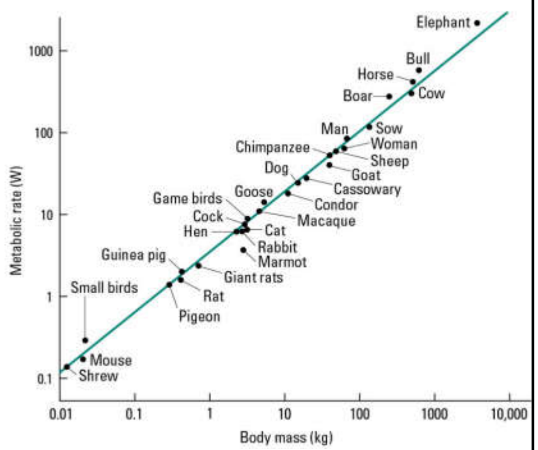
Allometry of metabolic rate – "mouse to elephant curve"

- b=0.75
- a=70
- rate = 70 $M^{0.74}$
  (Kleiber's Law)

- What does this mean biologically?
- Why isn't b=1.0?
- Why isn't b=0.67?



Biological Implications

- If we want to compare apples to apples…need to measure mass-specific metabolic rate (metabolic rate per unit mass)

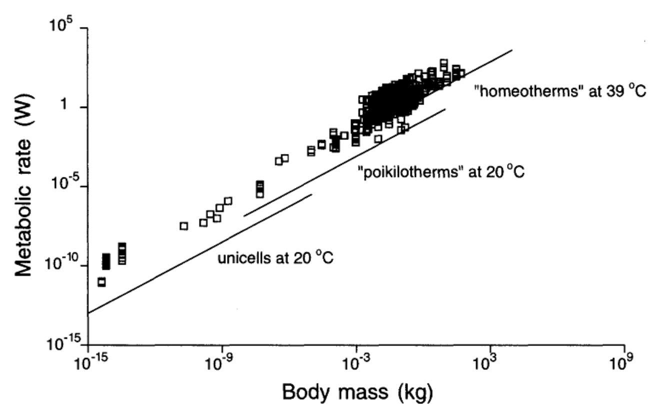
Basic efficiency and "speed" of biomass production

Utilization of 1 ton (907 kg) of hay by large and small mammals. From: Kleiber 1961.

Animals	1 Steer	300 rabbits
Total Body Weight	590 kg	590 kg
Food Consumption per day	7.5 kg	30.2 kg
Duration of 1 ton of food	120 days	30 days
Heat loss per day	20,000 kcal	80,000 kcal
Mass increase per day	0.91 kg	3.6 kg
Mass gain from 1 ton food	109 kg	109 kg

What about taxonomic differences?

Fig. 4. A comparison of the temperature-standardized relation for whole-organism metabolic rate (W) as a function of body mass (kg) obtained in this study with the depiction of Hemmingsen (*1*). Data points represent unicells, plants, ectotherms, and endotherms from Fig. 1, all standardized to 20°C. The three lines represent the relations obtained by Hemmingsen for unicells, ectotherms ("poikilotherms"), and endotherms ("homeotherms").



Note that slope is greater for ectotherms (0.81 vs. 0.78). Thus, the largest ectotherms were likely no different than current large endotherms. Why?

Gillooly, J. F., J. H. Brown, G. B. West, V. M. Savage, and E. L. Charnov. 2001. Effects of size and temperature on metabolic rate. Science 239:2248–2251.

An Exploration on Greenhouse Gas and Ammonia Production by Insect Species Suitable for Animal or Human Consumption

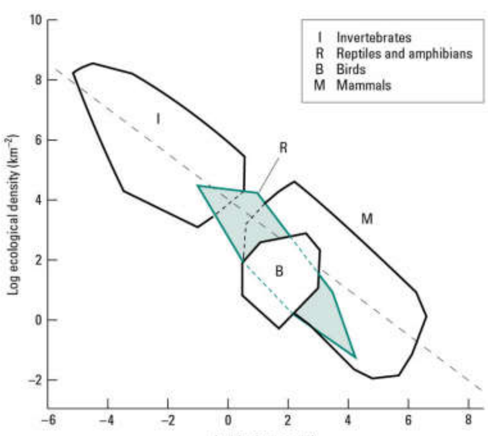
Dennis G. A. B. Oonincx[1*], Joost van Itterbeeck[1], Marcel J. W. Heetkamp[2], Henry van den Brand[2], Joop J. A. van Loon[1], Arnold van Huis[1]

Table 2. CO_2 production (average ± standard deviation) per kilogram of bodymass per day, per kg of mass gain and ave gain for five insect species, pigs and beef cattle.

