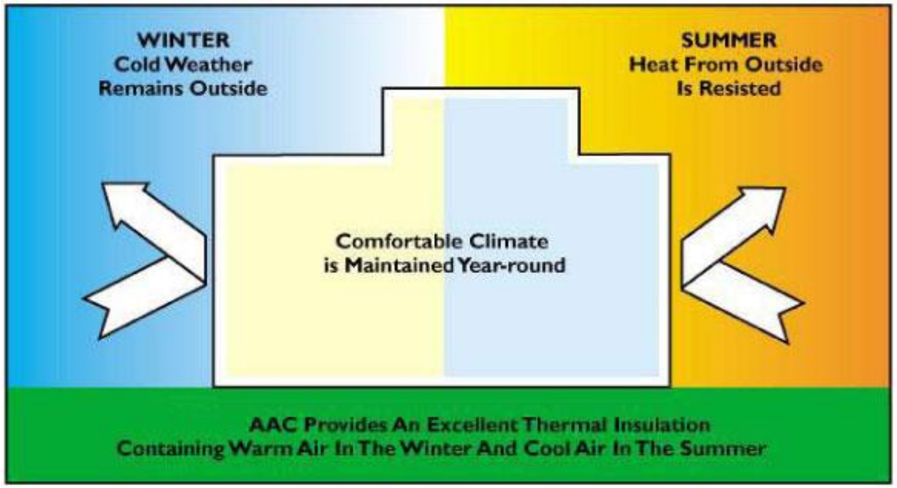
MECH 1905 Buildings for Contemporary Living

Heat Transfer in Buildings

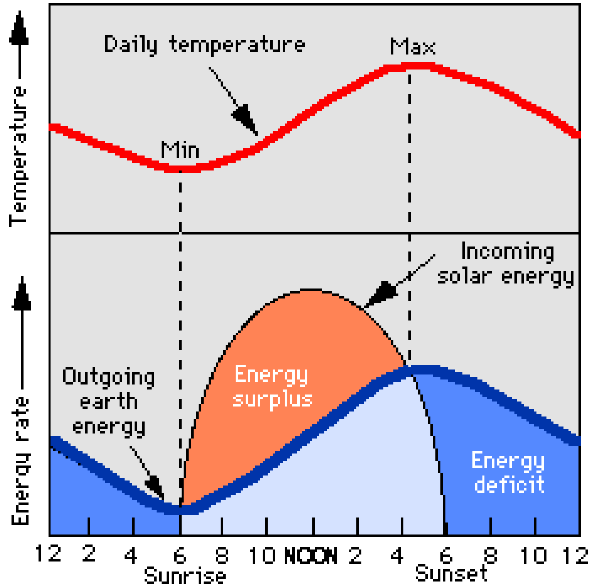
Prof. Yi-Kuen Lee
Department of Mechanical and Aerospace Engineering
Hong Kong University of Science and Technology

Contents

- Introduction
- Modes of Heat Transfer
  - Conduction
  - Convection
  - Radiation
  - Phase Change
- Passive House
- Passive Cooling and Heating



Diurnal Temperature Variation



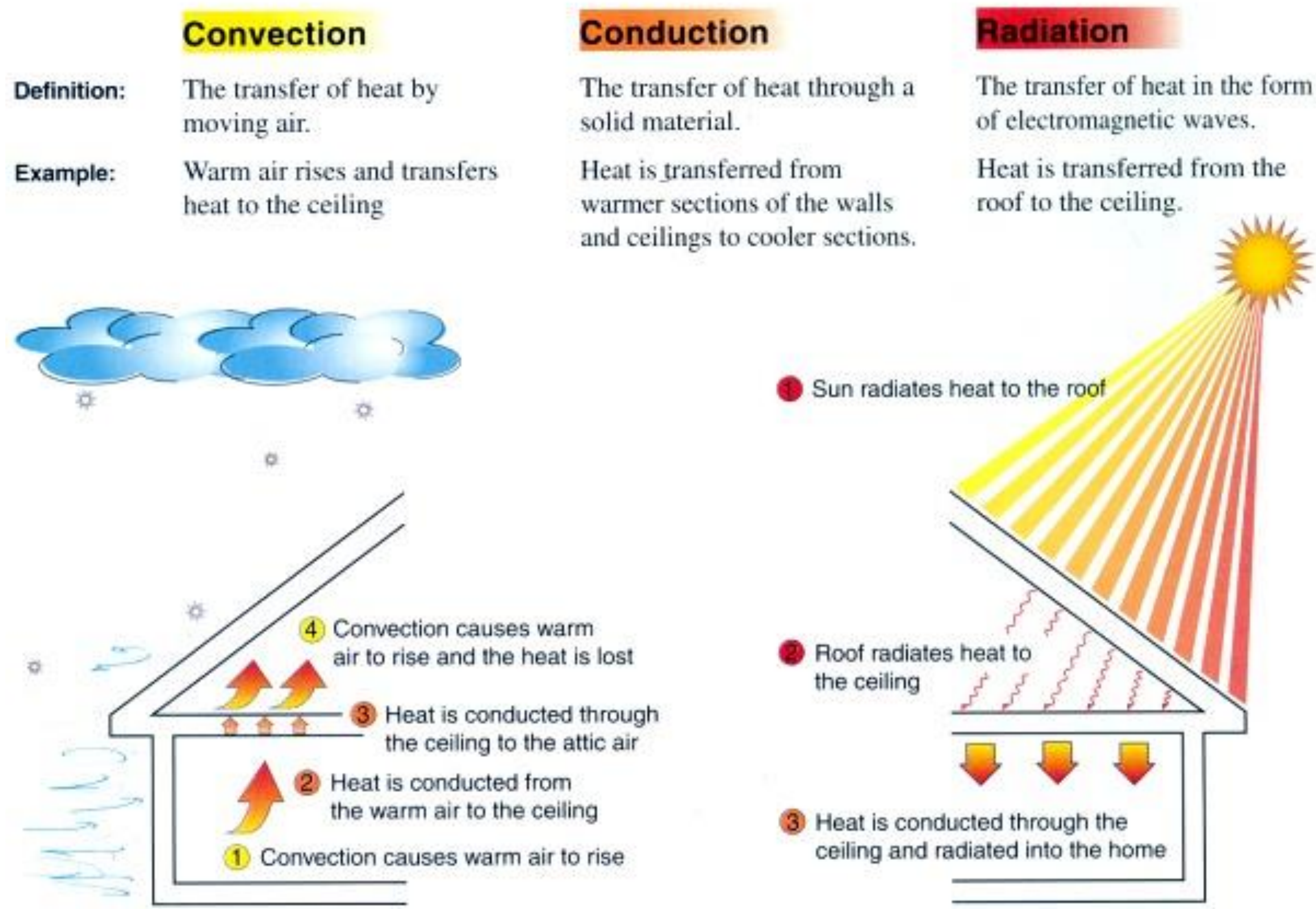
- Incoming solar energy is a maximum when the sun is highest in the sky. But the surface of the earth warms continuously from the time the sun rises to the time it sets.

- Therefore, the earth radiates its maximum amount at sunset, and does not begin to slow down until the sun sets (no more incoming radiation).
- The earth is releasing the least amount of energy early in the morning, before the sun rises.
- The earth emits and absorbs radiation much more efficiently than the atmosphere.
- The late afternoon is often much warmer than at noon, and the early morning is the coolest time of day.
- The atmosphere warms and cools slowly, but the ground warms and cools much more quickly.

