Basic Needs of Life – Energy and Metabolism

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Outline

- Introduction
- Energy and Metabolic rate
- Importance of Body Size
- Importance of Temperature
- Summary, Questions, and Readings

THE IMPORTANCE OF METABOLISM IN ECOLOGY

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The 'struggle for existence' of living beings is not for the fundamental constituents of food ... but for the possession of the free energy obtained, chiefly by means of the green plant, from the transfer of radiant energy from the hot sun to the cold earth.

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Read Brown et al (2004), "Toward a metabolic theory of ecology"

The importance of metabolism in ecology

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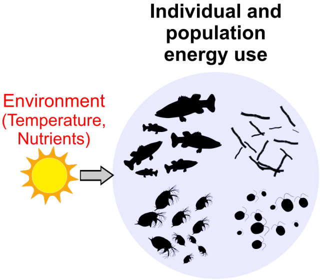
- *A* **metabolic** *(AKA "bottom-up" or "mechanistic") understanding of these complex ecosystems is necessary*

A metabolic ecology roadmap



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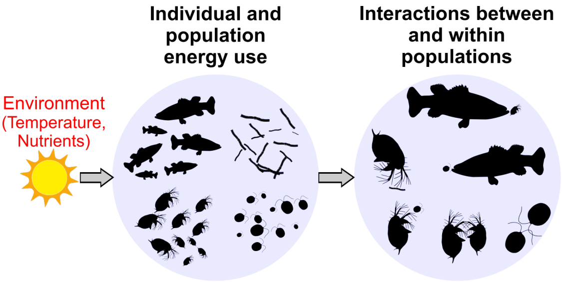

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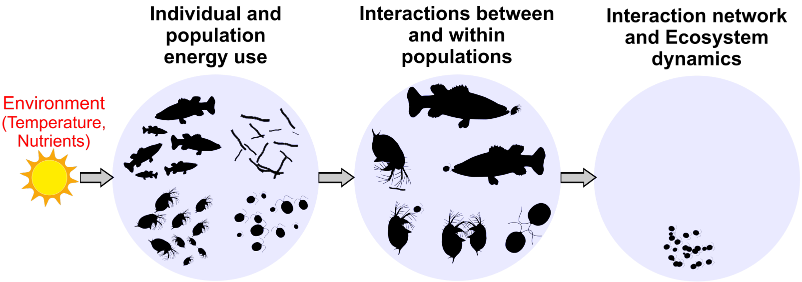

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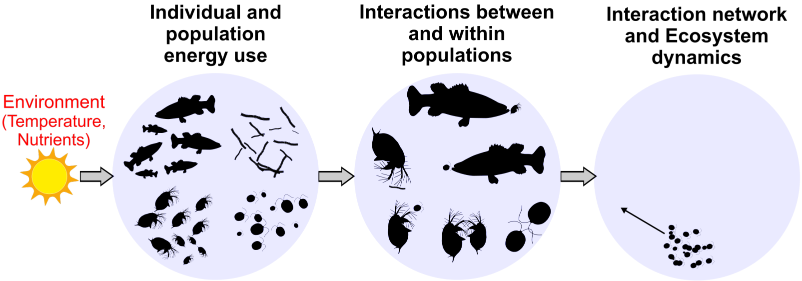

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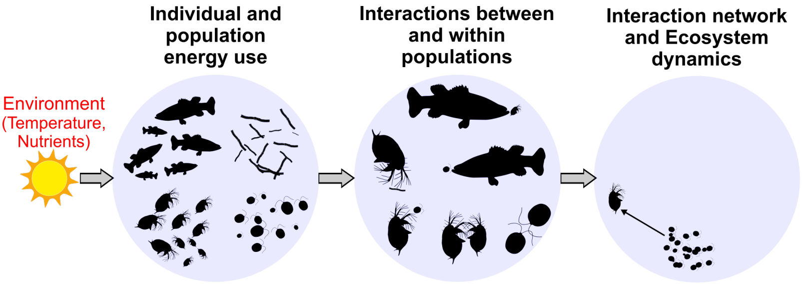

