CHANGING WHAT'S POSSIBLE

Tutorial #2: Thermal Engineering as a DELTA Performer

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DELTA Kick-Off
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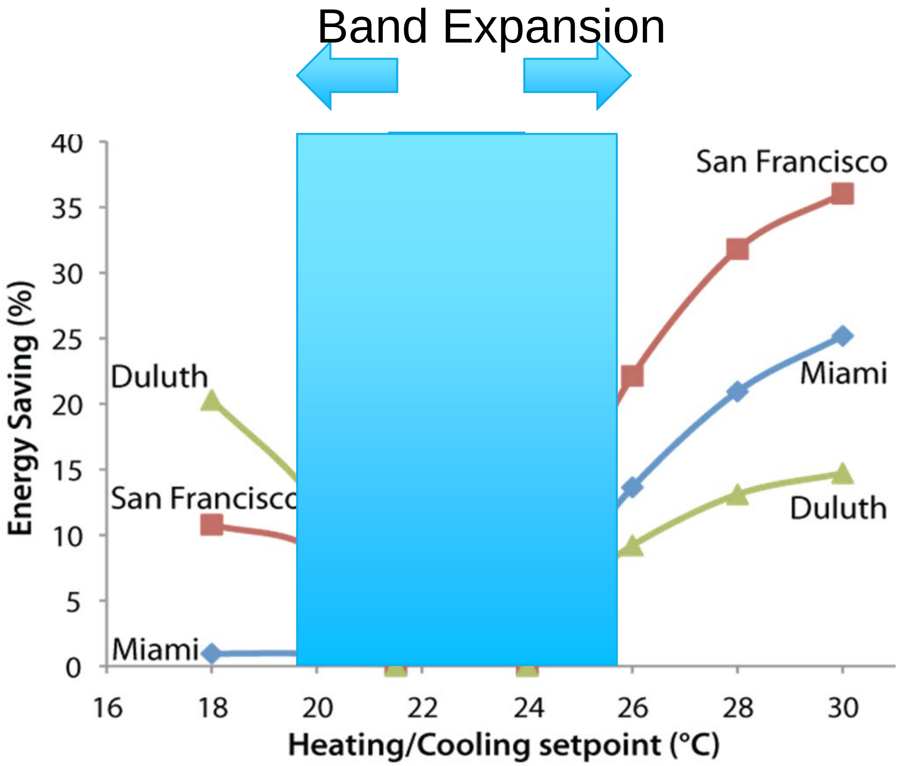
Outline

- Introduction and overview
- A scaling analysis
- The Modes of Heat Transfer
- Assessing each category type.
  - Performance at the interface that matters.
  - Calculating your Coefficient of Performance.

DELTA Program Objective

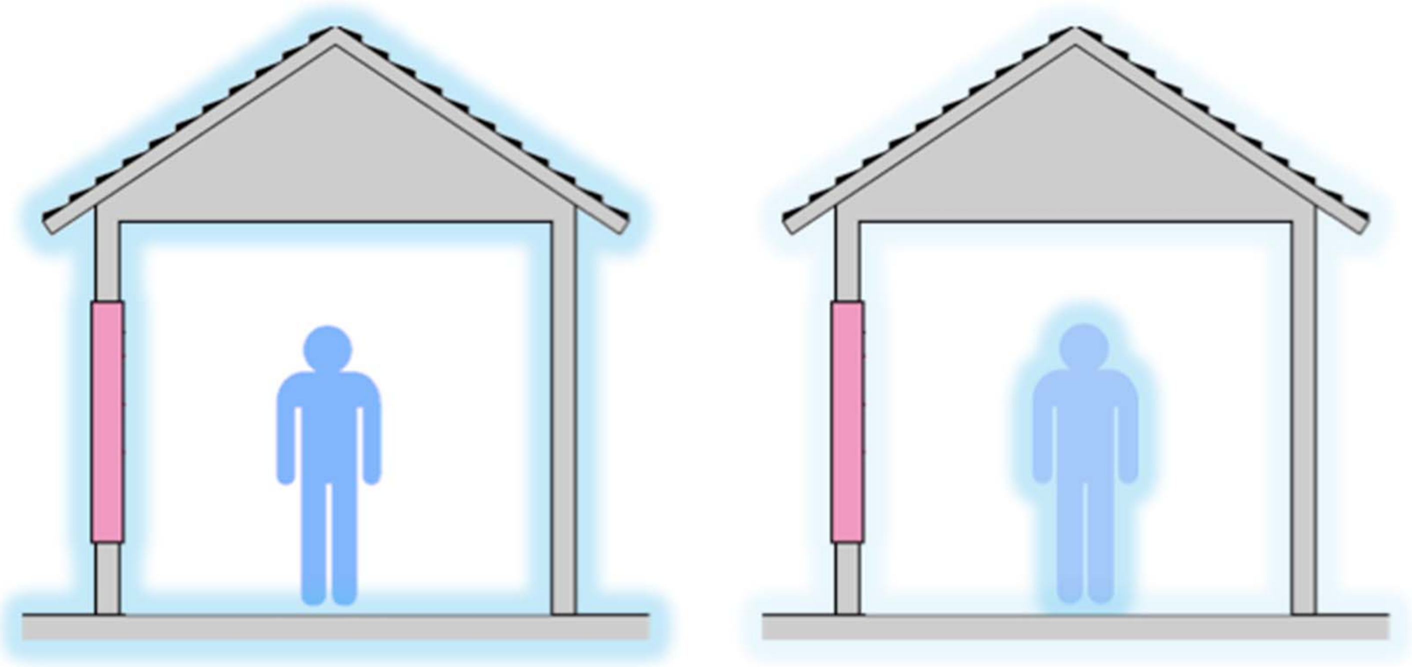
- **Save 2% of US heating and cooling energy (1.8 Qd) by expanding temperature setpoints of buildings by 2.2^{o}C in both directions**



Credit: Arens et al, UC Berkeley

Program Approach

Build a thermal envelope around people rather than buildings

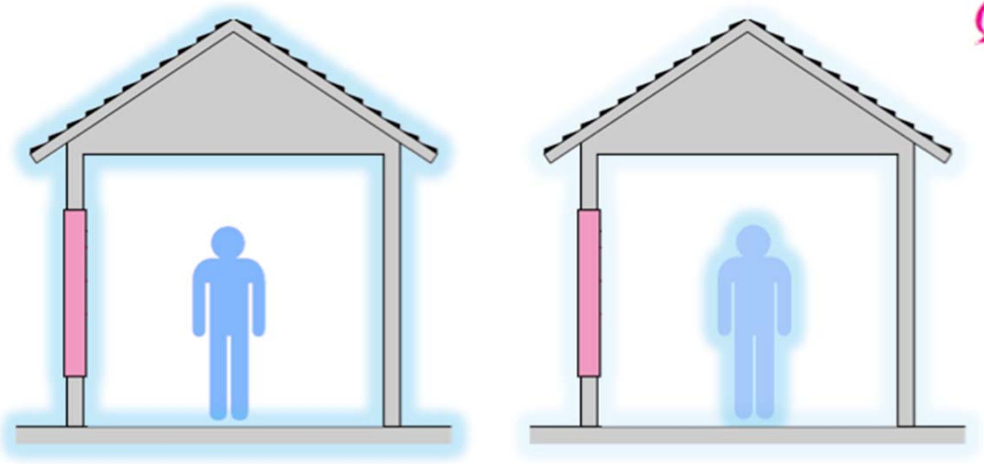


The reason…

Build a thermal envelope around people rather than buildings

Heat transfer rate Q proportional to surface area A_s and heat transfer coefficient U