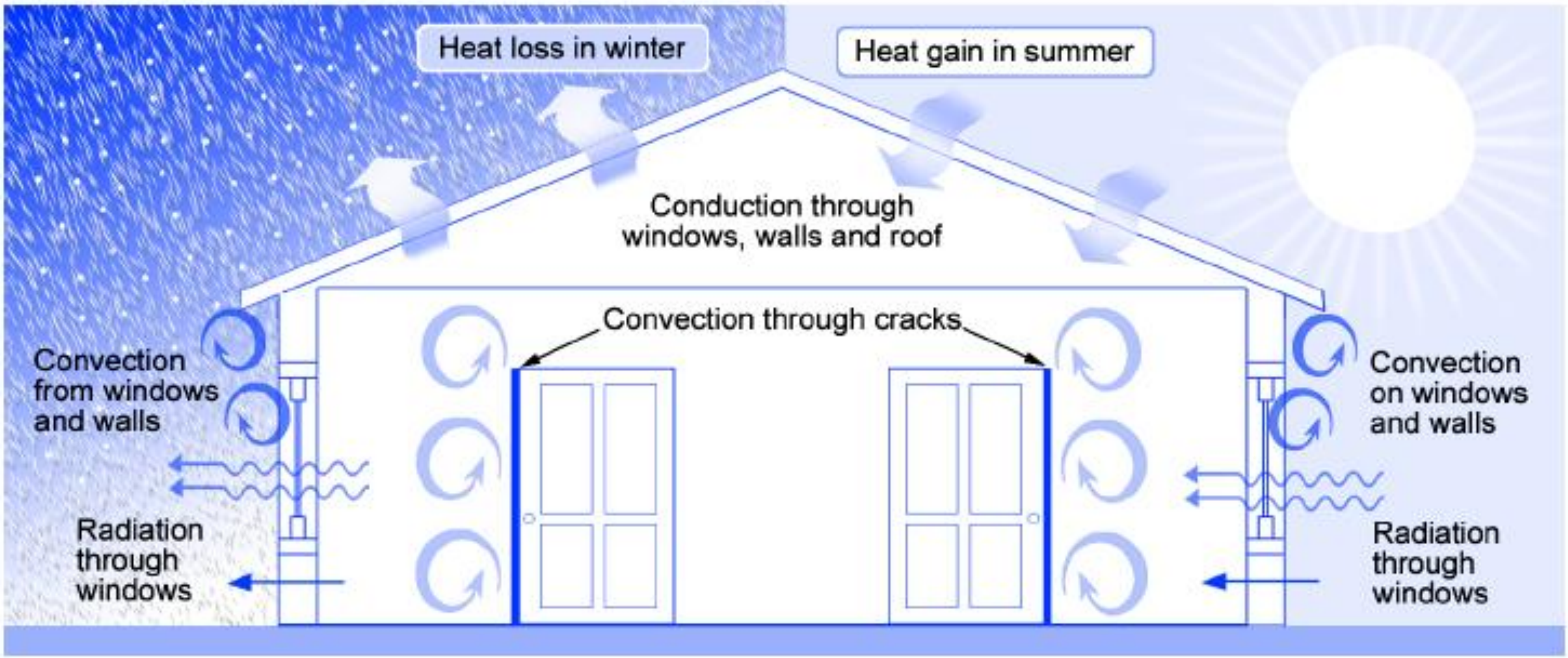
Modes of Heat Transfer

- Conduction – with direct contact
- Convection
  - natural (free) convection : fluid motion induced by the change of density caused by the temperature difference
  - forced convection : fluid motion caused by an external input of work (i.e. by means of a pump, fan, propulsive motion of an aircraft)
  - mixed natural and forced convection
- Radiation – without media contact
- Mixed (combination of any modes mentioned above)
- Phase change
  - boiling : change from liquid to gas
  - condensation : change from gas to liquid
  - freezing : change from liquid to solid
  - defrost : change from solid to liquid
  - sublimation : change from solid to gas
  - deposition : change from gas to solid

Buildings Gain or Loss Heat in All 3 Modes of Heat Transfer

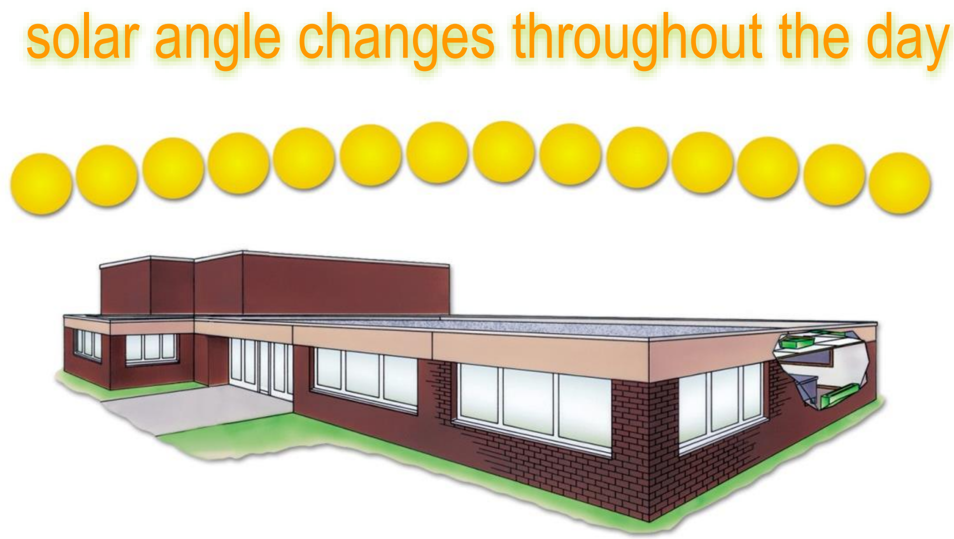


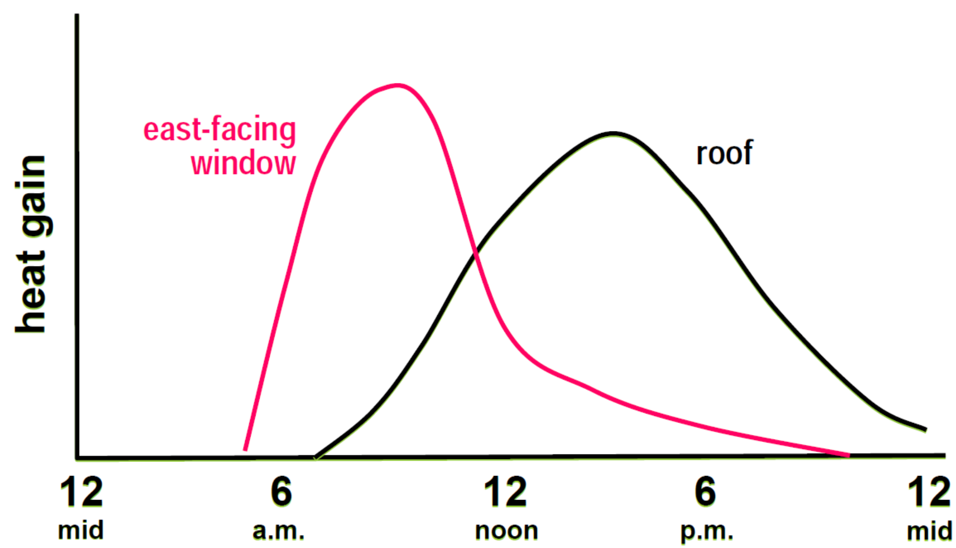
Heat Transfer Processes in Buildings



Solar Heat Gain Factors

- Direction that the window faces
- Time of day
- Month
- Latitude
- Construction of interior partition walls
- Type of floor covering
- Existence of internal shading devices





Heat Conduction

Conduction is the transfer of heat through materials without net mass motion of the materials. The rate equation which describes this mechanism is : (Newton's Law of Cooling)

