Animal Physiology

Temperature & Heat Exchange

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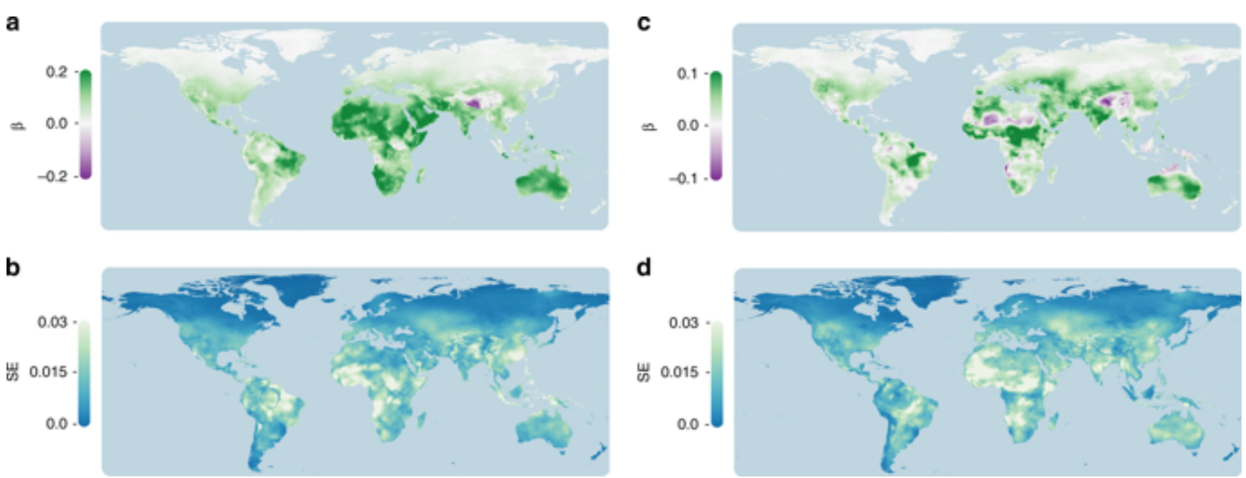
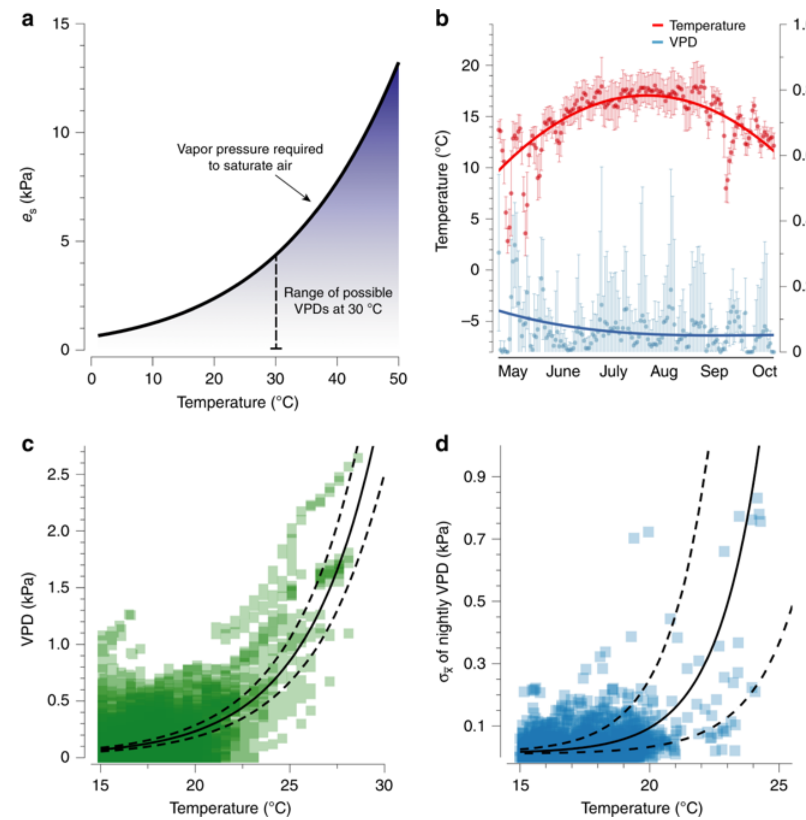
Thermal cues drive plasticity of desiccation resistance in montane salamanders with implications for climate change

Eric A. Riddell, Emma Y. Roback, Christina E. Wells, Kelly R. Zamudio & Michael W. Sears

Nature Communications **10**, Article number: 4091 (2019) | Download Citation



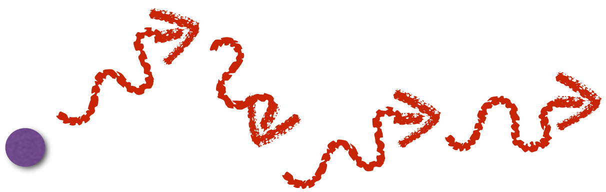


https://www.nature.com/articles/s41467-019-11990-4?fbclid=IwAR1iISn3Z-OXs2ETr7ZjRMMv_52CRfA1wNz7YSehdTiXf4s4F_I7C2I7Nqs

Plethodon metcalfi


© Gary Nafis

Temperature ≡ a measure of the average thermally induced molecular motion.



In order for reactions to occur, molecular have to come together (collide).

↑ motion ↔ ↑ collisions ↔ ↑ reactions

<u>Kelvins</u>: absolute temperature

@K=0 → all molecular motion stops

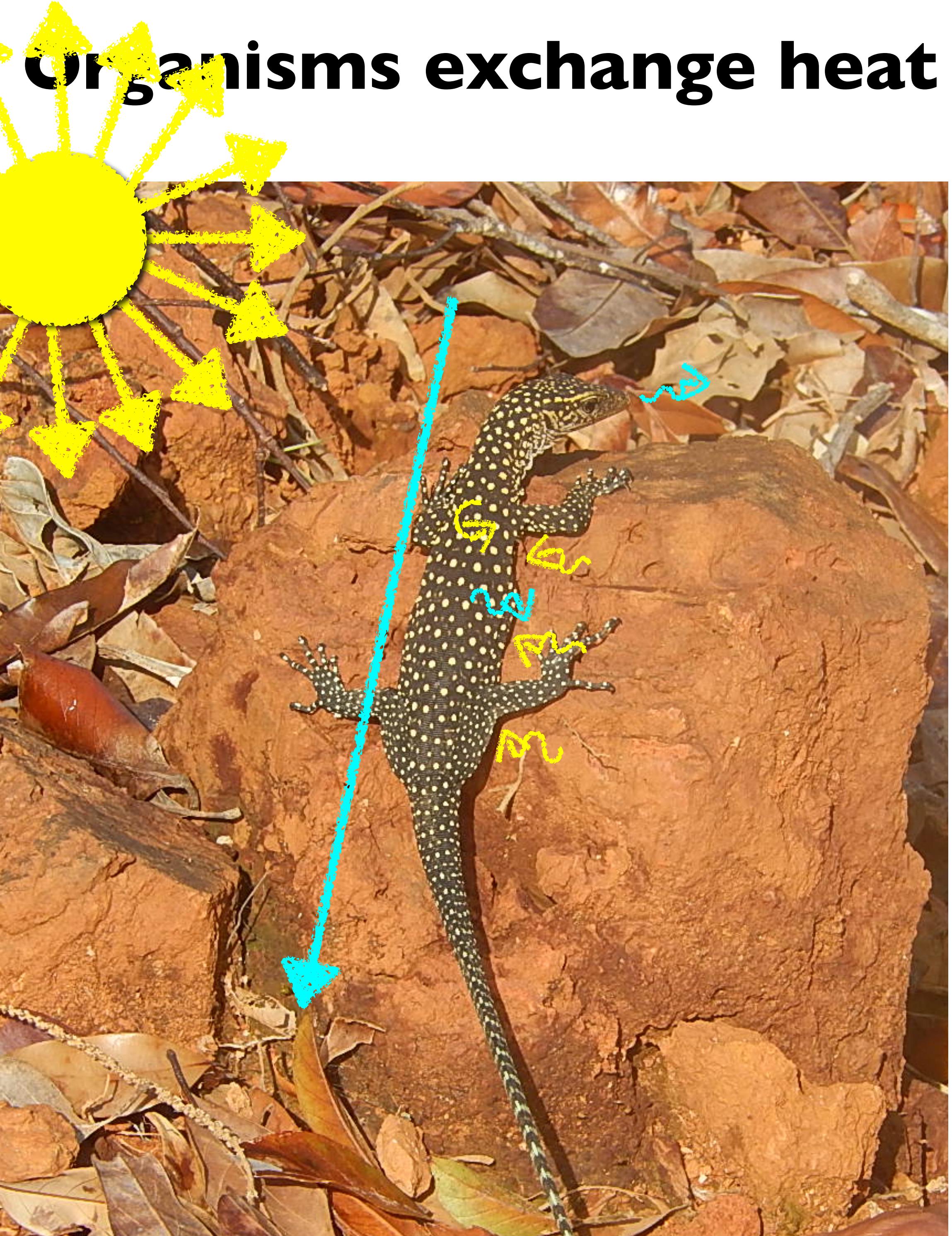
$K = C + 273.15$

Temperature is directly proportional to the E of molecular motions

$KE = 1/2\ m\ V^2 = 1.5\ k\ T$

mass velocity Boltzman‘s constant

Organisms exchange heat with the environment



Metabolism

Radiation

Conduction

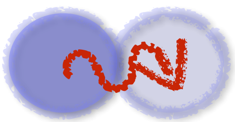
Convection

Evaporation

- Respiratory EWL
- Cutaneous EWL

Mechanisms of Heat Transfer

Conduction: The direct transfer of heat between two solids in contact



$$Q_{cond} = -\, kA(T_2\text{-}T_1)/x \;\; = C\Delta T$$

direct contact

k = thermal conductivity (a material property)

A = surface area

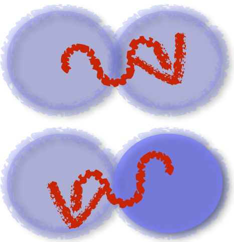
T_2-T_1 = temperature gradient

x = distance between two temperatures

$C\Delta T$ = conductive heat transfer coefficient * ΔT

Rate of Conduction : proportional to

- surface area
- T_2–T_1

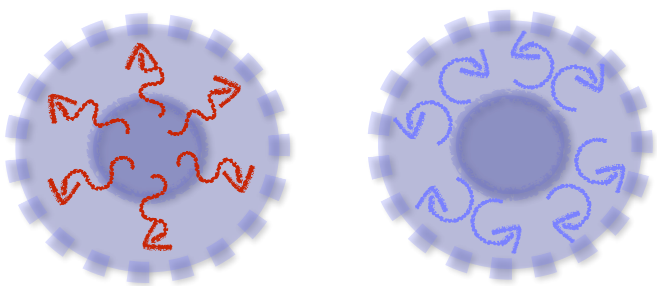


Mechanisms of Heat Transfer

Convection: The transfer of heat by movement of a fluid

$$Q_{cond} = -\ kA(T_2\text{-}T_1)/\delta \quad = h_{conv}\Delta T$$

heat exchange with the fluid boundary layer



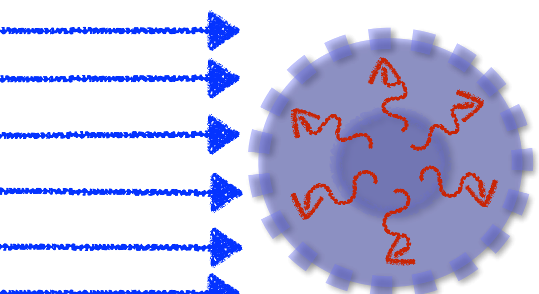
Mechanisms of Heat Transfer

Convection: The transfer of heat by movement of a fluid

$$Q_{cond} = -\, kA(T_2 - T_1)/\delta \quad = h_{conv}\Delta T$$

δ = thickness of fluid boundary layer

heat exchange with the fluid boundary layer

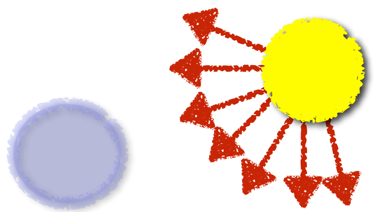


Rate of Convection : proportional to

- surface area
- $T_2 - T_1$
- Can be **much higher**!

Mechanisms of Heat Transfer

Radiation: The heat transfer via spectral emissions



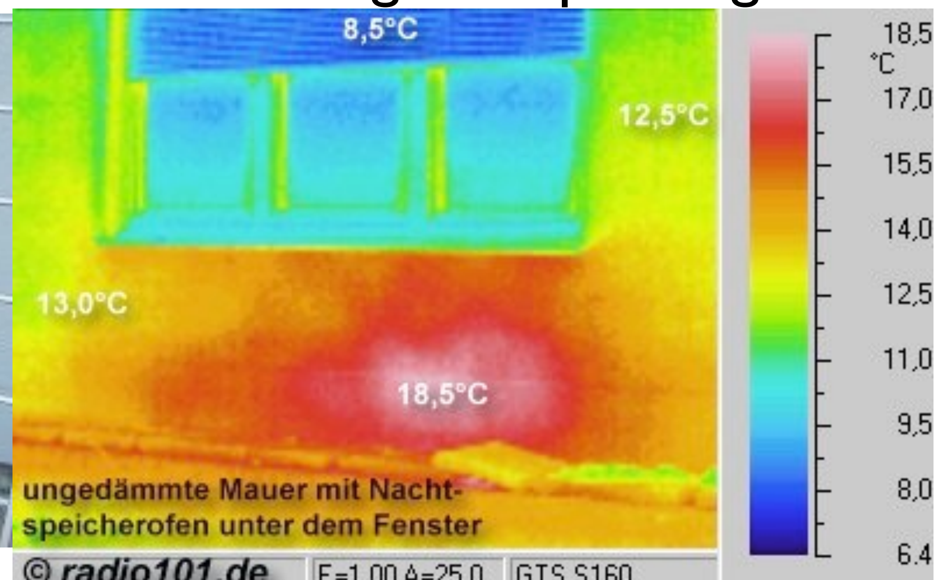
All objects emit spectra!

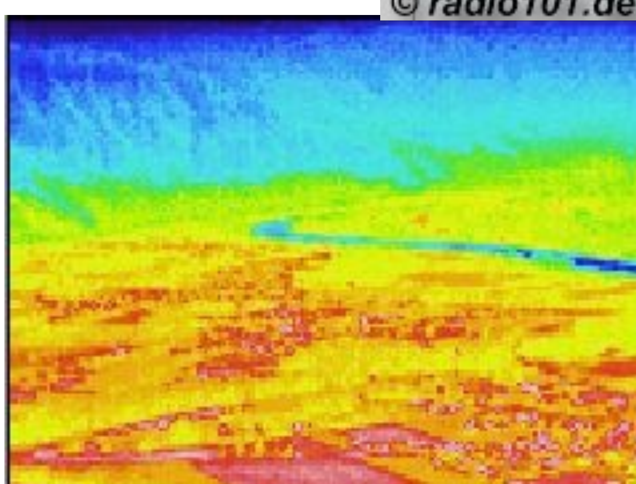
Animals emit light, and absorb light energy

