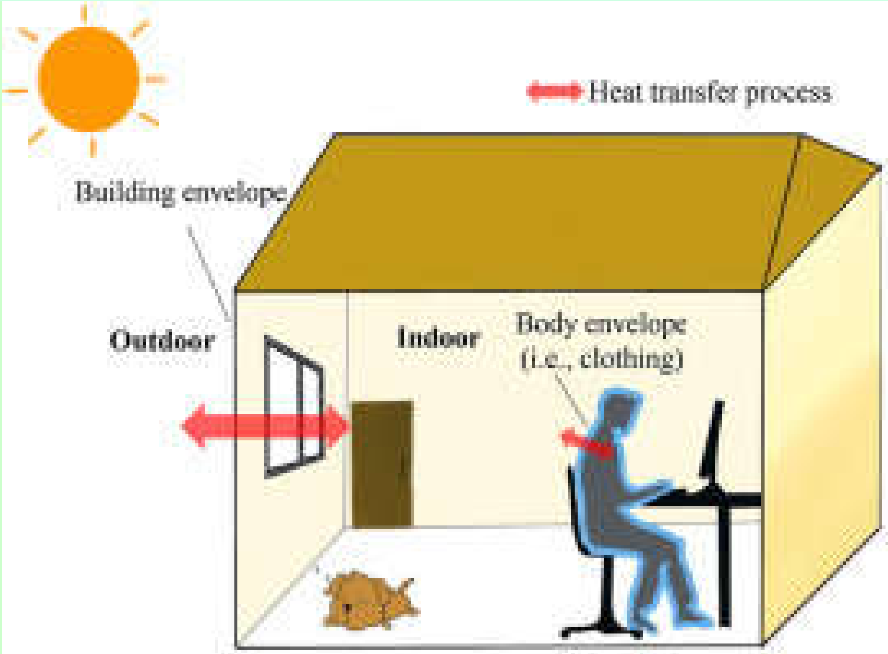
MEBS6004 Built Environment

http://ibse.hk/MEBS6004/



Thermal environment and heat transmission

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- Basic concepts
- Thermal behaviour of buildings
- Passive building design
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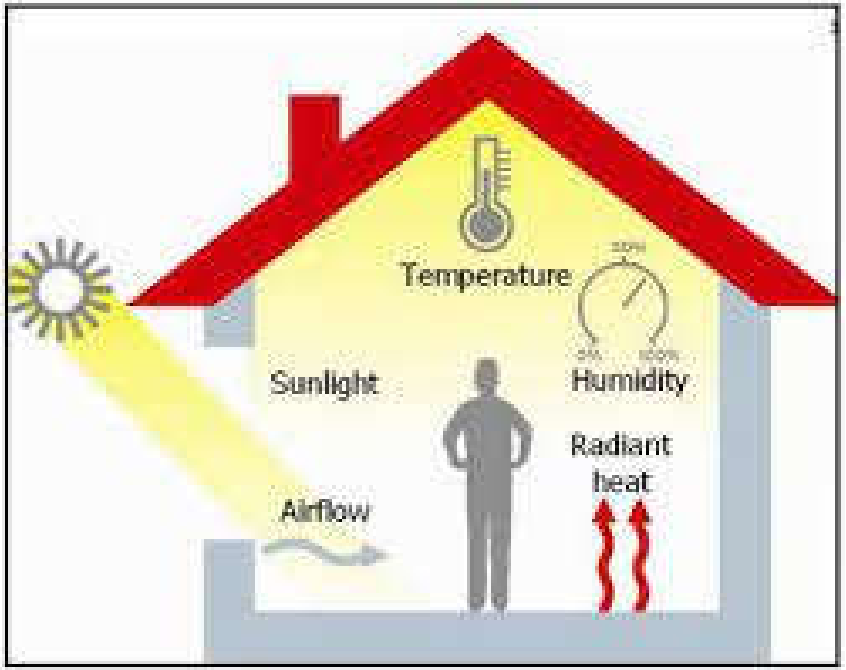
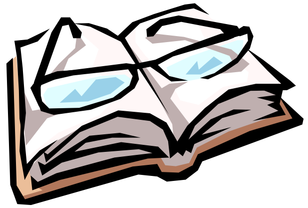


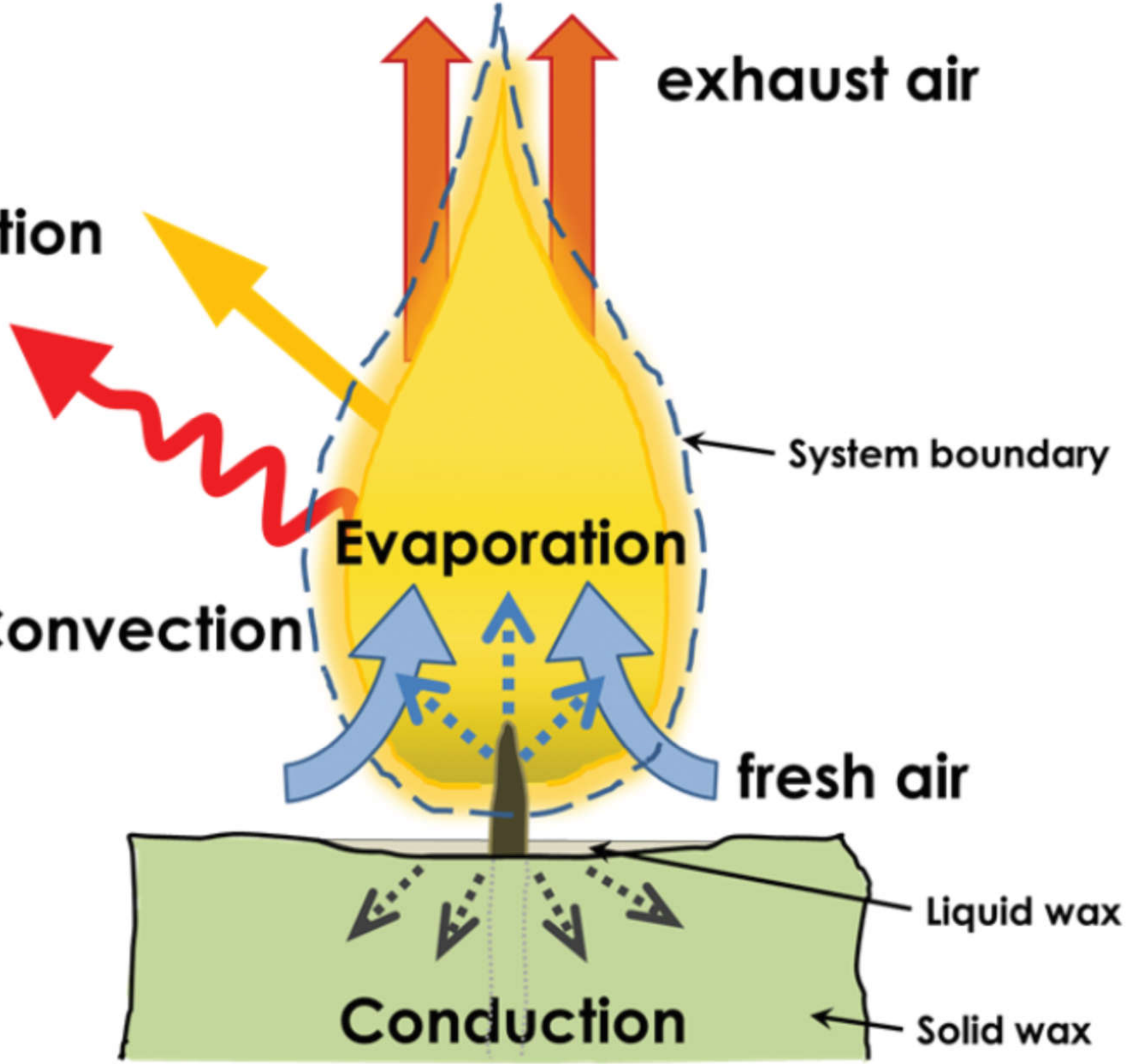
Basic concepts



- Physics of heat
  - Heat and temperature (°C or K)
  - Specific heat (J/kg.K) & latent heat (kJ/kg)
  - Heat flow rate, Q (J/s or W)
  - Heat flux density (W/m^3)

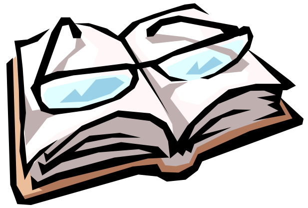
- Heat flow
  - Density (kg/m^3), conductivity (W/m.K)
  - Heat loss: the U-value [Q = U A ΔT]
  - Convection coefficient h_c, reflectance/emittance

A candle transferring heat into its environment by radiation, convection, evaporation and conduction

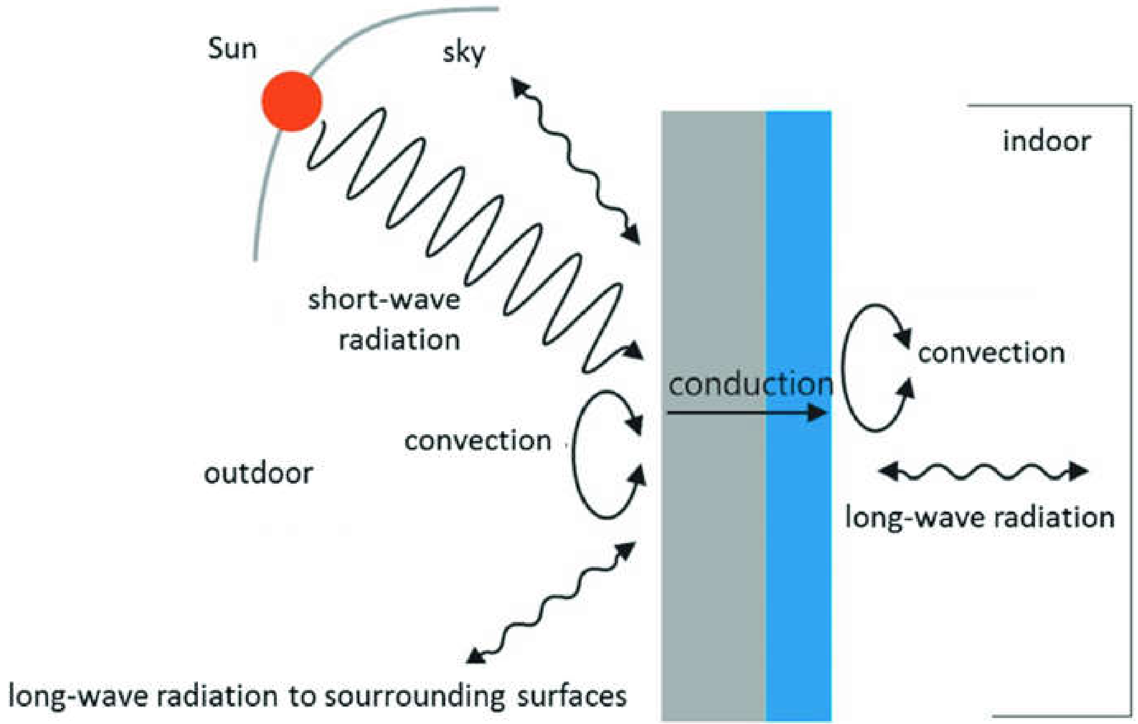


(Source: Shukuya M., 2019. *Bio-Climatology for the Built Environment*, Chapman and Hall/CRC, Milton.)

Basic concepts

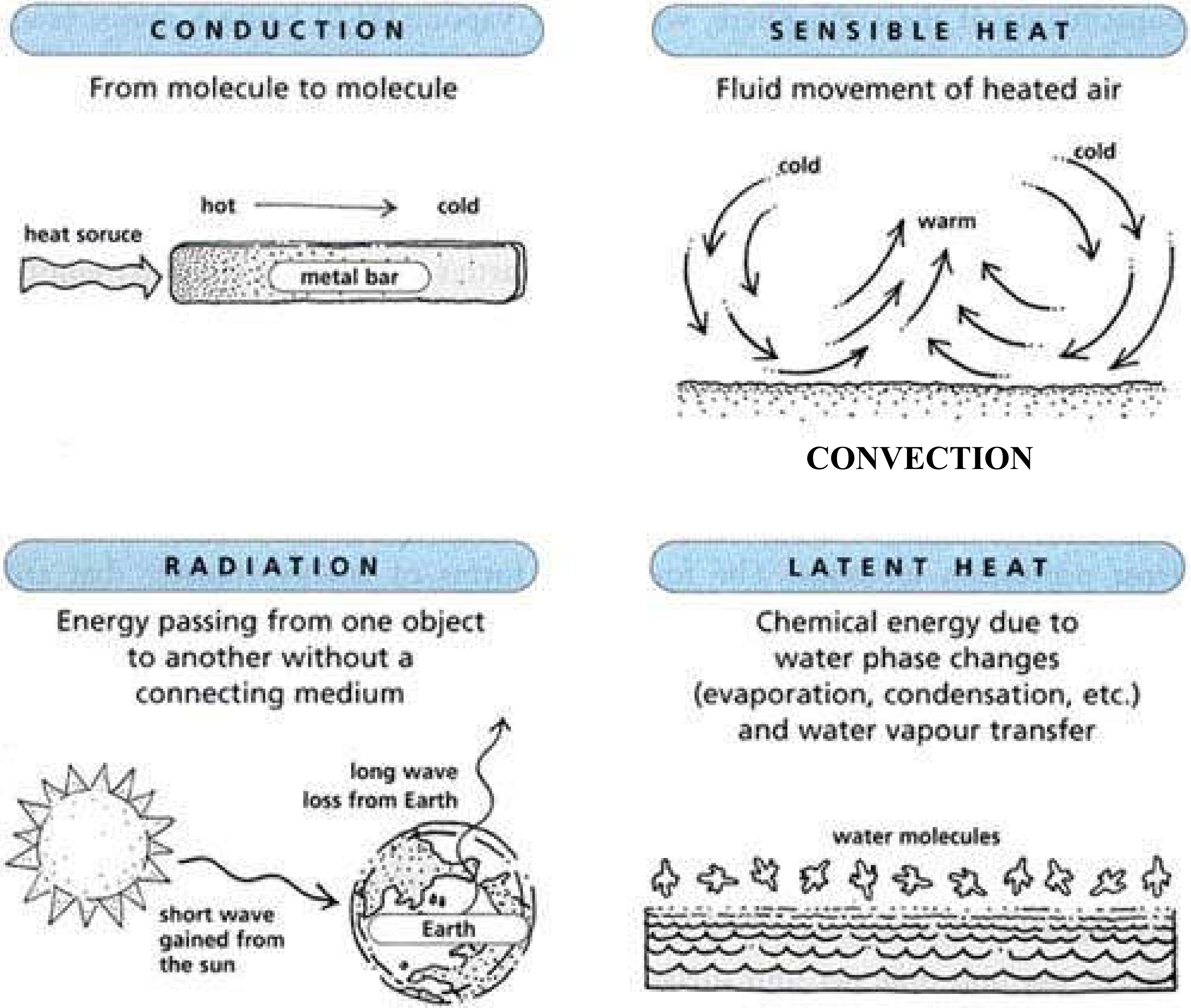


- Thermal environment refers to the things that can affect heat transfer at that point
- Mechanisms of heat transfer:
  - Conduction
  - Convection
  - Radiation
  - Phase change



(Source: https://www.designingbuildings.co.uk/wiki/Thermal_environment)

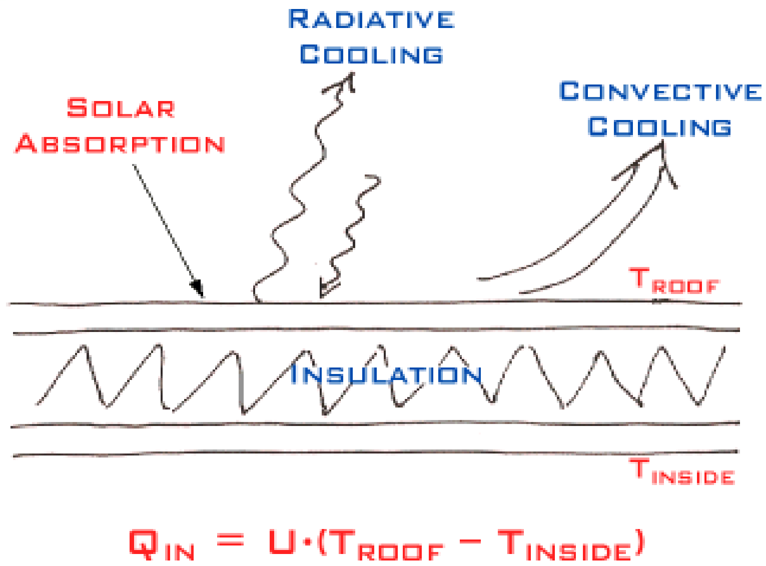
Four forms of heat transfer



(Source: Food and Agriculture Organization of the United Nations, www.fao.org)

Basic concepts

- Heat transfer mechanism
  - Conduction
  - Convection
  - Radiation



- Thermal properties of building materials
  - Overall thermal transmittance (U-value)
  - Thermal conductivity
  - Thermal capacity (specific heat)

$$Q = U\,A\,(\Delta t)$$

Typical properties of selected materials

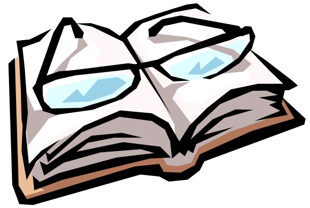
Material	*Density (kg/m³)*	*Thermal conductivity (W/m K)*	*Specific heat capacity (J/kg K)*
Bricks	1700	0.73 [a]	800
Concrete, dense	2000	1.13	1000
Glass fibre quilt	25	0.035	1000
Asphalt	1700	0.50	1000
Aluminium	2700	214	920
Water (20 °C)	1000	0.60	4187
Sand (dry)	1500	0.30	800
Steel	7800	45	480
Wood	500–700 [b]	0.12–0.23 [b]	1200–3400 [b]

[a] Mean of internal and external brick types. Consult manufacturers' data for precise values.
[b] Values vary depending on wood type, temperature and water content.

Video: Thermal Properties of Building Materials (5:52) https://youtu.be/ch0d5Hb-_qA

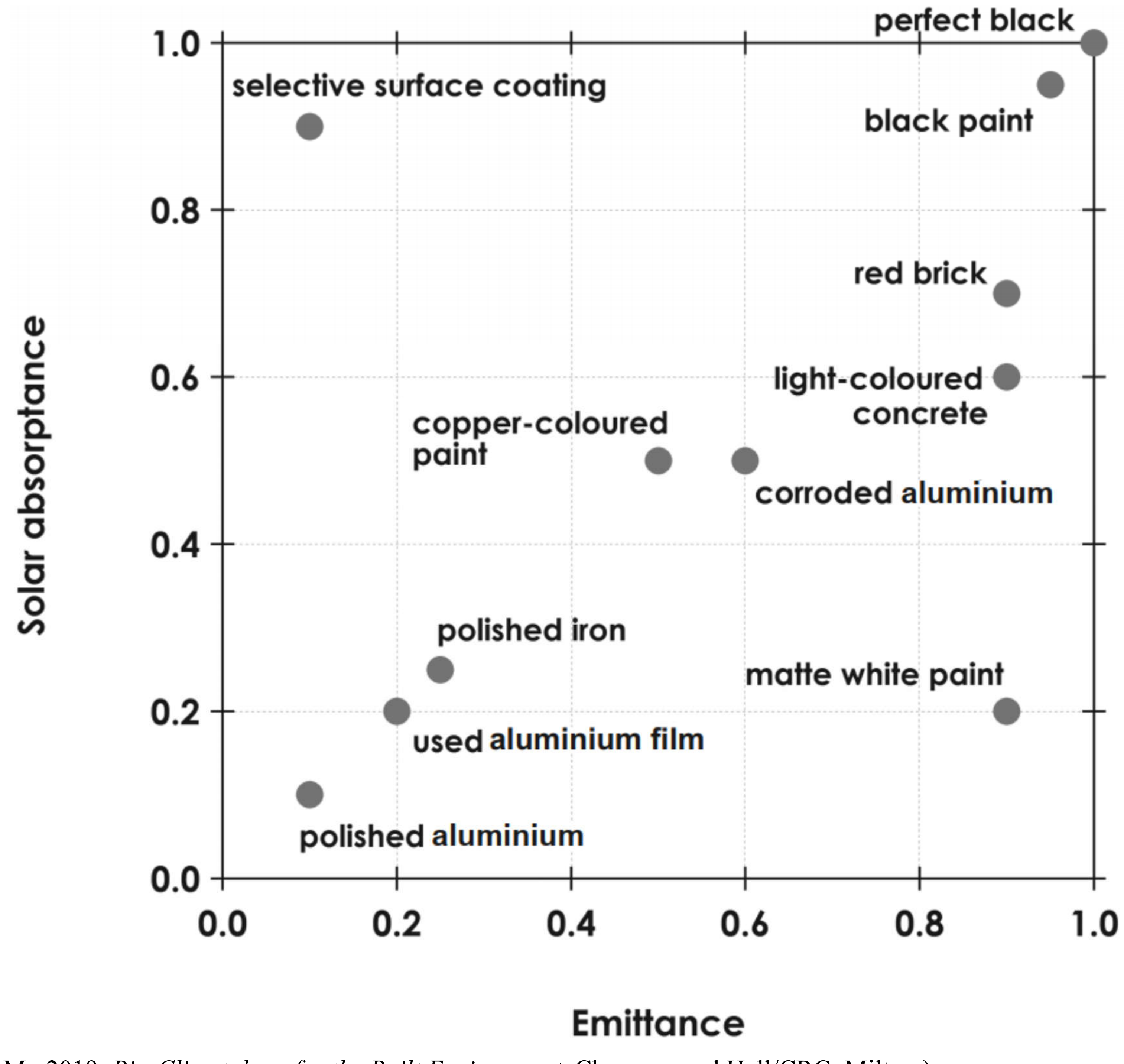
(Source: Thomas R., 2006. *Environmental Design: An introduction for architects and engineers*, Third edition, Taylor & Francis.)

Basic concepts



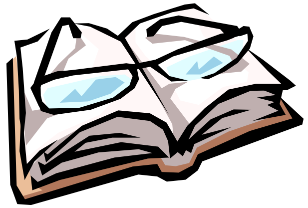
- **Emittance** (or emissive power)
  - It is the total amount of thermal energy emitted per unit area per unit time for all possible wavelengths
- **Emissivity** of a body at a given temperature
  - It is the ratio of the total emissive power of a body to the total emissive power of a perfectly black body at that temperature
- **Solar absorptance**
  - It is the proportion of the total incident solar radiation that is absorbed by the material (the remainder is reflected)

Emittance versus solar absorptance of some building materials

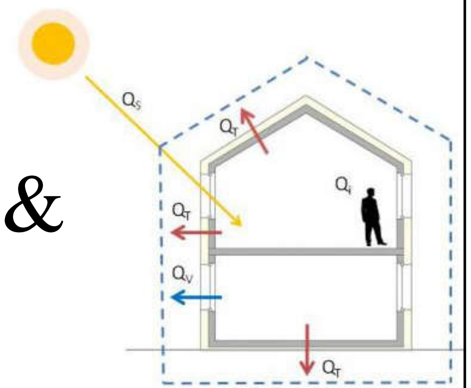


(Source: Shukuya M., 2019. *Bio-Climatology for the Built Environment*, Chapman and Hall/CRC, Milton.)

