HHMI-ISGE MM MODULES

INTRO TO ALLOMETRY INTEGRATIVE THEME

HHMI-ISGE MM MODULES

INTRO TO HHMI CONTEXT

HHMI-ISGE MM MODULES

CHALLENGES & STUDENT RESPONSES (SLO's)

HHMI-ISGE MM MODULES

ALTERNATIVES GRAPHICS

ALLOMETRY
AS AN INTEGRATIVE THEME

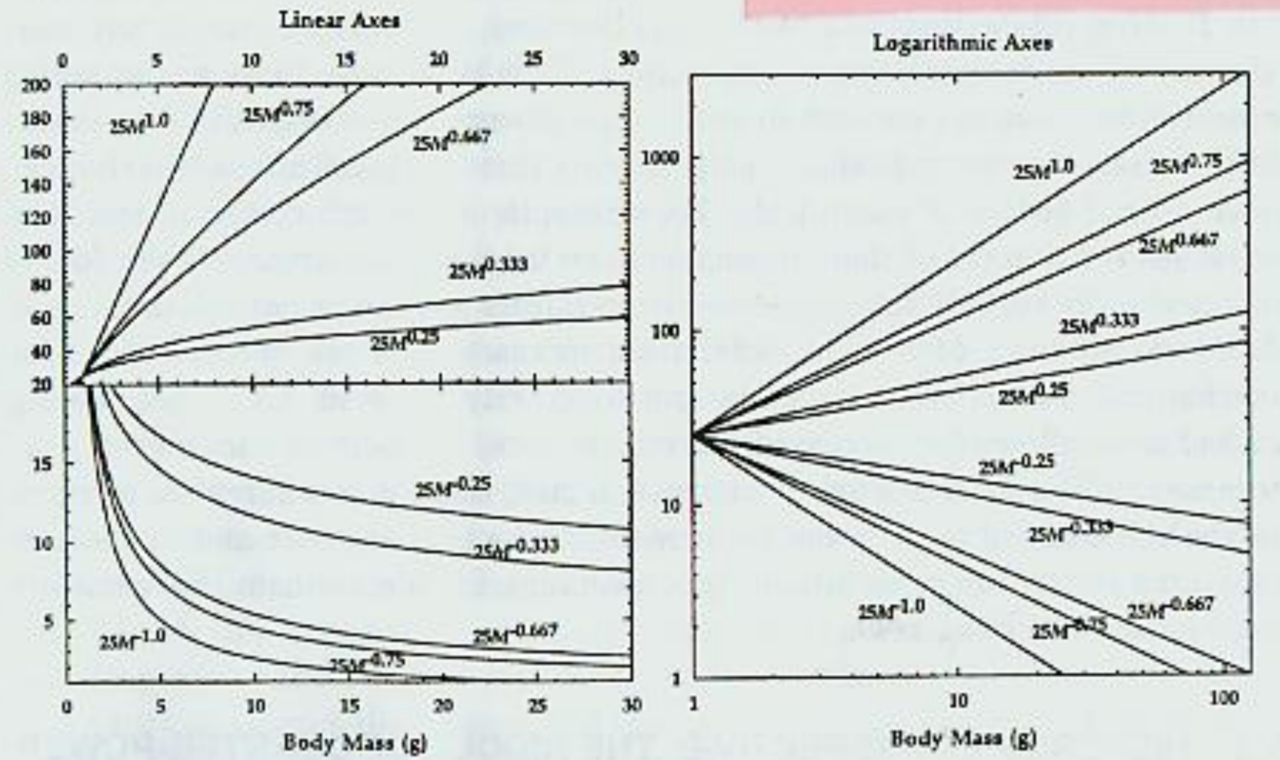
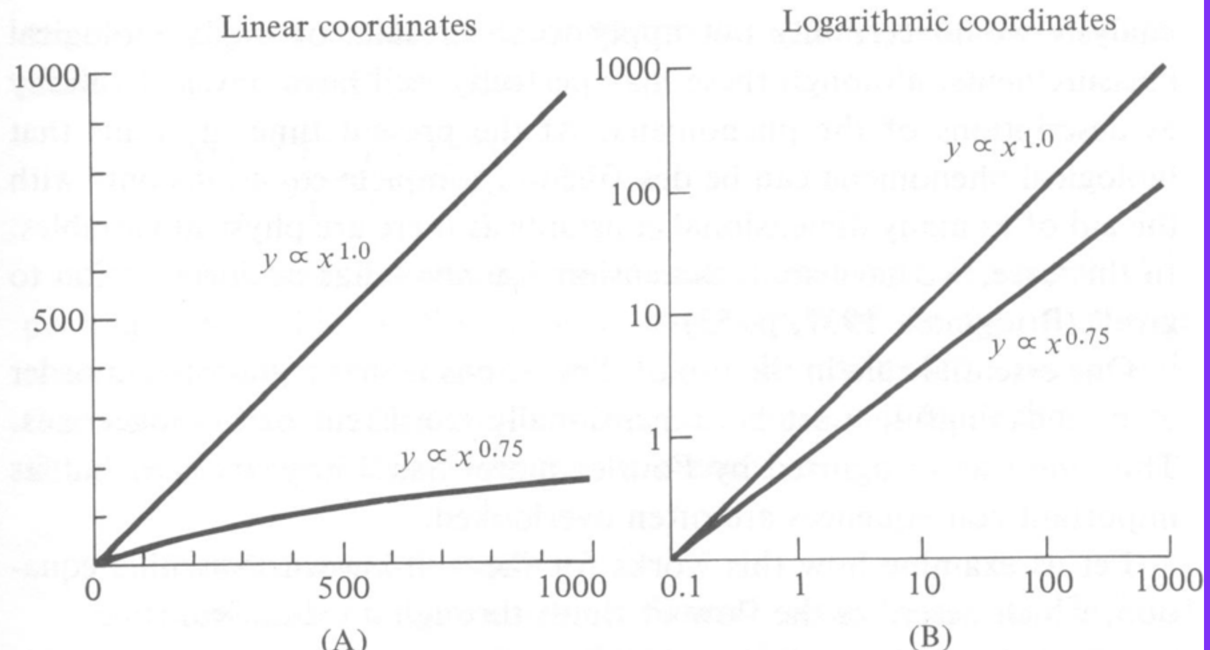


FIGURE 1 Plots of the same allometric relationships on linear and logarithmic axes. Note that the relationships are curvilinear when plotted on linear axes, but linear when plotted on logarithmic axes. Also, when the exponent, b, is > 1, the independent variable, Y, is an increasing function of body mass, M; when $b < 1$, it is a decreasing function.

ALLOMETRY
AS AN INTEGRATIVE THEME

Figure 2.7. Logarithmic functions that on linear coordinates yield strikingly different regression lines (A) give straight lines that appear to have closer similarity when plotted on logarithmic coordinates (B). It should be noted that an apparently minor difference in the slopes of two regression lines on logarithmic coordinates can be numerically very important.



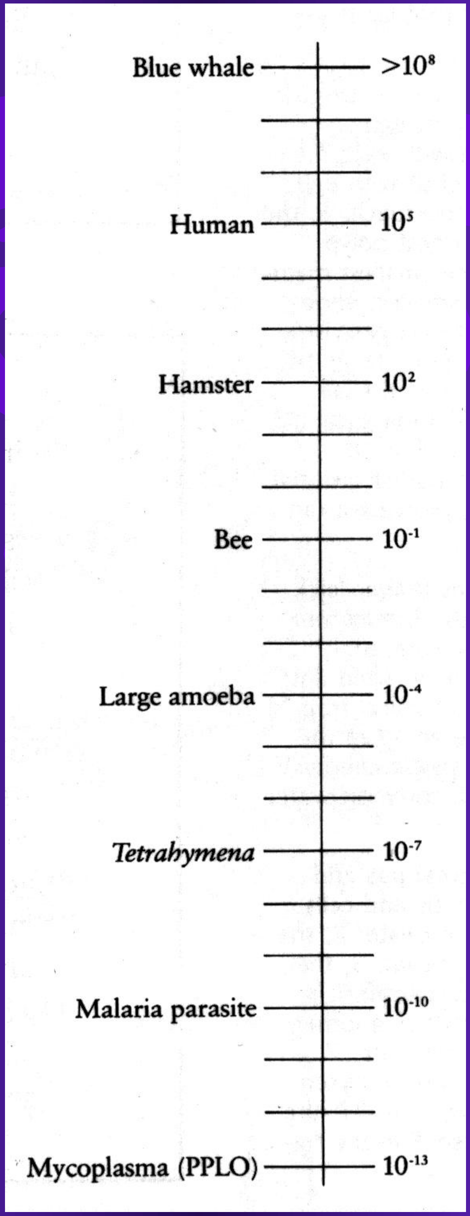
between the lines is striking. When the same functions are plotted on logarithmic coordinates, both give straight lines (Figure 2.7B), and the lines do not give the appearance of being very different. This should be kept carefully in mind; what appear to be small differences in exponents represent sizable magnitudes when expressed arithmetically.

HHMI-ISGE MM MODULES

GRAPHIC INTERACTION HHMI DATA INPUT

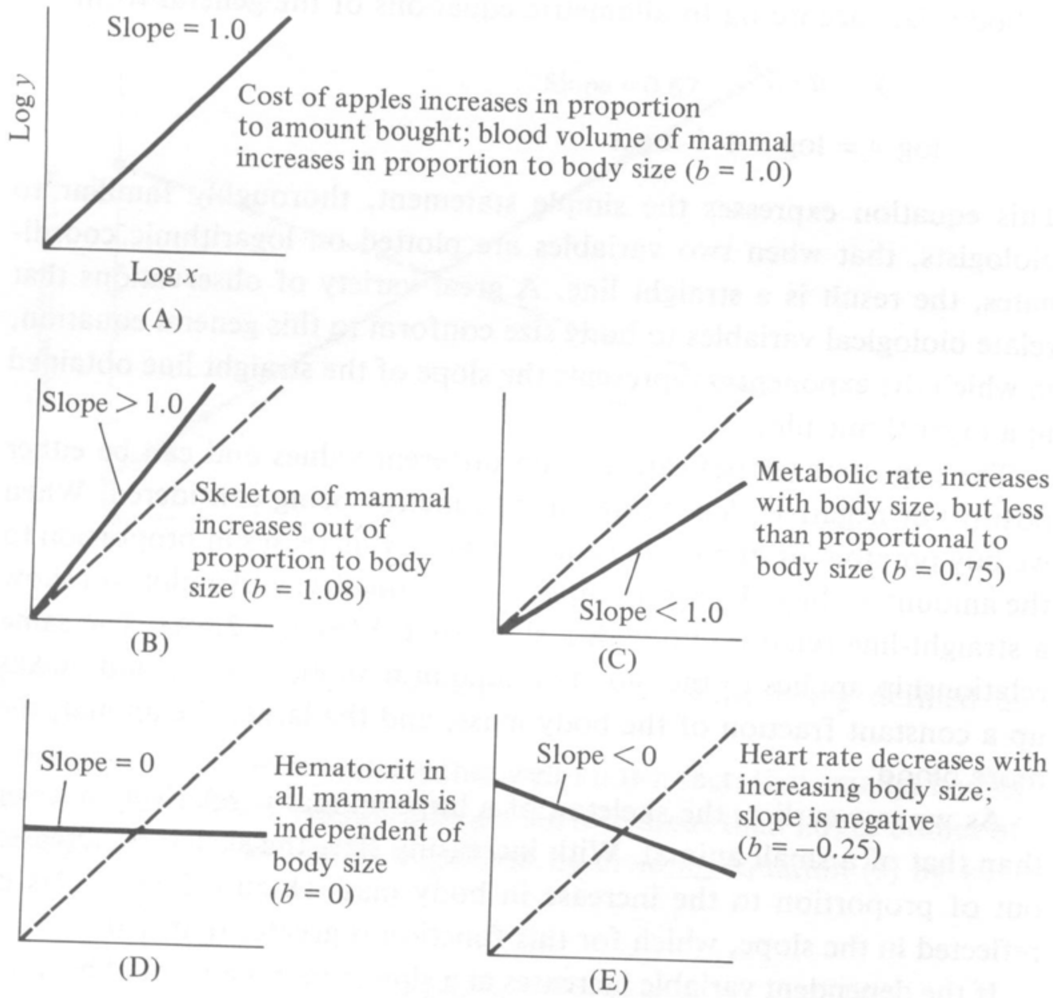
DEFINITION ALLOMETRY

ALLOMETRY
AS AN INTEGRATIVE THEME



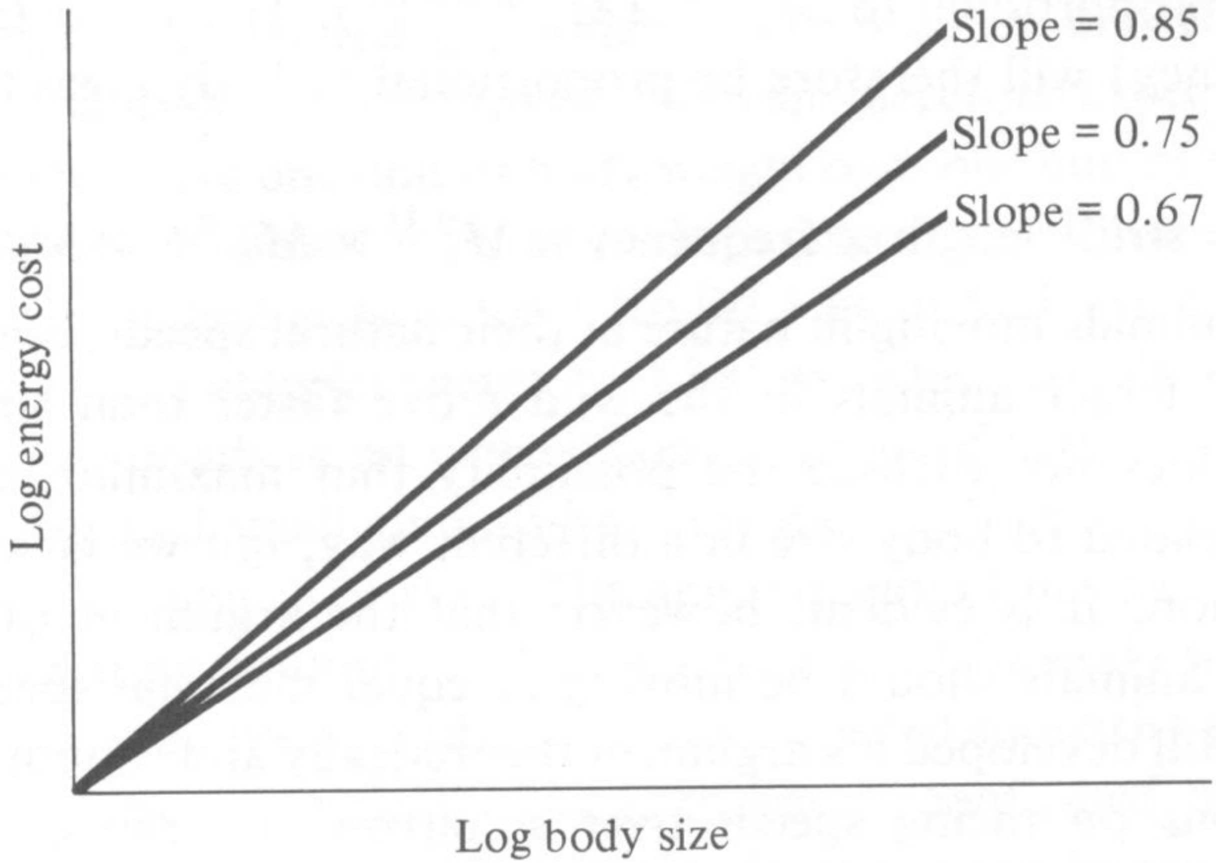
ALLOMETRY
AS AN INTEGRATIVE THEME

Figure 2.6. The regression lines for different exponents in the equation $y = ax^b$ (dashed lines) have different slopes depending on the value of b. The slope (b) may indicate proportionality (fully drawn line), but often deviates in a regular way from proportionality. All plots refer to logarithmic coordinates.

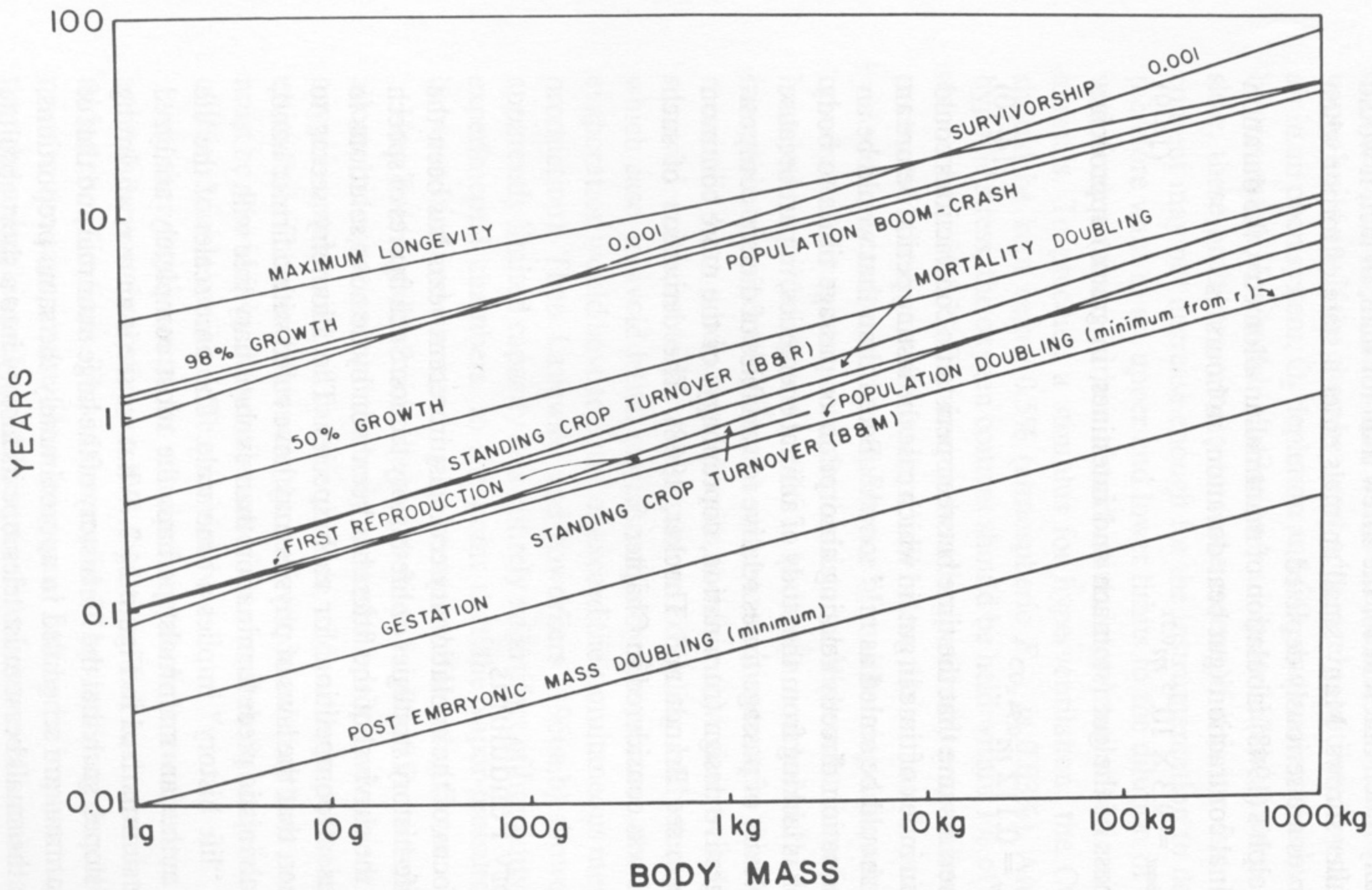


ALLOMETRY
AS AN INTEGRATIVE THEME

Figure 14.3. Comparison of slopes (without consideration of absolute magnitudes) for cost of running (slope = 0.67), for resting (slope = 0.75), and for maximal oxygen consumption (slope = 0.85).



ALLOMETRY
AS AN INTEGRATIVE THEME



14-2 An allometric summary of the life histories of eutherian mammals, based on equations given in previous chapters. Many of these relationships need fine-tuning with more extensive data bases, but the overall pattern is clear: the quantitative details of life histories are largely a matter of size and the pace of life that the size determines. Survivorship of 0.001 of the original adult cohort and t_{sc} derived from Banse and Mosher, 1980 (B & M), have the largest scaling exponents (0.32, 0.33), compared to maximum longevity (0.20) and t_{sc} derived from Beland and Russell, 1980 (B & R; 0.29).

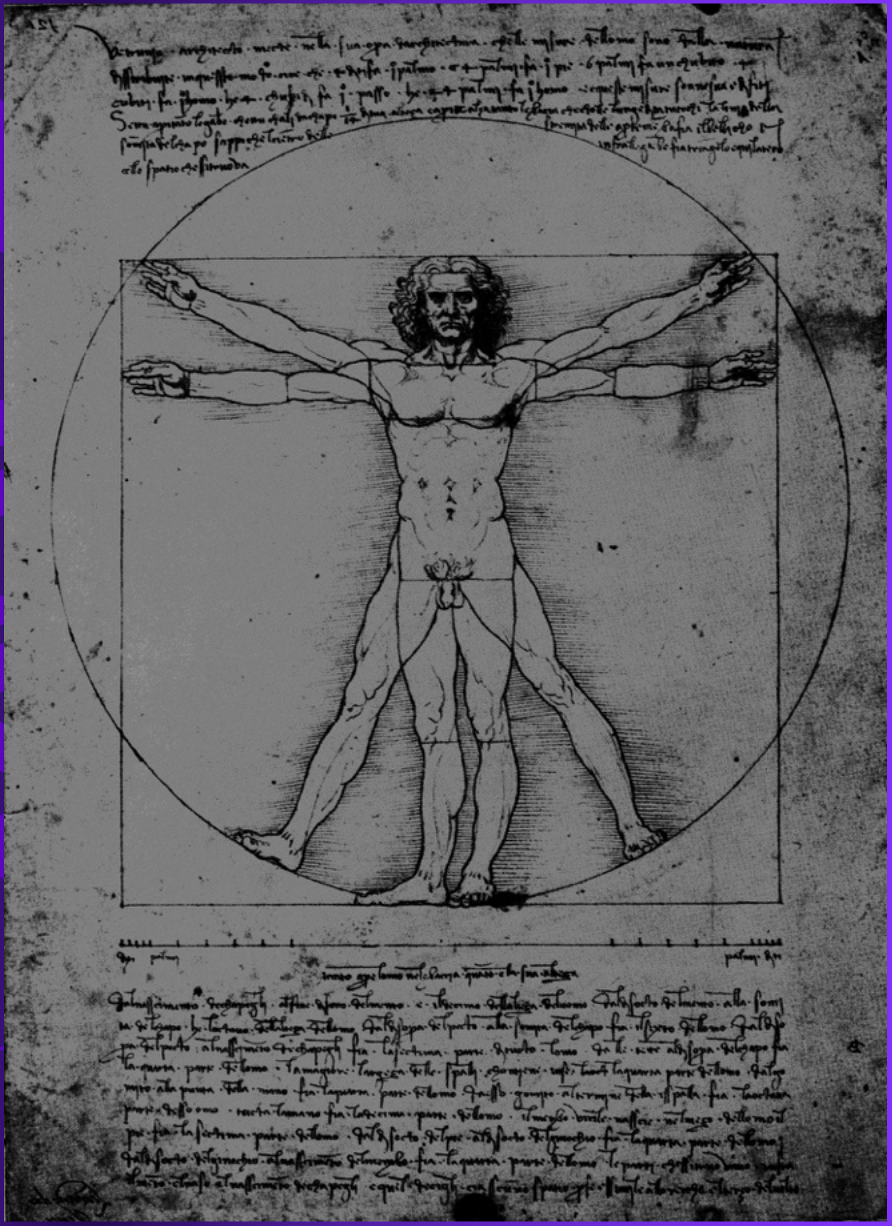
HHMI-ISGE MM MODULES

ALLOMETRY EQUATION INTERACTION

HHMI-ISGE MM MODULES

HISTORY OF ALLOMETRY

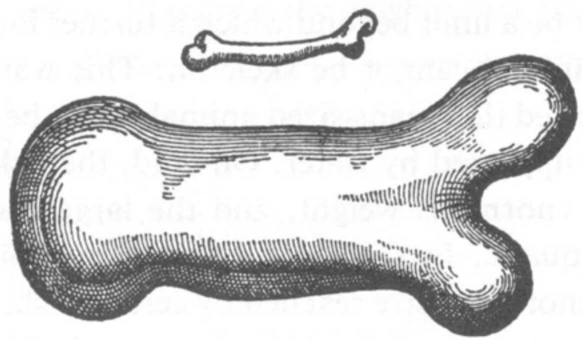
ALLOMETRY
AS AN INTEGRATIVE THEME



ALLOMETRY
AS AN INTEGRATIVE THEME

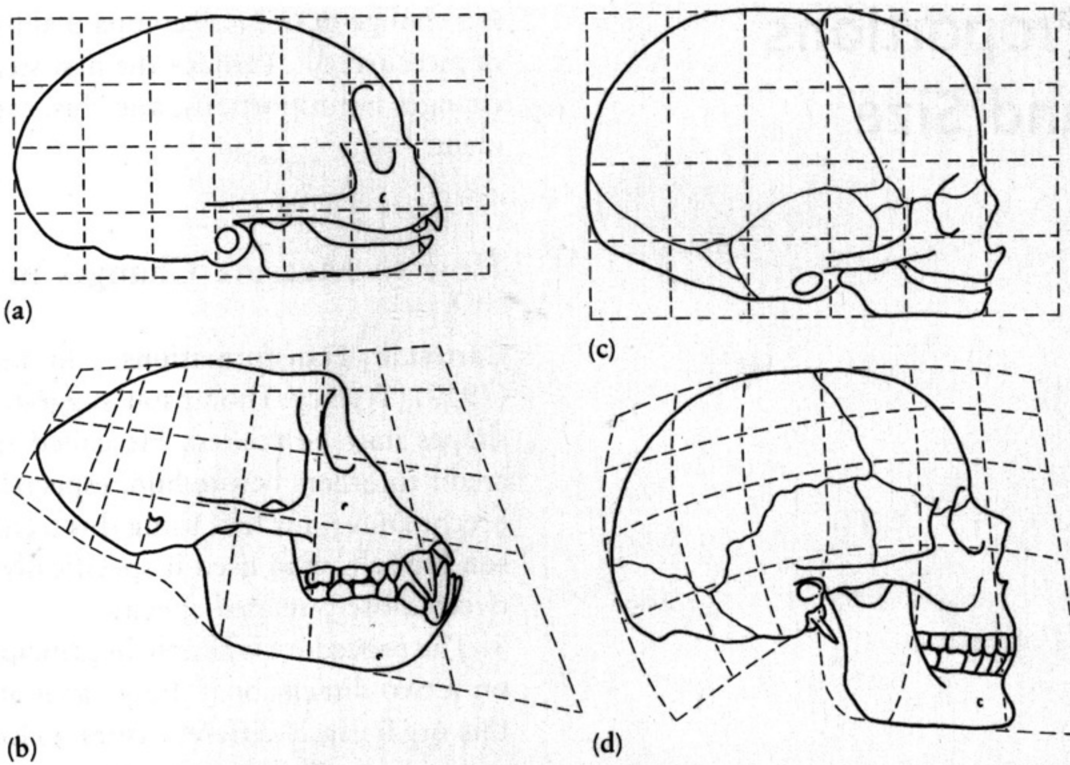
- **Get picture or sketch of Galileo**

Figure 5.1. Galileo was probably the first to point out that the bones of very large animals must be scaled out of proportion to their linear dimensions in order to support the weight of the animal, which increases with the third power of the linear dimension. From Galilei (1637).



