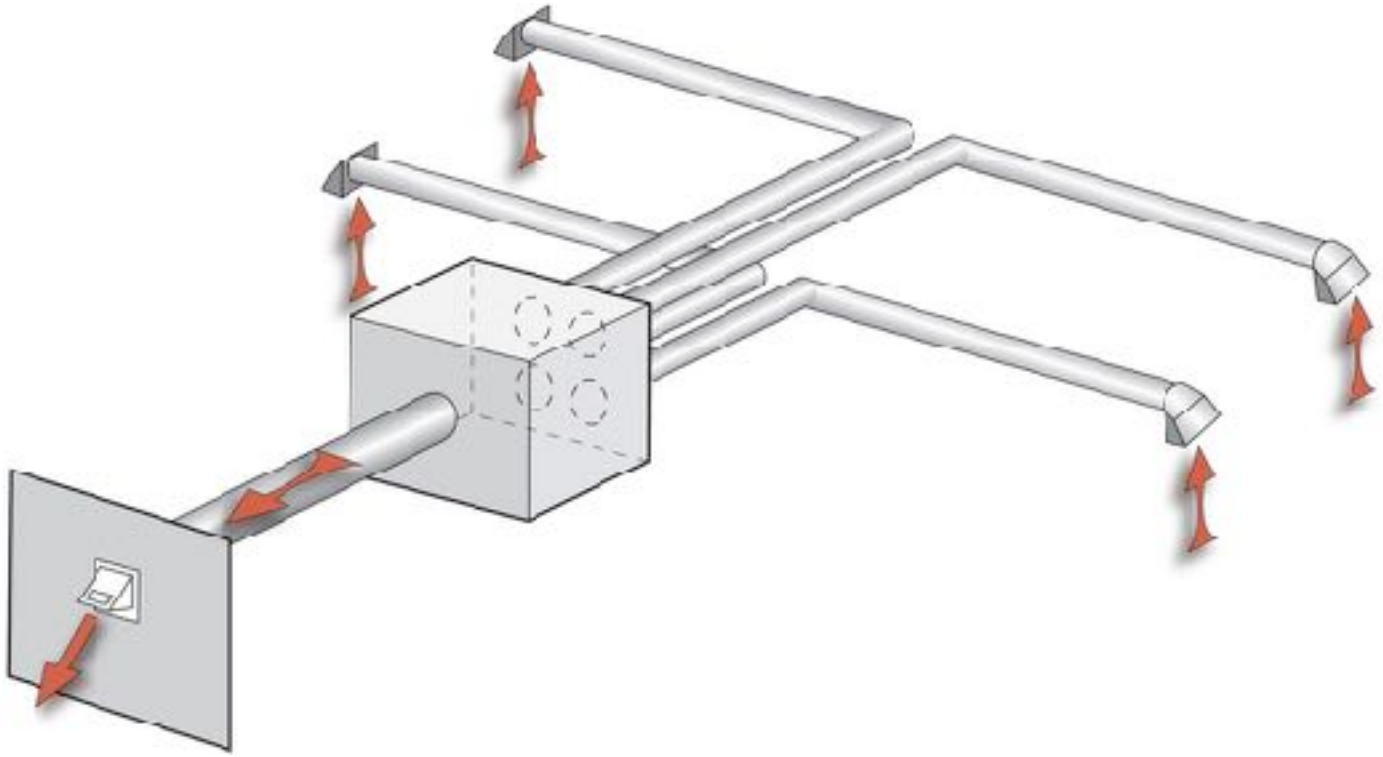
Balanced Ventilation

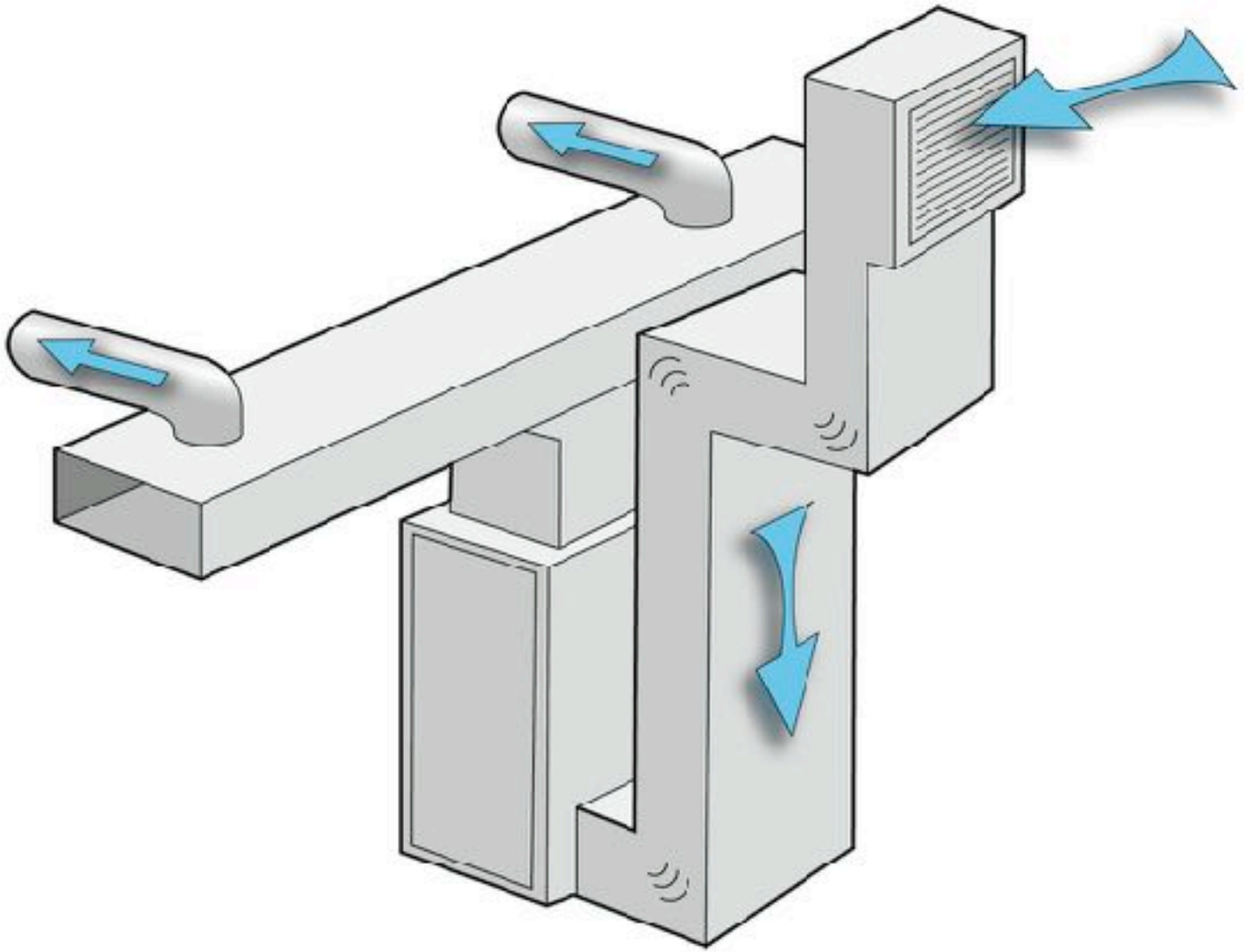

Induced
infiltration

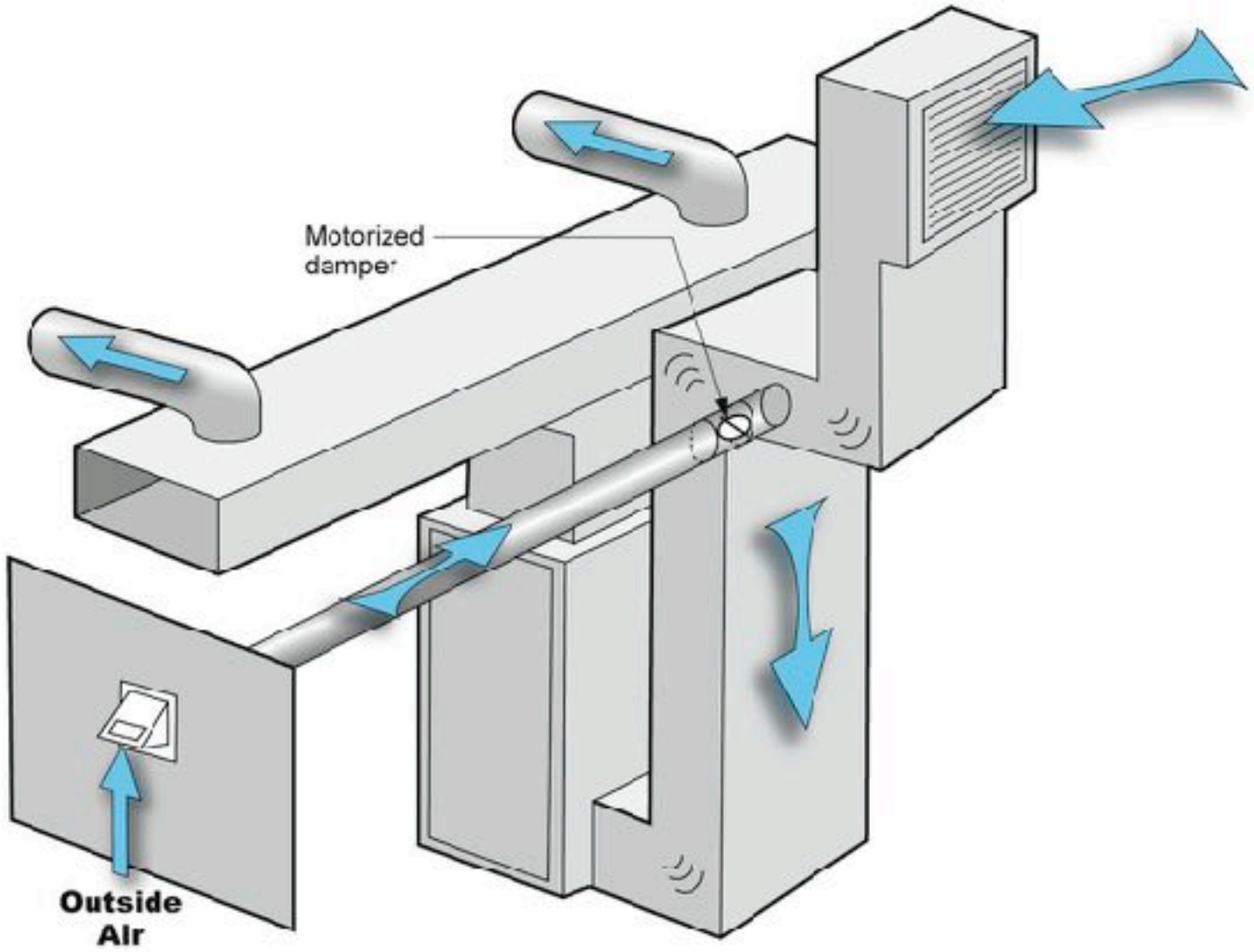

Induced
exfiltration

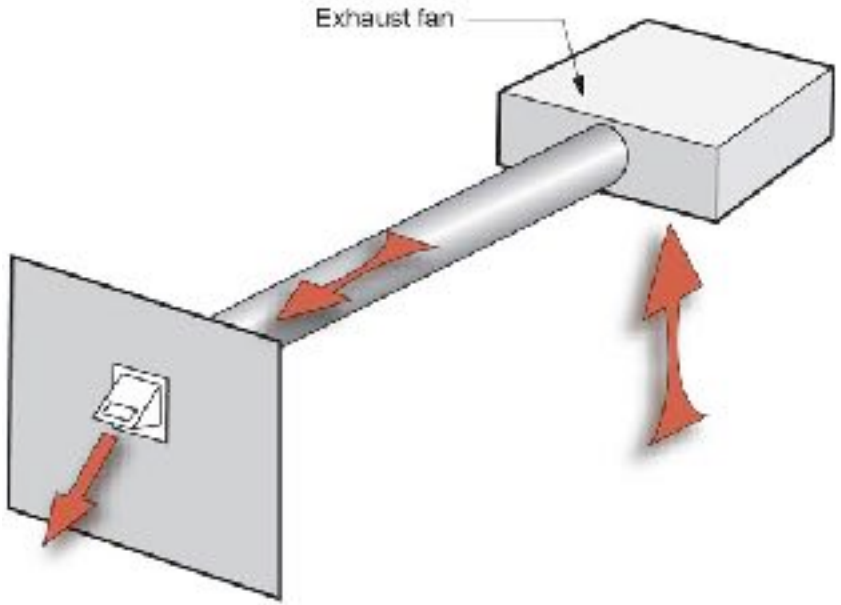


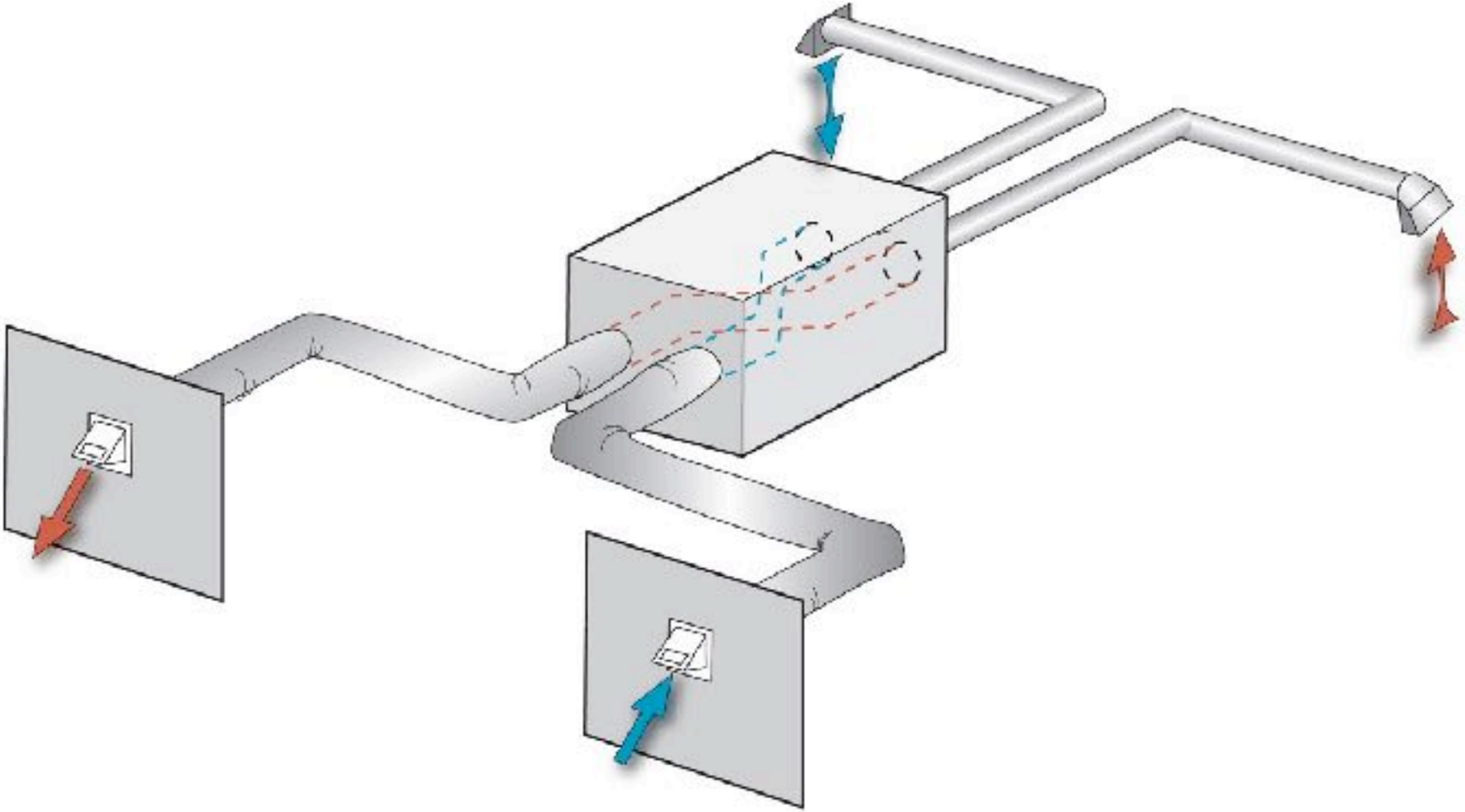

Exhaust fan






Motorized
damper
Outside
Air


Exhaust fan



Ventilation Rates Are Based on Odor Control

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- Health Science Basis for Ventilation Rates is Extremely Limited

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- The Applicable Studies Focus on Dampness

ASHRAE Standard 62.2 calls for 7.5 cfm per person plus 0.03 cfm per square foot of conditioned area

Occupancy is deemed to be the number of bedrooms plus one

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Occupancy is deemed to be the number of bedrooms plus one

Outcome is often bad – part load humidity problems, dryness problems, energy problems

IRC 2015 and 2018 calls for 7.5 cfm per person plus 0.01 cfm per square foot of conditioned area

