Animal physiology and the materials and energy budget

Organisms are enormously complex molecular assemblies

They need to <u>exchange</u> energy and materials with their environments

(they are **open systems: no exchange = no life**)

Some exchanges are slow: atoms in a DNA molecule in a brain cell

Some are fast: half-life of water is days in a human, minutes in a small fish

ALL must be carefully balanced!

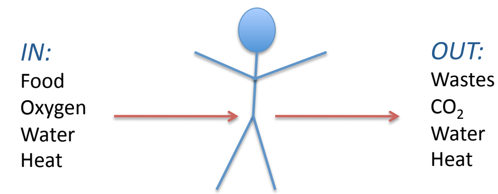
Energy and material exchange is a set of **budgets**:

gains: heat, food, water, oxygen

losses: heat, water, CO_2, urine, feces

Animal physiology is largely focused on the way these exchanges are managed.

Animal physiology and the materials and energy budget



Partial 'bookkeeping' for a young adult woman (.05 tons) over 10 years:

Food eaten:	2-3 tons
Oxygen used:	2 tons
Water intake:	6-10 tons
Heat produced:	7 million kilocalories (enough to heat 90 tons of water from room temperature to boiling)

Clearly, a balanced budget is critical!

Animal physiology and the materials and energy budget

For most animals, the only situations where budgets are not in balance are:

growth (change in body size or storage of fat)

reproduction (production of offspring)

We'll focus on **energy metabolism** and the **energy budget**

Measures both energy and materials:

Food can be used to produce energy (by using chemical potential energy) or to build tissue

Energy metabolism (metabolic rate): the sum total of all biochemical energy 'transactions' at a given time…

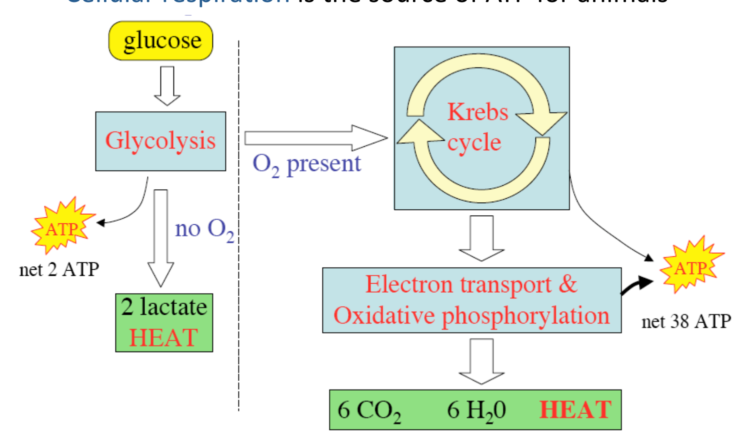
= *the rate of production and utilization of ATP*

An average human contains about 50 *grams* of ATP at a given time… but makes and uses about **40 kilograms of ATP per day**! About **5.5 x 10^{20} ATP molecules – 0.5 g – per second**.

Animal energy budgets

Metabolism (metabolic rate): *the rate of production and utilization of ATP.*

Cellular respiration is the source of ATP for animals



Animal energy budgets

Metabolism (metabolic rate): *the rate of production and utilization of ATP.*

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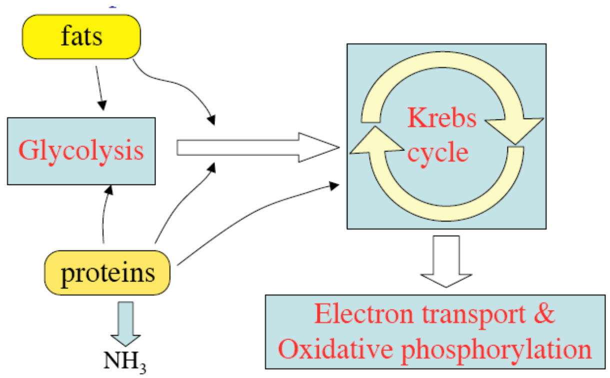


Animal energy budgets

How to measure metabolic rate (can't directly measure ATP production)

Measure heat production:

• cellular respiration is (at most) ~40% efficient; the rest of the chemical potential energy in fuels is lost as heat. **Second Law of Thermodynamics**

• when ATP is used, the energy is released as head (mostly).

Measure rate of use of reactants (food, O_2) or appearance of products (CO_2)

• food: 4.2-4.5 kcal/g of carbohydrate or protein
9.4 kcal/g of fat

• oxygen: ~4.8 kcal/liter of O_2 consumed

• CO_2: ~5-7 kcal/liter of CO_2 produced

What factors affect metabolic rate and energy balance?