ALLOMETRY
AS AN INTEGRATIVE THEME

Illustration of Cartesian transformations: *a*, the skull shape of a rhesus monkey a few days after birth; *b*, an old male rhesus monkey; *c*, a newborn human; *d*, an adult human.



(a) (b) (c) (d)

ALLOMETRY
AS AN INTEGRATIVE THEME

- Get picture or sketch of Huxley
- Have check Bonner?

HHMI-ISGE MM MODULES

IDENTIFYING FEATURES OF ALLOMETRY

HHMI-ISGE MM MODULES

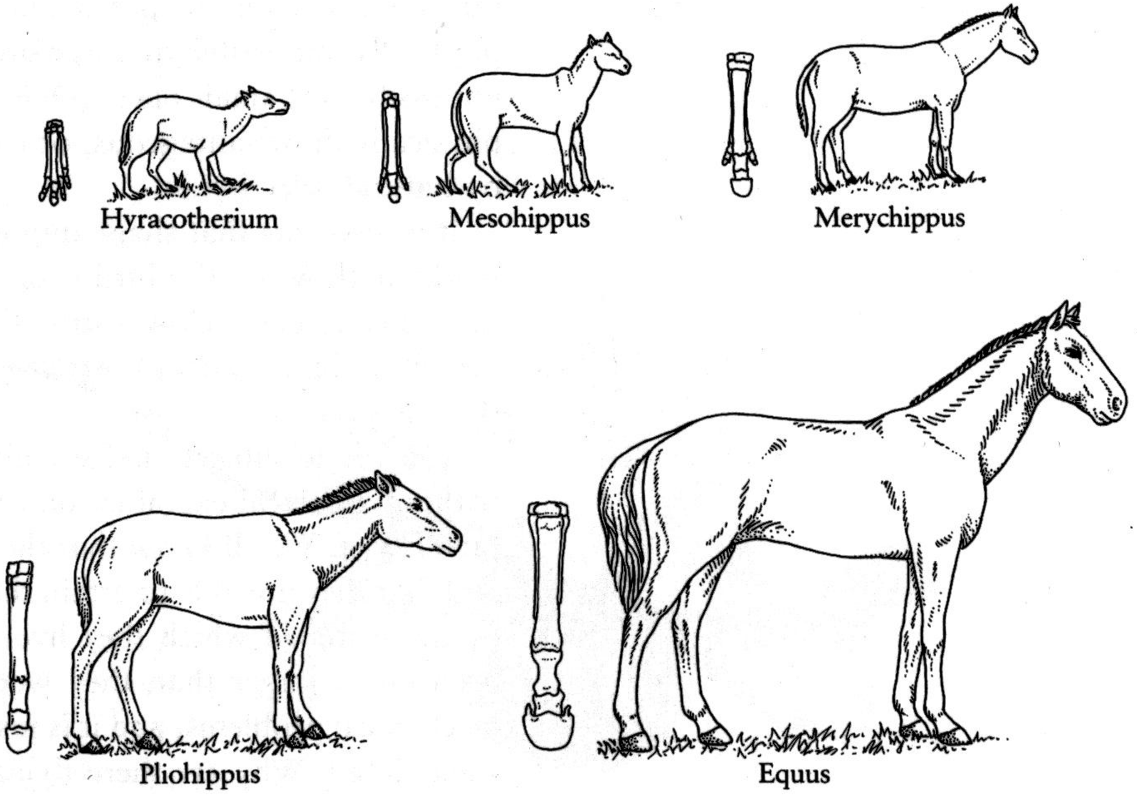
IDENTIFYING FUNCTIONS OF ALLOMETRY

HHMI-ISGE MM MODULES

BIOLOGICAL ALLOMETRY

ALLOMETRY
AS AN INTEGRATIVE THEME

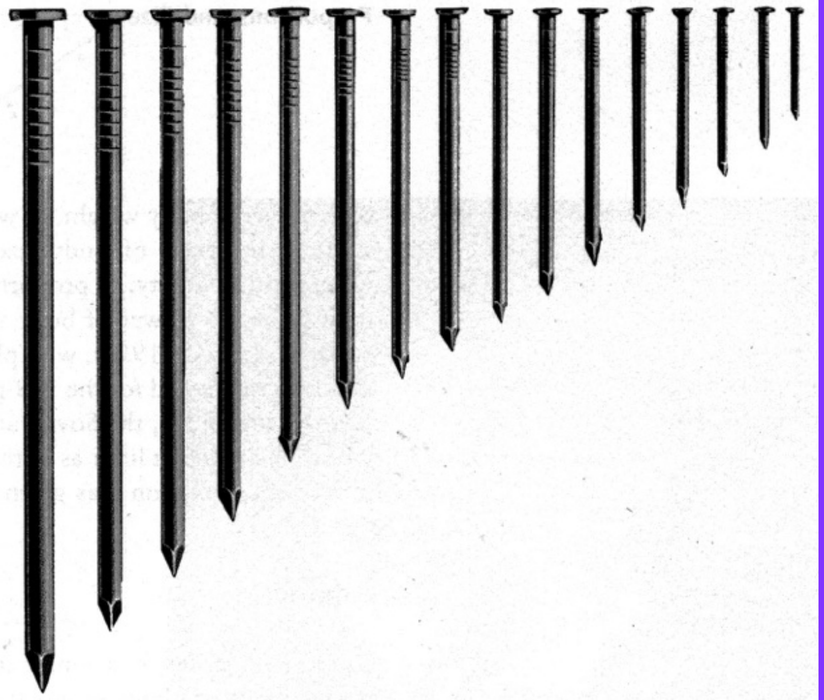
The evolution of the horse required about 60 million years. There has been a regular increase in the size of horses over time. As horses evolved, the structure of the foot changed. In the dawn horse or ''Eohippus'' (*Hyracotherium*), a tiny creature that walked on the moist floors of tropical forests, there were four distinct toes. Later, however, all of the toes but one disappeared as the horse became a plains-dwelling animal.



HHMI-ISGE MM MODULES

ENGINEERING ALLOMETRY

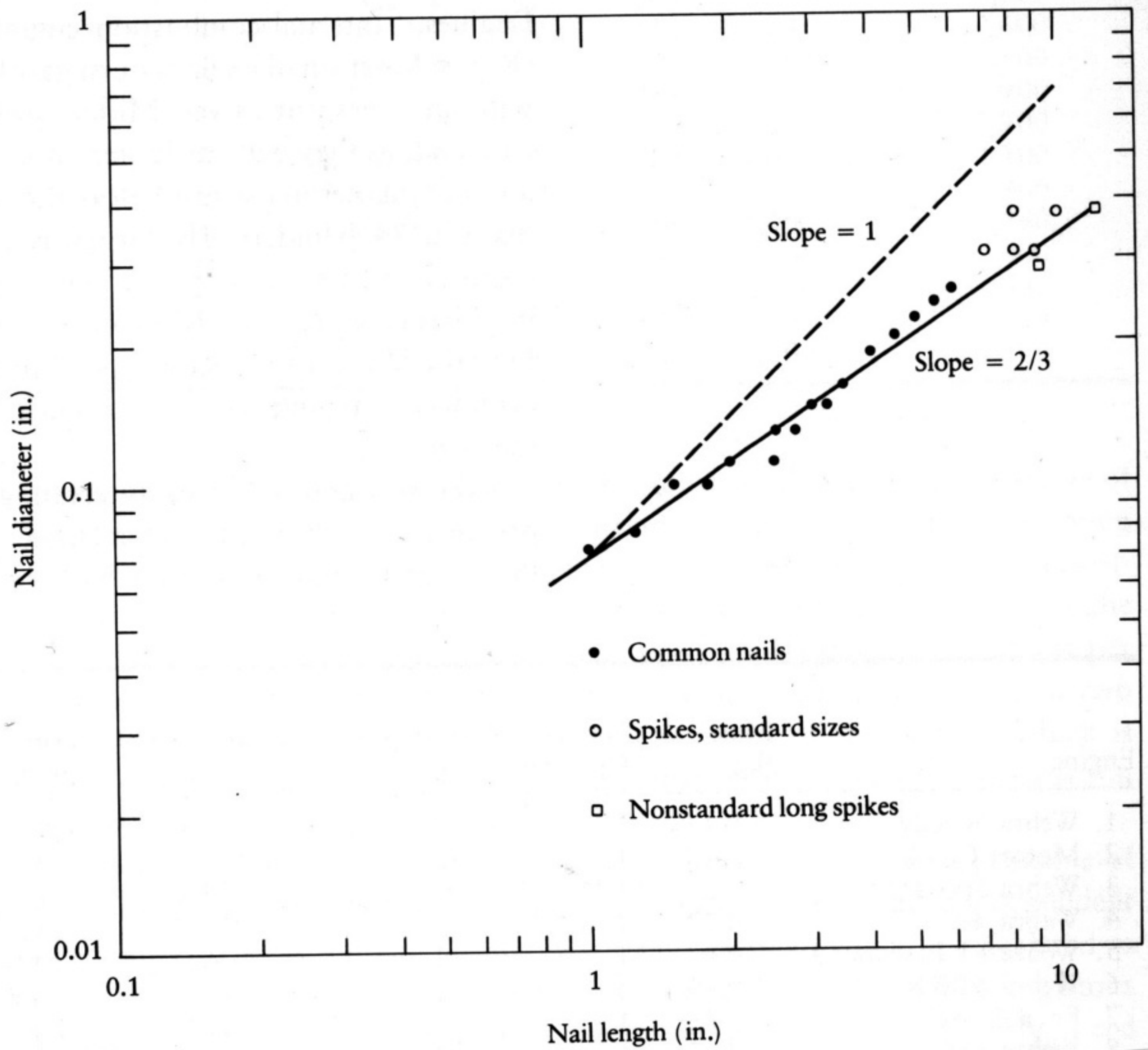
ALLOMETRY
AS AN INTEGRATIVE THEME



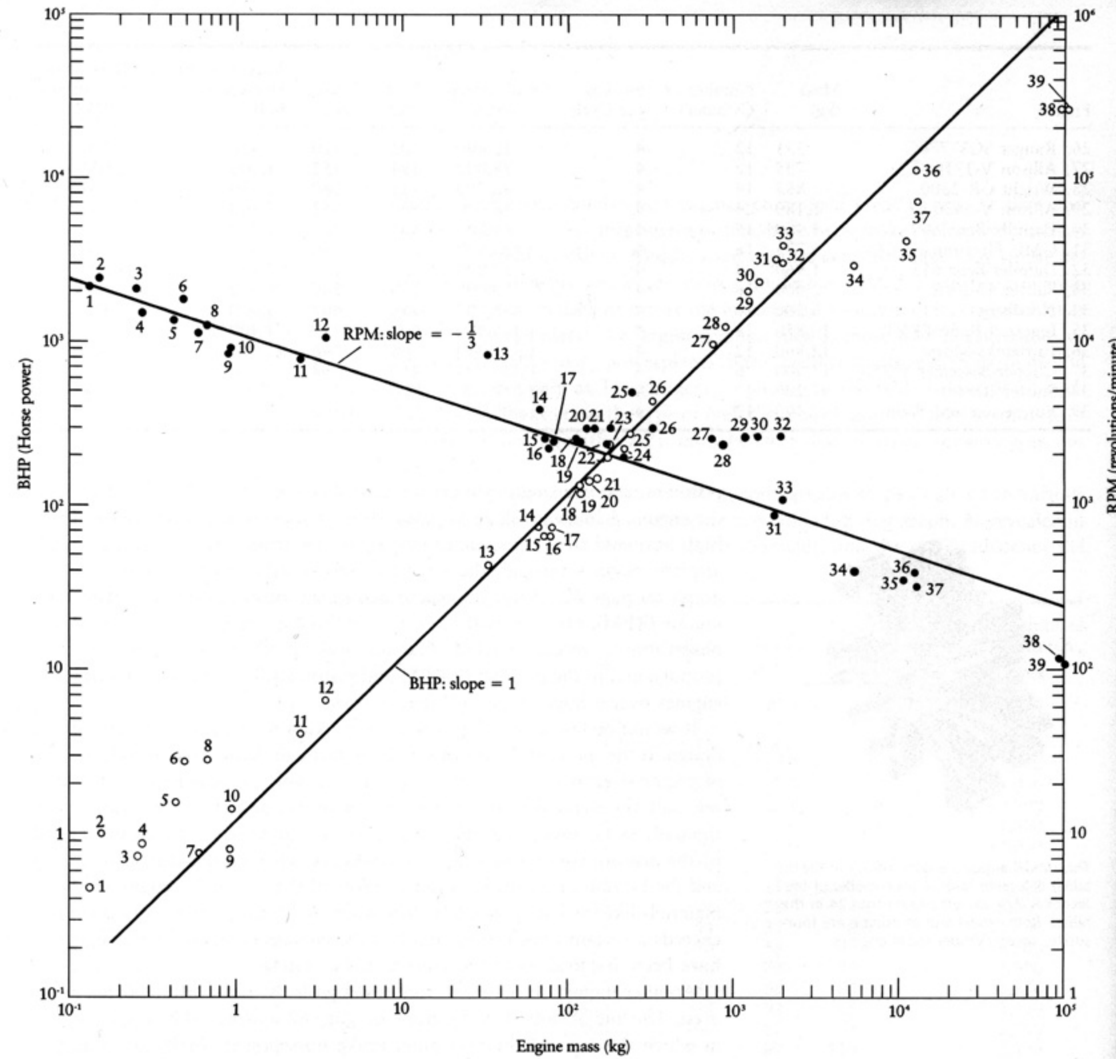
Common nails arranged by size from 60 penny (6 inches) to 2 penny (1 inch).

ALLOMETRY
AS AN INTEGRATIVE THEME

Nail diameter vs. nail length on a log–log plot, showing the allometric formula $d = 0.07l^{2/3}$. A broken line of slope 1.0, representing strict isometry, is also shown.



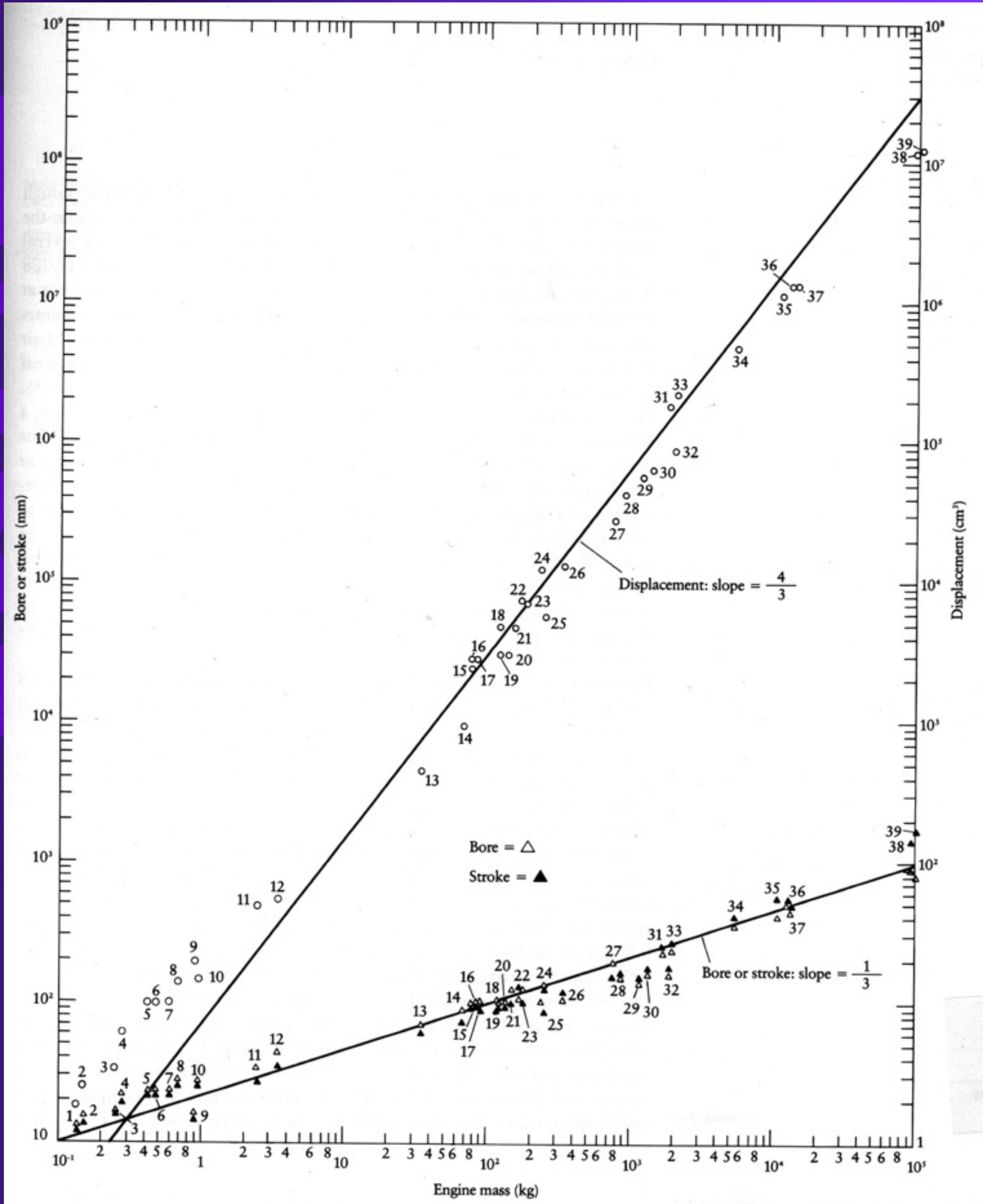
ALLOMETRY
AS AN INTEGRATIVE THEME



The allometry of internal-combustion engines. Although the number of cylinders, type of fuel, and type of ignition change with size, there are allometric relations between RPM, power, displacement, and engine mass.

power to mass constant because the requirements for a cooling apparatus are relatively more expensive, both in subtracted power and added mass, the larger the engine becomes. It is clear from the figure that nearly all the small model-airplane engines lie above the line and all the largest diesels lie below it. Part of the reason large airplanes and ships have several engines instead of one is that