Occupancy is deemed to be the number of bedrooms plus one

3 Bedroom House – 2,500 ft2

30 cfm plus 75 cfm

105 cfm

3 Bedroom House – 2,500 ft2

30 cfm plus 25 cfm

55 cfm

3 Bedroom House – 2,500 ft2

30 cfm plus 25 cfm

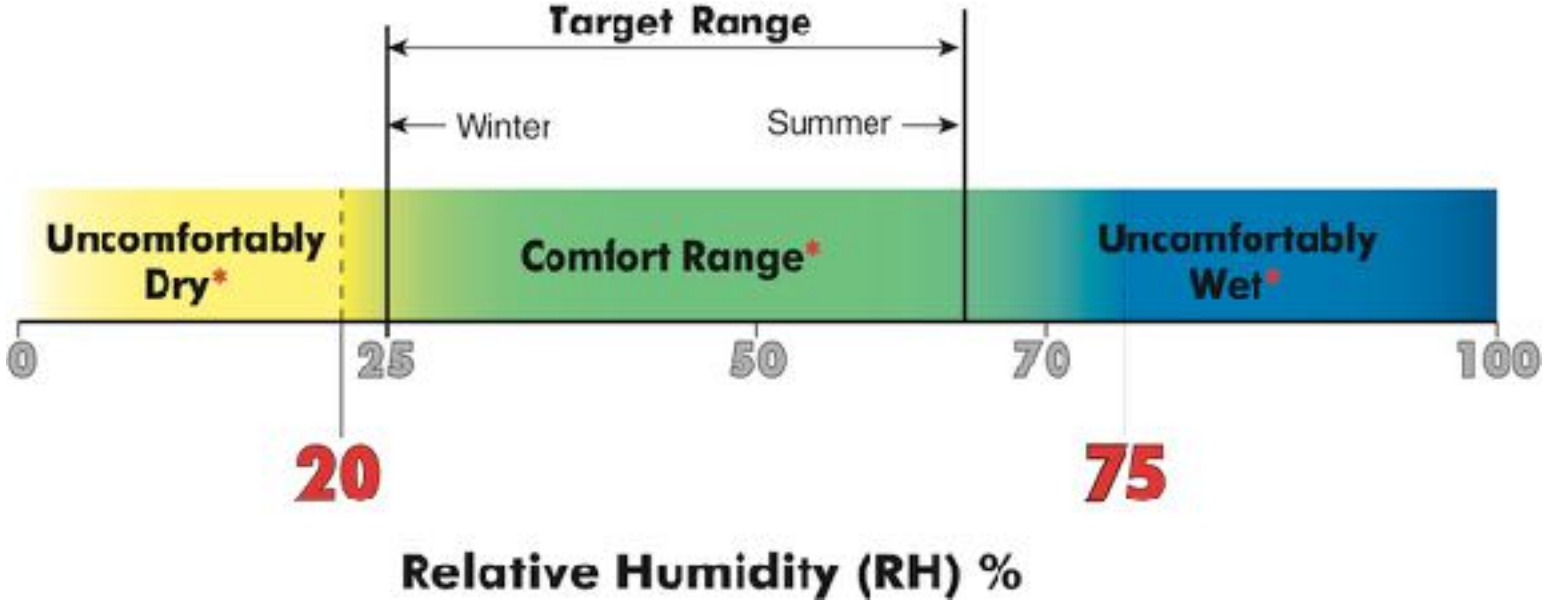
55 cfm

With Balanced and Distributed 30 percent credit

38.5 cfm

Dilution For People

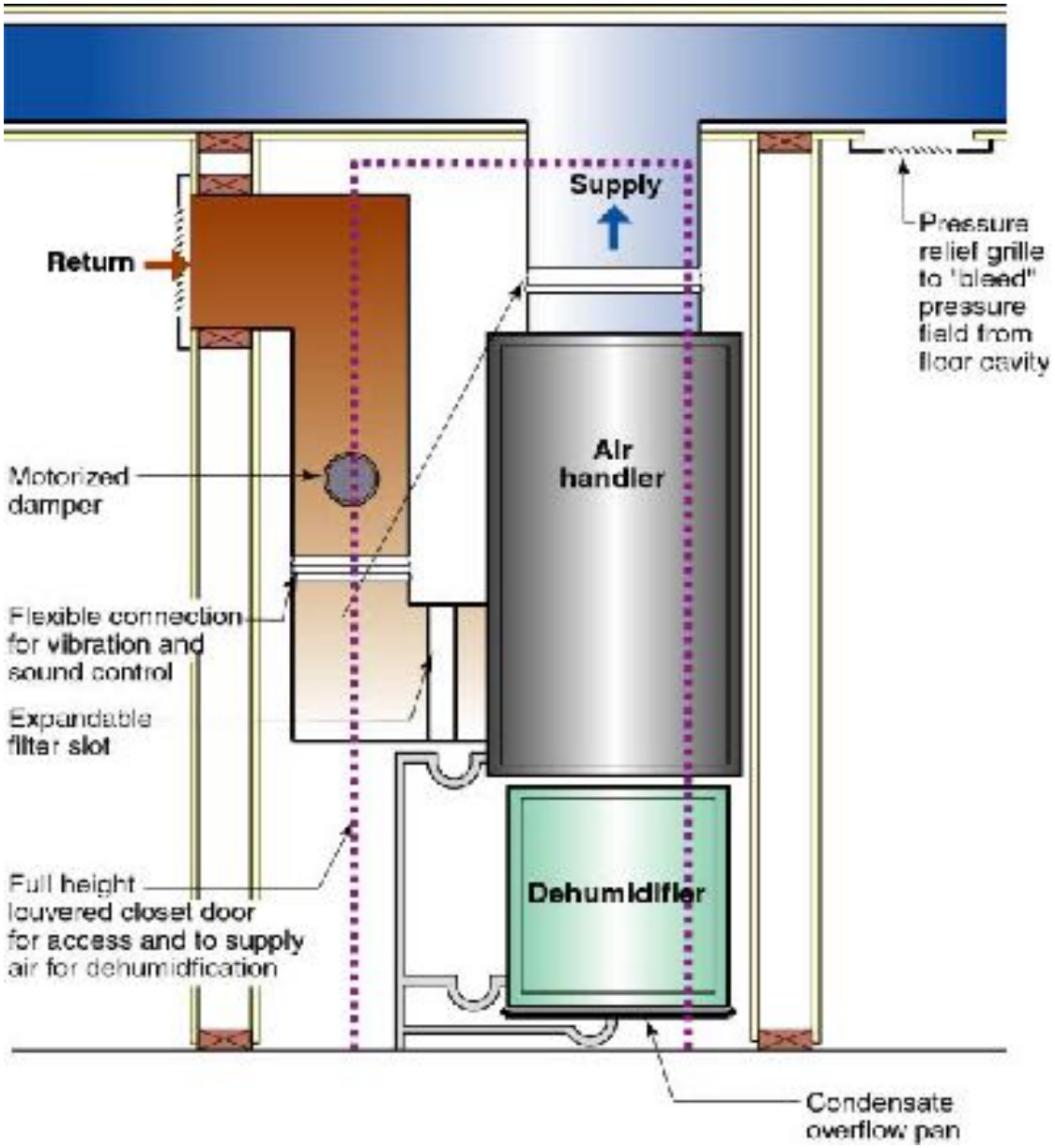
Source Control For The Building


Target Range
Winter
Summer
Uncomfortably Dry*
Comfort Range*
Uncomfortably Wet*
0
25
50
70
100
20
75
Relative Humidity (RH) %