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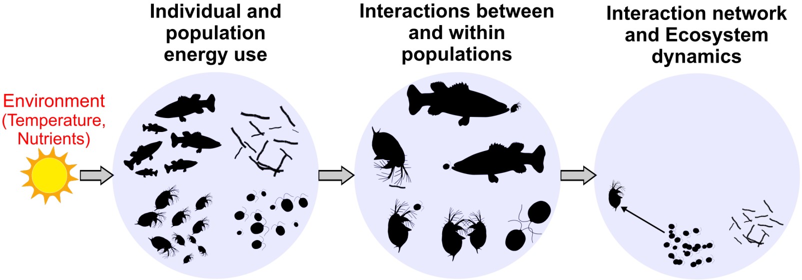

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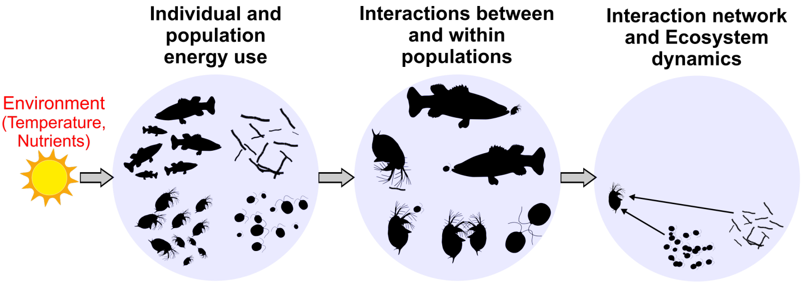

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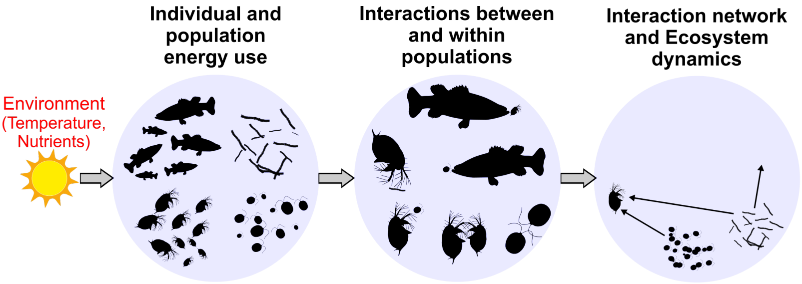

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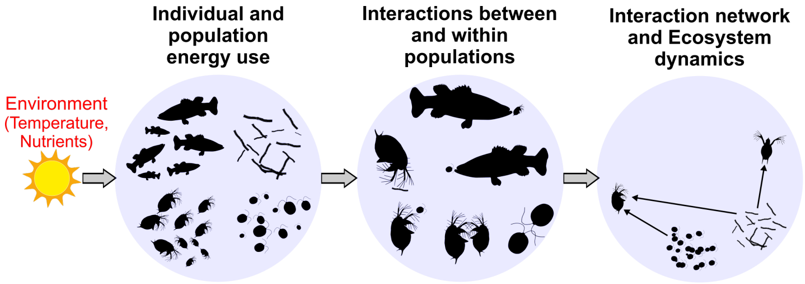

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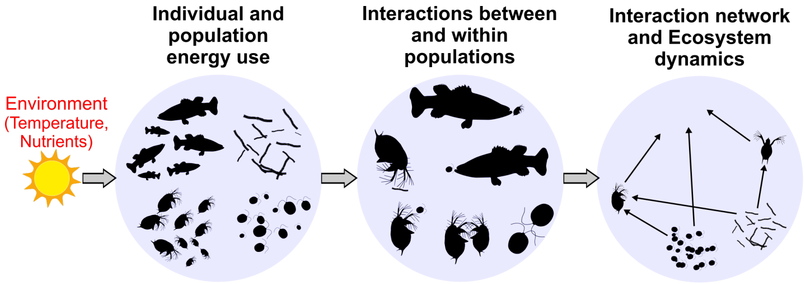

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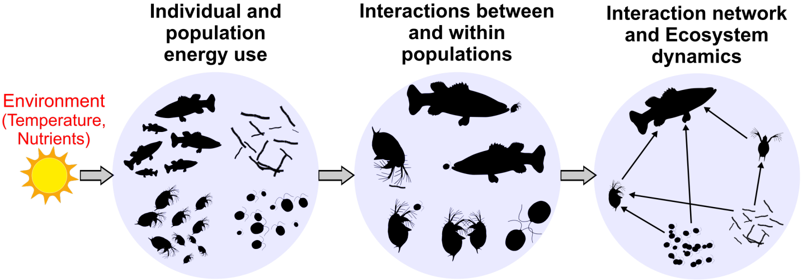