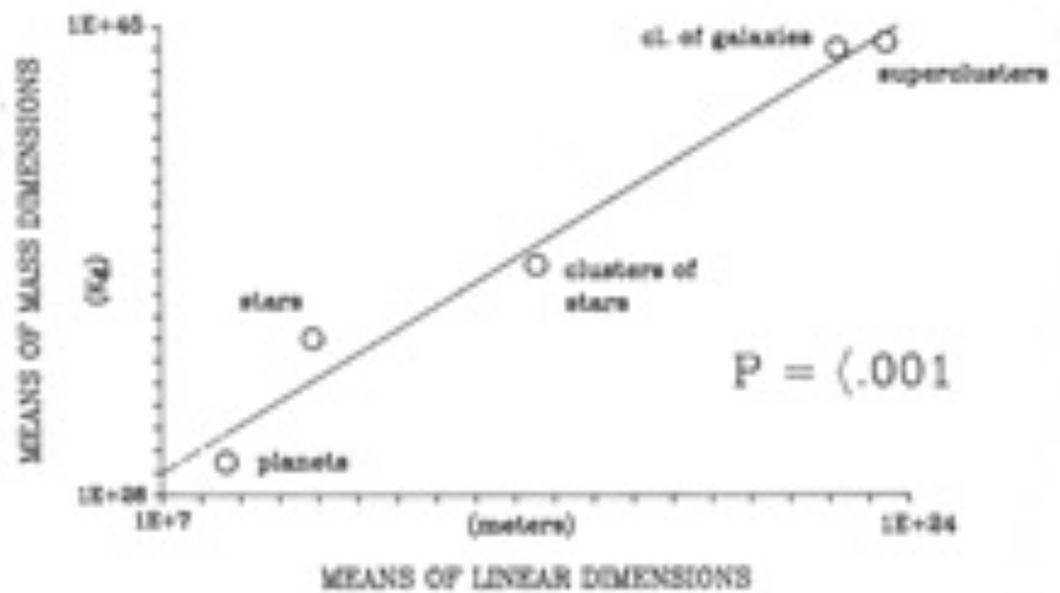
ALLOMETRY
AS AN INTEGRATIVE THEME

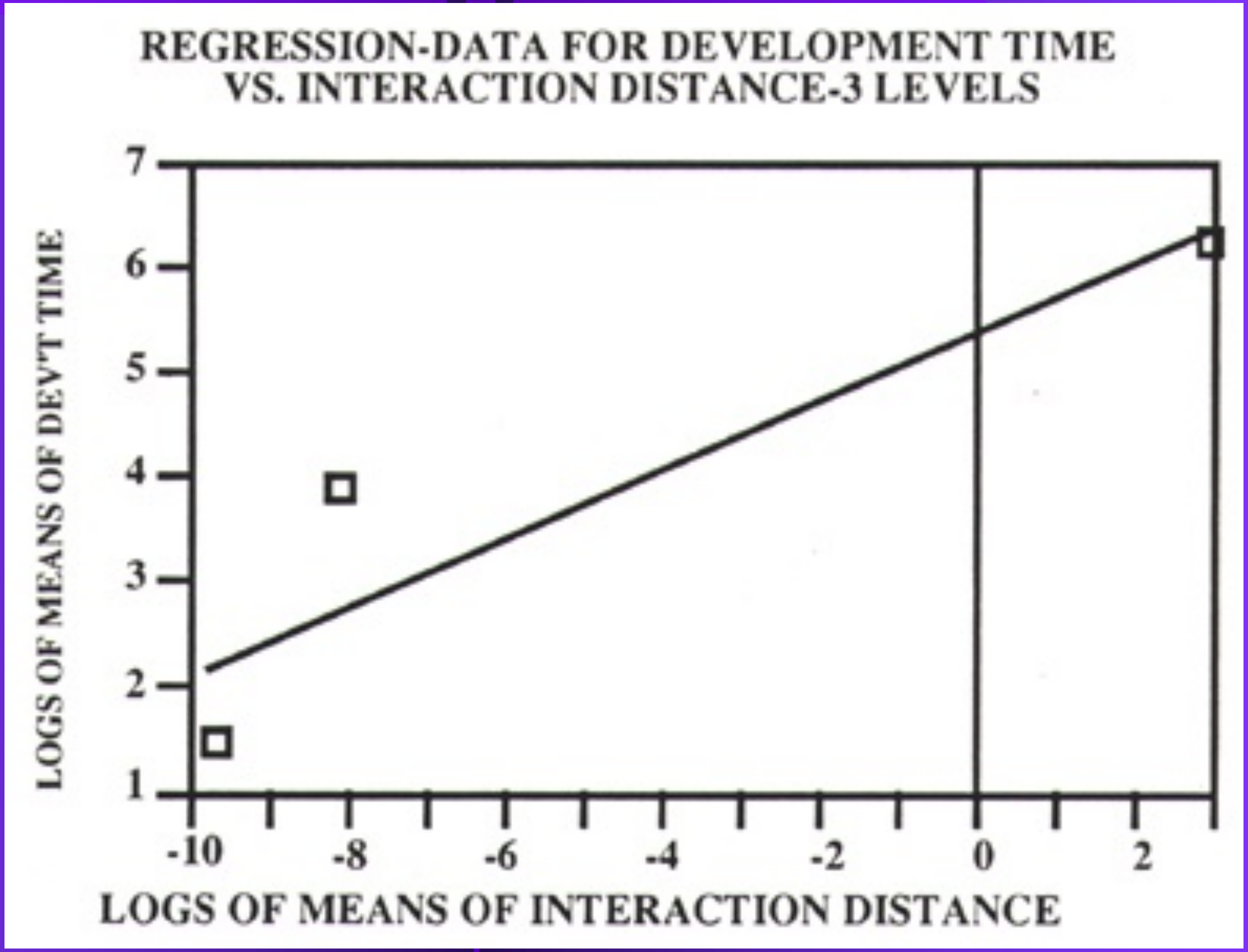


HHMI-ISGE MM MODULES

SYSTEMS ALLOMETRY

CORRELATION OF MASS VERSUS LINEAR DIMENSIONS+:
ASTRONOMICAL LEVELS – PLANETARY TO GALACTIC SUPERCLUST





REGRESSION-DATA FOR DEVELOPMENT TIME
VS. INTERACTION DISTANCE-3 LEVELS
LOGS OF MEANS OF DEV'T TIME
7
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5
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3
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1
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-8
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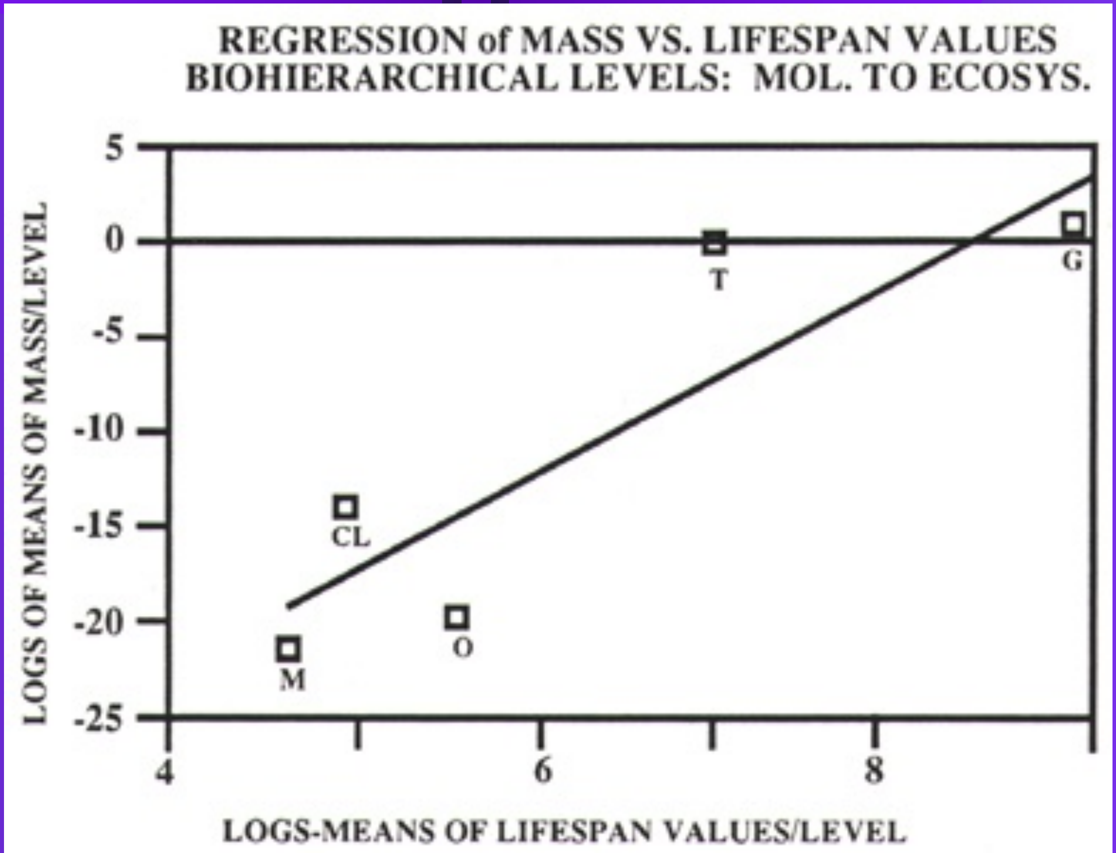
2
LOGS OF MEANS OF INTERACTION DISTANCE


REGRESSION of MASS VS. LIFESPAN VALUES
BIOHIERARCHICAL LEVELS: MOL. TO ECOSYS.
LOGS OF MEANS OF MASS/LEVEL
5
0
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-10
-15
-20
-25
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T
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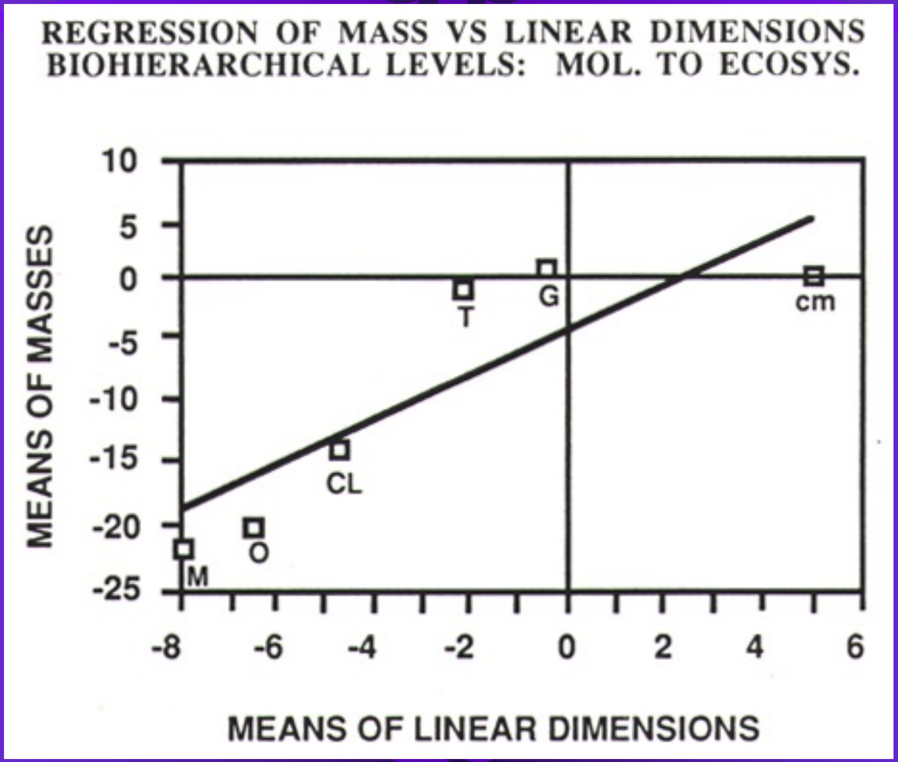
M
LOGS-MEANS OF LIFESPAN VALUES/LEVEL


REGRESSION OF MASS VS LINEAR DIMENSIONS
BIOHIERARCHICAL LEVELS: MOL. TO ECOSYS.
MEANS OF MASSES
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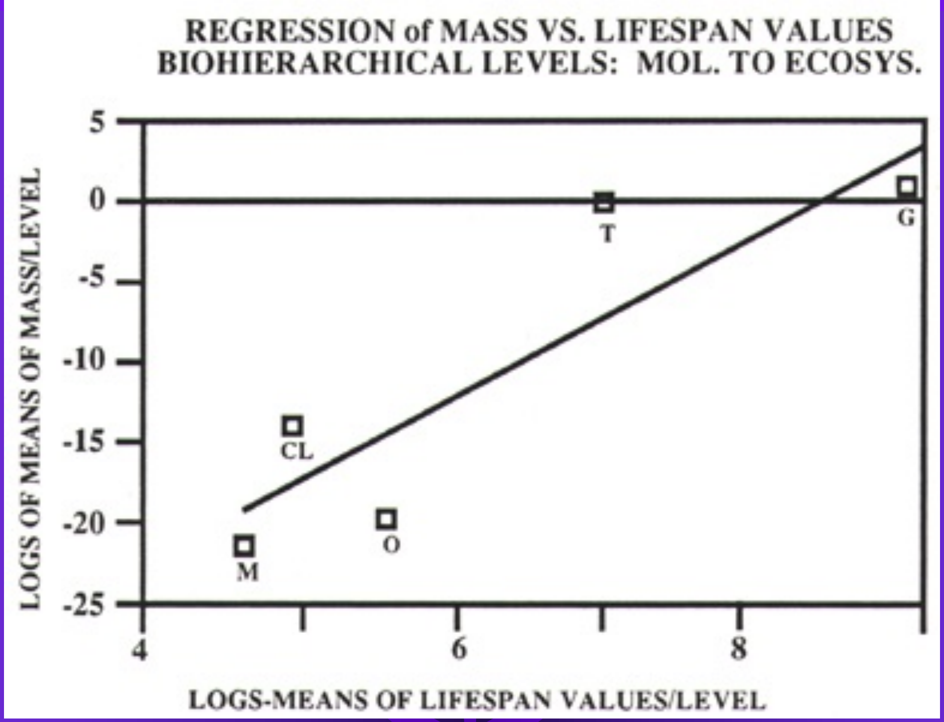
MEANS OF LINEAR DIMENSIONS


REGRESSION of MASS VS. LIFESPAN VALUES
BIOHIERARCHICAL LEVELS: MOL. TO ECOSYS.
LOGS OF MEANS OF MASS/LEVEL
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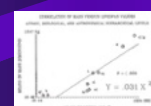
LOGS-MEANS OF LIFESPAN VALUES/LEVEL


Y = .031 X

CASE STUDIES OF ALLOMETRY

HHMI-ISGE MM MODULES

VISUAL CHOICE MATRIX

Figure 1.3. The largest land mammal that has ever lived, the *Baluchitherium,* was a relative of the modern rhinoceros. Its body weight has been estimated at about 30 tons. From Gregory (1951) with courtesy of the Library Services Department, American Museum of Natural History.

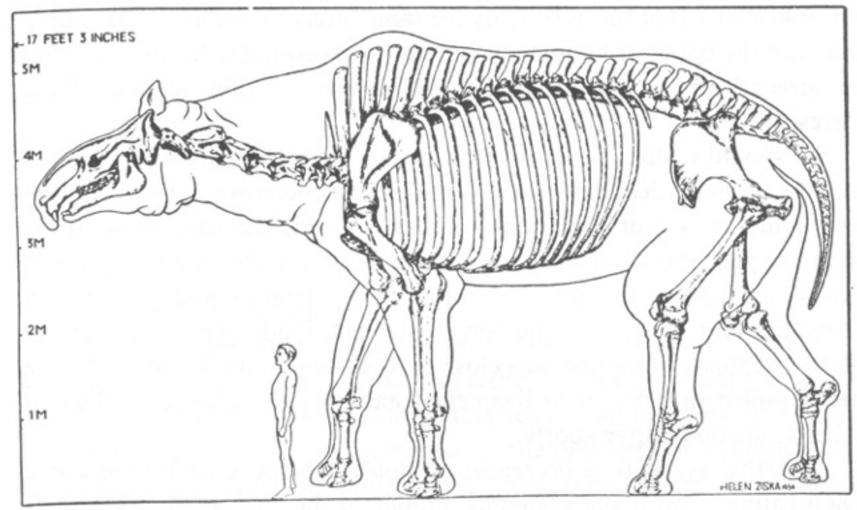
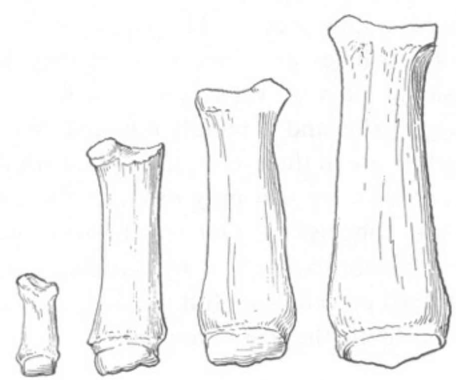


Figure 1.4. Metacarpal bones from three specimens of *Baluchitherium,* compared with the same bone from a modern rhinoceros (far left). The compressive strength of the largest metacarpal would have been about 280 tons, or nearly 10 times the body weight of the animal. From Gregory (1951) with courtesy of the Library Services Department, American Museum of Natural History.



ALLOMETRY
AS AN INTEGRATIVE THEME

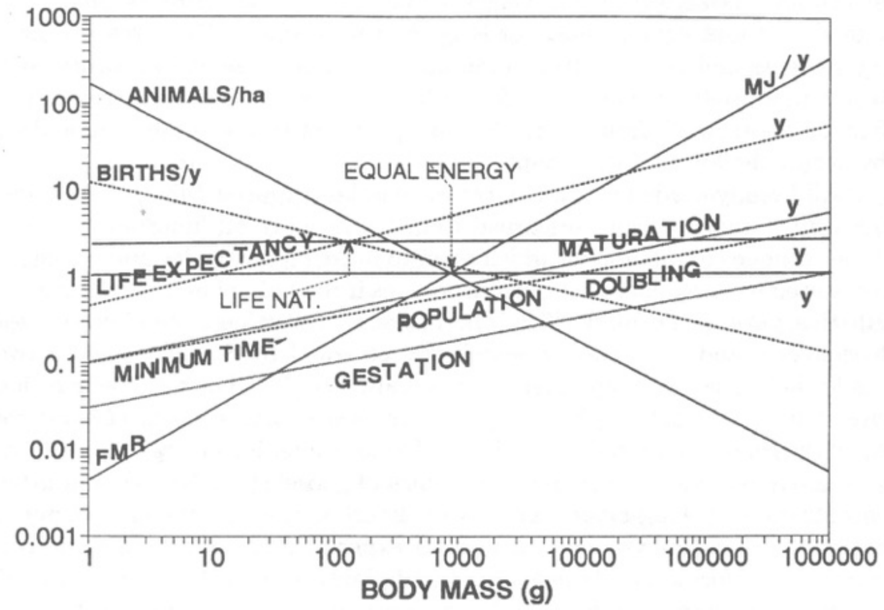
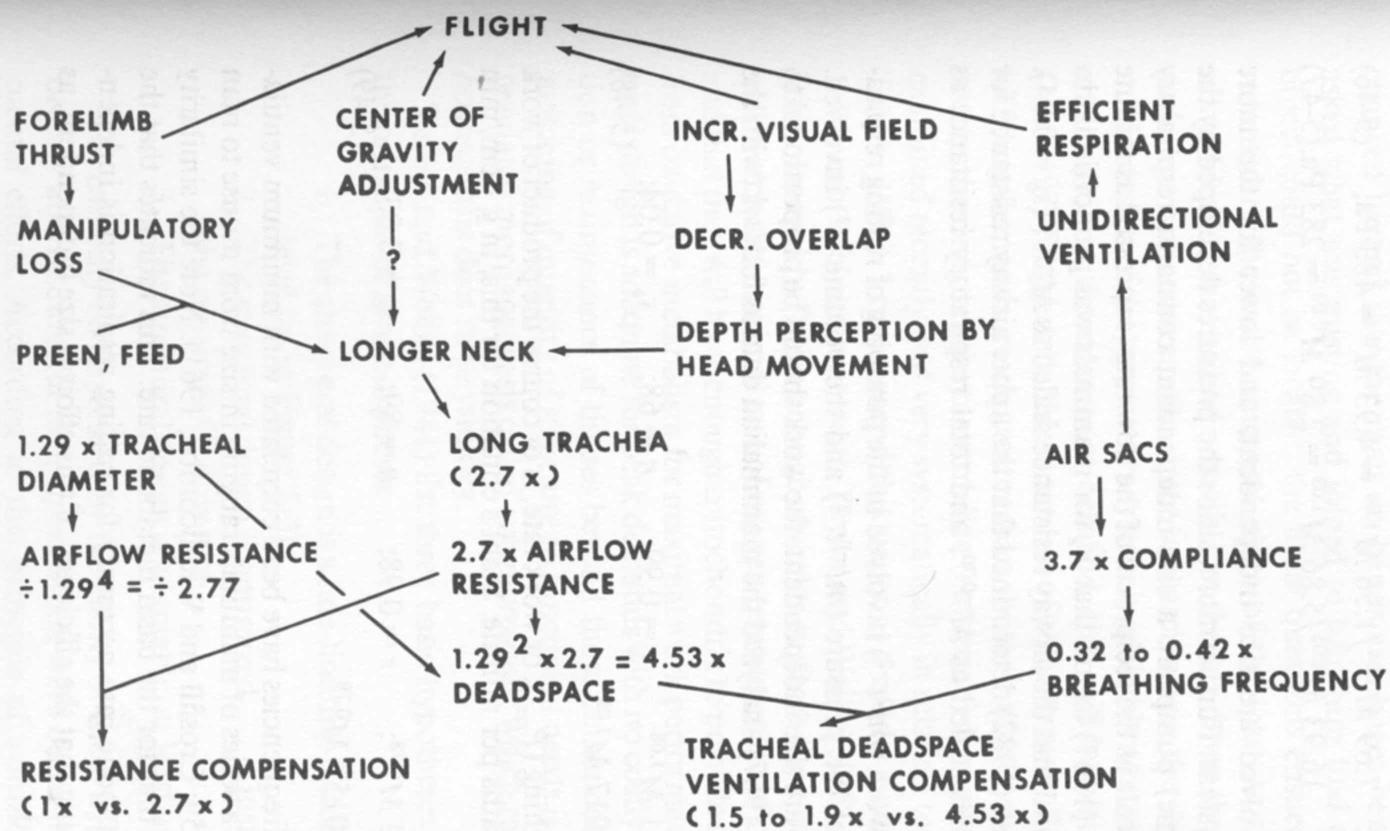


FIGURE 1 Sample empirical size regressions of primary consumer mammals. "Energy equivalence" is seen if the product of density per species (animals/ha) [28] times field metabolic rate (FMR) is size-independent, $M^{-3/4} \times M^{3/4} = M^0$. This essentially size-independent product is the upper bound of population metabolism at a level approximated by the crossing of FMR and density, FMR increase countering density increase, and vice versa). For replacement, annual fecundity times percent survival to reproduction times life expectancy should be 2 per monogamous pair (note that the regressions cross at ~ 2.5 "LIFE NAT").

ALLOMETRY
AS AN INTEGRATIVE THEME



5-2 An adaptive suite of characteristics for respiratory morphology and mechanics and the evolution of flight. Numbers are ratios of allometric coefficients (a_{bird}/a_{mammal} in $Y = aM^b$) for birds and mammals. The scaling exponents are roughly similar for the two classes. Given a longer neck, a longer trachea is needed, increasing the resistance to airflow. The tracheal diameters are also larger, compared to mammals, giving a compensatory reduction in airflow resistance. Assuming laminar airflow in the trachea, the resistance is decreased in proportion to the fourth power of the diameter increase. However, increases in both the length and diameter increase the deadspace volume of the trachea. Compared to mammals, birds breathe deeper tidal volumes at slower respiratory frequencies, thereby reducing the proportional dilution of the deadspace ventilation to 2.2 vs. 4.32-fold dilution. (From Hinds and Calder, *Evolution* 25:347, © 1971).

ALLOMETRY
AS AN INTEGRATIVE THEME

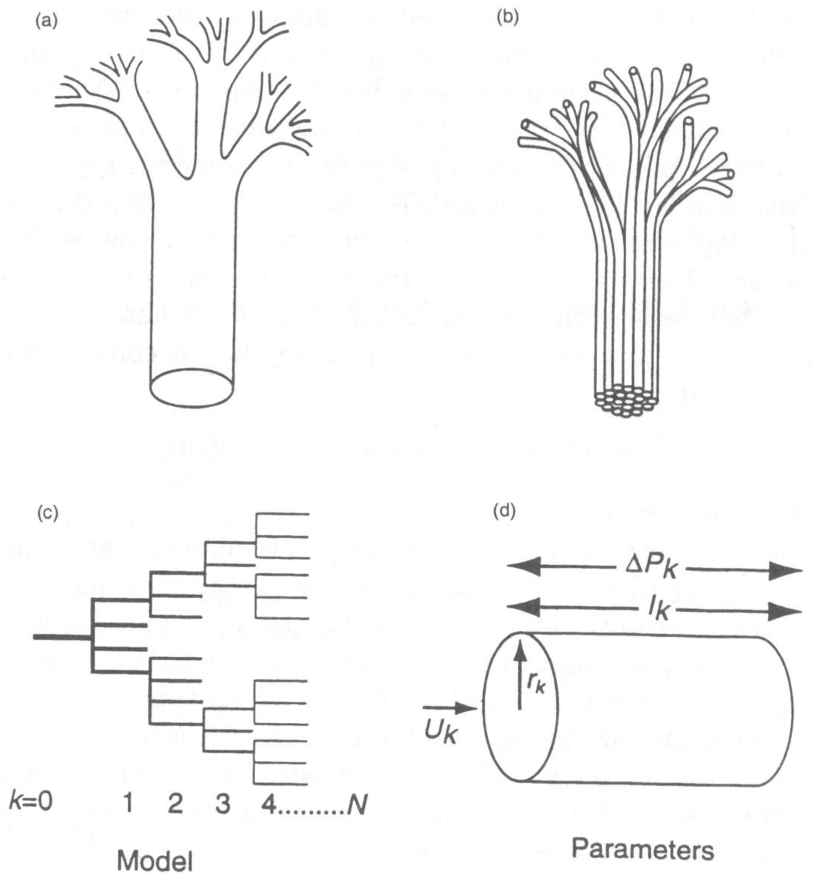
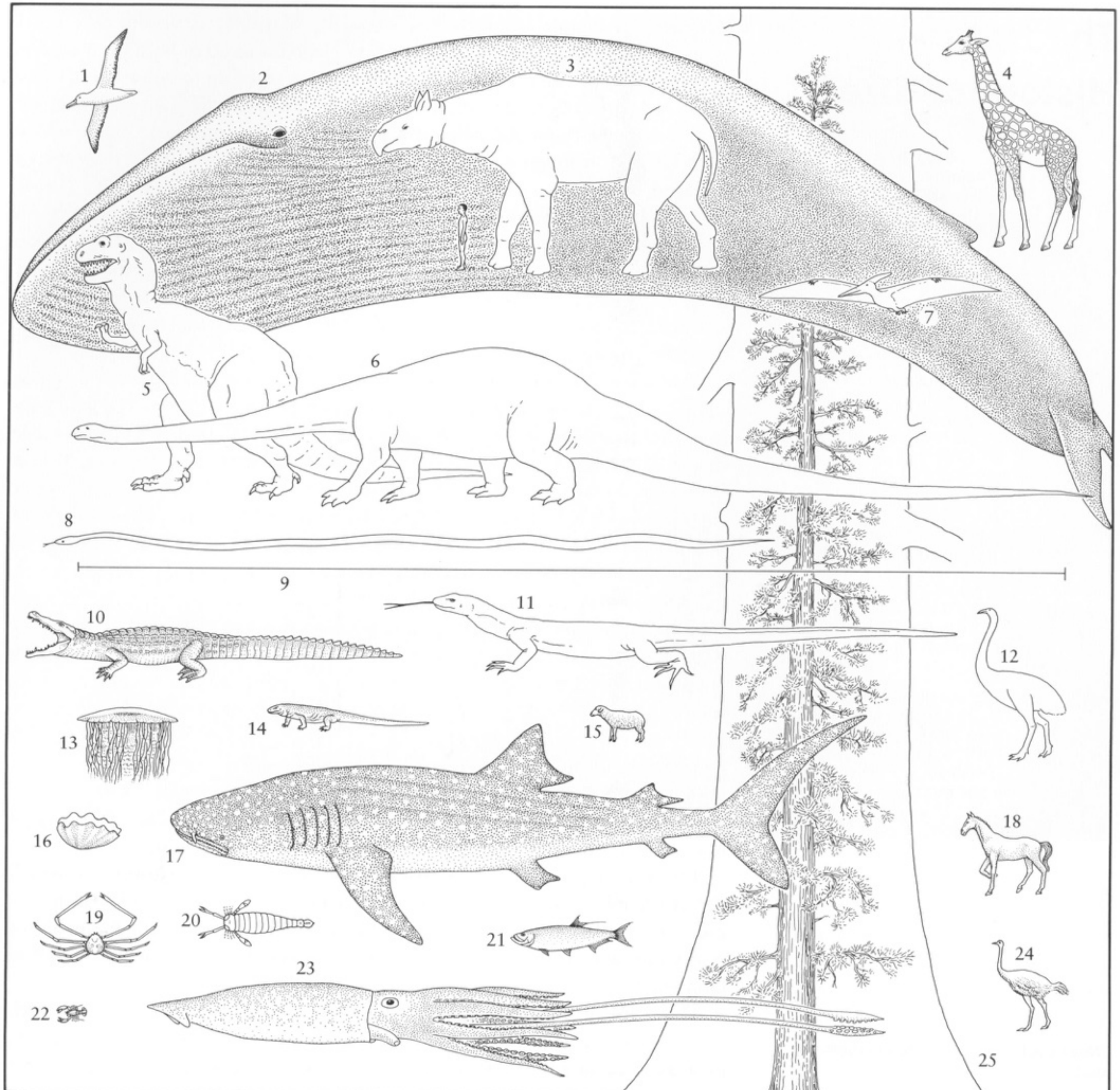


FIGURE 4 Diagrammatic examples of segments of biological distribution networks: (a) mammalian circulatory and respiratory systems comprised of branching tubes; (b) plant vessel-bundle vascular system comprised of diverging vessel elements (the "pipe model"); (c) topological representation of such networks, where k specifies the order of the level, beginning with the aorta ($k = 0$) and ending with the capillary ($k = N$); and (d) parameters of a typical tube at the kth level.