Body size

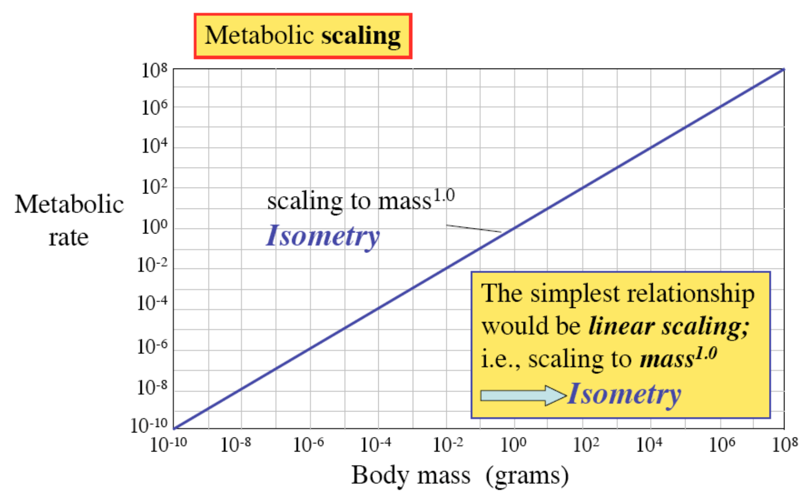
Metabolic 'strategy' (endothermy vs. ectothermy)

Temperature

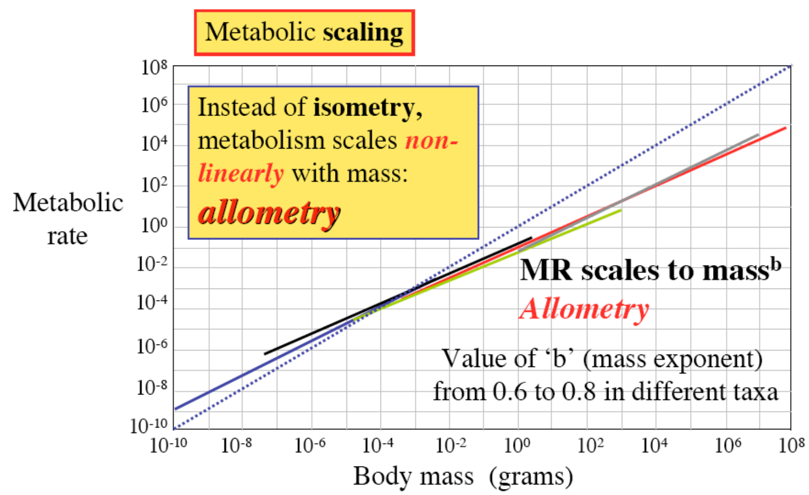
Activity

What does this mean for an animal's biology?

Metabolism and body size



Metabolism and body size



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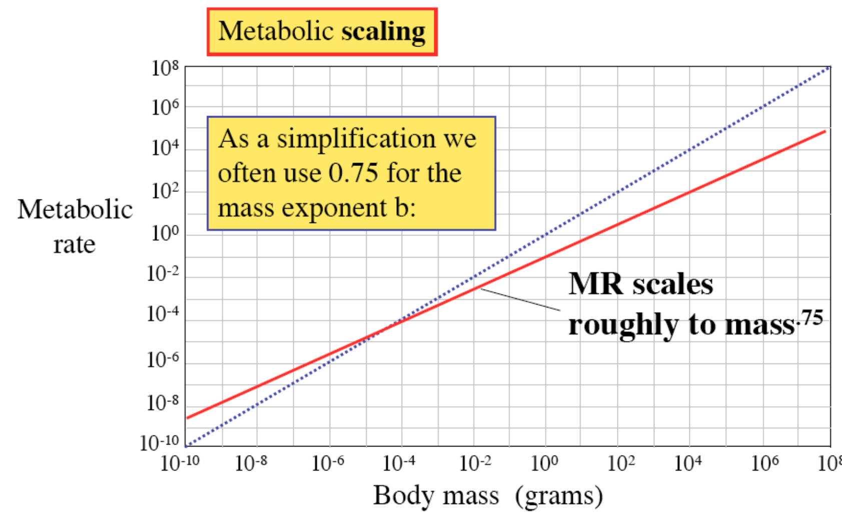