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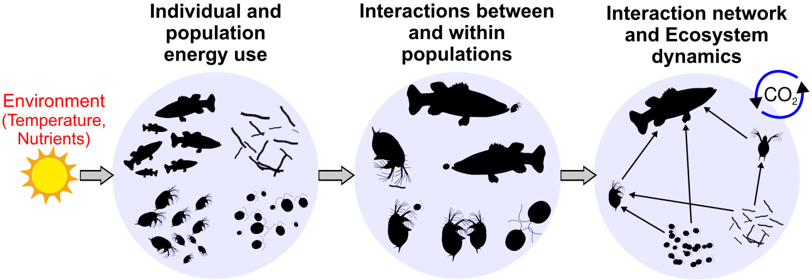

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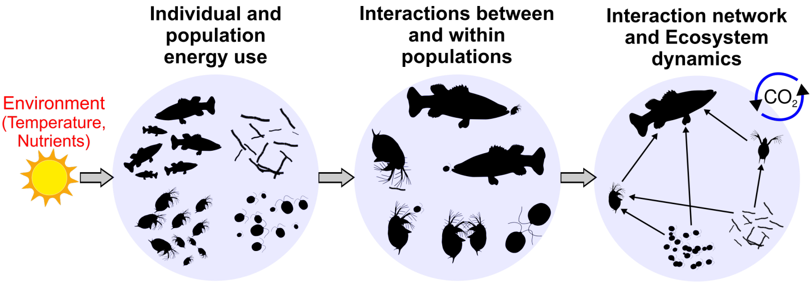

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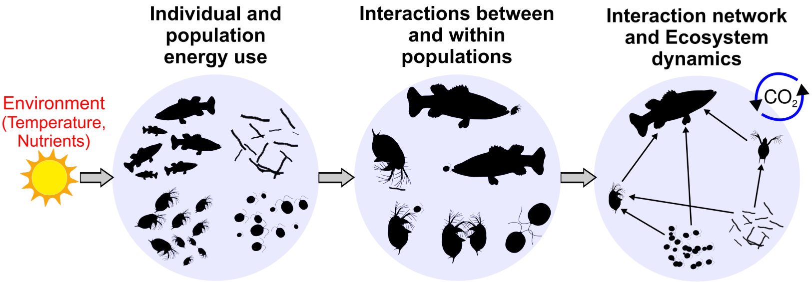

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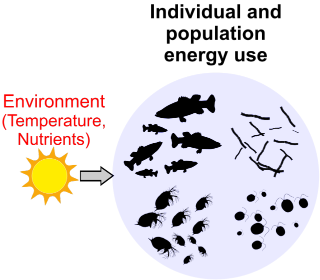
  - Interaction rates with other individuals (including consumption rates - another lecture)

Energy and Metabolic rate



- We will focus on the first “stop” on this roadmap in this lecture

Energy and life

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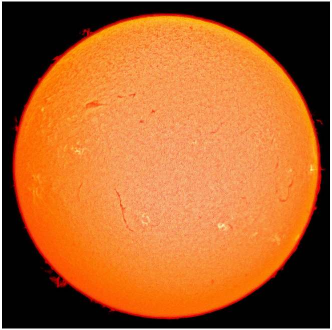

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- The Sun is the *ultimate* energy source for *most* of life on Earth

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  - Maximum population growth rate ($r_{\max}$)

The importance of size

- (Resting) metabolic rate (B) increases with body size (M)

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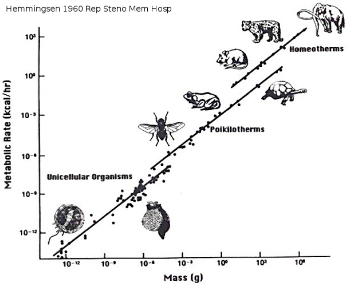

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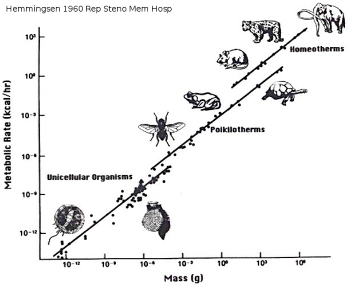