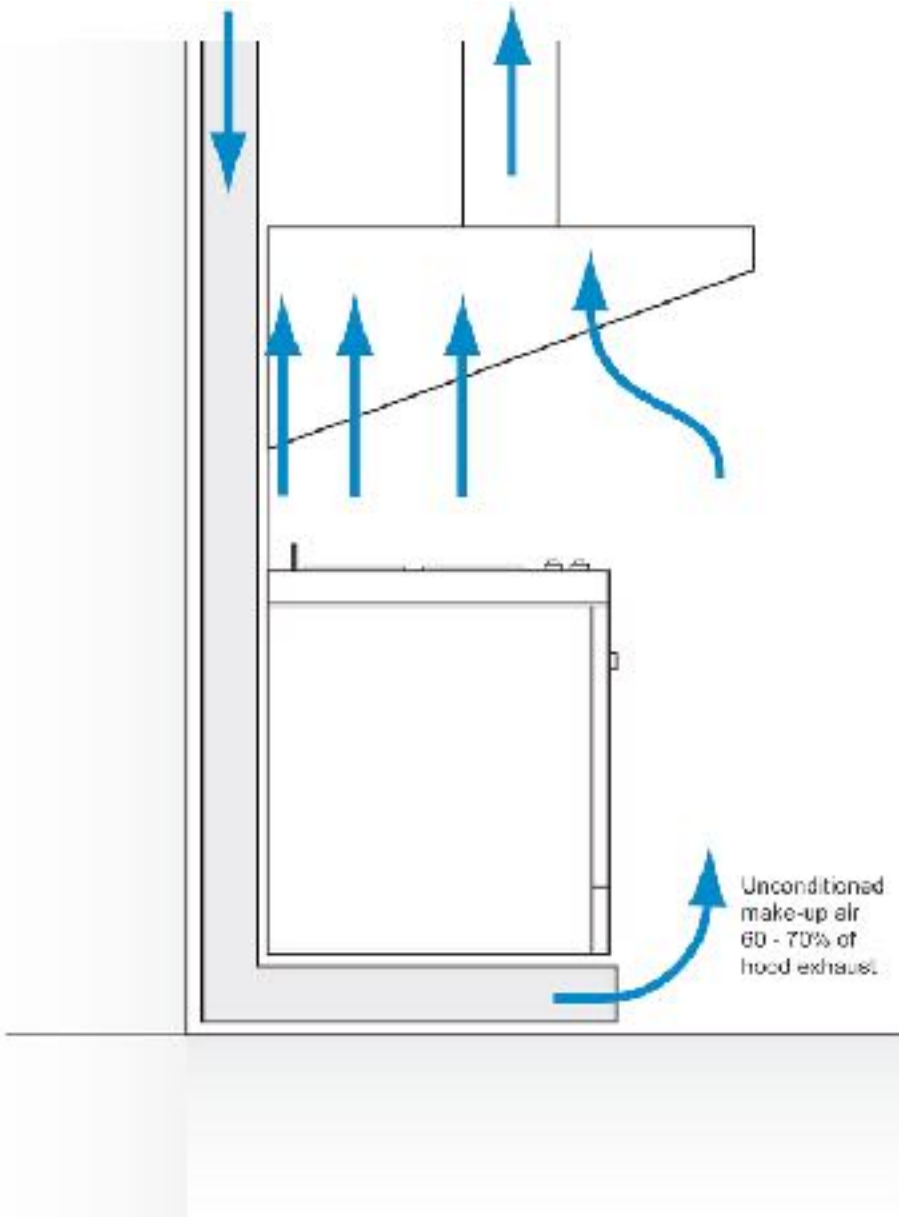
Recommended Range of Relative Humidity

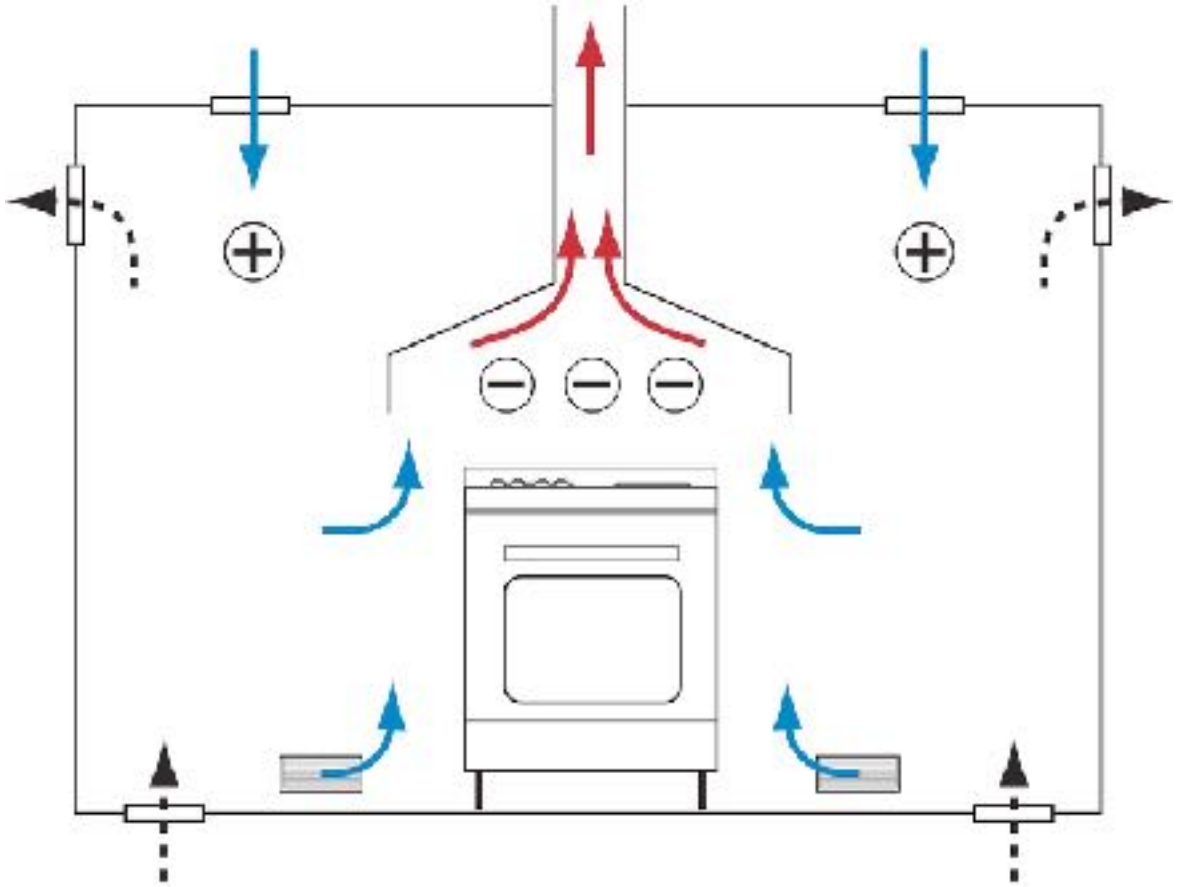
Above 25 percent during winter

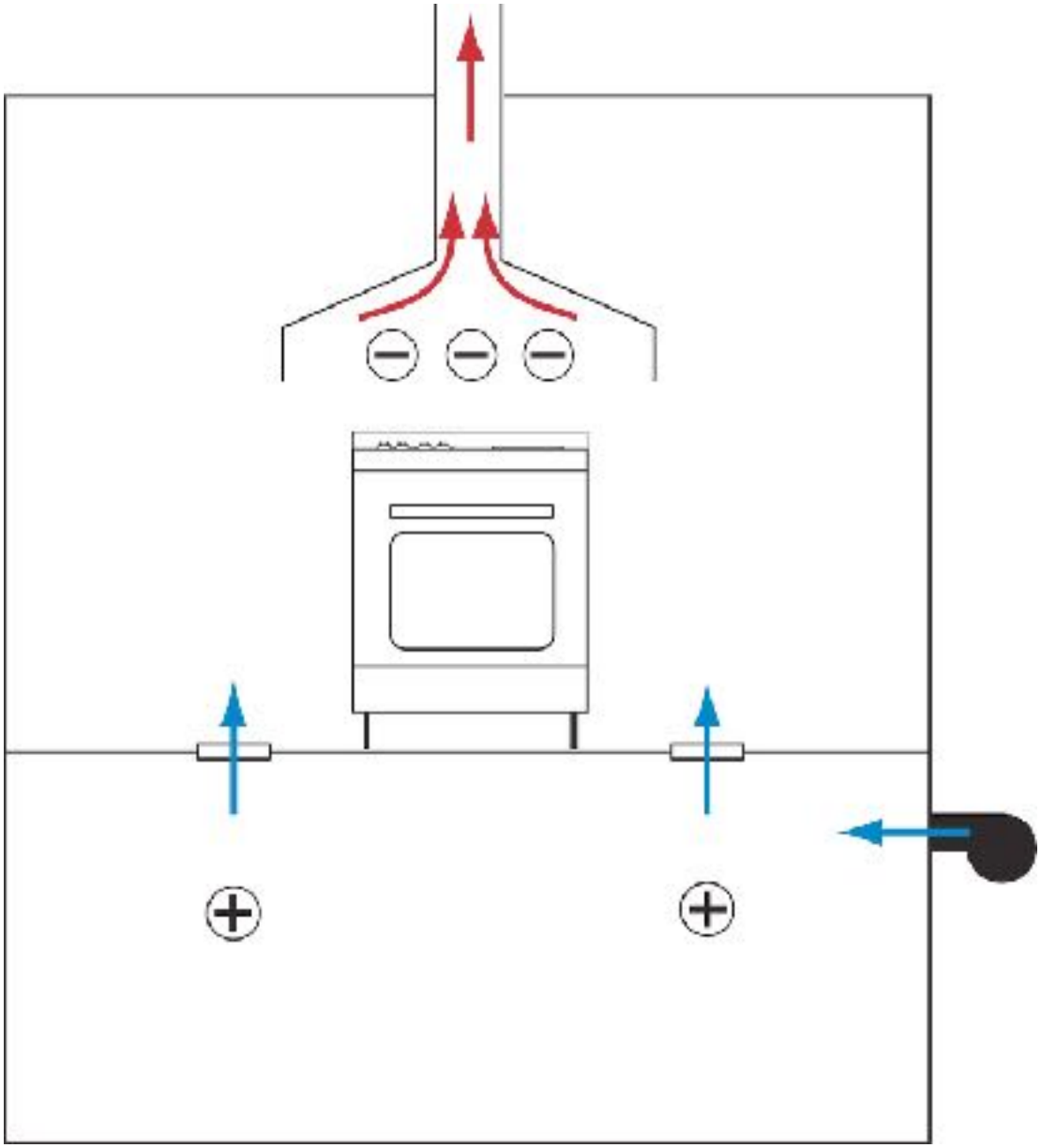
Below 70 percent during summer

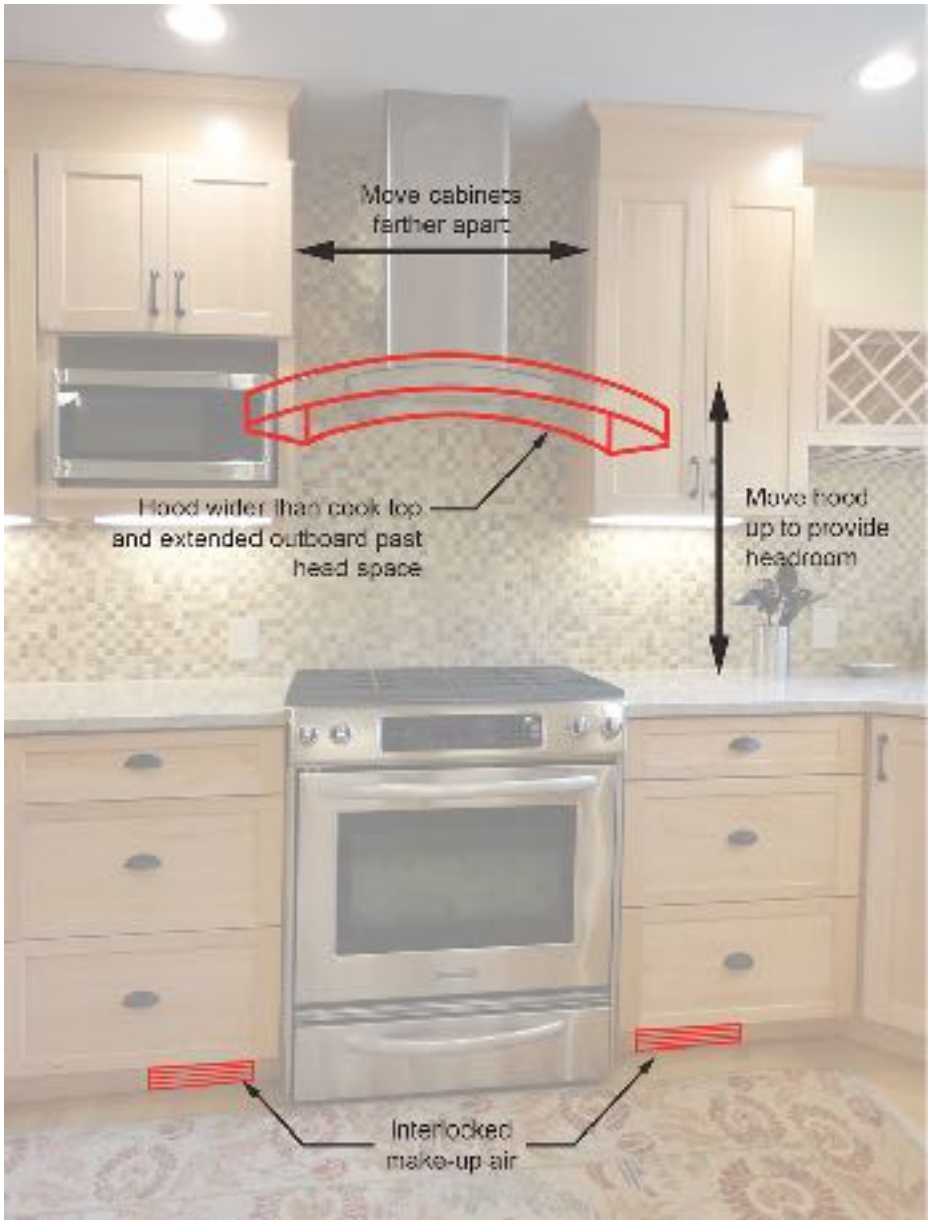

Supply
Return
Pressure relief grille to "bleed" pressure field from floor cavity
Air handler
Motorized damper
Flexible connection for vibration and sound control
Expandable filter slot
Dehumidifier
Full height louvered closet door for access and to supply air for dehumidification
Condensate overflow pan

Kitchen Exhaust Hoods


Unconditioned
make-up air
60 - 70% of
hood exhaust.