$$q = -kA \, \frac{T_2 - T_1}{d}$$

where

q = rate of heat flow in the n direction by conduction

k = thermal conductivity

A = area normal to n direction through which heat flows

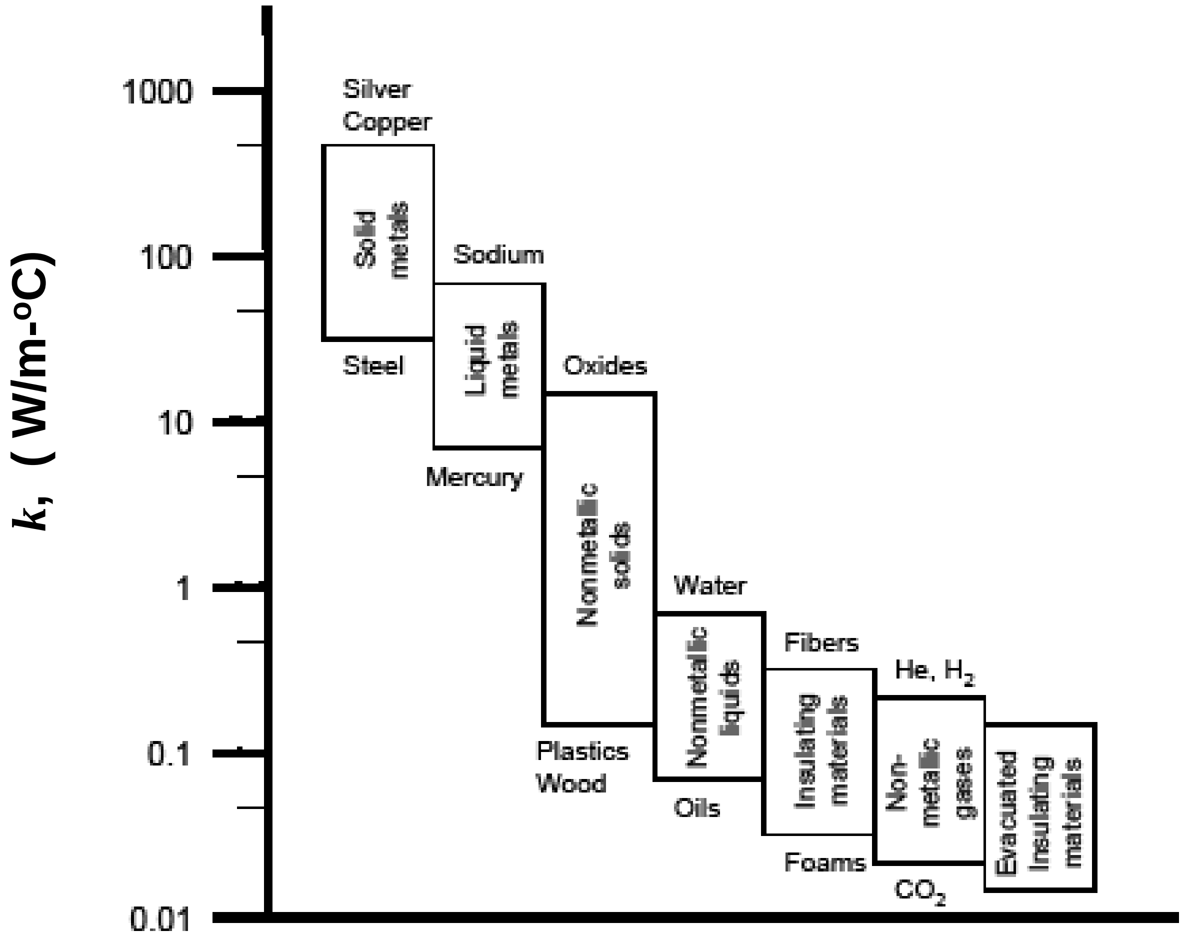
$T_2 - T_1$ = temperature difference

d = length variable

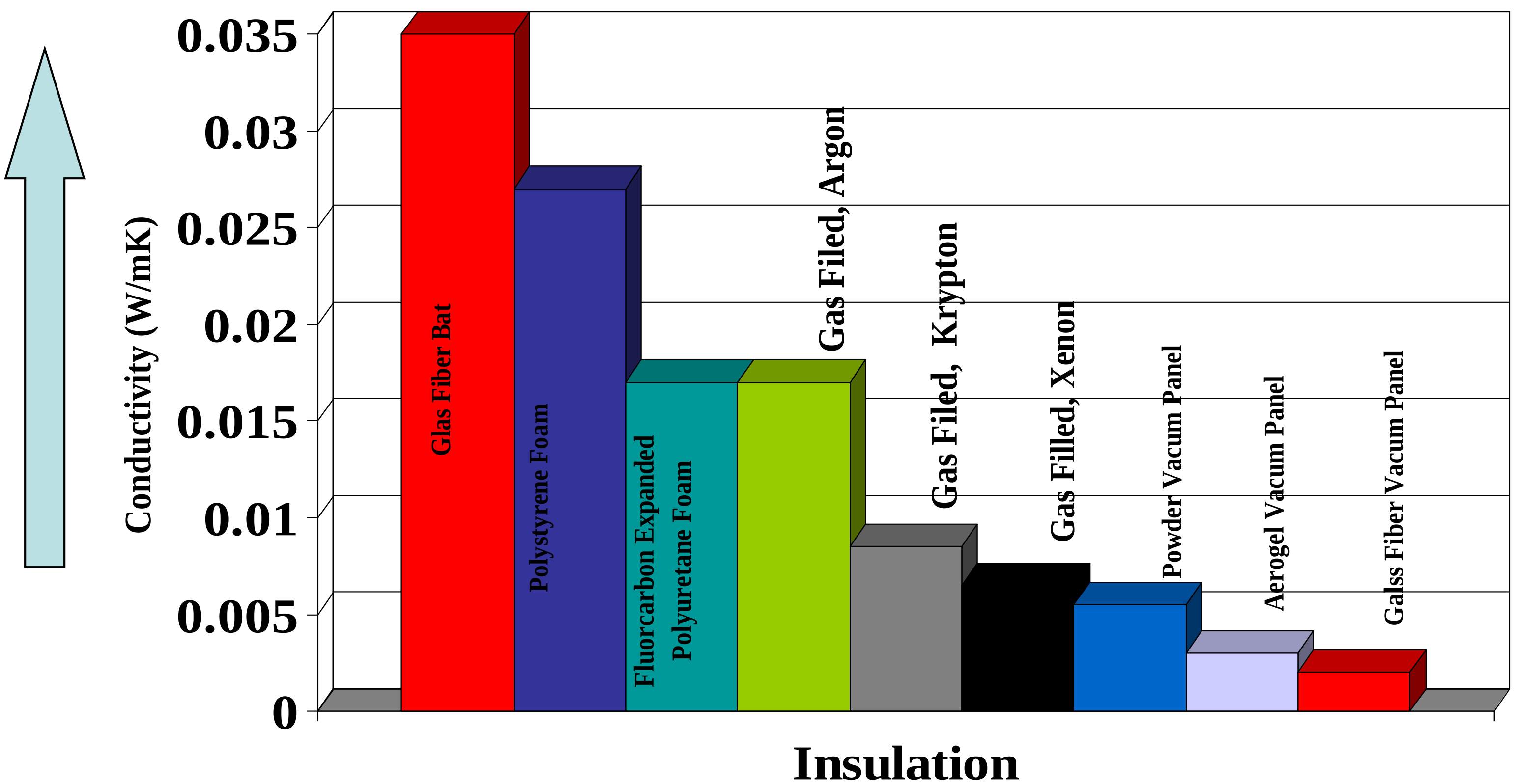
notice that the minus sign denotes the flow of heat is from high temperature to low temperature