$$\dot{Q} = UA_s(T_i - T_o) = \frac{A_s(T_i - T_o)}{R}$$

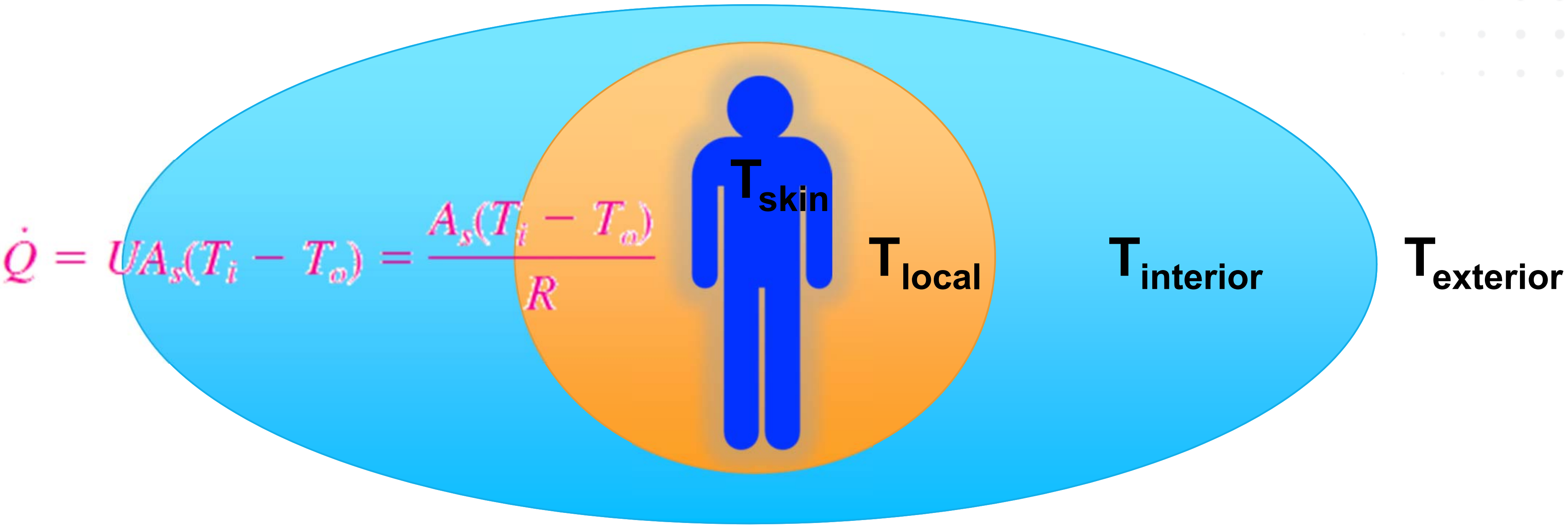


Buildings are

- A_s ~ 50 x person
- U ~ person ÷ 5
- Q ~ 10 x person

Local Thermal Management in a Building Envelope

The goal is to maintain constant T_{skin}



$$\dot{Q} = UA_s(T_i - T_o) = \frac{A_s(T_i - T_o)}{R}$$

Local thermal management allows T_{int} to be closer to T_{ext} without changing T_{skin}

Modes of heat transfer

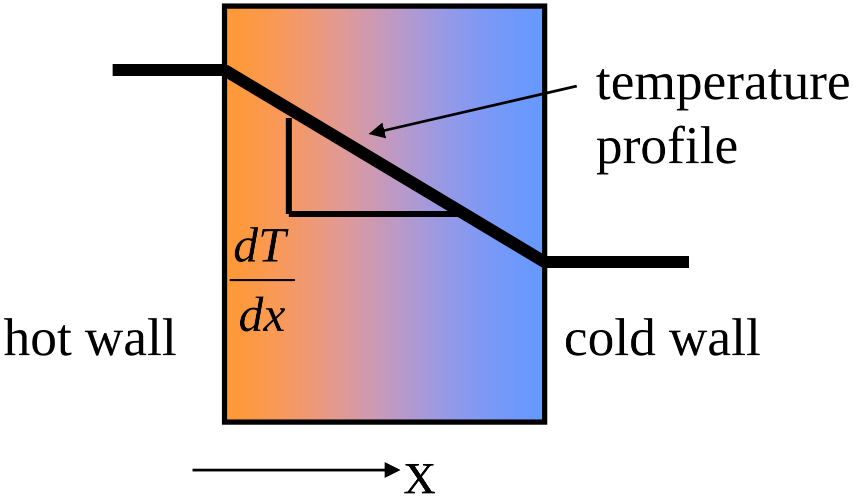
- Conduction: diffusion of heat due to temperature gradients.
- Convection: when heat is carried by moving fluid. The flow can either be caused by external influences, forced convection; or by buoyancy forces, natural convection.
- Radiation: transfer of energy by electromagnetic waves between surfaces with different temperatures, separated by a medium that is at least partially transparent to the (infrared) radiation.
- Phase Change: transfer of “latent” heat due to conversion of material between phases. Boiling, evaporation, freezing.

Heat conduction - Fourier’s law

- The heat flux is proportional to the temperature gradient:

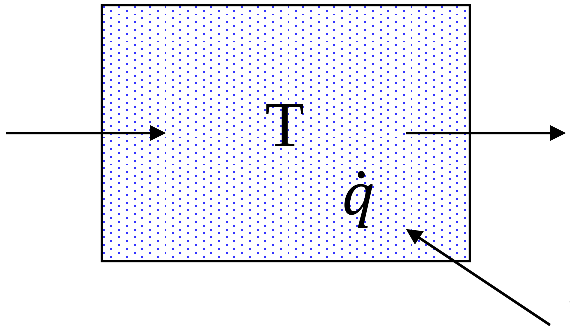
$$\frac{Q}{A} = q = -k\nabla T$$

  where *k(x,y,z,T)* is the thermal conductivity.
- In most practical situations conduction, convection, and radiation appear in combination. Also for convection, the heat transfer coefficient is important, because a flow can only carry heat away from a wall when that wall is conducting.