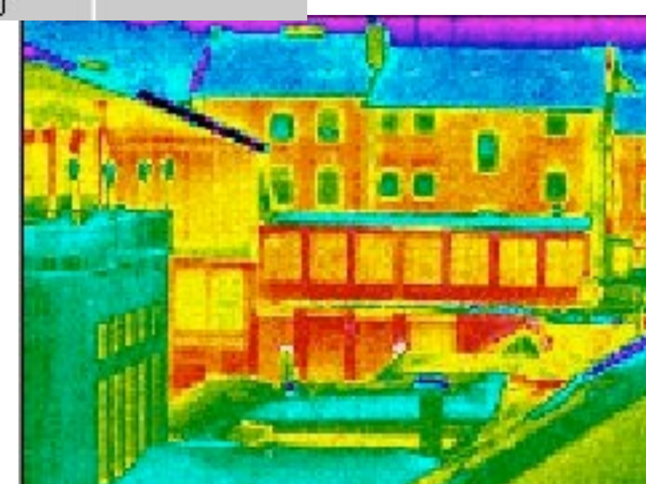
most from sun

Radiation: transfer of heat by spectral emission

All objects emit light of specific wavelengths depending on surface temperature

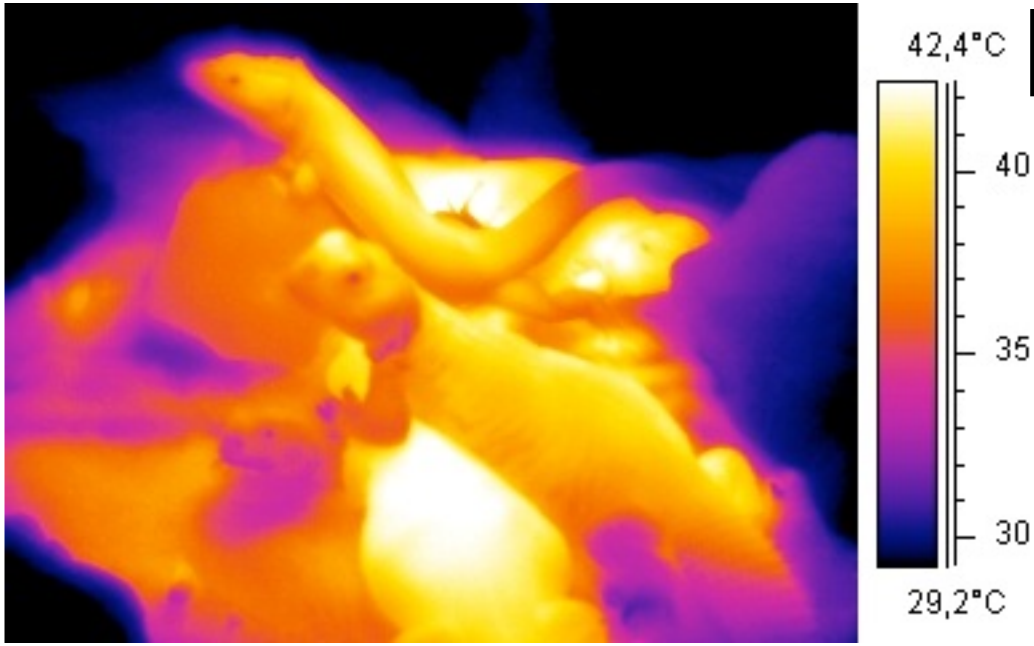


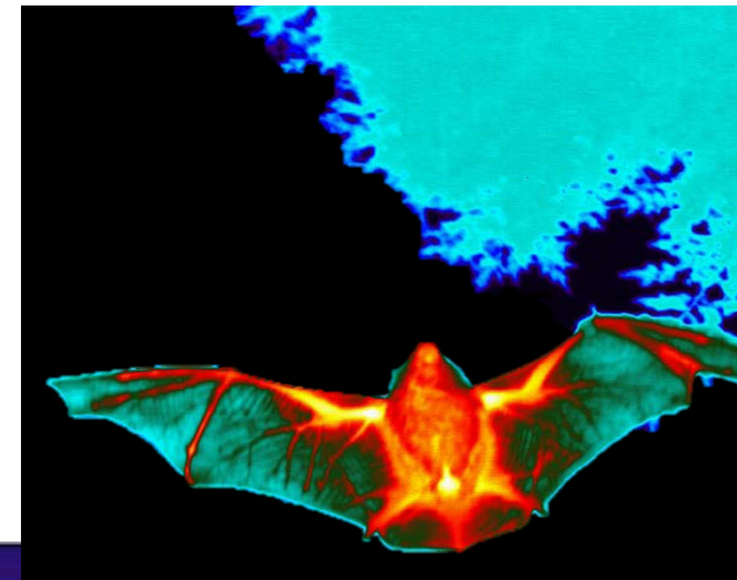




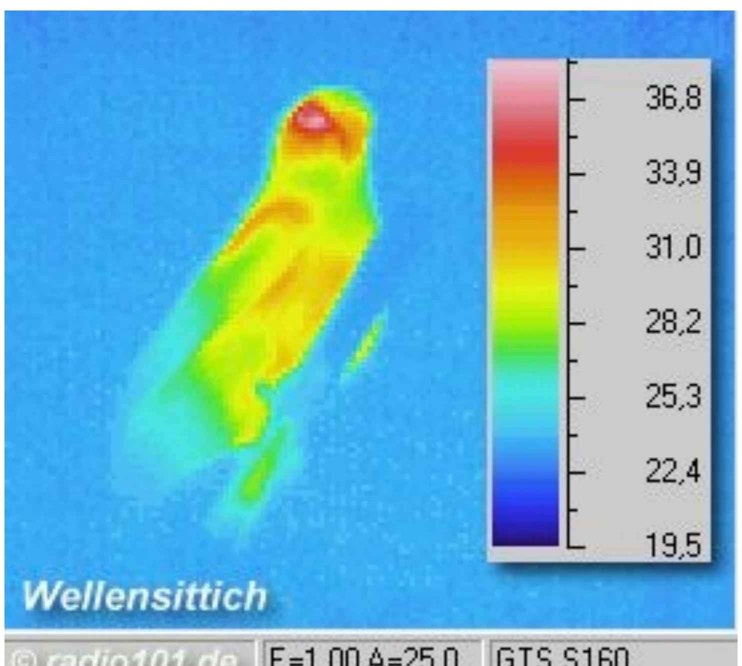
All objects emit light of specific wavelengths depending on surface temperature

Ectotherms



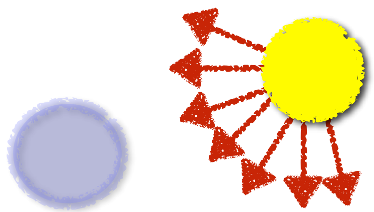


Endotherms



Mechanisms of Heat Transfer

Radiation: The heat transfer via spectral emissions



All objects emit spectra!

Animals emit light, and absorb light energy

most from sun

Q_{rad} is complex, depends on T of surfaces

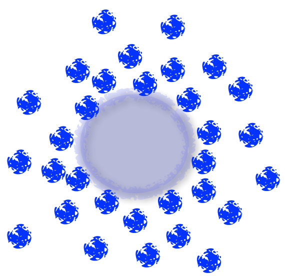
$Q_{rad\ sun} >>> Q_{rad\ animal\ skin}$

Rate of Net Radiative heat transfer : proportional to

- surface area
- time of sun exposure

Mechanisms of Heat Transfer

Evaporation: The heat released with evaporation of water



$Q_{cond} = A(\chi_2 - \chi_1)/r$

A = surface area

$\chi_2 - \chi_1$ = water vapor density gradient

r = resistance to water loss

Latent heat of evaporation is HUGE!

evaporating water releases a lot of heat! about 2400 J/g at 40C

it only takes 480 J/g to heat water from 0C to boiling!

Rate of evaporation : does NOT depend on Temperature!

– Assume surface of skin is 100% saturated with water vapor

– Relative humidity is very important, if RH=100% → no evaporation

the water vapor density of the environment depends on RH & $T_{ambient}$

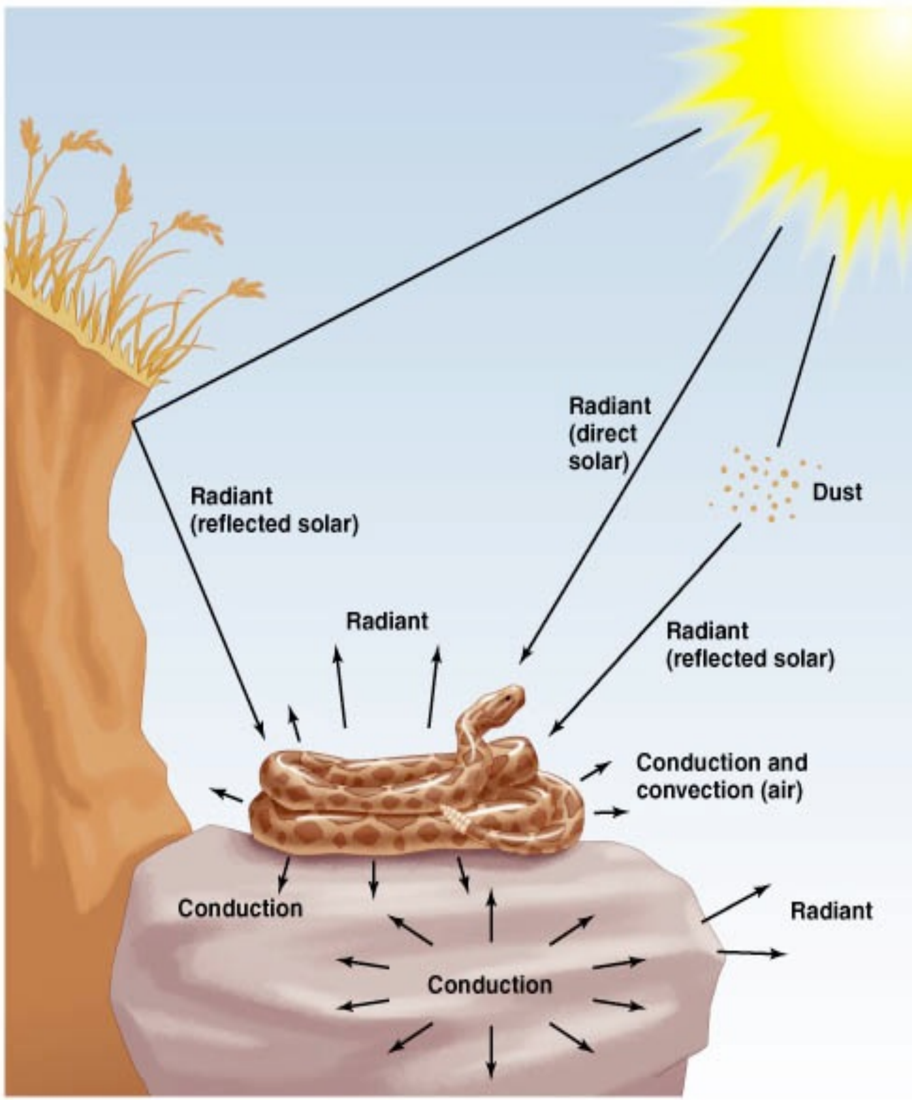
Only a few mammals sweat…

But there's more than one way

http://www.gla.ac.uk/schools/lifesciences/staff/malcolmkennedy/malcolmkennedy/latherin/

https://www.nwf.org/News-and-Magazines/National-Wildlife/Animals/Archives/2010/animals_beat_the_heat.aspx

Organisms exchange heat with the environment



Heat Balance Equation:

$$\Delta H_s = H_m \pm H_c \pm H_r \pm H_e$$

metabolism

radiation

conduction

evaporation

convection

Heat Balance

Haldane "Physiology is the story of evolution's struggle to maintain an appropriate SA/D ratio in relation to the volume of an animal"

$$\text{Flux} = C * \nabla \text{ (Mass or Energy)}$$

$$Q = C * M \, \Delta T$$

→ magnitude of the flux is $\propto$ SA (flux ↑ with ↑ SA)

→ magnitude of the flux is $\propto$ 1/distance (flux ↑ with ↓ distance)

→ as animals get very large, SA/vol ↓ (SA/vol $\propto$ size$^{2/3}$)

Strategies:

→ change shape with ↑ size (to ↑ SA)

→ change # compartments

→ maintain SA/D within compartments, but vary # compartments)

→ evolve novel transport systems to ↓distance

This lecture is intended to familiarize you with the mechanisms for **Heat Exchange**

We will be using scaling equations to estimate “average” values for the rate of metabolism, conduction, evaporation, etc. for various animal taxa

— informed by your values for environmental temperature (Ta), body temperature (Tb), mass, relative humidity (RH), etc.

— and you can refine your model if you wish based on your biological information (e.g., insulation? fur?)

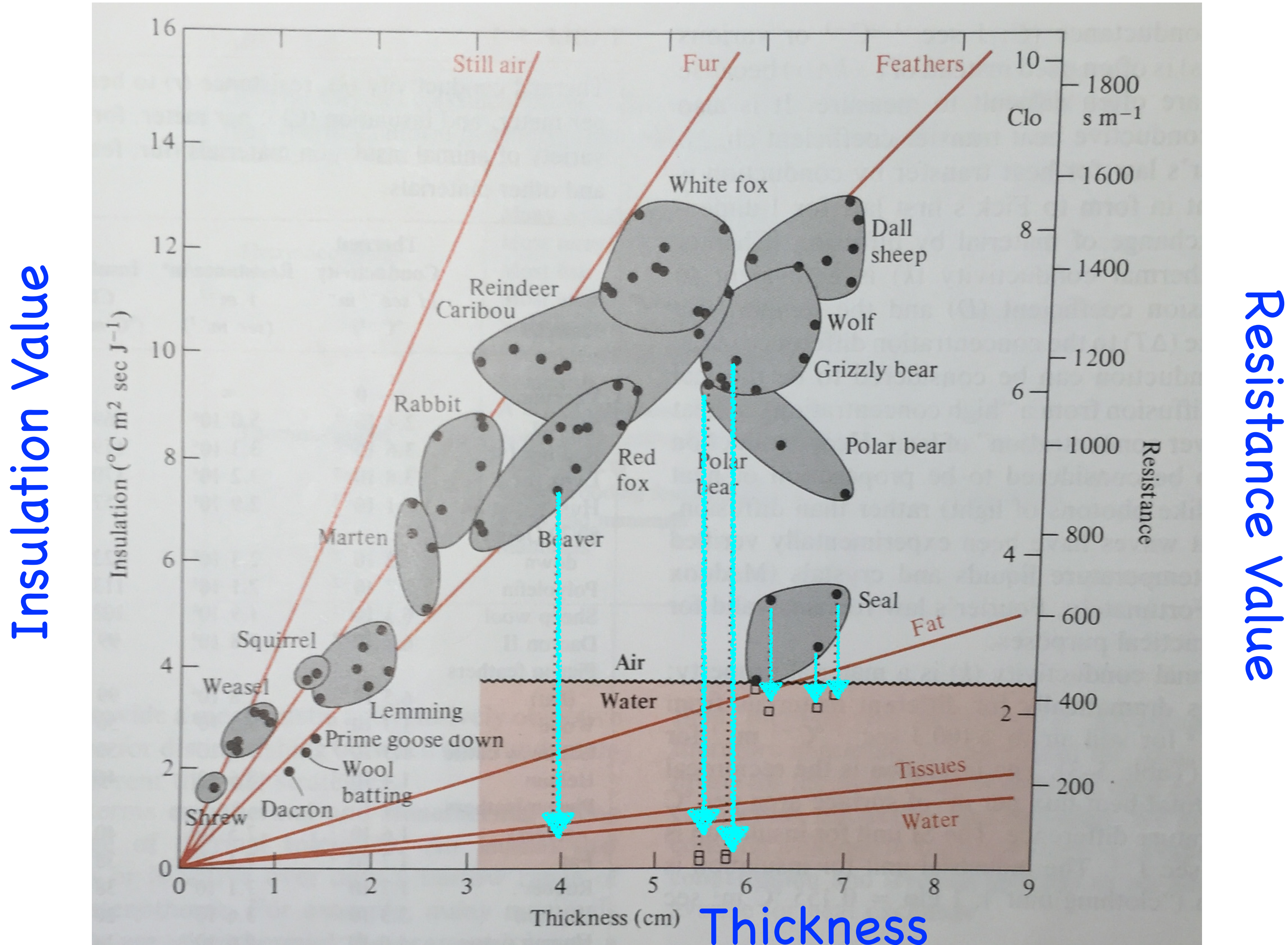
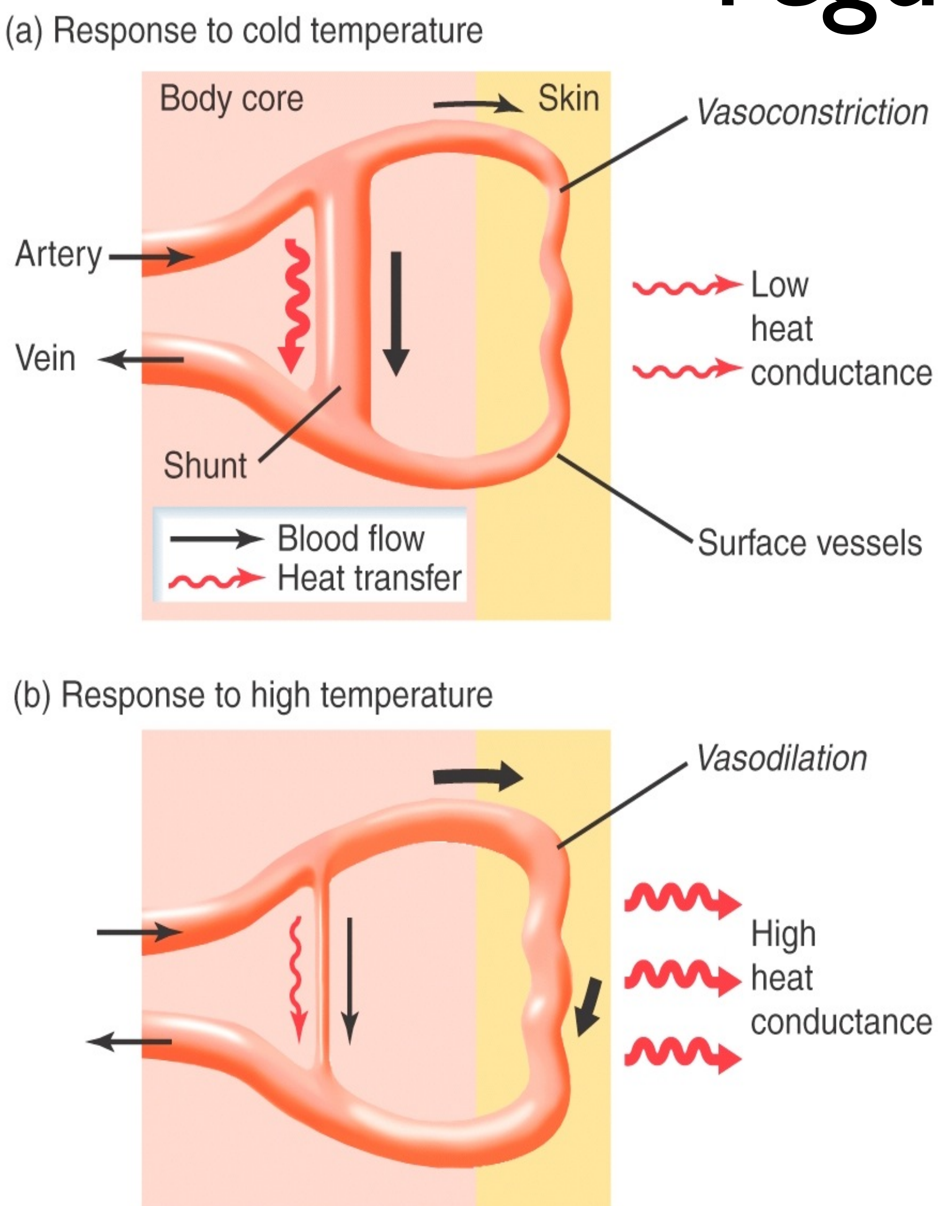
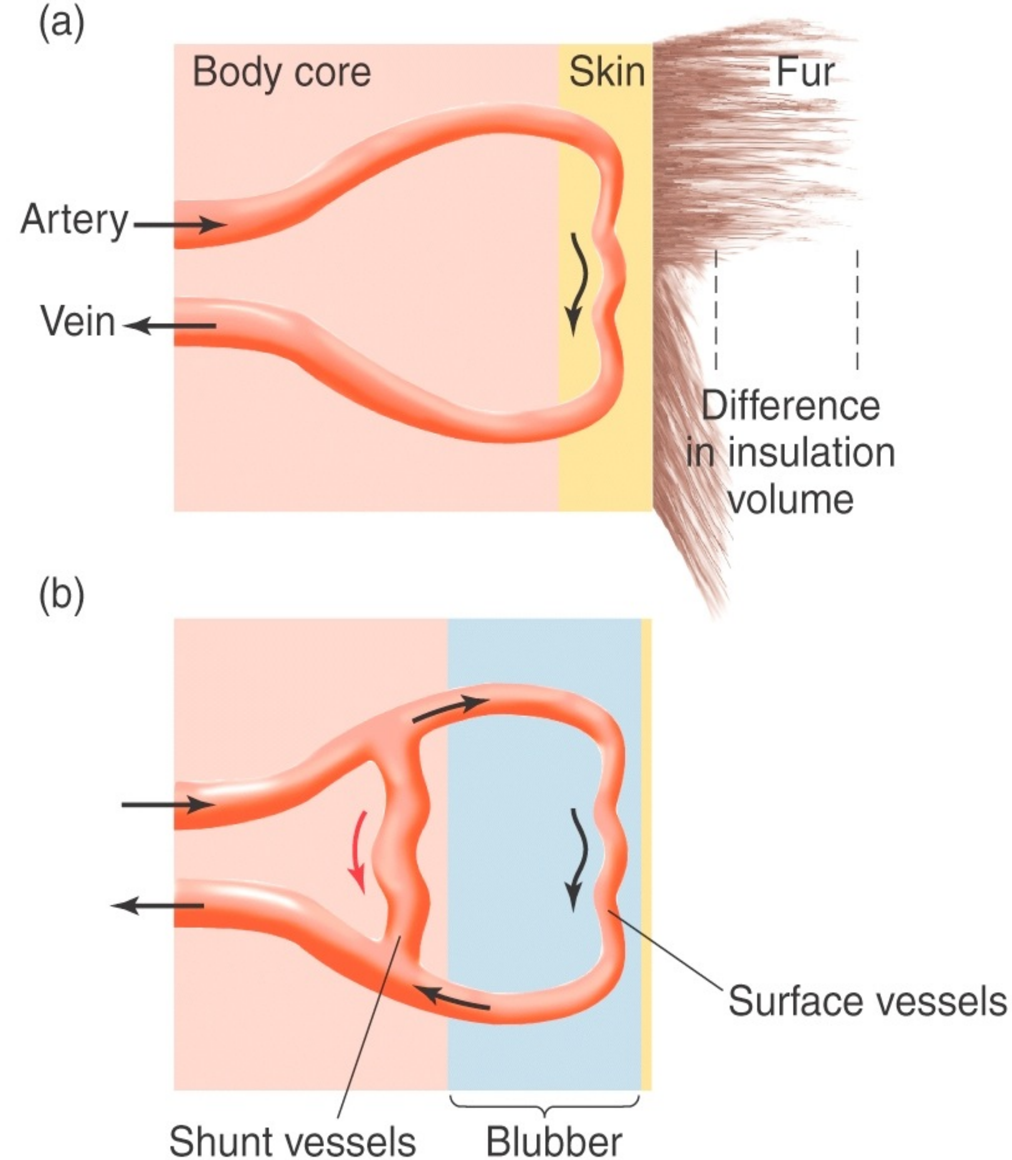