Basic concepts



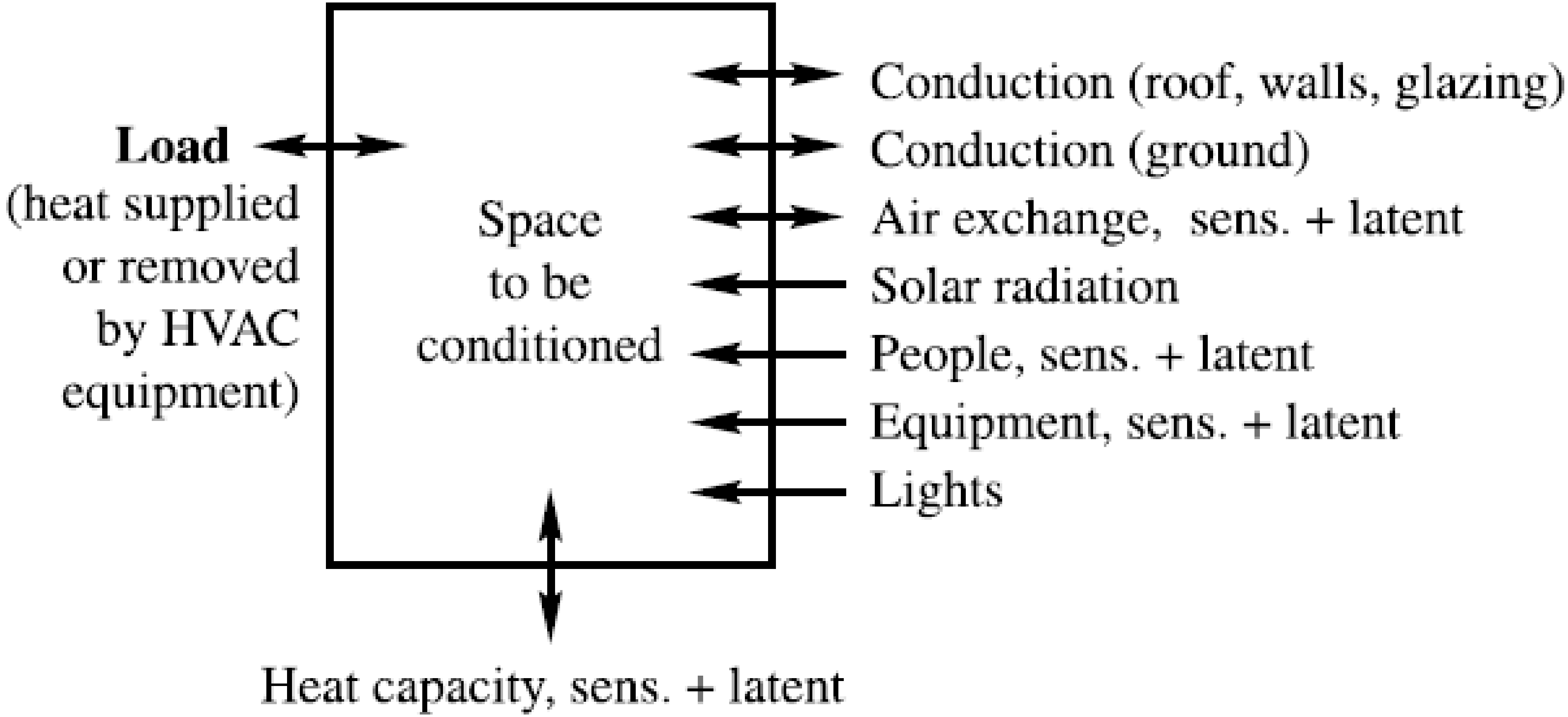
- Thermal transmission in buildings
  - External walls, windows, roof, doors and floors
  - Insulation (thermal) to reduce the heat transfer
  - Ventilation (infiltration & exfiltration)
  - Thermal properties of building materials & construction components
  - Determining U values for real building elements
    - https://www.cibsejournal.com/cpd/modules/2011-06/



Thermal load, heat gains/losses & heat storage

Thermal Load

Heat Gains/Losses

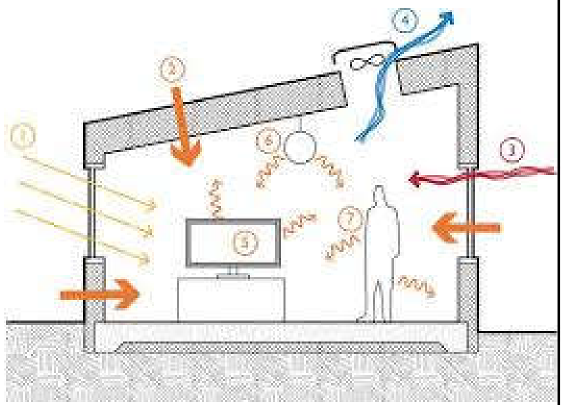


Heat storage

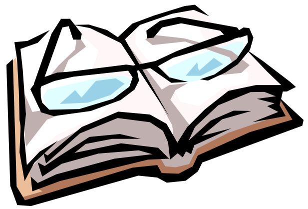
(Source: ASHRAE Handbook Fundamentals 2005)

Basic concepts

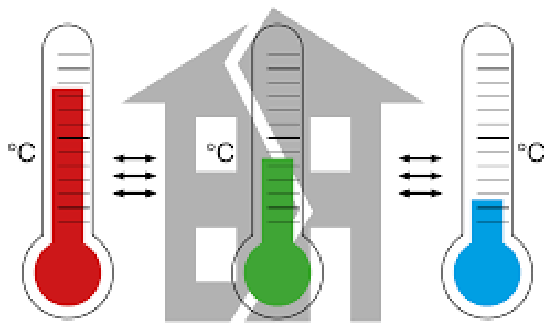
- Calculating heat gains (or losses)
  - Heat gain through external walls
  - Heat gain through roof
  - Solar heat gain through window glass
  - Conduction heat through window glass
  - Internal heat gains
  - Ventilation and/or infiltration heat gains
  - Latent heat gains (moisture transfer/generation)



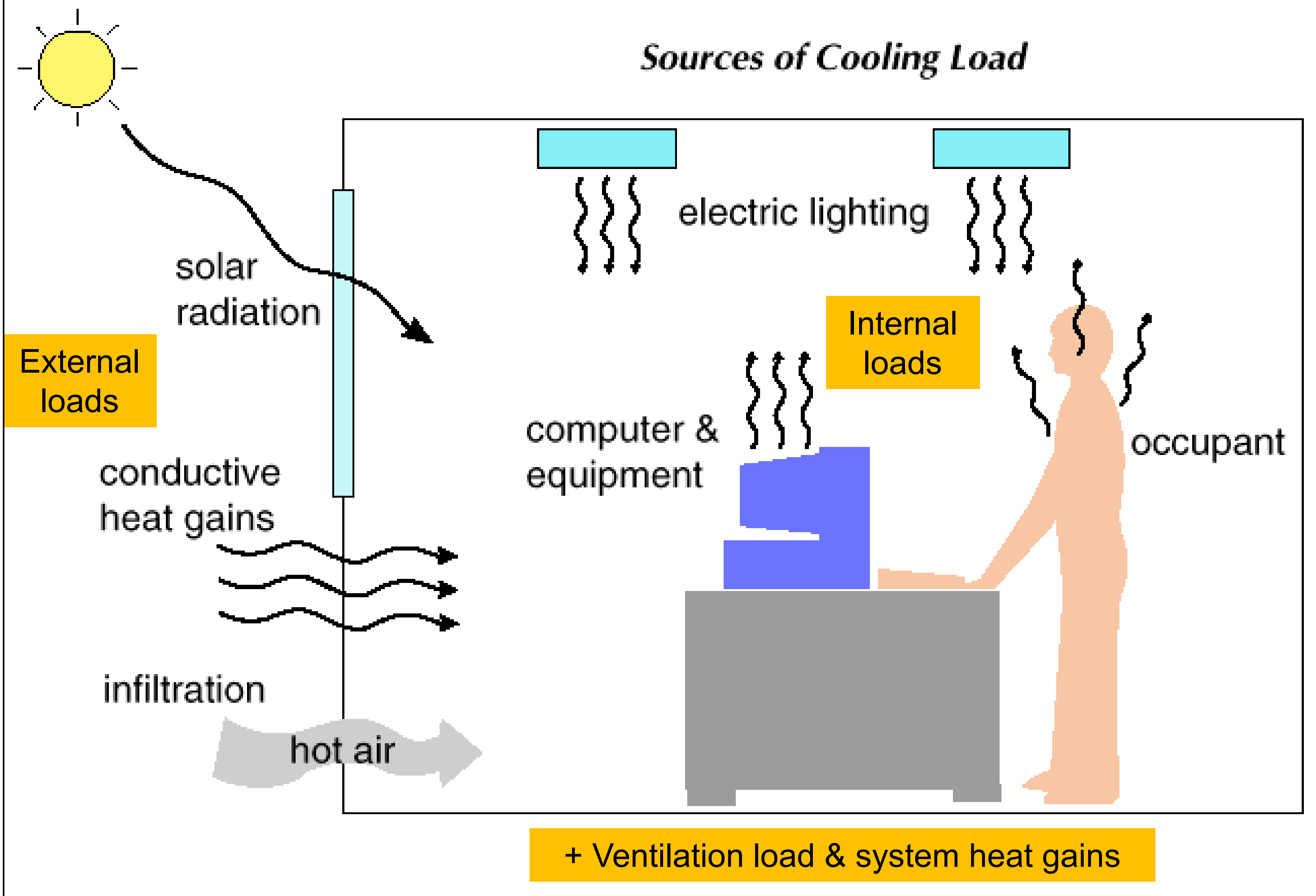
Basic concepts



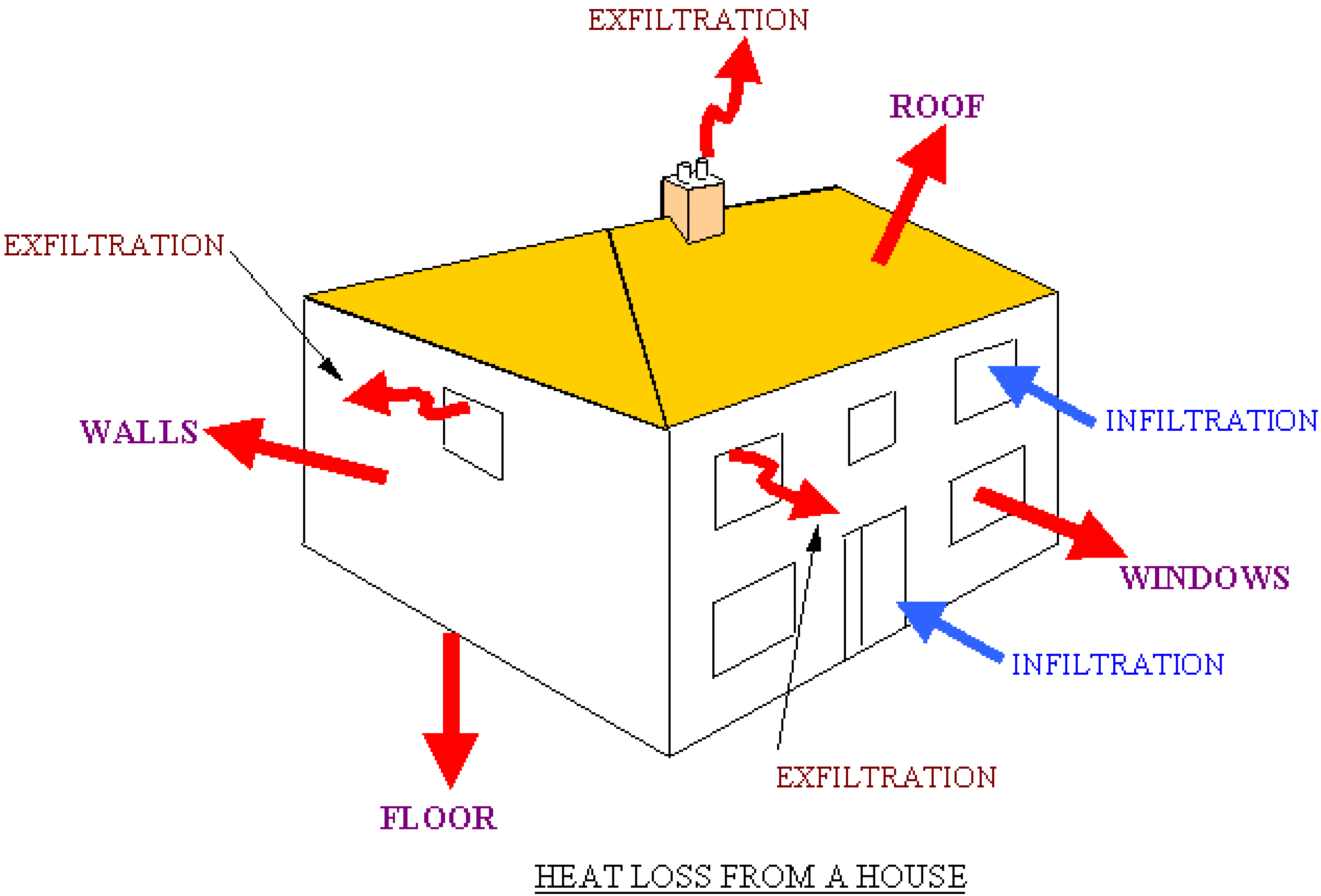
- Heat transfer basic relationships (for air at sea level) (SI units)
  - Sensible heat transfer rate:
    - $q_{\text{sensible}} = 1.23$ (Flow rate, L/s) (Δt)
  - Latent heat transfer rate:
    - $q_{\text{latent}} = 3010$ (Flow rate, L/s) (Δw)
  - Total heat transfer rate:
    - $q_{\text{total}} = 1.2$ (Flow rate, L/s) (Δh)
  - $q_{\text{total}} = q_{\text{sensible}} + q_{\text{latent}}$



Components of building cooling load

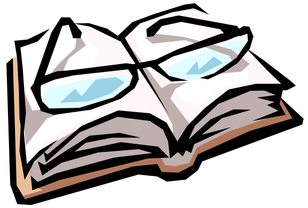


Heat losses for heating load calculation



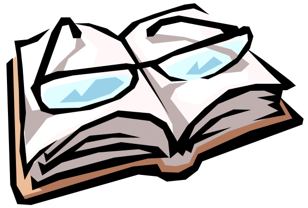
(Source: http://www.arca53.dsl.pipex.com/index_files/tt3.htm)

Basic concepts

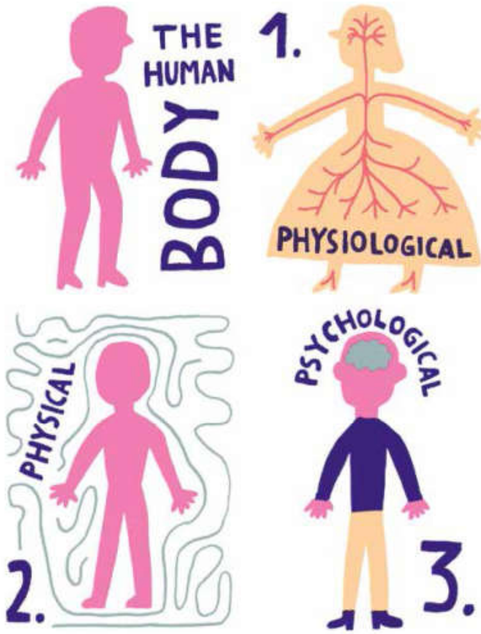


- Aspects that can affect the heat transfer:
  - Air temperature
  - Radiant temperature (long wave infrared radiation (surface temperatures) & short wave infrared radiation (solar radiation))
  - Air velocity
  - Humidity
  - The presence of surface water
  - The temperature of contacting objects

Basic concepts

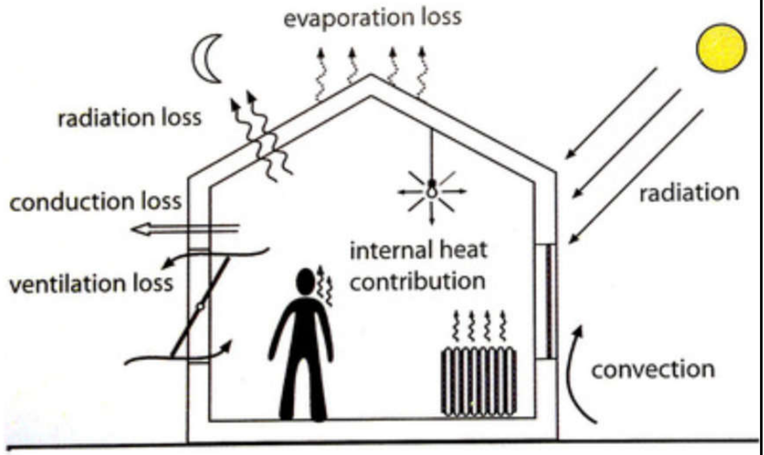


- The experience people have of the thermal environment that surrounds them will be affected by personal factors such as:
  - Clothing
  - Metabolic heat
  - Wellbeing & sickness
- Personal experience of thermal comfort
  - Thermal satisfaction is experienced via a number of conscious & unconscious interactions among physiological, physical & psychological factors



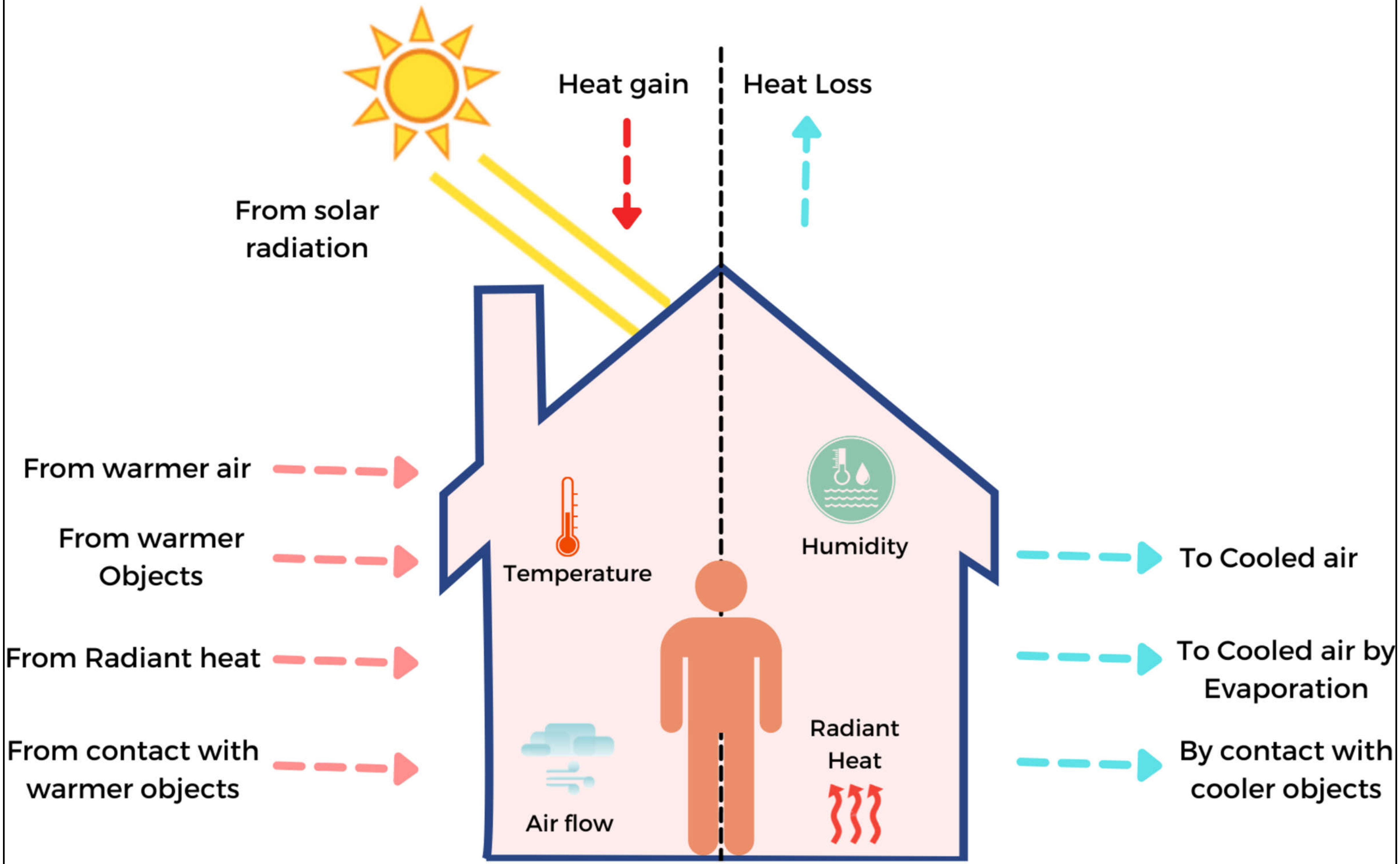
Thermal behaviour of buildings

- Thermal behaviour of buildings
  - Heat inputs and outputs:
    - Qi – internal heat gain
    - Qc – conduction heat gain or loss
    - Qs – solar heat gain
    - Qv – ventilation heat gain or loss
    - Qe – evaporative heat loss



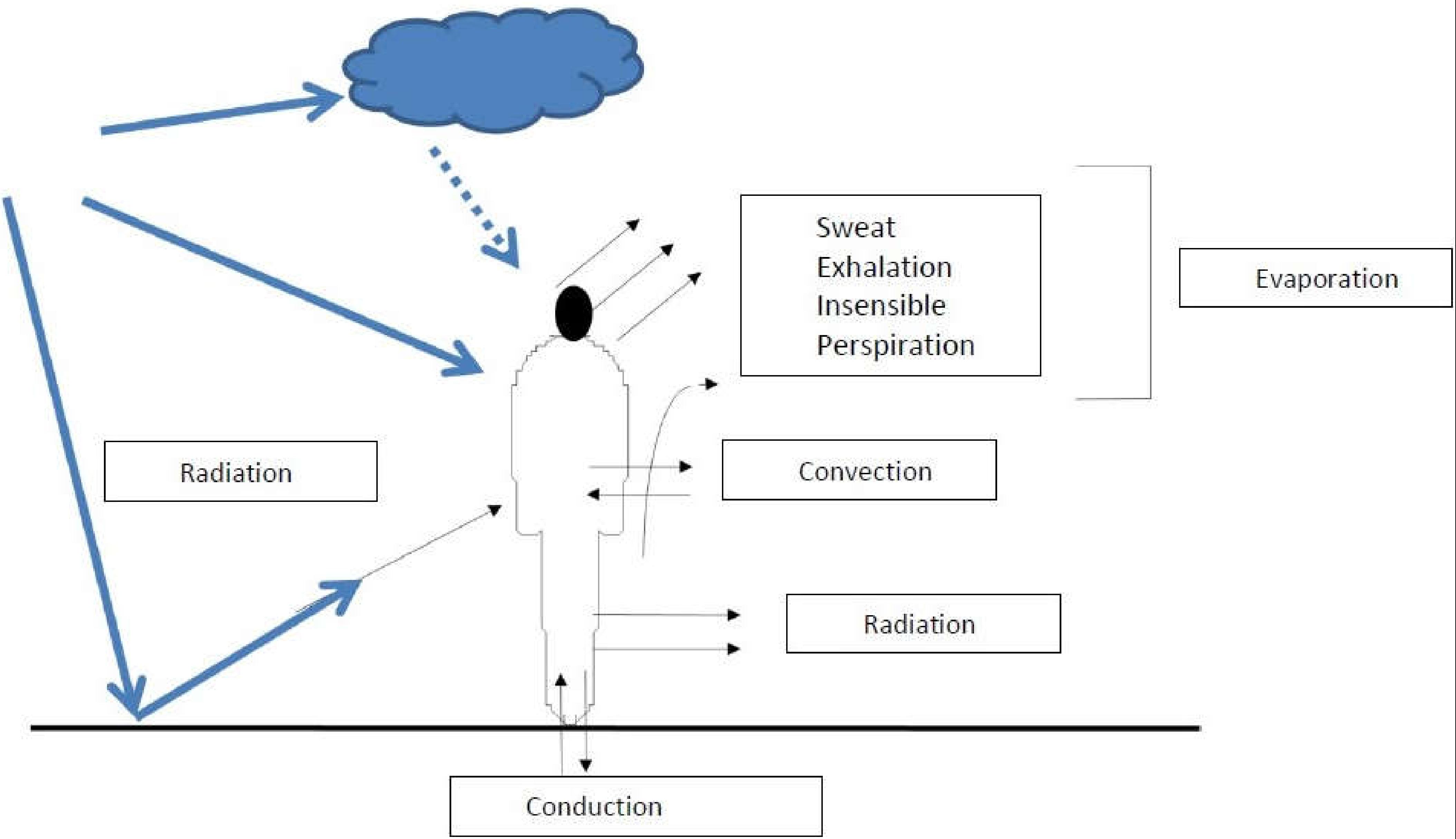
  - Thermal balance: $Qi + Qc + Qs + Qv + Qe = \Delta S$
  - If the sum $\Delta S > 0$, temp. inside the building is increasing, or if it is less than zero, the building is cooling down