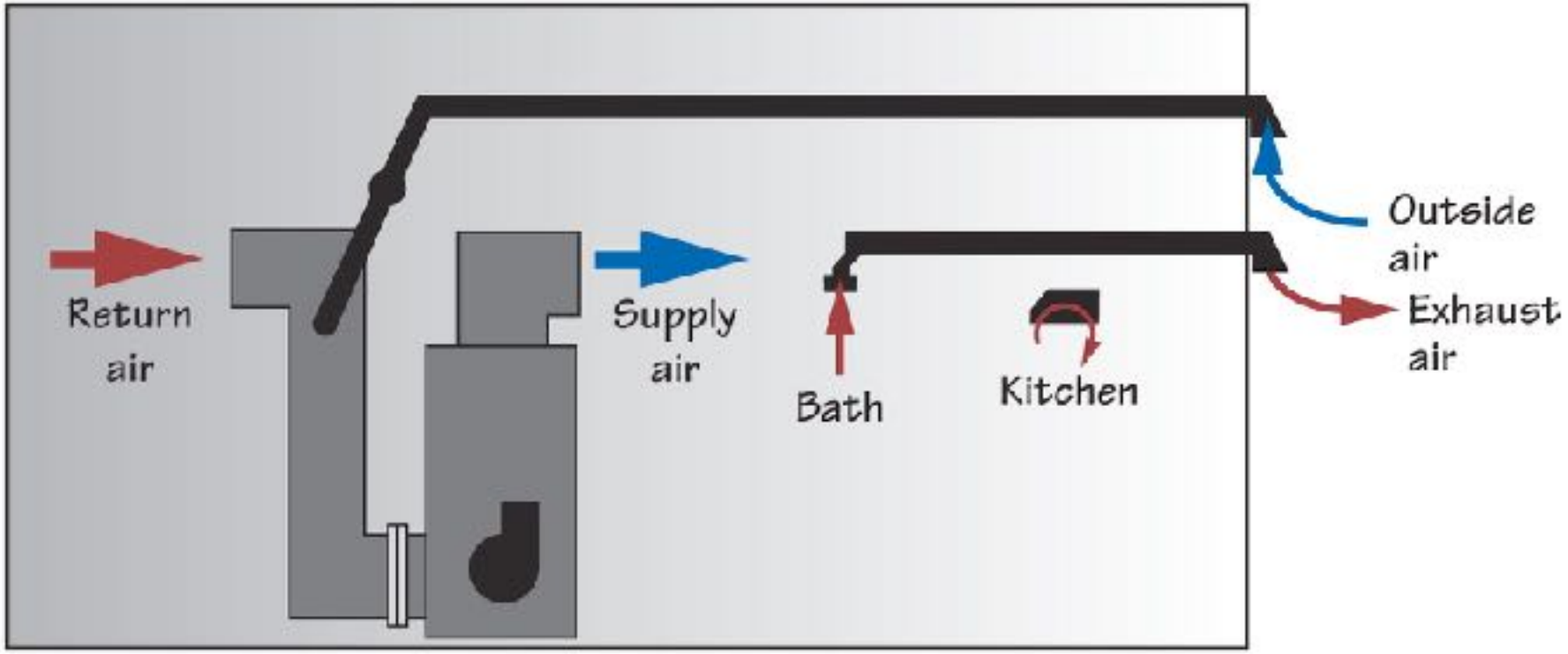


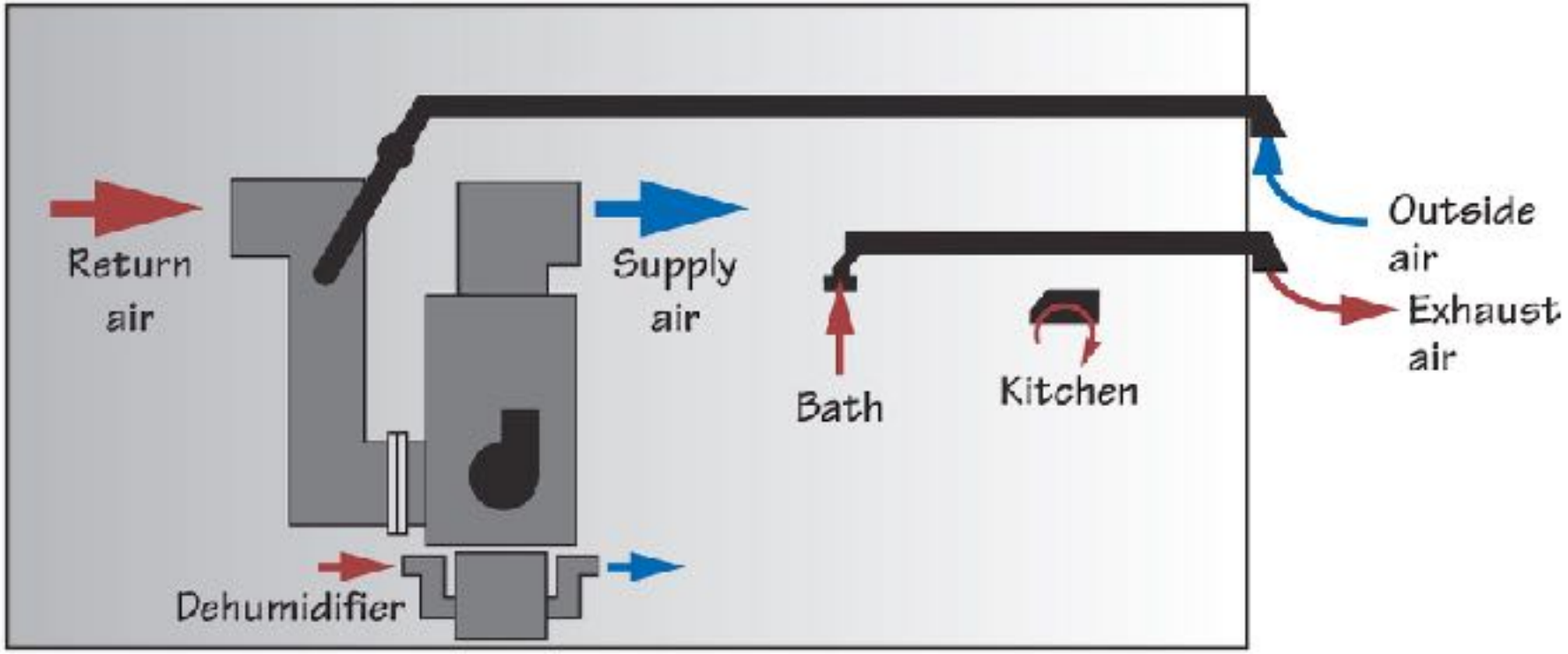

Move cabinets
farther apart
Hood wider than cook top
and extended outboard past
head space
Move hood
up to provide
headroom
Interlocked
make-up air