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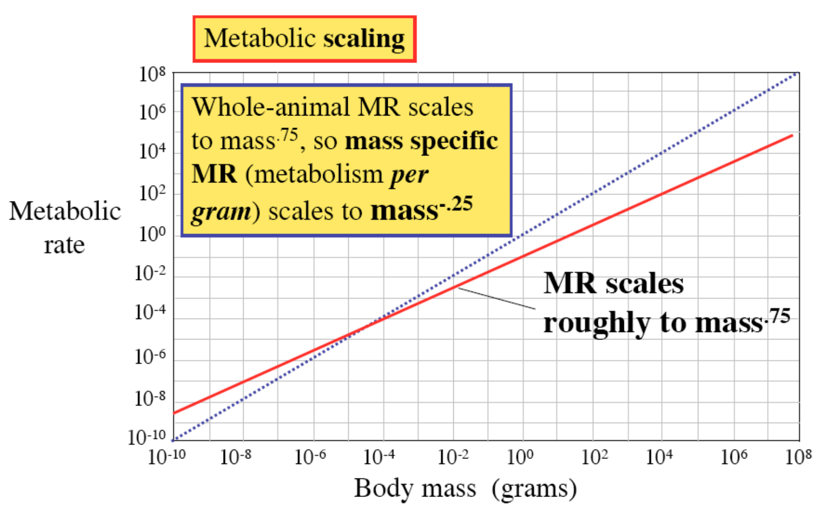


Metabolism and body size

Since whole-animal metabolism scales ~mass$^{0.75}$:

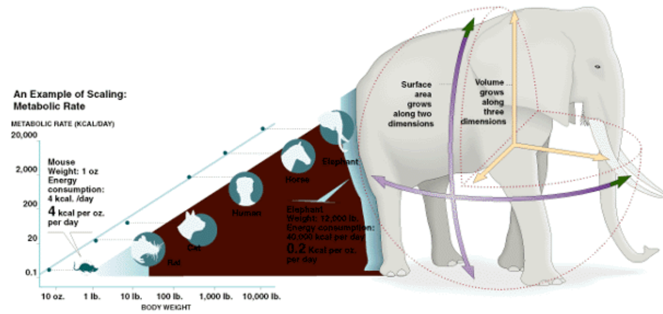
An elephant (4,000,000 g) has a *total* metabolic rate much higher than that of a mouse (25g)…

but each *gram* of mouse has a metabolic rate *twenty times higher* than each gram of elephant.

Why is this? Why mass$^{0.75}$?

No clear answer

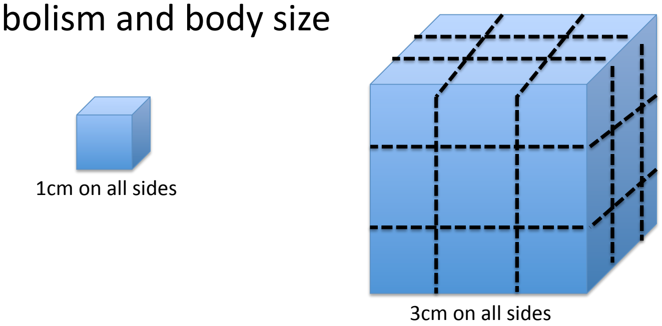
Metabolism and body size



The average elephant weighs 220,000 times as much as the average mouse, but requires only about 10,000 times as much energy (in the form of food calories) to sustain itself.

The reasons behind this relationship are hugely complex, but the simplest explanation lies in *surface area to volume ratios*…

Metabolism and body size

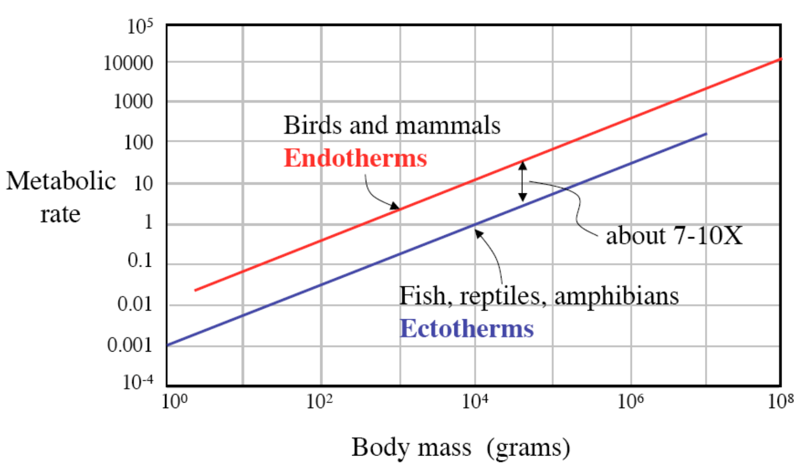


	Surface area	Volume	Surface area:volume
1 cm cube ('mouse')	6 cm^2	1 cm^3	6:1
3 cm cube ('elephant')	54 cm^2	27 cm^3	2:1

The 'mouse' has a larger surface area:volume ratio, causing it to lose heat to its environment much more quickly, resulting in a higher mass-specific metabolic rate.