ALLOMETRY
AS AN INTEGRATIVE THEME

Table 14-1 Some scalings that approximate the cube root.

Function	Scaling
Gut beat duration	$\propto M^{0.31}$
Respiration cycle duration (nonpasserine birds)	$\propto M^{0.31}$
Plasma albumen half-life (mammals)	$\propto M^{0.32}$
Wingbeat period (birds)	$\propto M^{0.38}$
Cooling time, 1°C drop (mammals)	$\propto M^{0.35}$
Euthermic interruption of mammalian hibernation	$\propto M^{0.32}$
Postembryonic doubling of mass (birds)	$\propto M^{0.34}$
Minimum time for population doubling (mammals, derived from Caughley and Krebs, 1983)	$\propto M^{0.36}$
Standing crop turnover time (mammals, according to Banse and Mosher, 1980)	$\propto M^{0.32}$
Time to puberty (mammals)	$\propto M^{0.30}$
Life expectancy, 1 in 1,000 (mammals)	$\propto M^{0.32}$
Minimum time difference between sound arrival at each ear (mammals)	$\propto M^{0.30}$
Time to metabolize 1% of body mass as fat at estimated field metabolic rate	$\propto M^{0.33}$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ALLOMETRY
AS AN INTEGRATIVE THEME

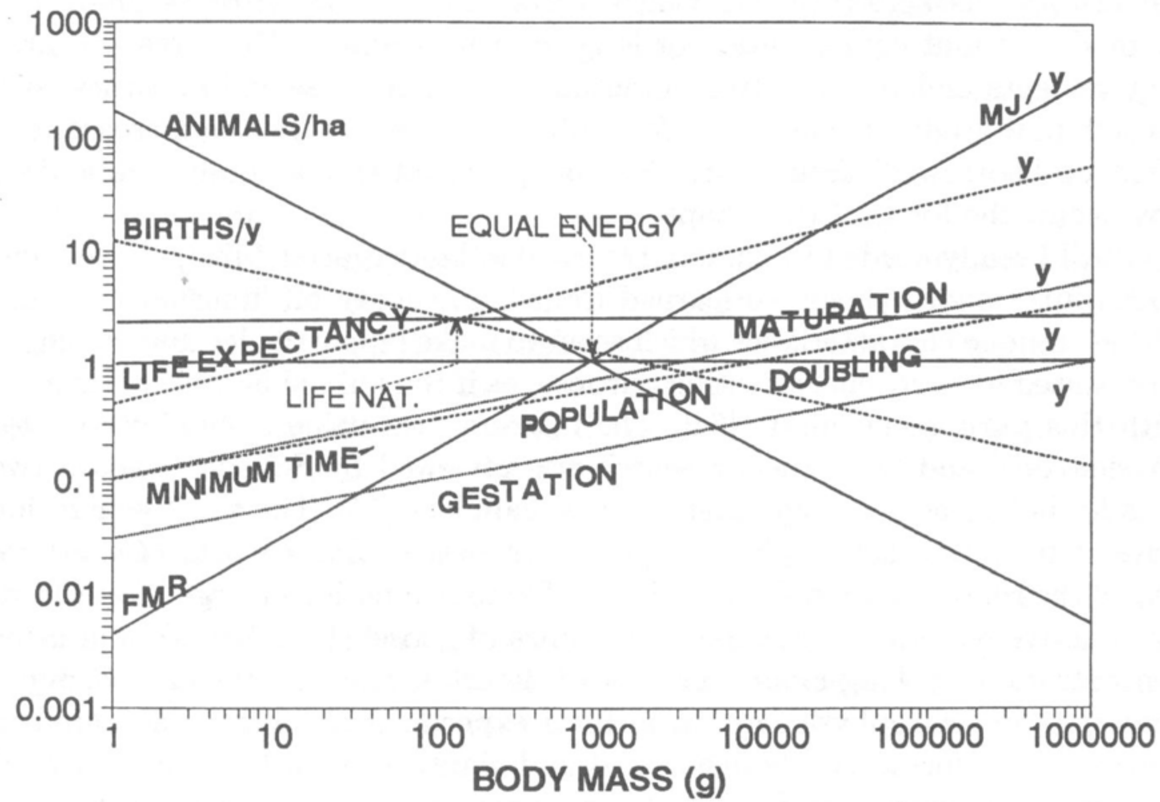


FIGURE 1 Sample empirical size regressions of primary consumer mammals. "Energy equivalence" is seen if the product of density per species (animals/ha) [28] times field metabolic rate (FMR) is size-independent, $M^{-3/4} \times M^{3/4} = M^0$. This essentially size-independent product is the upper bound of population metabolism at a level approximated by the crossing of FMR and density, FMR increase countering density increase, and vice versa). For replacement, annual fecundity times percent survival to reproduction times life expectancy should be 2 per monogamous pair (note that the regressions cross at ~ 2.5 "LIFE NAT").

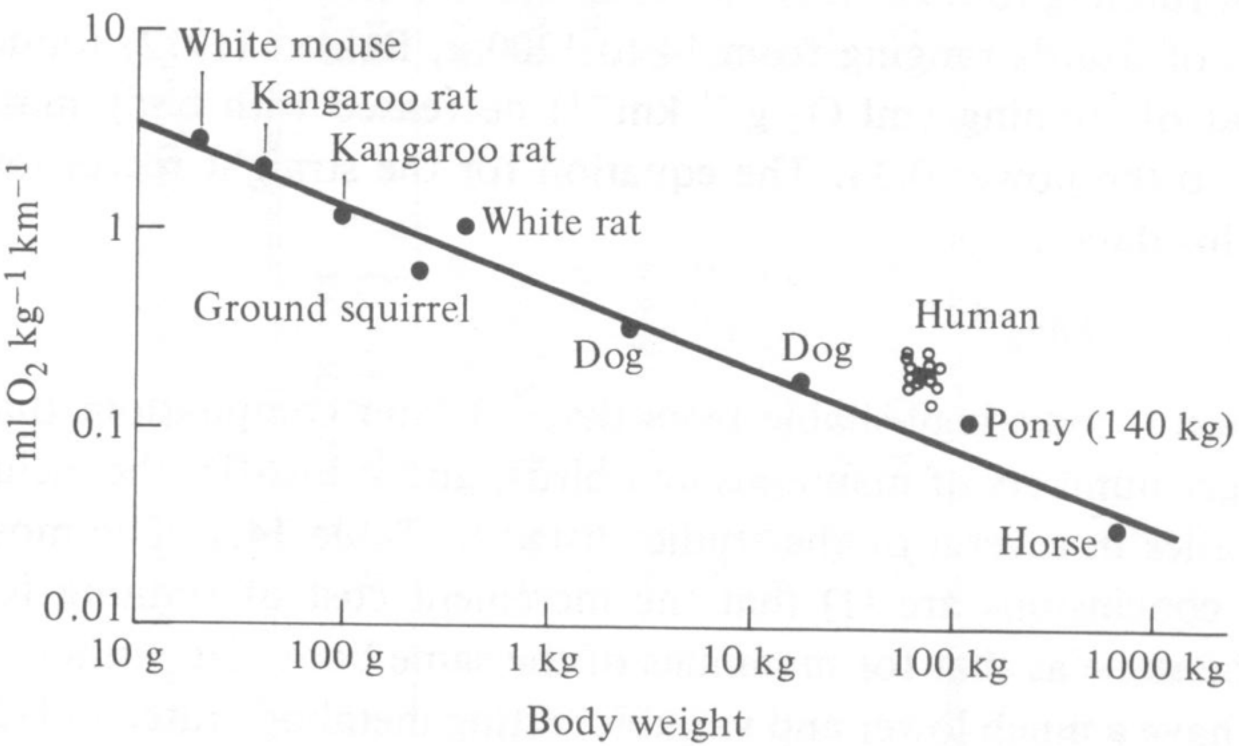
ALLOMETRY
AS AN INTEGRATIVE THEME

TABLE 2 Values of allometric exponents for variables of the mammalian respiratory system predicted by the model compared with empirical observations.

VARIABLE Respiratory	SCALING EXPONENT Predicted	Observed	REFERENCE
Lung Volume	$1 = 1.00$	1.05	Weibel [40]
Respiratory Frequency	$-1/4 = -0.25$	−0.26	Stahl [33]
Volume Flow to Lung	$3/4 = 0.75$	0.80	Stahl [33]
Interpleural Pressure	$0 = 0.00$	0.004	Gunther & de la Barra [11]
Diameter of Trachea	$3/8 = 0.375$	0.39	Tenney & Bartlett [36] and pers. comm. in Calder [2]
Air Velocity in Trachea	$0 = 0.00$	0.02	Calder (calculated) [2]
Tidal Volume	$1 = 1.00$	1.041	Maina & Settle [18]
Power Dissipated	$3/4 = 0.75$	0.78	Stahl [33]
Number of Alveoli, N_A	$3/4 = 0.75$	ND	–
Volume of Alveolus, V_A	$1/4 = 0.25$	ND	–
Radius of Alveolus, r_A	$1/12 = 0.083$	0.13	Tenney & Remmers [37]
Surface Area of Alveolus, A_A	$1/6 = 0.083$	ND	–
Surface Area of Lung, A_L	$11/12 = 0.92$	0.95	Gehr et al. [8]
Oxygen Diffusing Capacity	$1 = 1.00$	0.99	Gehr et al. [8]
Total Airway Resistance	$-3/4 = -0.75$	−0.70	Stahl [33]
Oxygen Consumption Rate	$3/4 = 0.75$	0.76	Stahl [33]

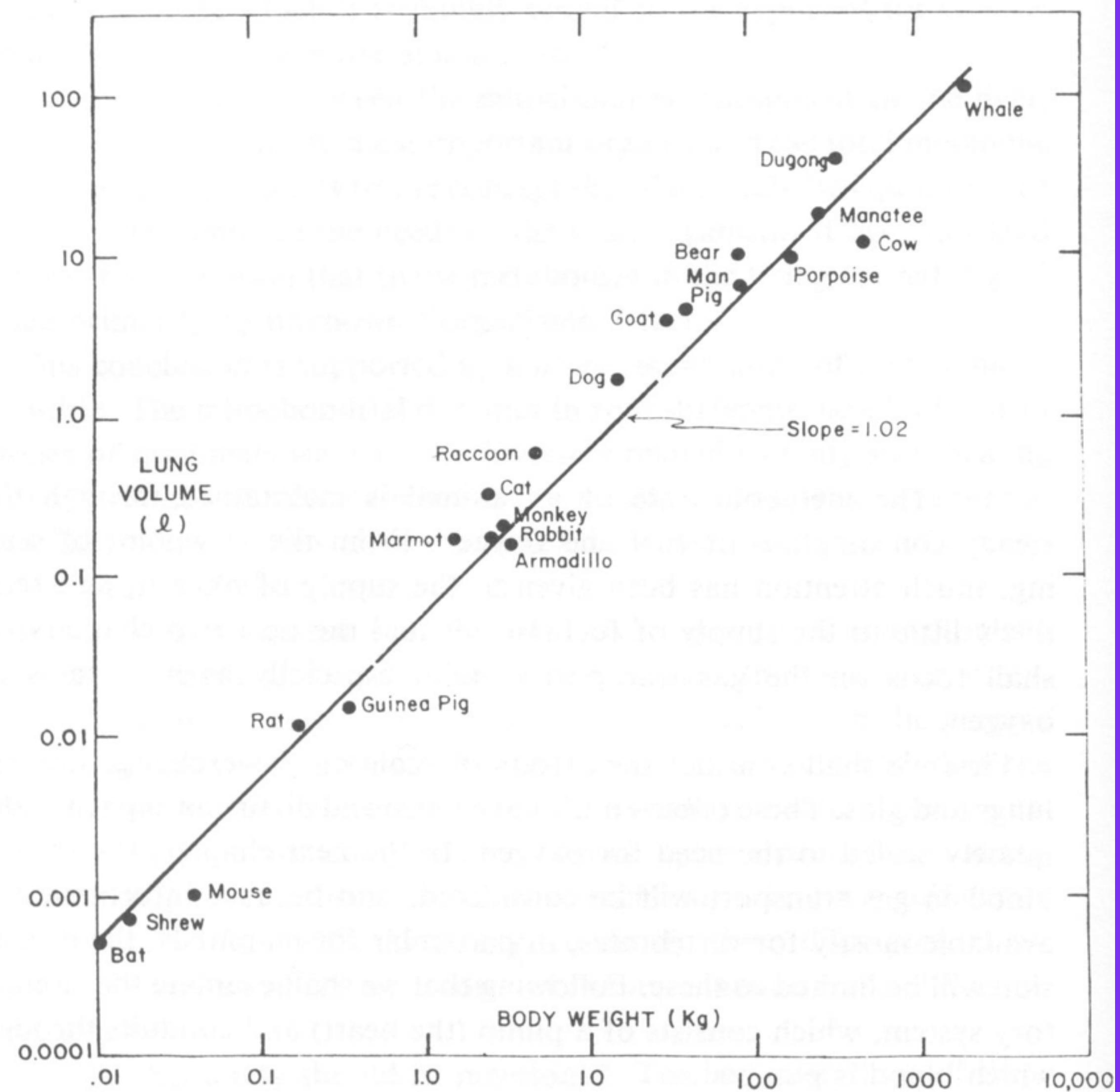
ALLOMETRY
AS AN INTEGRATIVE THEME

Figure 14.2. The cost of running, expressed as the oxygen needed to transport 1 kg of body weight over 1 km, decreases regularly with increasing body size. Data for man (bipedal running) fall above the line representing data for mammals running on all four legs. From Taylor et al. (1970).



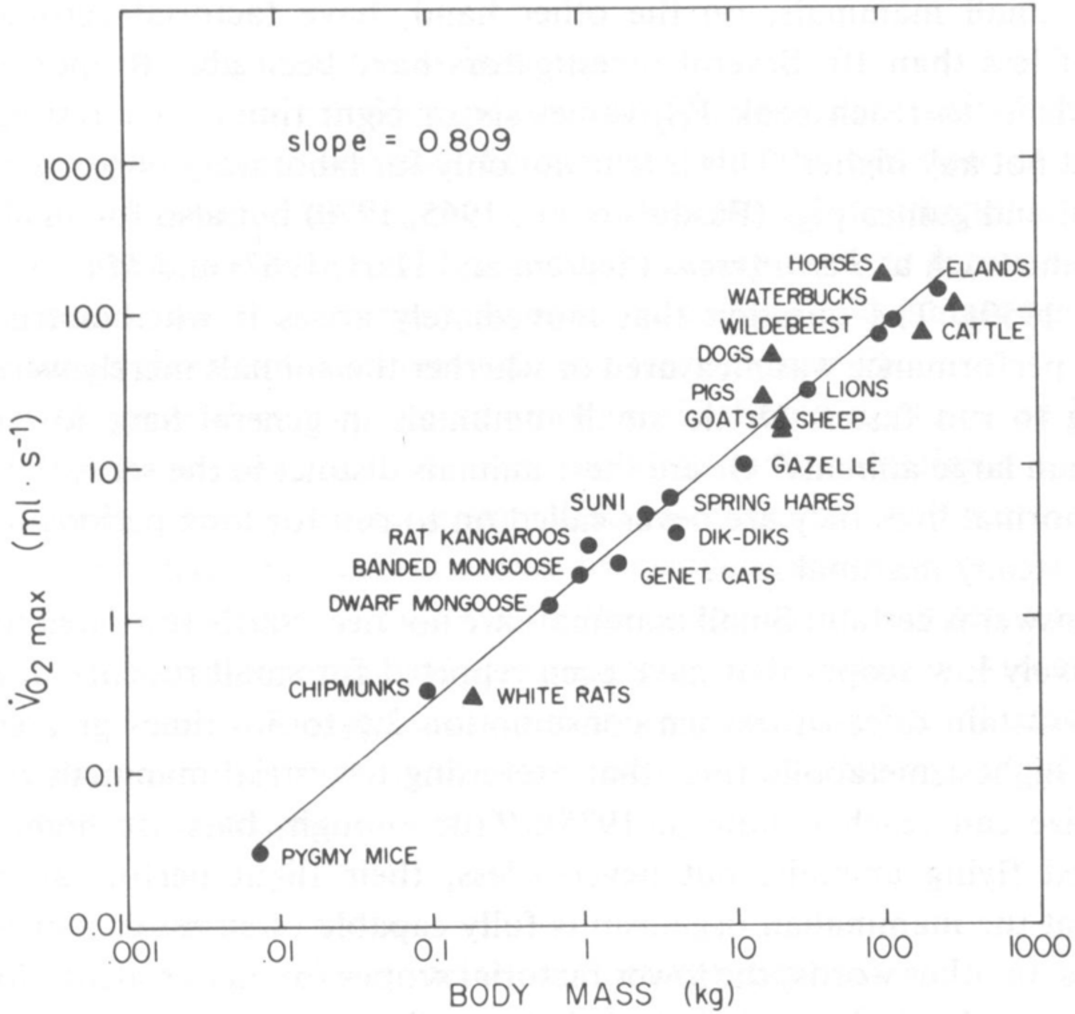
ALLOMETRY
AS AN INTEGRATIVE THEME

Figure 9.1. Logarithmic plot of lung volume as a function of body size. From Tenney and Remmers (1963).

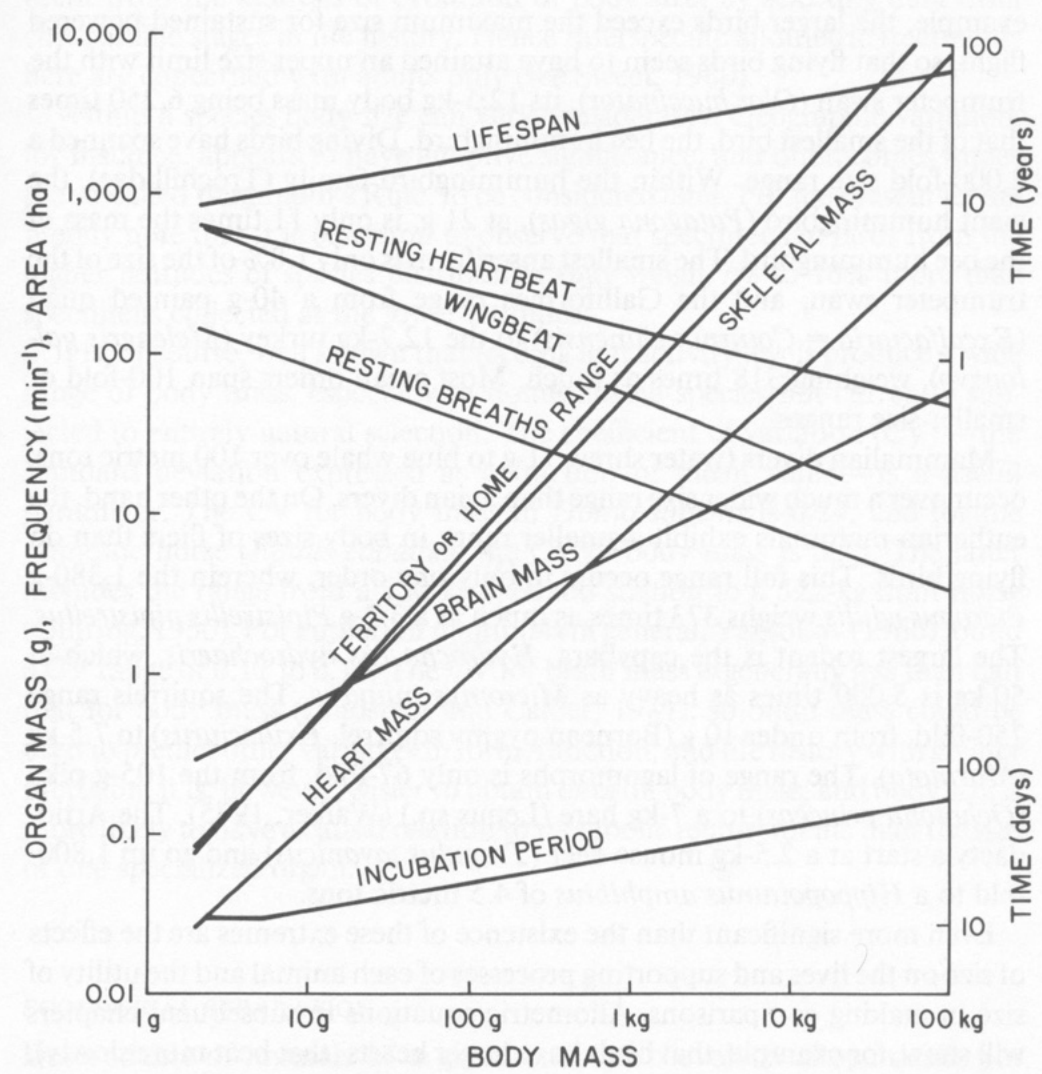


ALLOMETRY
AS AN INTEGRATIVE THEME

Figure 13.1. Maximal rates of oxygen consumption during running for 22 species of African mammals, ranging from 0.007 to 263 kg. From Taylor et al. (1981).