U value = thermal transmittance = 1/ R value = k / thickness

Typical Range of Thermal Conductivity of Various Materials

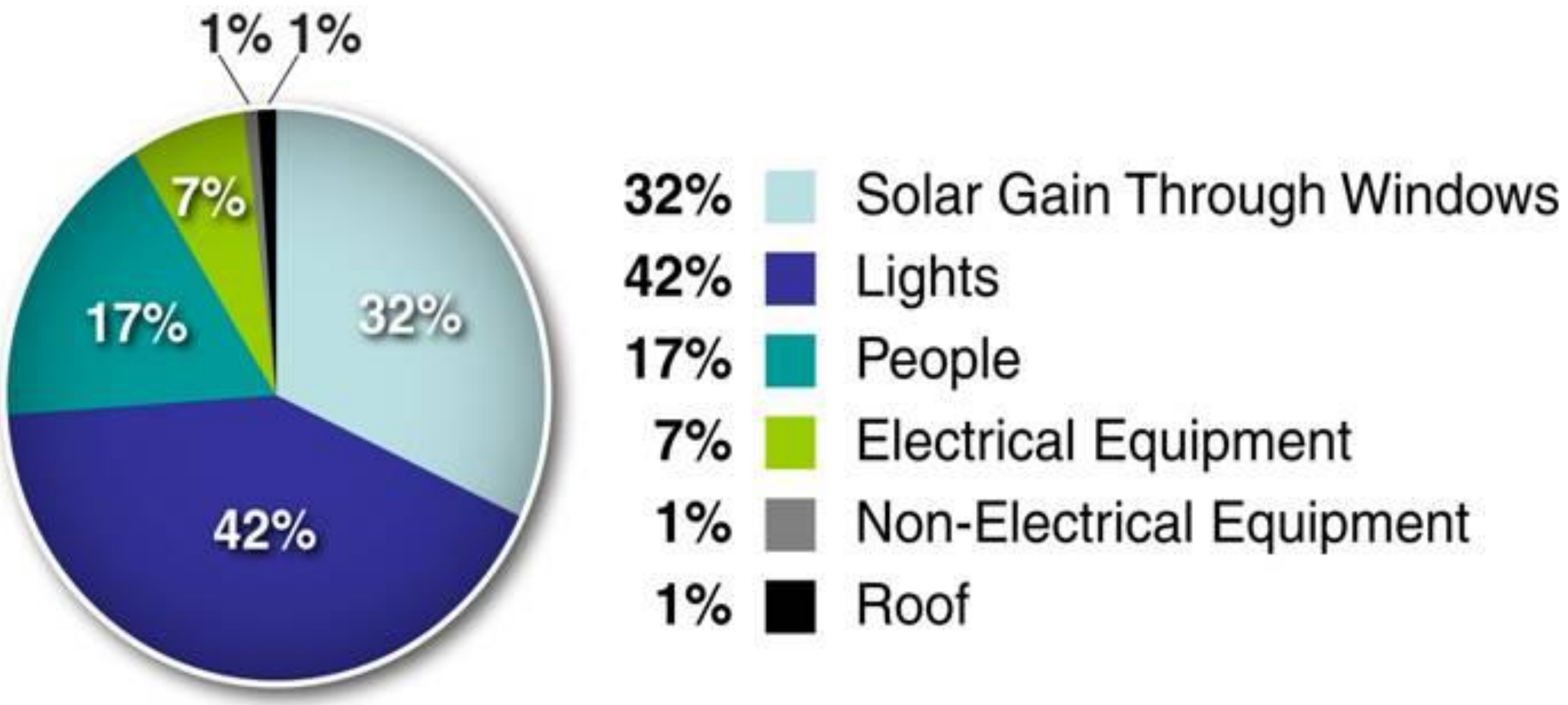


Insulation Performance

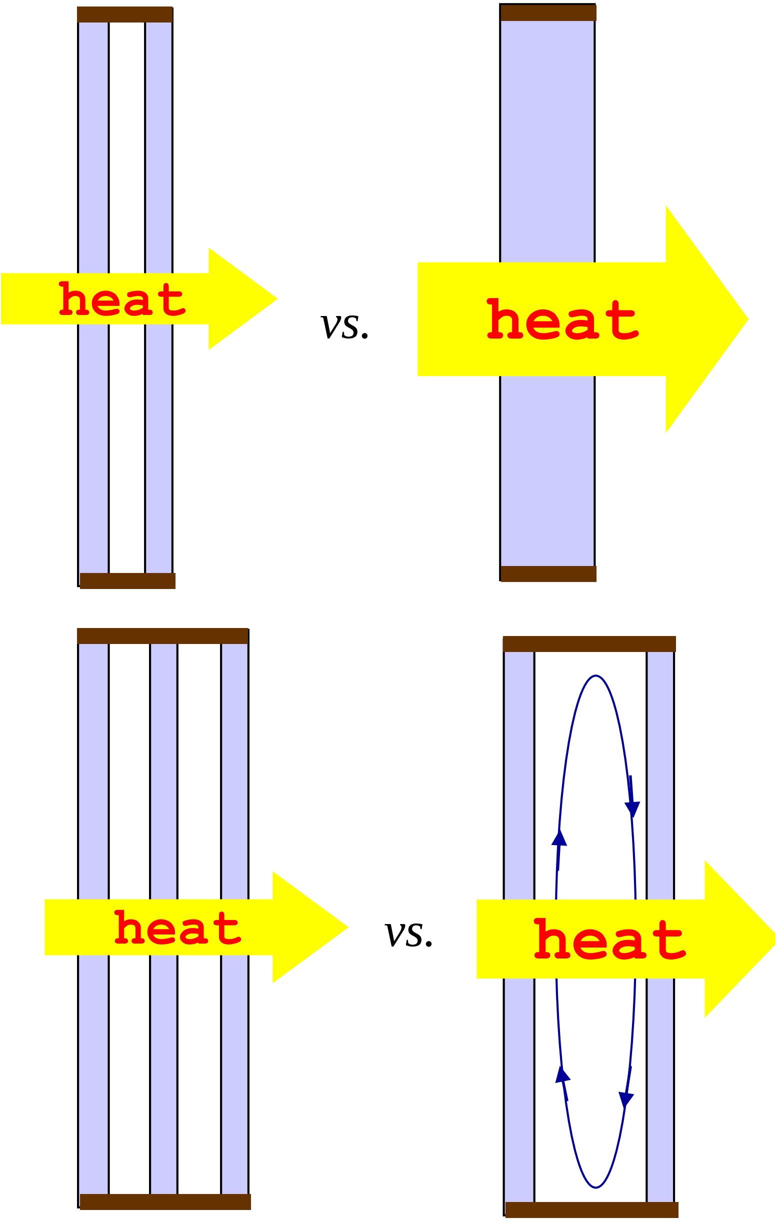


Conventional | **Advanced**

Window Systems Impact Building Efficiency



Thermopane Windows/Double-Pane Window

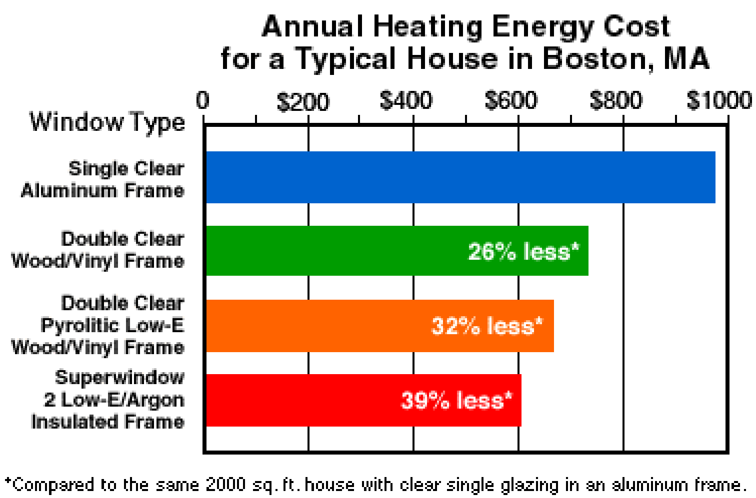


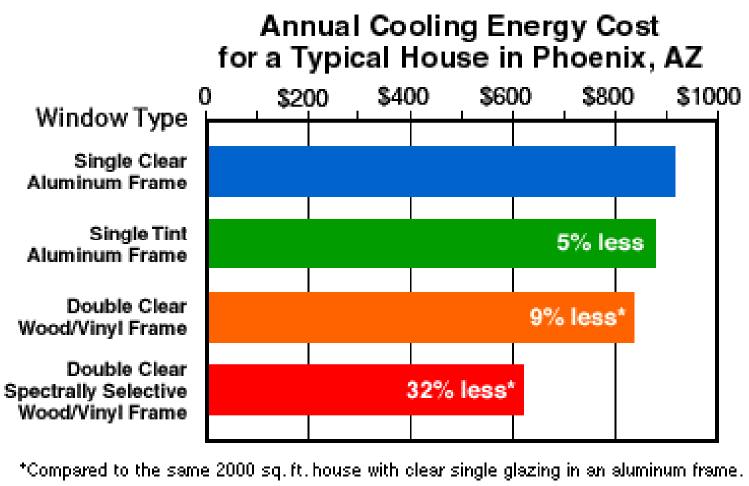
There is more glass in the single pane window to block the heat, but the air in between the panes of the double pane window has thermal conductivity that is about 35 times lower than that of the glass itself. So more heat would be transferred through the single pane.

The double pane window has more air between the outer panes, so its thermal conductivity is lower. However, air is a mobile medium, and convection currents can shuttle warm air from the warm side to the cold side. On the warm side the air rises, moves across the the cold side, and sinks, moving in a loop and carrying its energy from the warm side to the cold side. The middle pane in the triple pane window reduces the energy transfers due to convection and is the better window (but probably more expensive).

Energy Efficient Windows

* Can decrease heating costs by 40%
* Can decrease cooling costs by 32%





Convection

Convection is the name given to the process of which thermal energy is transferred between a solid and a fluid flowing past it.

$$q_c = hA(T_w - T_\infty)$$

where q_c = rate of heat flow by convection

h = heat transfer coefficient

$T_w - T_\infty$ = temperature potential for heat flow away from surface

A = surface area through which heat flows

The heat transfer coefficient h is dependent on the shape of the solid, fluid flows, temperature difference $(T_w - T_\infty)$, etc. where T_w is the temperature of heated wall and T_∞ is the temperature chosen at a far away distance that it is relatively constant.

Convective Heat Transfer

- To establish the physical and mathematical basis for the understanding of convective transport and to reveal various heat transfer correlations
- For engineering applications, this study enables to <u>predict pressure drop or drag force </u>inflow inside ducts or over bodies (fluid mechanics)
- Complicated analysis, as the fluid motion affects the pressure drop, the drag force and the heat transfer.
  - To determine the drag force or the pressure drop, the velocity field in the immediate vicinity of the surface must be known.
  - To determine the heat transfer by convection, the velocity distribution in the flow also is needed, because the velocity enters the energy equation; the solution of the energy equation yields the temperature distribution in the flow field.

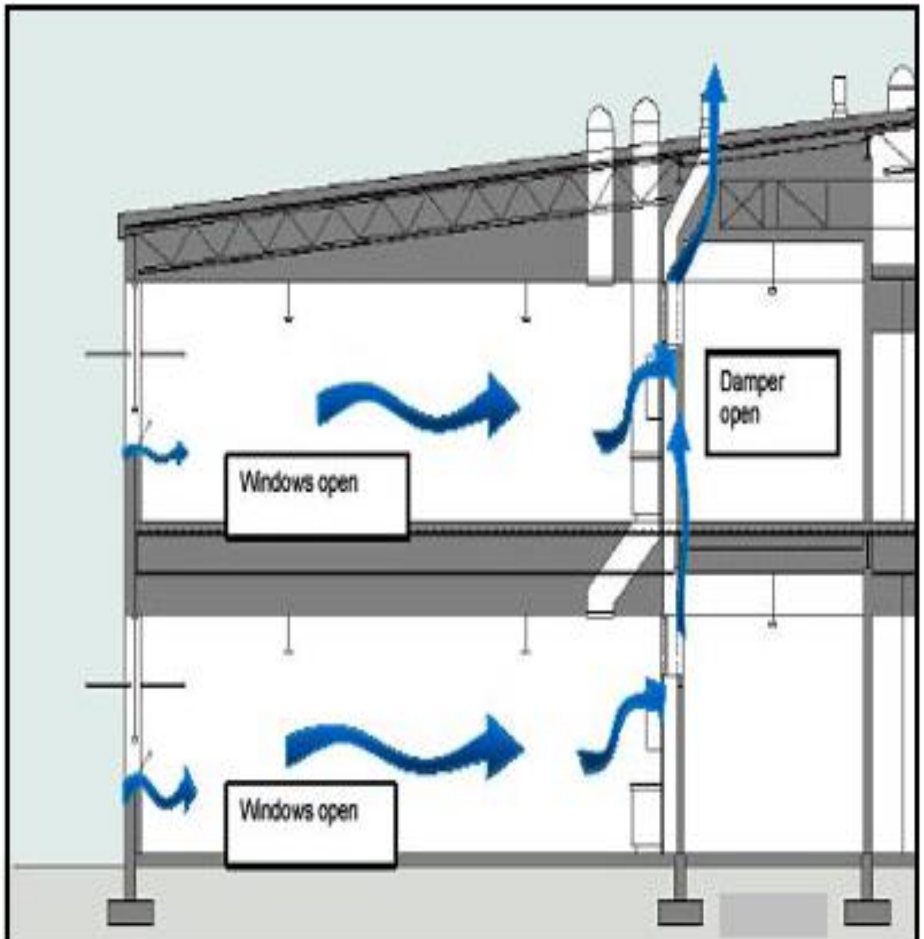
Typical Values of the Convective Heat Transfer Coefficient *h* (1)