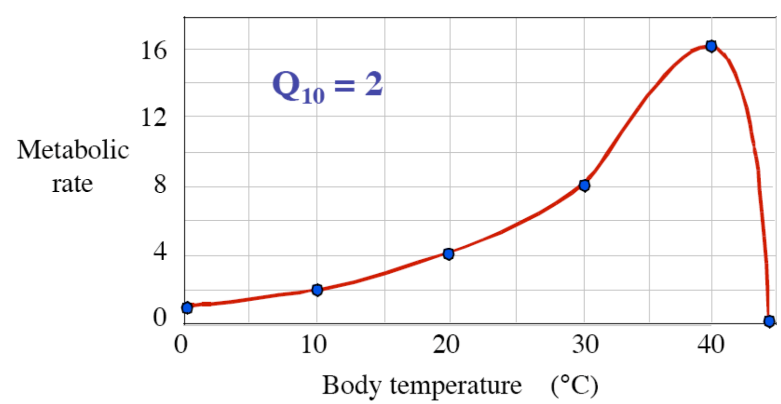
Two metabolic 'strategies'

Why this difference? Need to discuss *temperature* effects!



Body temperature and metabolism

- Metabolic rate increases roughly 2-2.5 times for every 10°C increase in body temperature: Q_{10} effect
- Rapid fall in MR as body temperature exceeds ~45°C in most animals (protein denaturation, etc. → **death**)



Environmental temperature and body temperature: ectotherms and endotherms

Scrub Jay, active at ~0 °F in Mesa Verde National Park, Colorado

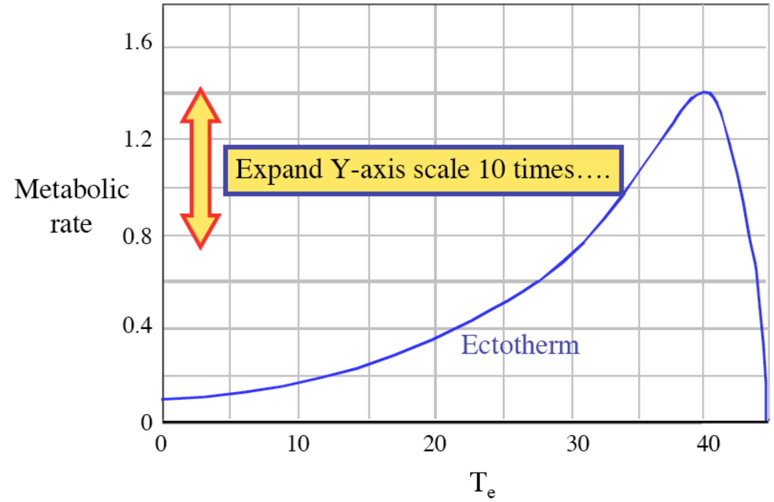
Ectotherms have low metabolic rates (**low** heat production)

- not enough heat produced to affect body temperature
- Therefore, body temperature (T_b) is very close to environmental temperature (T_e)
- Can adjust T_b behaviorally (select T_e)

Endotherms have high metabolic rates (high heat production)

- Enough heat produced to raise T_b well above T_e
- Can keep T_b fairly constant in variable T_e
- Insulation (fur, feathers) helps keep T_b high
- Can also actively cool (sweating, etc.) at high T_e

Environmental temperature and body temperature: ectotherms and endotherms



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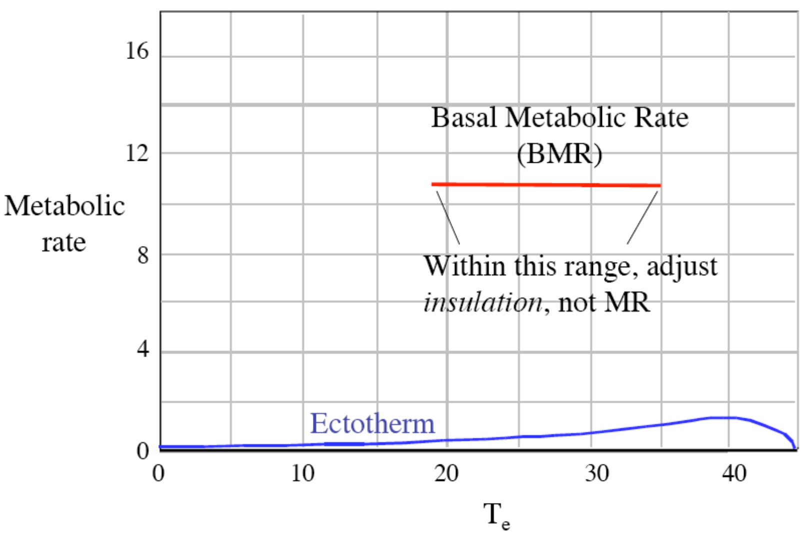