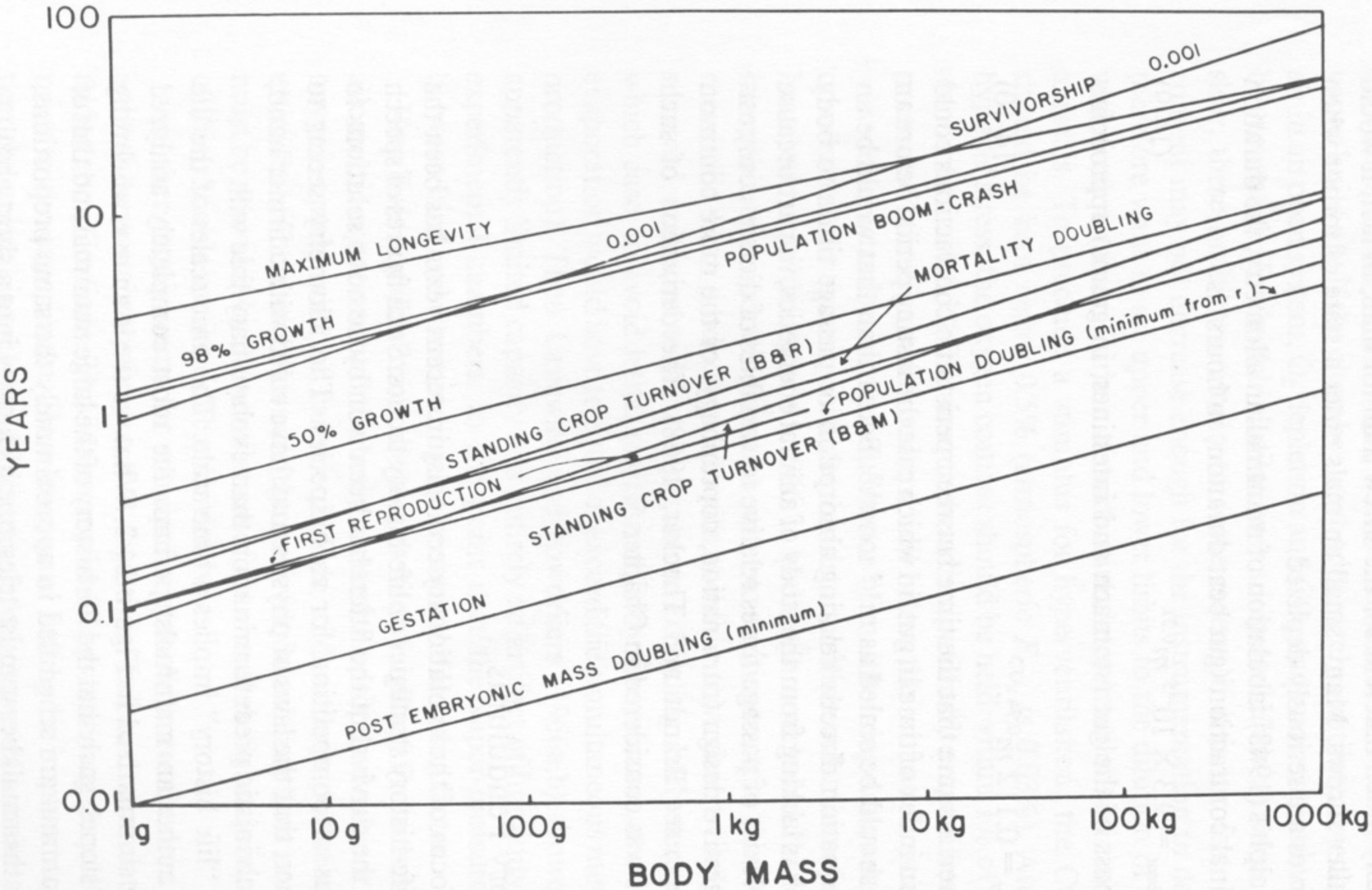


ALLOMETRY
AS AN INTEGRATIVE THEME



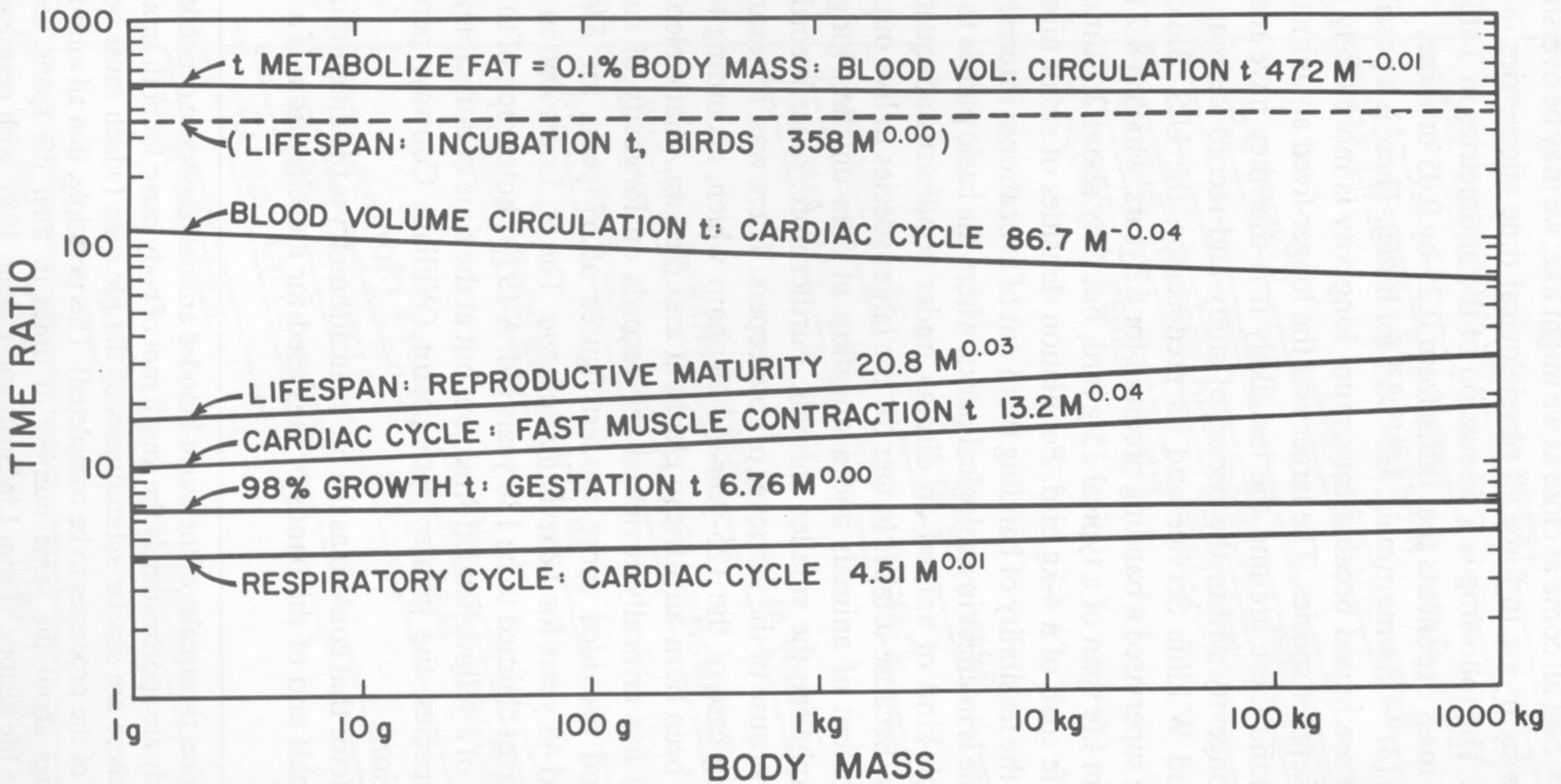
1-1 A sampler of the allometry of birds. None of the changes required for larger or smaller size is exactly proportional to the body-mass change, so the scaling involved in evolutionary size change is no simple matter.

ALLOMETRY
AS AN INTEGRATIVE THEME



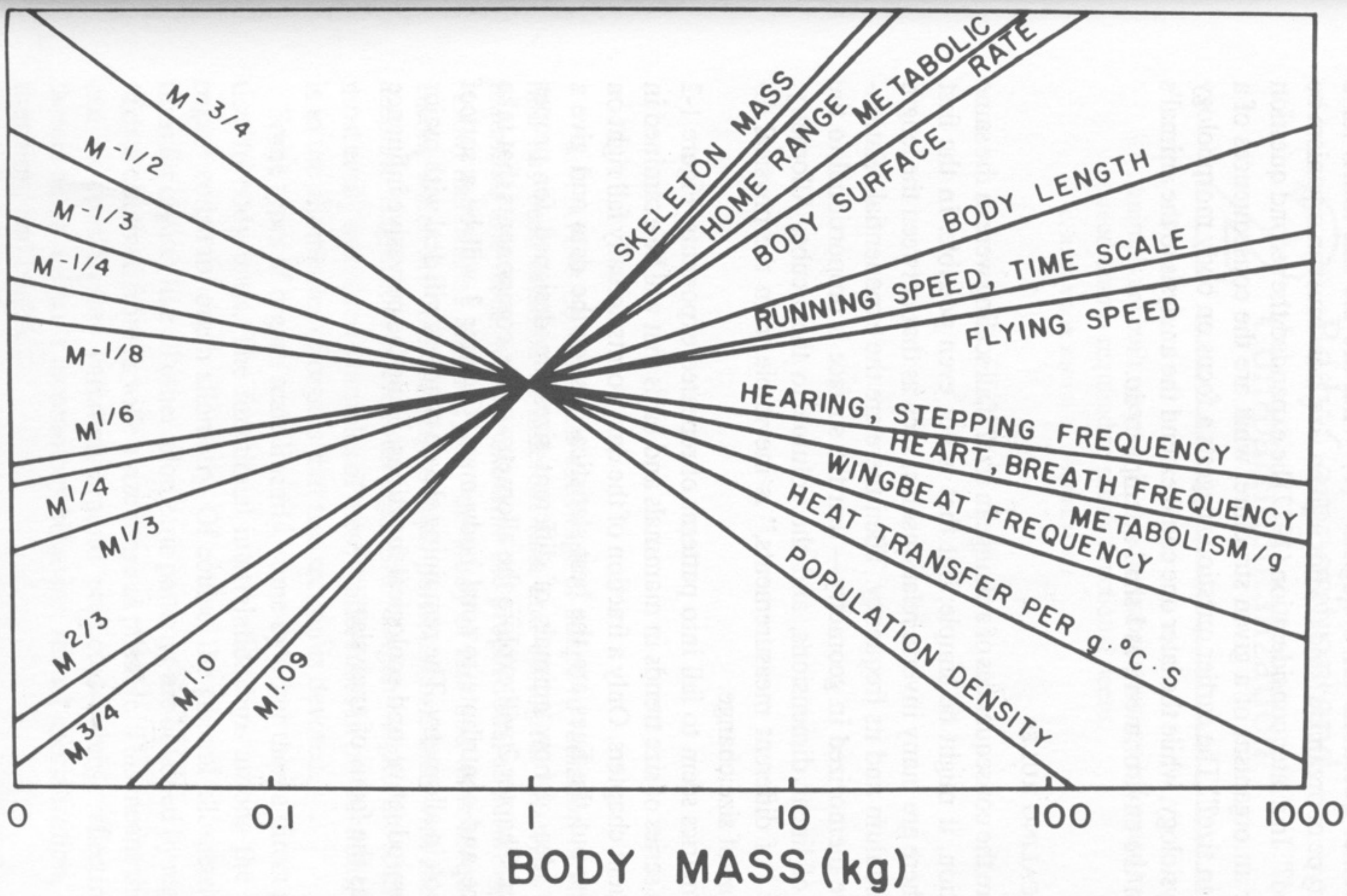
14-2 An allometric summary of the life histories of eutherian mammals, based on equations given in previous chapters. Many of these relationships need fine-tuning with more extensive data bases, but the overall pattern is clear: the quantitative details of life histories are largely a matter of size and the pace of life that the size determines. Survivorship of 0.001 of the original adult cohort and t_{sc} derived from Banse and Mosher, 1980 (B & M), have the largest scaling exponents (0.32, 0.33), compared to maximum longevity (0.20) and t_{sc} derived from Beland and Russell, 1980 (B & R; 0.29).

ALLOMETRY
AS AN INTEGRATIVE THEME



6-2 Ratios of the allometries of various physiological time scales are essentially size independent. This means that the life spans are similarly proportioned, and that physiology can be described by the dimensionless "design criteria" of Stahl (1962). (From Lindstedt and Calder, 1981; with permission of the *Quarterly Review of Biology*.)

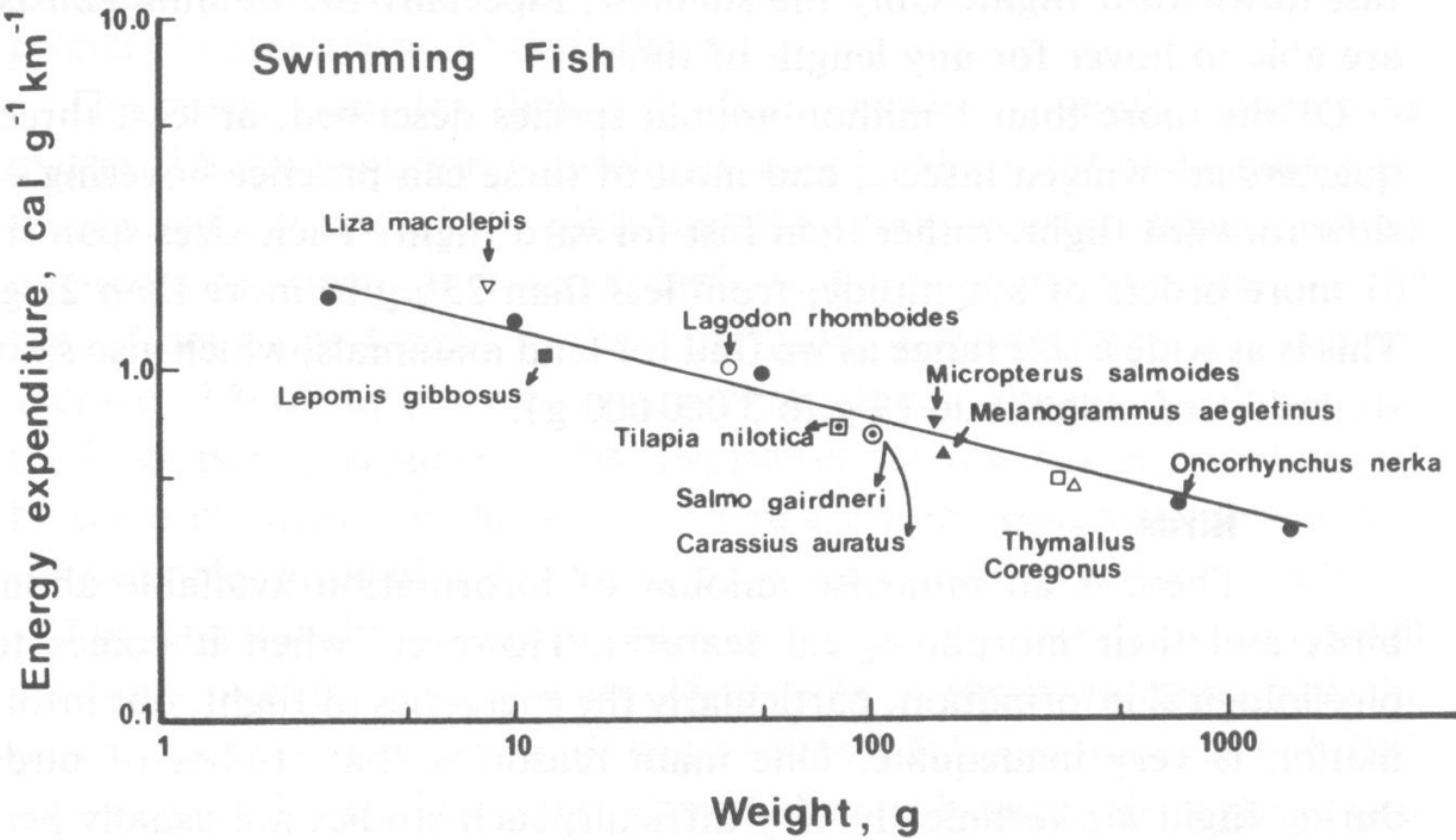
ALLOMETRY
AS AN INTEGRATIVE THEME



1-2 Some allometric generalizations, mostly for eutherian mammals. When plotted on log-log paper, the fractional exponential powers of body mass appear as the slopes of the lines. For example, body surfaces of animals, like surface areas of geometric figures, are proportional to volume (or mass, assuming constant density) raised to the ⅔ power. On the log-log plot the ⅔ becomes the slope, that is, an increase of 10^2 in surface when mass increases by a factor of 10^3. (Adapted from Zar, 1968a; Calder, 1974; and Bartholomew, 1982.)

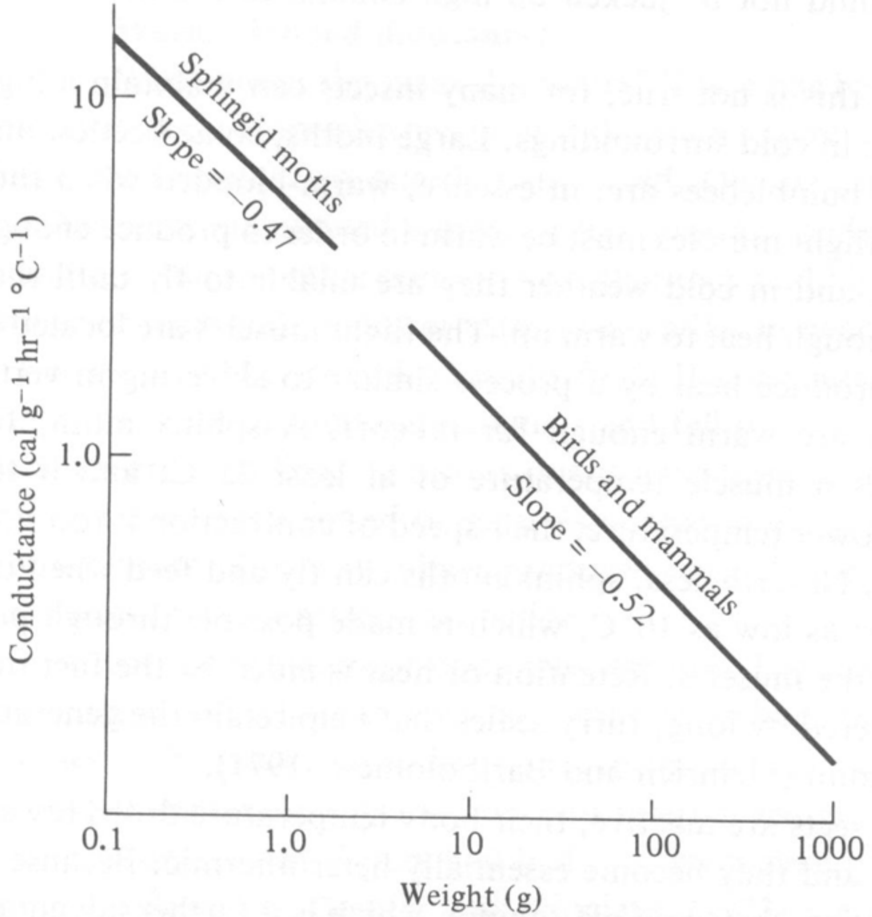
ALLOMETRY
AS AN INTEGRATIVE THEME

Figure 15.3. Energy cost of swimming relative to body size for a variety of fish, as reported by Beamish (1978).



ALLOMETRY AS AN INTEGRATIVE THEME

Figure 16.1. Specific thermal conductances for large sphingid moths and for birds and mammals. The slope of the regression line for moths is within the confidence limits of the bird-plus-mammal line, and the intercepts at unity body mass are identical for the two lines. Note that the apparently steep slopes of the lines are caused by the different scales on the two axes. From Bartholomew and Epting (1975).



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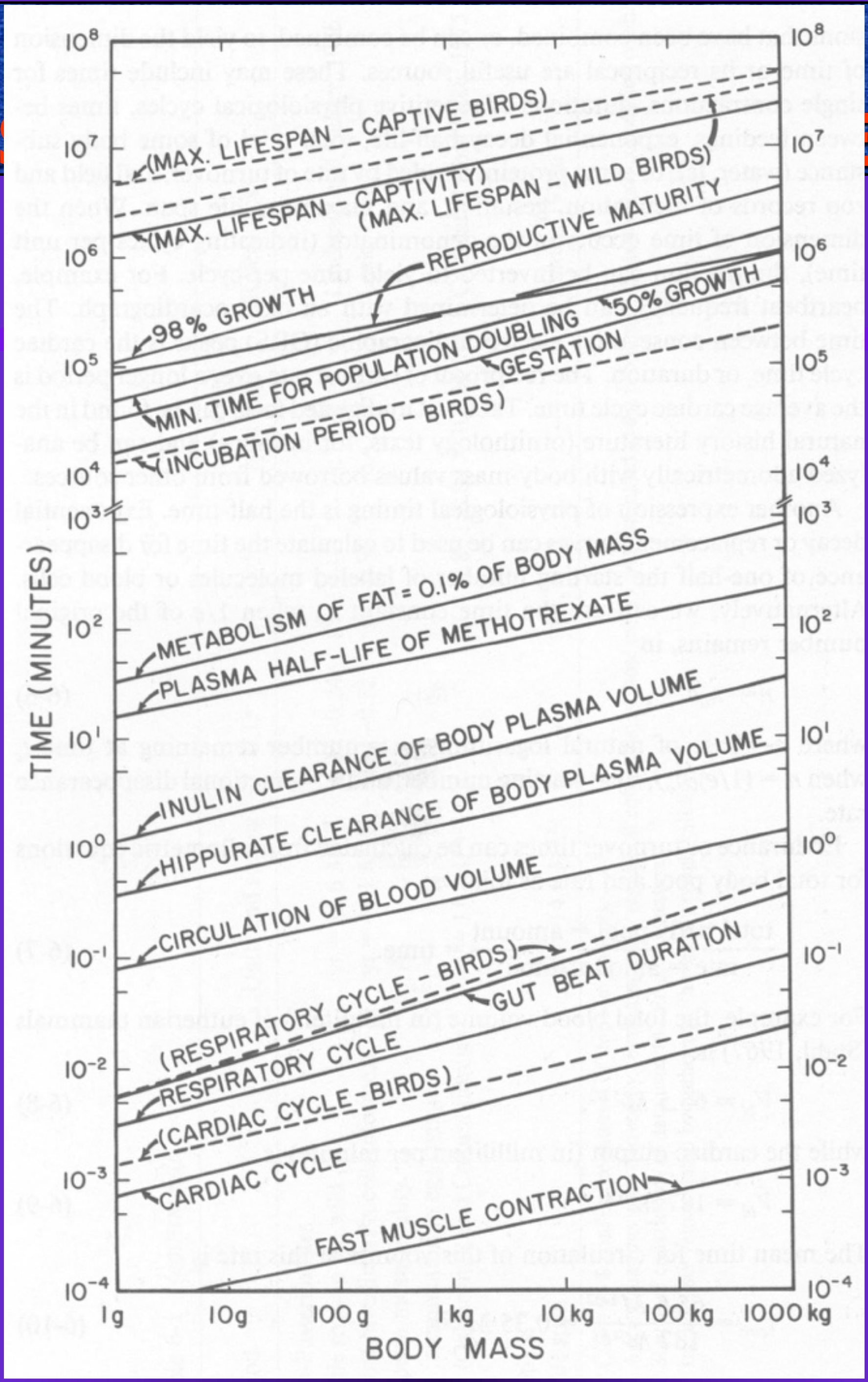
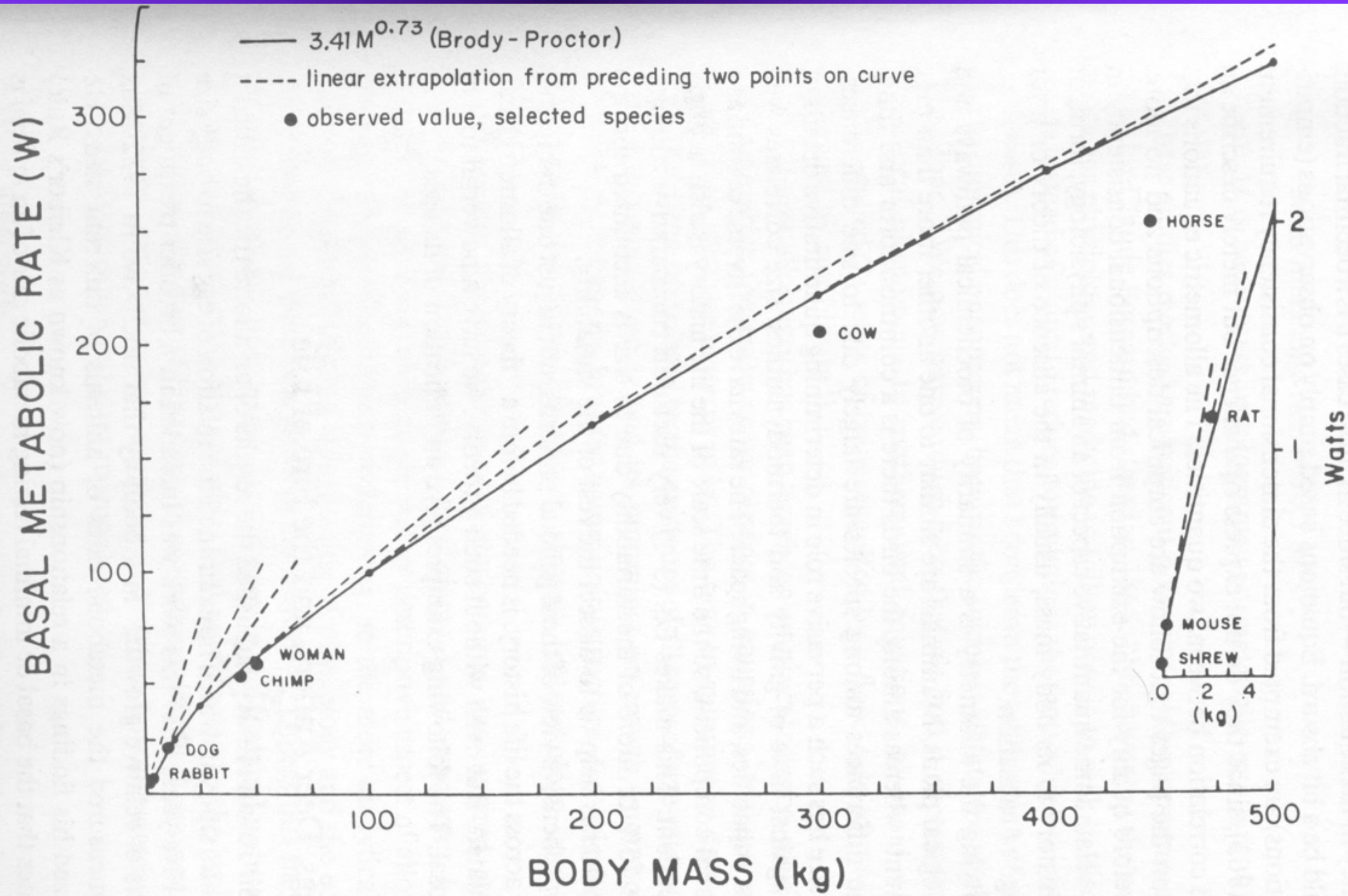