FIGURE 5–5 The insulative value (°C m² sec J^{-1}) of animal fur varies with its thickness. Fur has a markedly reduced insulative value in water (dotted lines; squares). Seal skin has a low insulative value in air compared to fur but retains most of its insulative value in water. Solid lines indicate the expected values for still air, average values for fur and feathers, fat, tissues, and still water; the slopes of these lines equal 1/thermal conductivity. Solid points indicate some insulative values for artificial insulation (prime 80/20 goose down, wool fiber batting, and Dacron). The alternative insulation scales of resistance (*r*; sec m^{-1}) and Clo (1 Clo = 0.155 °C m² sec J^{-1}) are also indicated. *(Modified from Scholander et al. 1950; artificial insulation values from Kaufman, Bothe, and Meyer 1982.)*

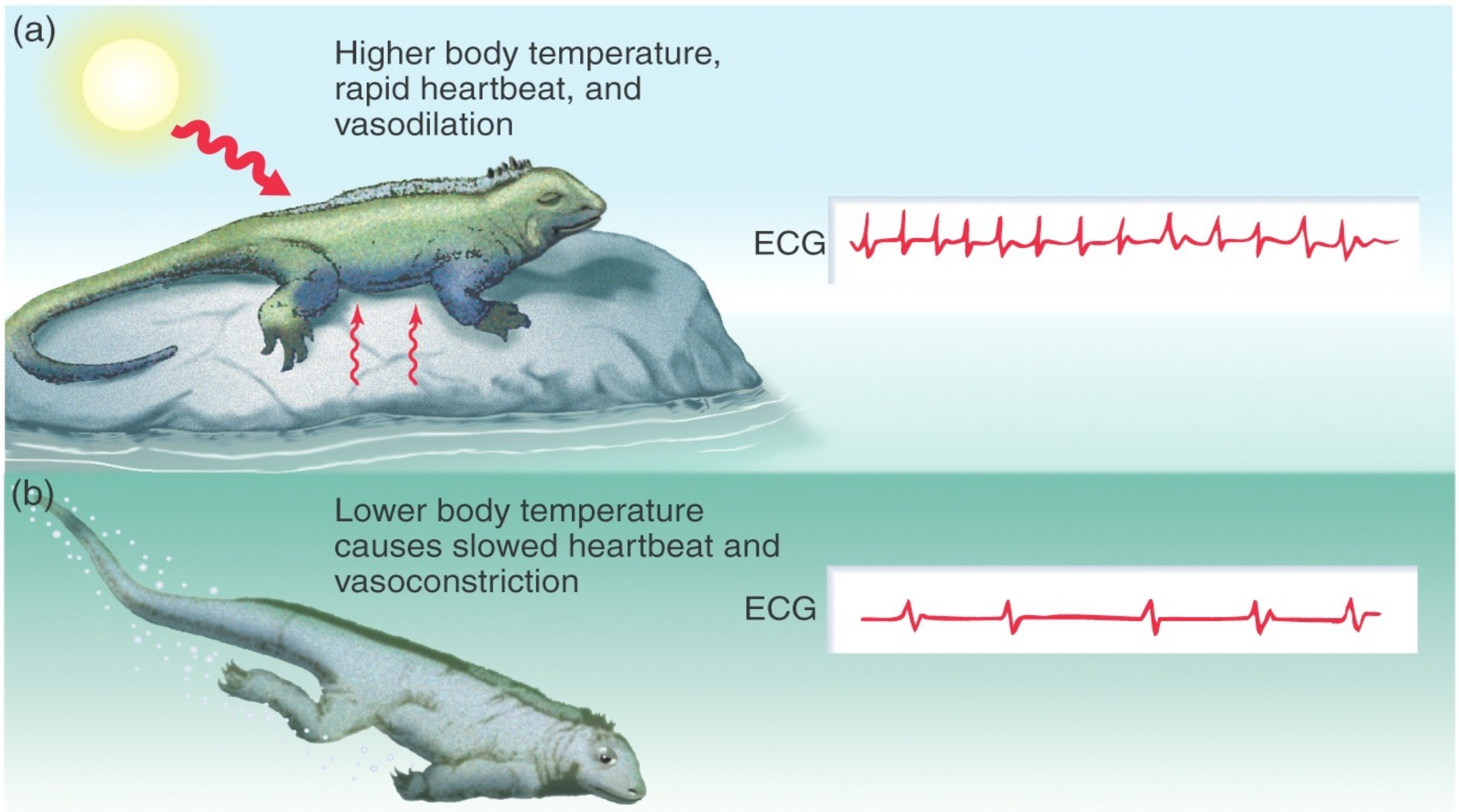
Circulation also transports heat

Circulatory Shunts aid in temperature regulation





Regulating heat loss/gain by vasodilation

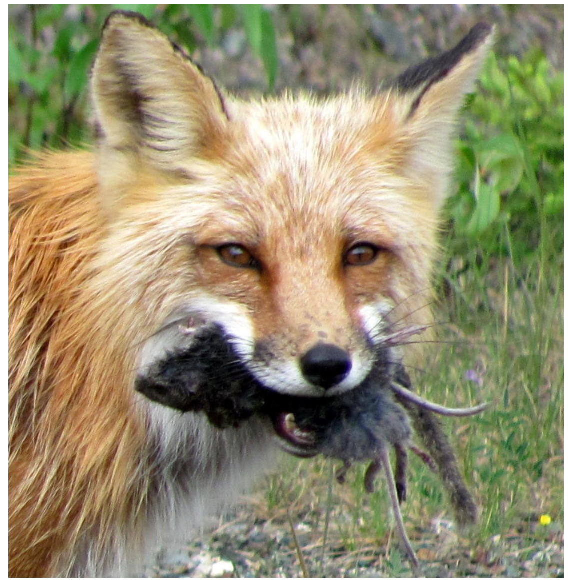


Adaptations to Moderate Heat Loss

Kit Fox

Desert

http://www.wildlifeheritage.org/gallery/san-joaquin-kit-fox/



Red Fox

Temperate

"Kanadai róka" by Veronika Ronkos - Own work. Licensed under Creative Commons http://commons.wikimedia.org/wiki/File:Kanadai_r%C3%B3ka.jpg#mediaviewer/File:Kanadai_r%C3%B3ka.jpg

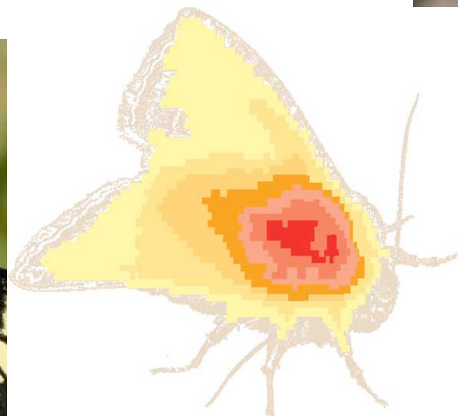
Arctic Fox

Cold

http://www.zmescience.com/other/arctic-fox-14042011/

Behavioral Thermoregulation: Basking

Flying insects maintain High Thoracic Temp
Basking Postures Maximize Heat Gain



http://bio1152.nicerweb.com/Locked/media/ch40/

Basking to Minimize Heat Gain

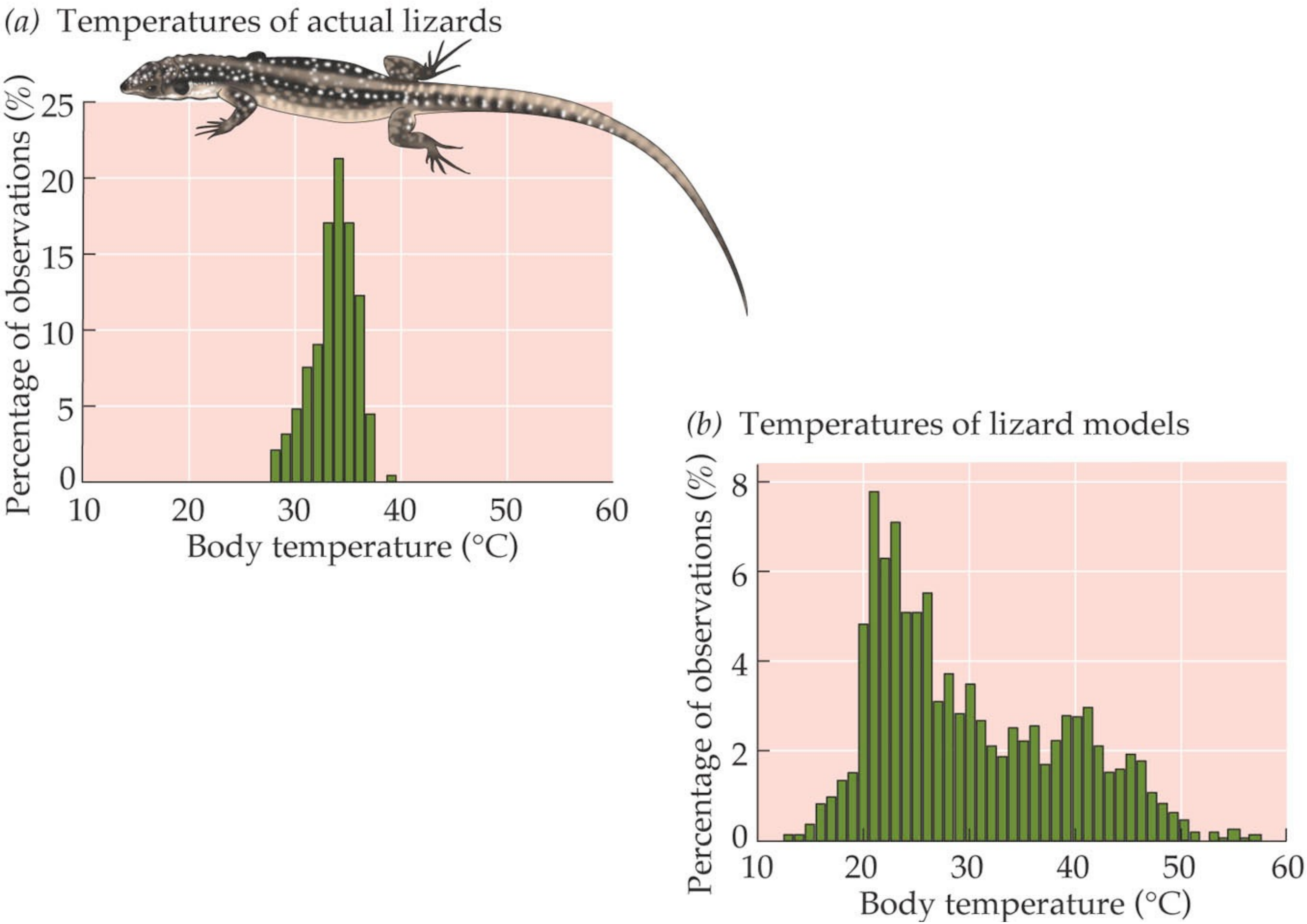
http://bio1152.nicerweb.com/Locked/media/ch40/

Desert animals: high heat load!

Cataglyphis fortis: Sahara desert ant
long legs - **lift body away from ground**
point abdomen straight up

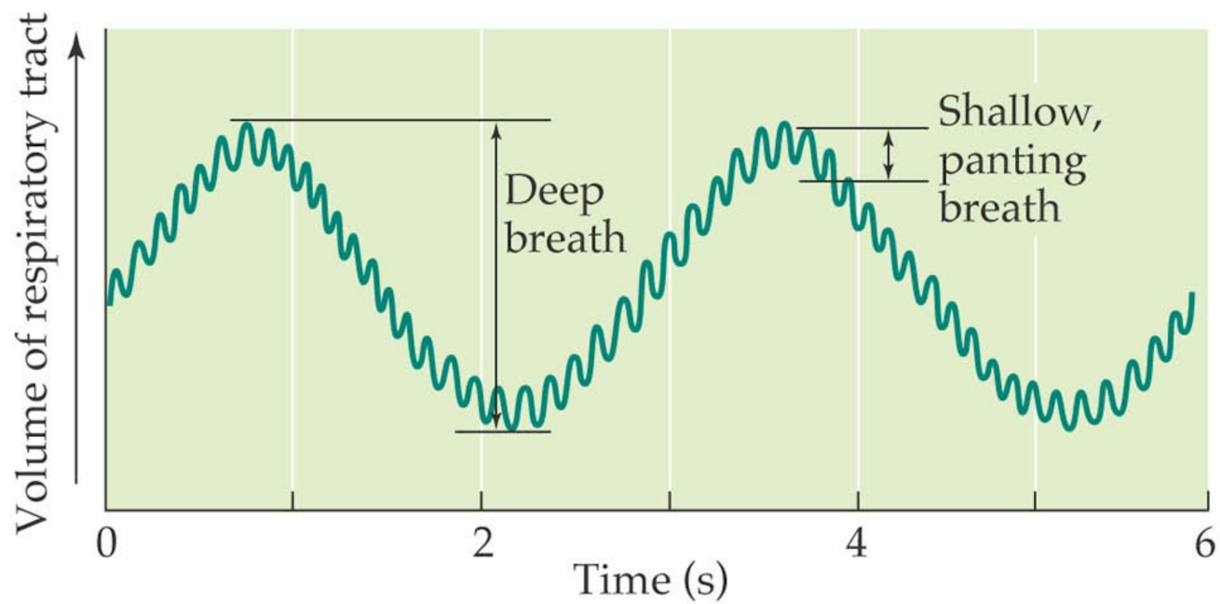
Scorpion

Behavioral thermoregulation



Keeping cool: Evaporative Cooling

- Behavioral (bathing, squirting)
- Loss of Respiratory Water
- Panting - Gular Fluttering
  – Low gas exchange during shallow breaths



Panting!