Species	CO_2 (g/kg BM/day)	CO_2 (g/kg mass gain)	ADG (%)
Pachnoda marginata (n = 4)	50±22 [a]	1,539±518 [a]	4.0±2.1% [a]
Tenebrio molitor (n = 4)	61±9 [b]	1,031±349 [b]	7.3±2.5% [b]
Blaptica dubia (n = 3)	19±3 [c]	337±51 [c]	6.1±0.7% [c]
Acheta domesticus (n = 4)	68±10 [d]	1,468±971 [a]	7.2±3.4% [b]
Locusta migratoria (n = 6)	110±21 [e]	734±119 [d]	19.6±2.1% [d]
Pigs	21.6–29.6	865–1,194	3.2±0.53%
Beef cattle	5.3–7.0	2,835	0.3±0.07%

BM = Body Mass;
ADG = Average daily gain;

Other correlates…



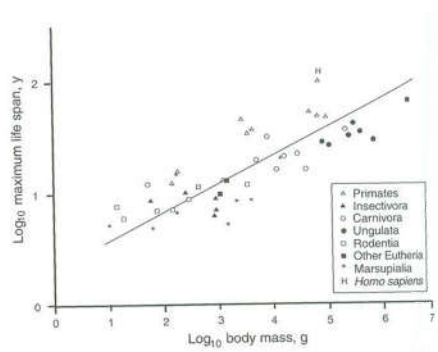


Figure 13.7 $\log_{10}$ maximal life span in mammals as a function of $\log_{10}$ body mass. Source: Modified from Hofman (1993).

Metabolic Theory of Ecology (MTE)

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A General Model for the Origin of Allometric Scaling Laws in Biology

Geoffrey B. West, James H. Brown,* Brian J. Enquist

Allometric scaling relations, including the 3/4 power law for metabolic rates, are characteristic of all organisms and are here derived from a general model that describes how essential materials are transported through space-filling fractal networks of branching tubes. The model assumes that the energy dissipated is minimized and that the terminal tubes do not vary with body size. It provides a complete analysis of scaling relations for mammalian circulatory systems that are in agreement with data. More generally, the model predicts structural and functional properties of vertebrate cardiovascular and respiratory systems, plant vascular systems, insect tracheal tubes, and other distribution networks.

Biological diversity is largely a matter of body size, which varies over 21 orders of magnitude (*1*). Size affects rates of all biological structures and processes from cellular metabolism to population dynamics (*2*, *3*). The dependence of a biological variable Y on body mass M is typically characterized by an allometric scaling law of the form

$$Y = Y_0 M^b \qquad (1)$$

underlies these laws: Living things are sustained by the transport of materials through linear networks that branch to supply all parts of the organism. We develop a quantitative model that explains the origin and ubiquity of quarter-power scaling; it predicts the essential features of transport systems, such as mammalian blood vessels and bronchial trees, plant vascular systems, and insect tracheal

imal population growth rate (*1–3*). Because organisms of different body sizes have different requirements for resources and operate on different spatial and temporal scales, quarter-power allometric scaling is perhaps the single most pervasive theme underlying all biological diversity.

Physiological facts of life

- Based on body size alone, you can fairly accurately predict:
  - Metabolic rate
  - Rate of energy assimilation
  - Lifespan
- For each of these, a and b describe allometric relationships (six facts of life).

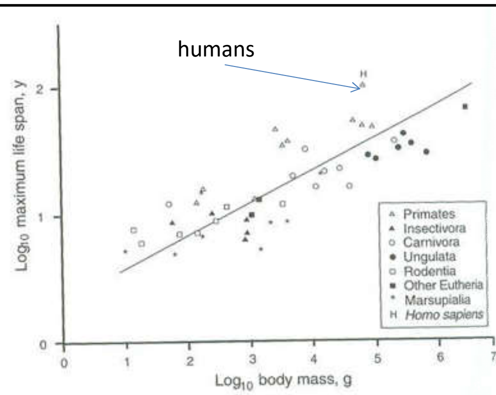


Figure 13.7 Log_{10} maximal life span in mammals as a function of log_{10} body mass. Source: Modified from Hofman (1993).

From an evolutionary perspective, what is often most interesting is the deviation from these patterns.