The equation[1] of each line is

$$\log_{10}(B) = \log_{10}(B_0) + b\log_{10}(M)$$

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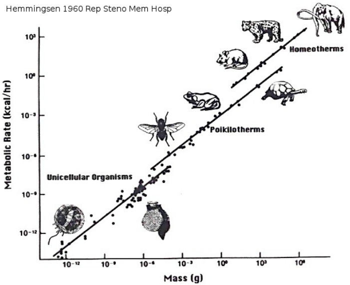

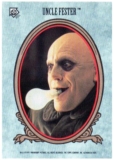

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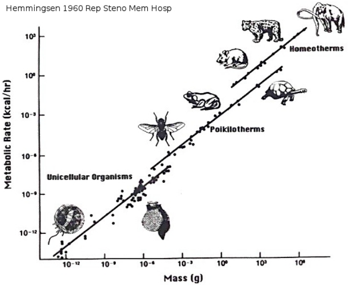

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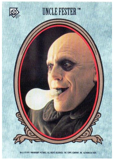

- Your *resting* metabolic rate is ~ 75 W (~ 1500 kcal/day)

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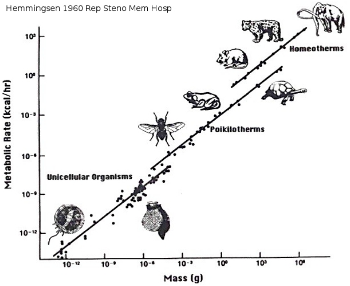

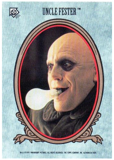

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- Your *resting* metabolic rate is $\sim$ 75 W ($\sim$ 1500 kcal/day)
- But *right now* hopefully somewhat higher, because otherwise this lecture has already put you to sleep!

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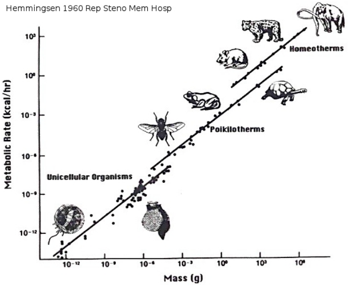

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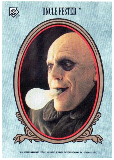

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- This relationship is actually an allometric "power-law" (AKA a scaling law)[1]: $B = B_0 M^b$

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Why rabbits eat and breed like rabbits

- Let's look more closely at metabolic scaling in mammals

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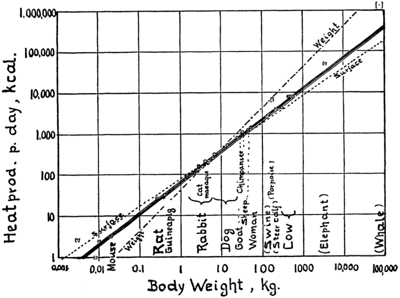

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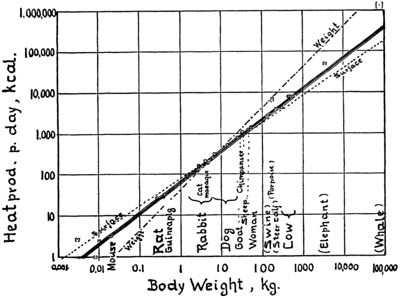

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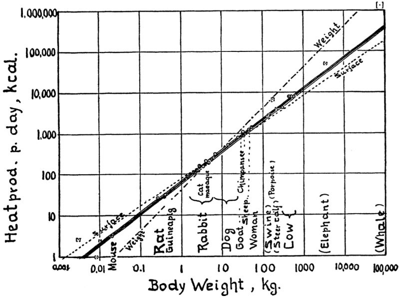

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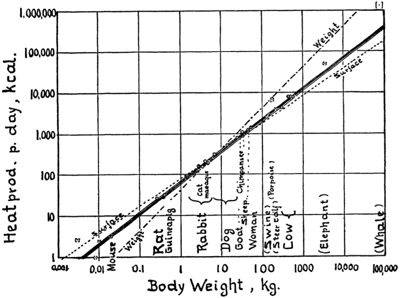

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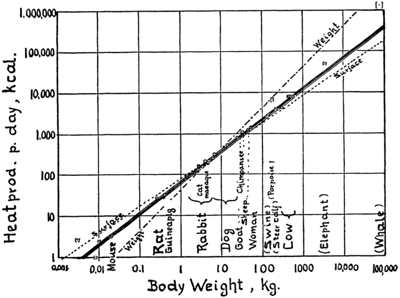