In direct line of action of the FAN!

↑ Convection

Increasing SA in contact with cooler surface

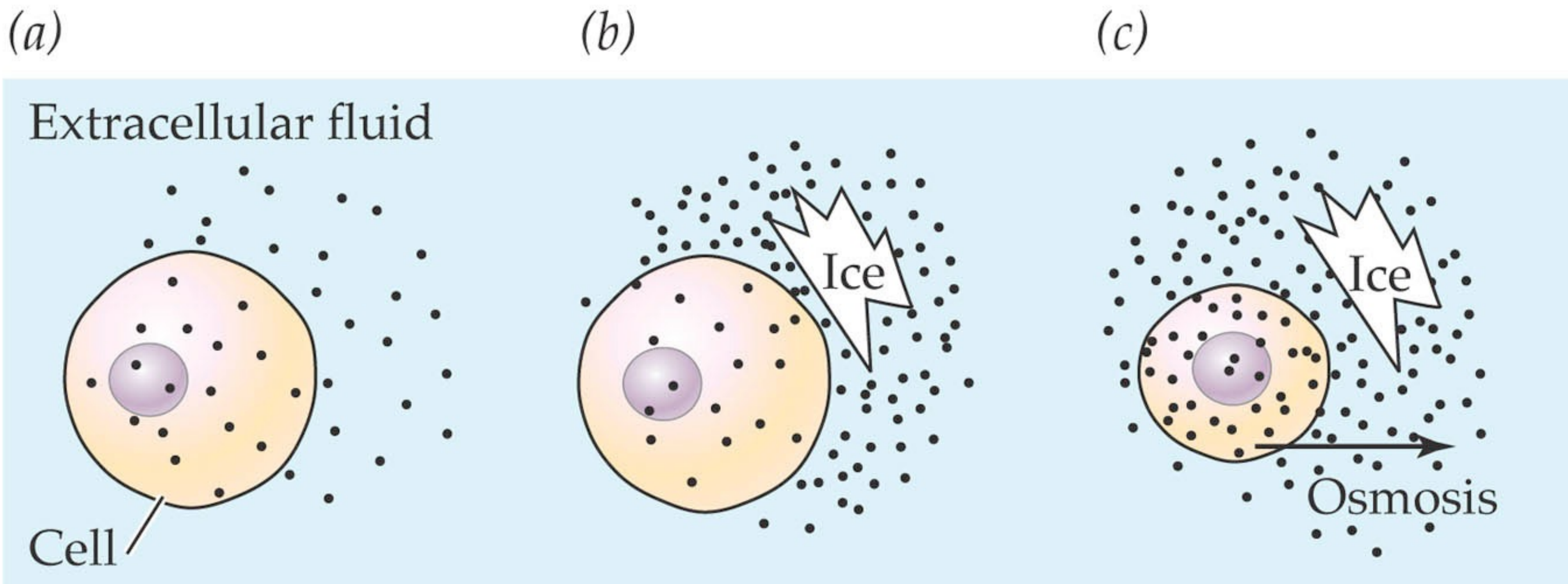
↑ Conduction

The intelligence of dogs!

Adaptations to Cold
Strategies for Cold Tolerance

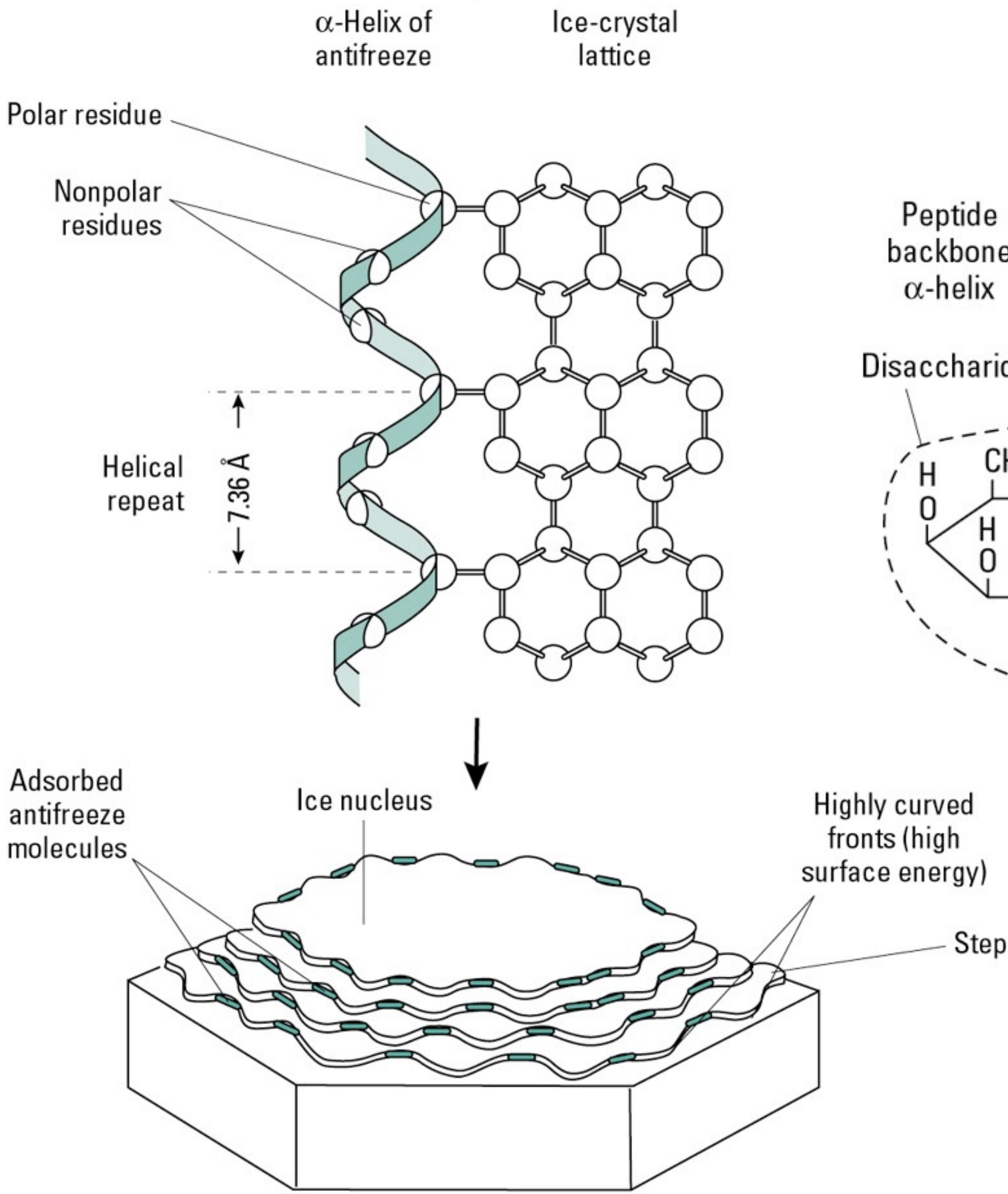
Anti-Freeze Strategies

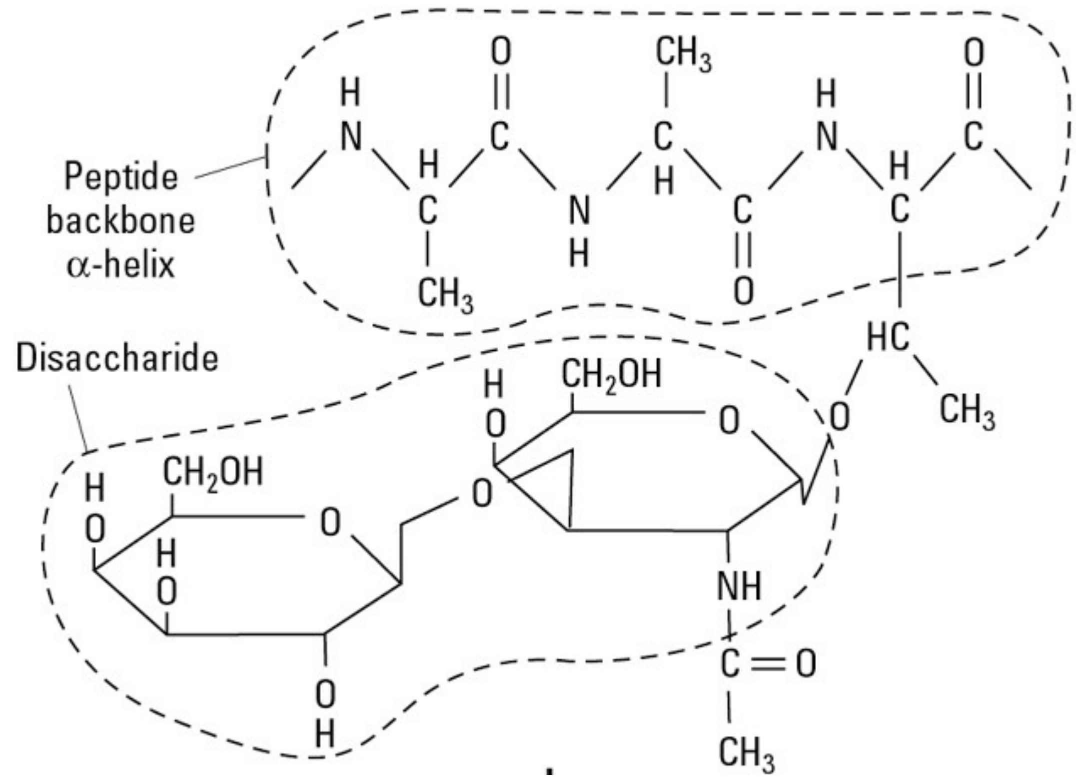
A major danger is ice crystals



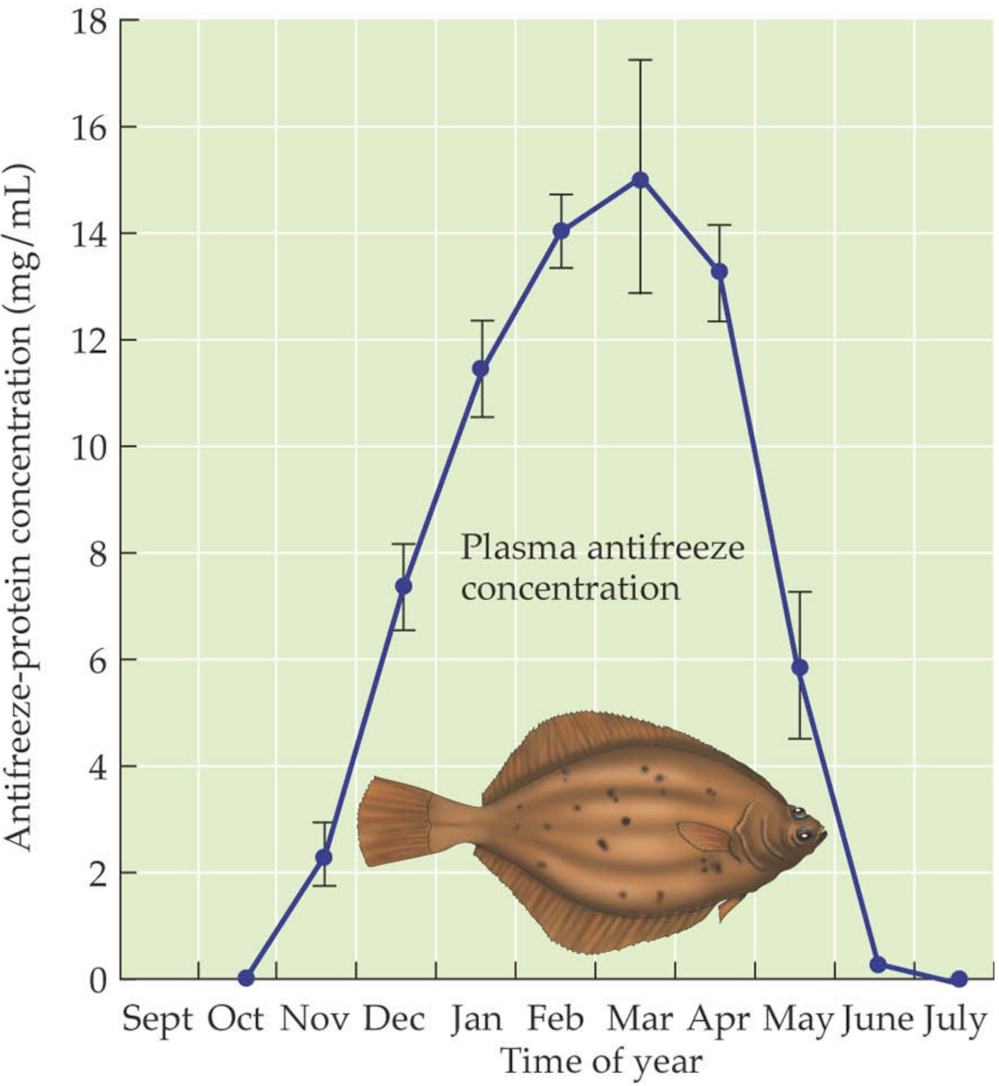
Extracellular freezing and solute concentration