Generalized heat diffusion equation

- If we perform an energy balance on a small volume of material….



heat conduction
in

T

$\dot{q}$

heat conduction
out

heat generation

- … we get:

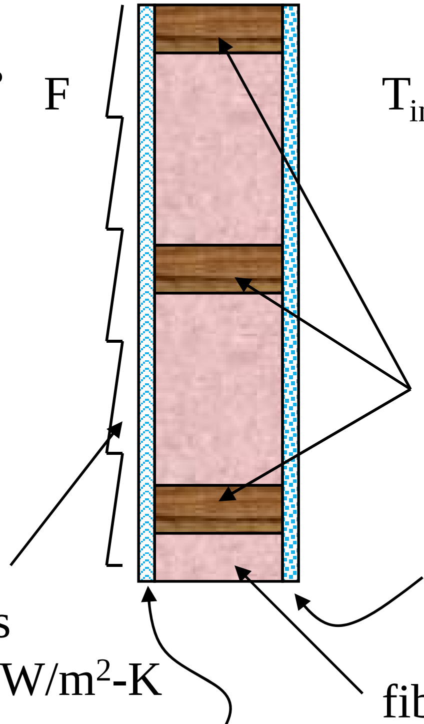
$$\rho c \frac{\partial T}{\partial t} = k\nabla^2 T + \dot{q}$$

rate of change of temperature — *heat cond. in/out* — *heat generation*

$$\alpha = \frac{k}{\rho c} =$$ thermal diffusivity

Conduction example

- Compute the heat transfer through the wall of a home:



$T_{out} = 20^\circ$ F

$T_{in} = 68^\circ$ F

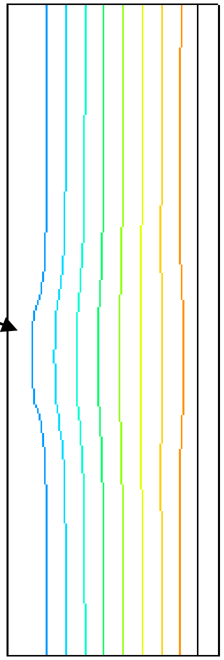
2x6 stud
$k=0.15$ W/m^2-K

sheetrock
$k=0.4$ W/m^2-K

shingles
$k=0.15$ W/m^2-K

sheathing
$k=0.15$ W/m^2-K

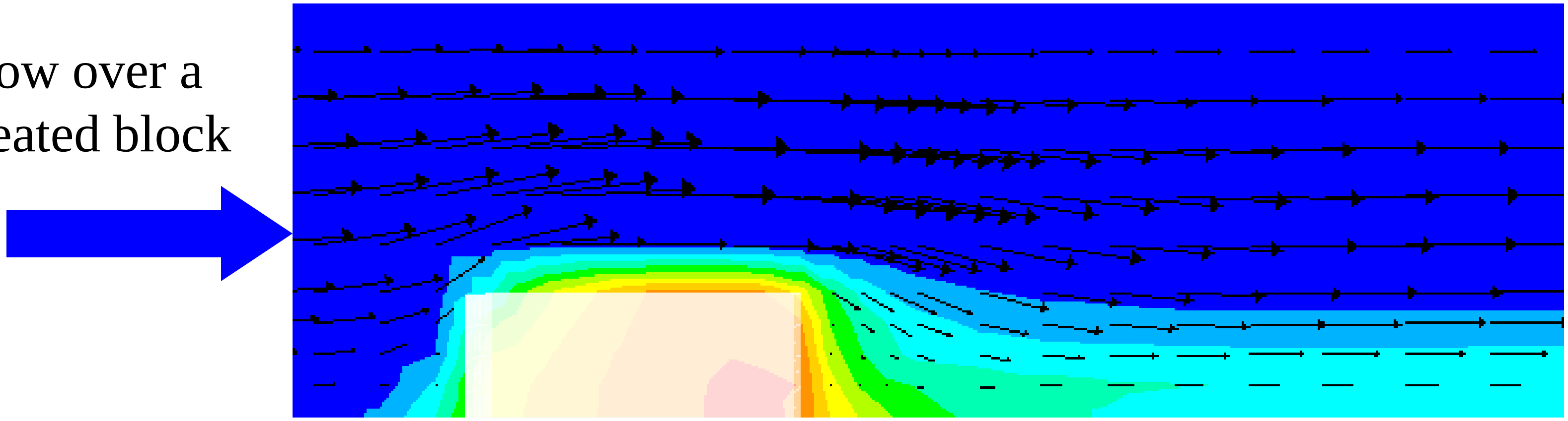
fiberglass
insulation
$k=0.004$ W/m^2-K



Although slight, you can see the "thermal bridging" effect through the studs

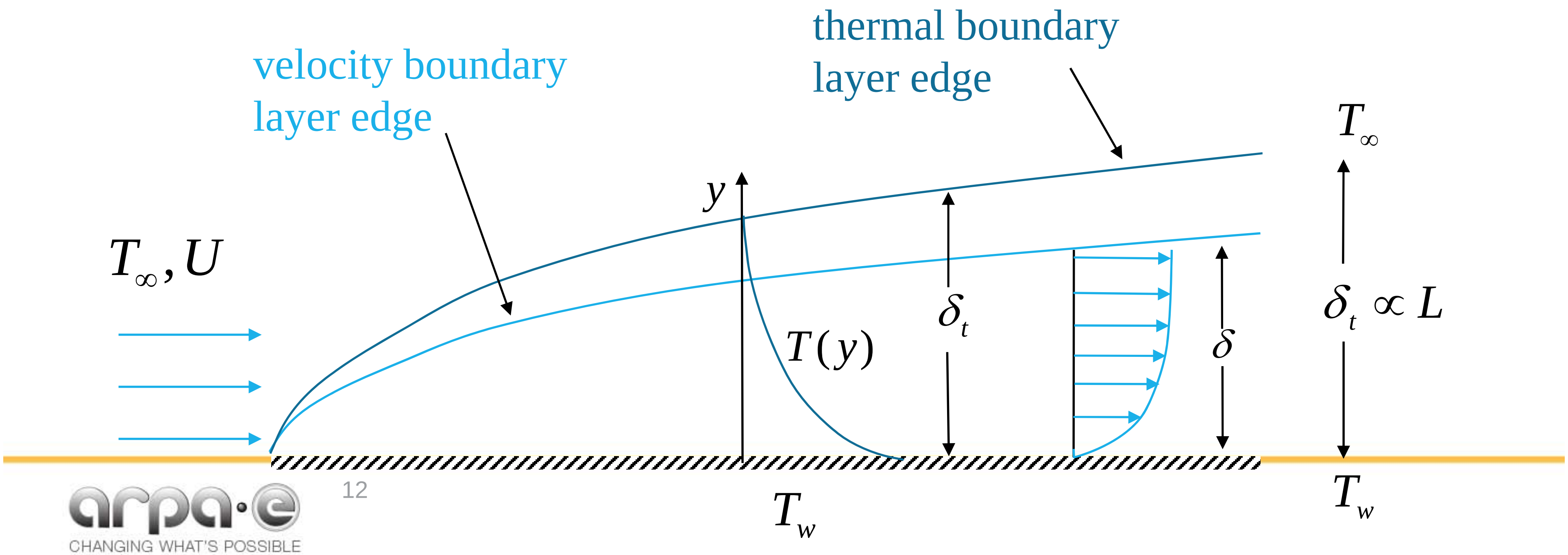
Convection heat transfer

- Convection is movement of heat with a fluid.
- E.g., when cold air sweeps past a warm body, it draws away warm air near the body and replaces it with cold air.



Thermal boundary layer

- Convective heat transfer rate is directly proportional to the thickness of the so-called "boundary layer", the area nearest the surface which is directly effected by viscous drag.
- Heat transfer is highly coupled to fluid flow through this mechanism.