Type of Flow	***h*, W/m^2 · ^{o}C**
Free Convection, ΔT = 25 ^{o}C	
• 0.25 m vertical plate in : Atmospheric air Engine oil Water	 5 37 440
• 0.02 m OD horizontal cylinder in : Atmospheric air Engine oil Water	 8 62 741
• 0.02 m diameter sphere in : Atmospheric air Engine oil Water	 9 60 606

Typical Values of the Convective Heat Transfer Coefficient *h* (2)

Type of Flow	h, $W/m^2 \cdot {}^oC$
Forced Convection	
• Atmospheric air at 25 ^oC with U_∞ = 10 m/s over a flat plate : L = 0.1 m L = 0.5 m	 39 17
• Flow at 5 m/s across 1 cm OD cylinder of : Atmospheric air Engine oil	 85 1,800
• Water at 1 kg/s inside 2.5 cm ID tube	10,500
Boiling of Water at 1 atm	
• Pool boiling in a container • Pool boiling at peak heat flux • Film boiling	3,000 35,000 300
Condensation of steam at 1 atm	
• Film condensation on horizontal tubes • Film condensation on vertical surfaces • Dropwise condensation	9,000 - 25,000 4,000 - 11,000 60,000 - 120,000

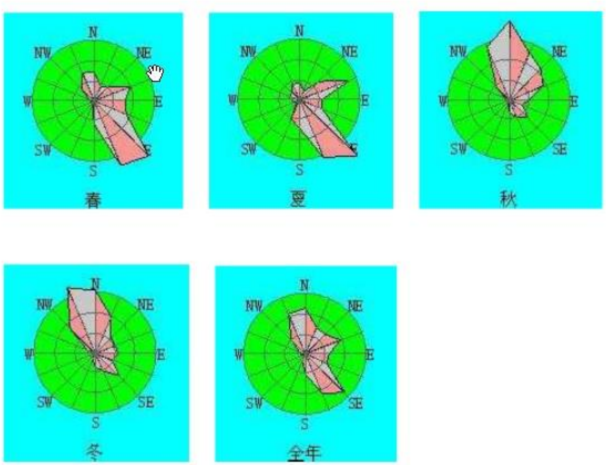
Natural Ventilation



- Operable windows pull fresh air into one side of the classroom, while ventilation stacks pull the air out on the opposite side of the classroom
- At extreme temperatures, automatic backup mechanical ventilation systems used

Temperature diff is the driving force ➔ density diff

Forced Ventilation



- Buildings with windows opening to the direction of predominant wind in the summer could save energy in the cooling load.
- Walls facing the direction of predominant wind in the winter should be blocked to save energy for heating.

Ventilation fans are driving force

Radiation

- All bodies continuously emit energy because of their temperature, and the energy thus emitted is called thermal radiation.
- The radiation energy emitted by a body is transmitted in the space in the form of electromagnetic waves according to Maxwell's classic electromagnetic wave theory, or in the form of discrete photons according to Planck's hypothesis.
- The emission or absorption of radiation energy by a body is a bulk process, it is either absorbed, transmitted, or reflected.
- It is only in a vacuum that radiation propagates with no attenuation.
- Gases such as carbon dioxide, carbon monoxide, water vapor, and ammonia in air absorb thermal radiation over certain wavelength bands, making air semitransparent to thermal radiation.

Radiation Heat Transfer

Radiation heat transfer is the net exchange of thermal energy between two surfaces obeying the laws of electromagnetics.

$$q_r = \sigma\varepsilon A(T_w^4 - T_\infty^4)$$

where q_r = rate of heat flow by radiation

σ = Stefan-Boltzmann constant

$= 5.670\ 400\times10^{-8}\ \mathrm{W\cdot m^{-2}\cdot K^{-4}}$

ε = emissivity of the surface

A = surface area through which heat flows

T_w = absolute surface temperature

T_∞ = absolute ambient temperature

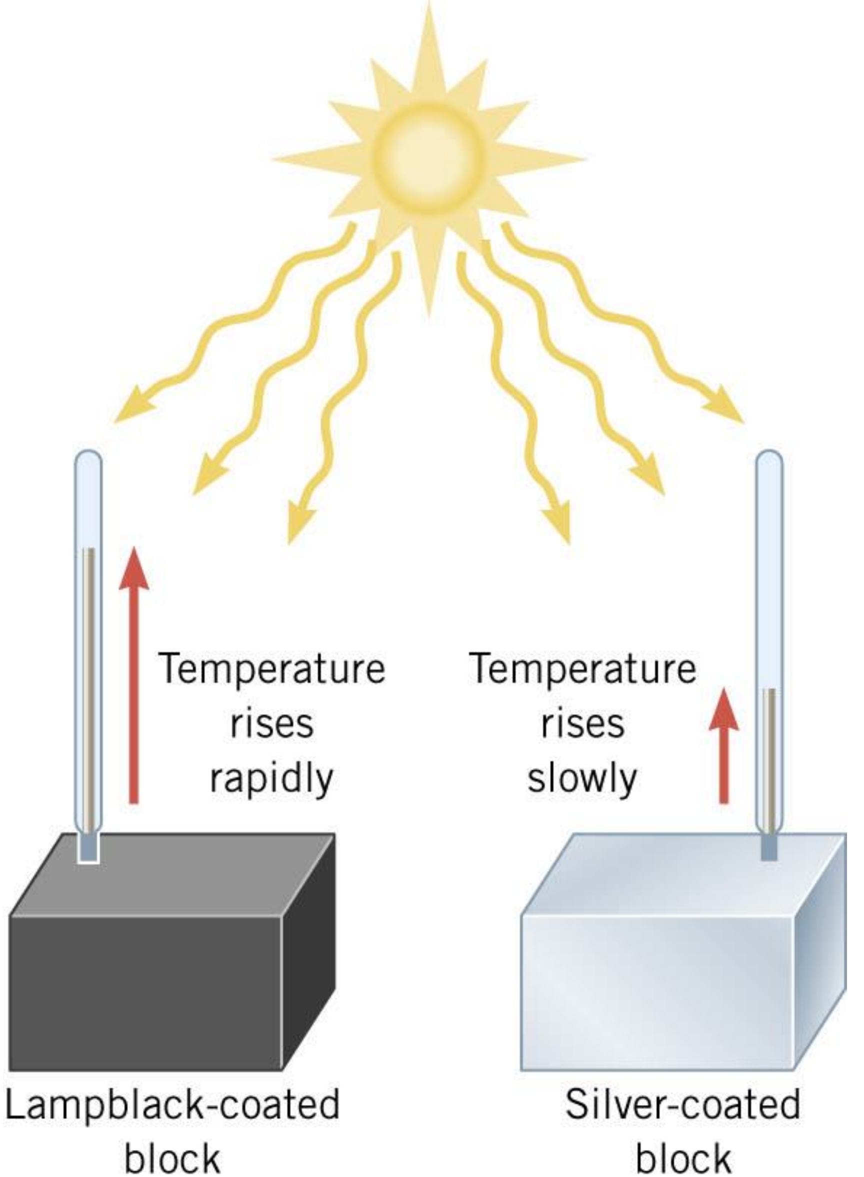
Notice that the temperature are in absolute temperature scale

Radiation Properties of Selected Materials
Normal Emissivity of Surfaces

	Surface	T (^oC)	ε_n
Metal	Aluminum		
	Highly polished, plate	200-600	0.038-0.06
	Bright, foil	21	0.04
	Heavily oxidized	100-500	0.20-0.33
	Zinc		
	Polished	225-325	0.05-0.06
	Oxidized at 400 ^oC	400	0.11
	Galvanized iron, bright	27	0.23
	Galvanized iron, gray	23	0.28
Non-Metal	Brick		
	Magnesite, refractory	1000	0.38
	Red, rough	21	0.93
	Gray, glazed	1100	0.75
	Silica	540	0.80
	Soil	37	0.93-0.96
	Water, deep	0-100	0.96
	Wood	20	0.80-0.90

Radiation Heat Transfer in Buildings

- A reflective roof can reduce solar heat gain through the roof by up to 40%.
- Using light pavement surfaces will lower ambient air temperature around a building, thus reducing the building's cooling load.
- High-performance window glazing often includes a thin film or films to reflect infrared light (heat) either out of a building (in a hot climate) or back into a building (in a cold climate).
- Passive solar design in cold climates usually involves allowing the sun's radiation to enter a building and be absorbed into thermal mass for re-release later.