Heat transmission in buildings



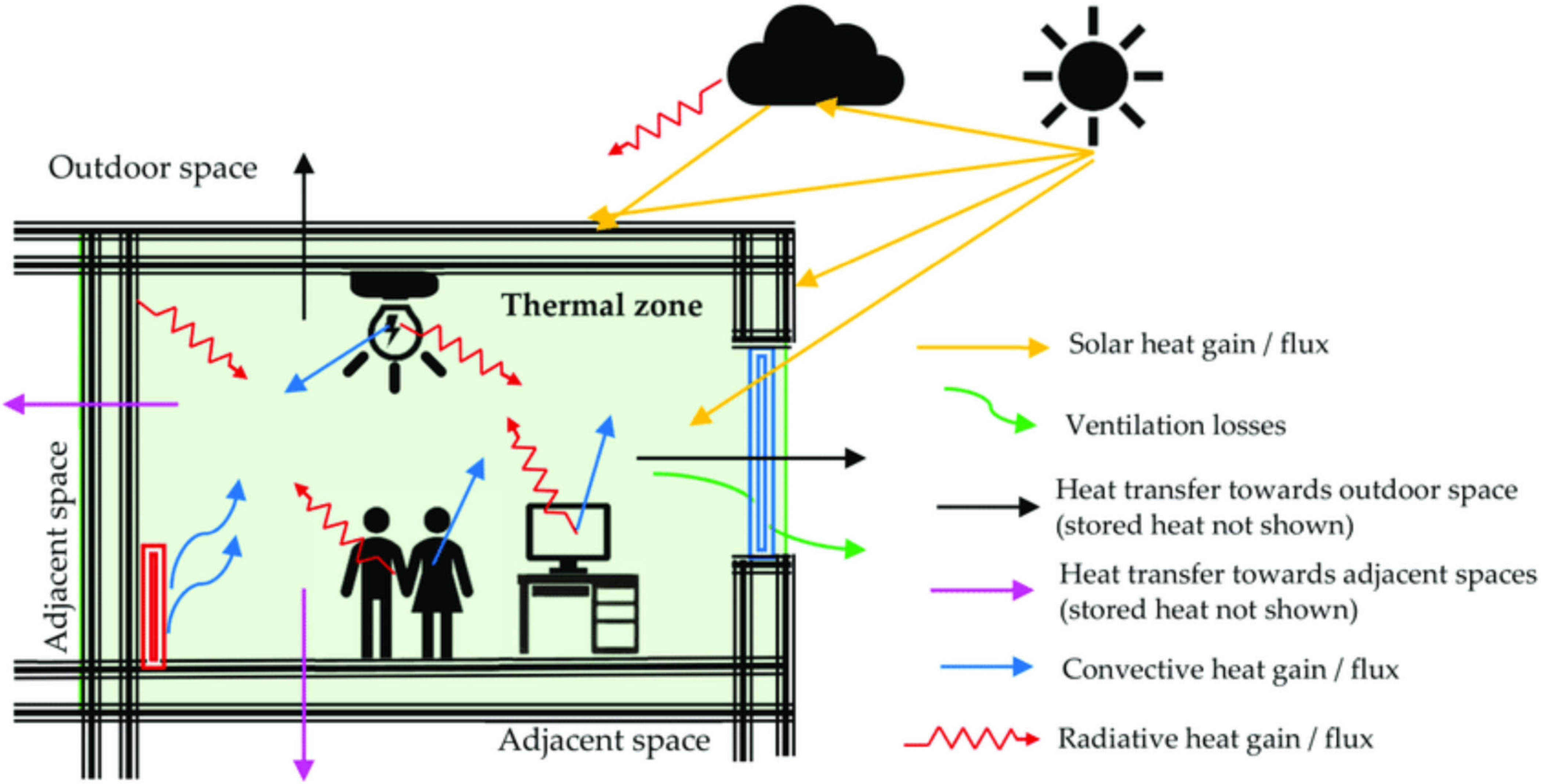
(Source: https://www.linkedin.com/pulse/building-thermal-comfort-analysis-ecologikol/)

Heat transfer at human body



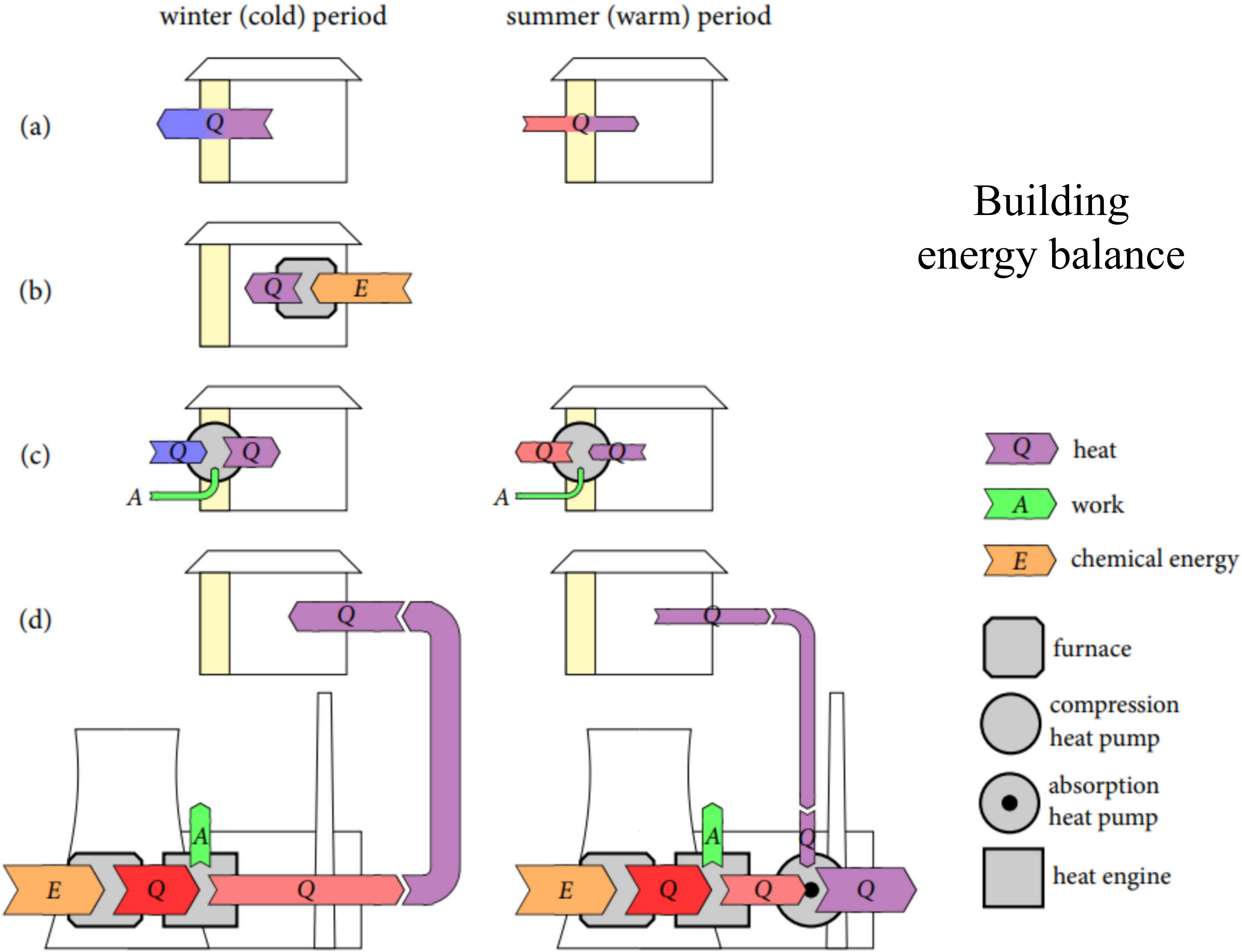
(Source: https://archi-monarch.com/climate-and-thermal-comfort/)

Main energy/heat fluxes affecting the building energy balance



(Source: http://dx.doi.org/10.3390/en13174498)

Building energy balance



(Source: Pinterić M., 2021. *Building Physics: From physical principles to international standards*, Second Edition, Springer, Cham, Switzerland.)

Thermal behaviour of buildings

- Steady state heat flow
  - Air temperature: ventilation & building envelope
  - Solar radiation: opaque elements & windows
- Dynamic response of buildings
  - Magnitude of heat flow & its timing
  - Affected by thermal capacity (e.g. massive construction)
  - Periodic heat flow & time lag
  - Thermal response simulation (software programs)

Summary of steady state heat flow expressions

Air temperature

Ventilation

$$Qv = qv \times \Delta T$$
$$qv = 1200 \times vr = 0.33 \times V \times N$$
$$\Delta T = T_o - T_i$$

All elements

$$Qc = qc \times \Delta T$$
$$qc = \Sigma(A \times U)$$
$$\Delta T = T_o - T_i$$

Solar radiation

Opaque elements

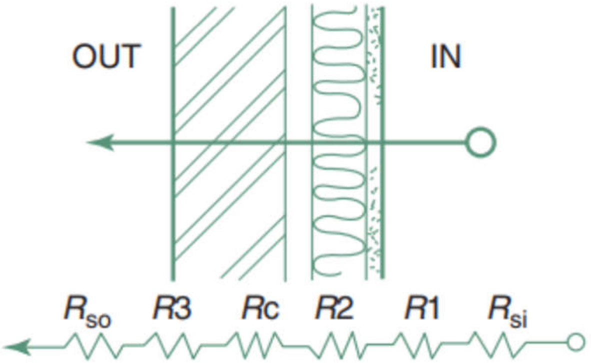
$$Qs_o = qc \times dTe$$
$$qc = \Sigma(A \times U)$$
$$dTe = G \times \alpha \times Rso$$
$$\text{roof: } (G \times \alpha - E) \times Rso$$

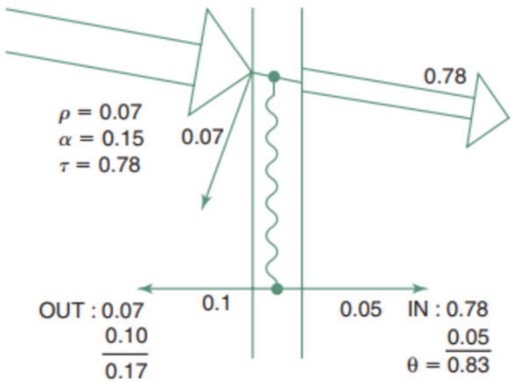
Windows

$$Qs_w = A \times G \times \theta$$

ii

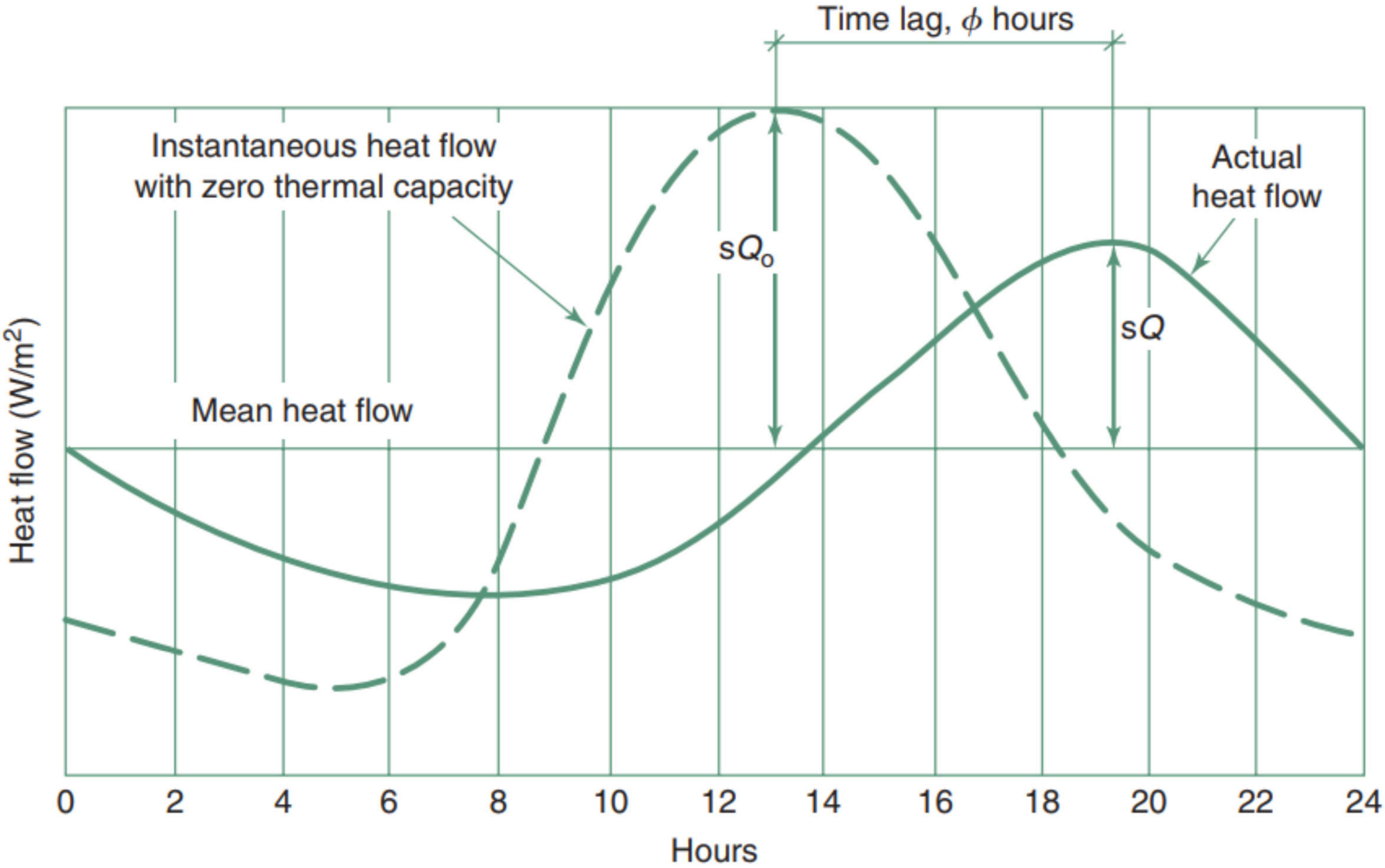
$$Q = (qc + qv) \times \Delta T + Qs_o + Qs_w$$





(Source: Szokolay S. V., 2008. *Introduction to Architectural Science: the Basis of Sustainable Design*, Second edition.)

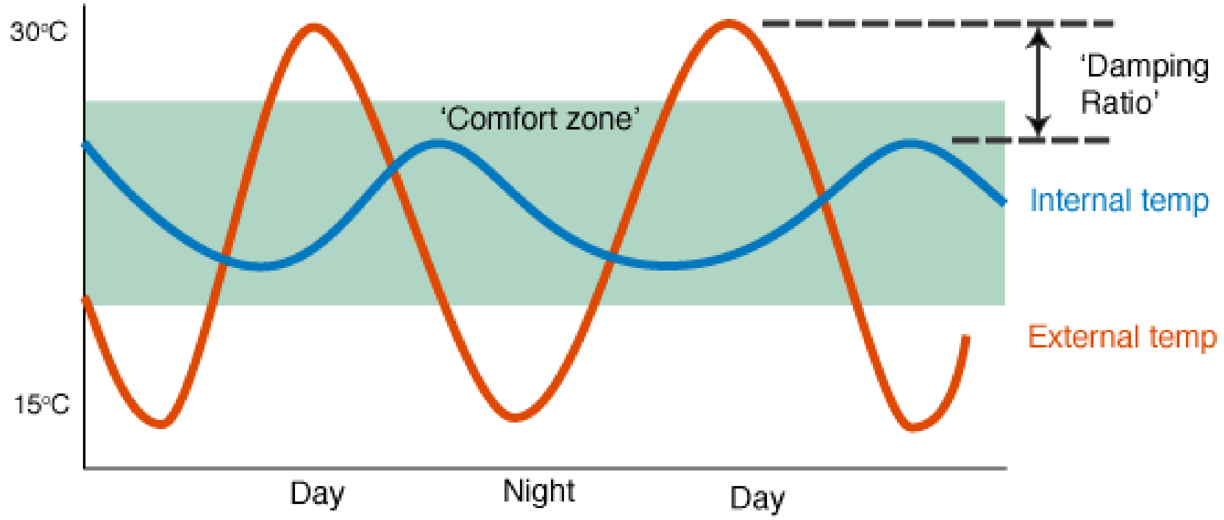
Heat flow through a real wall, compared with a wall of zero mass



(Source: Szokolay S. V., 2008. *Introduction to Architectural Science: the Basis of Sustainable Design*, Second edition.)

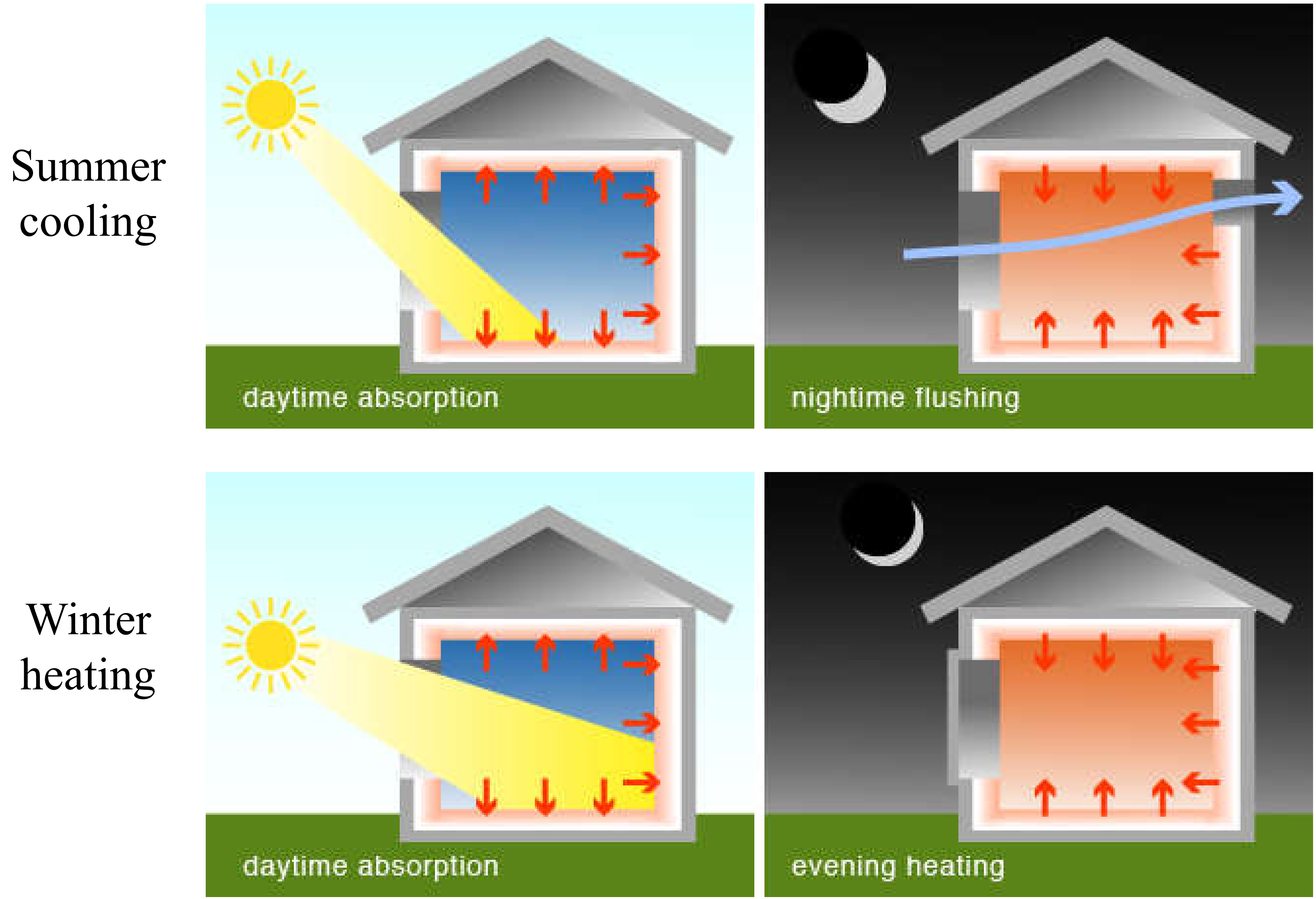
Thermal behaviour of buildings

- Thermal mass
  - A material's capacity to absorb, store and release heat, measured by thermal admittance [W/(m^2.K)]
    - Specific heat capacity, density, thermal conductivity
  - To assess heat flows into & out of thermal storage



(See also: Module 48: Simple thermal analysis for buildings https://www.cibsejournal.com/cpd/modules/2013-01/)

How thermal mass works

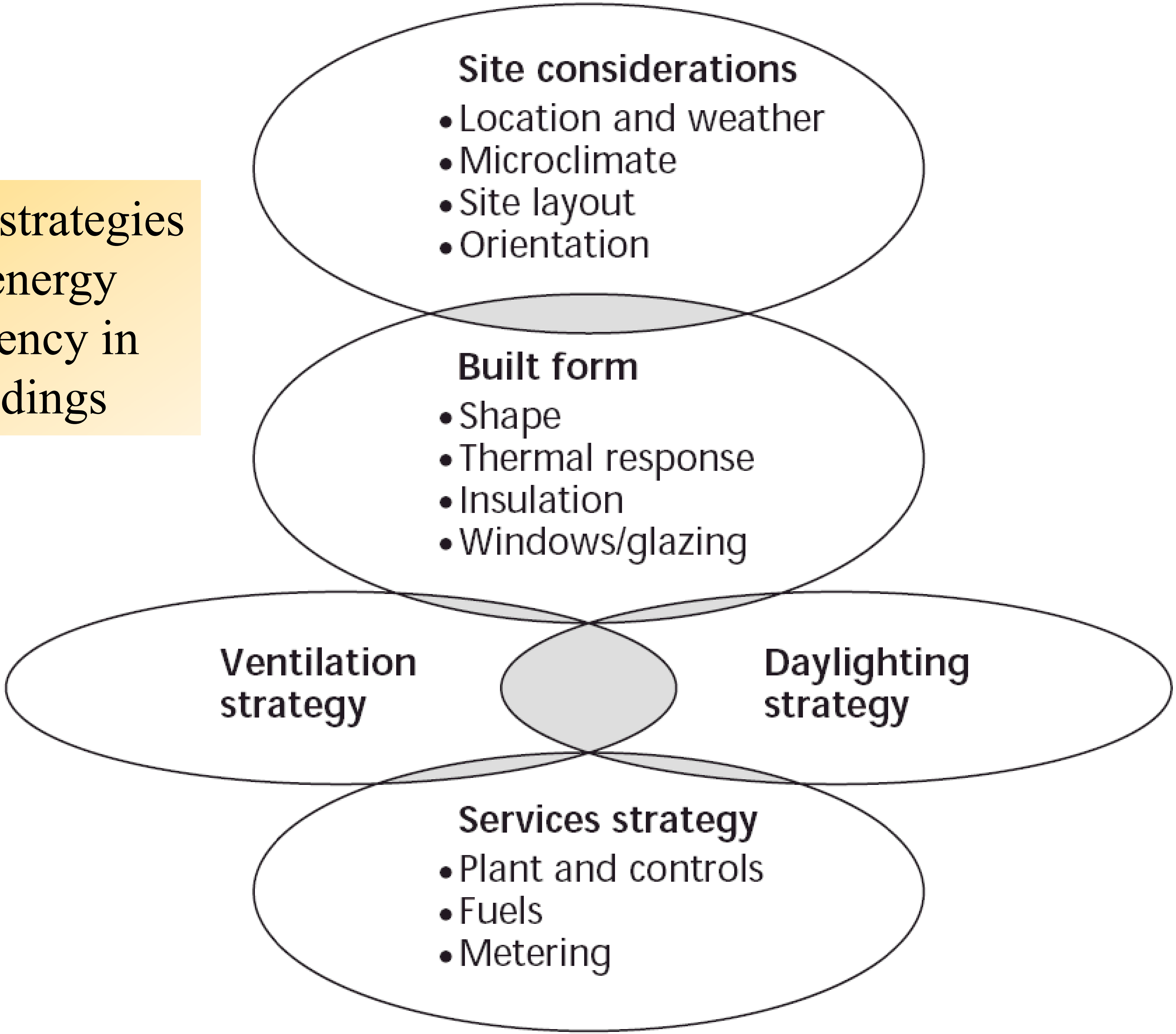


(Source: https://www.greenspec.co.uk/building-design/thermal-mass/)

Thermal behaviour of buildings

- Within the built environment, the thermal environment can be influenced by:
  - 1. Passive building design (e.g. shading, windows, insulation, thermal mass, natural ventilation and so on)
  - 2. Active building systems (e.g. heating, cooling and air conditioning)
  - 3. Personal behaviour (e.g. removing clothing, reducing activity and so on)