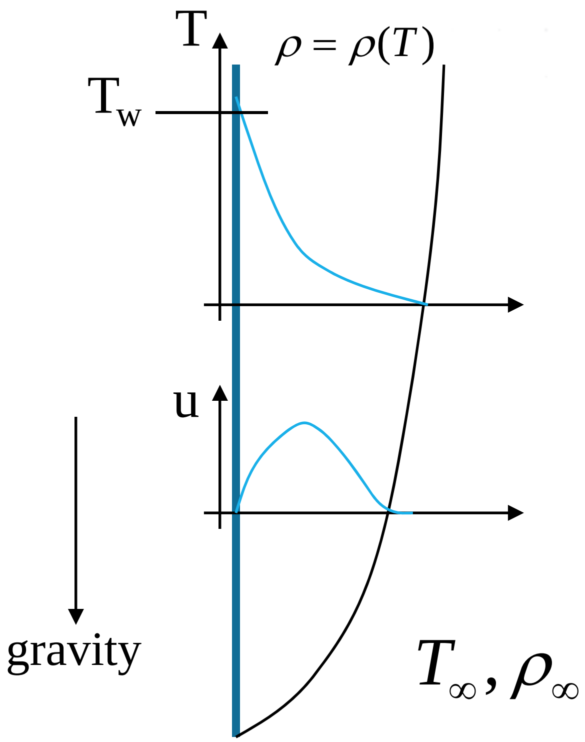


Natural convection

- Natural convection (from a heated vertical plate).
- As the fluid is warmed by the plate, its density decreases and a buoyant force arises which induces flow in the vertical direction. The force is proportional to $(\rho - \rho_\infty)g.$
- The dimensionless group that governs natural convection is the Rayleigh number:

$$Ra = Gr.Pr = \frac{g\beta\Delta T L^3}{\alpha\upsilon}$$

- Typically: $Nu \propto Ra^x \quad \frac{1}{4} < x < \frac{1}{3}$

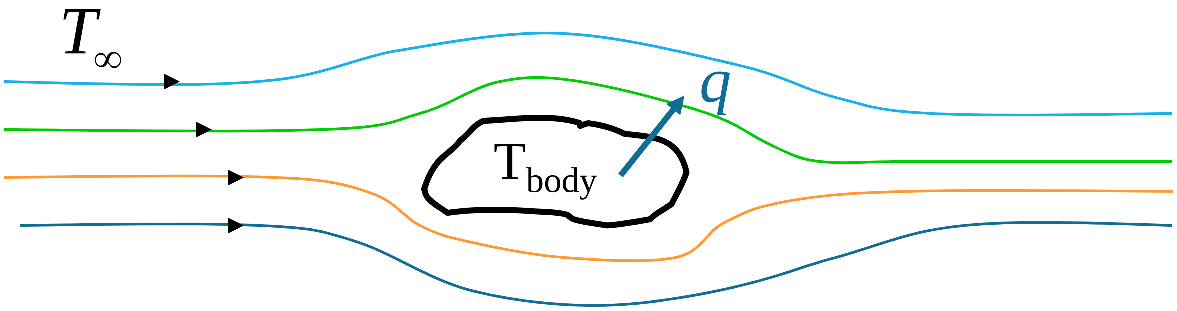


Natural convection around a person

- Light weight warm air tends to move upward when surrounded by cooler air.
- Thus, warm-blooded animals are surrounded by thermal plumes of rising warm air.
- This plume is made visible by means of a Schlieren optical system that is based on the fact that the refraction of light through a gas is dependent on the density of the gas.

Newton's law of cooling

- Newton described the cooling of objects with an arbitrary shape in a pragmatic way. He postulated that the heat transfer *Q* is proportional to the surface area *A* of the object and a temperature difference ΔT.
- The proportionality constant is the heat transfer coefficient *h*(W/m^2-K). This empirical constant lumps together all the information about the heat transfer process that we don't know or don't understand.



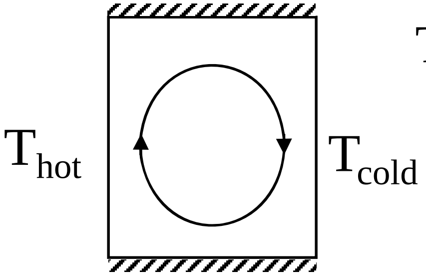
$$Q = qA = \bar{h} A(T_{body} - T_\infty) = \bar{h} A \Delta T$$

$\bar{h} =$ average heat transfer coefficient (W/m^2-K)

Heat transfer coefficient

- *h* is not a constant, but *h = h(ΔT).*
- Three types of convection.
- Natural convection. Fluid moves due to buoyancy.

$$h \propto \Delta T^{x} \qquad \frac{1}{4} < x < \frac{1}{3}$$

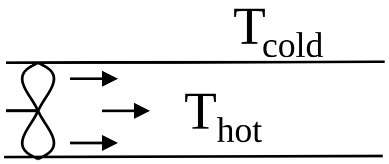


Typical values of *h:*

4 - 4,000 W/m^2-K

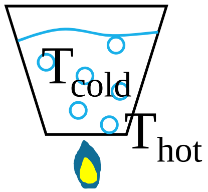
- Forced convection: flow is induced by external means.

$$h = const$$



80 - 75,000

- Boiling convection: body is hot enough to boil liquid.



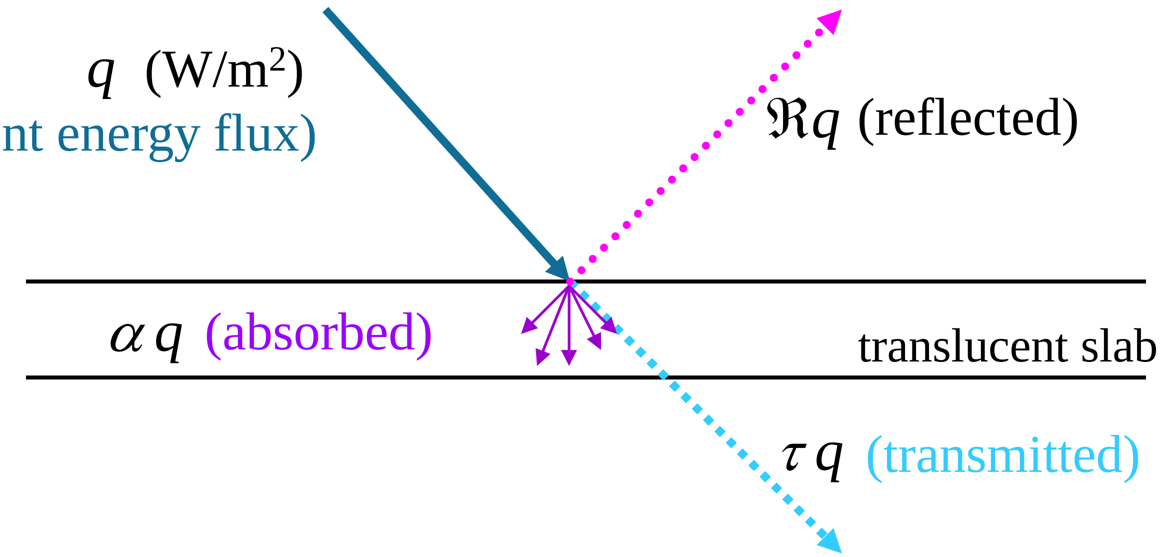
300 - 900,000

$$h \propto \Delta T^{2}$$

Radiation heat transfer

- Thermal radiation is emission of energy as electromagnetic waves.
- Intensity depends on body temperature and surface characteristics.
- Important mode of heat transfer at high temperatures, e.g. combustion.
- Can also be important in natural convection problems.
- Radiation properties can be strong functions of chemical composition, especially CO_2, H_2O.
- Radiation heat exchange is difficult solve (except for simple configurations). We must rely on computational methods.