Heat Transfer with Phase Change

- A substance that has reached the temperature required for a phase change **maintains its temperature** during the phase change.
- All energy lost or gained is used to change the phase of the substance.
- The amount of heat energy per unit mass that must be added or removed from a substance to change phase is the **latent heat**.

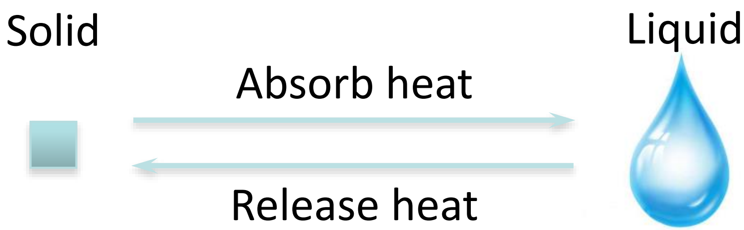
$$\boxed{\mathbf{Q = mL}}$$

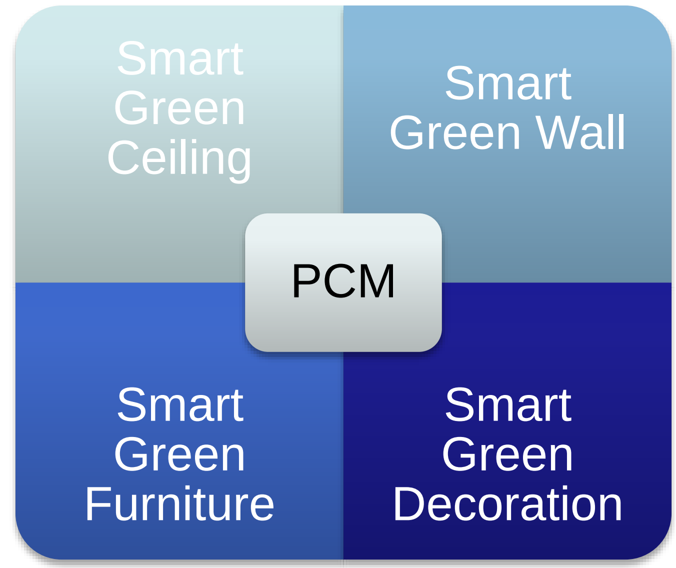
  - Latent heat of fusion ($\mathbf{L_f}$): *solid* ↔ *liquid*
  - Latent heat of vaporization ($\mathbf{L_v}$): *liquid* ↔ *gas*

Classification of Phase Change

- **Freezing** *(Liquid to solid)*
  - A molecule with low kinetic energy loses enough energy through collision to change phase to solid.
- **Melting** *(Solid to liquid)*
  - A molecule with a high average kinetic energy gains enough energy through collisions to escape the solid and change phase to liquid.
- **Evaporation or Boiling** *(Liquid to gas)*
  - A molecule with a high average kinetic energy gains enough energy through collisions to escape the liquid and change phase to gas.
- **Condensation** *(Gas to liquid)*
  - A molecule with low kinetic energy loses enough energy through collision to change phase to liquid.

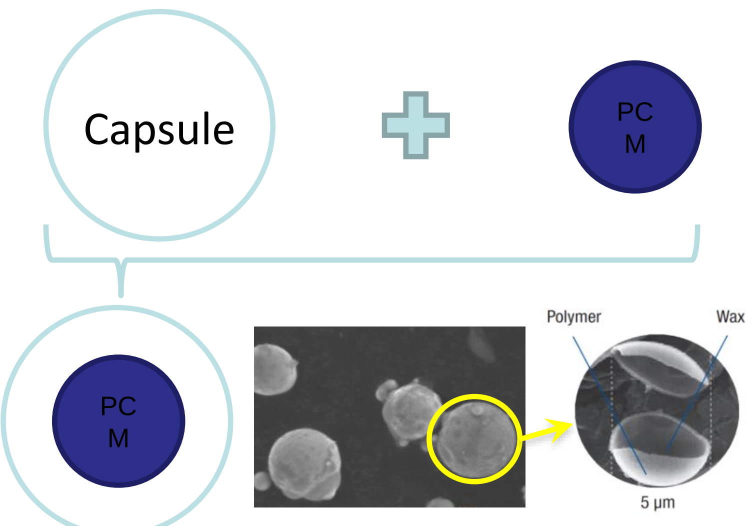
Building Envelop with Phase Change Materials





Energy Saving

- Heat absorption and release
- Reduce the usage of temperature adjusting equipment



PCM with firm shell strengthened by nano-composite

Research issue of this material

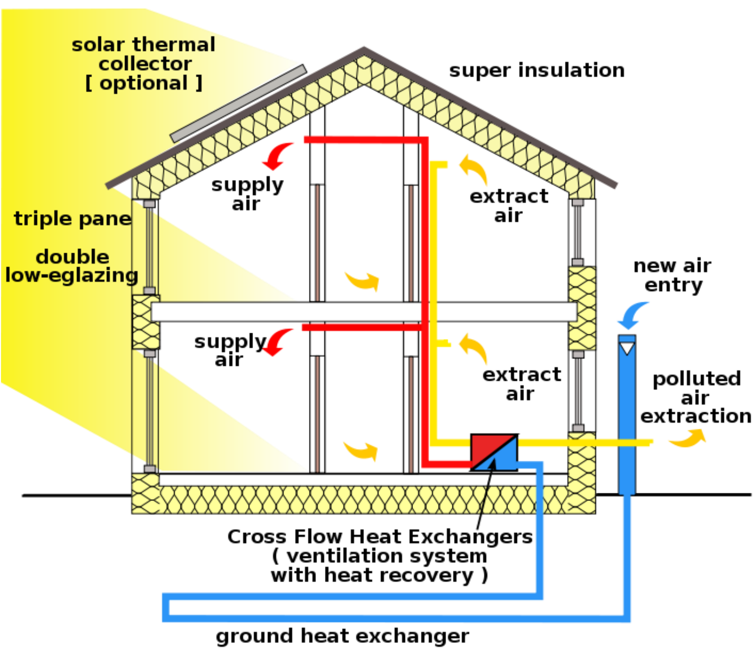
- *Well control the volume during the phase change*
- *Largely Increase the latent heat*
- *Greatly Improve the reliability in long-term use*

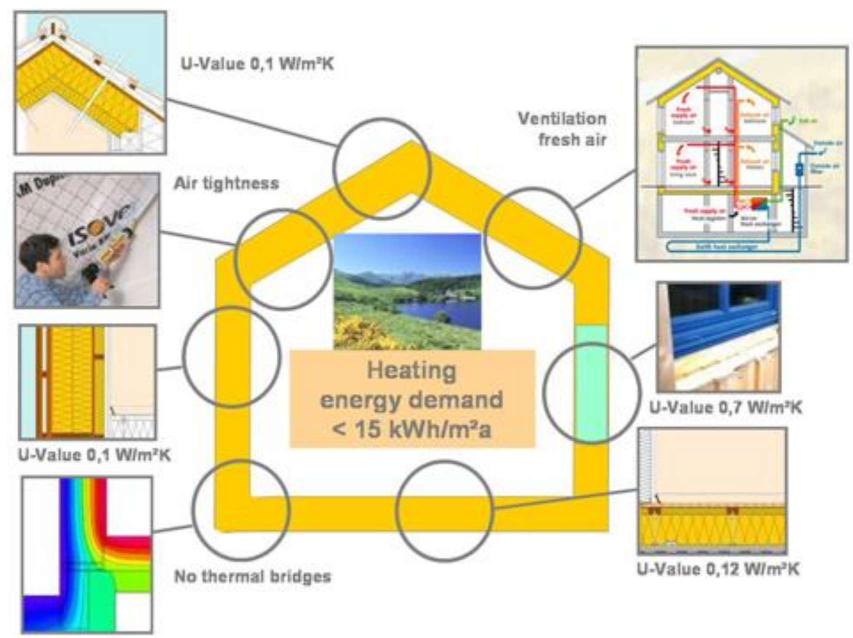
Boiling and Condensation

- Heat transfer in boiling and condensation represent an important class of heat as large quantity of heat is transferred in the phase changing process.
- Boiling especially in the nucleate boiling regime is a very efficient mode of heat transfer, and it is utilized in various energy conversion and heat exchange systems and in cooling of high energy density electronic components such as heat pipe.
- Boiling is subdivided into pool boiling (under natural convection), and flow boiling (under forced convection) which is further subdivided into external and internal flow boiling.
- Condensation is the change of the physical state of matter from gaseous phase into liquid phase which occurs when the matter in gaseous state is cooled to its dew point.
- Beside their importance in the applications of heat transfer, boiling and condensation occur in many natural and industrial processes such as power generation, and distillation of petroleum products.

Concept of Passive House

- A passive house is energy-efficient construction, it represents the highest energy standards.
- It is well insulated and air-tight building.
- It is mainly heated by passive solar gain and by internal gains from people, electrical equipment, etc.
- Energy losses are minimized.