TIME (MINUTES)
BODY MASS
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1g
10g
100g
1kg
10kg
100kg
1000kg
(MAX. LIFESPAN - CAPTIVE BIRDS)
(MAX. LIFESPAN - WILD BIRDS)
(MAX. LIFESPAN - CAPTIVITY)
REPRODUCTIVE MATURITY
98% GROWTH
50% GROWTH
MIN. TIME FOR POPULATION DOUBLING
GESTATION
(INCUBATION PERIOD - BIRDS)
METABOLISM OF FAT = 0.1% OF BODY MASS
PLASMA HALF-LIFE OF METHOTREXATE
INULIN CLEARANCE OF BODY PLASMA VOLUME
HIPPURATE CLEARANCE OF BODY PLASMA VOLUME
CIRCULATION OF BLOOD VOLUME
(RESPIRATORY CYCLE - BIRDS)
GUT BEAT DURATION
RESPIRATORY CYCLE
(CARDIAC CYCLE - BIRDS)
CARDIAC CYCLE
FAST MUSCLE CONTRACTION

ALLOMETRY
AS AN INTEGRATIVE THEME

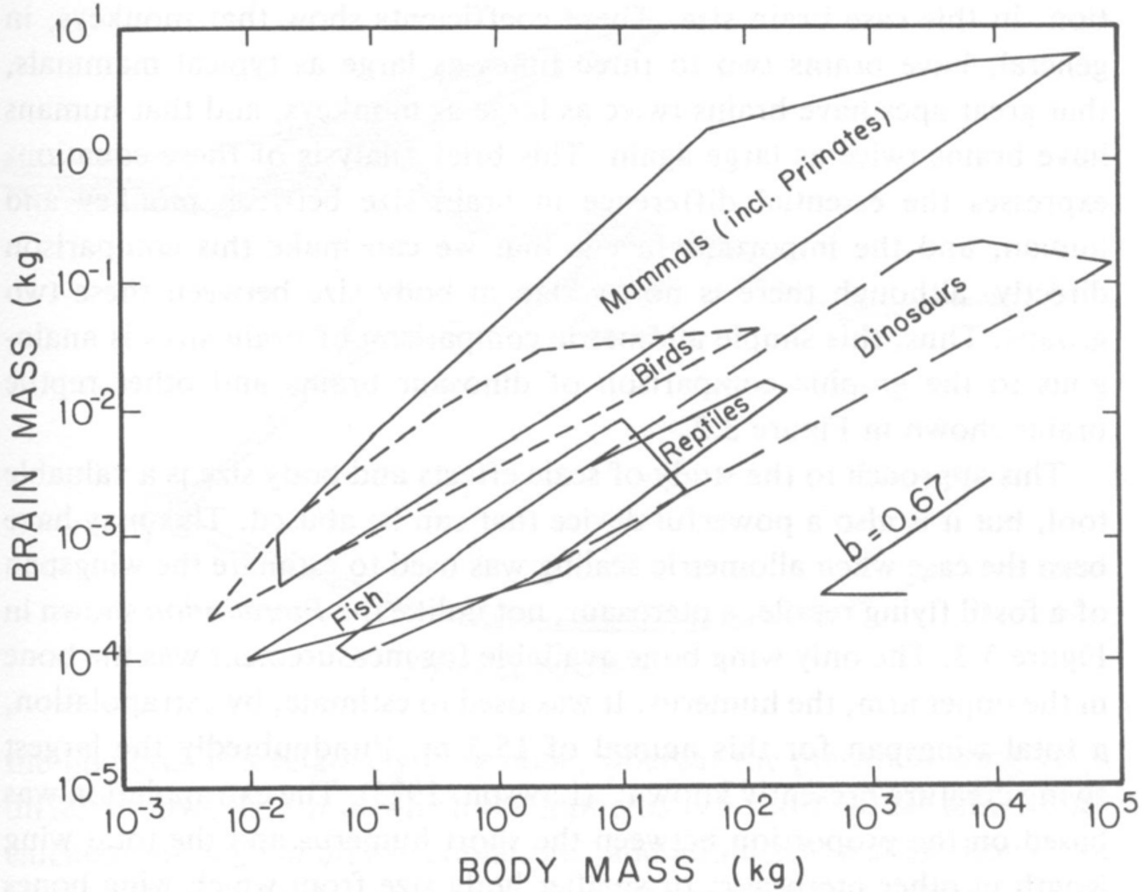


3-1 Basal metabolic rates of eutherian mammals plotted on linear scales to show the curvilinear consequences of $M^{3/4}$ scaling. The dashed lines show the consequences of a linear increase from the previous two points on the curve; note the progressive decrease in the slope (or progressive decrease in the increment of added cost of being larger). The two ungulates have even lower metabolic rates than the general equation predicts. Allometric equation by Brody and Proctor, cited in Brody (1945) and Kleiber (1961), units converted.

ALLOMETRY
AS AN INTEGRATIVE THEME

- **Brain sizes**

Figure 3.2. Brain sizes for various vertebrates fall within ranges characteristic for each group. Within each group, brain size increases roughly with body size to the $\frac{2}{3}$ power. The brain sizes of the large extinct dinosaurs fall within an extension of the range characteristic for modern reptiles, and the statement that dinosaurs had disproportionately small brains does not seem justified. From Jerison (1970).



ALLOMETRY
AS AN INTEGRATIVE THEME

- **Density spacing**

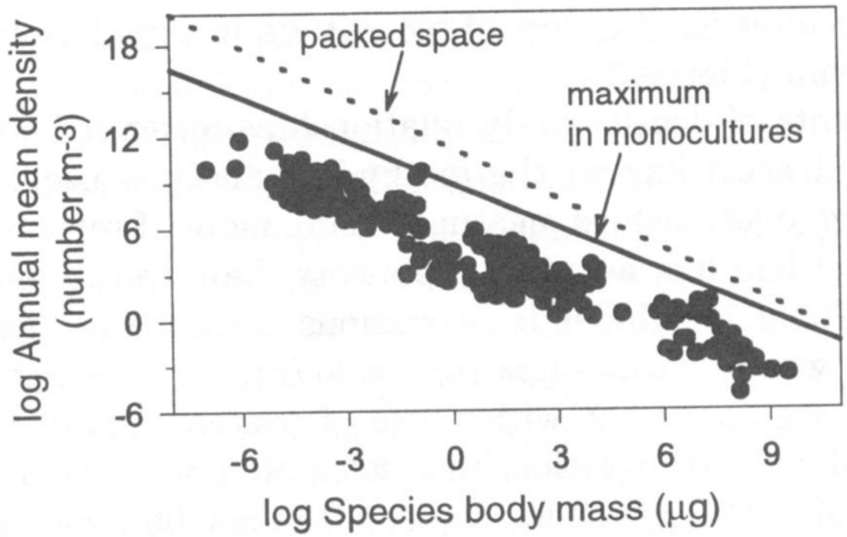


FIGURE 2 Density-body size relationship for lakes. This relationship includes phytoplankton, zooplankton, and fish species from 18 lakes worldwide for which volumetric densities (i.e., number m^{-3}) could be calculated (i.e., excludes zoobenthos; $\log D = 4.8 - 0.91 \log M, n = 240, r^2 = 0.92, P < 0.0001$). The solid line indicates maximum densities of organisms grown in monocultures ($\log D = 8.83 - 0.95 \log M$[36]). The dashed line indicates densities of organisms which would completely fill the available space ($\log D = 12 - 1 \log M$; assuming specific gravity of 1 g cm^{-3} for all organisms).

ALLOMETRY
AS AN INTEGRATIVE THEME

- **Population Doubling Times (mammals)**

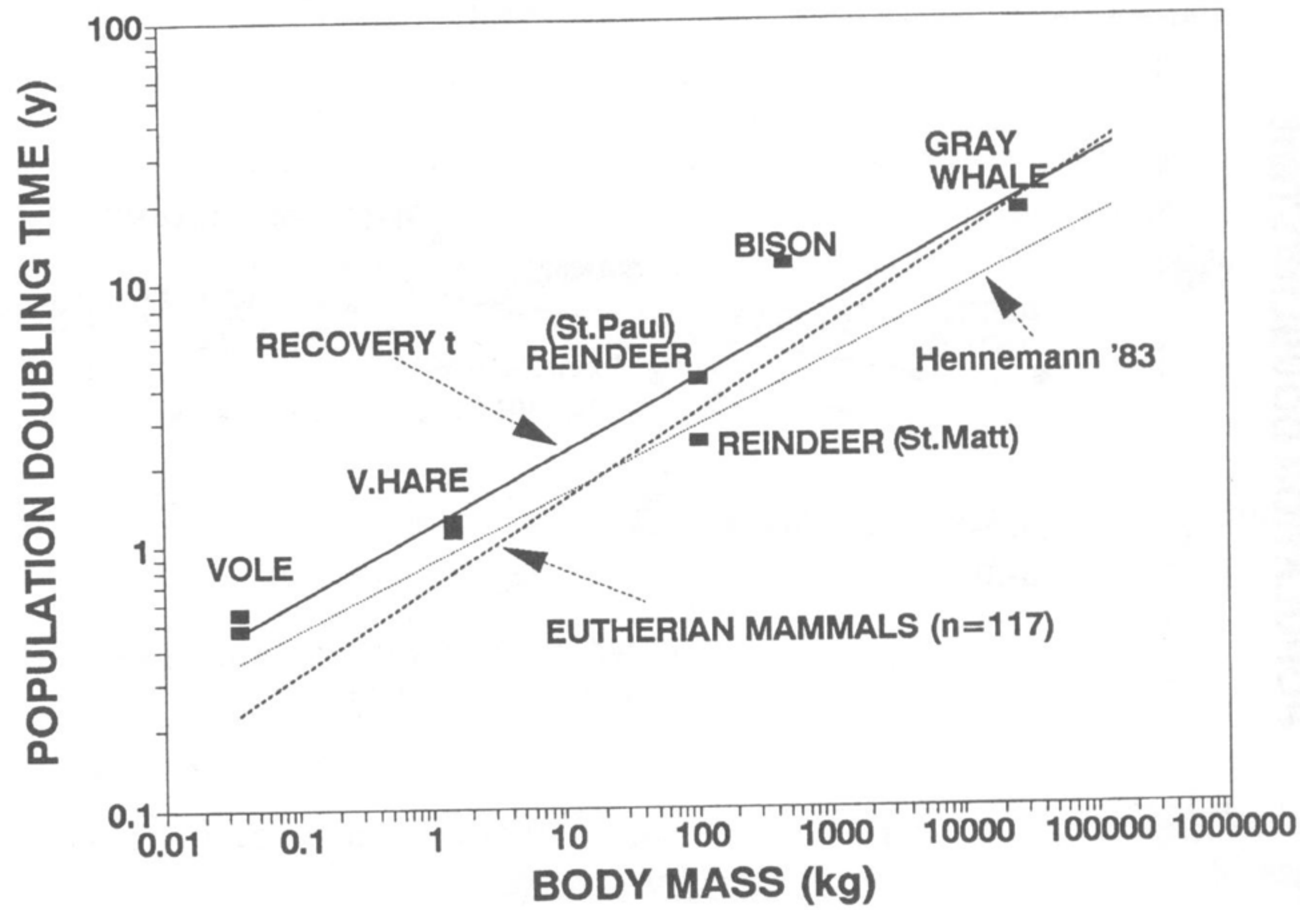


FIGURE 4 Population doubling times of mammals, calculated from Hennemann [37] and a pooling of $n = 117\, R_m$ values from several authors, and from recovery time mammals (squares).

ALLOMETRY
AS AN INTEGRATIVE THEME

- **Population Doubling Times (birds, mammals & recovery times**

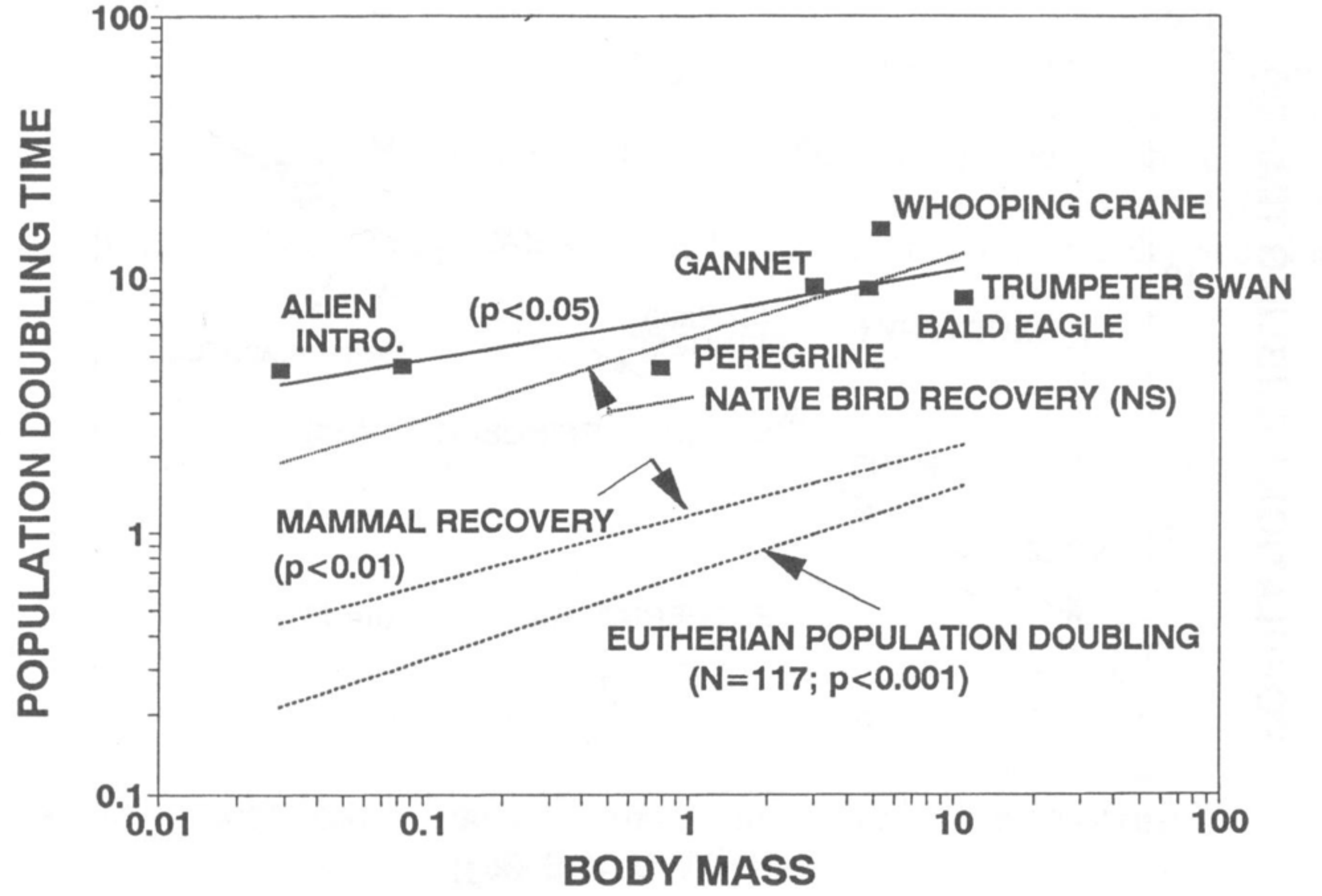
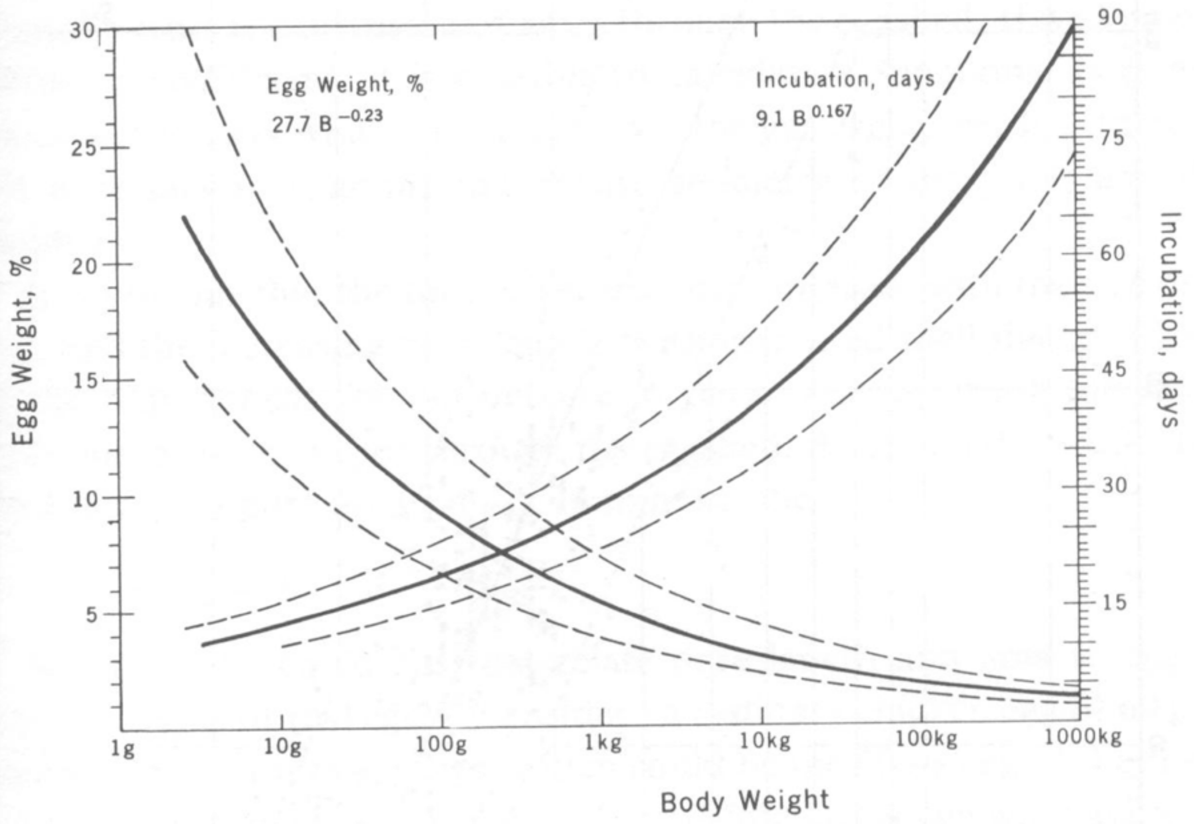


FIGURE 5 Population doubling times and recovery times of native birds, with and without population growth estimates for introduced house sparrows and starlings (to supply small bird data points), compared with mammalian recoveries and minimum population doubling times.

ALLOMETRY
AS AN INTEGRATIVE THEME

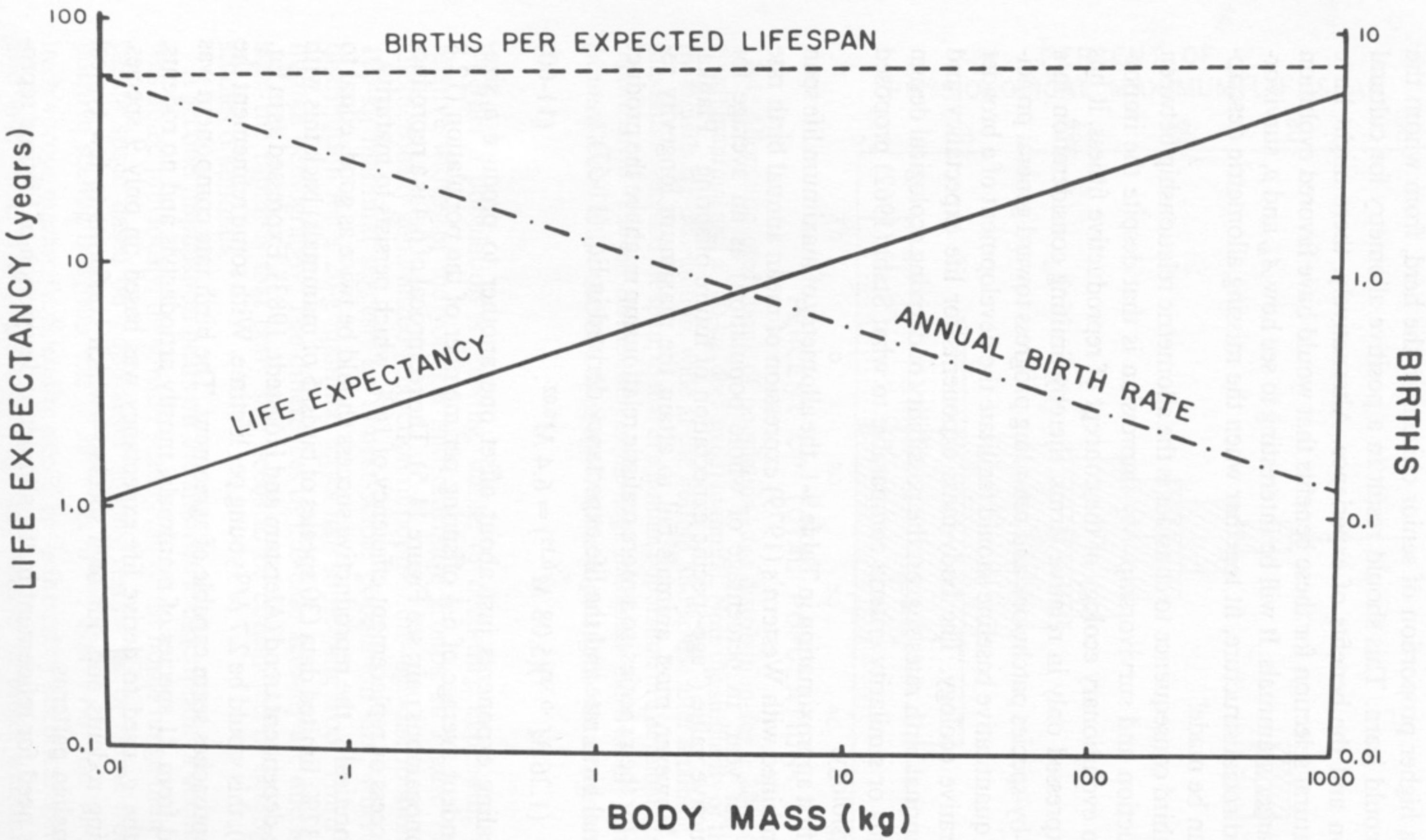
- **Eggs**

Figure 4.2. Larger birds lay proportionately smaller eggs, and the incubation time for an egg increases with increasing body size of the parent. When the egg size is expressed as a percentage of the adult bird weight, egg weight becomes an increasingly smaller fraction of body mass for larger birds. The dotted lines span the 68% confidence limits, which indicate that the variability is substantial. Note that the ordinates for egg weights and incubation days both are on arithmetic scales. From Rahn et al. (1975).