Surface characteristics



q (W/m^2)

(incident energy flux)

$\Re q$ (reflected)

$\alpha\, q$ (absorbed)

translucent slab

$\tau\, q$ (transmitted)

$$1 = \alpha + \Re + \tau$$

absorptance

reflectance

transmittance

Black body radiation

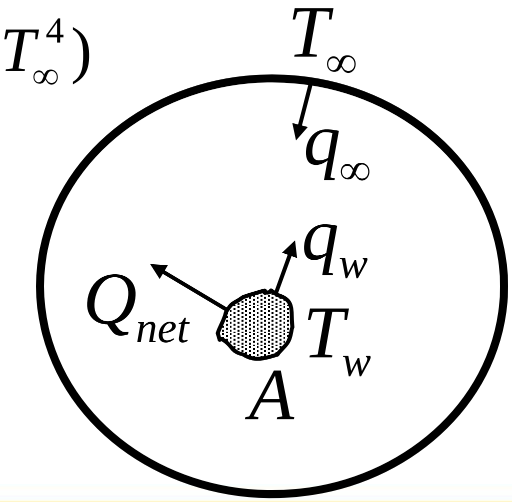
- A “black body”:
  - Is a model of a perfect radiator.
  - Absorbs all energy that reaches it; reflects nothing.
  - Therefore $\alpha = 1,\ \Re = \tau = 0.$
- The energy emitted by a black body is the theoretical maximum:

$$q = \sigma T^4$$

- This is Stefan-Boltzmann law; σ is the Stefan-Boltzmann constant (5.6697E-8 W/m^{2}K^4).
- Typical wavelengths are $\lambda_{\max}$ = 10 μm (far infrared) at room temperature and $\lambda_{\max}$ = 0.5 μm (green) at 6000K.

Real bodies

- Real bodies will emit less radiation than a black body: $q = \varepsilon\sigma T^4$
- Here ε is the emissivity, which is a number between 0 and 1. Such a body would be called "gray" because the emissivity is the average over the spectrum.
- Example: radiation from a small body to its surroundings.
  - Both the body and its surroundings emit thermal radiation.
  - The net heat transfer will be from the hotter to the colder.
- The net heat transfer is then: $Q_{net} = \varepsilon A\sigma (T_w^4 - T_\infty^4)$
- For small ΔT the term $(T_w{}^4 - T_\infty{}^4)$ can be approximated as $4\overline{T}^3(T_w - T_\infty)$ and $Q_{net} = Ah_r \Delta T$ with h_r as an effective radiation heat transfer coefficient.

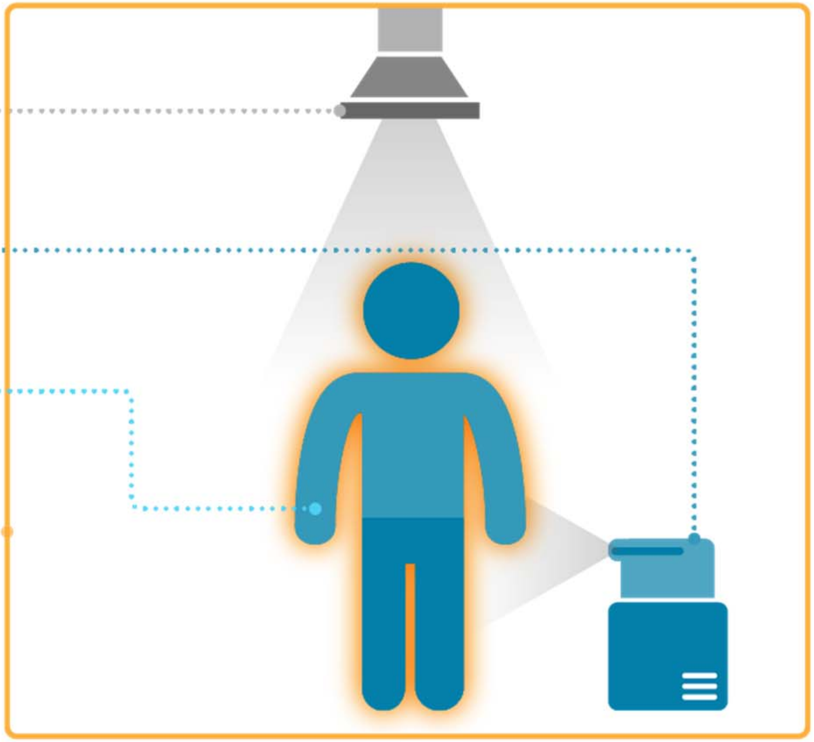


Technology Categories

Program considers

FOUR APPROACHES

to balance the risks and benefits of each.



1. **EXTENDED RANGE (>1M)**
   wireless, directed energy transfer
2. **CLOSE PROXIMITY (<1M)**
   wireless, directed energy transfer
3. **WEARABLE TECHNOLOGY**
   (e.g. adaptive insulation) to reduce energy consumption
4. **SYSTEM LEVEL SOLUTIONS**
   using combinations of approaches 1-3

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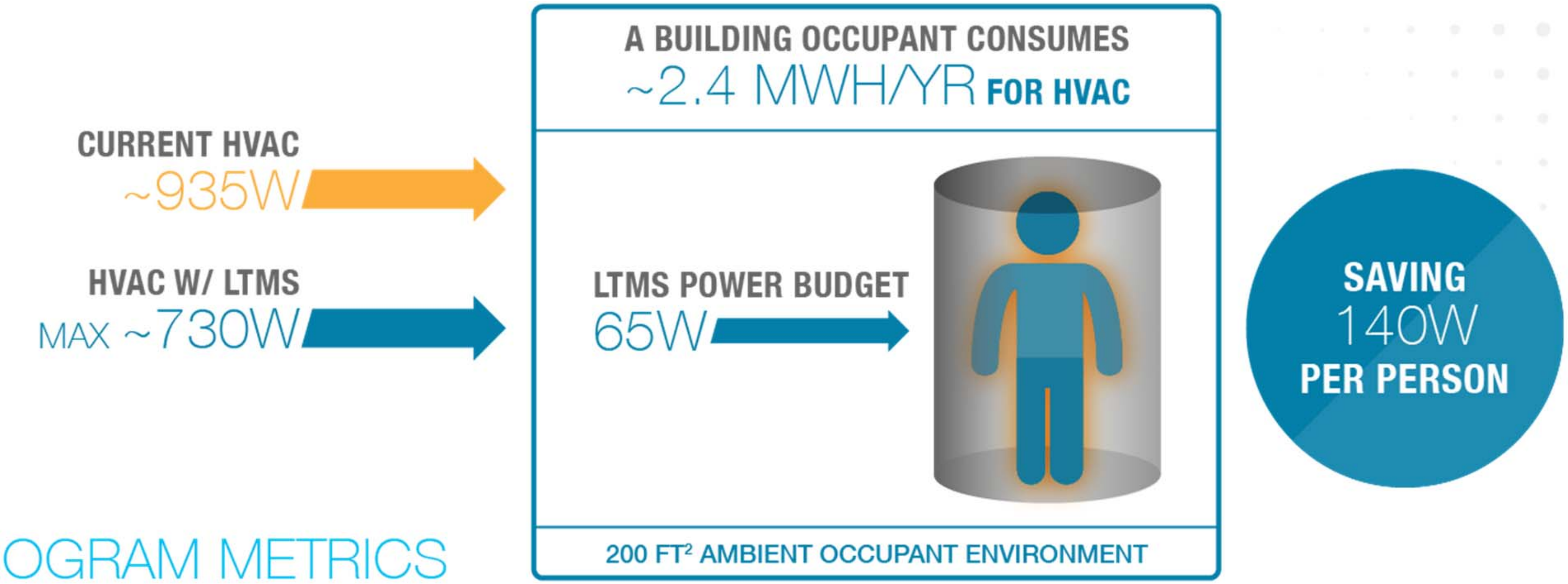
Primary Metrics, Enabling ≥ 15% Energy Savings