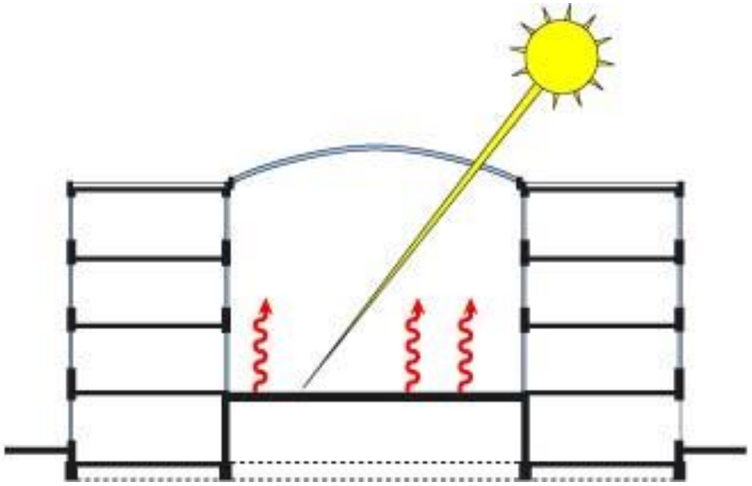


Basic Passive House Solutions

1. Insulation (wall, roof, floors, windows and doors)
2. Thermal bridge-free construction
3. Air tightness
4. Ventilation heat recovery
5. Insulation of ventilation ducts and domestic hot water pipes
6. Minimal space heating for comfortable indoor climate
7. Good indoor air quality through ventilation rate
8. Window glazing and solar orientation

General Aspects of Passive Heating

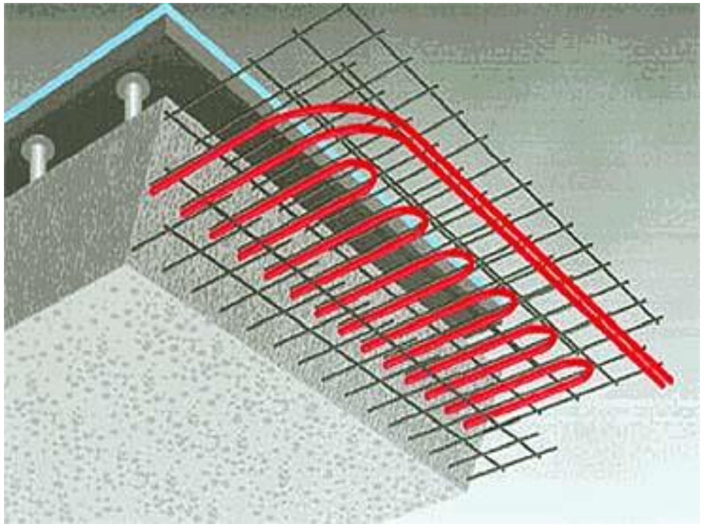
- **Solar energy – the base of passive heating**
  - Solar heating ≠ Passive heating, when solar panels and mechanical systems are involved
  - Passive solar heating = Direct heat gain of solar radiation
- **Features of passive heating**
  - Maximizing solar heat gain
  - Minimizing heat losses



Schematic illustration of direct solar heat gain in an atrium with a glazed roof

General Aspects of Passive Cooling

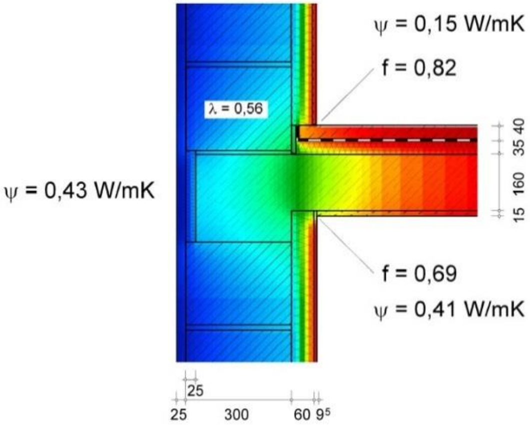
- **Features of passive cooling**
  - Minimizing solar heat gain
  - Removing unwanted heat
- **Principles**
  - Thermal protection
  - Air tightness
  - Use of technologies cooling buildings without fossil energy consumption



Thermo-active ceilings – Cold water flowing through the red coloured pipe serves as passive cooling

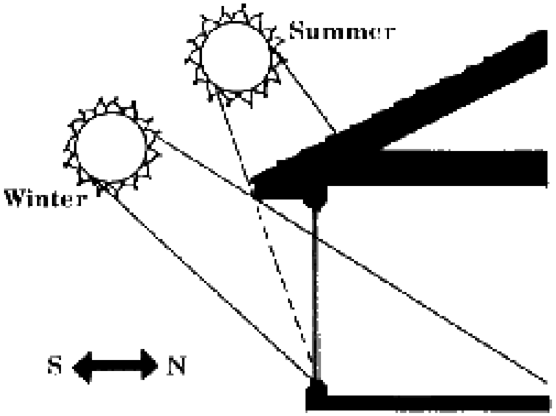
Structural Measures

- Orientating the main facade southwards (坐北朝南)
- Aiming at compactness
- Improving the building’s air tightness
- Improving the quality of the building’s envelope
- Avoiding thermal bridges
- Increasing the building’s thermal mass
- Adapting the distribution of the rooms
- Effective planning and installation of ventilation devices



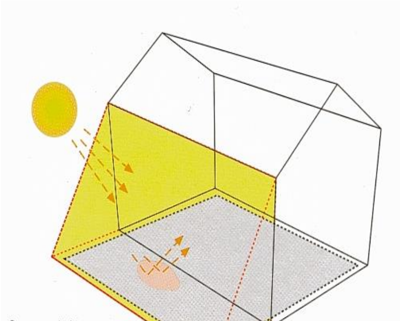
Gaining from Solar Rays

The sun's rays can warm a building: glazing on the south side of buildings will increase this 'solar gain'.



The sun is higher in the sky in the summer, large over hangs reduce heat gains in summer but allow solar gain in winter.

Attached sun spaces trap heat from the sun. Direct and indirect energy transfer provides heat to the adjacent building.

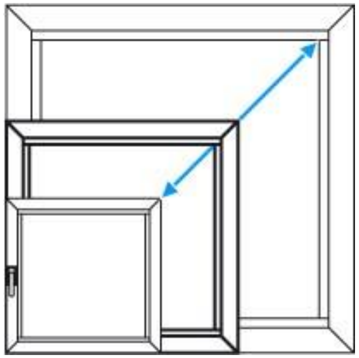


Sunspace / wintergarden acts as thermal buffer and passive solar heat store. Exposed thermal mass should be used to store heat.

Glazed windows gain heat from the sun's rays. The floor and walls then heat the rest of the building. In the winter such buffer zones separate the cold outside and the warm inside.

Calculation of Solar Heat Gains

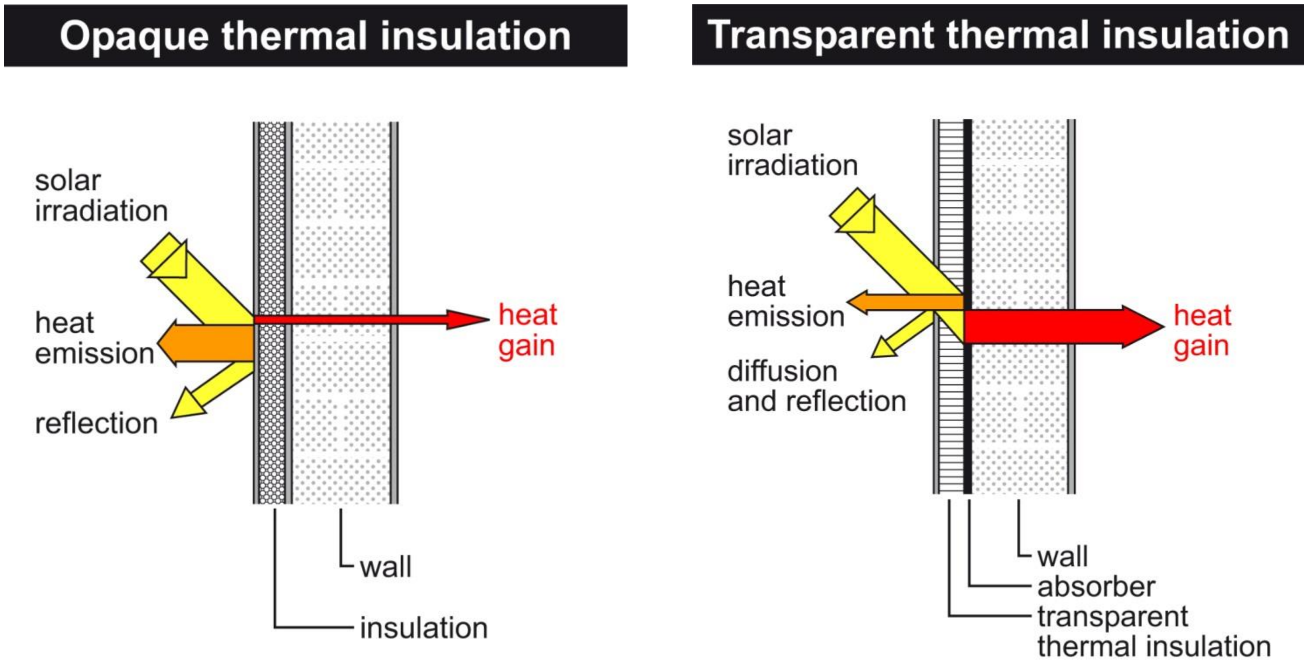
- **Two main types of heat flow**
  - Solar gains through building elements
  - Thermal radiation to the sky (mostly insignificant)
  - Overall heat flow = Solar gains - Thermal radiation