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[2] This is *qualitatively* same as the scaling equation in the previous slide, and the anti-log transformation we did there

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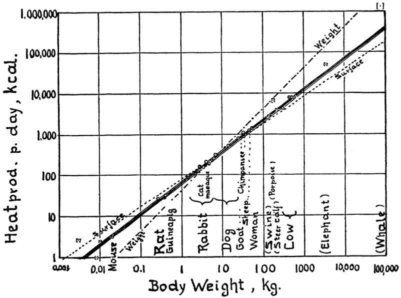

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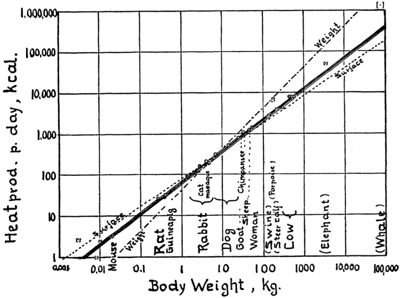

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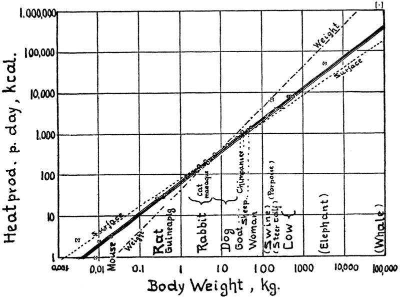

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  - B = heat produced (measure of metabolic rate)
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- Raising both sides to the power of 10 gives: $B = 67.61M^{0.74}$

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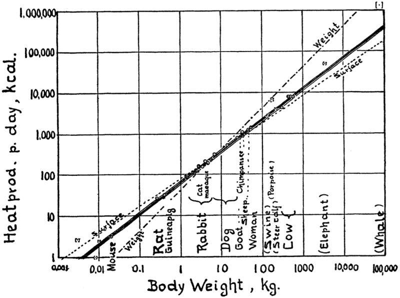

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- This is from Kleiber’s (1947) study (so, AKA ”Kleiber’s Law“)
- The equation[2]of the line is $\log_{10}(B) = 1.83 + 0.74 \log_{10}(M)$
  - B = heat produced (measure of metabolic rate)
  - M = weight
- Raising both sides to the power of 10 gives: $B = 67.61M^{0.74}$

- So larger (individual) mammals use more energy

[2] This is *qualitatively* same as the scaling equation in the previous slide, and the anti-log transformation we did there

WHY RABBITS EAT AND BREED LIKE RABBITS

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- **Thus, larger animals process energy at a slower rate than smaller ones (measured by per-unit mass or per-cell metabolic rate)**

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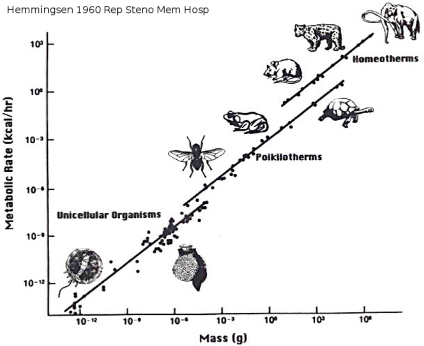
- We will *not worry too much* about the origin of scaling laws here, but focus on their *ecological implications instead*

ECOLOGICAL IMPLICATIONS OF METABOLIC SCALING

Because resting metabolic rate,

$$B = B_0 M^{0.75}$$

Hemmingsen 1960 Rep Steno Mem Hosp



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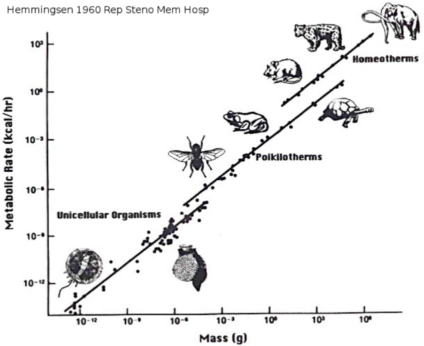

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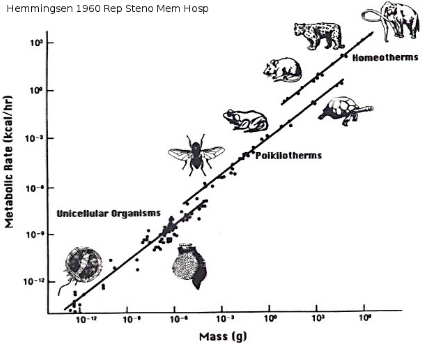