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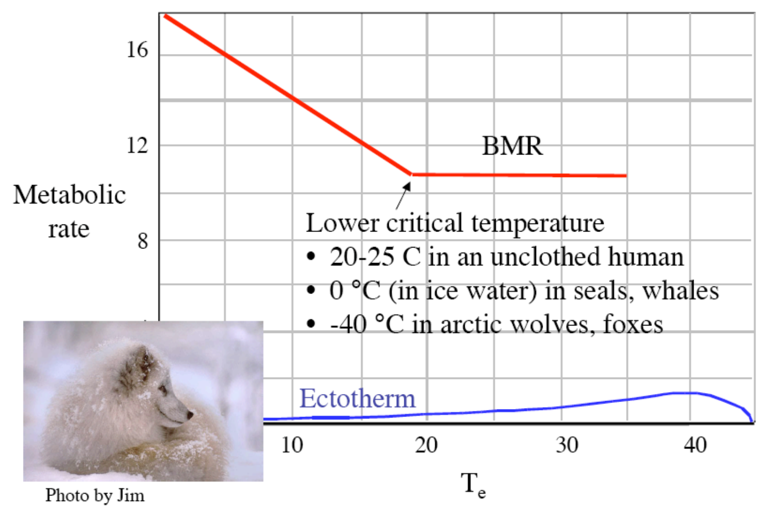

Photo by Jim Brandenberg

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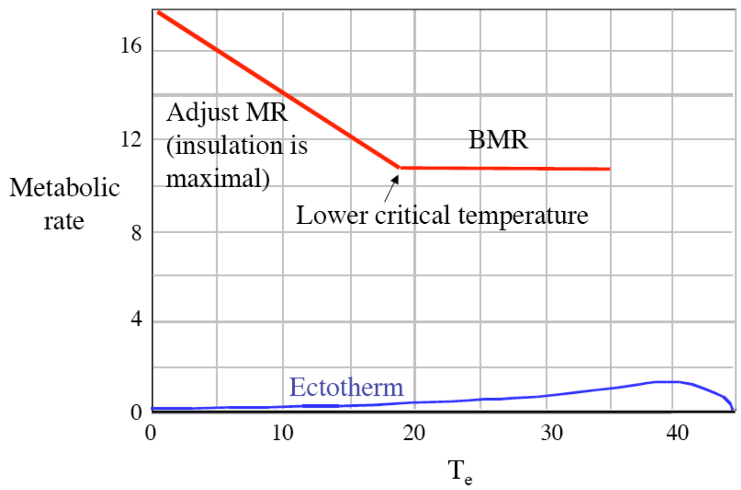

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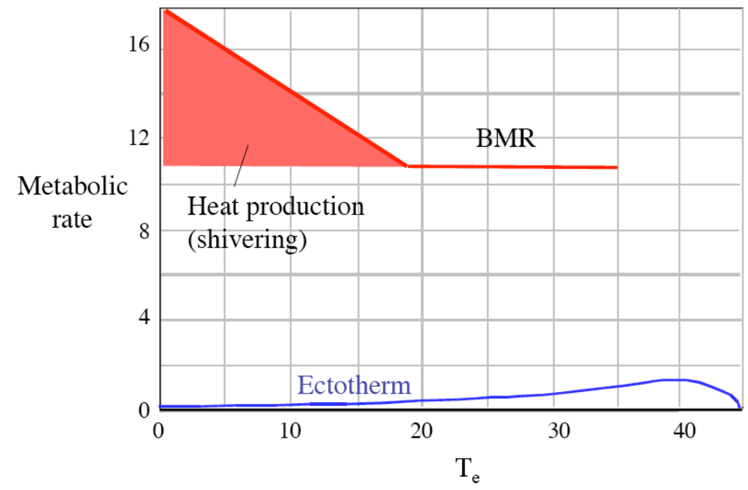