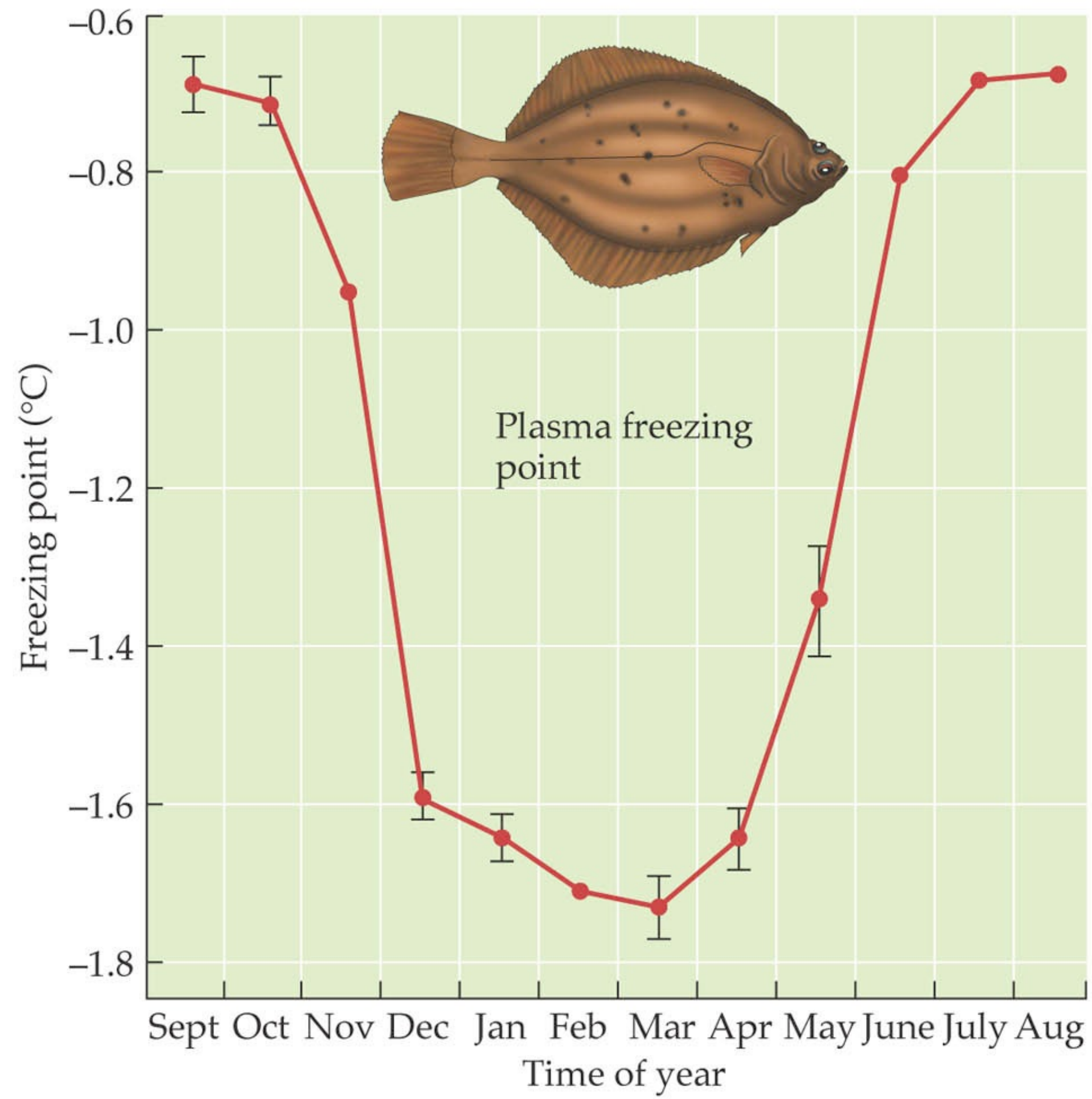
Antifreeze Proteins



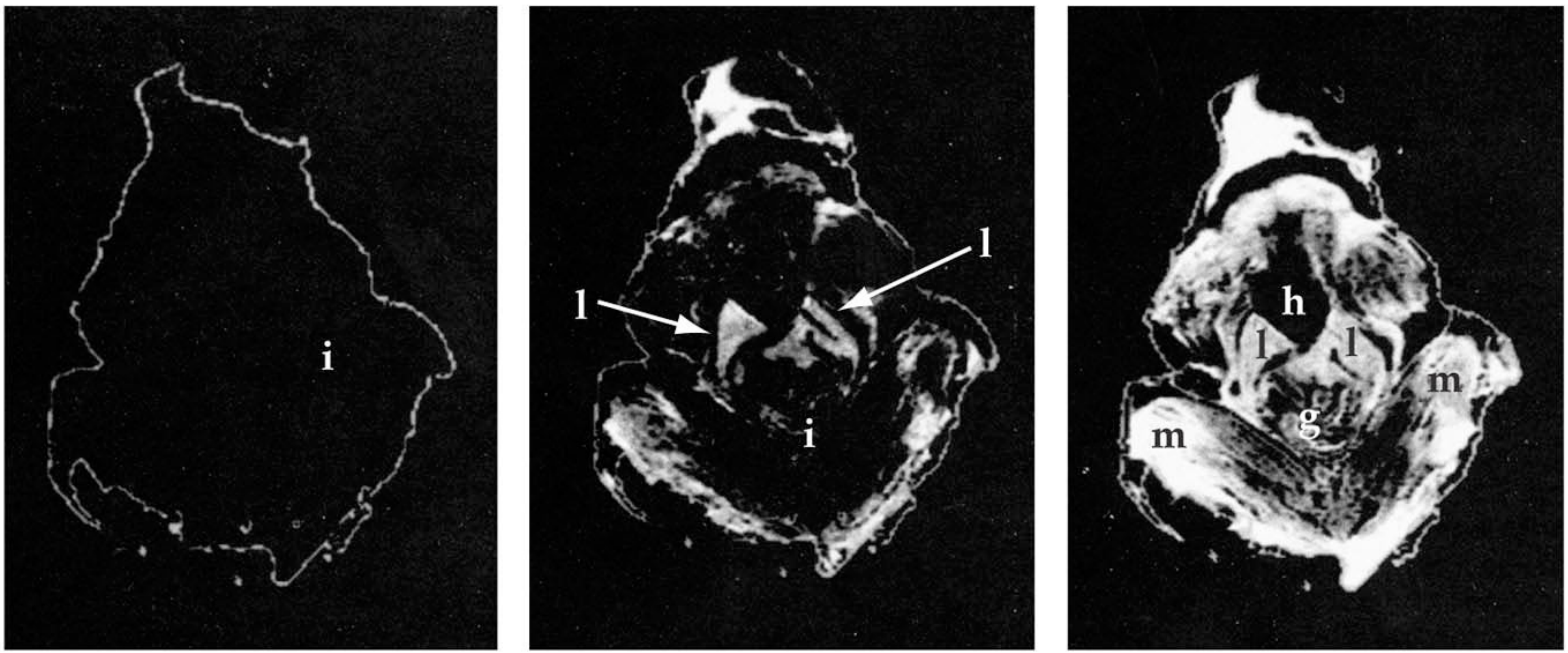


Antifreeze Proteins





Dessication to prevent ice crystals



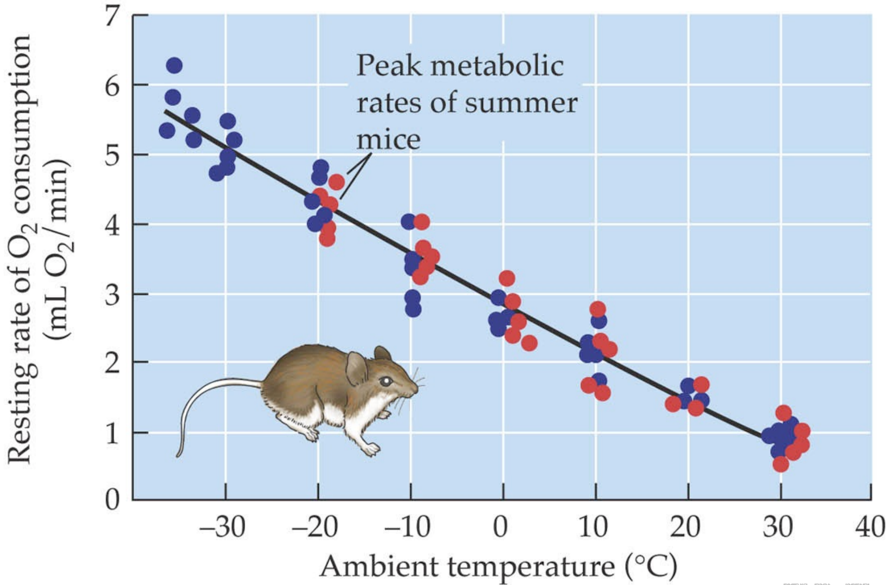
0 min 52 min 87 min

Adaptations to Cold
Strategies for Cold Tolerance

Decrease Heat Loss

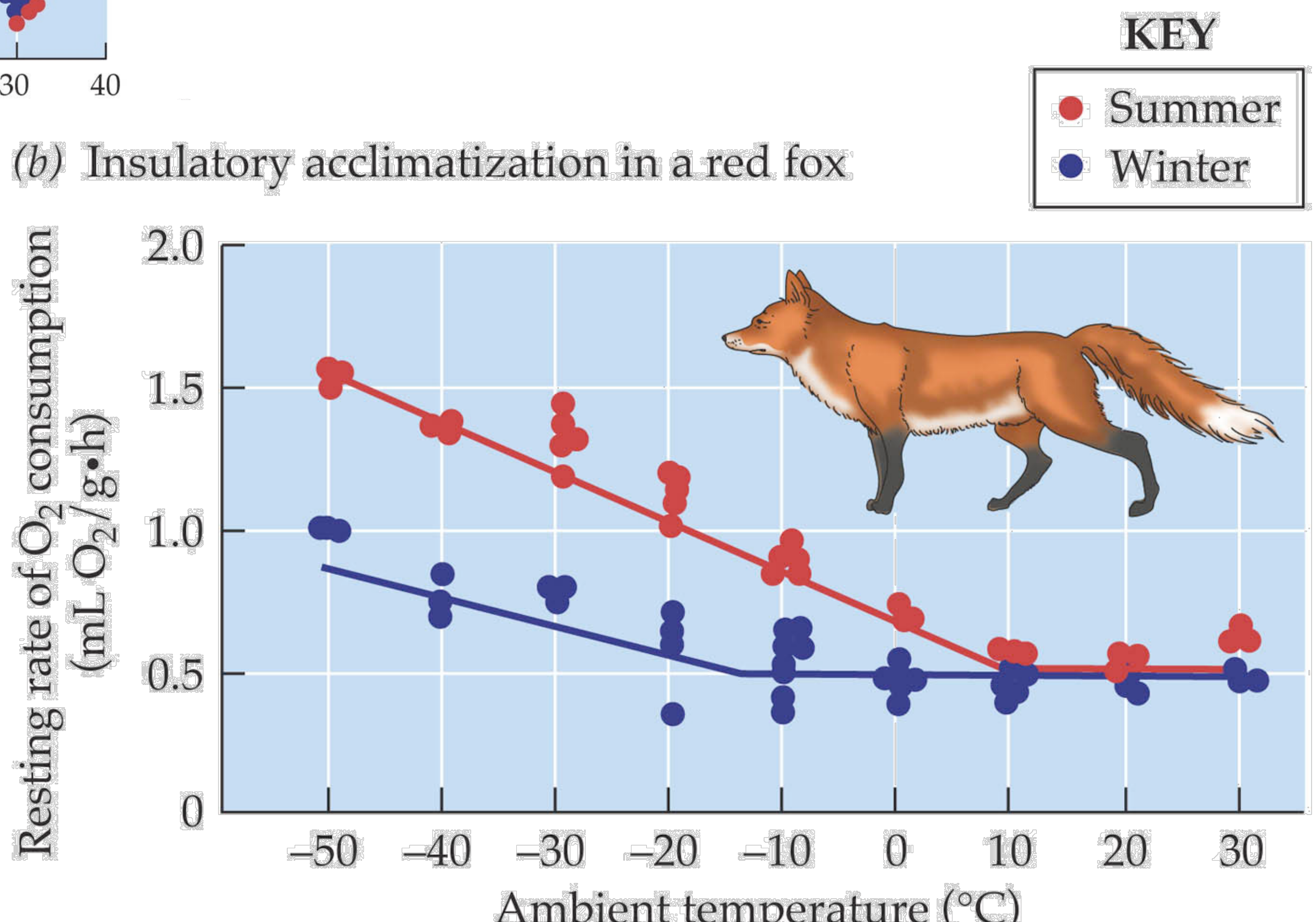
Emperor Penguins in Antarctica reduce heat loss by huddling (behavior)

Insulation Acclimatization

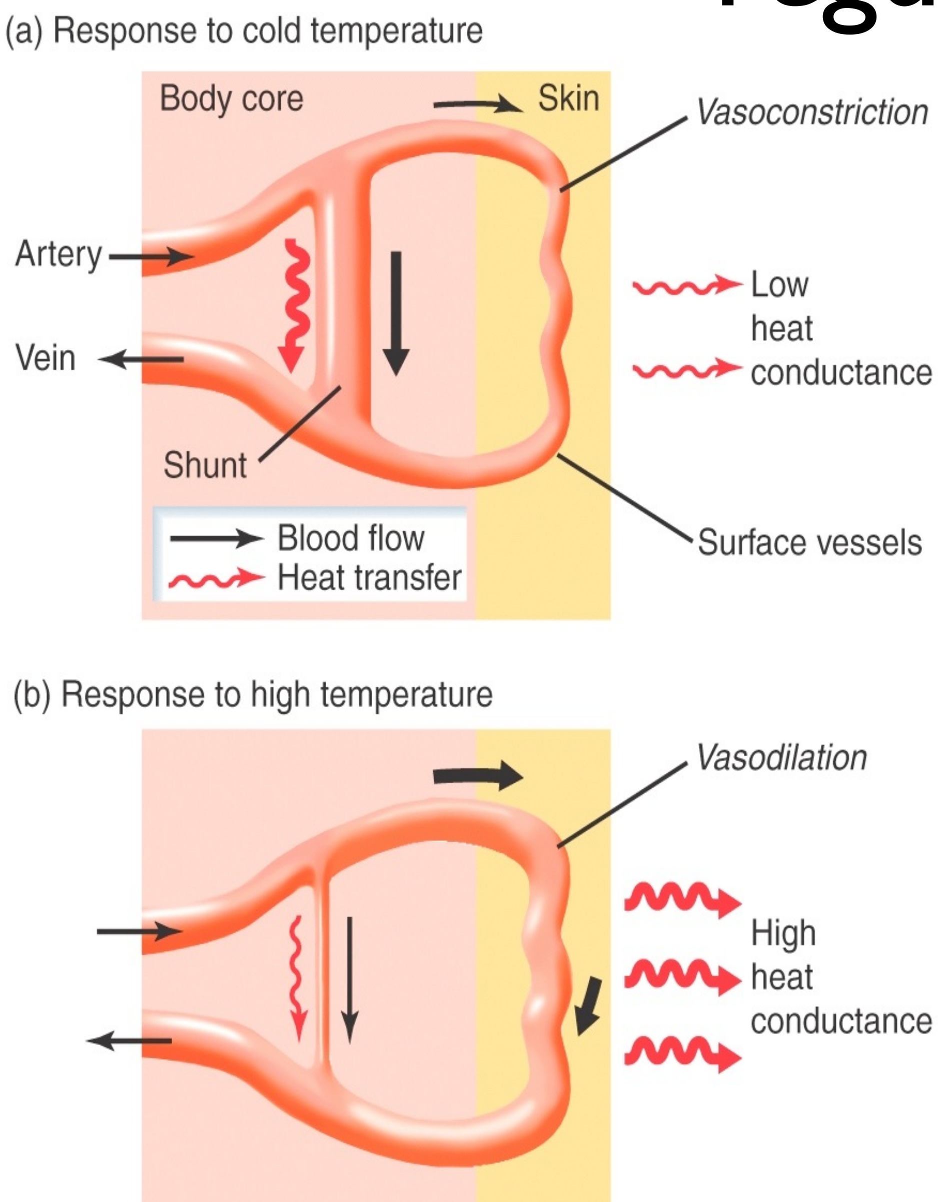


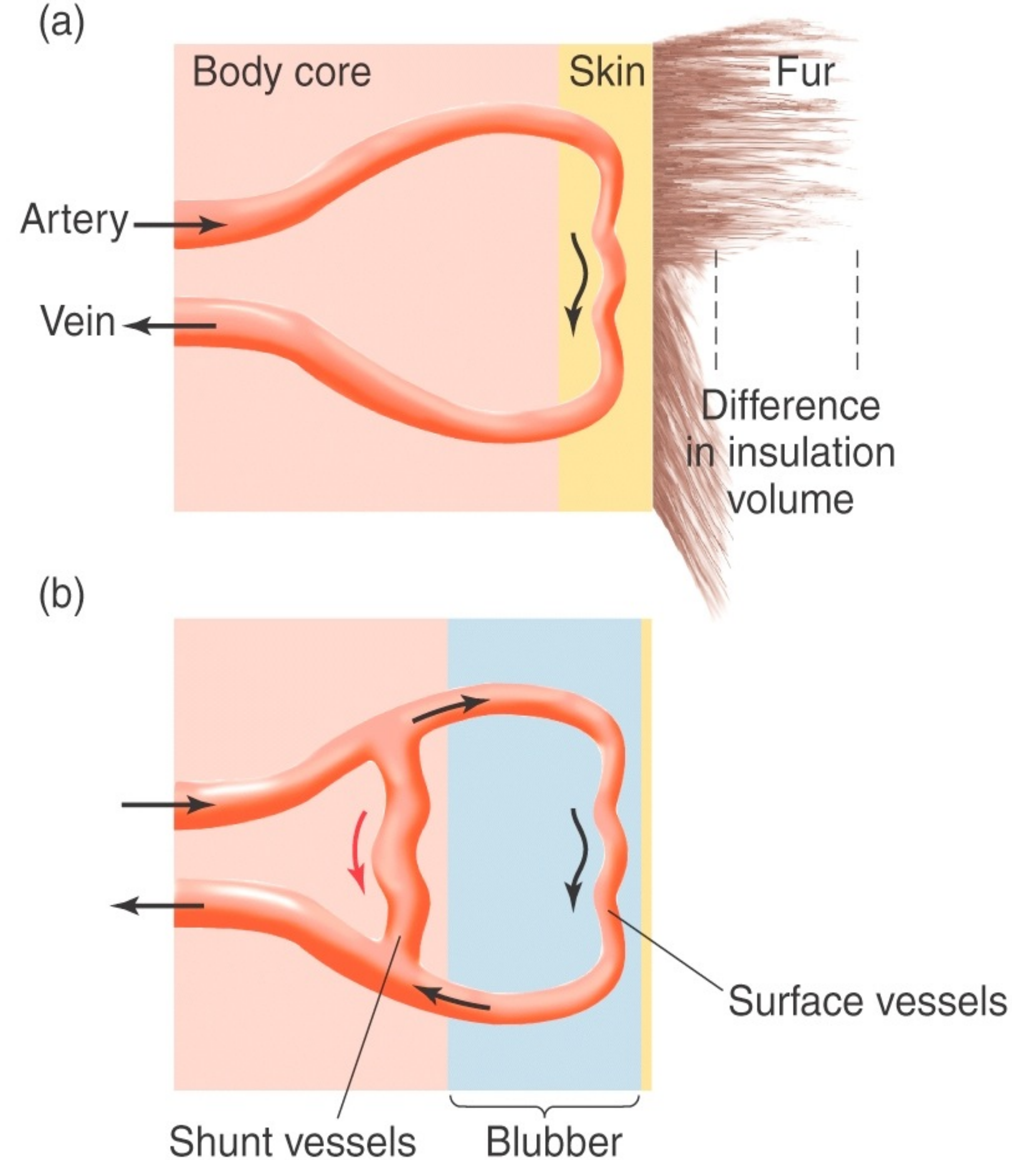
No seasonal variation in insulation increases metabolic costs of cold exposure