Design strategies for energy efficiency in buildings



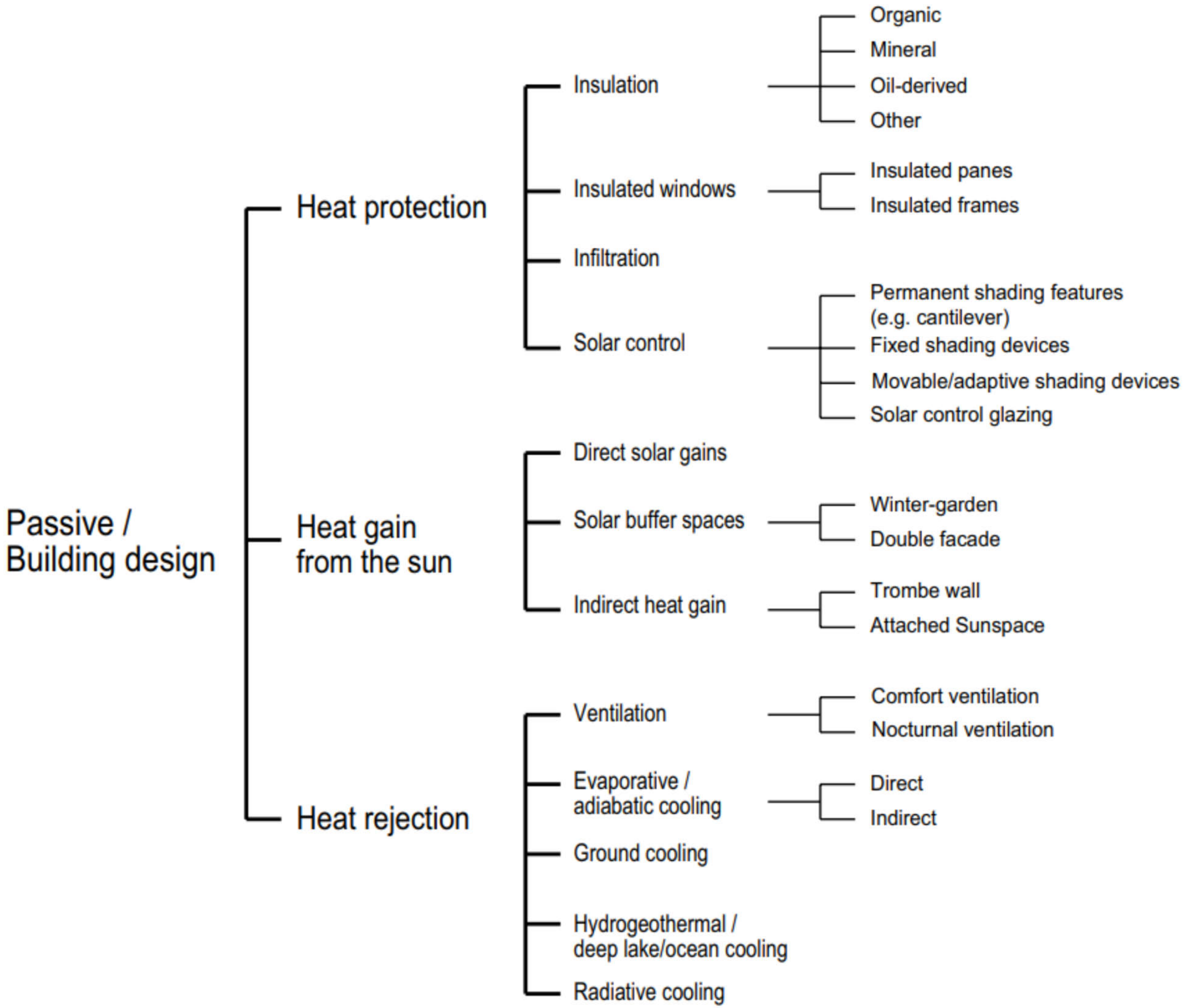
(Source: Energy Efficiency in Buildings: CIBSE Guide F)

Passive building design

- *Passive design* uses layout, fabric and form to reduce or remove mechanical cooling, heating, ventilation & lighting demand
  - Passive cooling/heating + natural ventilation
  - Examples: optimising spatial planning & orientation to control solar gains & maximise daylighting, manipulating the building form & fabric to facilitate natural ventilation strategies and making effective use of thermal mass to help reduce peak internal temperatures

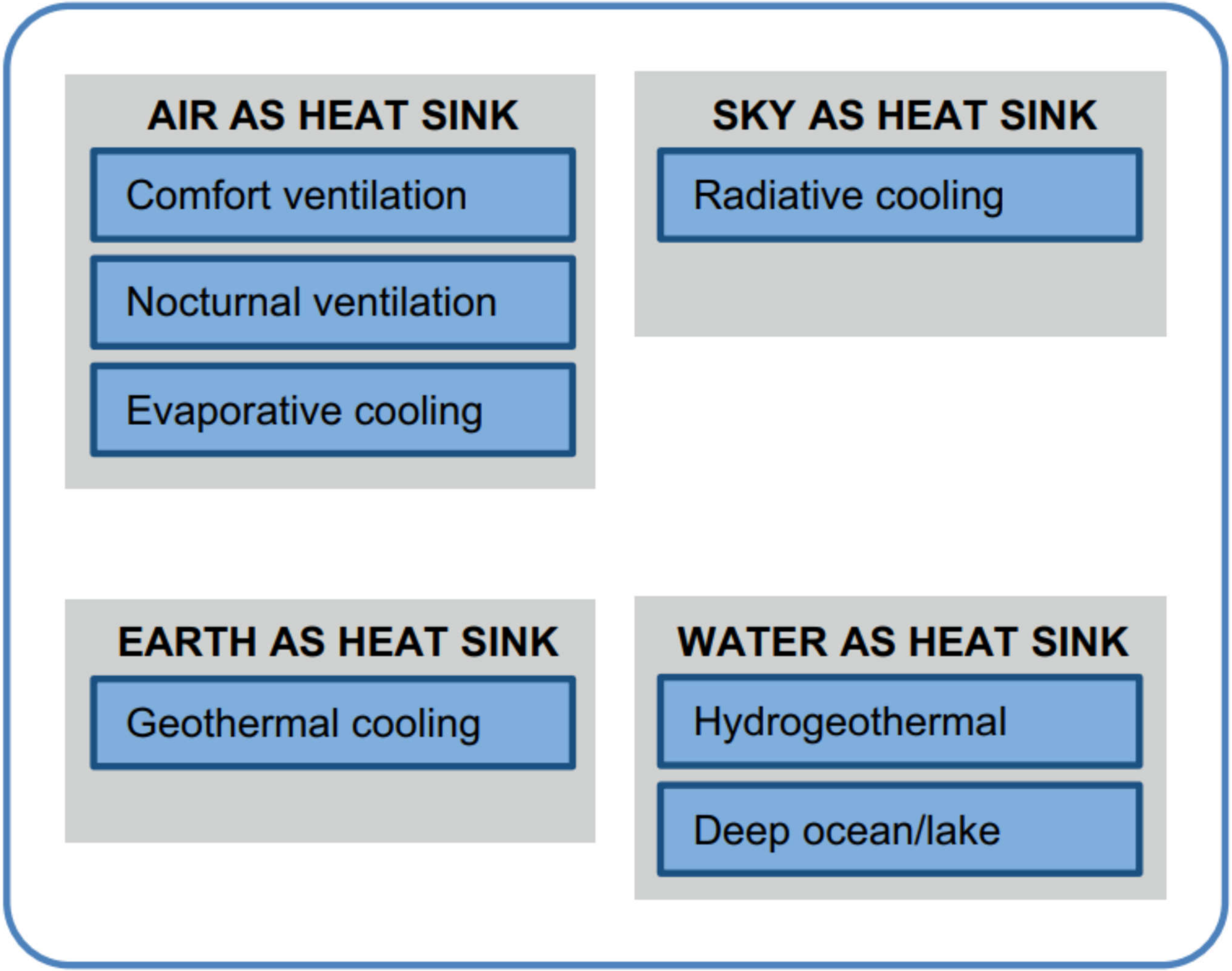
(Source: https://www.designingbuildings.co.uk/wiki/Passive_building_design)

Passive building design measures and their objective



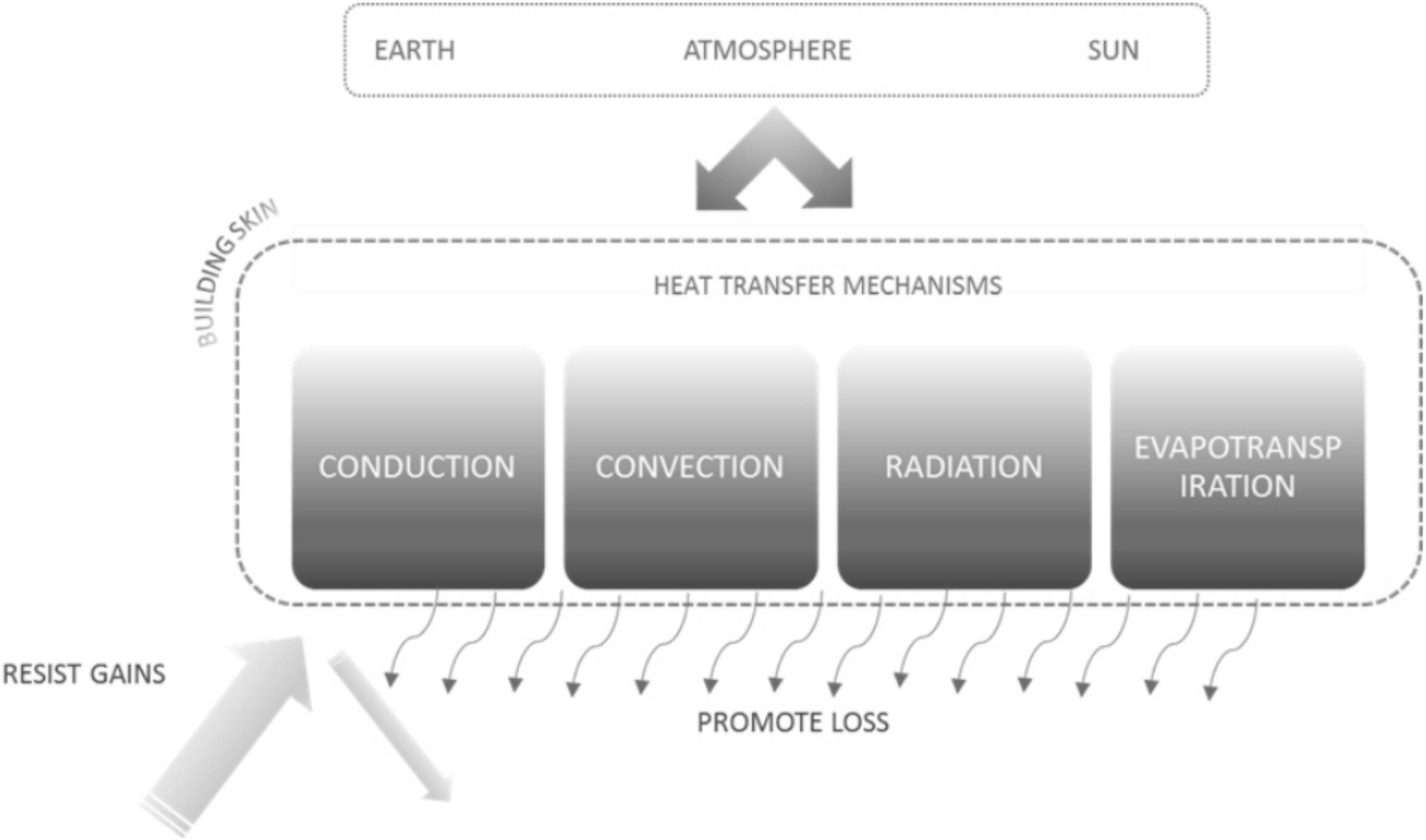
(Source: https://www.researchgate.net/publication/326626129_Environmental_Design_Principles_for_the_Building_Envelope_and_More_Passive_and_Active_Measures)

Passive heat dissipation strategies according to the heat sinks



(Source: https://www.researchgate.net/publication/326626129_Environmental_Design_Principles_for_the_Building_Envelope_and_More_Passive_and_Active_Measures)

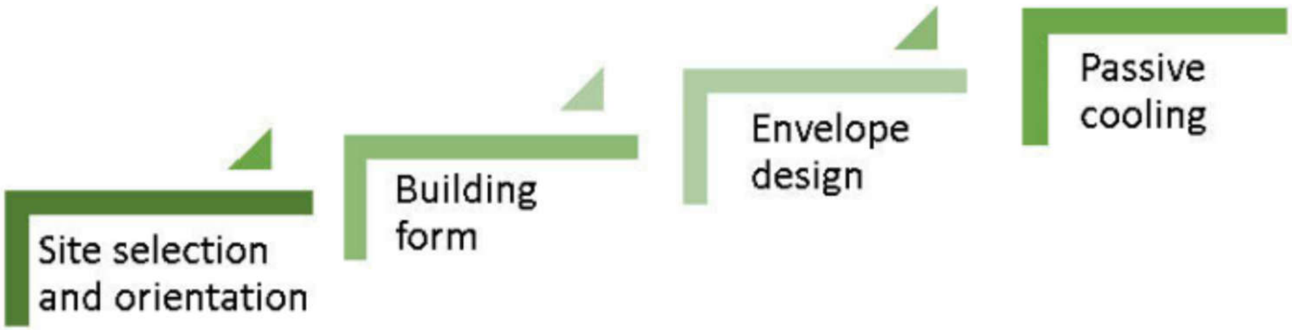
Bioclimatic design strategies for buildings in hot climate: to minimise heat gains into the building and promote heat loss



(Source: https://energypedia.info/images/c/c7/Building_Energy_Efficiency_Guideline_for_Nigeria_2016.pdf)

Passive/Bioclimatic building design strategies for hot climates

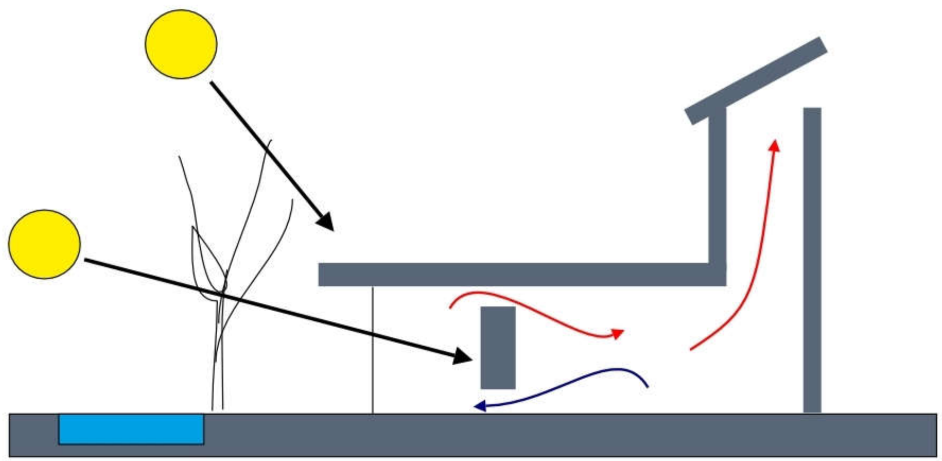
Strategy	**Hot & dry**	**Hot & humid**
Compact geometry	√	X
Exterior shading	√	√
Daylighting	√	√
Window low solar heat gain coefficient	√	√
Cross/stack ventilation (if naturally ventilated)	√	√
Building permeability (if naturally ventilated)	X	√
Roof insulation	√	√
Wall insulation (exterior)	√	X
High thermal mass	√	X
Low thermal mass	X	√
Evaporative cooling	√	X



(Source: https://energypedia.info/images/c/c7/Building_Energy_Efficiency_Guideline_for_Nigeria_2016.pdf)

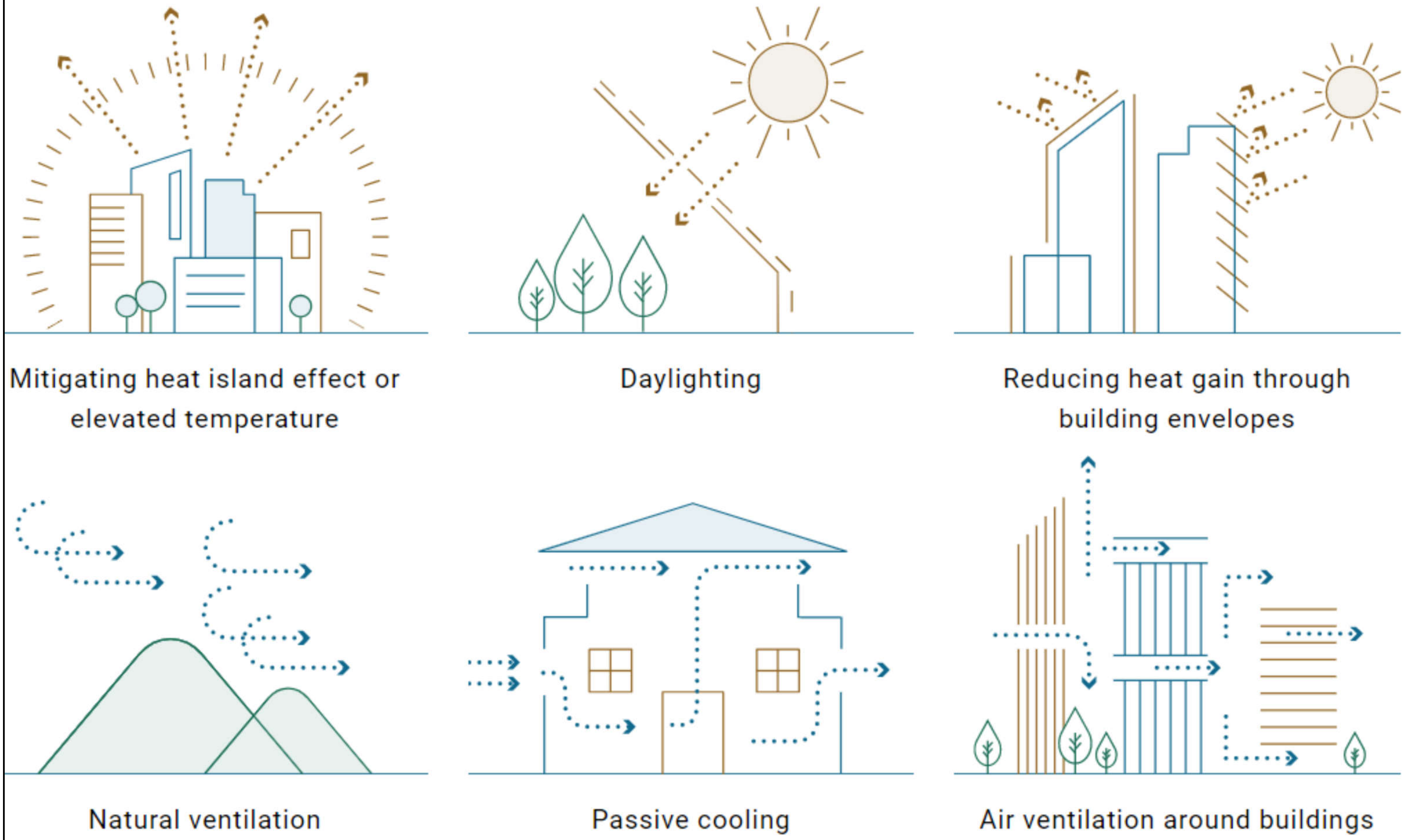
Passive building design

- Passive design considerations:
  - Location, landscape, orientation
  - Massing, shading
  - Material selection
  - Thermal mass, insulation
  - Internal layout



  - The positioning of openings to allow the penetration of solar radiation, visible light and for ventilation

Different aspects of passive design approaches

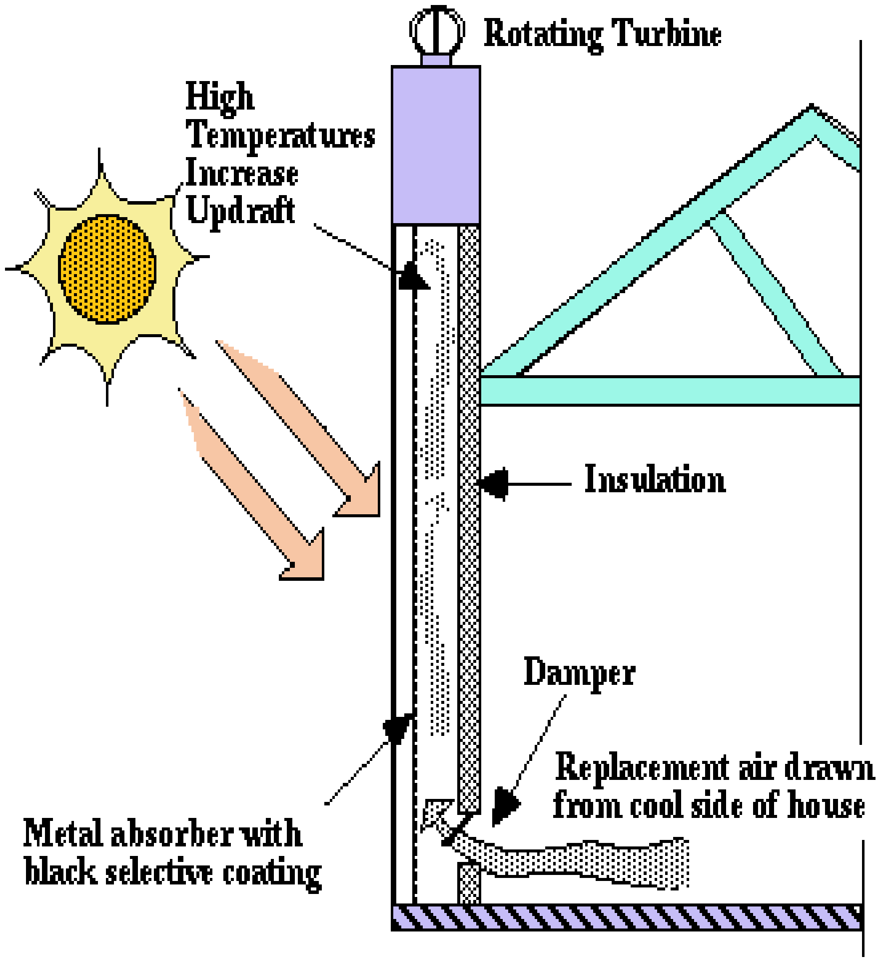


(Source: https://www.archsd.gov.hk/archsd/html/report2021/en/sustainable-building.html)

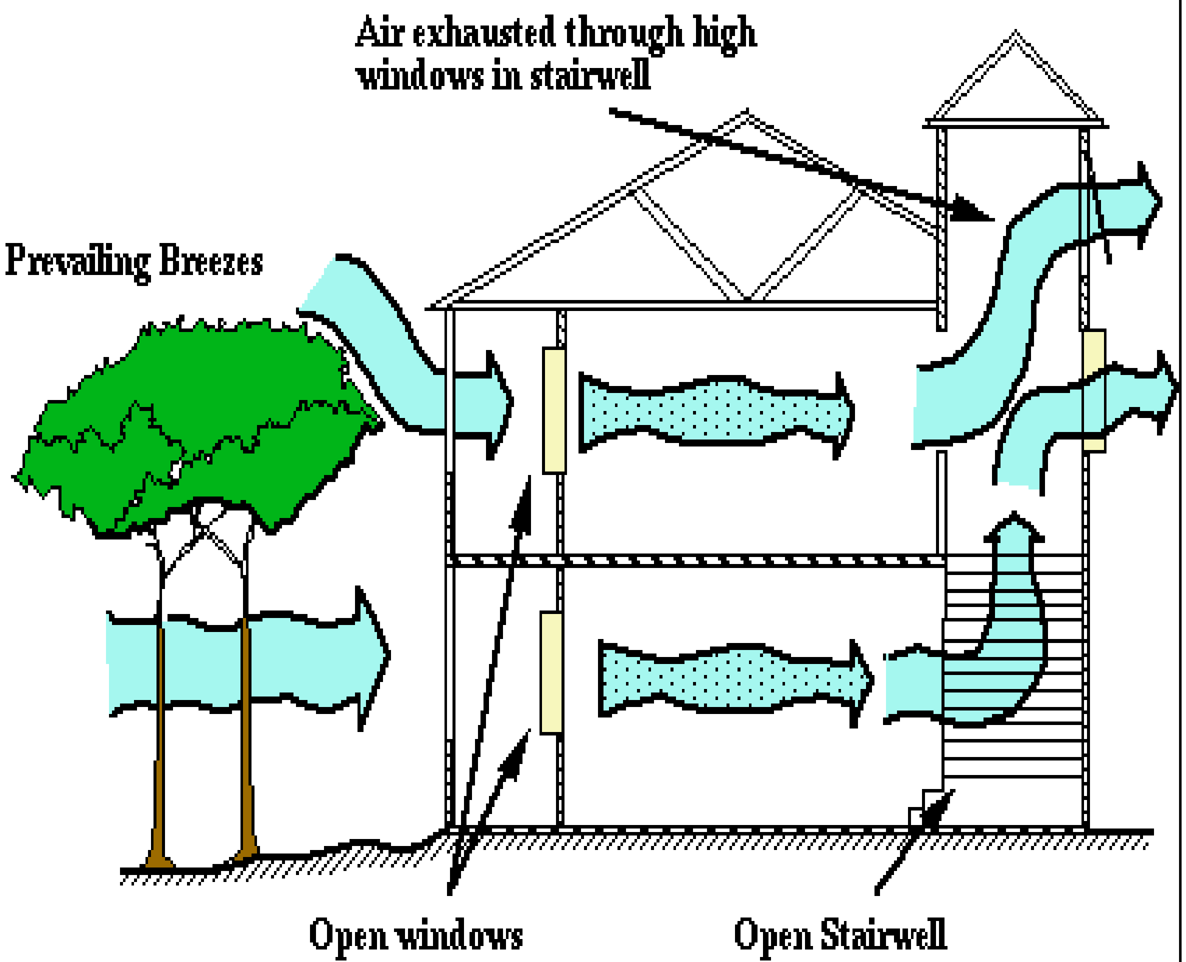
Passive building design

- Passive cooling
  - A building design approach that focuses on *heat gain control* and *heat dissipation* in a building in order to improve the indoor thermal comfort with low or nil energy consumption
  - This approach works either by preventing heat from entering the interior (*heat gain prevention*) or by removing heat from the building (*natural cooling*)