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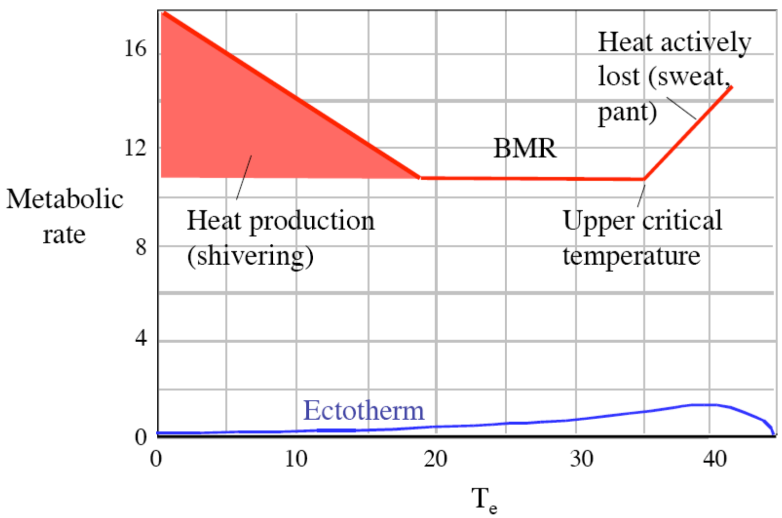

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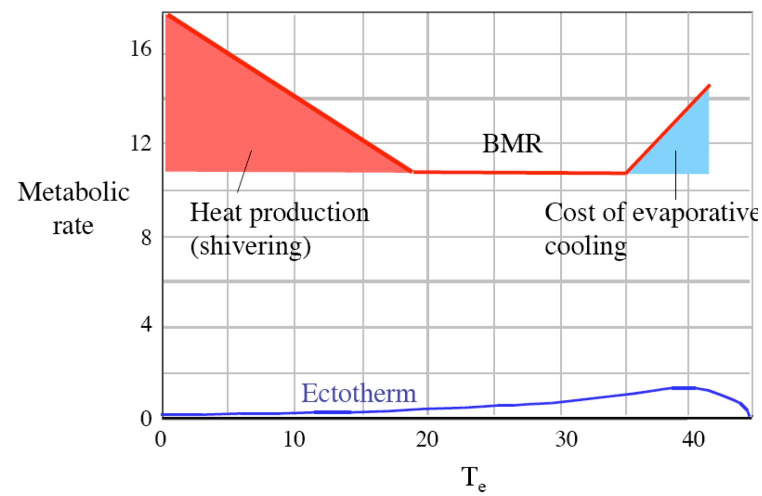


Endotherm temperature control: Negative feedback

How do endotherms maintain a constant body temperature?

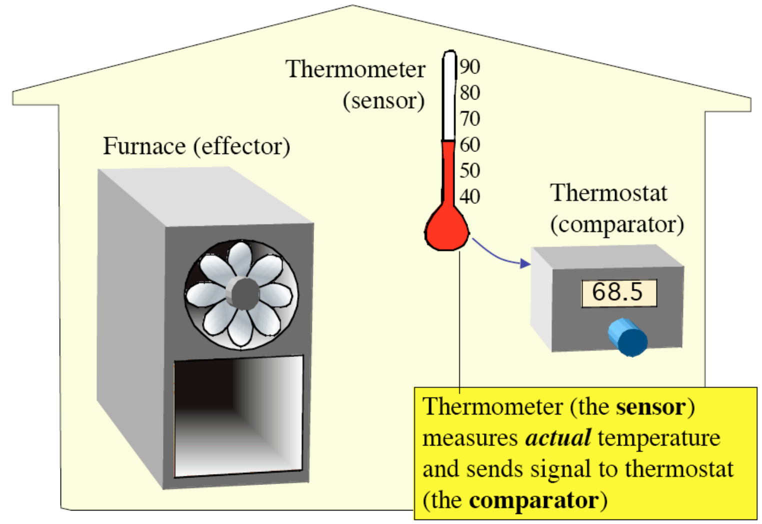
→ *Negative feedback control*

Similar negative feedback systems used for nearly all control mechanisms in organisms

Components of negative feedback system:

- sensor: measures a parameter of interest (temperature, etc., etc.)
- comparator (controller): compares actual value of the parameter with the desired value (the 'setpoint')
- an effector, which responds to signals from the comparator and affects the level or intensity of the parameter.