Seasonal variation decreases cost of cold exposure

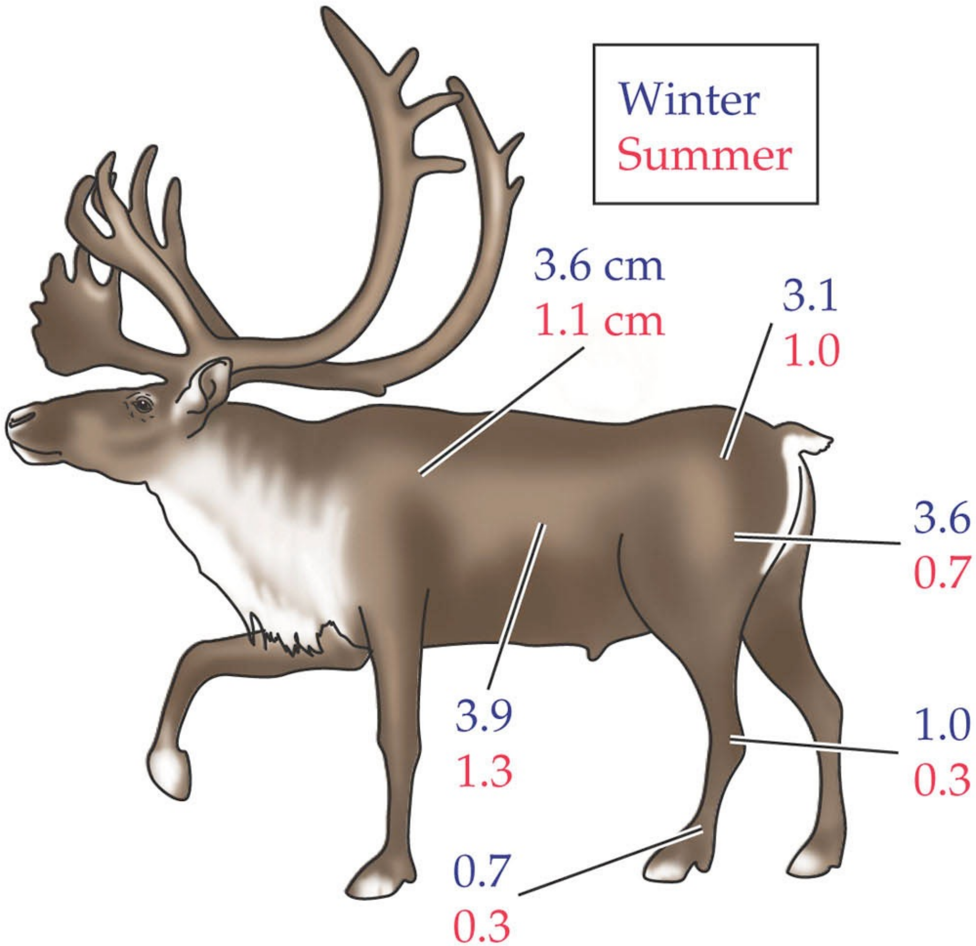


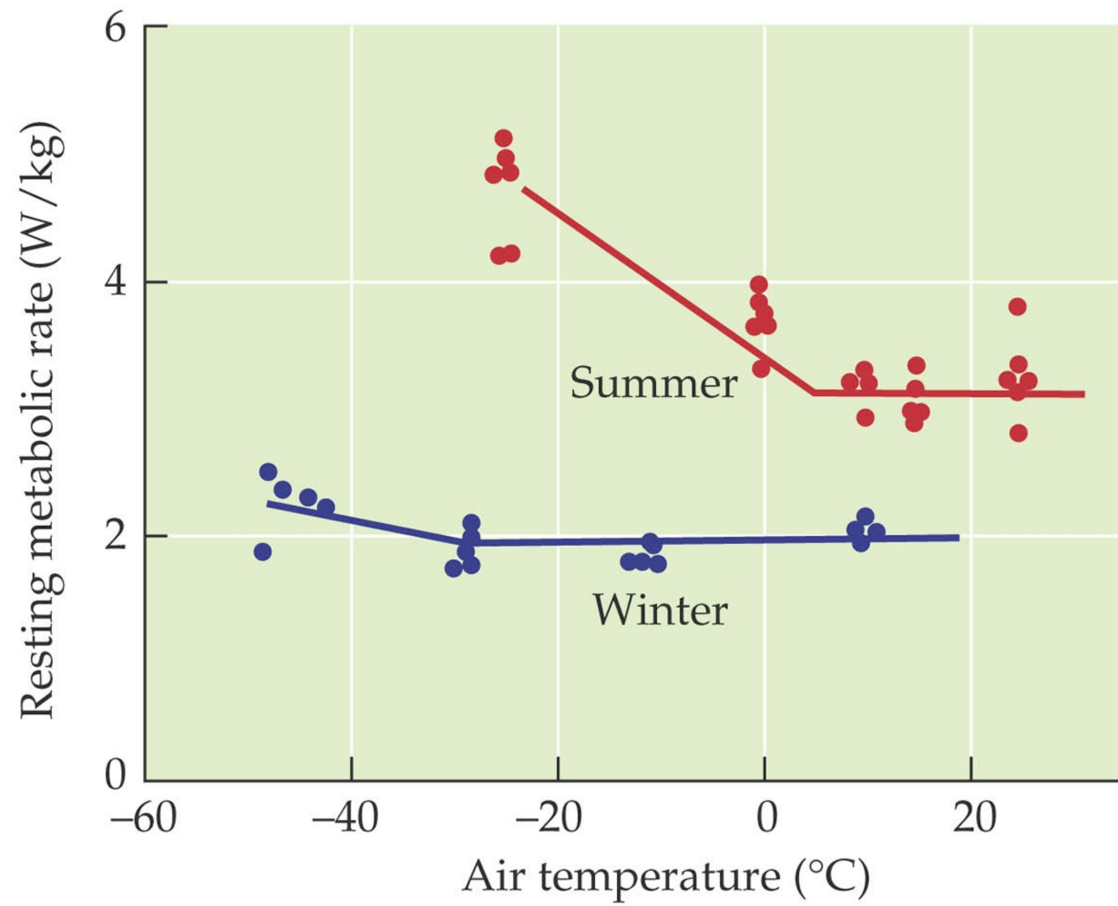
Circulatory Shunts aid in temperature regulation





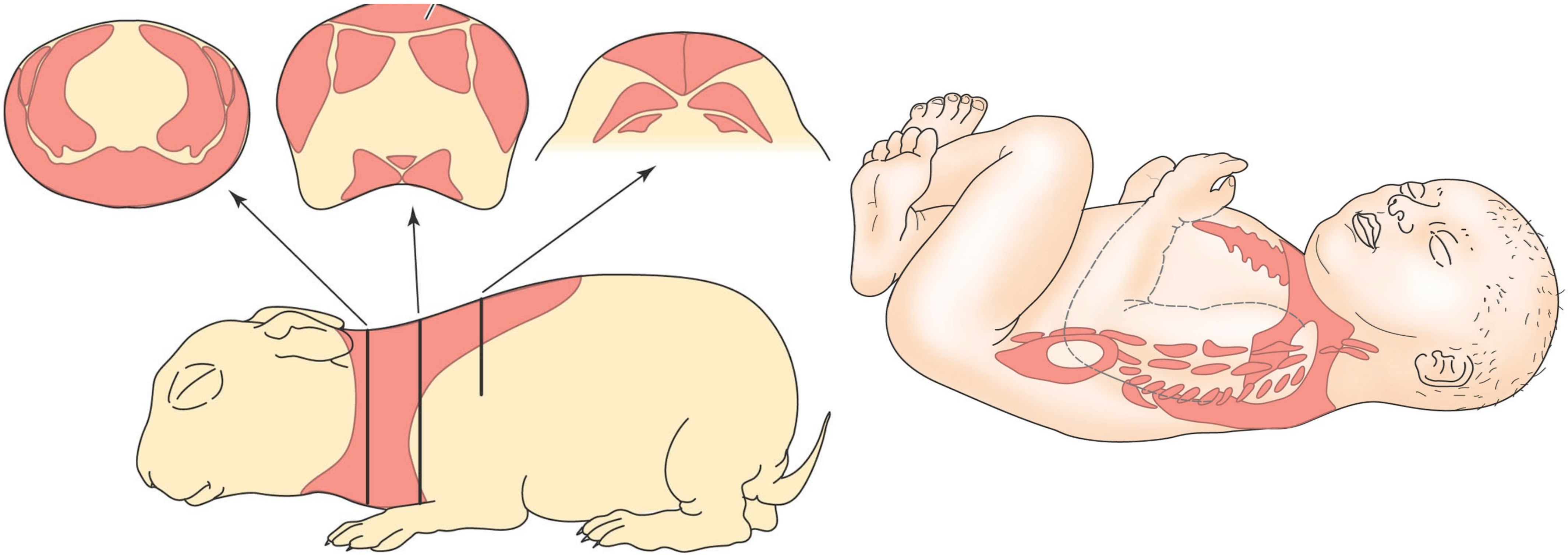
Winter vs. Summer Reindeer RMR





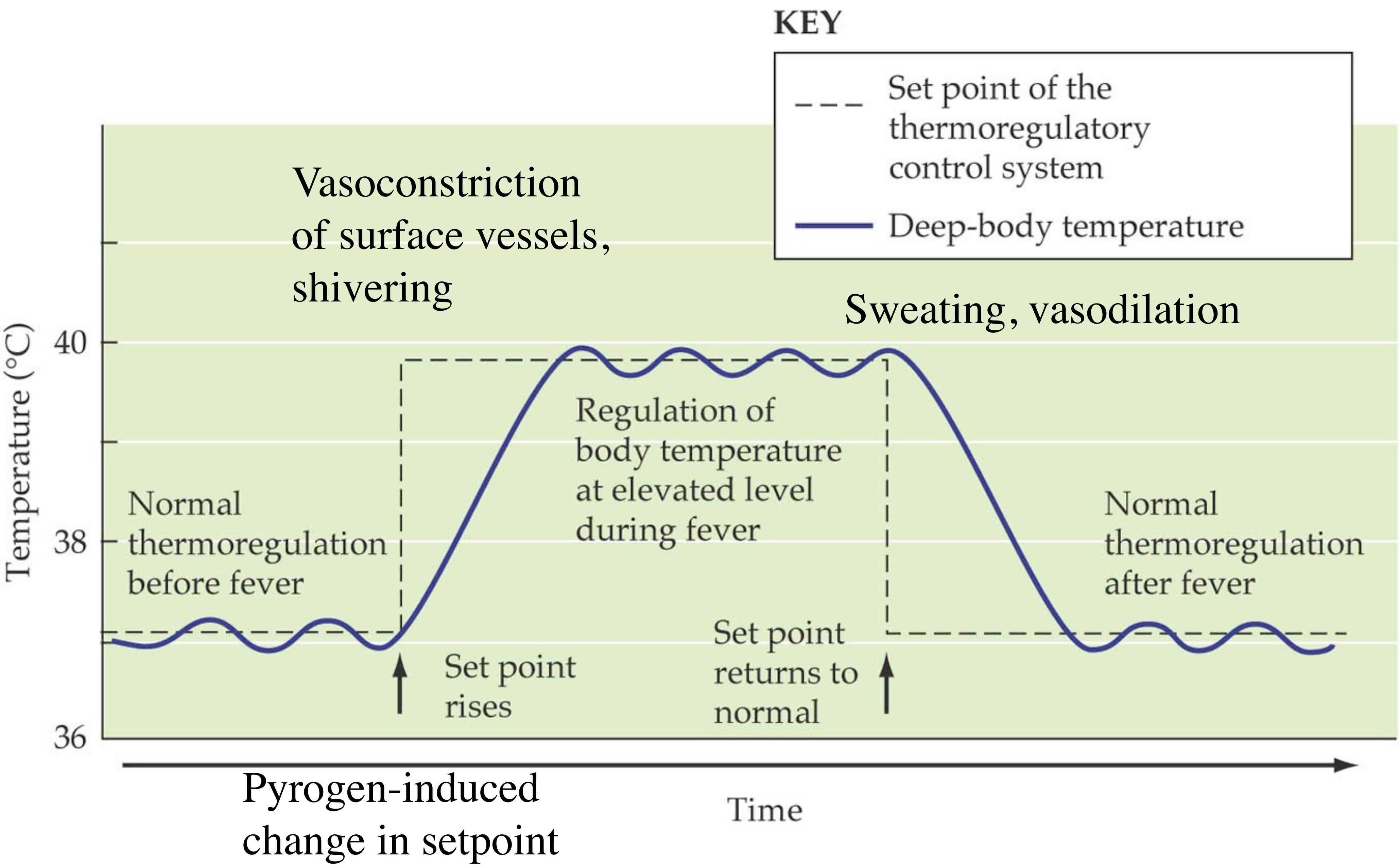
Brown Fat in Mammal Newborns

Non-shivering thermogenesis protects newborns from cold stress

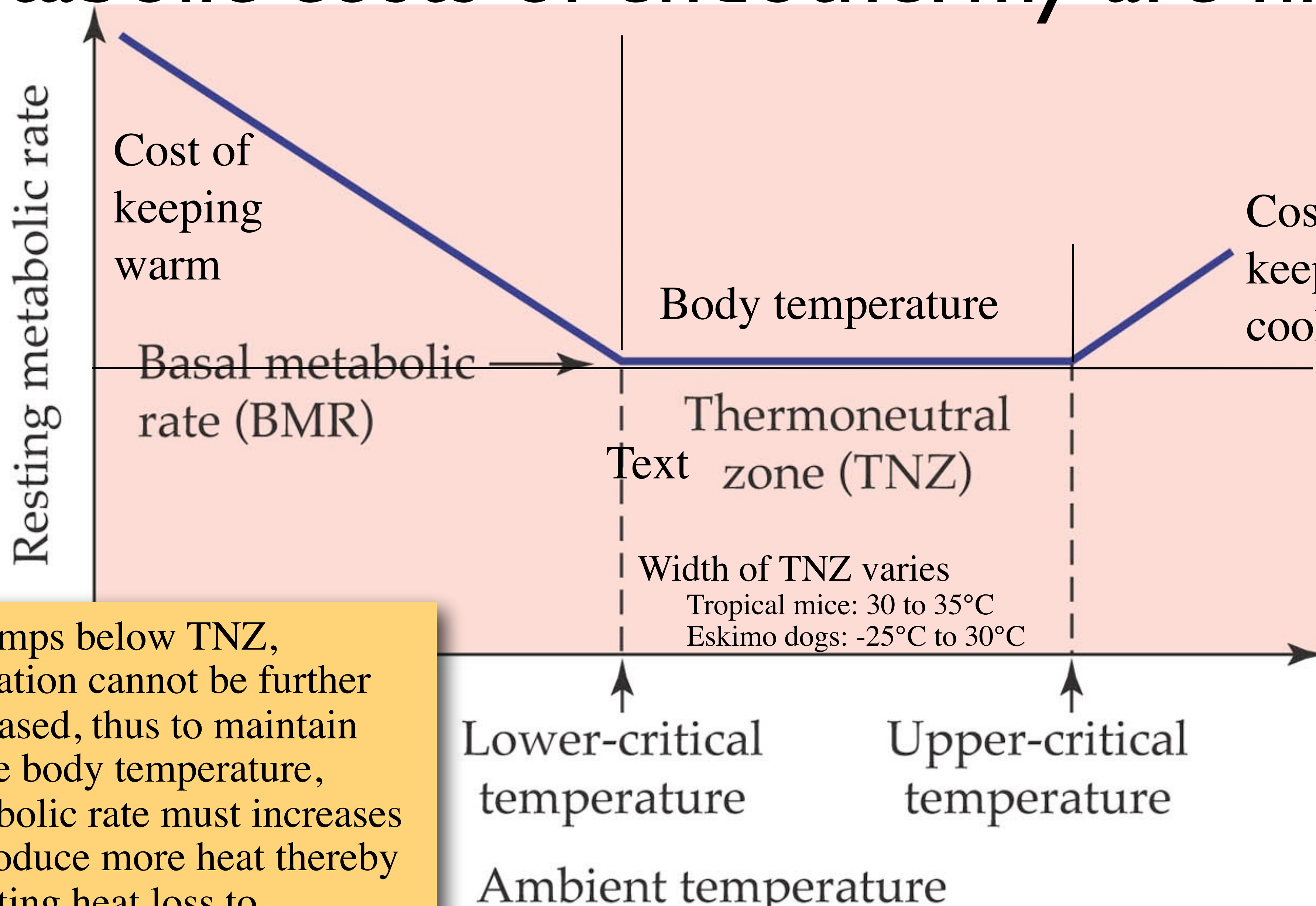


Body Temperature Regulation

Thermoregulation and fever

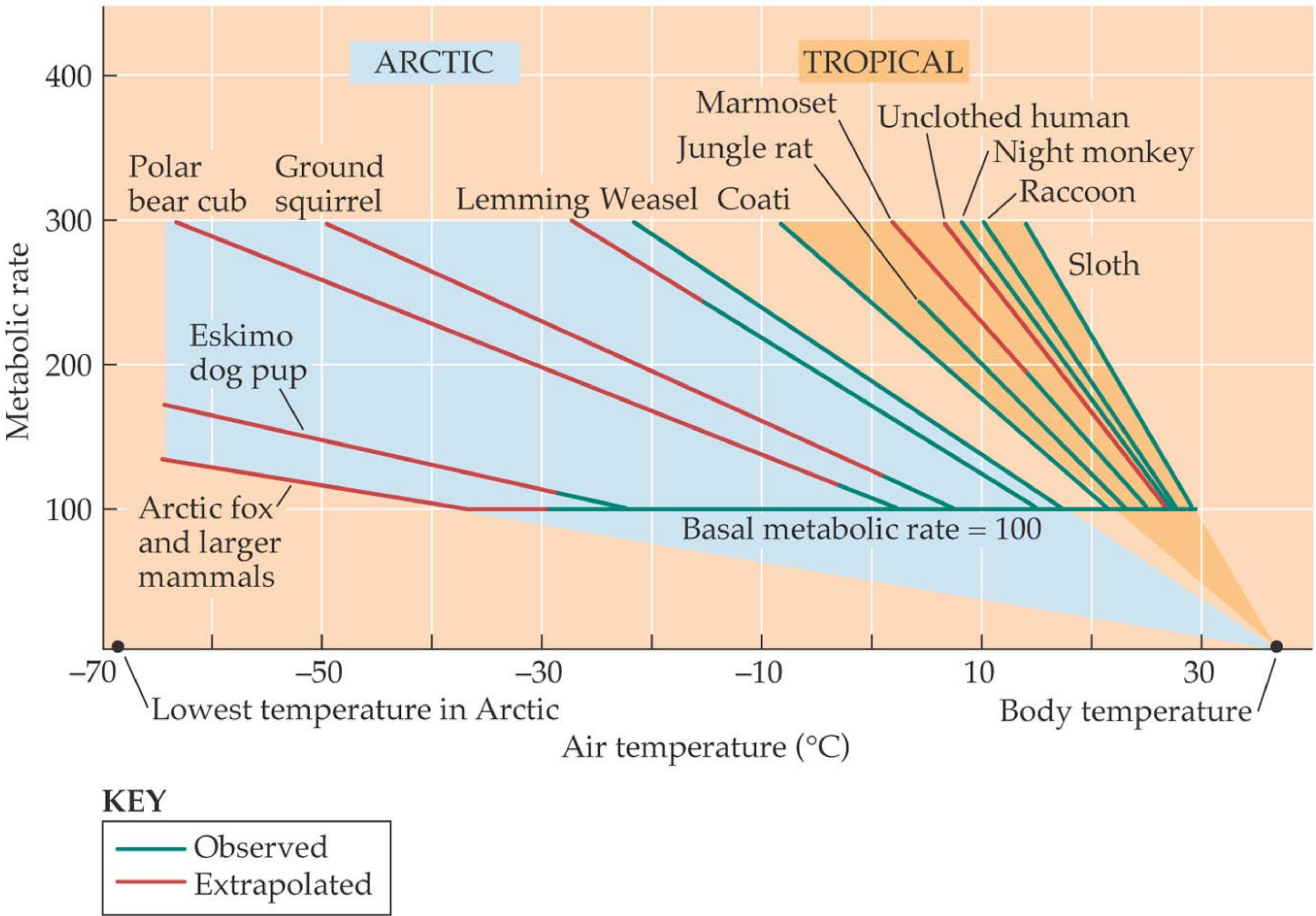


Metabolic costs of endothermy are high



At temps below TNZ, insulation cannot be further increased, thus to maintain stable body temperature, metabolic rate must increases to produce more heat thereby offseting heat loss to environment