ALLOMETRY
AS AN INTEGRATIVE THEME

- **Life Expectancy**



11-5 Life expectancy scales up with the same exponent as annual birth rate scales down, so that the production of offspring per life span is the same, independent of body size. This provides a reference point of "average fitness" for comparison in the study of reproductive strategies.

ALLOMETRY
AS AN INTEGRATIVE THEME

- **Metabolic Rate**

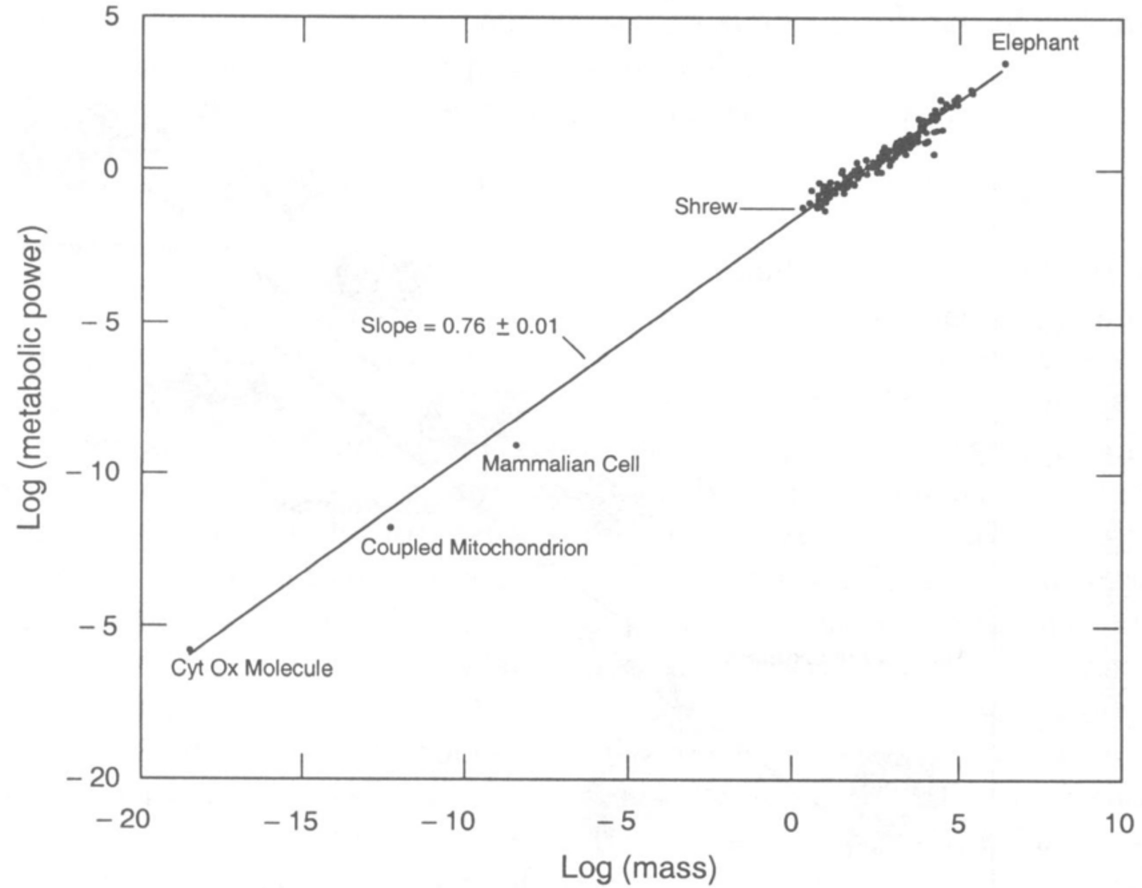
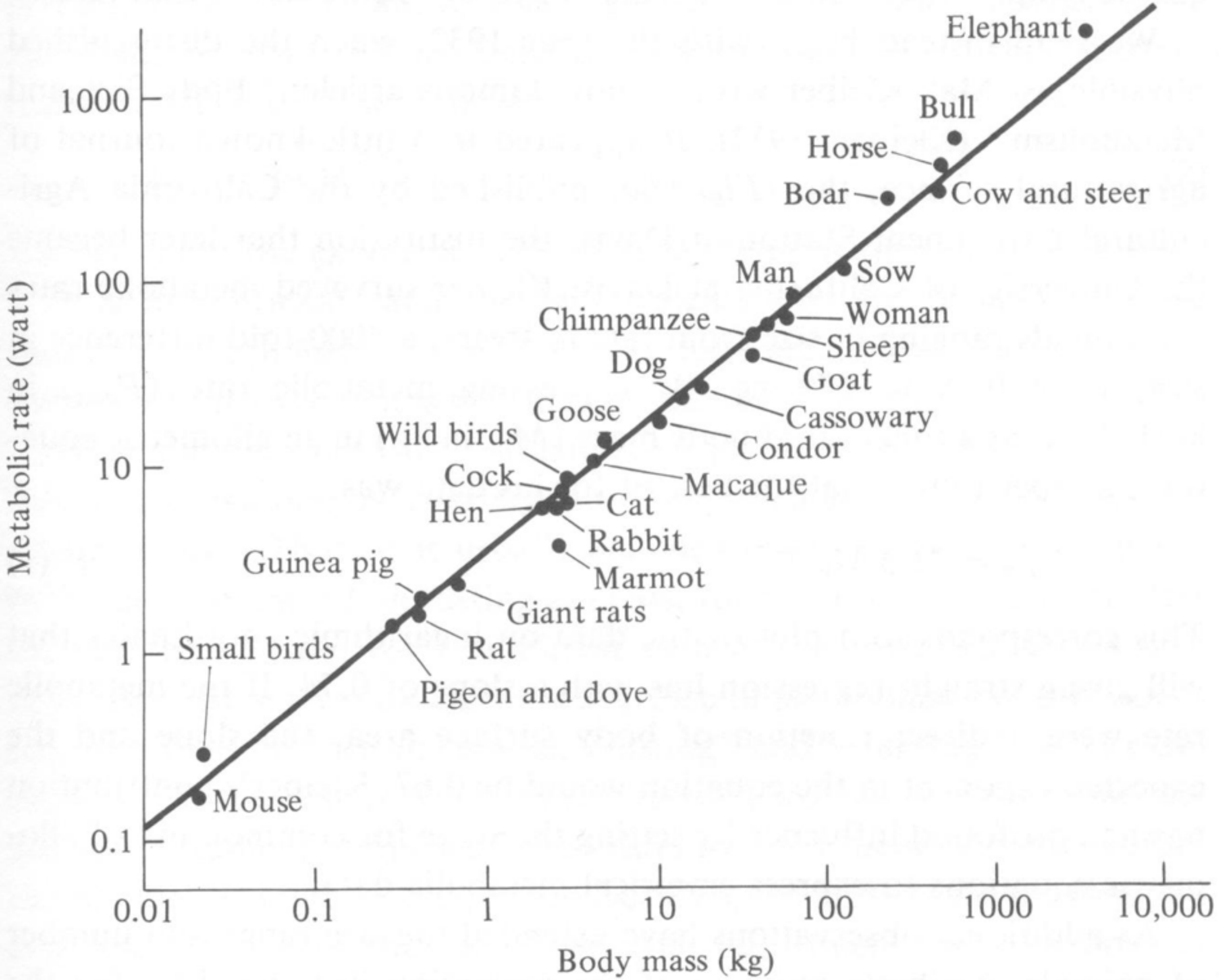


FIGURE 3 The straight line is the best fit to the metabolic rate of 389 mammals shown at the top versus their mass; it has a slope of 0.751 ± 0.005. When extrapolated 20 orders of magnitude, it agrees well with similar *in vitro* data on the mammalian cell and mitochondrion, and, finally, the cytochrome oxidase molecule of the respiratory complex inside mitochondria (Woodruff et al. [44]).

ALLOMETRY
AS AN INTEGRATIVE THEME

- **Metabolic Rate**

Figure 6.1. Metabolic rates for mammals and birds, when plotted against body mass on logarithmic coordinates, tend to fall along a single straight line. Adapted from Benedict (1938).



ALLOMETRY
AS AN INTEGRATIVE THEME

- **Metabolic Rate**

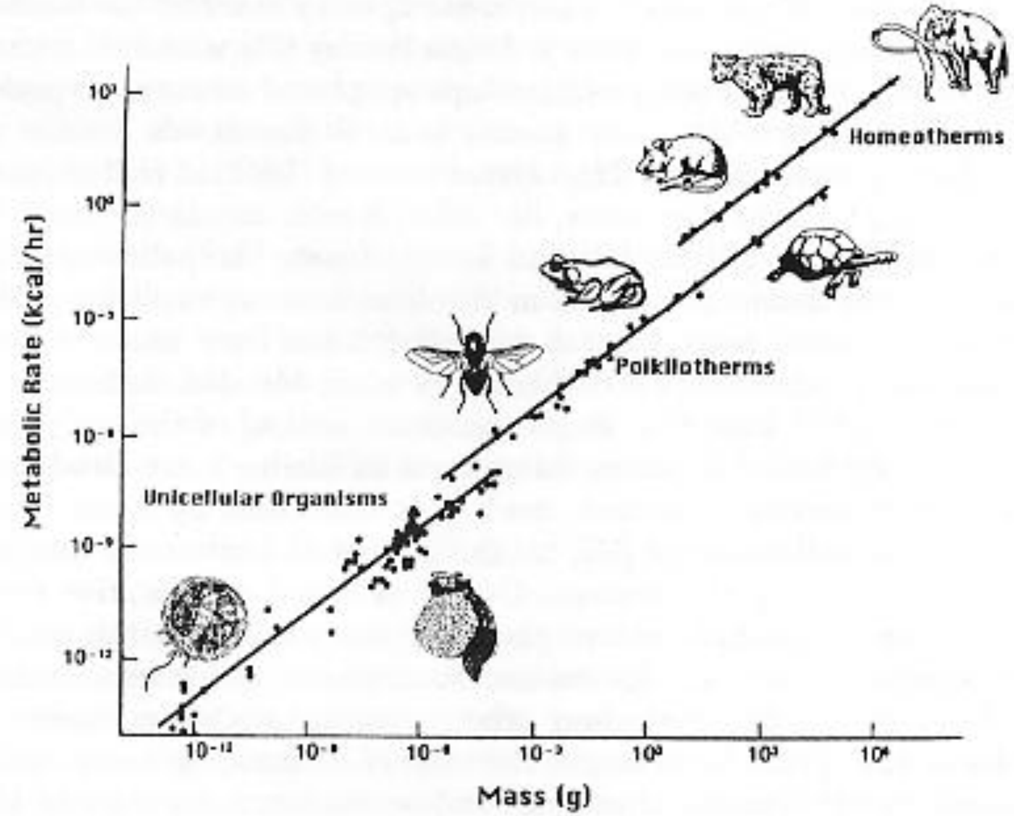


FIGURE 2 Hemmingsen's [26] classic plot of metabolic rate as a function of body size for three functional groups of organisms: endothermic birds and mammals, ectothermic vertebrates and invertebrates, and unicellular organisms. A line corresponding to $M^{3/4}$ has been fitted to each of the three data sets. Note, that the relationships are parallel, with identical allometric exponents, b, but different normalization constants, Y^0. Reprinted with Permission from Novo Nordisk of North America, Inc.

ALLOMETRY
AS AN INTEGRATIVE THEME

- **Metabolic Rate Birds & Mammals**

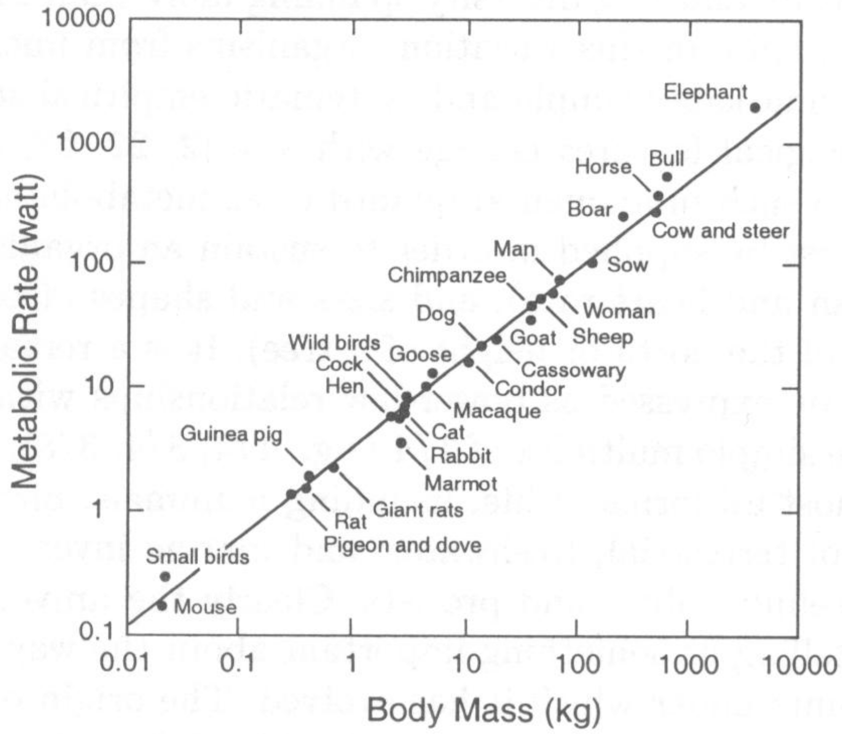


FIGURE 1 Metabolic rate (in watts) for a series of mammals and birds as a function of mass (in kg); the scale is logarithmic and exemplifies the 3/4-power scaling law discovered by Kleiber [2, 22, 27, 29].

ALLOMETRY
AS AN INTEGRATIVE THEME

- **Muscle advantage**

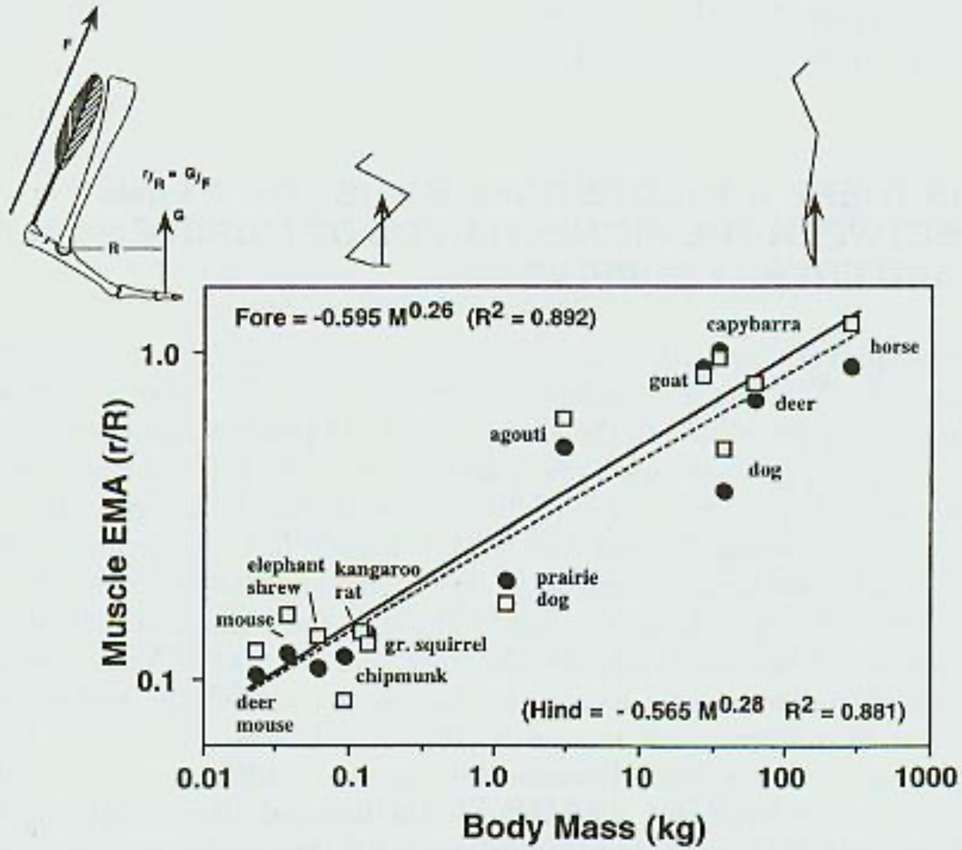
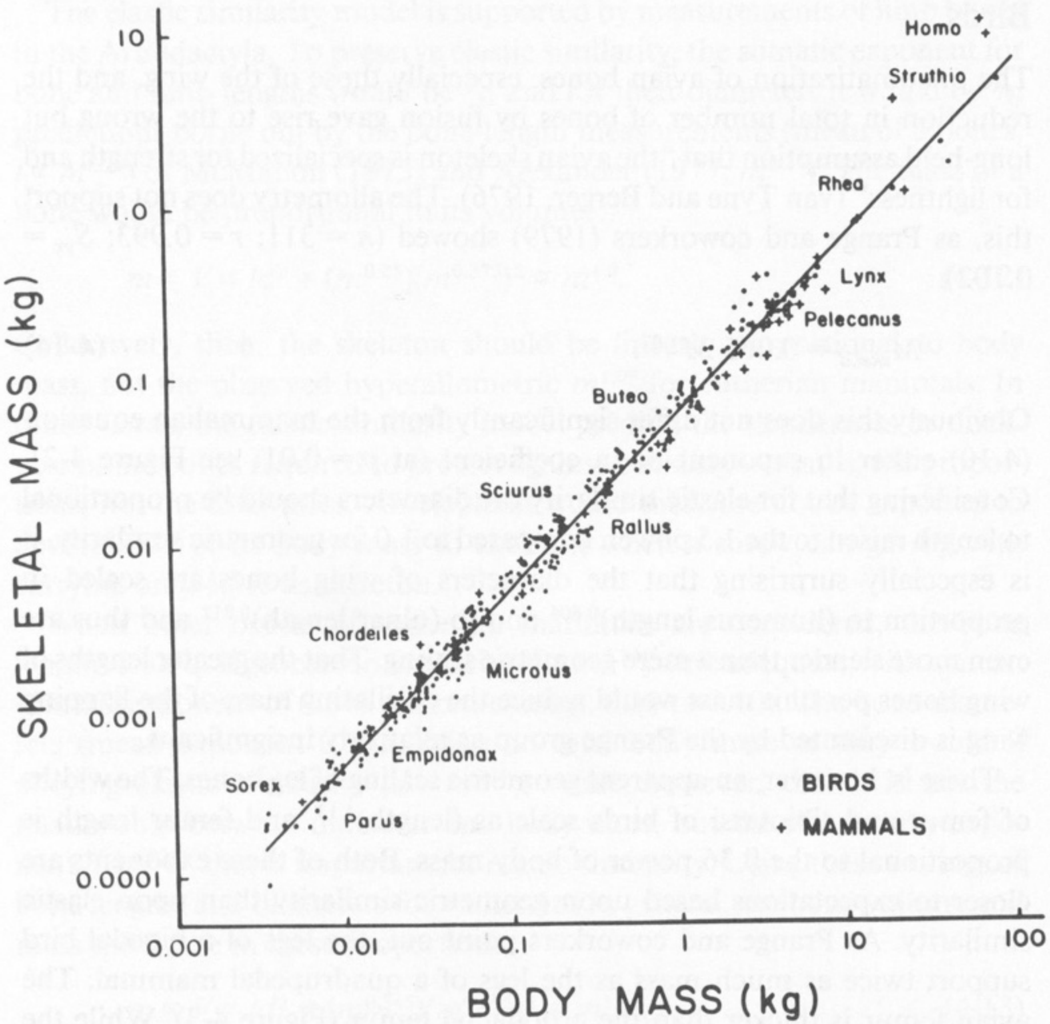


FIGURE 1 Scaling of posture-related muscle mechanical advantage ($EMA = r/R$, depicted in the upper left inset) in terrestrial mammals plotted against body mass on logarithmic coordinates. Least-squares (L-S) regression equations for forelimb and hindlimb show a similar pattern with the combined scaling of muscle $EMA \alpha M^{0.27}$ (which implies muscle force $F \alpha M^{0.73}$). Changes from crouched locomotor postures in small mammals to more upright postures in larger mammals explains the similarity of peak bone and muscle stress in different-sized species.

ALLOMETRY AS AN INTEGRATIVE THEME

- Skeletal Mass

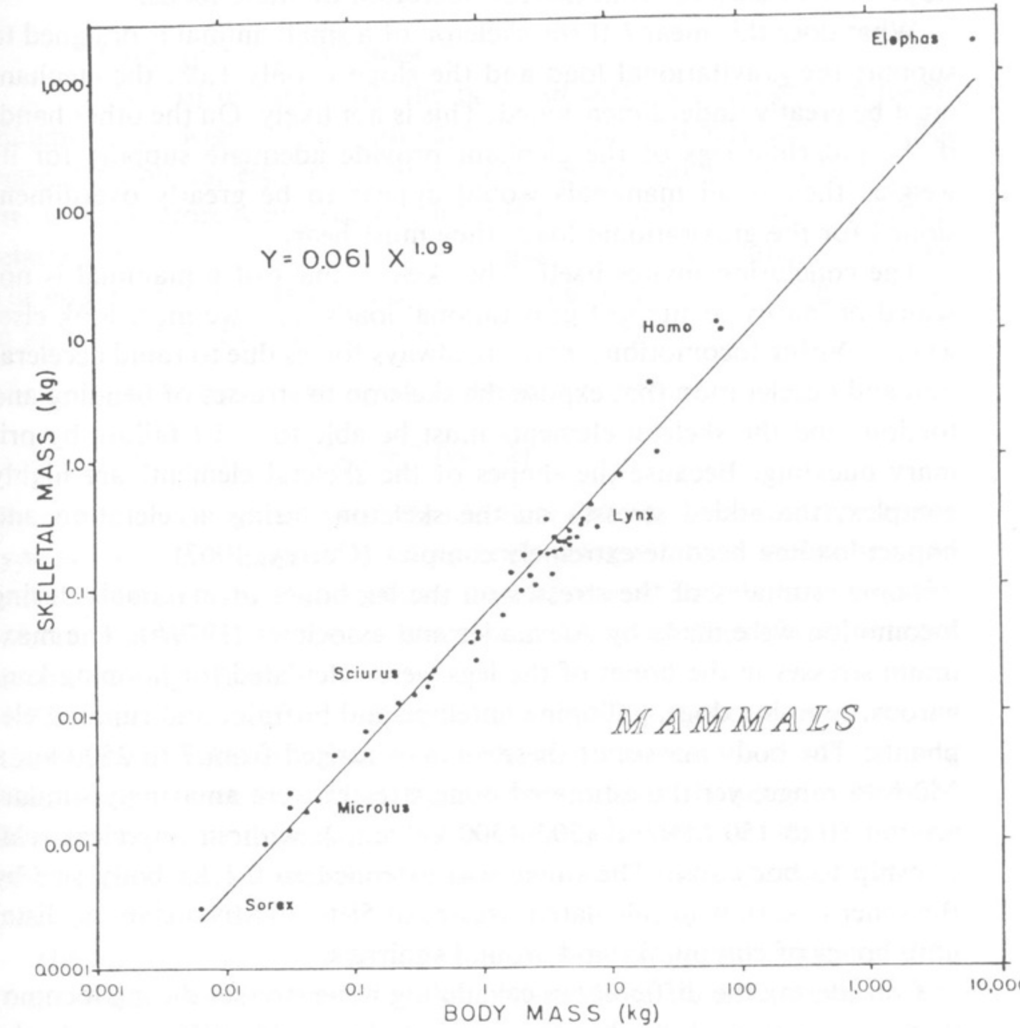


4-2 Skeletal mass as a function of body mass for birds and mammals. The allometric line plotted is actually for mammals, but the line for bird skeletons is indistinguishable; see Eqs. (4-10) and (4-14). (Redrawn from Prange et al., 1979; © 1979 by the University of Chicago Press.)

ALLOMETRY
AS AN INTEGRATIVE THEME

- **Skeletal mass**

Figure 5.2. The mass of the mammalian skeleton increases out of proportion to an increase in body mass, as would be expected for theoretical reasons. However, the slope of the empirical regression line, 1.09, is less than expected from considerations of the compressive strength needed to support the weight of the body. From Prange et al. (1979).