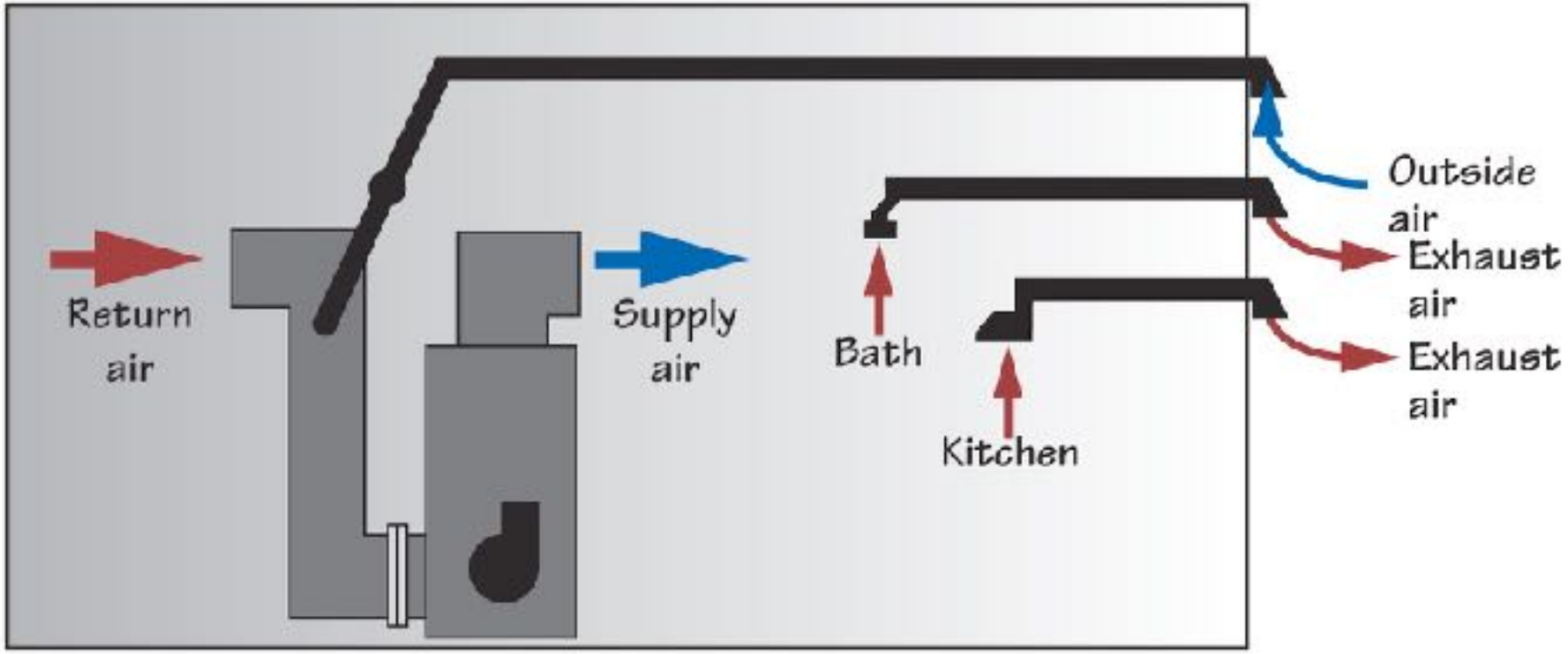
Clothes Dryers

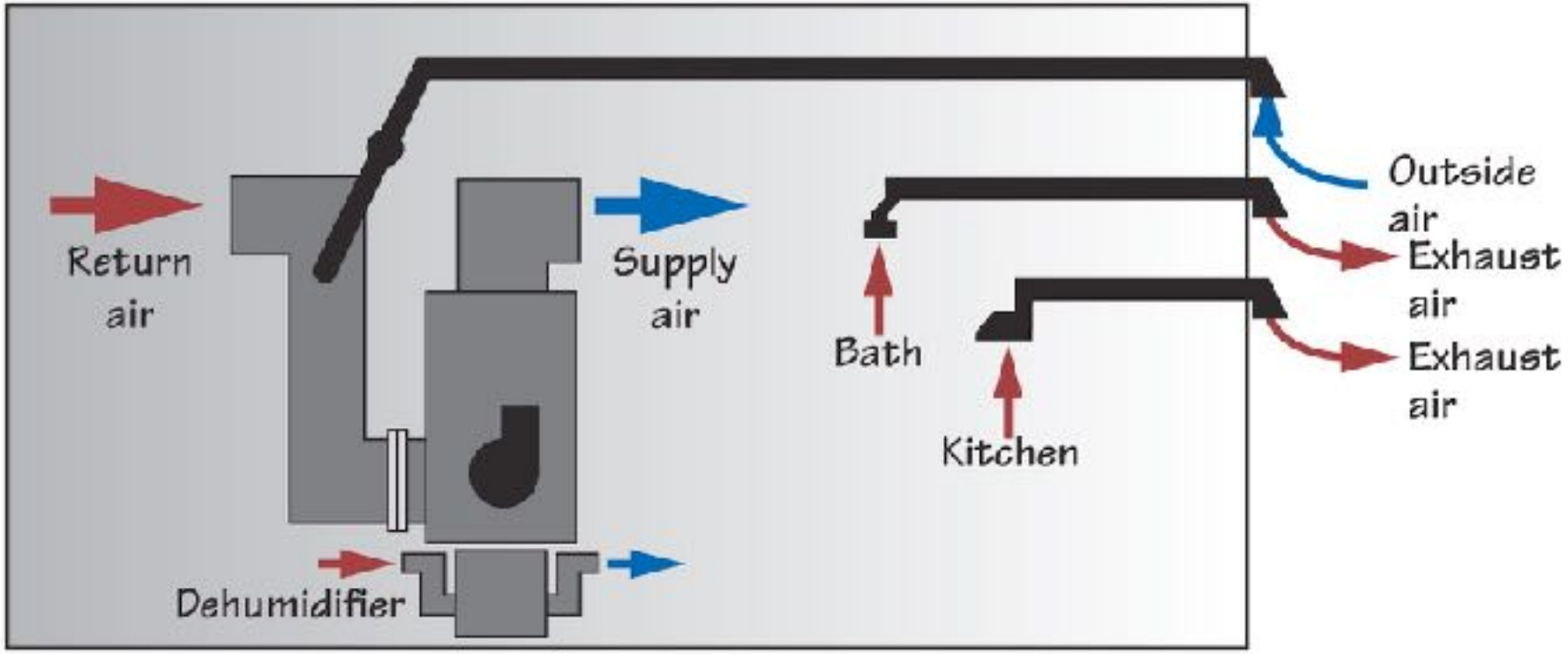
Fireplaces

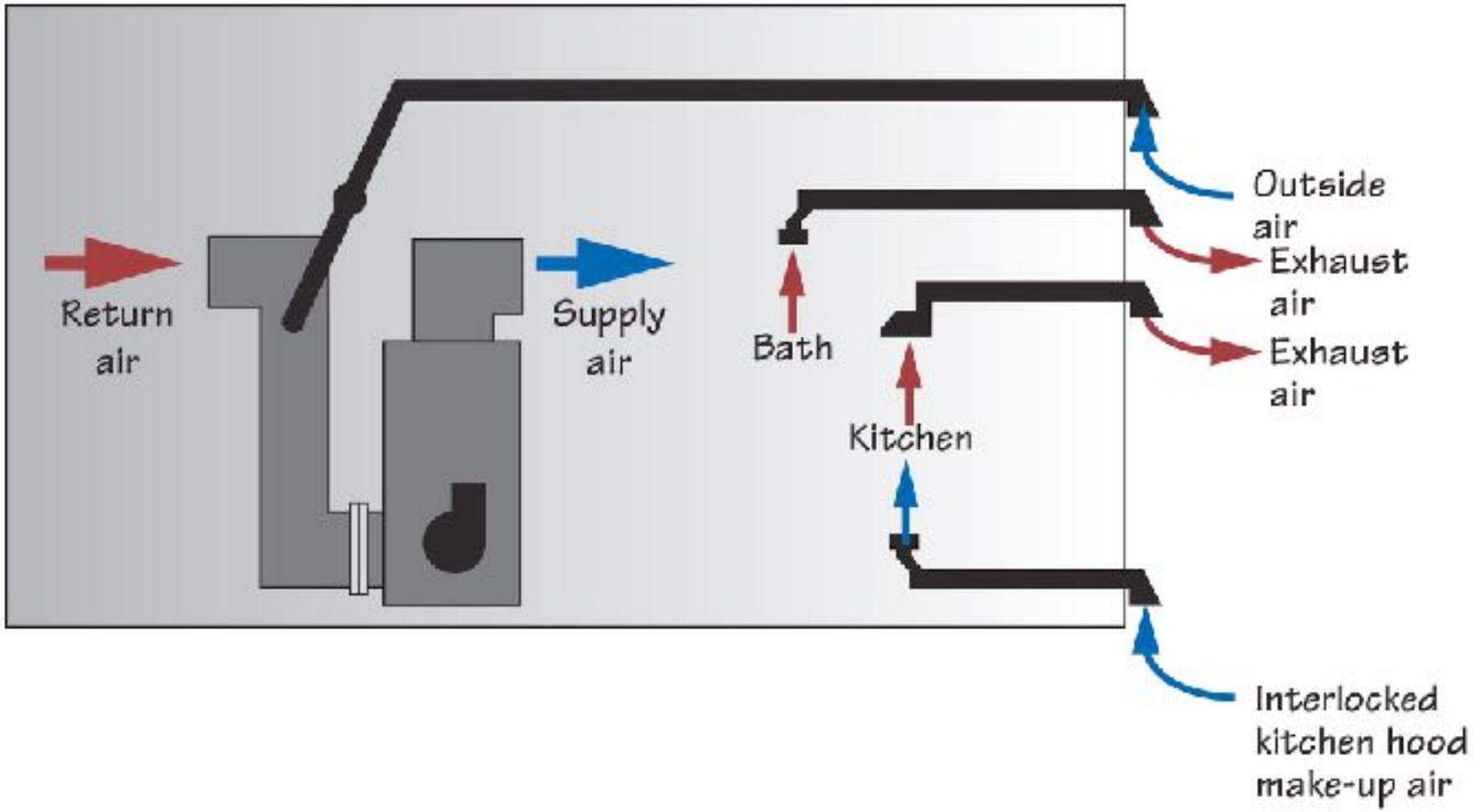
Approaches

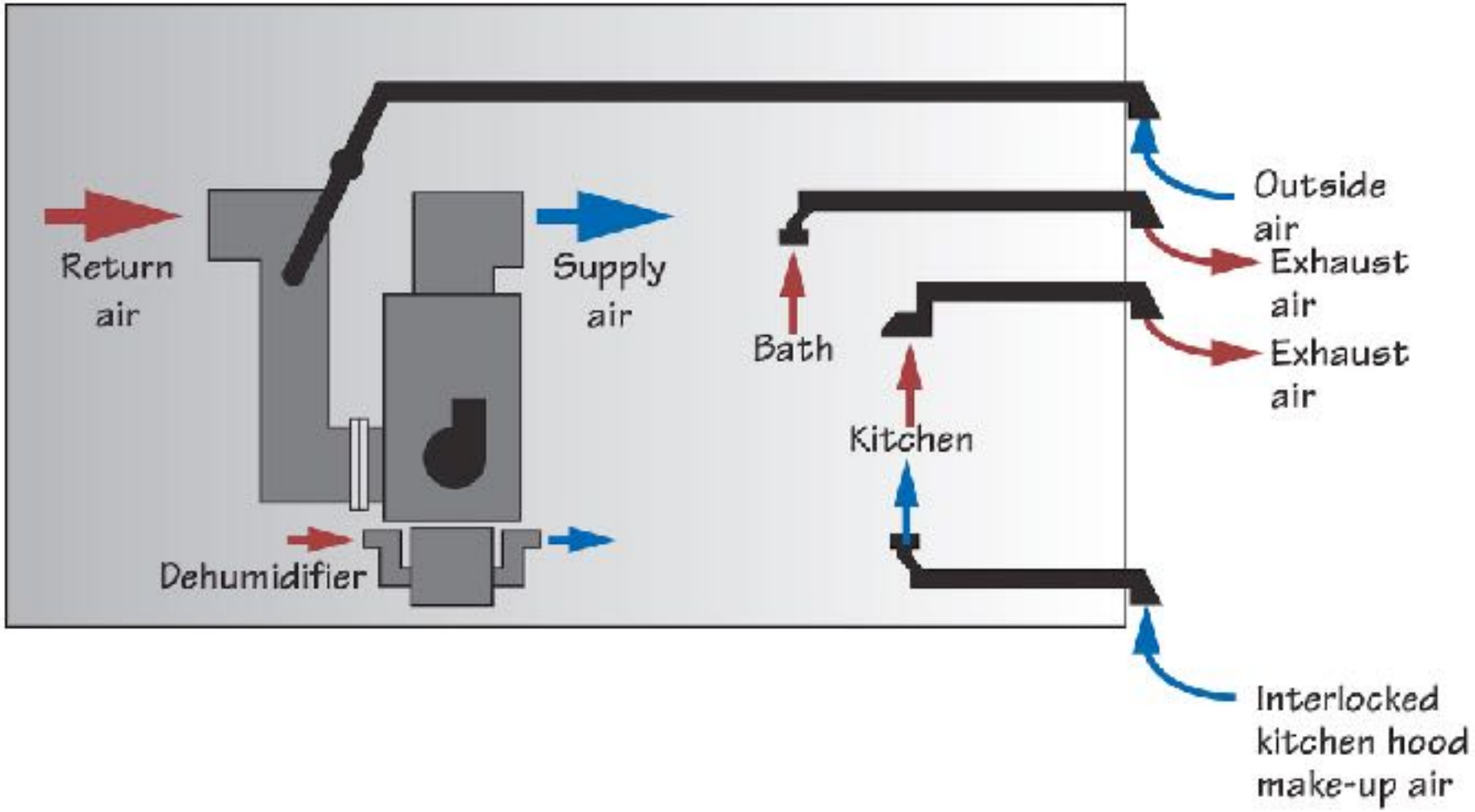

Return
air
Supply
air
Bath
Kitchen
Outside
air
Exhaust
air

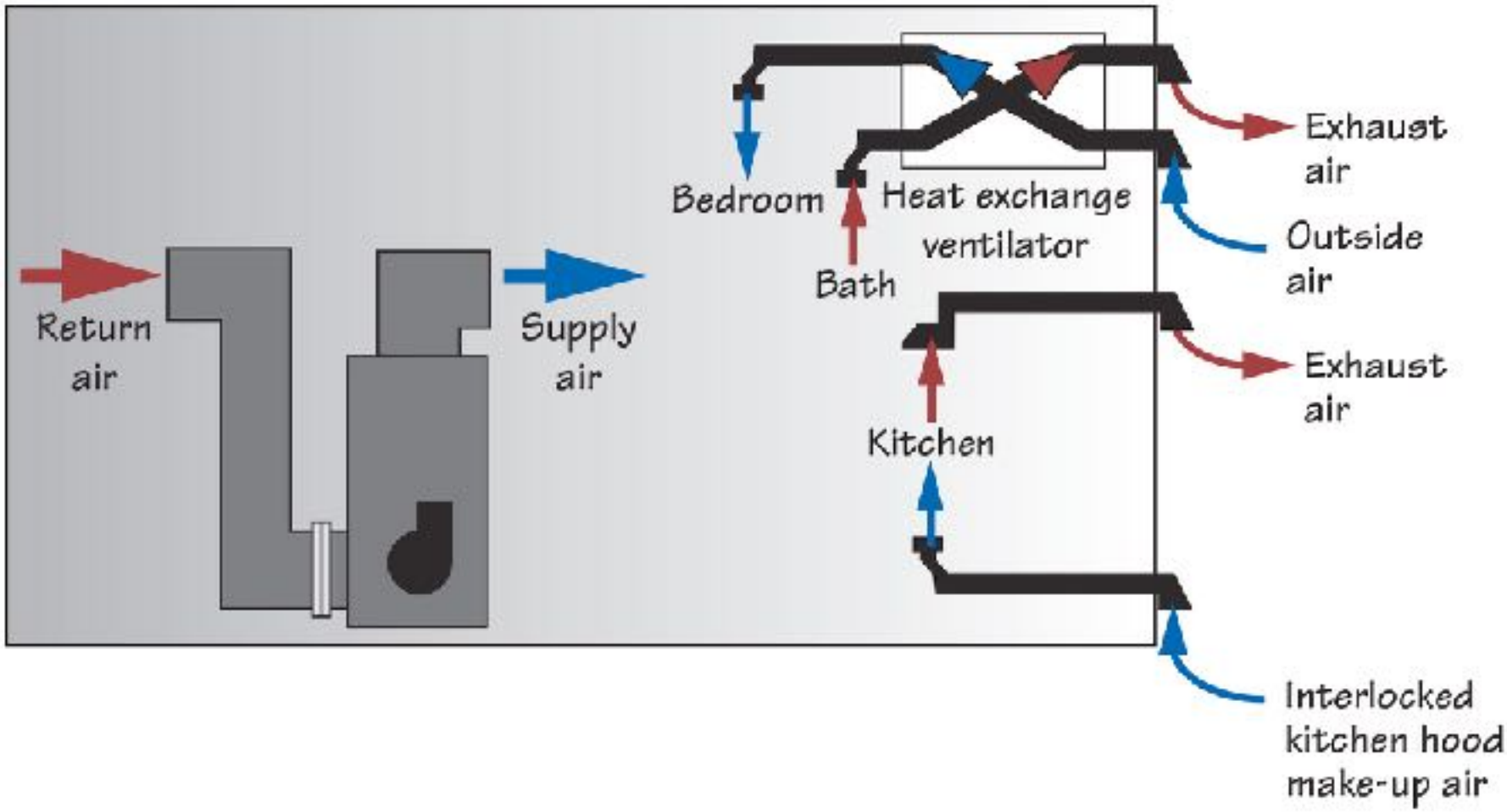