Negative feedback example: home heating system



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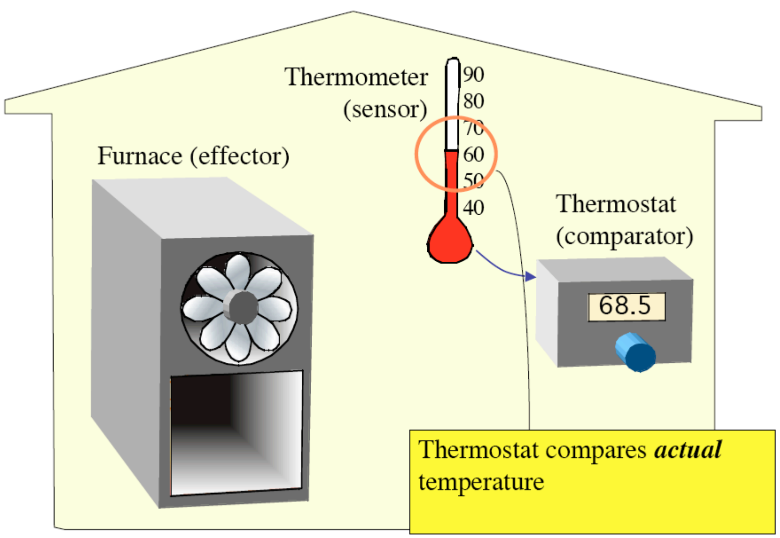

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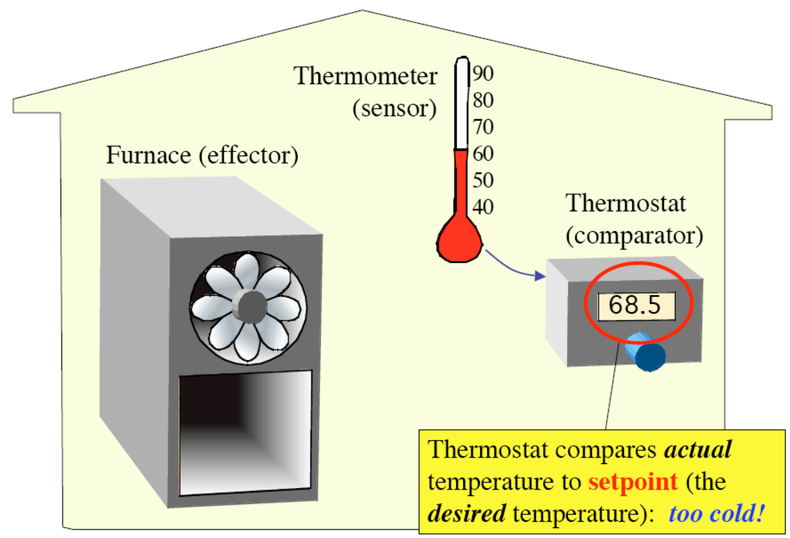

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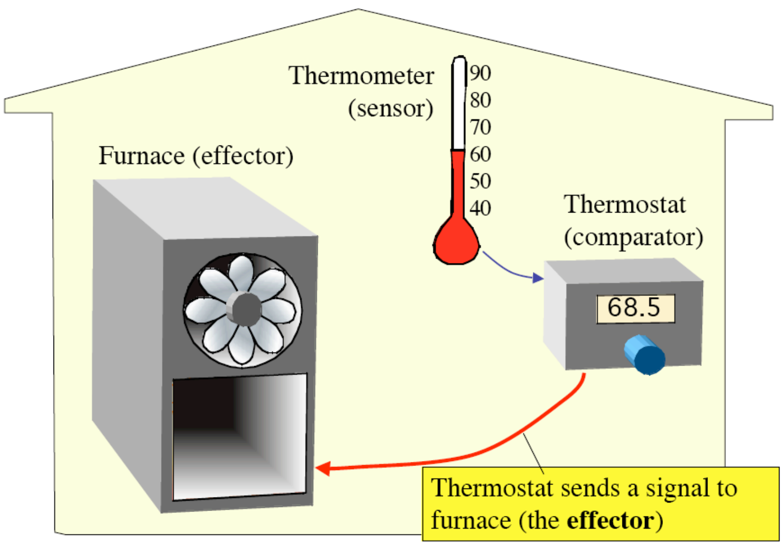

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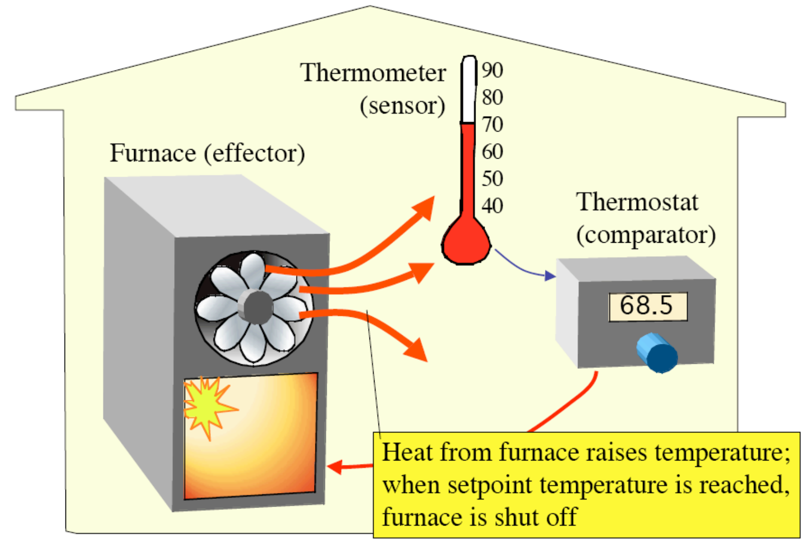