Variation in lower critical temperature among mammals

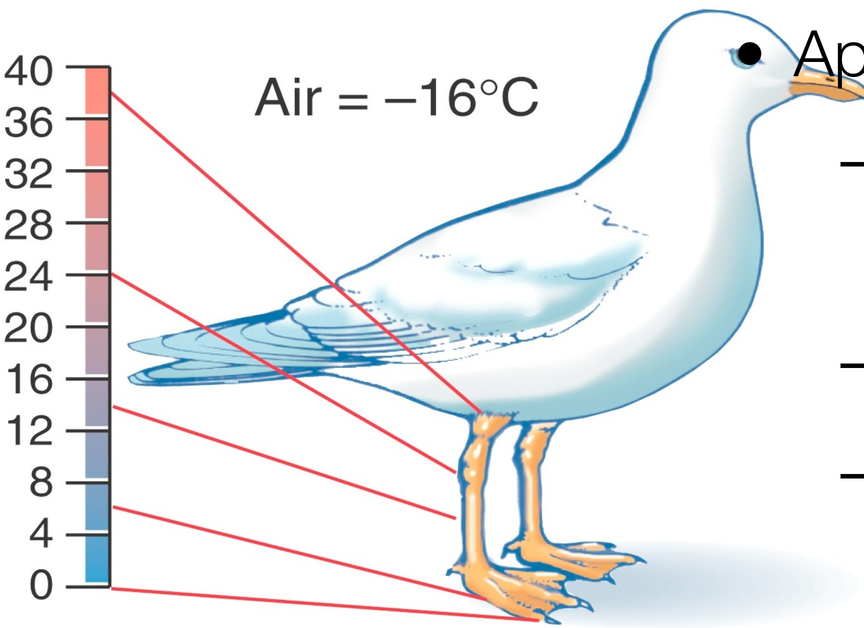


Z

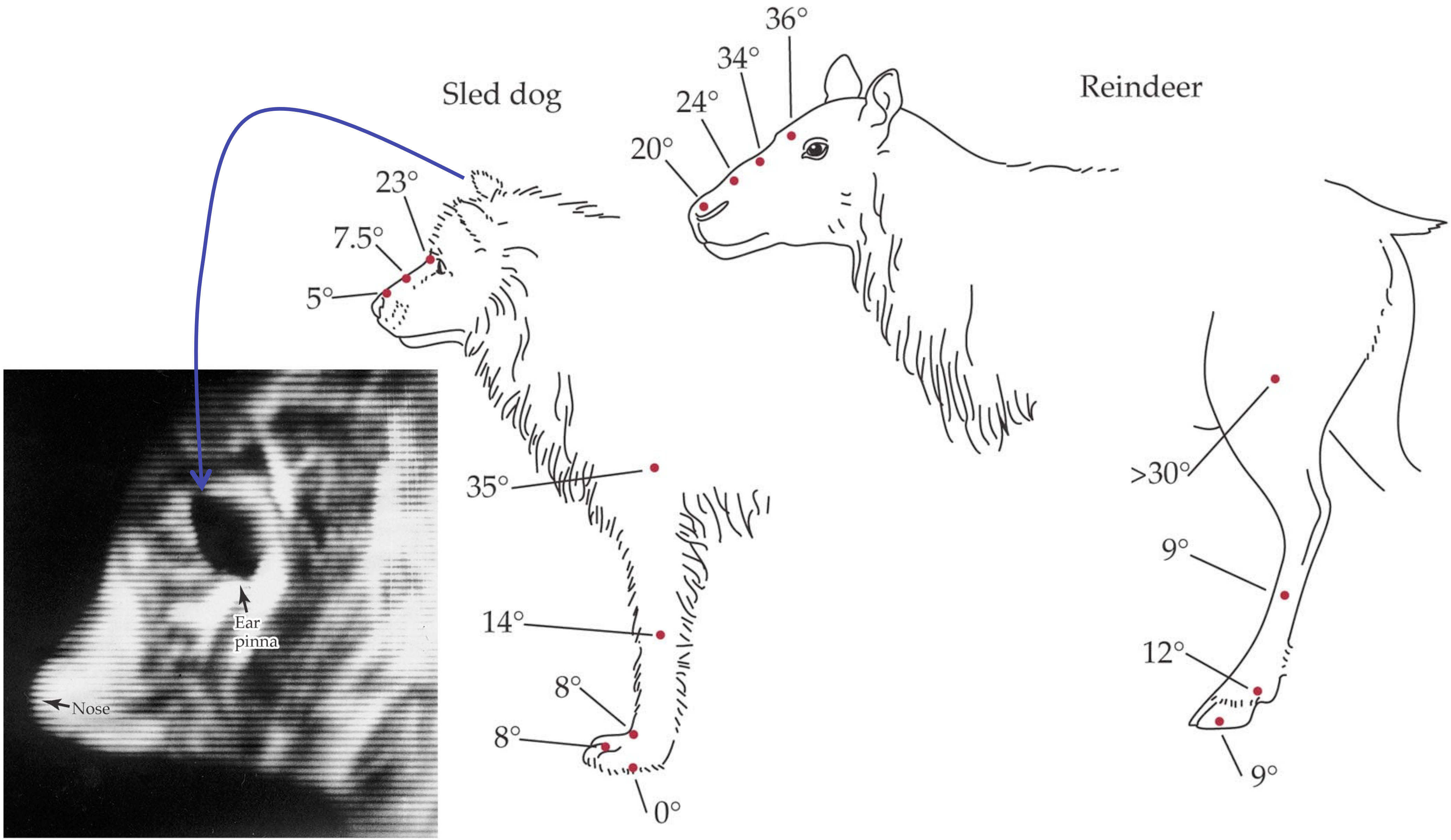
Heterothermy

- Big metabolic cost to endothermy (it's energetically expensive)
- Some can reduce costs by allowing T of peripheral tissues to cool, keeping only core warm
- Appendages have high S/V ratio -> heat loss
  - cold-adapted often have shorter limbs
  - limbs tend to have little insulation!
  - allow T_b of foot to reach T_a -> lower H_{cond} loss

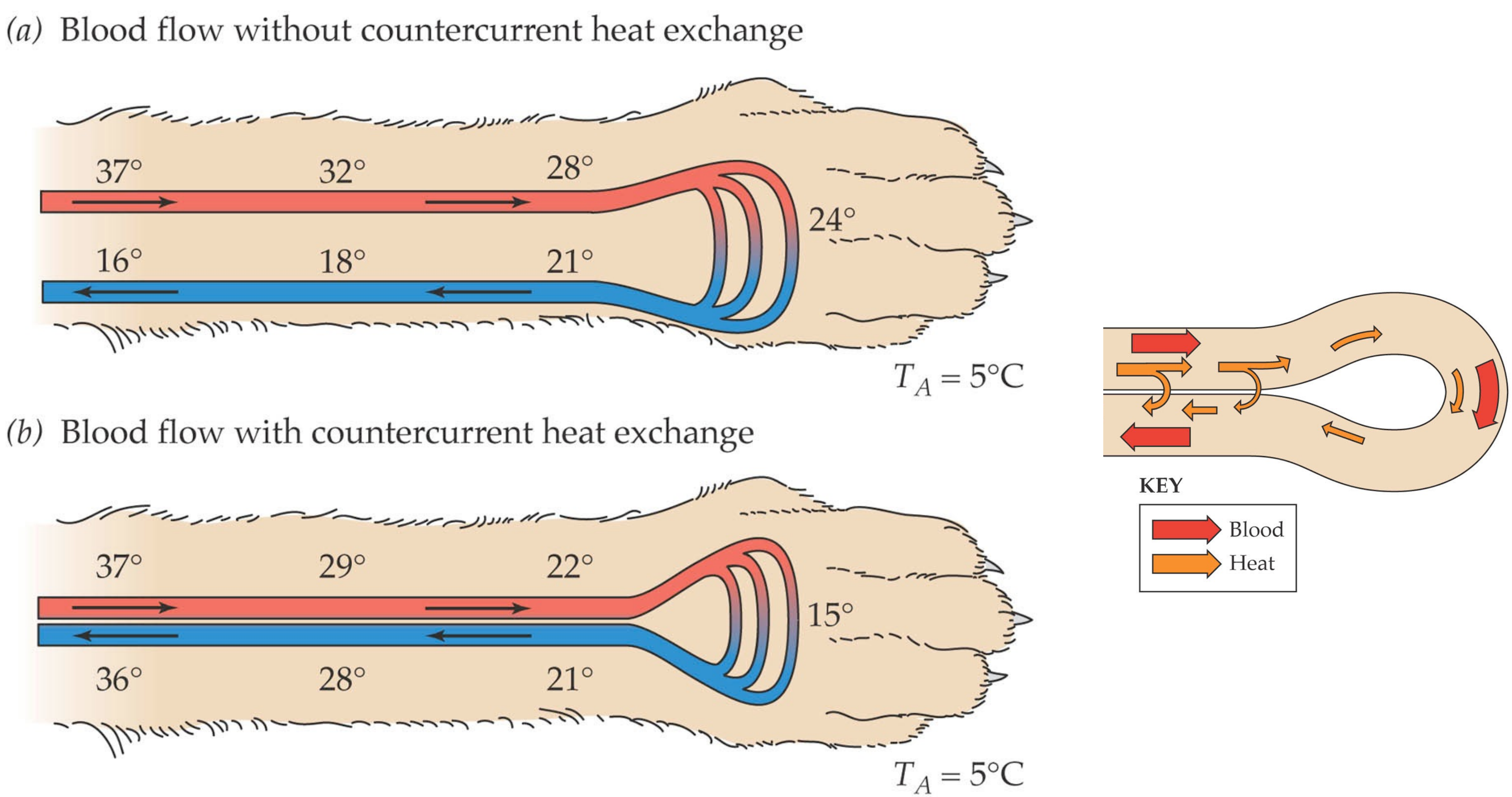
Temp variation by body region



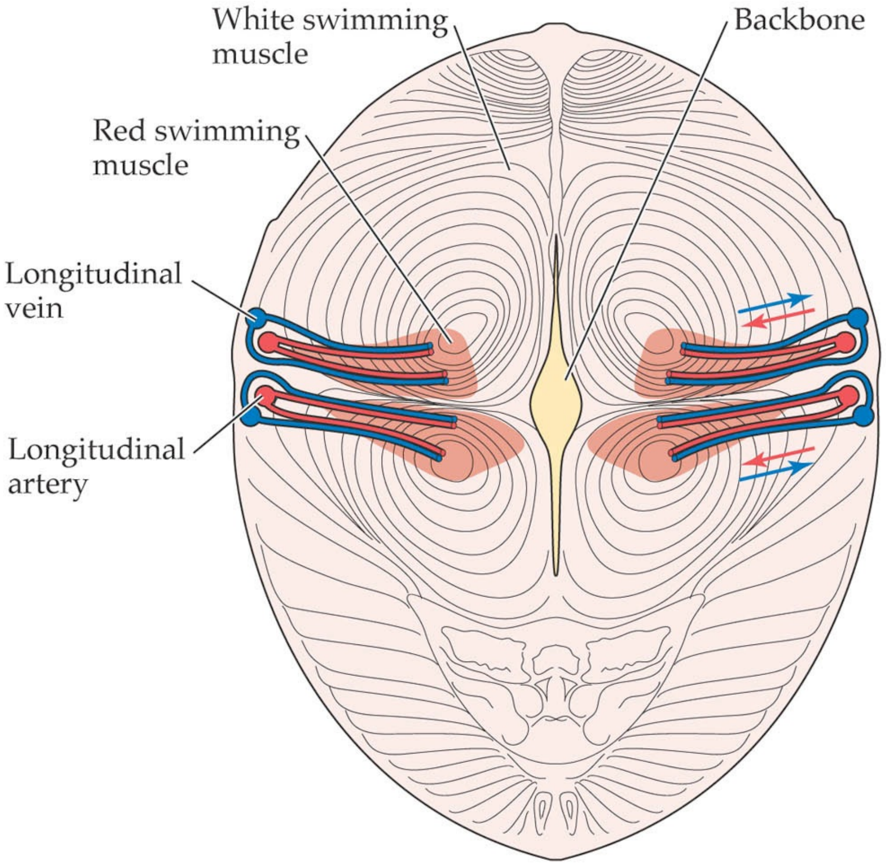
Regional Heterothermy in cold environments