CURRENT HVAC
~935W

HVAC W/ LTMS
MAX ~730W

A BUILDING OCCUPANT CONSUMES
~2.4 MWH/YR FOR HVAC

LTMS POWER BUDGET
65W

200 FT² AMBIENT OCCUPANT ENVIRONMENT

SAVING
140W
PER PERSON

PROGRAM METRICS

1. **TECHNOLOGY MUST SUPPORT A TEMPERATURE SETPOINT ΔT OF ≥ 4ºF WHILE MAINTAINING A CONSTANT SKIN TEMPERATURE**
2. **TECHNOLOGY MUST HAVE A COP TARGET OF >0.35**
   Systems can be passive or active w/ a max power consumption of 65 W/person
3. **ALL APPLICANTS MUST PRESENT A PATH TO PAYBACK WITHIN A 3 YEAR TIMETABLE**
   Payback allowance of $20/person/year @5.4¢/kWh for ΔT of 4ºF in both directions

Requirements to Manage a 4°F ΔT

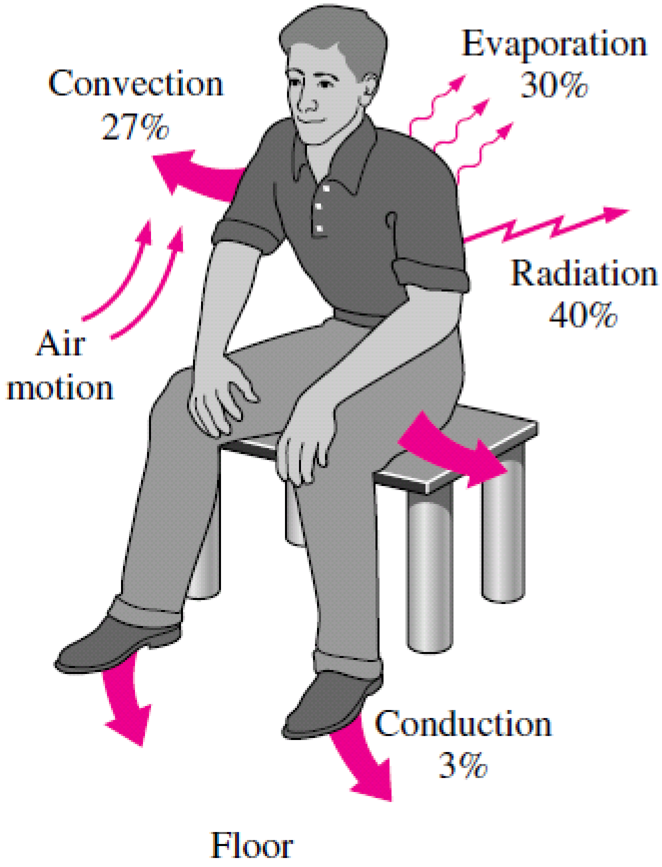
$$\dot{Q} = UA_s(T_i - T_o) = \frac{A_s(T_i - T_o)}{R}$$

- For a constant Q, R is proportional to T_i-T_o
- T_i is a constant at 93.2°F, a change of T_o from 75 to 79°F requires a reduction of R by 22%, or 5%/°F
- R needs to increase by 4.5%/°F to lower T_o from 70 to 66°F.

Changing R is preferred over supplying or extracting heat -Little energy consumption is needed

Requirements to Manage a 4°F ΔT

-Supply or Extract The Heat



A person sitting at a desk:
100 W heat dissipation

For a 5%/°F change, we need to remove or supply extra 24 W

J. Fan, 2013

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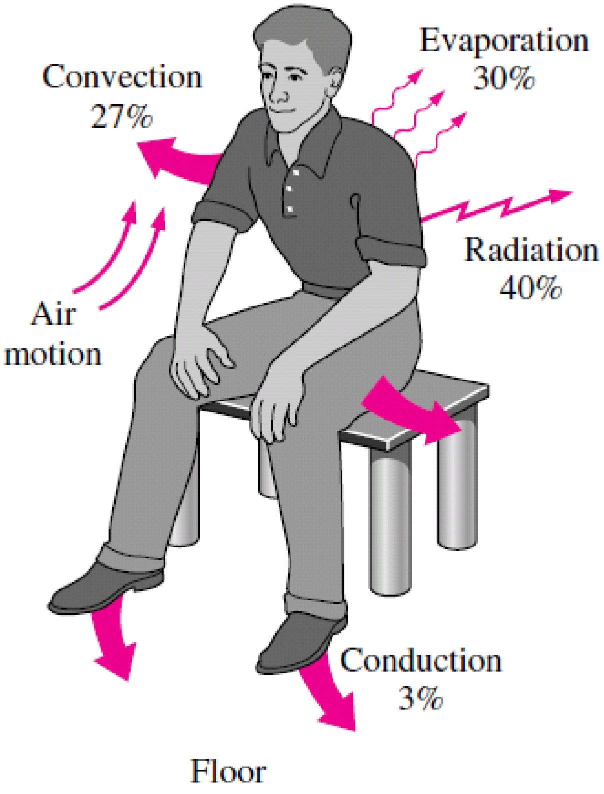
Thermal Regulation in Indoor Environments

$$Q_{Body} = (Q_{Convection} + Q_{Radiation} + Q_{Latent})_{Skin}$$



Managing Thermal Flux, Q:

1) Alter materials for thermal transport

2) Alter ambient conditions

Requires Energy Input

*Typical Occupant Thermal Load : ~**105 W***

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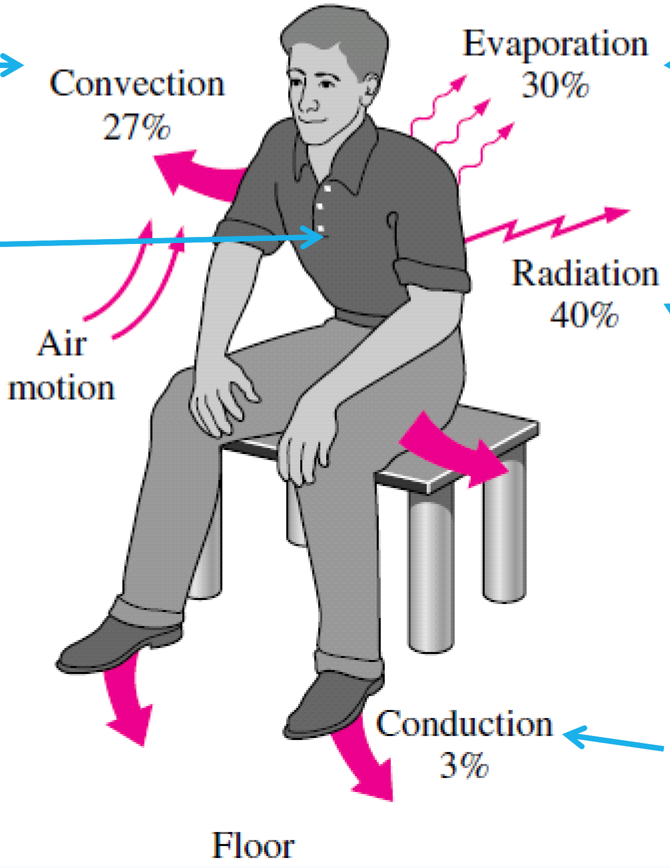
*ASHRAE Handbook: Fundamentals 2009