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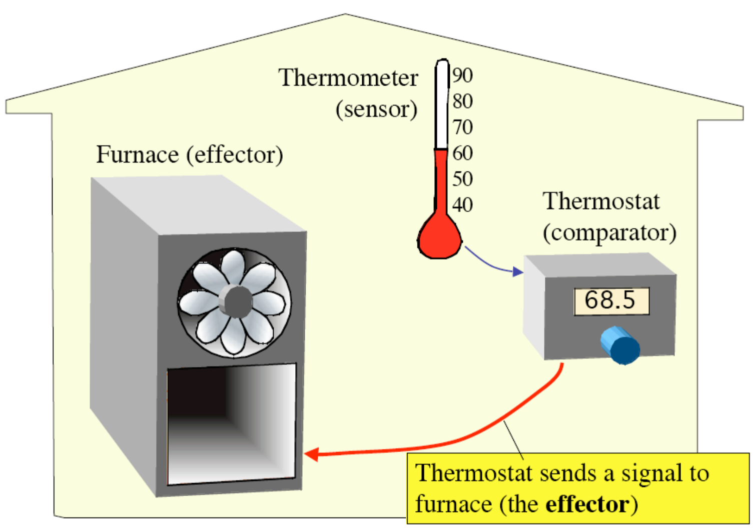

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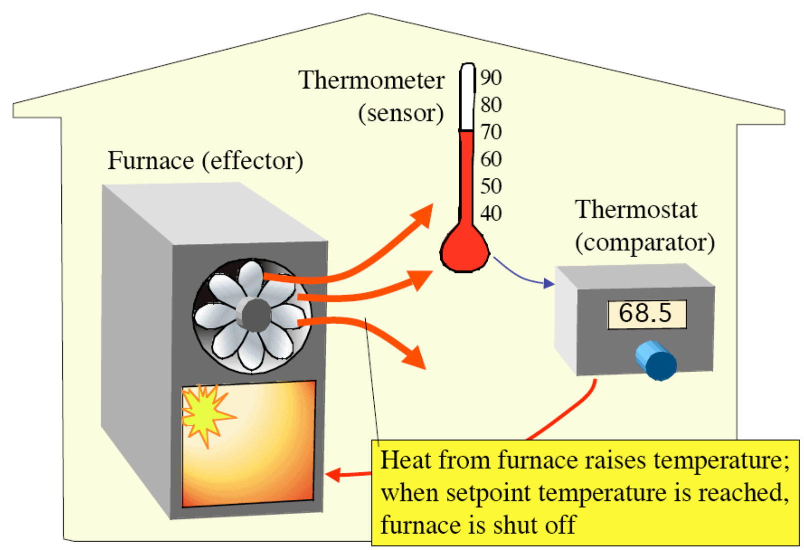

Endotherm temperature control

Body temperature control in endotherms is *almost identical*:

- the sensor for T_b is a set of temperature-sensitive cells in the brain, skin, and body core.
- The comparator is a small brain region called the **hypothalamus** that integrates sensor inputs in comparison to a T_b setpoint.
- The effectors are metabolic rate (to produce heat by shivering), cooling mechanisms (sweating or panting), vasoconstriction and vasodilation, behavior

Endotherms and ectotherms

Remember:

For *ALL* organisms, life is a set of budgets…and over long periods, for *any* organism:

What goes in must equal what comes out (budgets must balance)

Otherwise, there is no alternative but **growth, shrinkage, or death.**

Endotherms and ectotherms

Endothermy (in birds and mammals)

- permits maintenance of a constant body temperature (good for enzyme function) – even if T_e is highly variable
- Easiest to attain in *large* animals
- Endotherms can thrive in seasons and habitats that would be lethal for ectotherms (anything below freezing).
- But it is *EXTREMELY EXPENSIVE* due to high metabolic heat production: endotherms need LOTS of food.

Ectothermy is an economical, 'thrifty' way of life:

- if habitat permits, behavior can keep T_b constant at little cost
- Ectotherms can thrive in habitats too food-poor for many endotherms