Examples of passive cooling designs



Thermal chimney

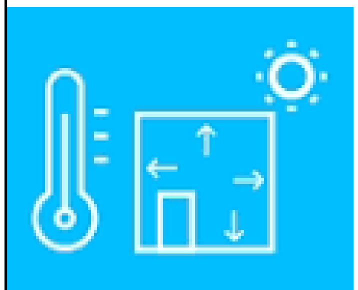


Natural ventilation

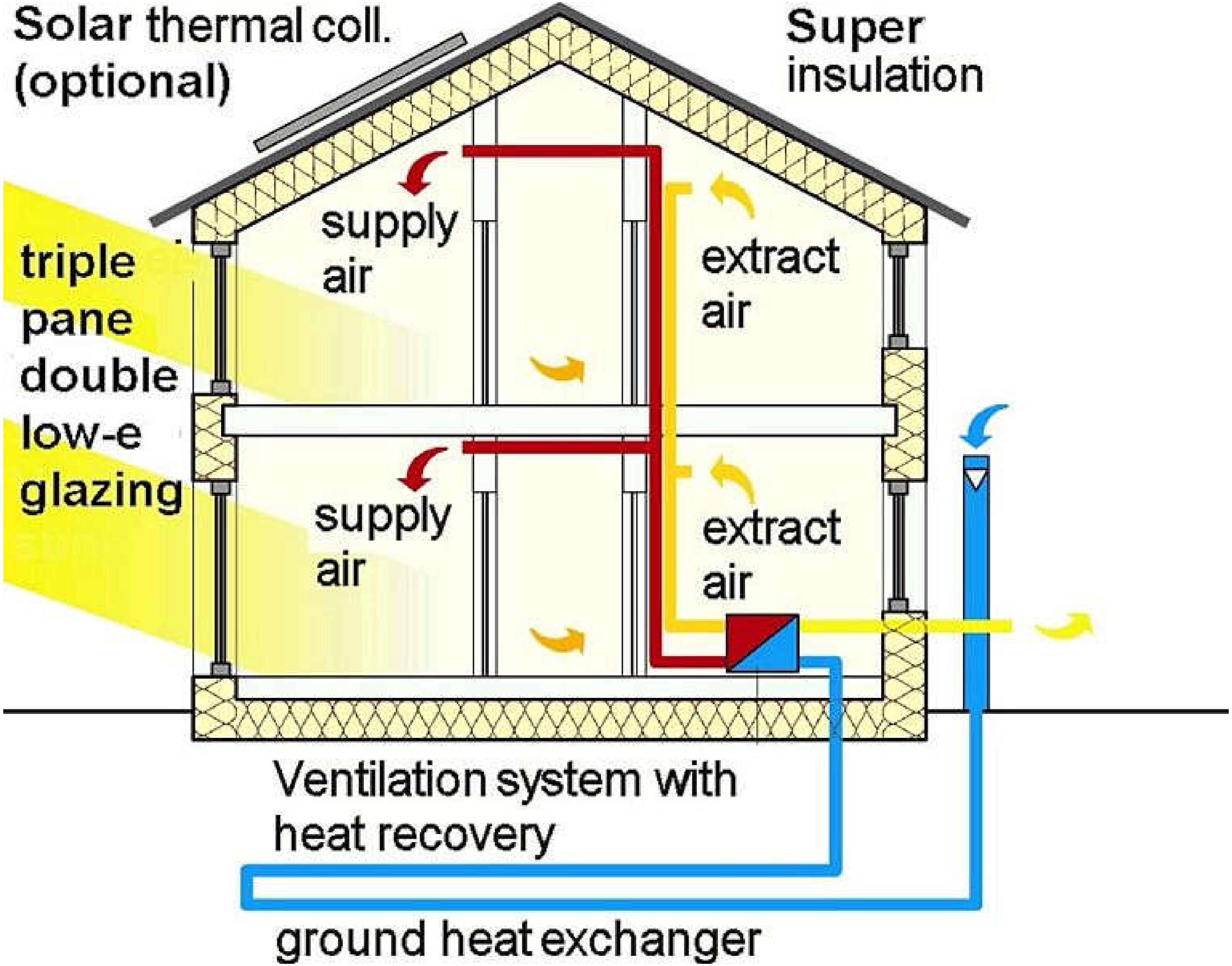
(See also: http://en.wikipedia.org/wiki/Passive_cooling and http://passivesolar.sustainablesources.com/)

Passive building design

- Passive cooling (cont'd)
  - Natural cooling utilizes on-site energy, available from the natural environment, combined with the architectural design of building components (e.g. building envelope), rather than mechanical systems to dissipate heat
    - It depends not only on the architectural design but how it uses the local site natural resources as heat sinks (i.e. everything that absorbs or dissipates heat). Examples of on-site heat sinks are the upper atmosphere (night sky), the outdoor air (wind), and the earth/soil

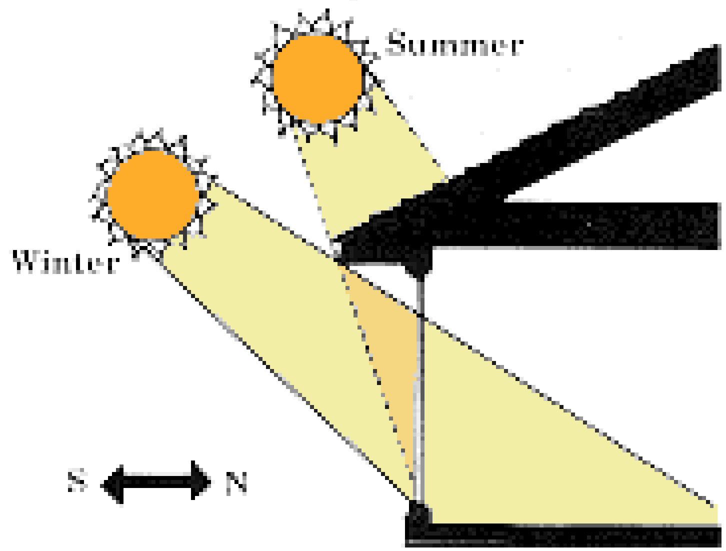


Passive house design to achieve low energy requirements for the building energy balance



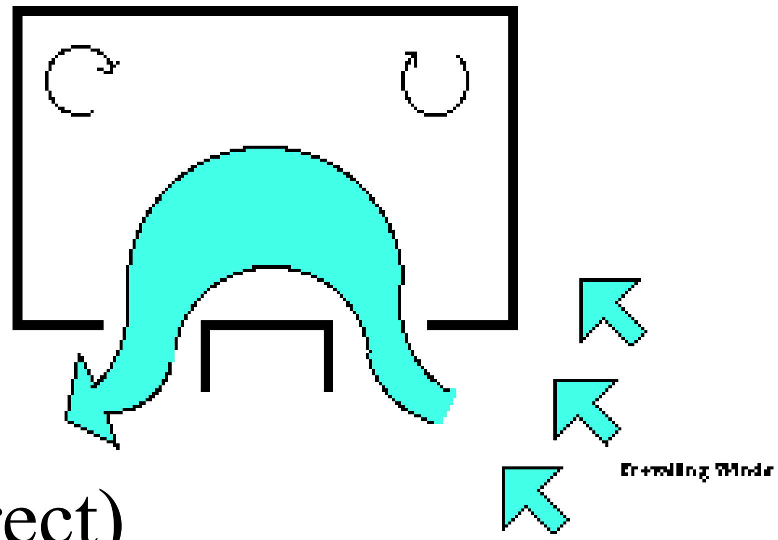
Passive building design

- Passive cooling (cont'd)
  - Preventative techniques
    - Microclimate and site design
    - Solar control
    - Building form and layout
    - Thermal insulation
    - Behavioral and occupancy patterns
    - Internal gain control
  - Modulation and heat dissipation techniques
    - Thermal mass + Natural cooling



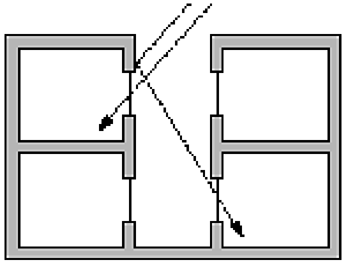
Passive building design

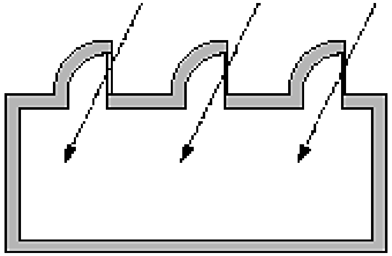
- Passive cooling (cont'd)
  - Ventilation
    - Cross ventilation
    - Stack ventilation
    - Night flush ventilation
  - Radiative cooling (direct/indirect)
  - Evaporative cooling
  - Earth coupling (direct/indirect)

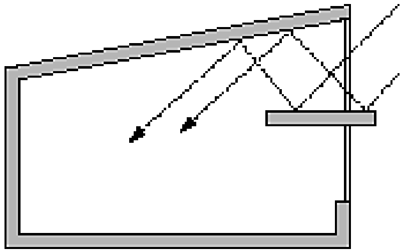


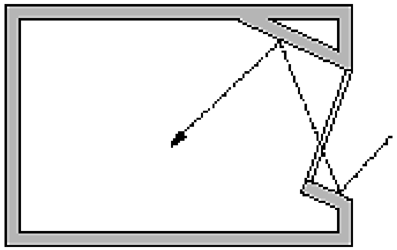
(See also: http://en.wikipedia.org/wiki/Passive_cooling)

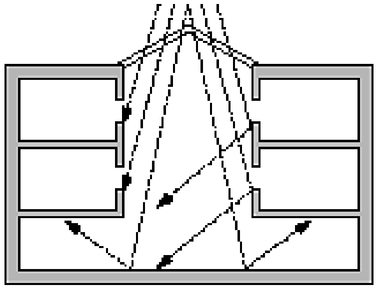
Daylighting design and control

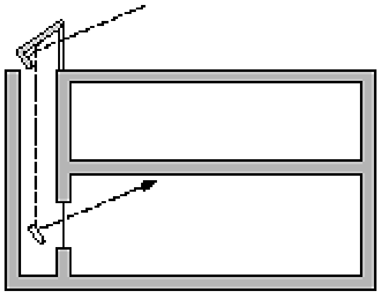

Light well

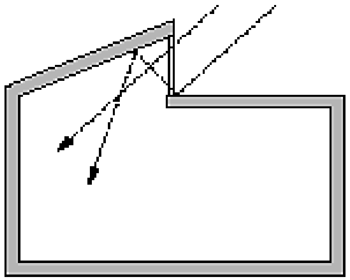

Roof monitor

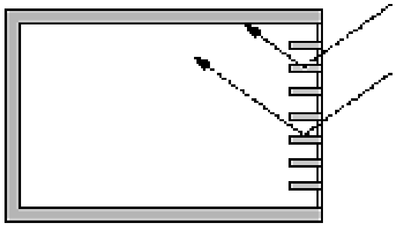

Light shelf

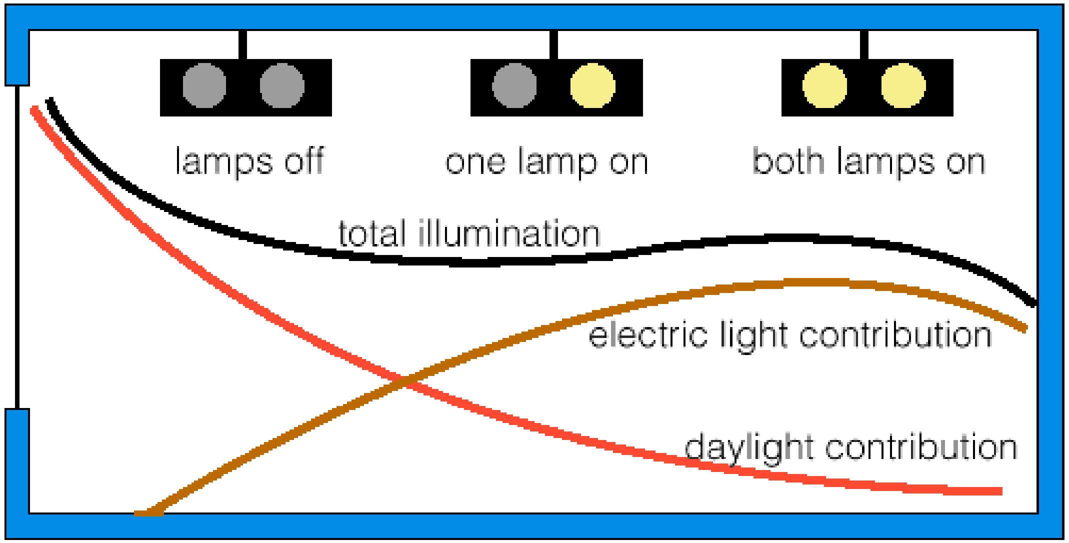

External reflectors


Atrium


Light duct


Clerestory

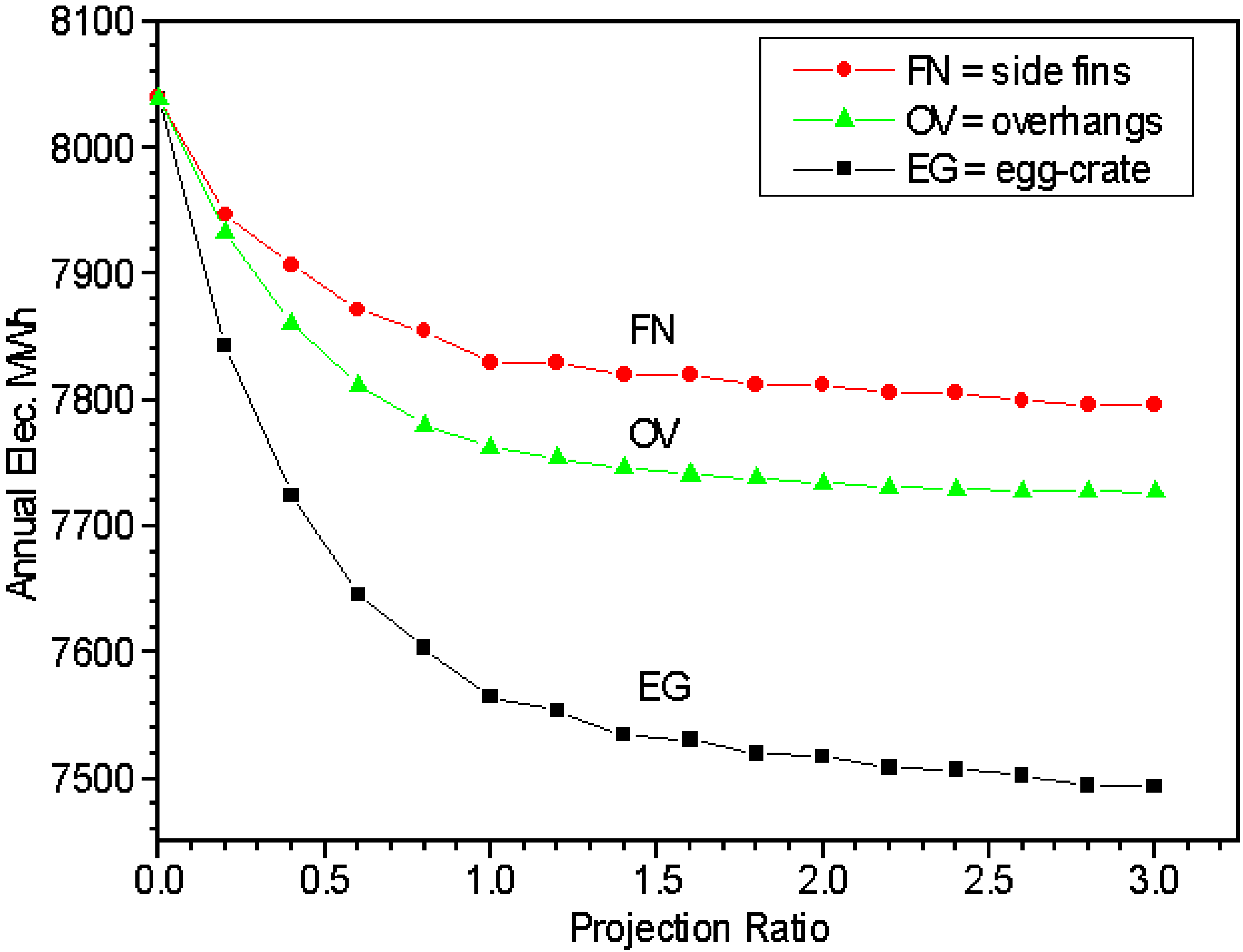

Reflective blinds



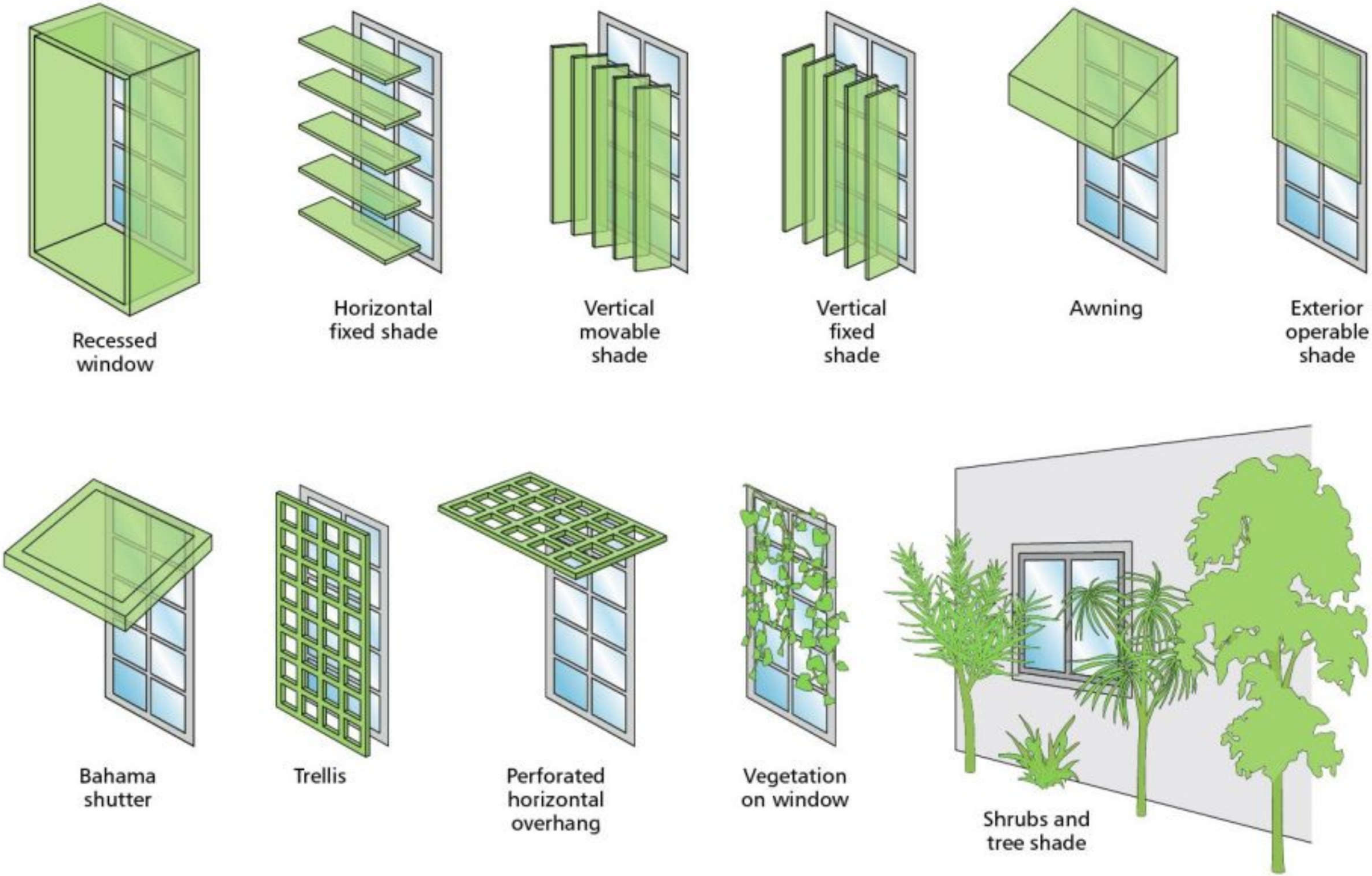
Solar control

- First determine when solar radiation would be a welcome input (solar heating for the underheated period) or when it should be excluded (the overheated period)
- Shading design 遮陽設計
  - 1. Vertical devices (e.g. vertical louvres or fins)
  - 2. Horizontal devices (e.g. projecting eaves)
  - 3. Egg-crate devices

Example: Effects of external shading on energy consumption

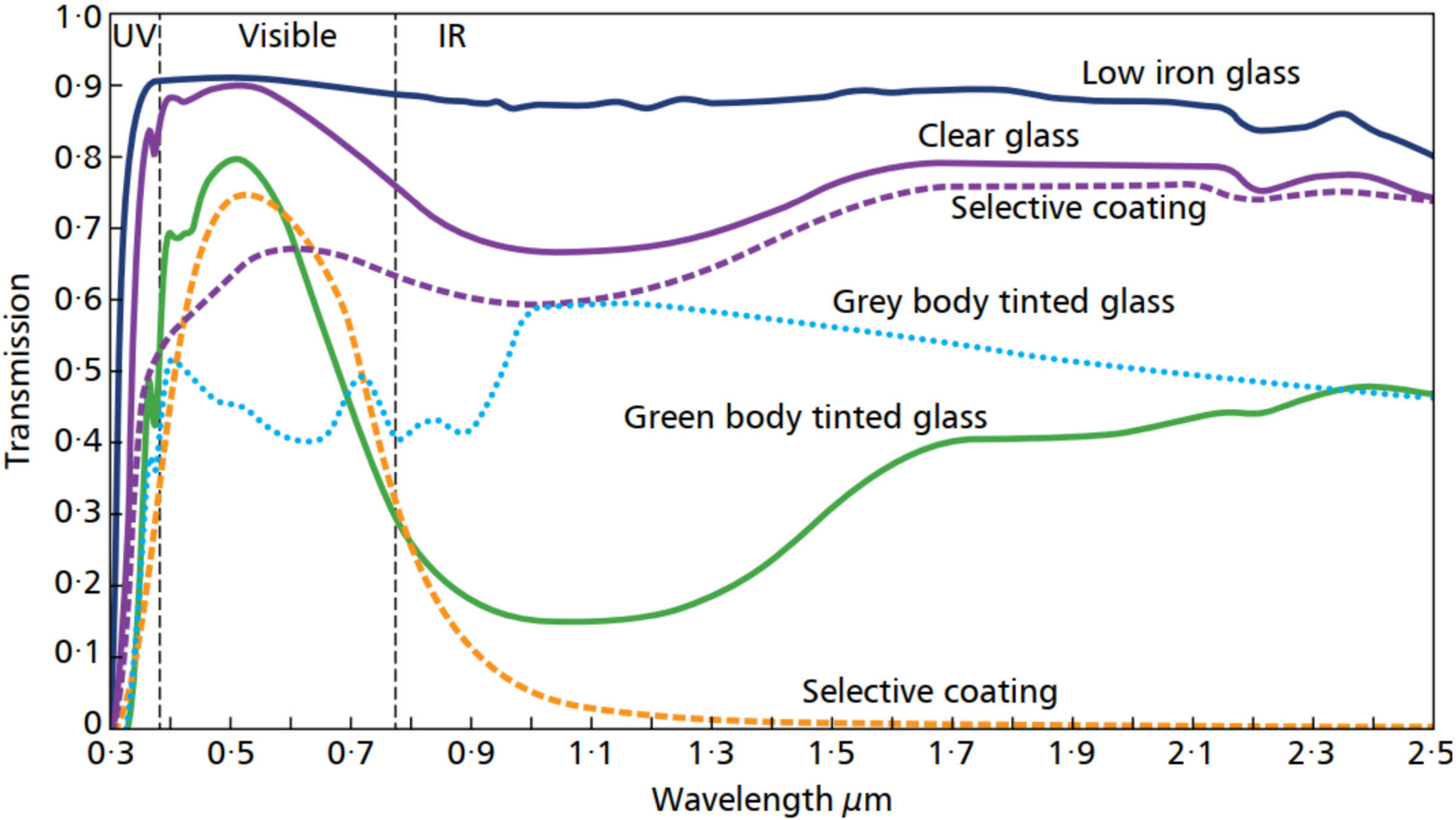


Examples of window shading methods



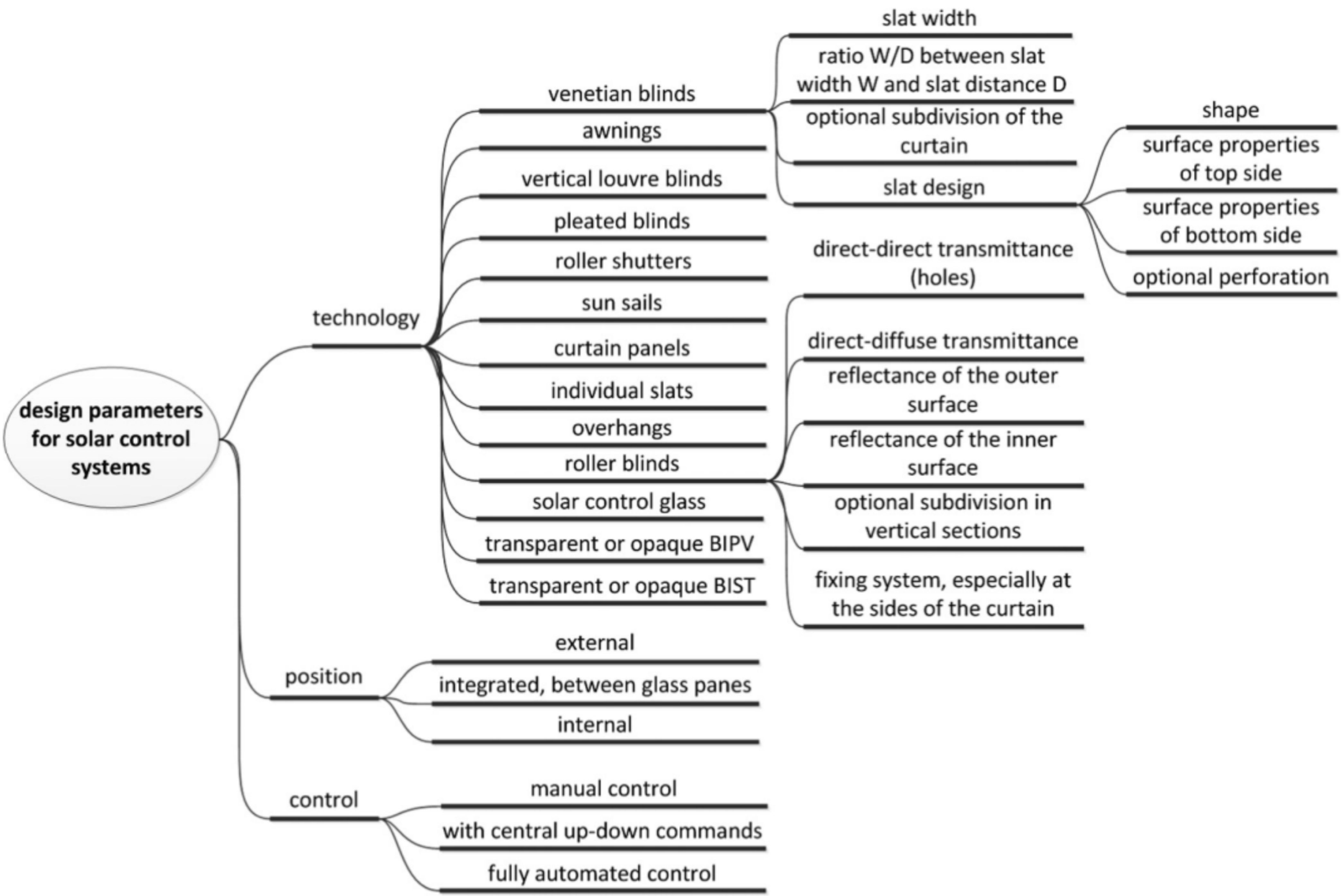
(Source: https://mitsidi.com/new-cibse-guide-building-tropical-environments/)

Spectral transmittance of different glass types



(Source: SLL, 2014. *Daylighting: A Guide for Designers*, Lighting Guide 10, The Society of Light and Lighting (SLL), London.)