FOA Category 1a Thermally Adaptive Apparel Technologies-Cooling

- Maintain same skin temperature between 79^{o}F and 75^{o}F through control of thermal loss mechanisms



Clothing with tunable porosity and small movement

“damp” clothing

Actively cooled garment

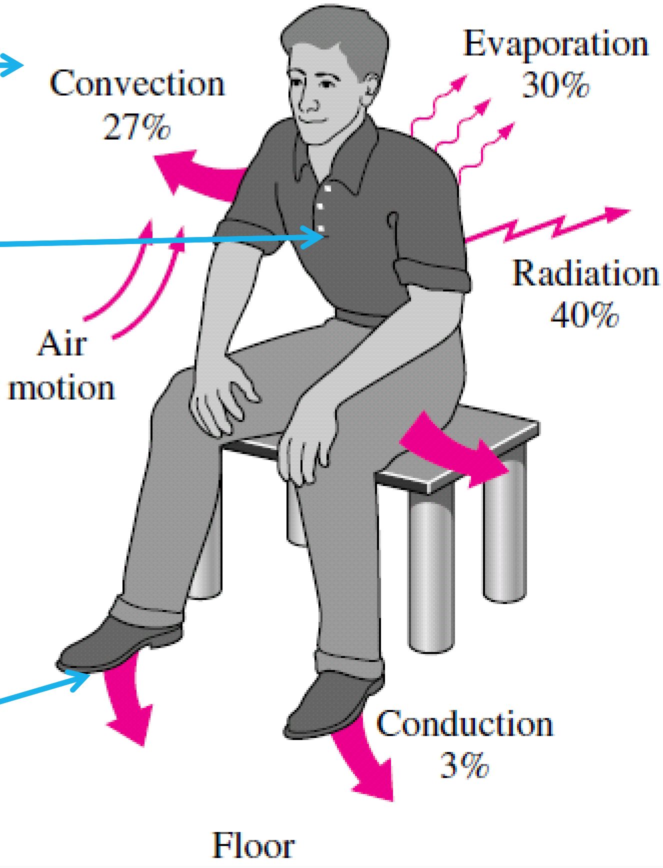
Fabric with enhanced emissivity

Thermally conductive fibers

Control heat loss through breakthrough technologies employing all mechanisms

FOA Category 1b Thermally Adaptive Apparel Technologies-Heating

- Maintain same skin temperature between 66^{o}F and 70^{o}F through control of thermal loss mechanisms



Clothing with tunable loftiness/thickness

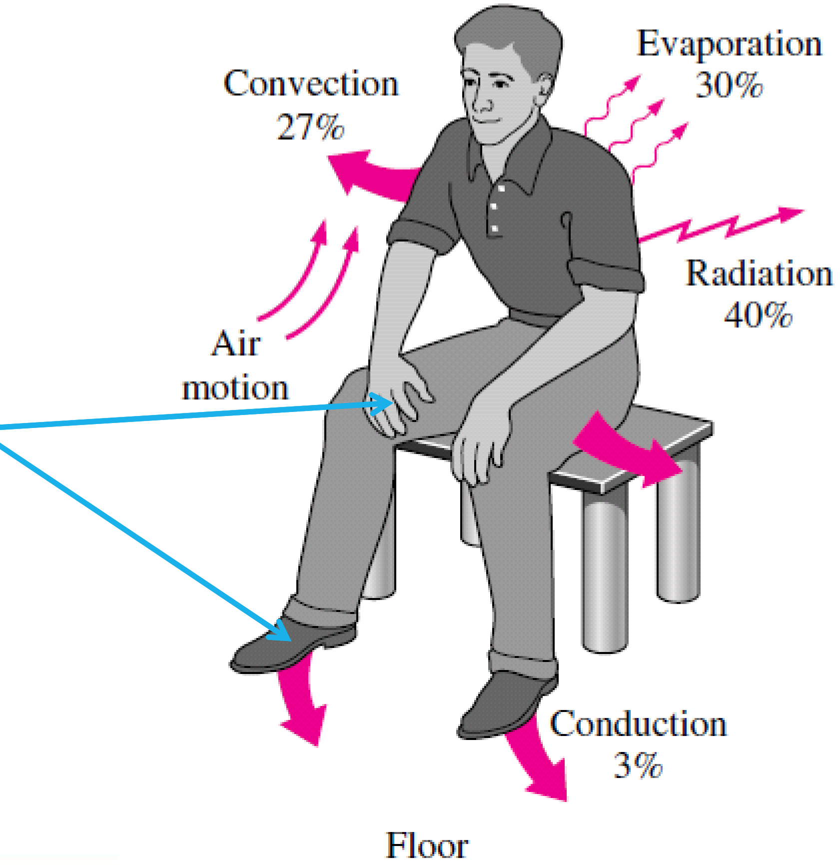
Actively heated garment

Fabric with variable emissivity

Actively heated shoes

FOA Category 1c Wearable Devices to Regulate Body Temperature

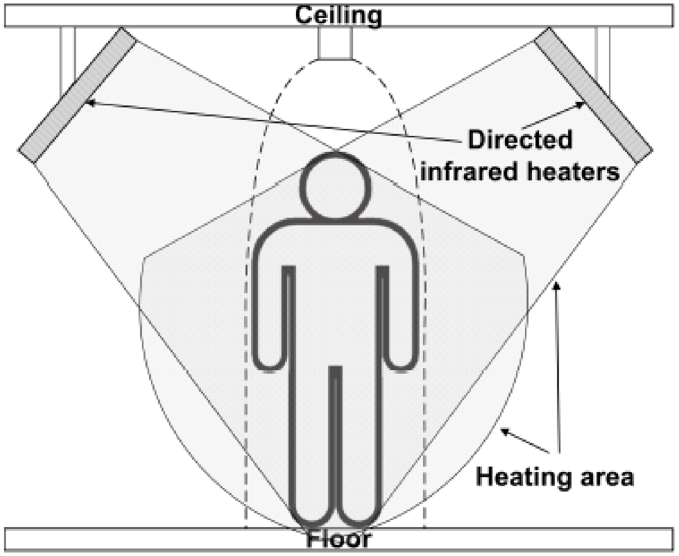
- Control body core temperature/maintain thermal comfort through effective heat exchange in selected body surfaces



Wearable devices to supply or extract heat from human’s natural heat exchanger

FOA Category 2 Long-Range LTMS

- Provide *location insensitive*, directed heating and cooling to building occupants
  - High efficiency energy source
  - High efficiency transfer mechanism
  - Uniform thermal gradient
  - Low cost tracking system