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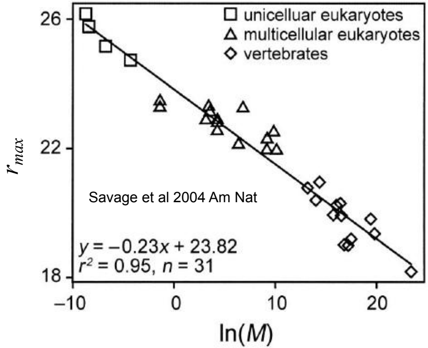
Therefore,
$r_{\max} = r_0 M^{-0.25}$



Population growth rate declines allometrically with body size

IMPLICATIONS OF METABOLIC SCALING

- That is, larger organisms have *relatively* less power to crank out offspring per-unit mass (per-cell)[4]
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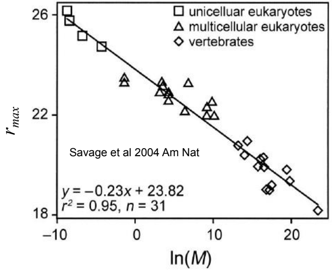

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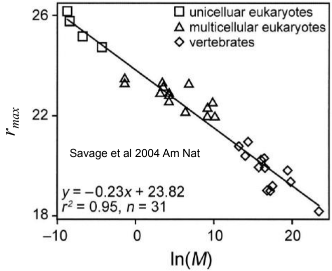

- Therefore, smaller organisms typically show stronger exponential growth

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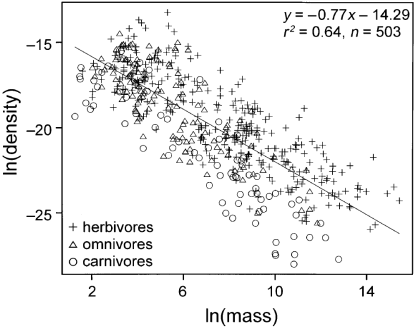
Implications of metabolic scaling

- So, assuming sufficient energy supply to all species, population density scales *negatively* with body size (*Damuth's law*):

Brown et al., Ecology, 2004



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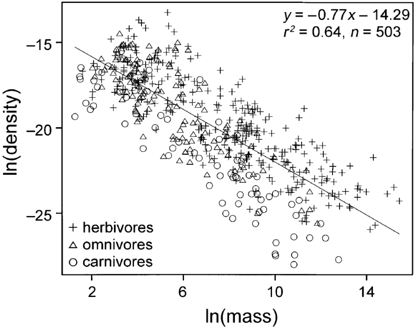
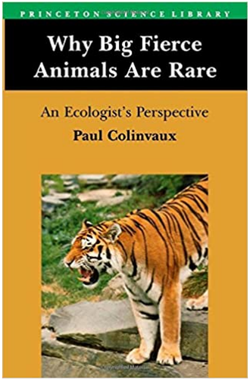


- So big animals and plants are rarer (have smaller population size)

IMPLICATIONS OF METABOLIC SCALING

- Carnivores of a given size are rarer than herbivores of the same size because less energy is available higher up in food chains



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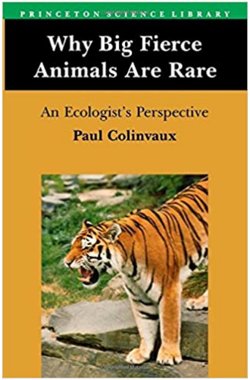

- This also underlies why *Number and Biomass pyramids* (AKA Ecological pyramids) exist

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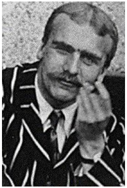

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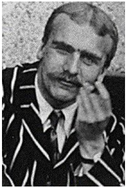

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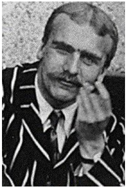

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You can drop a mouse down a thousand-yard mine shaft; and, on arriving at the bottom, it gets a slight shock and walks away, provided that the ground is fairly soft. A rat is killed, a man is broken, a horse splashes.