Design parameters for solar-control systems



(Source: https://doi.org/10.1016/j.solener.2016.12.044)

Solar control

- Glare/Thermal control strategies:
  - Automated exterior shading
  - Fixed exterior architectural shading
  - Exterior fabric awnings
  - High performance glazing
  - Operable windows
  - Automated interior shading / double skin systems
  - Manual interior shading

Different shading solutions & their effects

Interior shading, Venetian blind

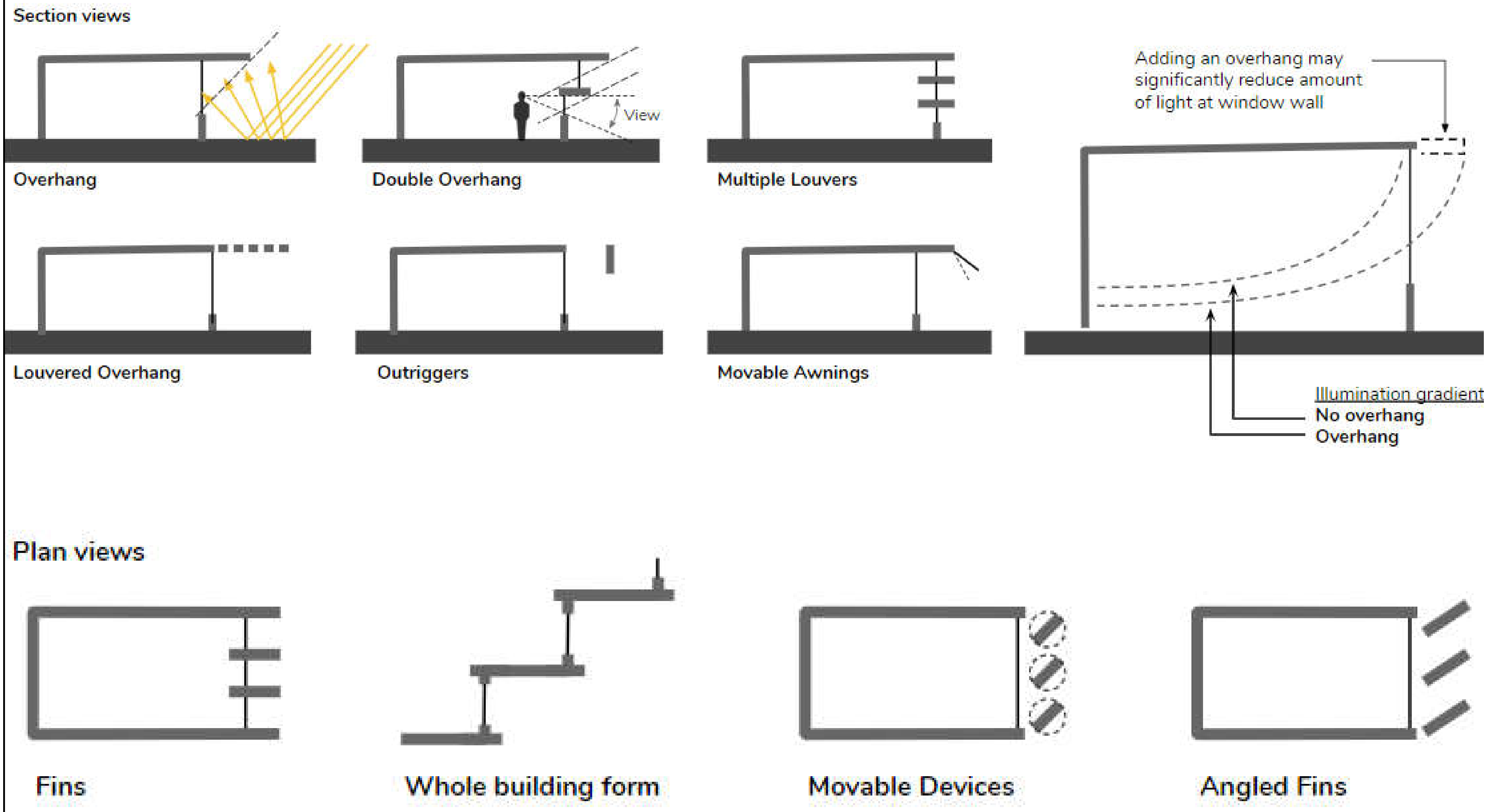
Exterior shading, roller shutter

Interior shading, pleated Blind

Exterior shading, awning blind

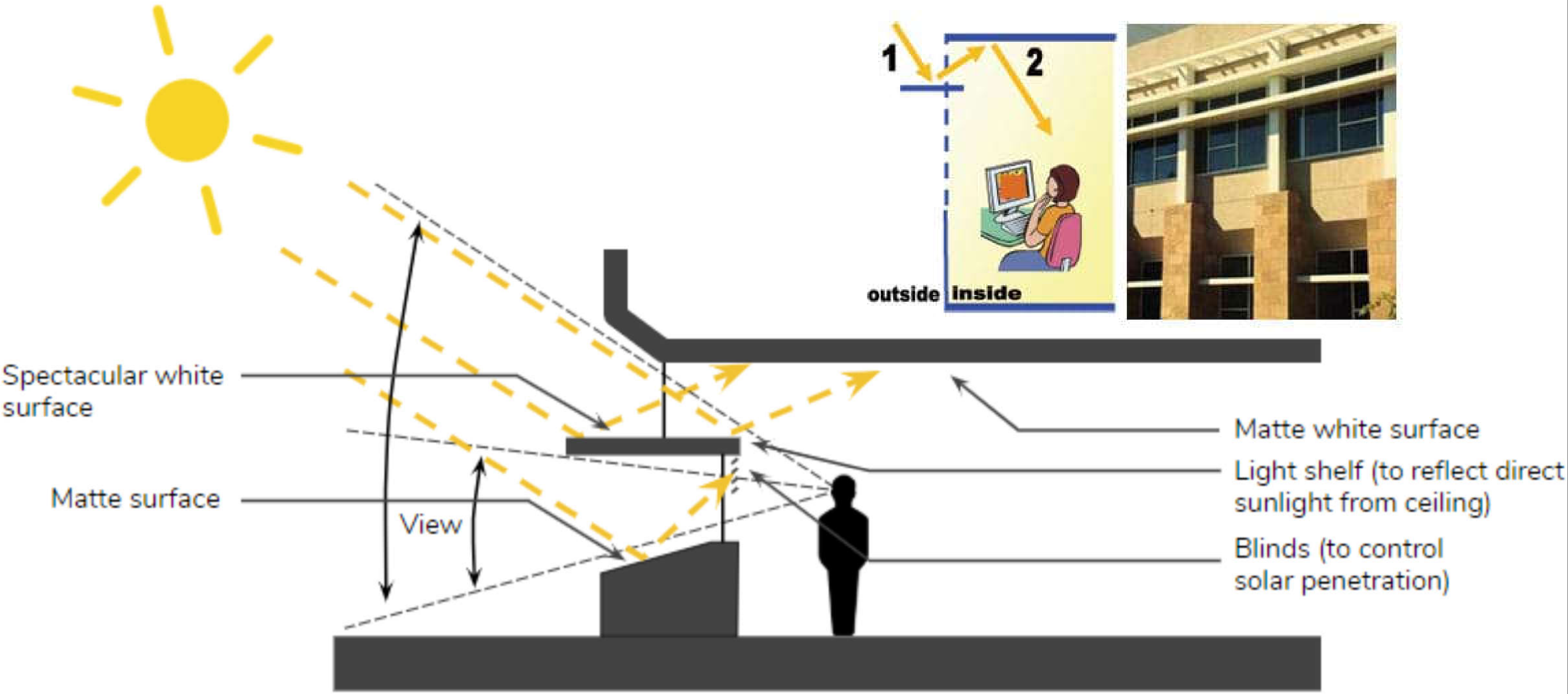
(Source: https://www.velux.com/what-we-do/research-and-knowledge/deic-basic-book/daylight/parameters-influencing-daylighting-performance)

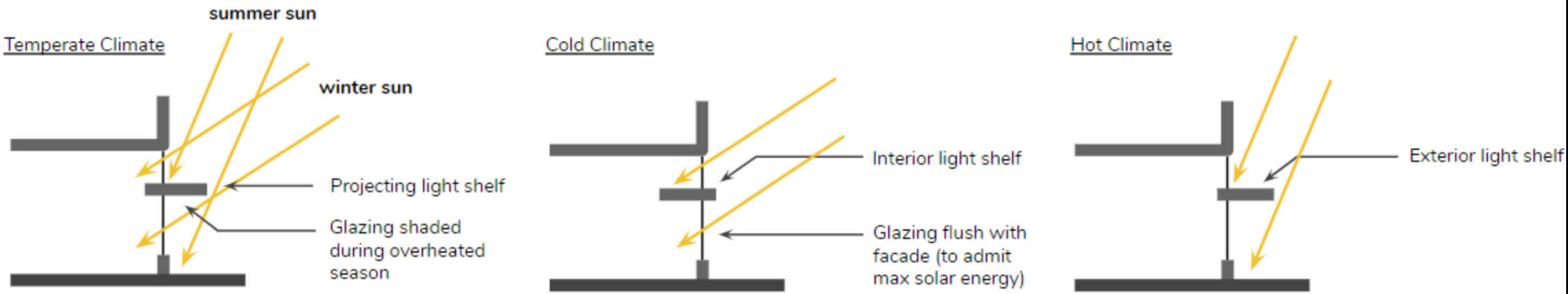
Horizontal & vertical shading devices



(Source: https://planlux.net/sunlight-shading-redirecting-devices/)

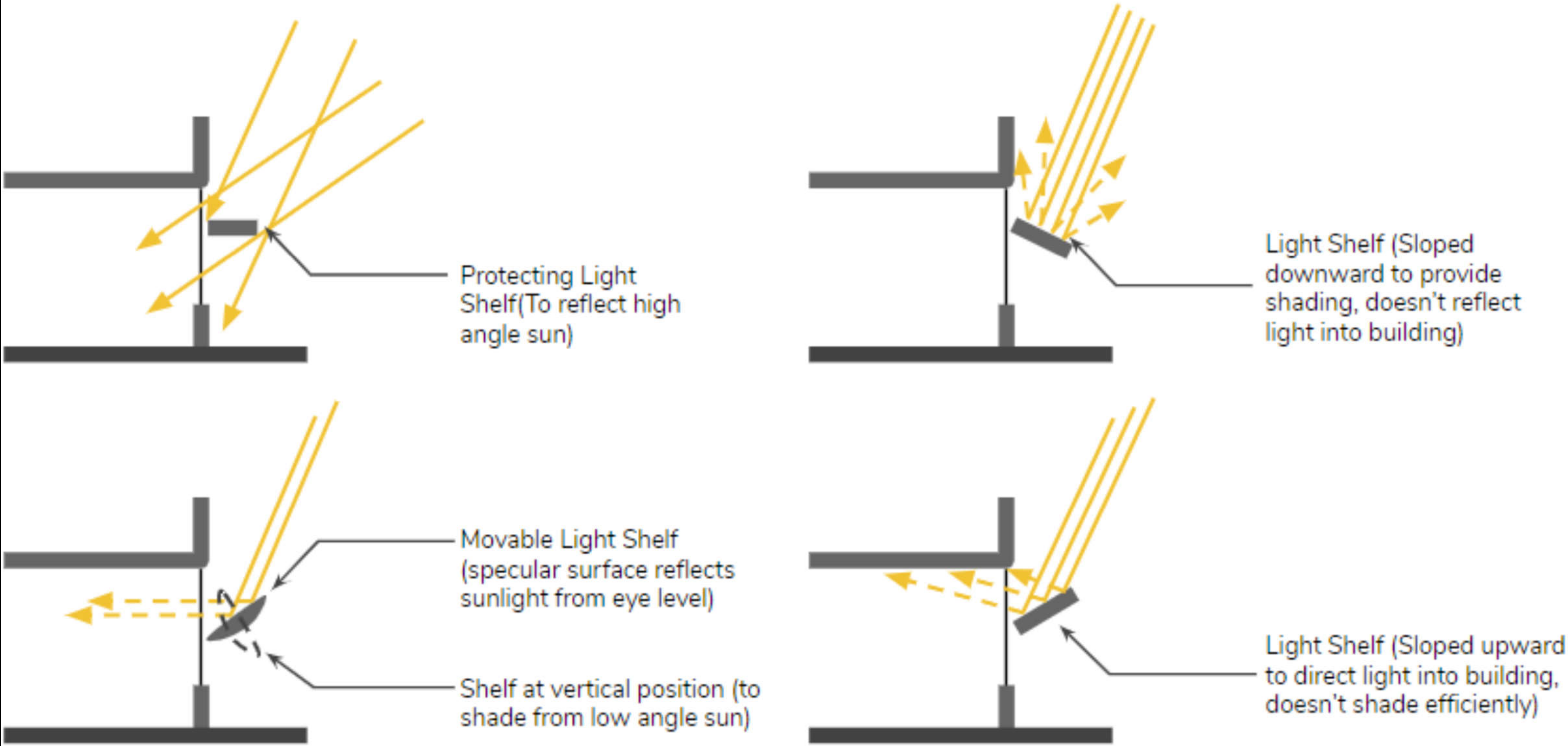
Light shelves for horizontal shading & redirecting





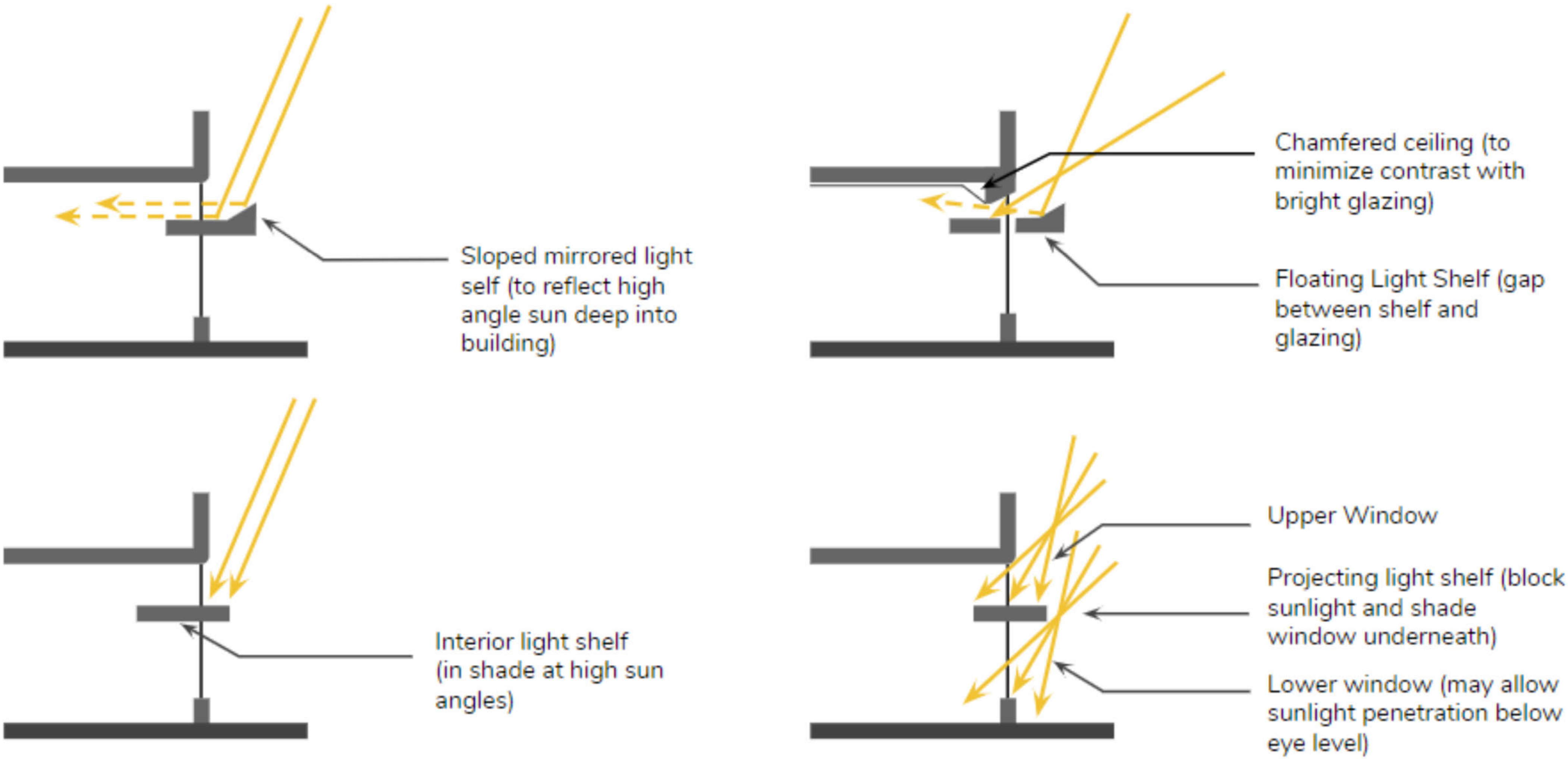
(Source: https://planlux.net/sunlight-shading-redirecting-devices/)

Projecting light shelves provide additional shading for the lower window; sloping the shelves to distribute light



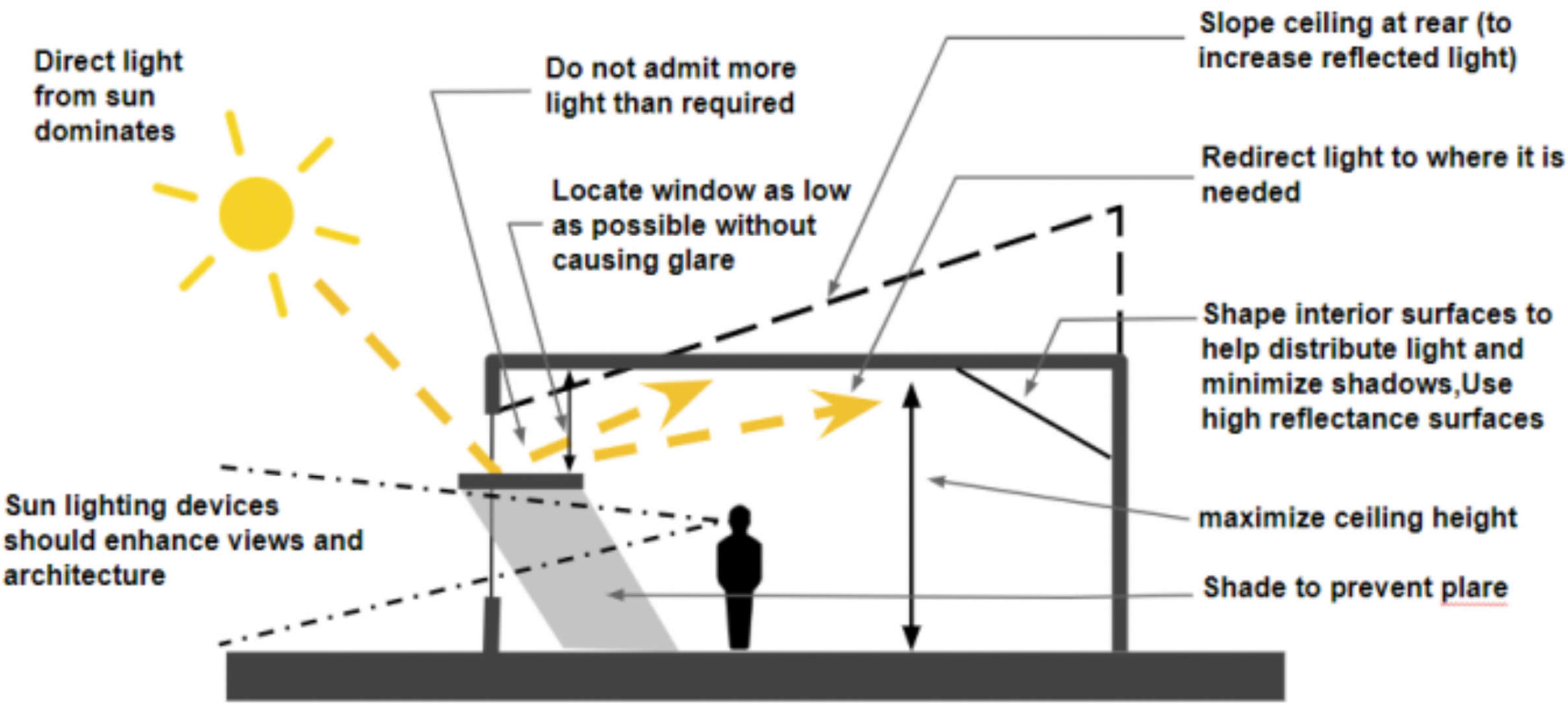
(Source: https://planlux.net/sunlight-shading-redirecting-devices/)

Level light shelf with an inward sloping wedge pushing high angle sunlight more deeply into space