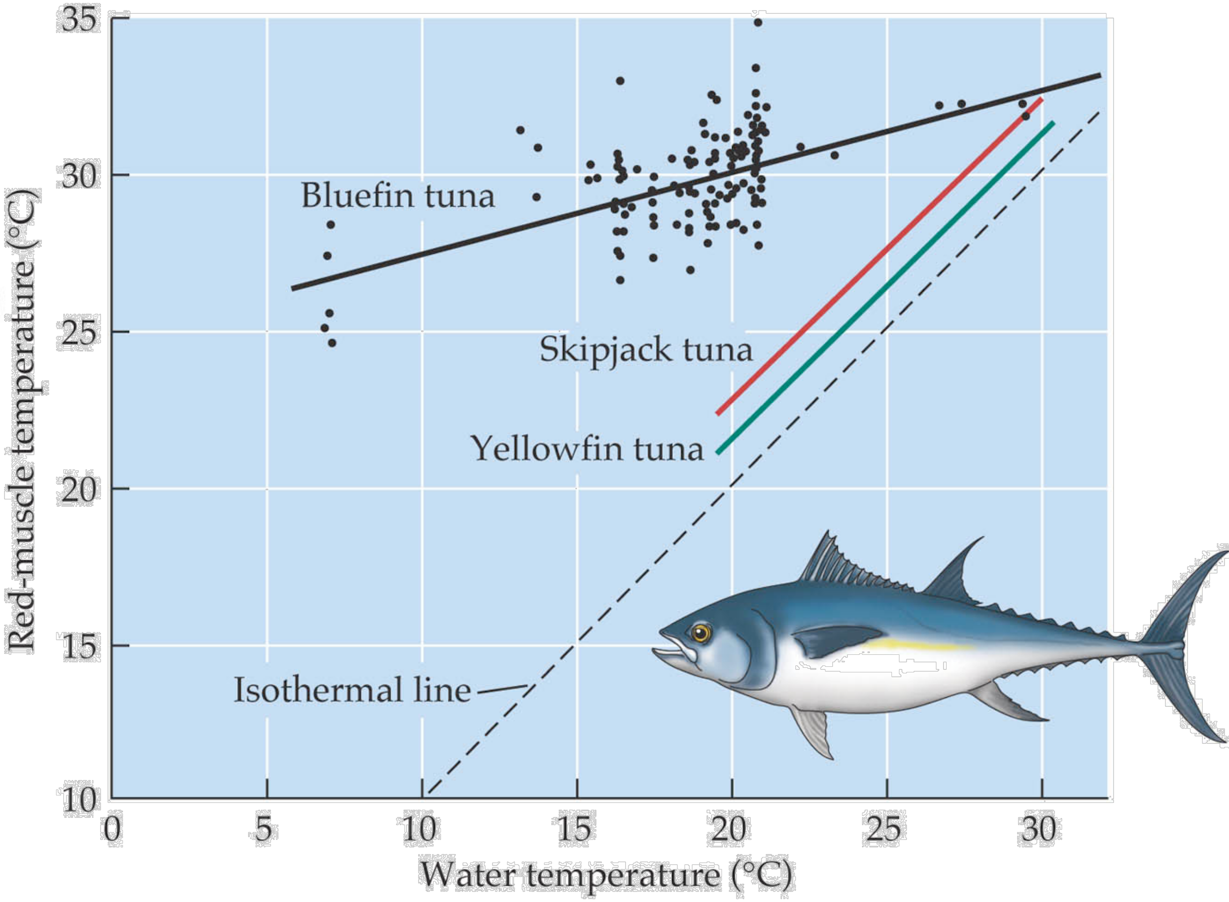


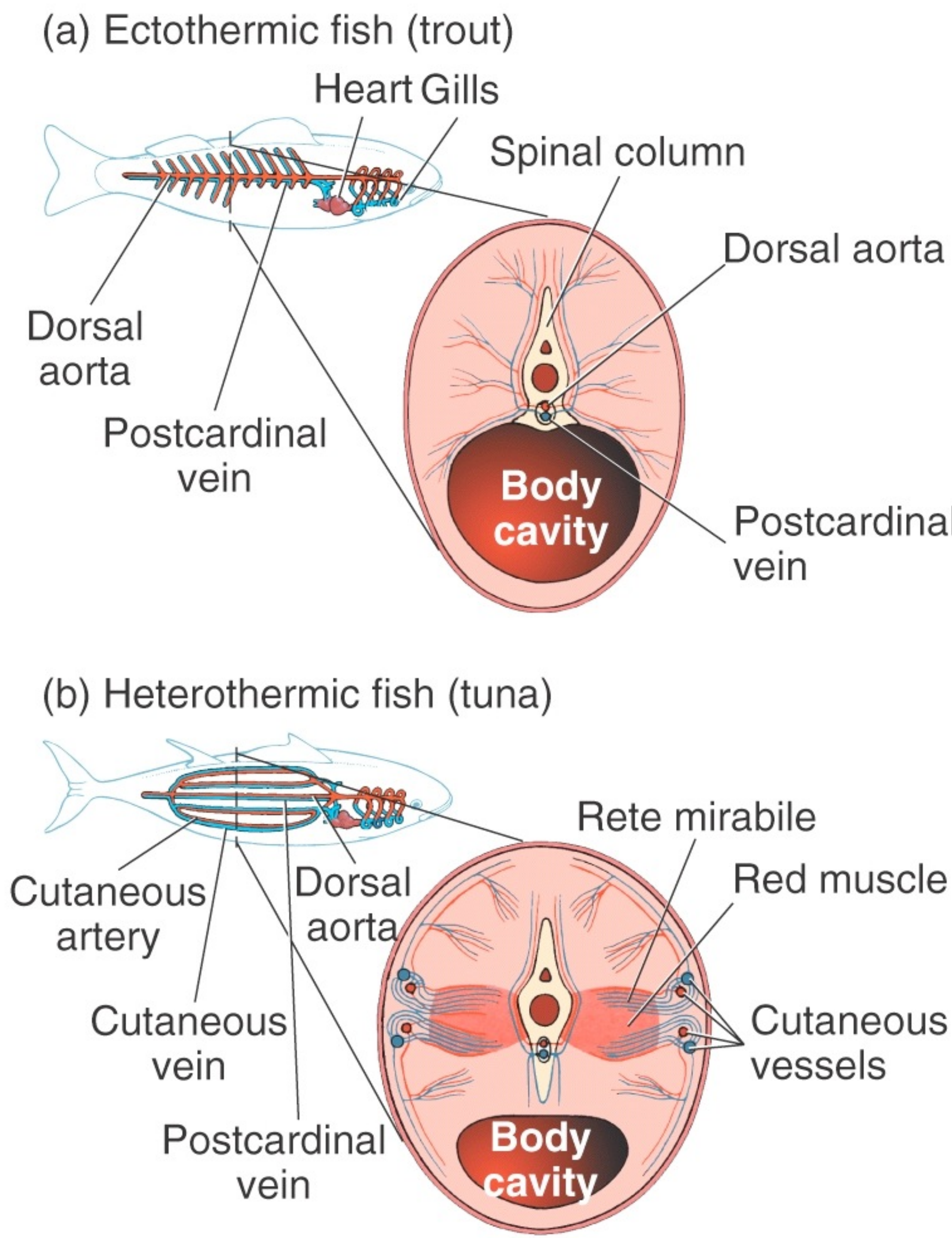
Regional Heterothermy is achieved by countercurrent heat exchangers



Countercurrent heat exchangers in fish

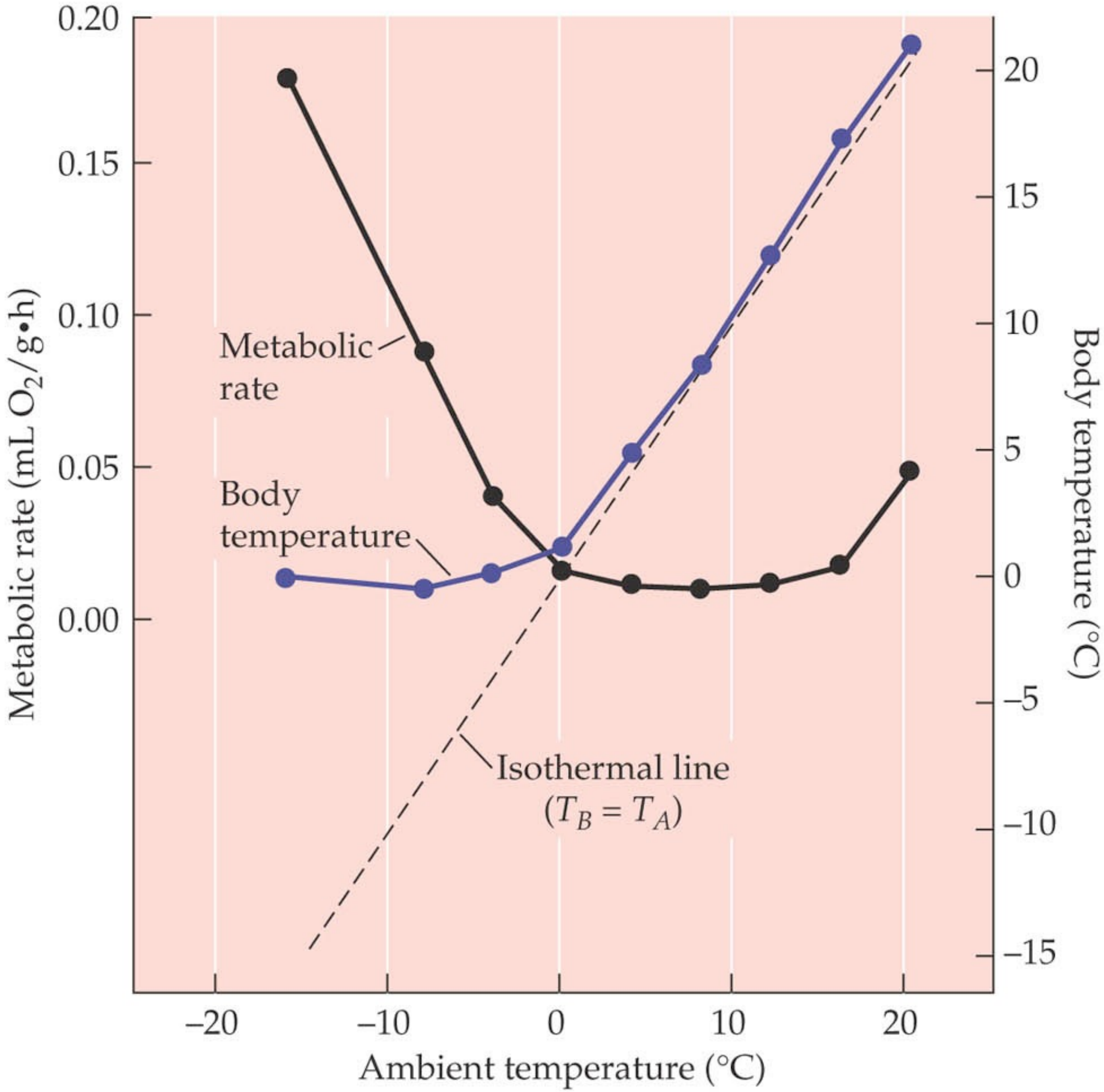





(a) Ectothermic fish (trout)
Heart
Gills
Spinal column
Dorsal aorta
Dorsal aorta
Postcardinal vein
Body cavity
Postcardinal vein
(b) Heterothermic fish (tuna)
Rete mirabile
Red muscle
Cutaneous artery
Dorsal aorta
Cutaneous vein
Cutaneous vessels
Postcardinal vein
Body cavity

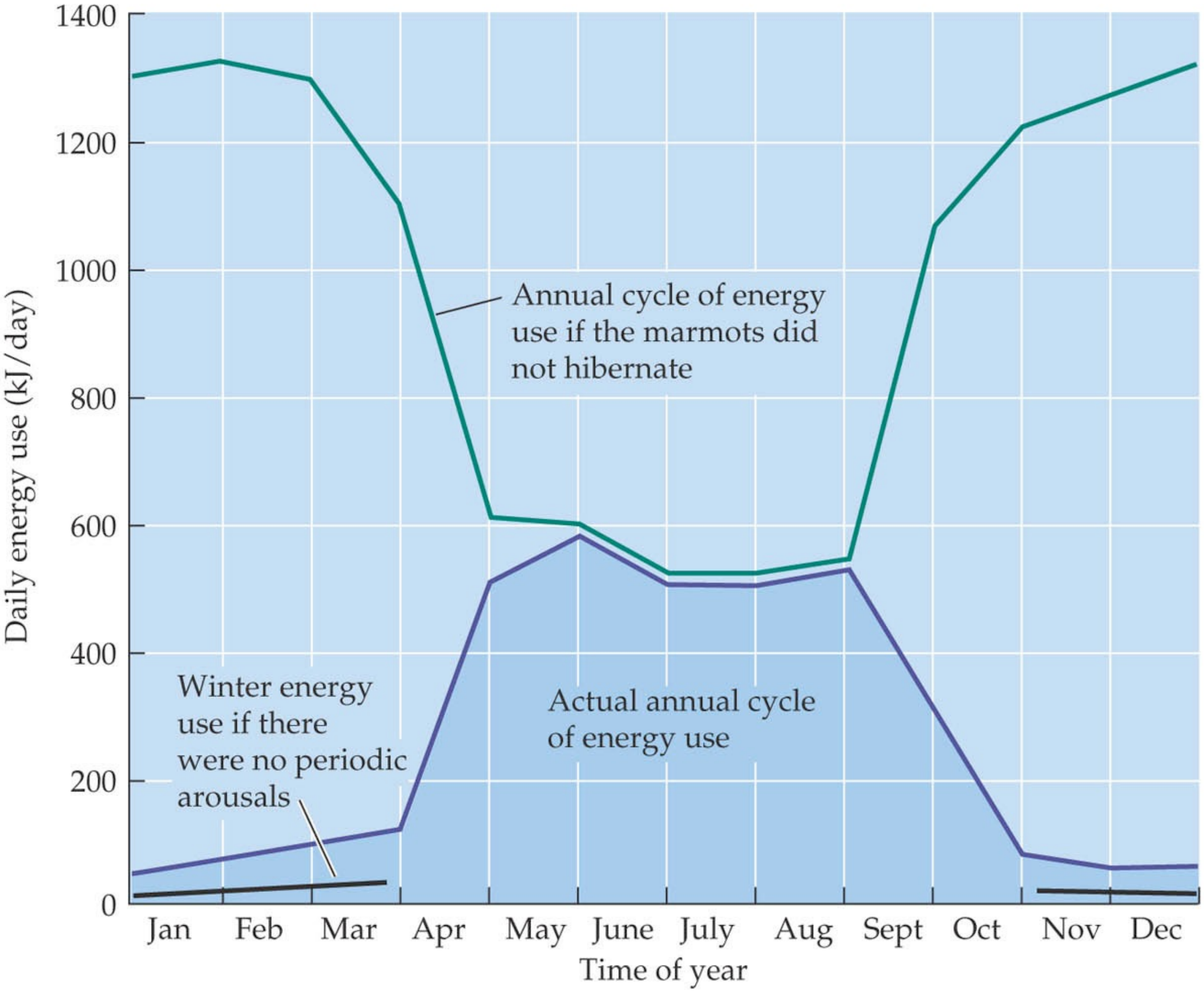
Heterothermy by time/season: Hibernation or Torpor

Hibernation does involve thermoregulation

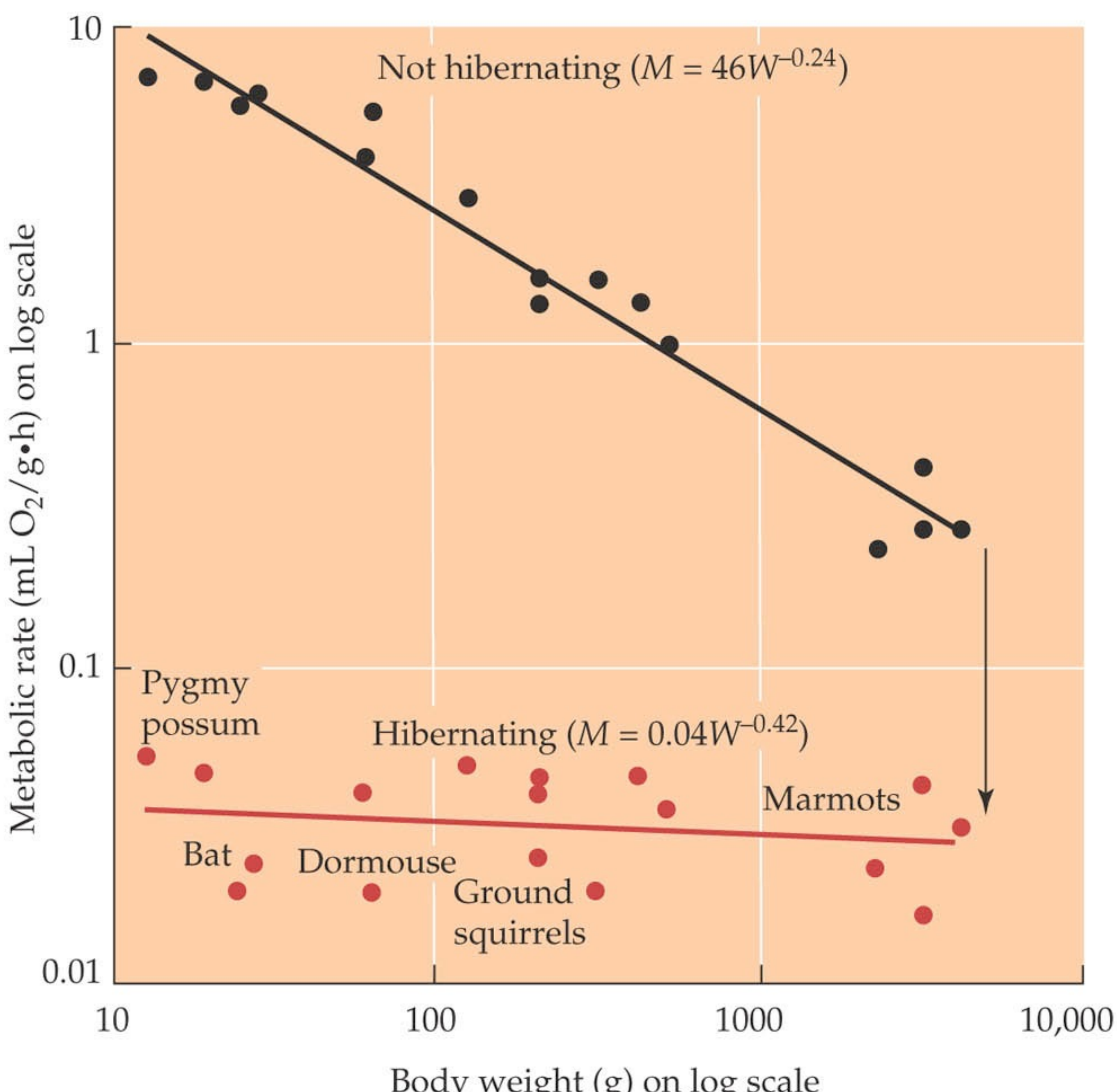


…but at a lower metabolic cost

Energy Savings of Hibernation



Metabolic savings of hibernation across species



Z

Design Projects

Projects are about analysis and design of metabolic systems, the are not meant to be literature reviews ("review papers").

- ☐ Use due diligence, but don't spend inordinate amounts of time looking for "the" paper.
- ☐ THE VALUE OF MODELS:
  - Models allow you to understand the relationship between physiological variable A & B.
  - Models illustrate the meaning of different assumptions (and the sensitivity of the results to different assumptions.
  - Models allow you to test your ideas about what really "drives" a system.
- ☑ Concentrate your efforts on the important aspects of the model:
  - What were the critical assumptions, and why did you choose them?
  - What did you get, and what does it mean?
  - Are any of your assumptions likely to be wrong?
    - If so, would a different choice have made a big impact?
  - Have you discovered a significant difference (maybe between endothermy/ectothermy, or a huge effect of size, etc.)?