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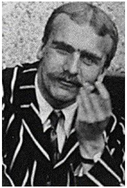

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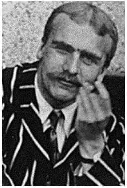

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- Watch: https://www.youtube.com/watch?v=f7KSfjv4Oq0
- Size is also important in microbes (but in somewhat different ways); Watch: https://www.youtube.com/watch?v=E1KkQrFEl2I

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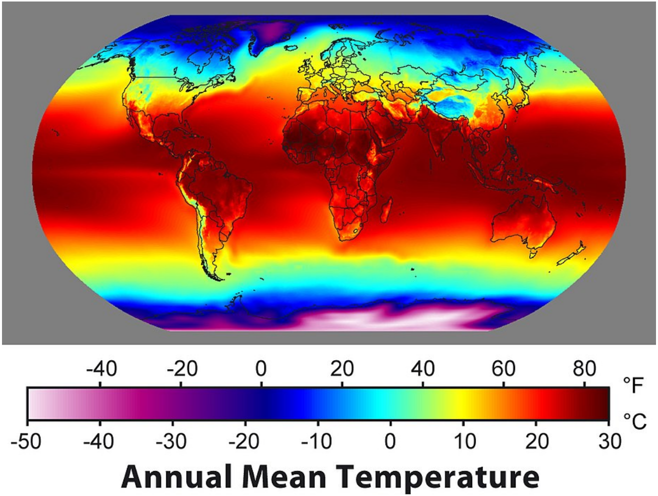

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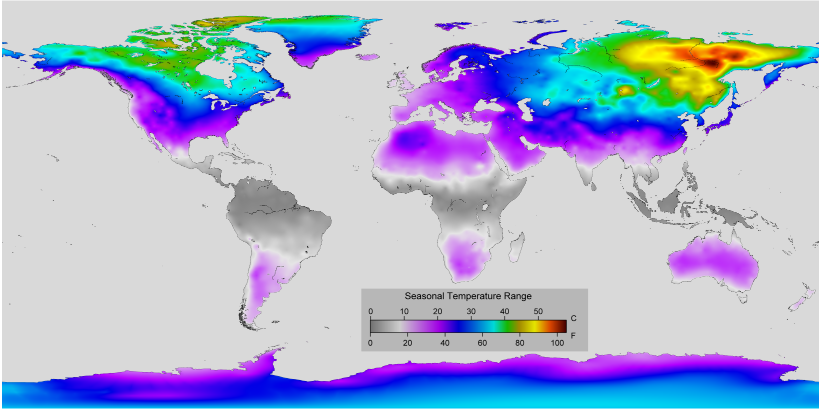

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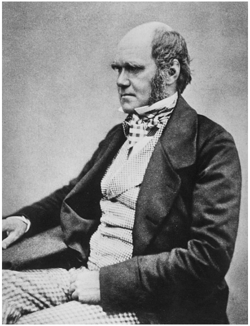

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Climate plays an important part in determining the average numbers of a species, and periodical seasons of extreme cold or drought seem to be the most effective of all checks.

– Darwin 1859, "The origin of species"

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- Therefore, metabolic rates go up (approximately) exponentially with temperature to a point and then decline: this is the "Thermal Performance Curve"

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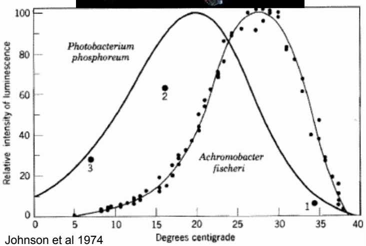

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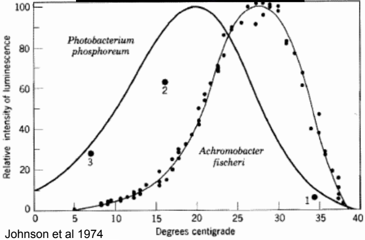

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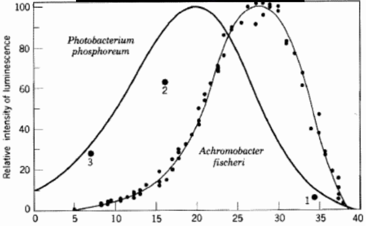

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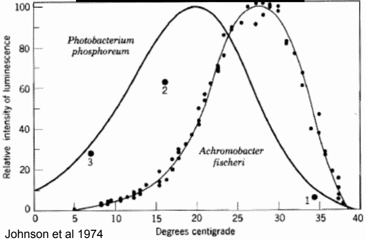