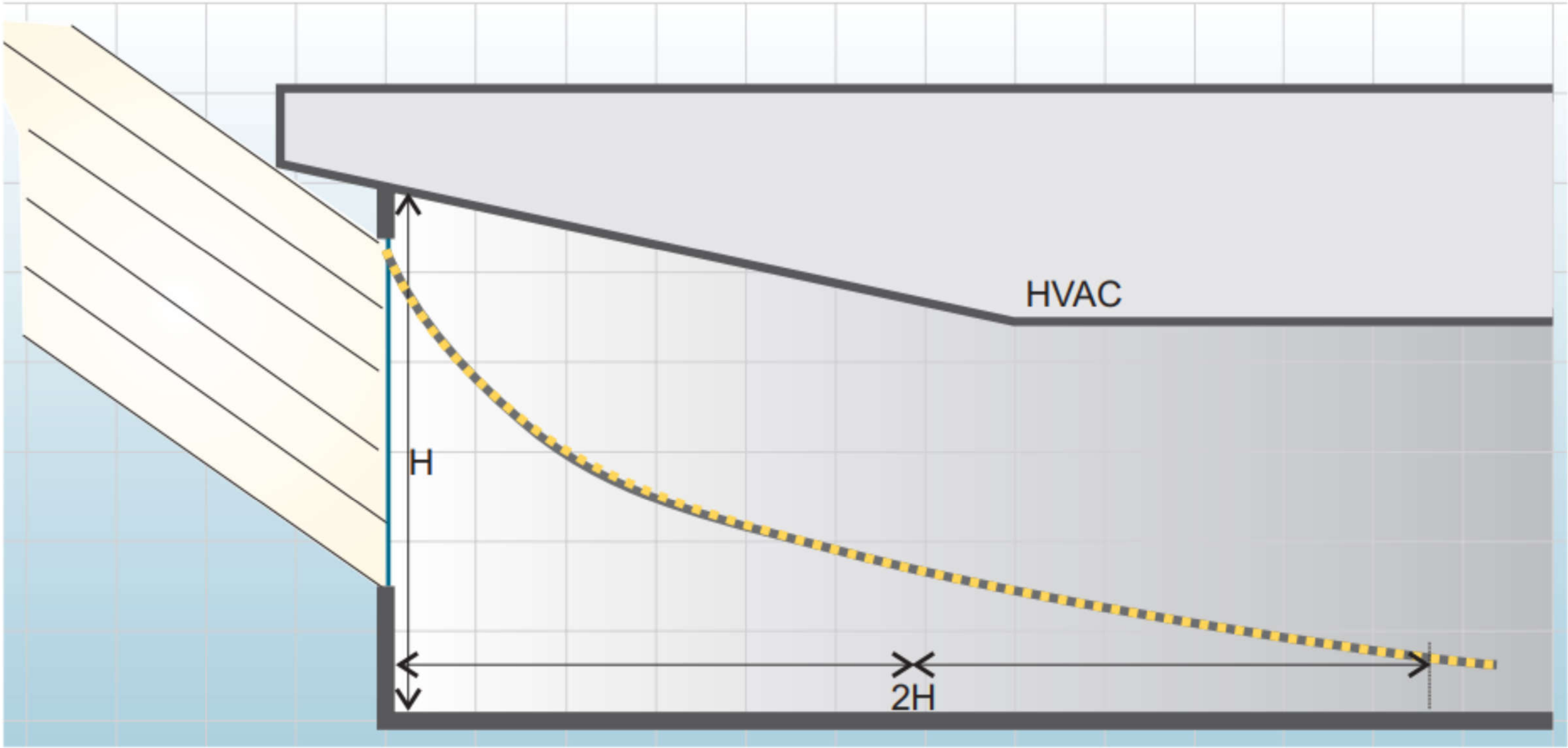
(Source: https://planlux.net/sunlight-shading-redirecting-devices/)

Sunlighting strategies (should be integrated with architecture to use the sunlight indirectly)



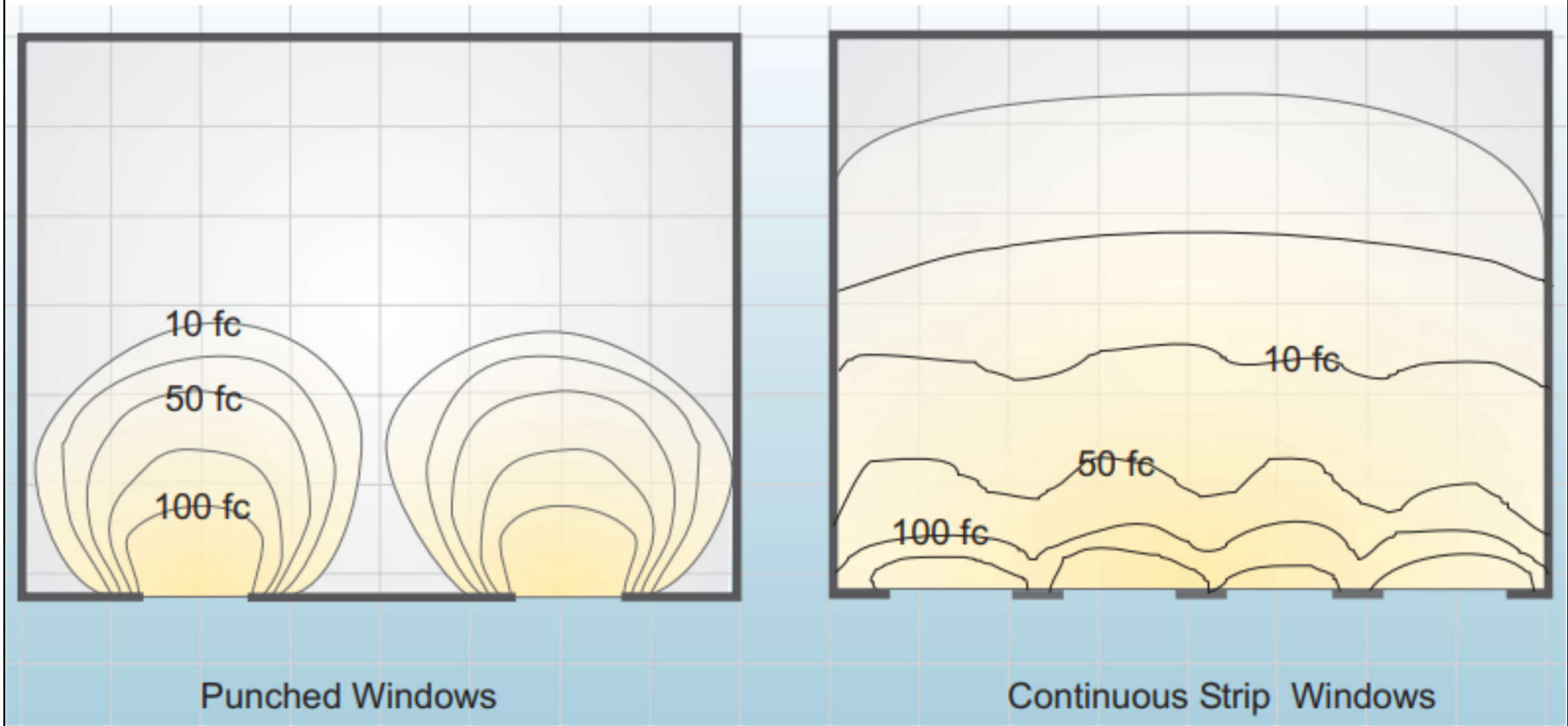
(Source: https://planlux.net/sources-of-natural-light-sunlight-strategies/)

Sidelit building with sloped ceiling at perimeter



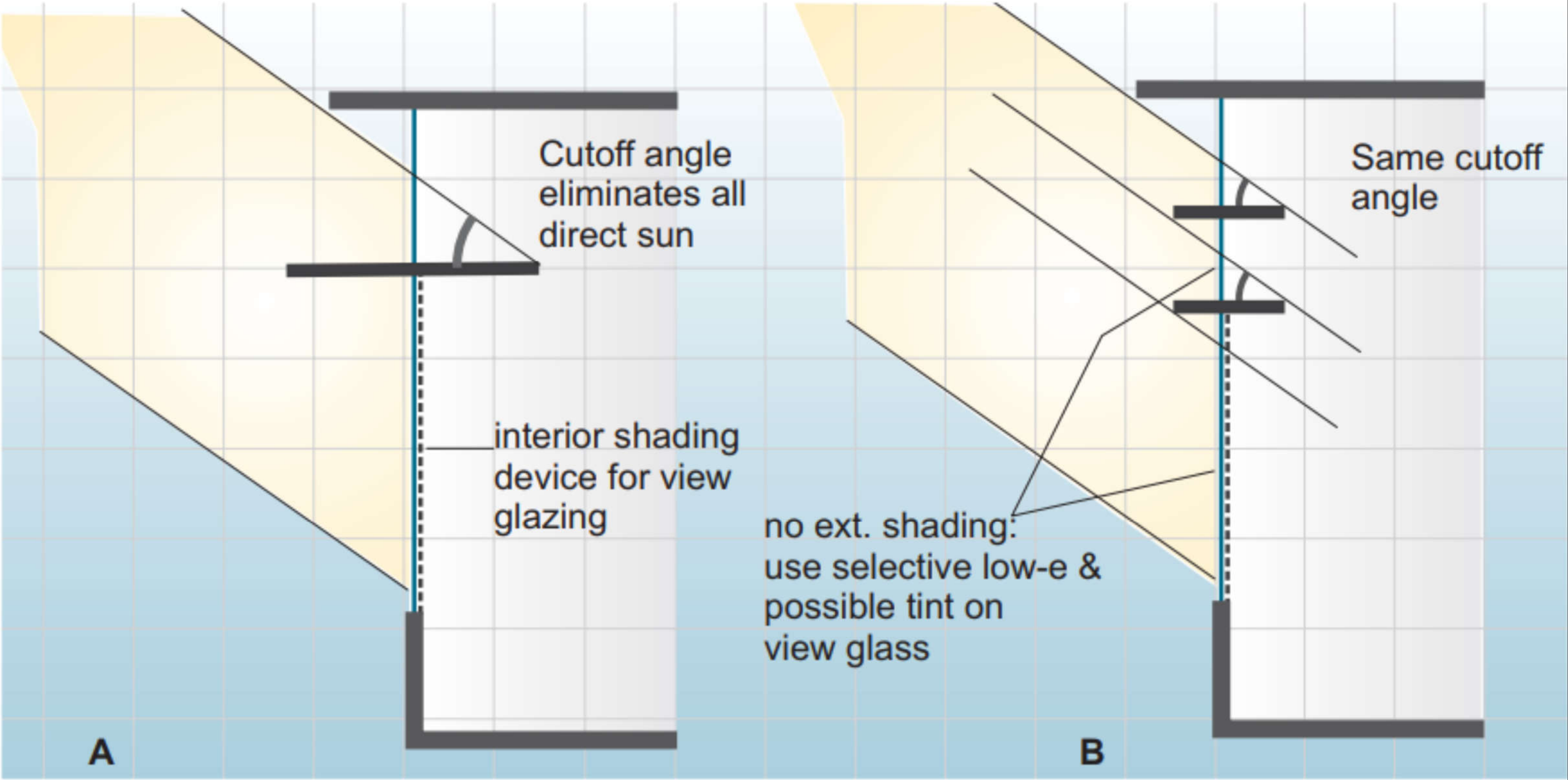
(Source: Advanced Lighting Guidelines 2003)

Lighting level contours for punched windows & continuous strip windows



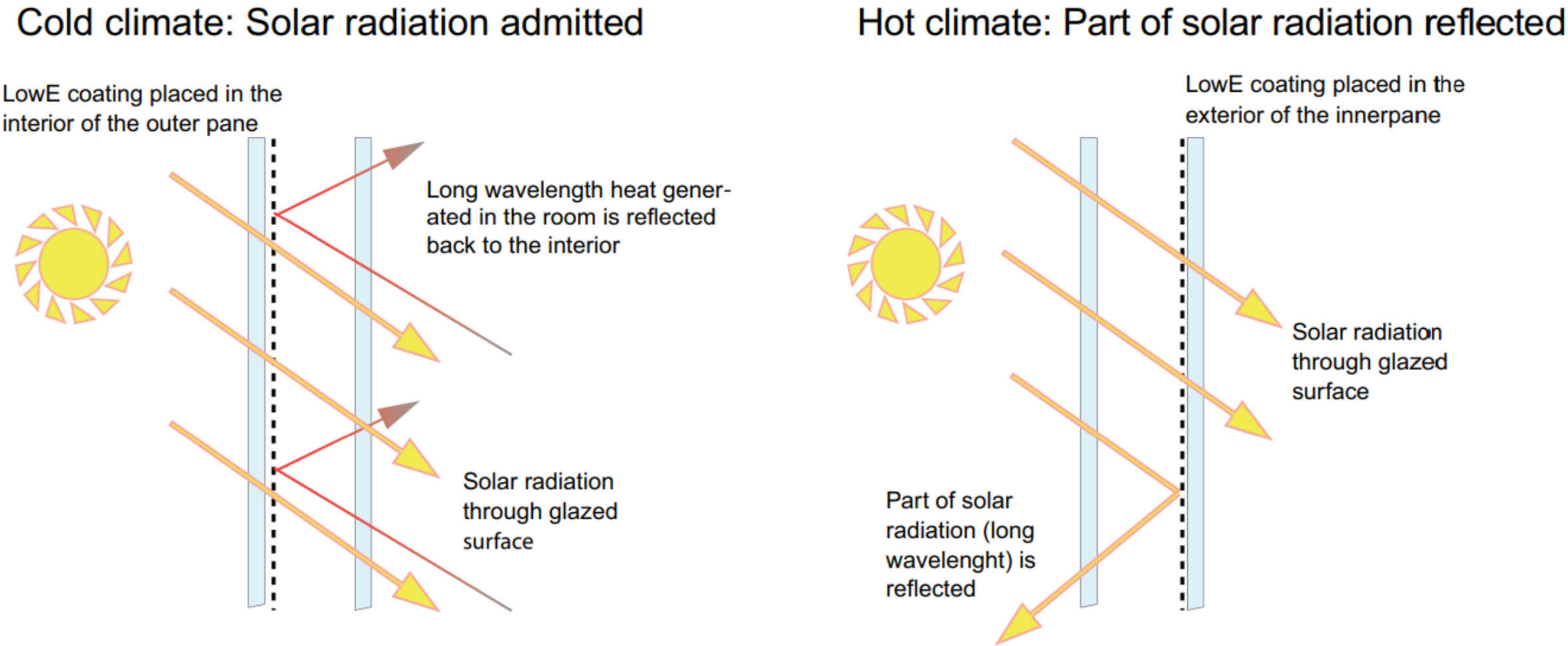
(Source: Advanced Lighting Guidelines 2003)

Cut-off angles for light shelf & louvre system



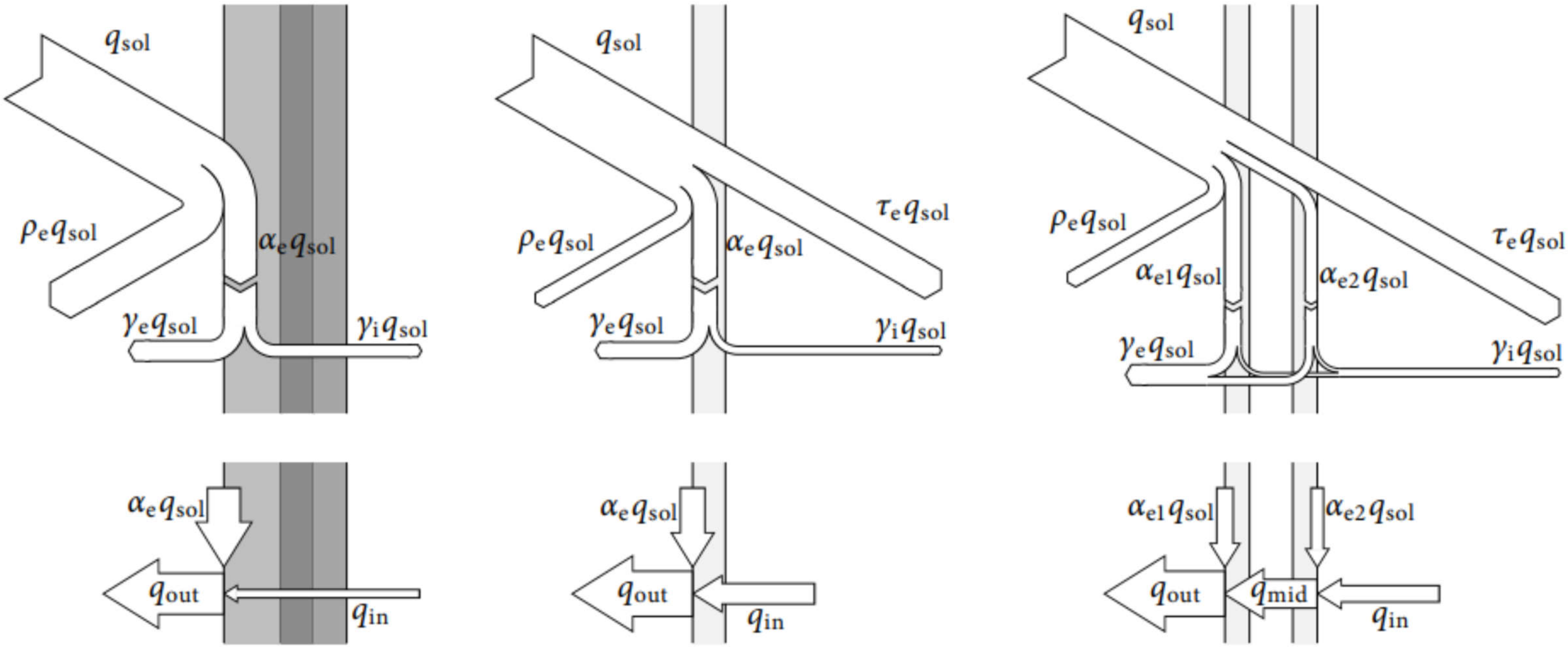
(Source: Advanced Lighting Guidelines 2003)

Scheme of low-e coating placement in cold and hot climates



(Source: https://www.researchgate.net/publication/326626129_Environmental_Design_Principles_for_the_Building_Envelope_and_More_Passive_and_Active_Measures)

Solar gains for a non-transparent building element (left), a transparent or single glazed building element (middle) and a double glazed building element (right)

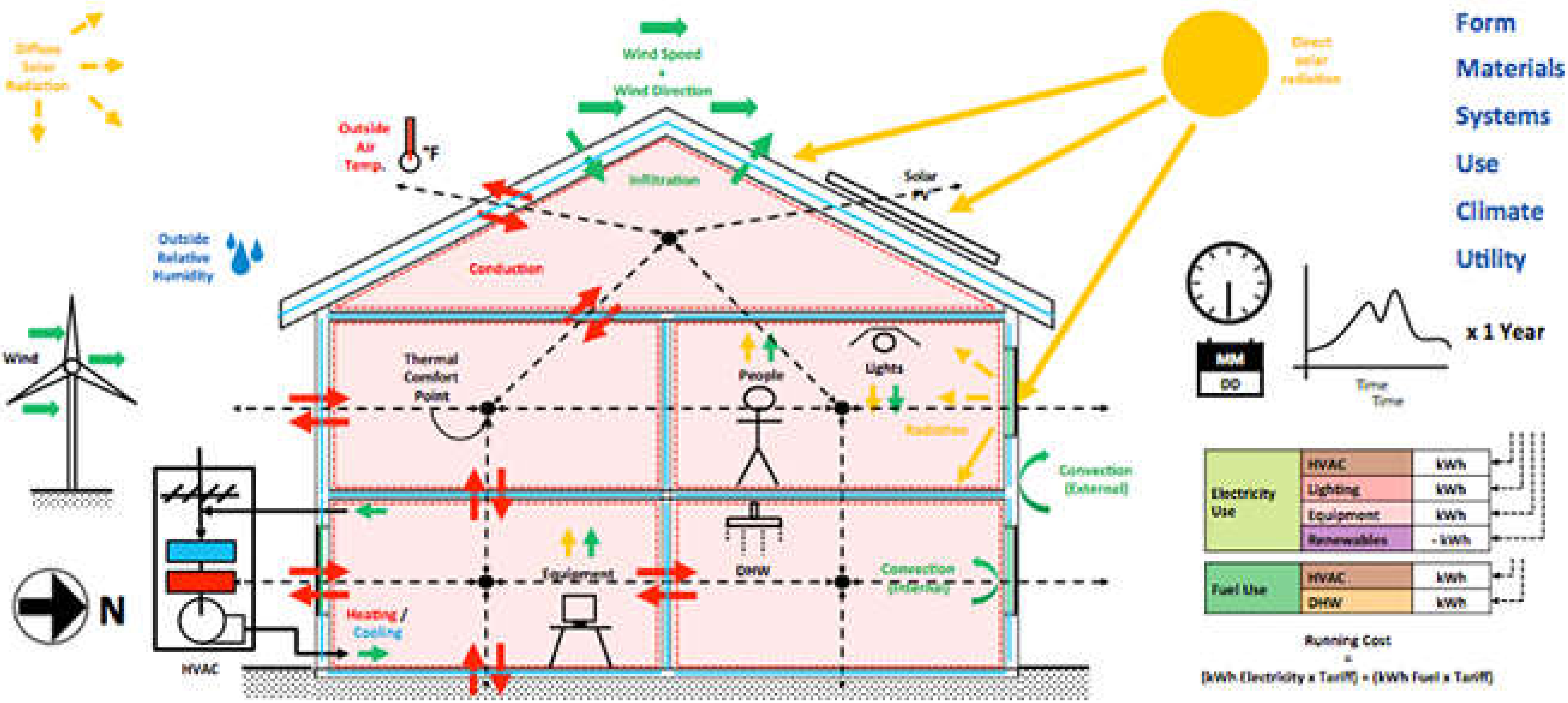


(Source: Pinterić M., 2021. *Building Physics: From physical principles to international standards*, Second Edition, Springer, Cham, Switzerland.)

Dynamic simulation

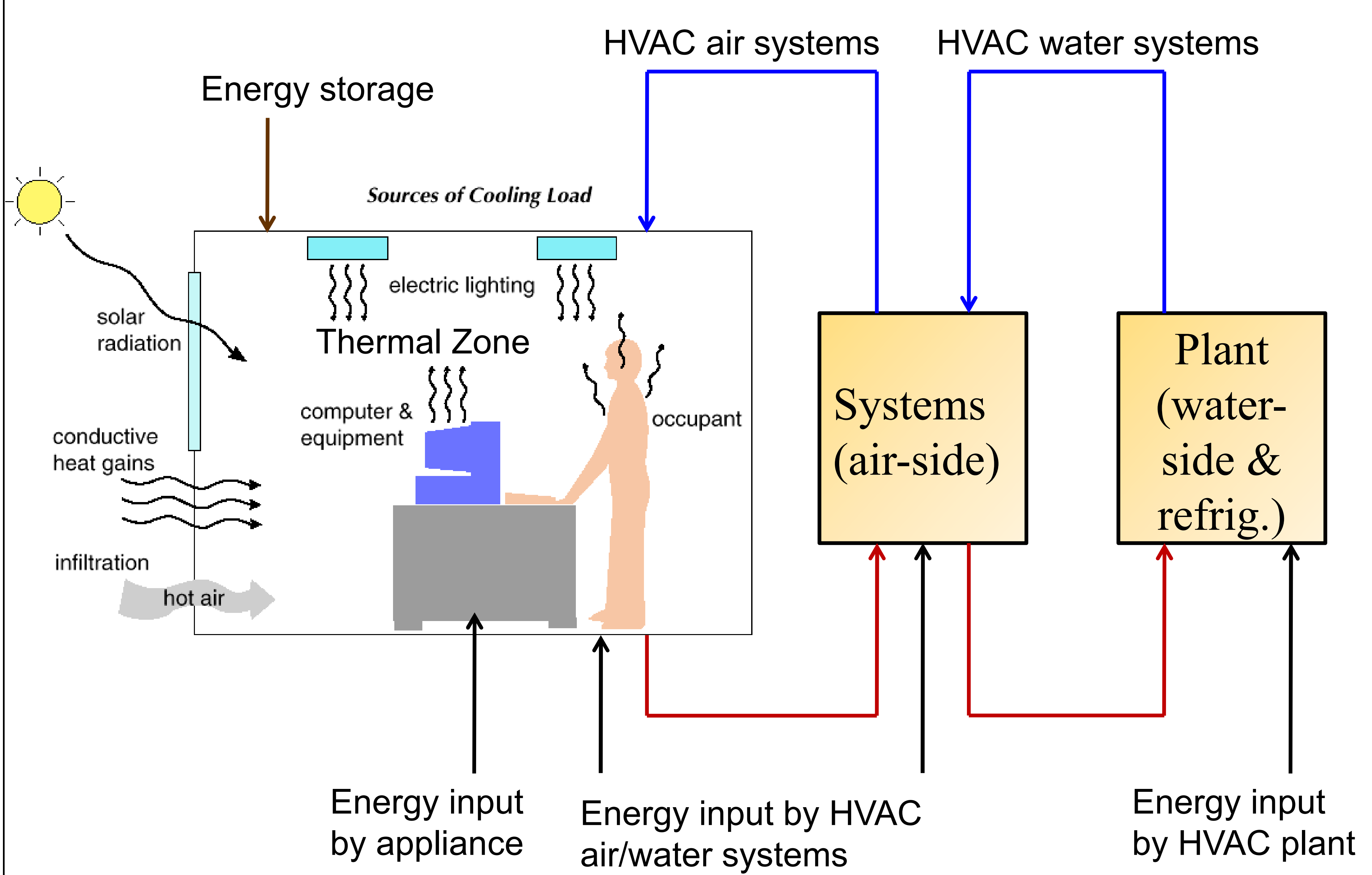
- Dynamic simulation methods
  - Usually hour-by-hour, for 8,760 hours (24 x 365)
  - Thermal & energy calculation sequence:
    - Space or building load [LOAD]
    - Secondary equipment load (airside) [SYSTEMS]
    - Primary equipment energy requirement (e.g. chiller) [PLANT]
  - Computer software
    - Building energy simulation programs, e.g. Energy-10, DOE-2, TRACE 700, Carrier HAP