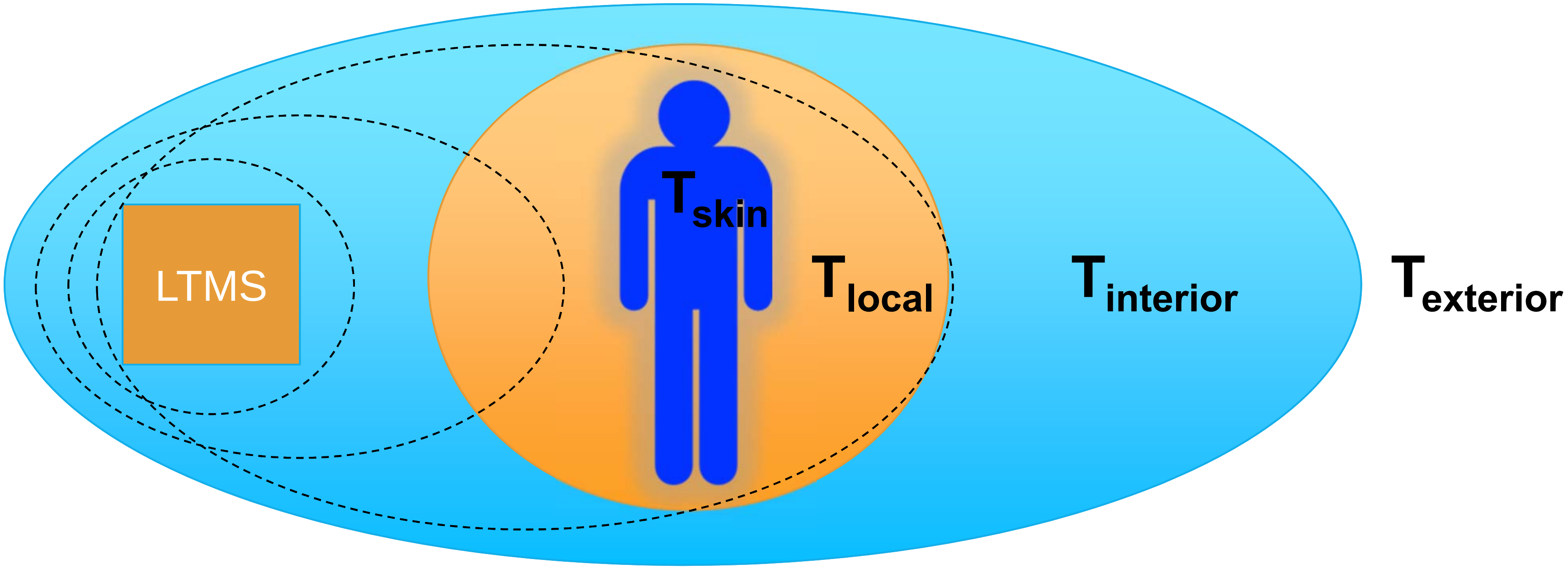
(a) Localized heating using two heaters per occupant

Calculating the COP of your LTMS Device

- The Coefficient of Performance (COP) is the ratio of delivered heat transfer to electrical energy consumed.
  - $COP = Q/W$
- From the second law of thermodynamics, that COP for heating and cooling have theoretical limits:
  - $COP_{cool,max} = \frac{T_{cool}}{T_{hot} - T_{cool}}$ ~ 38.5
  - $COP_{heat,max} = \frac{T_{hot}}{T_{hot} - T_{cool}}$ ~ 20.5

Calculating the COP of your LTMS Device

- When it comes to the COP only one heat transfer interface matters: The User’s Skin!



FOA Category 3 Short-Range LTMS

- Low-cost, user controllable office furniture and accessories
  - Efficient cooling and heating designs to achieve uniform temperature on occupants
  - Generation of air temperature below ambient without hot exhaust
  - Range of thermal envelope > 2 ft

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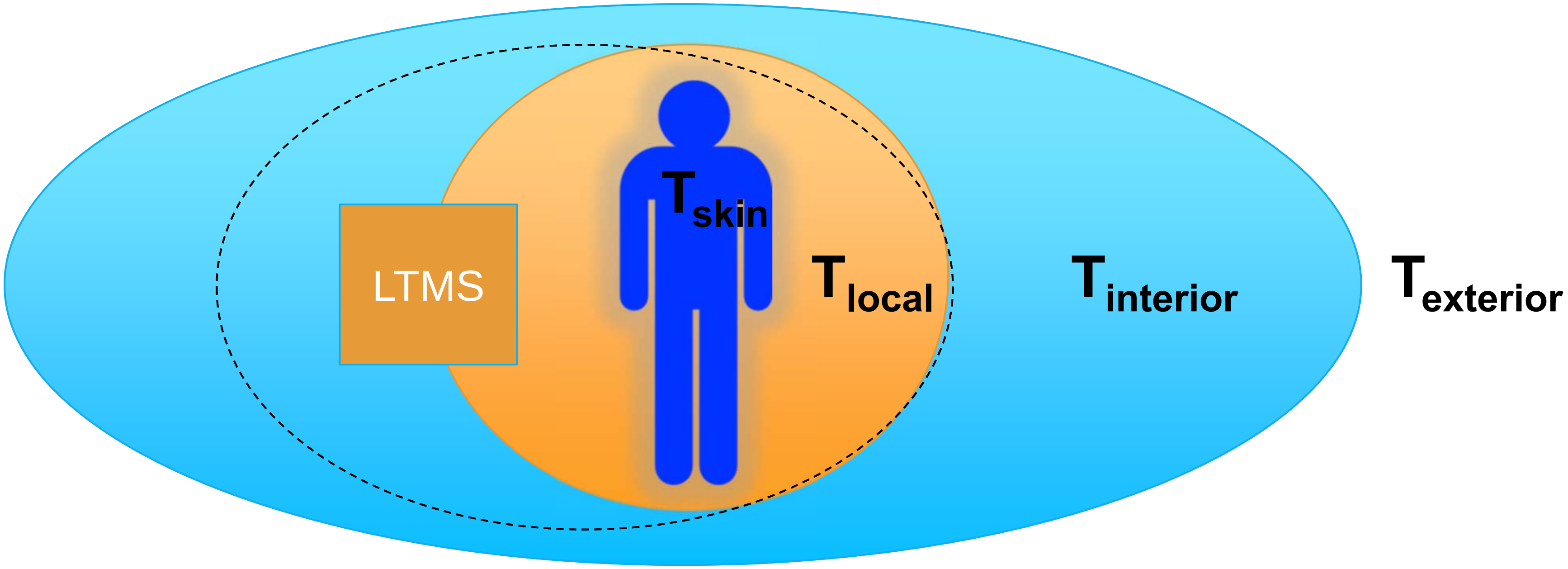
Calculating the COP of your LTMS Device

- When it comes to the COP only one heat transfer interface matters: The User’s Skin!



Summary and Conclusions

- There are three main modes of heat transfer, conduction, convection and radiation (for us, phase change is also important… sweating).
  - It is a highly coupled and incredibly rich field of study.
- The skin interface is what matters!
  - Performance calculations should reflect this.
- Different approaches inherently develop different local envelopes, must be analyzed accordingly
  - Apparel develops zone under textile layers next to skin
  - Long-Range and Short-Range LTMS may create larger zone