- **Solar gains**
  - **Opaque elements - Indirect gains**
    mostly insignificant
  - **Glazed elements - Direct gains**

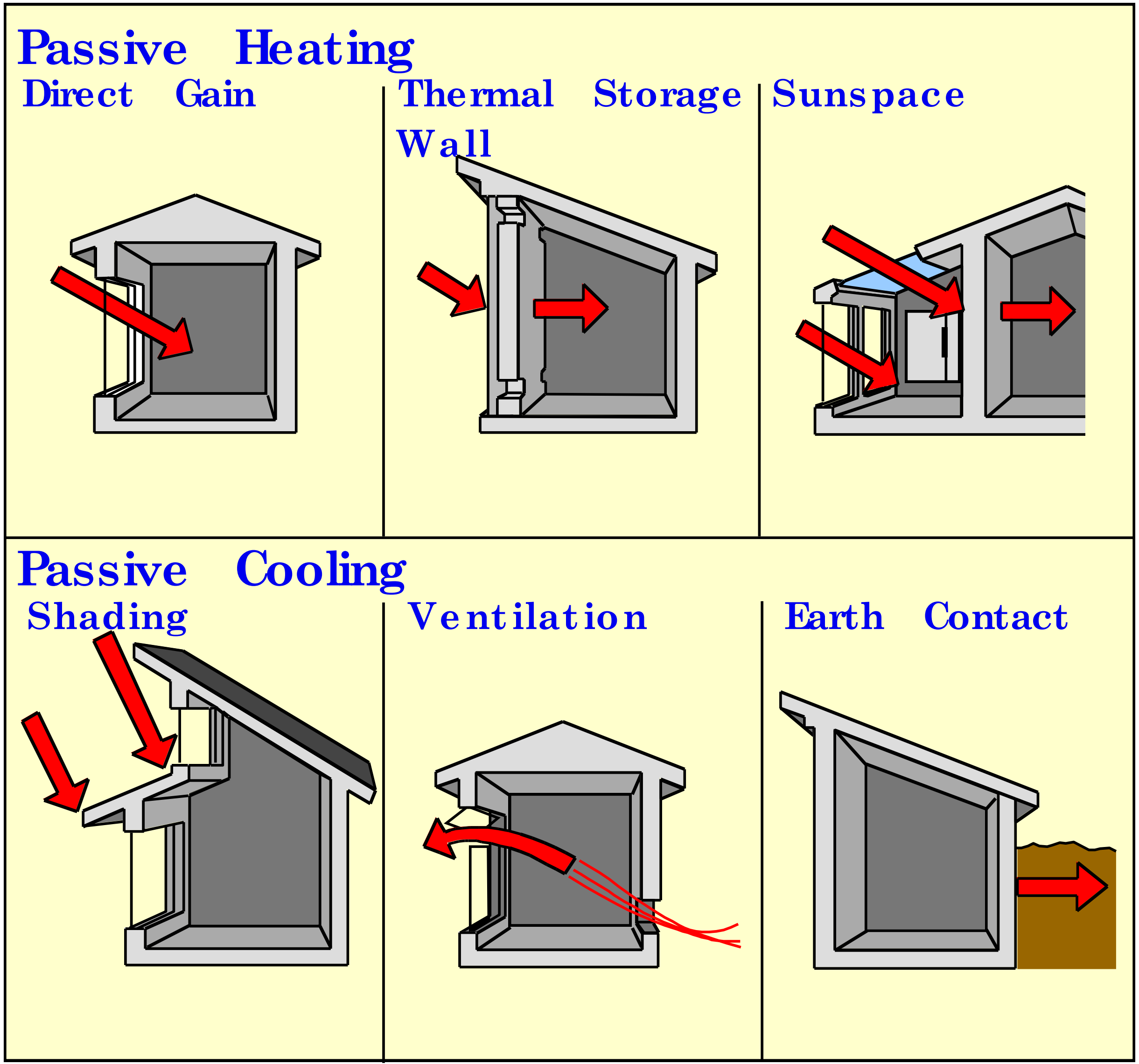
    Influenceable by
    * Product properties:
      g-value, U-value, frame area fraction
    * Size and orientation
    * Shading devices

Opaque Elements with Transparent Insulations

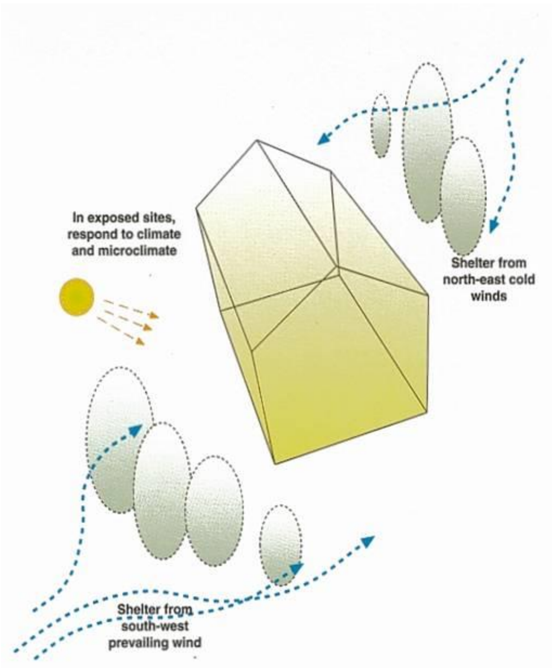


- Developed to collect solar energy
- Positive in heating season, negative when cooling
- Transparent characteristic irrelevant regarding heat transfer by transmission

Passive Heating and Cooling in Buildings



Location

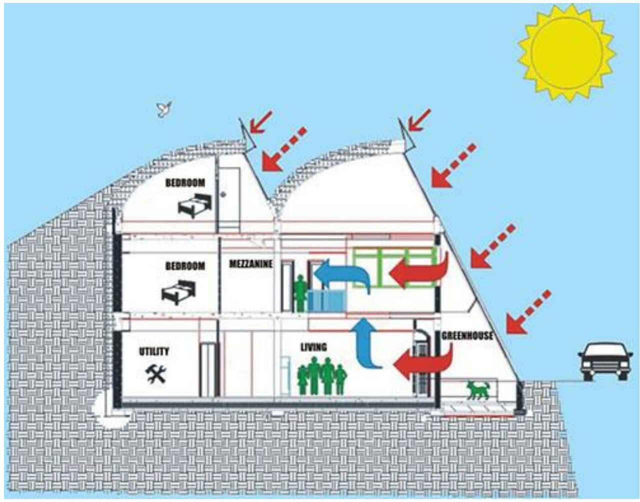


Good design uses natural features such as slopes or vegetation to shelter buildings from the wind and maximise solar gains. A significant reduction in heat loss can be achieved through properly planned siting.

坐北朝南

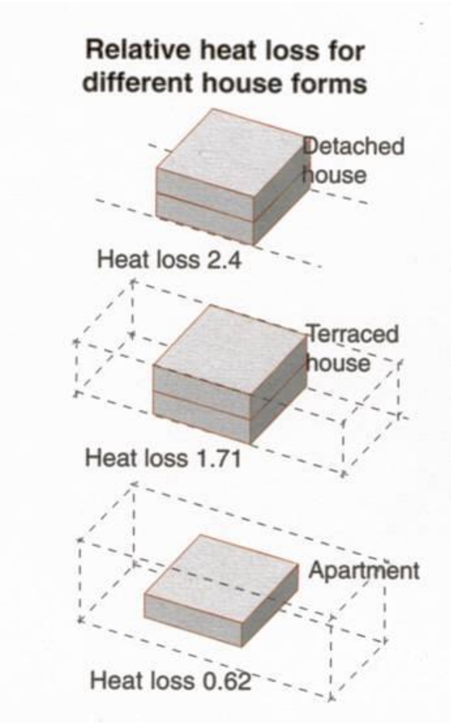
Being located on a south facing slope with large amounts of glazing results in solar gain.

Form and Shelter



To protect a building from:

- wind
- rain
- sun
- temperature variations



The shape and size of a building influences heat transfer. Compact buildings that have a small ratio of surface area to volume will loose less heat. Apartments also benefit from sharing warmth with adjacent properties compared with detached houses.

Roof Garden and Green Walls

- A roof garden offers a building and its surrounding invaluable environment benefits including storm-water management, reducing heat load of the building, biodiversity, improved urban air quality, extension of roof life and a reduction of the urban heat island effect.
- Green walls offer similar effects with direction being vertical instead of horizontal as in the case of roof garden.