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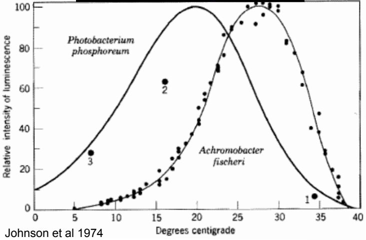

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- Key biological rates—Respiration, photosynthesis, individual growth, etc.—all also depend upon temperature in a similar way

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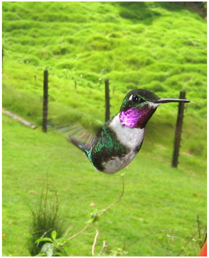

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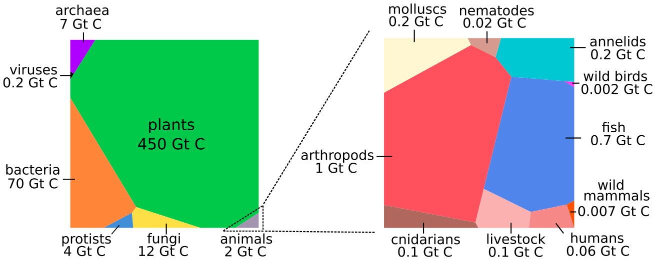

Bar-On et al, "The Biomass Distribution on Earth" PNAS 2018

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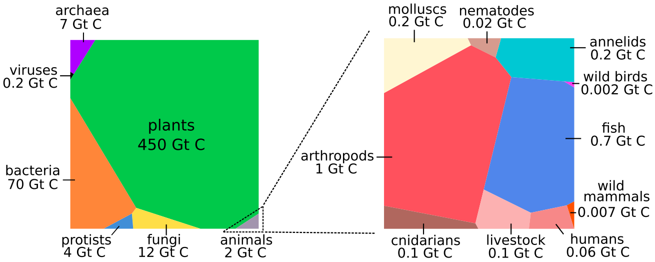

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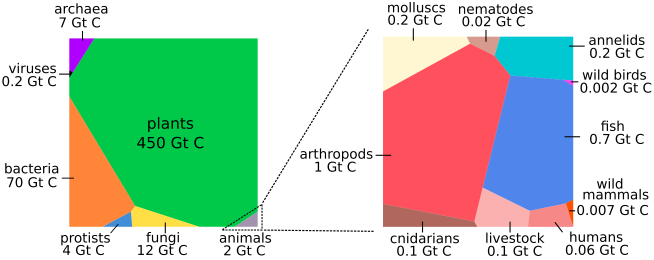

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- Individual metabolism drives individual and population growth rate
- Metabolic rate increases as a power-law with size
  - Thus, size determines population growth rate and population size
- Metabolic rate increases (approximately) exponentially with temperature (to a point)
  - Thus, temperature also determines population growth rate and population size
- *Between metabolic rate and production (r_{max}), lies consumption — what must consumption rate scale like?* (Next lecture)

DISCUSSION QUESTIONS

1. Given the way resting metabolic rate scales with body size, what must consumption rate scale like?
2. Why did we focus on *resting* (or "basal") metabolic rate?
3. How much energy would a *resting* rabbit ($\sim$ 1 kg), a human ($\sim$ 70 kg, and an Asian elephant ($\sim$ 4000 kg) need for metabolic balance[5],
   - at the individual level?
   - per unit mass?
4. How does the value you calculated in the previous question compare with the recommended calorie intake for humans? Is it lower or higher? Why?
5. What are the optimal temperatures for the enzyme underlying bioluminescence in the two bacteria in the given example? Why might they have different thermal optima?

[5] Calculate it using Kleiber's law (allometric/scaling equation), as we did for a mouse

Readings

1. Kleiber, M. Body size and metabolic rate. Physiological Reviews 27, 511–541 (1947).
2. West, G. B. & Brown, J. H. The origin of allometric scaling laws in biology from genomes to ecosystems: towards a quantitative unifying theory of biological structure and organization. Journal of Experimental Biology 208, 1575–92 (2005).
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4. Brown, J. H., et al. Toward a metabolic theory of ecology. Ecology 85, 1771–1789 (2004).
5. Dell, A. I., Pawar, S. & Savage, V. M. Systematic variation in the temperature dependence of physiological and ecological traits. PNAS 108, 10591–10596 (2011).