Return air
Supply air
Outside air
Exhaust air
Bath
Kitchen
Dehumidifier

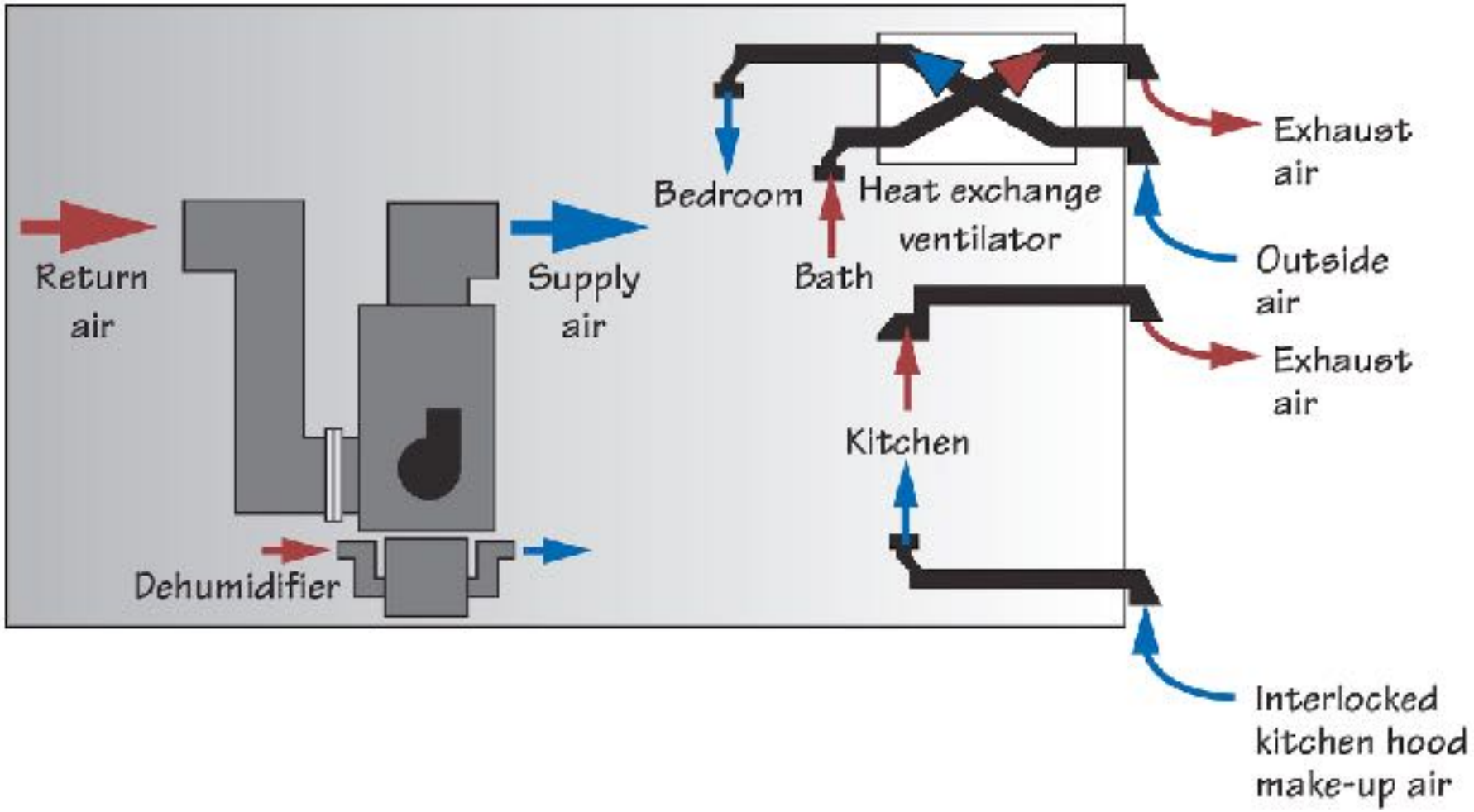

Return air
Supply air
Bath
Kitchen
Outside air
Exhaust air
Exhaust air

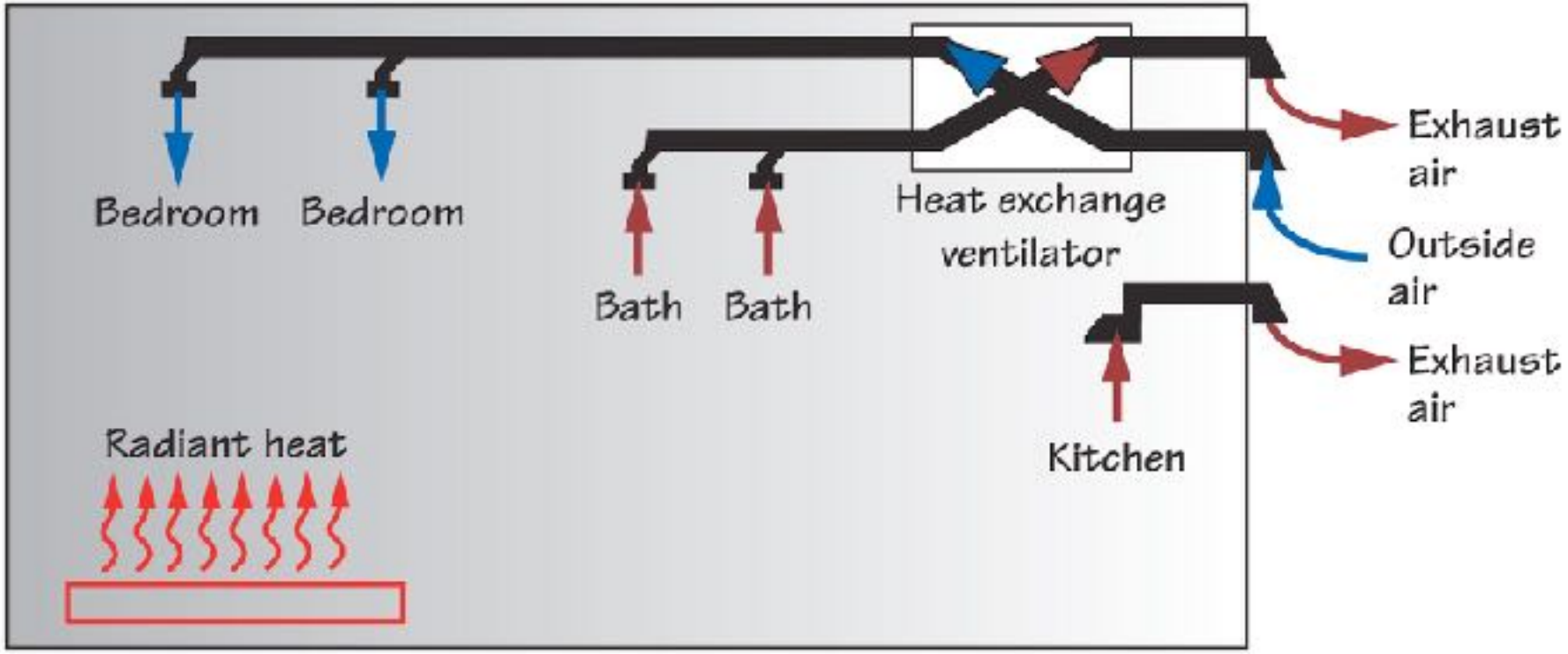

Return air
Supply air
Outside air
Exhaust air
Exhaust air
Bath
Kitchen
Dehumidifier