- **Times**

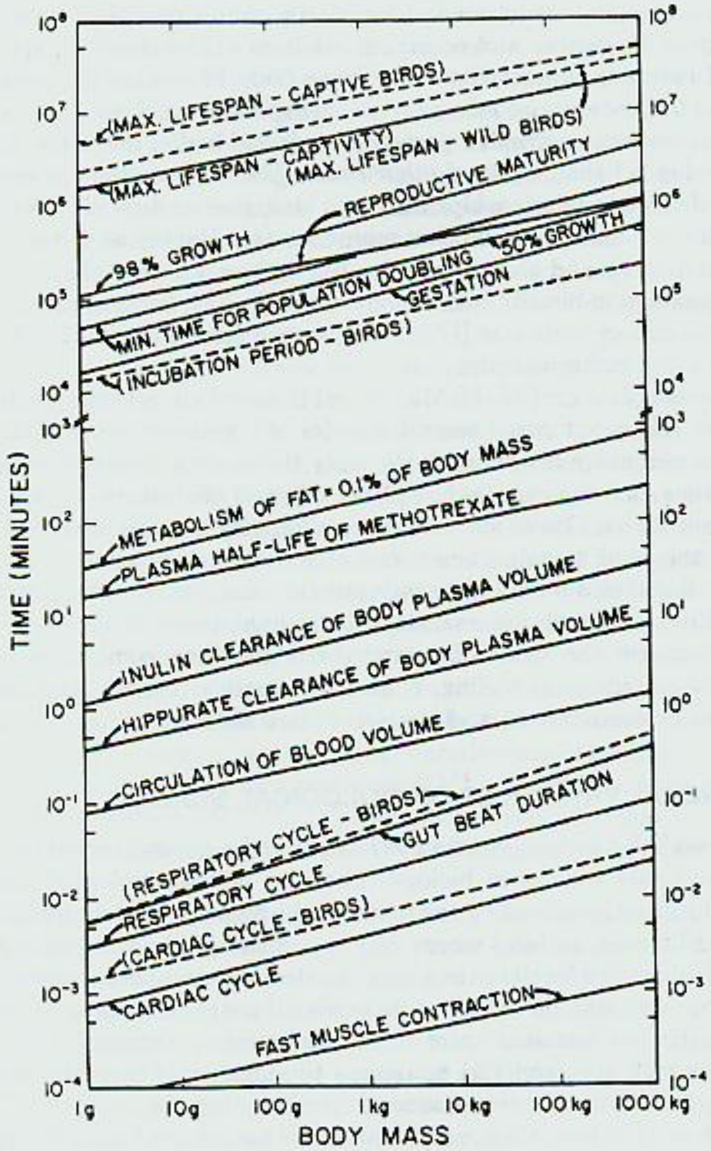


FIGURE 3 Scaling of biological times. Plotted here are allometric relationships for times of biological events, ranging from skeletal muscle contraction to life span, that have been derived for birds (dashed lines) and mammals (undashed lines) by various workers. Note that the slopes are all very similar, corresponding closely to a value of $b = 1/4$. (From Linstedt and Calder [35]. Reprinted with permission from The University of Chicago Press.)

ALLOMETRY
AS AN INTEGRATIVE THEME

- **Fractal roots**

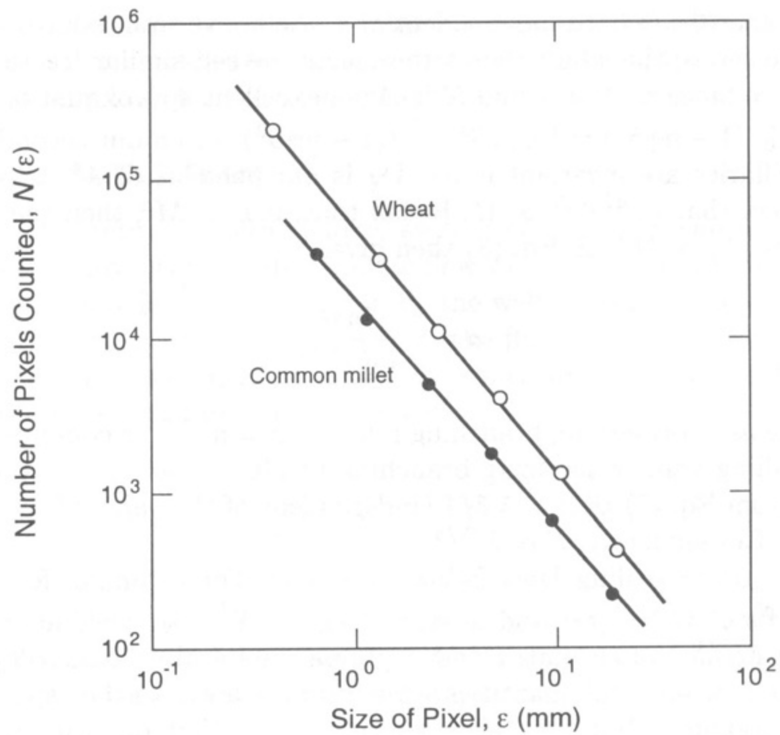


FIGURE 6 A plot of log $\mathcal{N}$ vs. log ϵ for a root system; the straight line indicates a self-similar fractal structure with dimension $d \approx 1.5$ [6, 24, 35].

the observations do indeed support a self-similar fractal structure. It is probably not practical to carry out an analogous empirical study of mammalian network systems; it might, however, be possible to use casts of the lung to make analogous measurements for the respiratory system. Furthermore, measurements of tube radii and lengths of the cardiovascular system do support the geometric progression of vessel sizes and branching ratios [3, 7] (see also Zamir this volume).

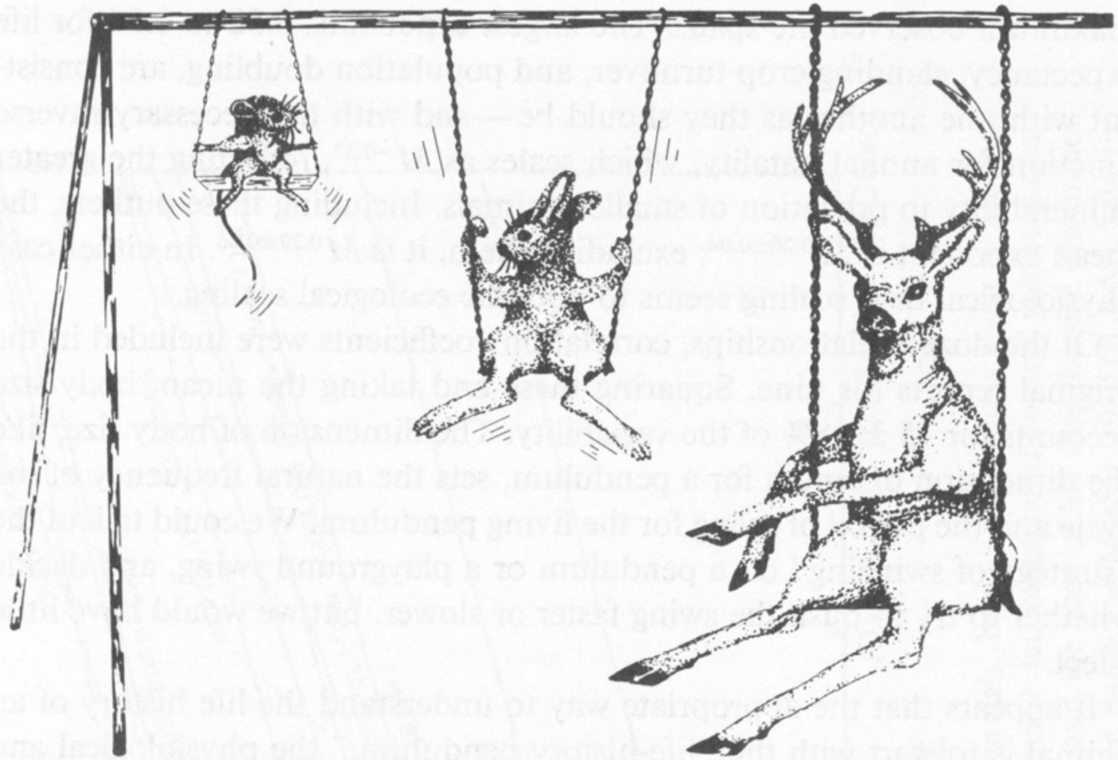
ALLOMETRY
AS AN INTEGRATIVE THEME

- Size ranges
- For mass in weight = 21 orders of magnitude
- Explain what an order of magnitude means
- Significance of
- Relation to Log values

Table 1.1. Size range of living organisms, arranged to show a 1000-fold difference in mass between each step.

Organism	Mass	
Mycoplasma	<0.1 pg	$<10^{-13}$ g
Average bacterium	0.1 ng	10^{-10} g
Tetrahymena (ciliate)	0.1 μg	10^{-7} g
Large amoeba	0.1 mg	10^{-4} g
Bee	100 mg	10^{-1} g
Hamster	100 g	10^{2} g
Human	100 kg	10^{5} g
Blue whale	>100 tons	$>10^{8}$ g

ALLOMETRY
AS AN INTEGRATIVE THEME

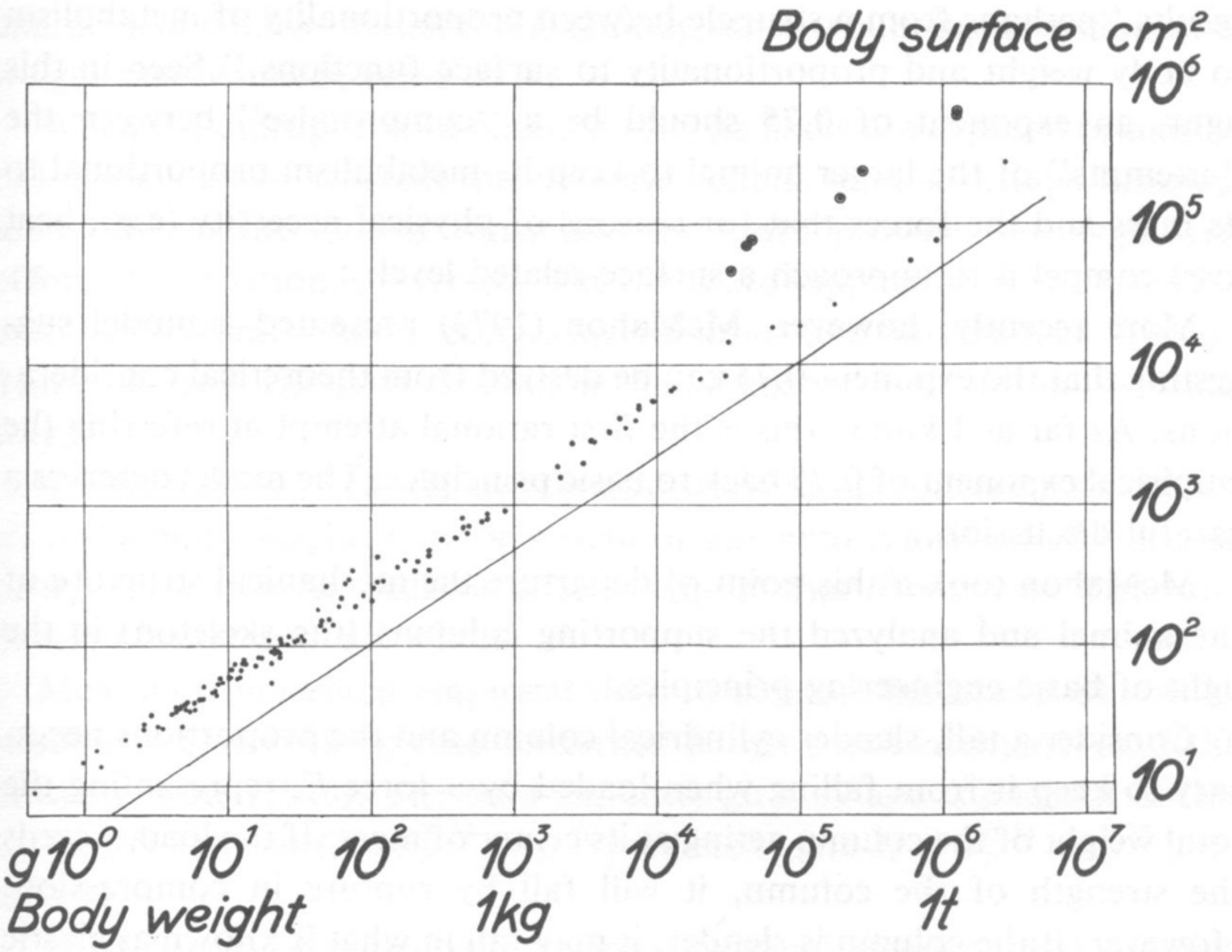


14-3 The quantitative details of a mammal's life history may be less a matter of strategies, accounting for perhaps only 25% of the variation, and more (75% or better) a matter of the dimensions of the pendulum that swings through that life history. Each animal is allowed the same size-independent number of actions. The smaller dimensions of the mouse-sized swing result in a higher frequency of oscillation and an earlier completion of the mouse's swing through life. (Drawing by Lorene Calder.)

ALLOMETRY
AS AN INTEGRATIVE THEME

- **Surface to Mass**

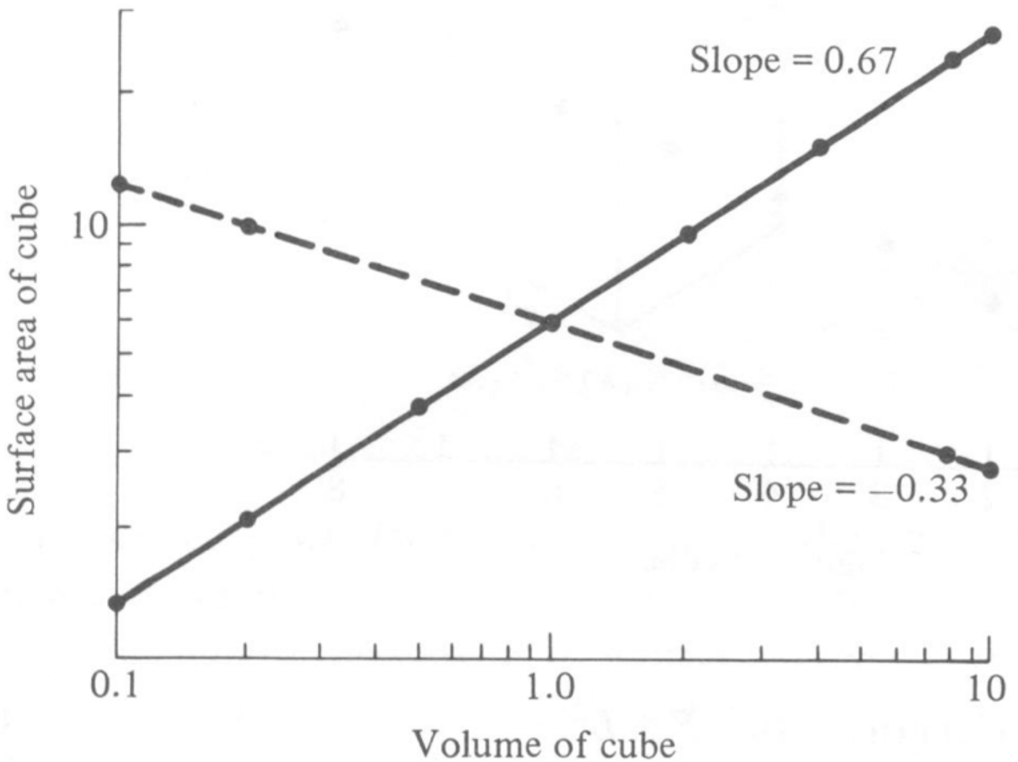
Figure 7.1. Relationship of body surface to body mass in vertebrates. The points surrounded by a circle represent beech trees. From Hemmingsen (1960).



ALLOMETRY
AS AN INTEGRATIVE THEME

- **Surface to Volume**

Figure 2.5. If the surface area of a cube is plotted against the volume on logarithmic coordinates, we obtain a straight regression line with a slope of 0.67. If, instead, the surface area *per unit volume* of the cube is plotted (dashed line), the regression line shows that the relative surface area decreases with increasing size of the cube. The slope of the dashed line is −0.33.



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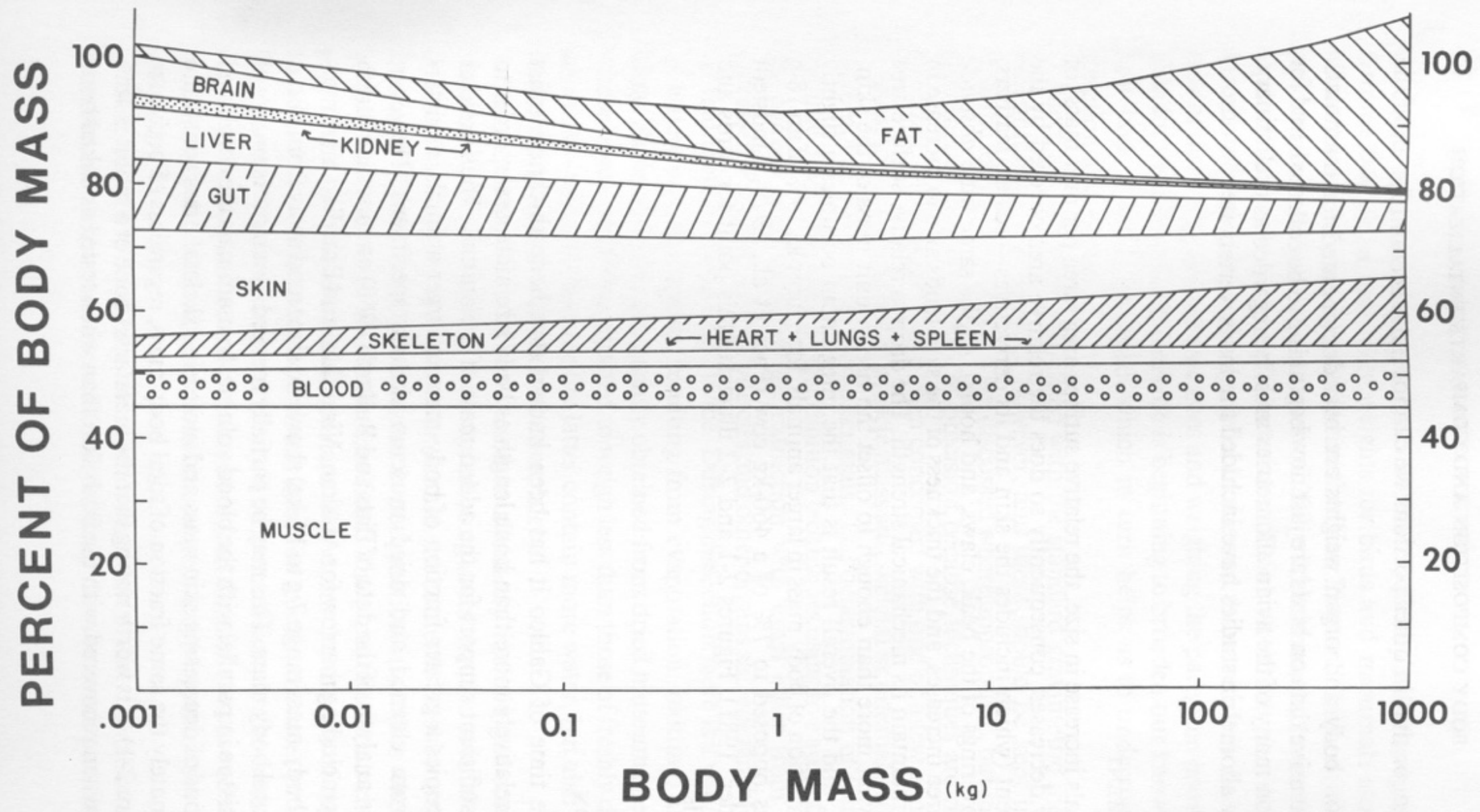

2-1 The body composition of eutherian mammals, reconstituted from available allometric generalizations (equations shown in Table 3-4). Skeletal muscle, blood, heart, lungs, and spleen account for about 52% of body mass, regardless of animal size. Skeleton and fat contribute proportionately more of the total mass in larger mammals, while the skin, brain, and many organs scale up in less than linear fashion. There is considerable variation in what the graph would predict for a particular size, though there are relatively few studies that give complete analyses for one species (see Table 3-6).

HHMI-ISGE MM MODULES

SIGNIFICANCE
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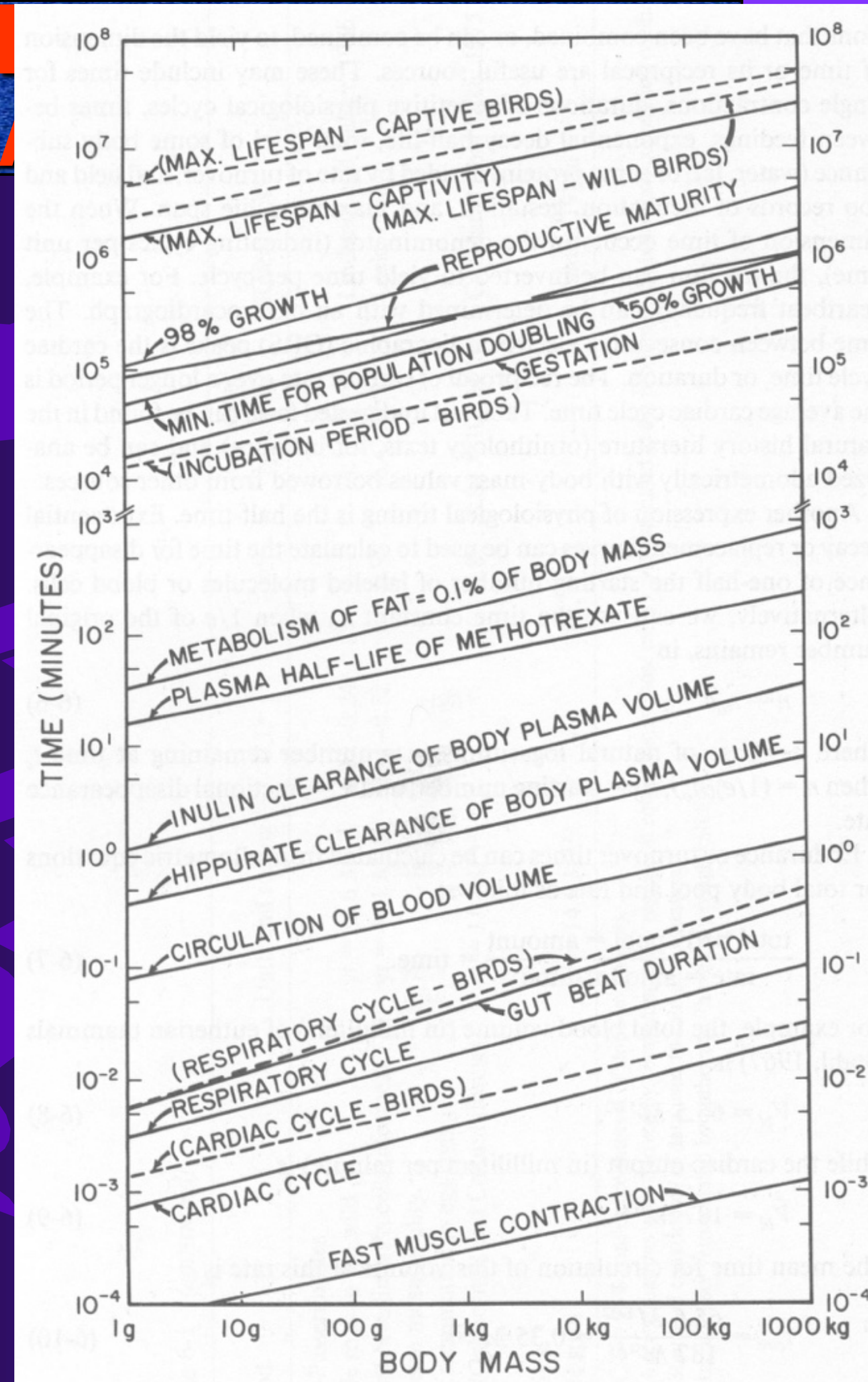

HHMI-ISGE MM MODULES

POWER LAWS IN BIOLOGY

ALLOMETRY
AS AN INTEGRATIVE THEME

SCALING IN BIOLOGY

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SOME EXAMPLES OF FEEDBACKS IN YOUR LIFE

- How certain proteins control whether a gene is “on” or “off”
- End-product inhibition of enzymes in metabolism
- How hormones change the behavior of a body
- The presence of predators or not in an ecosystem
- How much resources are available to a species in evolution

PERS/SOCIAL FEEDBACKS

- The "tests" you will take in this class
- Control or regulation of personal behavior
- Control or regulation of business activities
- Controls on government activities
  - Particularly well illustrated in the "balance of powers" or our constitution
  - Founders were natural sci & philosophers
- Emotions are regulators of personal & social behavior
  - They are binding principle for higher than individual units