Dynamic whole building energy analysis



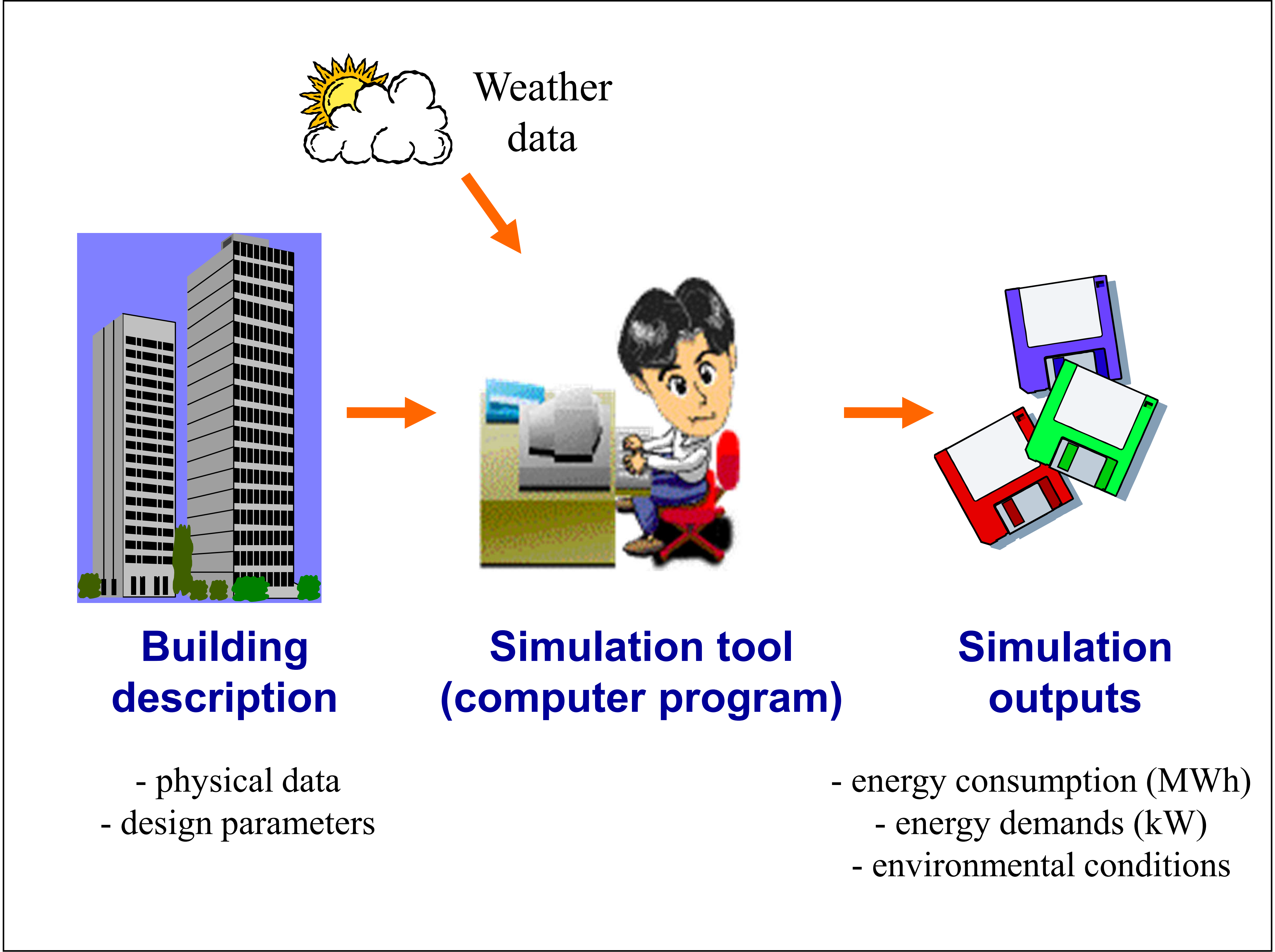
(Source: https://gbs.autodesk.com/GBS/)

Building energy simulation process



Dynamic simulation

- Building energy simulation
  - Analysis of energy performance of building using computer modelling and simulation techniques
  - Many issues can be studied, such as:
    - Thermal performance (e.g. building fabric, glazing)
    - Comfort & indoor environment
    - Ventilation & infiltration
    - Daylighting & overshadowing
    - Energy consumption/performance of building systems


Weather data
Building description
- physical data
- design parameters
Simulation tool (computer program)
Simulation outputs
- energy consumption (MWh)
- energy demands (kW)
- environmental conditions

Building Energy Simulation Software

ENERGY-10

blast

EnergyPlus

DOE-2

Solar-5

ESP-r

ENER-WIN©
Hourly Energy Simulation Program for Buildings

TRNSYS

Carrier
E-20-II & HAP

HOT2000

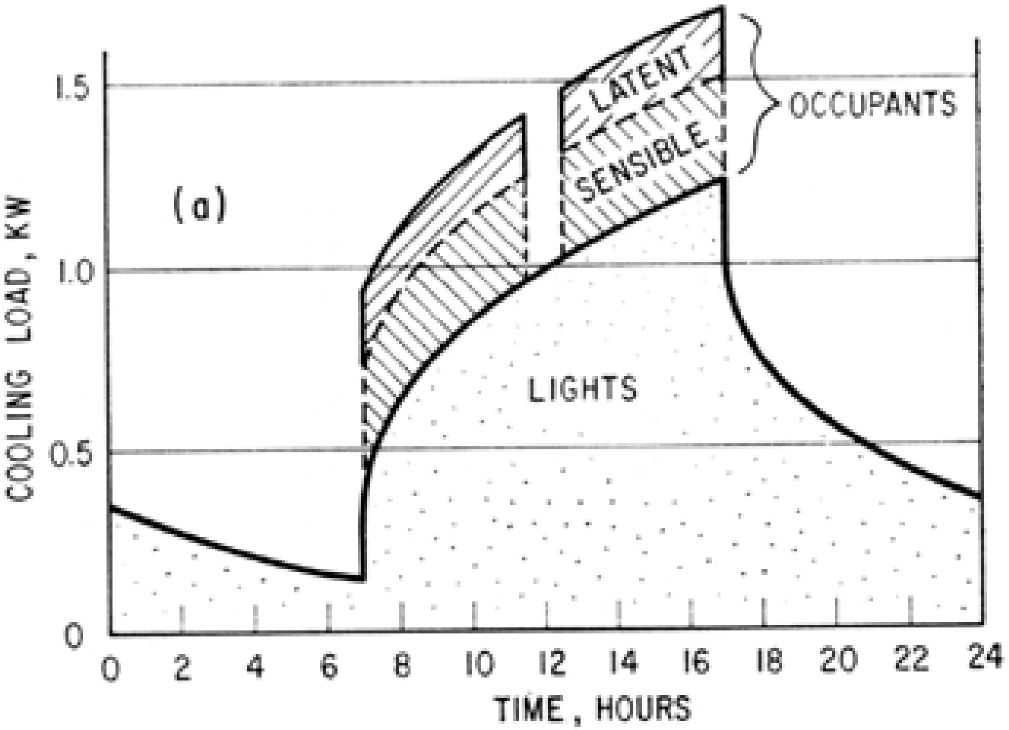
TRANE
TRACE 700

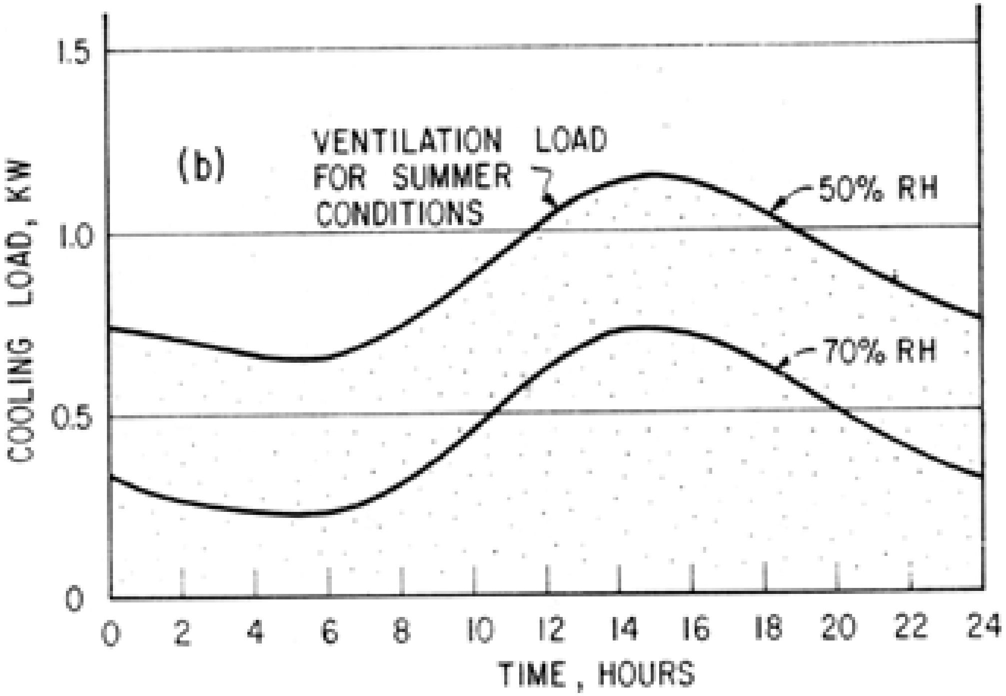
ADELINE

Tas

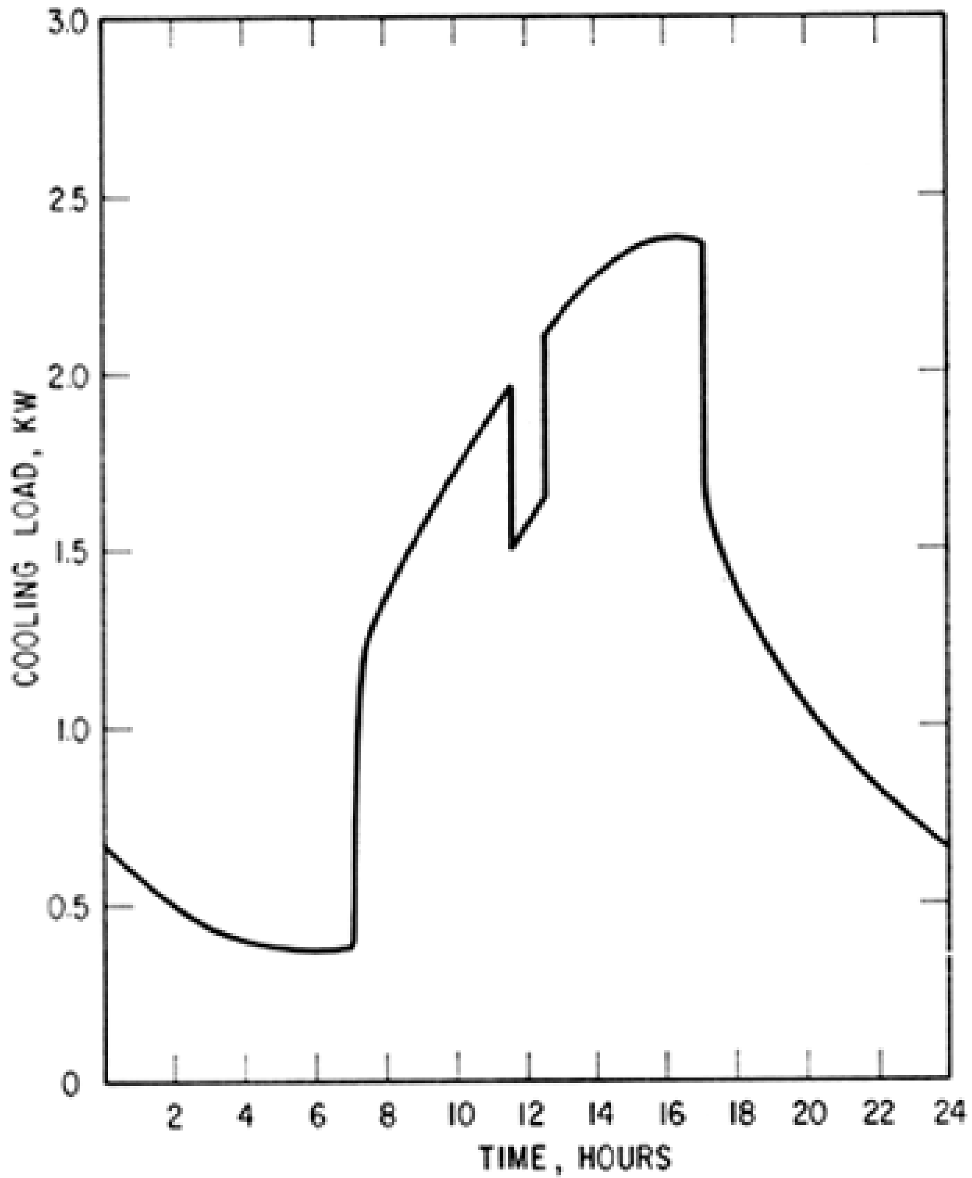
EE4

Cooling load profiles determined from simulation



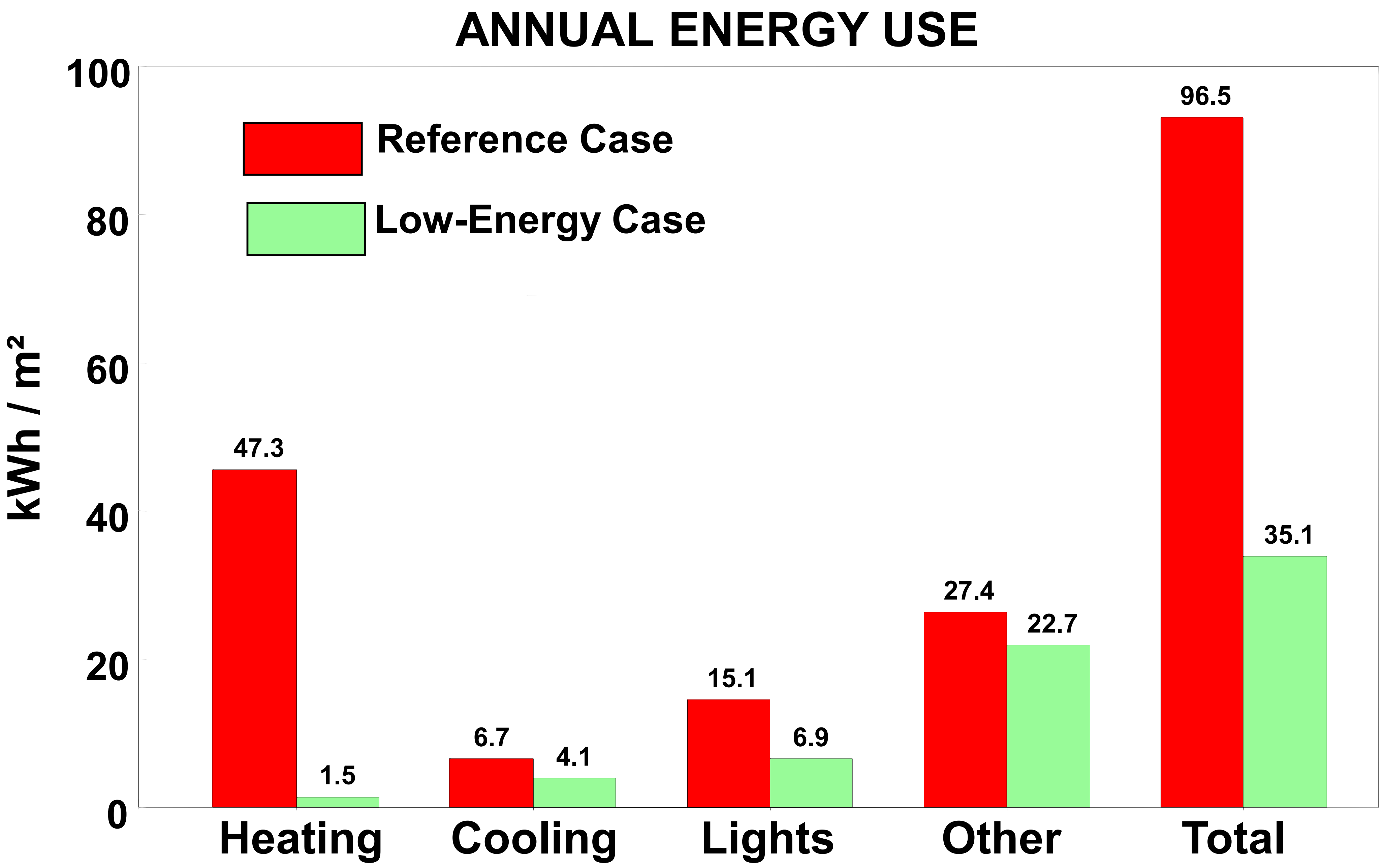


Total cooling load

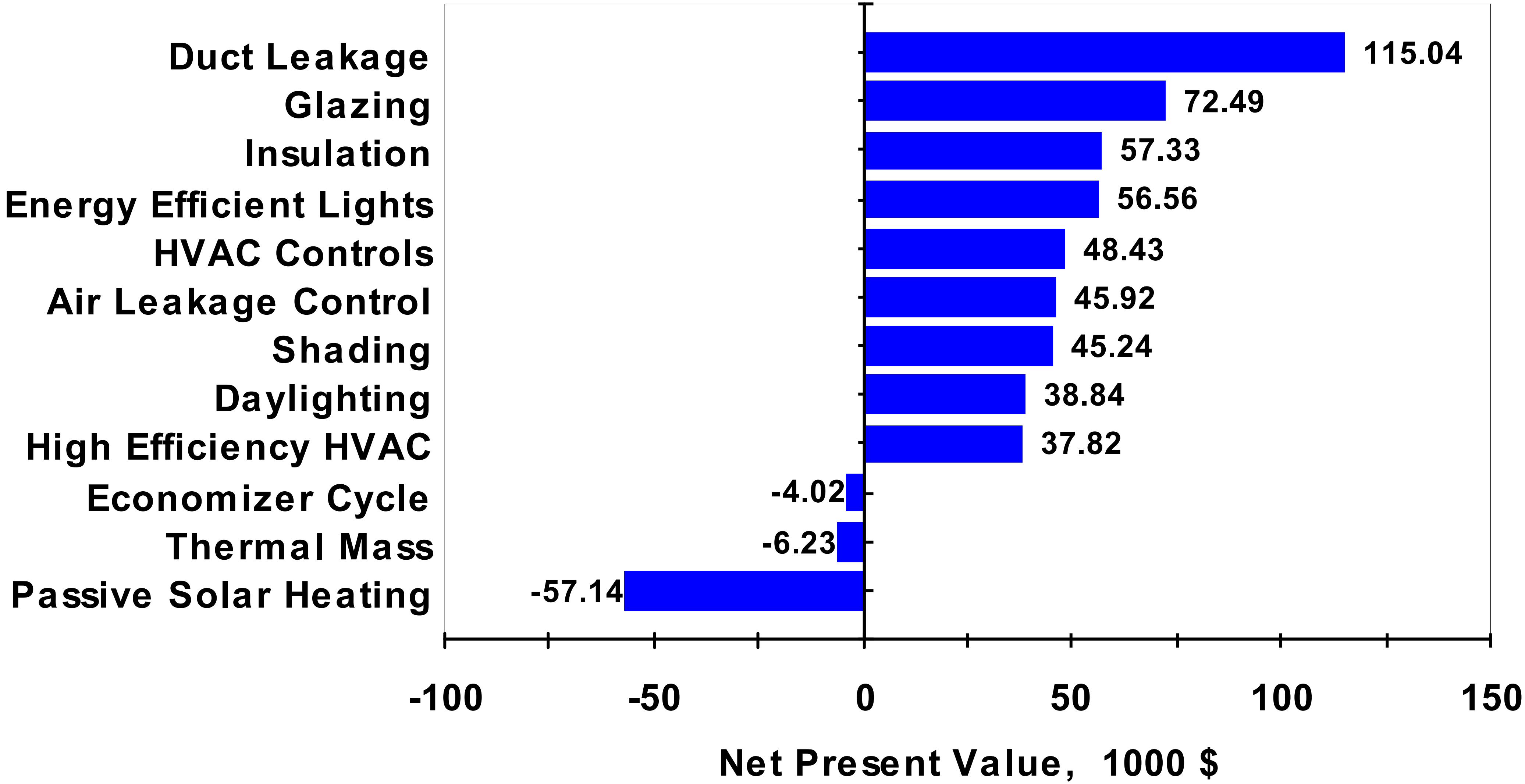


(Source: D.G. Stephenson, 1968)

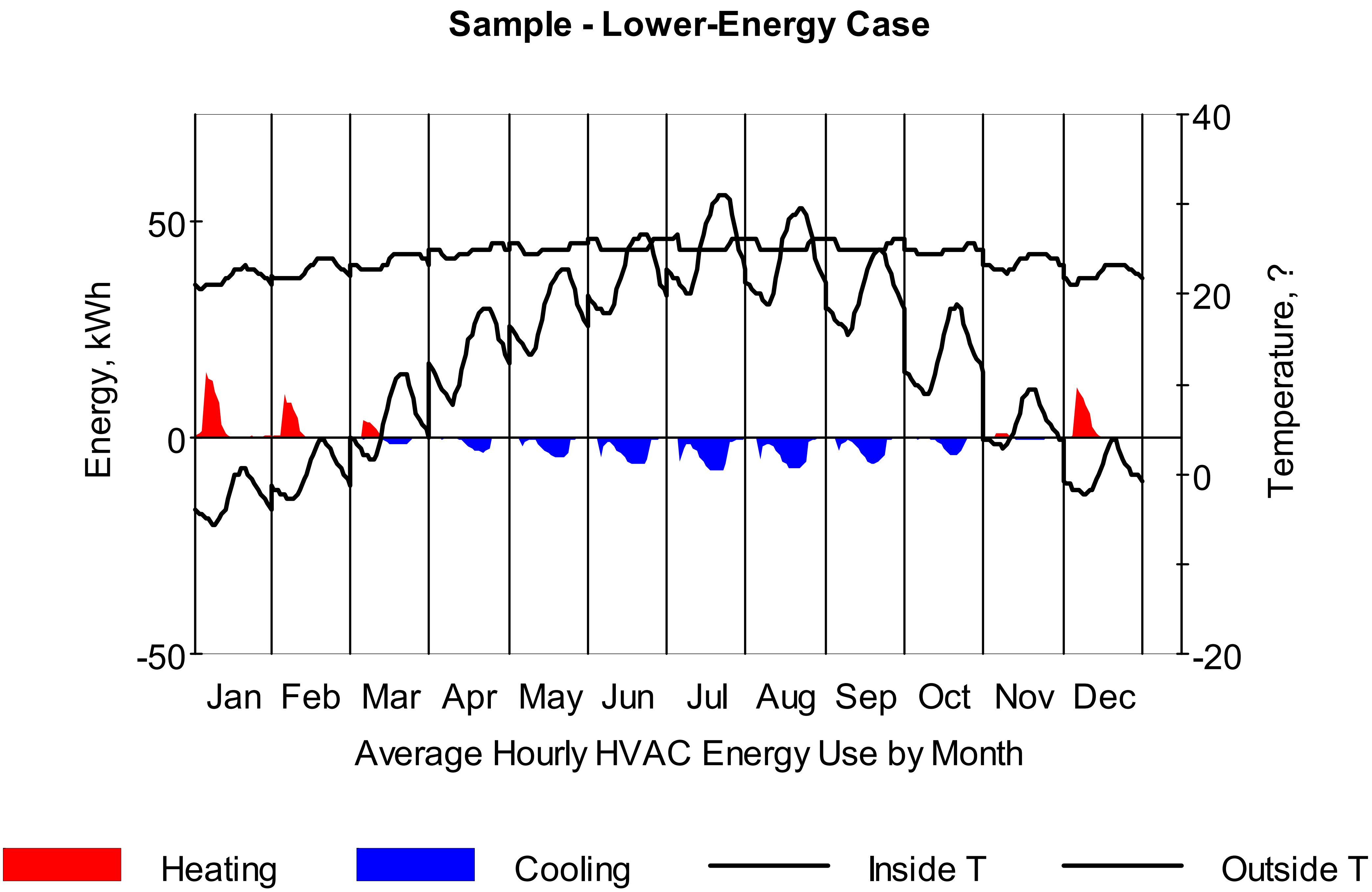
Examples of simulation results for evaluating annual building energy use



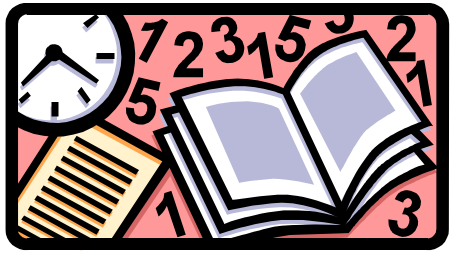
Examples of simulation results for ranking energy efficiency strategies



Examples of simulation results for energy & indoor temperature analysis



Further Reading



- Module 29: Determining U values for real building elements
  https://www.cibsejournal.com/cpd/modules/2011-06/
- Passive building design - Design Building Wiki
  https://www.designingbuildings.co.uk/wiki/Passive_building_design
- Module 48: Simple thermal analysis for buildings
  https://www.cibsejournal.com/cpd/modules/2013-01/