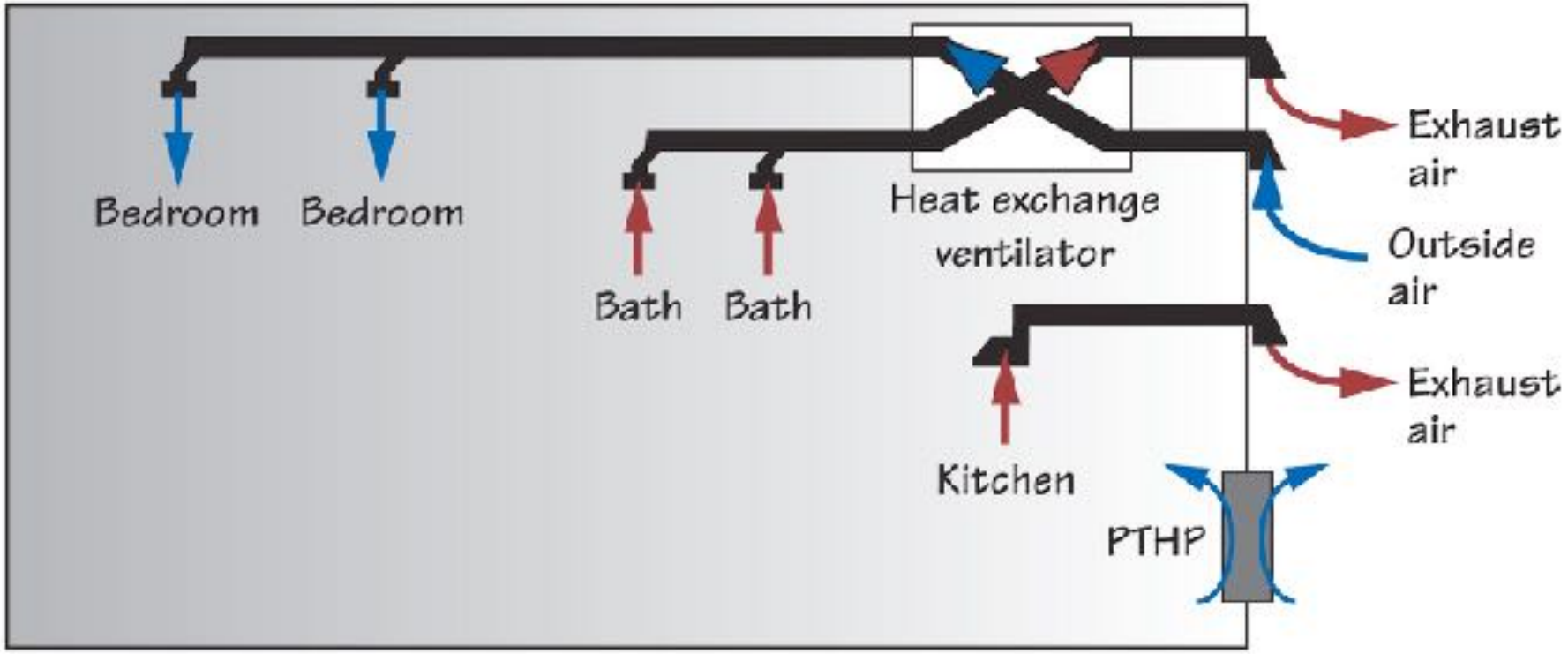

Return air
Supply air
Bath
Kitchen
Outside air
Exhaust air
Exhaust air
Interlocked kitchen hood make-up air

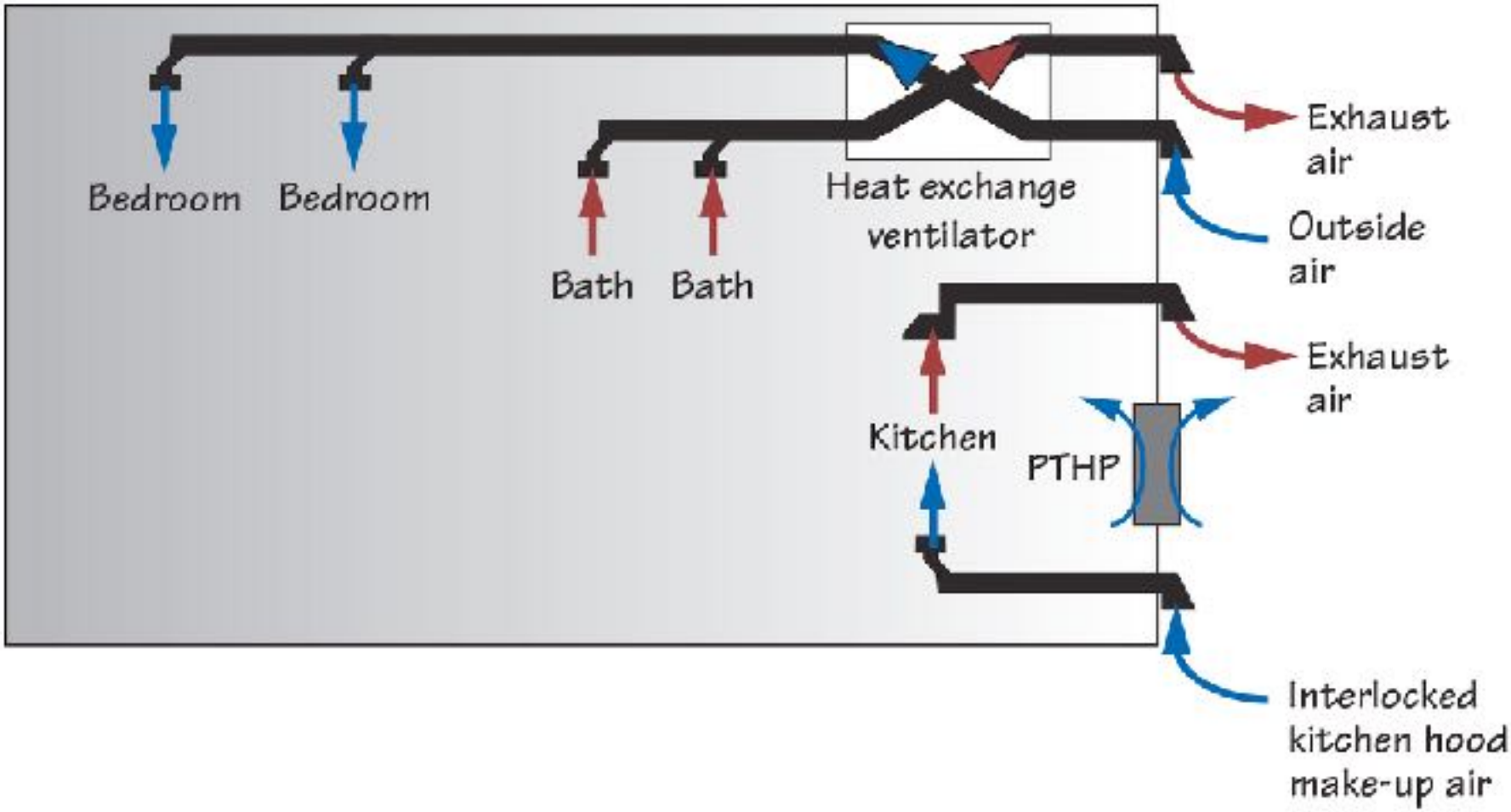

Return air
Supply air
Dehumidifier
Bath
Kitchen
Outside air
Exhaust air
Exhaust air
Interlocked kitchen hood make-up air

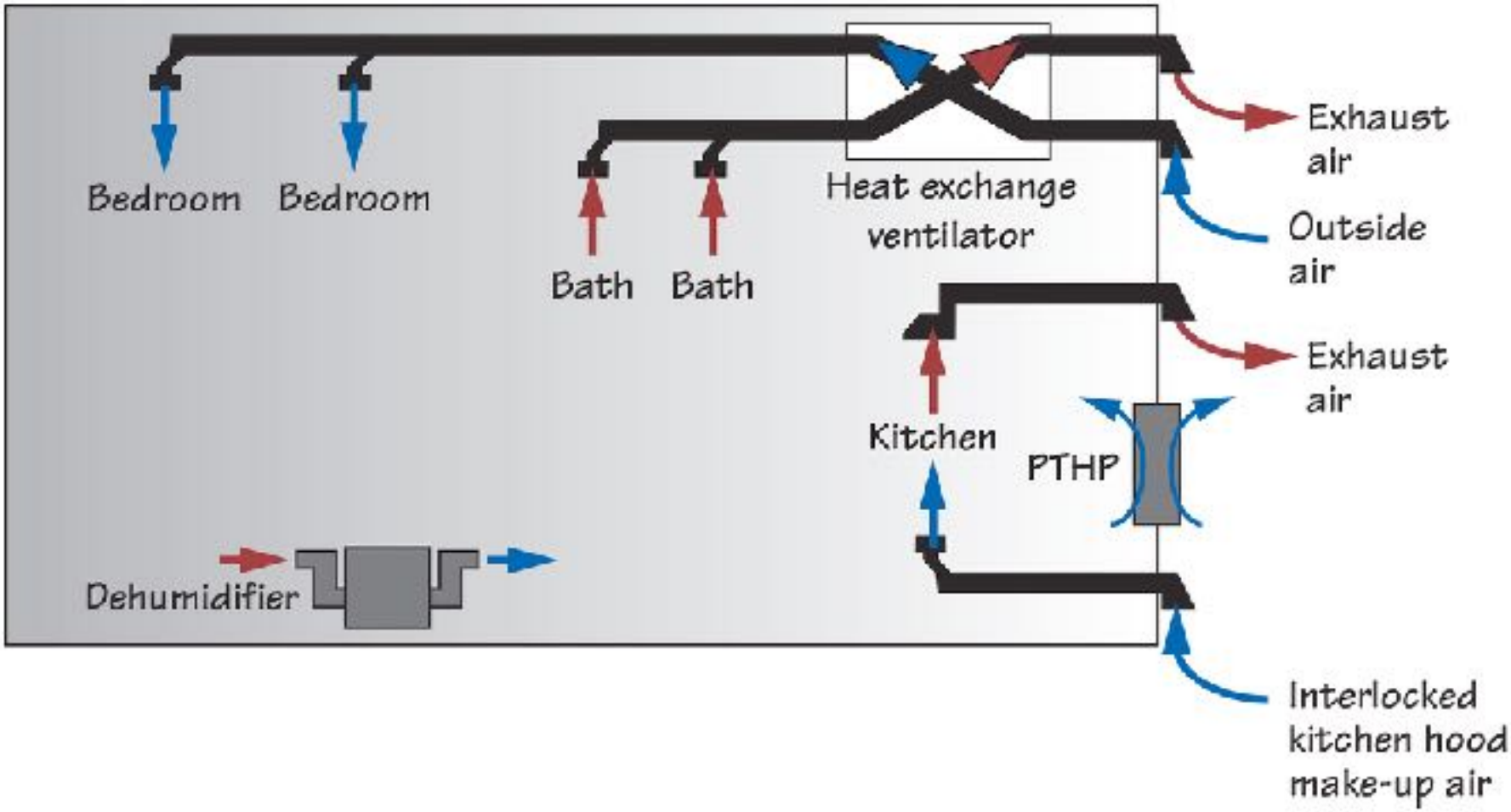

Return air
Supply air
Bedroom
Bath
Heat exchange ventilator
Exhaust air
Outside air
Exhaust air
Kitchen
Interlocked kitchen hood make-up air


Return air
Supply air
Dehumidifier
Bedroom
Bath
Heat exchange ventilator
Exhaust air
Outside air
Exhaust air
Kitchen
Interlocked kitchen hood make-up air


Bedroom
Bedroom
Bath
Bath
Heat exchange ventilator
Exhaust air
Outside air
Exhaust air
Kitchen
Radiant heat


Bedroom
Bedroom
Bath
Bath
Heat exchange ventilator
Exhaust air
Outside air
Exhaust air
Kitchen
PTHP


Bedroom
Bedroom
Bath
Bath
Heat exchange ventilator
Exhaust air
Outside air
Exhaust air
Kitchen
PTHP
Interlocked kitchen hood make-up air


Bedroom
Bedroom
Bath
Bath
Heat exchange ventilator
Exhaust air
Outside air
Exhaust air
Kitchen
PTHP
Dehumidifier
Interlocked kitchen hood make-up air