What do positive and negative **residuals** represent in this figure?

Body size and heat exchange

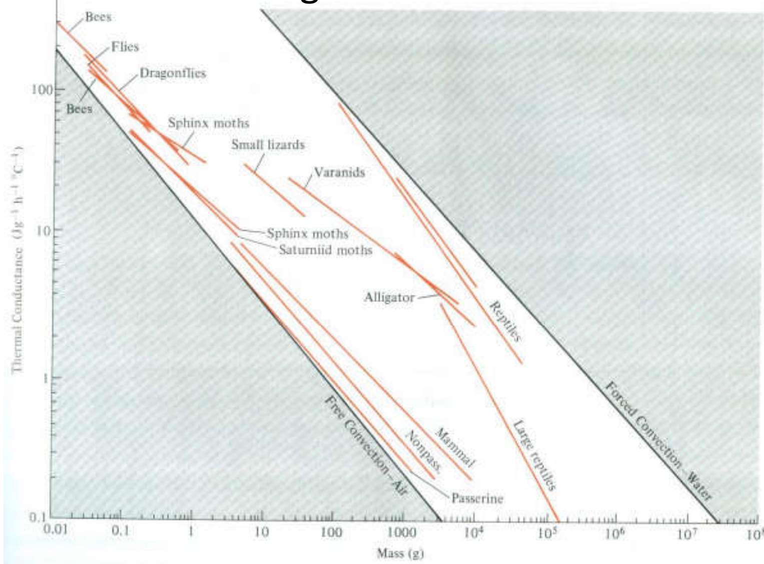


FIGURE 5–9 Allometric relationships for minimal thermal conductance of insects and vertebrates. Thin lines indicate relationships for air; heavy lines indicate relationships for water. Free convection air line indicates the minimal thermal conductance for free convective heat loss from a sphere in still air. Forced convection water line indicates the maximal thermal conductance for forced convective heat loss of a cylinder in water.

Movement through fluids

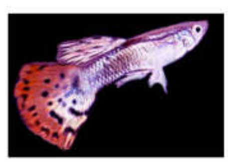
- Air and water act as fluids.
- **Reynolds Number** – dimensionless number representing the ratio of inertial forces (skin friction) vs. viscous forces (pressure drag).

$$R_e = \frac{pvL}{u}$$

Where:
R_e=Reynolds number

L = length of object
v=relative speed
p=fluid density
u=viscosity

- Low R_e – viscous>inertial
  - No coasting, "jump" through water
  - Shape not important
- High R_e – inertial>viscous
  - Coasting, hydrodynamic shapes more efficient



Guppy: $R \approx 10^2$

Michael Phelps: $R \approx 10^4$

Limnol. Oceanogr., 26(6), 1981, 1062–1073

Copepod feeding currents: Food capture at low Reynolds number[1]

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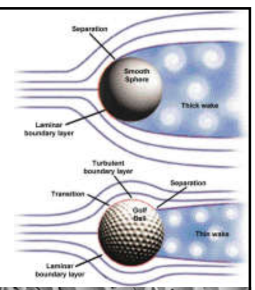
Abstract

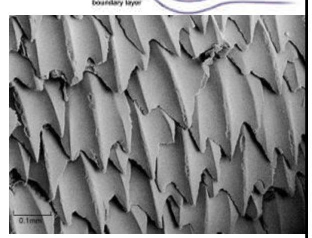
High-speed motion pictures of dye streams around feeding calanoid copepods revealed that these important planktonic herbivores do not strain algae out of the water as previously described. Rather, a copepod flaps four pairs of feeding appendages to propel water past itself and uses its second maxillae to actively capture parcels of that water containing food particles. The feeding appendages of *Eucalanus pileatus* operate at Reynolds numbers of only 10^{-2} to 10^{-1}. In the viscous world of a feeding copepod, water flow is laminar, bristled appendages behave as solid paddles rather then open rakes, particles can neither be scooped up nor left behind because appendages have thick layers of water adhering to them, and water and particle movement stops immediately when an animal stops beating its appendages.

Streamlining and skin properties

- Golf ball dimples and shark skin dermal denticles both decrease drag
  - Golf ball flies further
  - Shark glides further = less energy expended for swimming a given distance

- Air and water both act as fluids…





$$R_e = \frac{pvL}{u}$$

Where:
R_e=Reynolds number

L = length of object
v=relative speed
p=fluid density
u=viscosity