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The Size of Living Things

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Most General Biology II courses focus on animal, plant, and fungi taxonomy, while addressing some relevant biological processes, i.e. reproduction, digestion, etc. This procession through the kingdoms of life often leaves biology students unengaged. Here, we present an alternative to teaching this type of course. We base our method on work by biologist John Tyler Bonner (*Why Size Matters: From Bacteria to Blue Whales*, 2006) and others who illustrate the limitations and advantages of size on life processes within organisms. The laboratory exercises presented guide students as they graph data showing the relationship between size and strength, speed, or complexity. All of these size relationships are proportional with profound significance. While becoming proficient on Excel™, students learn biological concepts and scientific literature mining. Using this method, students gladly discover size rules that illustrate the unity and diversity of life.

Keywords: Size, Size rules, General Biology II, *Volvox*, Strength, Speed

Introduction

Size is an issue that many scientists have devoted themselves to studying; perhaps because it has captivated the human imagination for centuries. Children stories like *Gulliver's Travels* and *Alice in Wonderland* are great examples of our fascination with size. A recent course development is what did it for me. I was charged with the daunting task of designing an introductory organismal-type course along with related laboratory exercises. If any reader is honest with him/herself, they would readily admit that interesting and relevant labs are not easy to come by for this type of course. Most General Biology II courses focus on animal, plant, and fungi taxonomy, while addressing some relevant biological processes, i.e. reproduction, digestion, etc. This procession through the kingdoms of life often leaves biology students unengaged. Here, we present an alternative to teaching this type of course. We base our method on work by biologist John Tyler Bonner (*Why Size Matters: From Bacteria to Blue Whales*, 2006) and others who illustrate the limitations and advantages of size on life processes within organisms.

The laboratory plan for studying size is as follows but only some of the labs I have used are highlighted in this paper. Students are introduced to the study of size and the results of size changes, known as scaling, through a simple internet-based research lab. They begin to appreciate the grand and minute nature of size by collecting size data from various and reliable sources. Next, they begin to understand the relationships among length, area, and volume by studying cubes of different dimensions (Salm, et al. 2011). Additionally, students model how cell shape changes influence cell function. This lab allowed for an introduction to allometry, the study of how shape changes coincide with and/or result from size changes in organisms. The *Complexity Lab* allows students to explore origin of multicellularity and cell differentiation. It also introduces the concept of quorum sensing, which is genetic mechanism that allows for microorganisms to respond to changes in population density. Student evaluate whether quorum sensing gave rise to cell differentiation. Of course, the *Volvox* is a great undergraduate lab model organism in which to study this phenomenon. The *Locomotion or Speed Exercise* examines prokaryotic versus eukaryotic flagellar locomotion. Students here learn about Reynolds number, which is a ratio of inertial forces to viscous forces; thereby providing a measure that is particularly applicable to movement in the micro-world.

Students are challenged to determine whether particular concepts are directly (α) or indirectly (1/α) proportional to size. In this manner, they discover the size rules established by Dr. Bonner in his book (Bonner, 2006). The laboratory exercises presented here guide students as they graph data showing the relationship between size and strength, speed, or complexity. All of these size relationships are proportional with profound significance. While becoming proficient on Excel™, students learn biological concepts and scientific literature mining. Using this method, students gladly discover size rules that illustrate the unity and diversity of life.

Student Outline

Size of Living Things Exercise

A. Microorganisms

1. If the common name of the organism is not listed in Fig. 1, provide the common name. If the scientific name is not listed, provide the scientific name also. Find the size details (dimensions and/or weight) of each of the above organisms. Rank the organisms in Fig. 1 from lightest (smallest) to heaviest weight (largest). Include website address that you used to find the size details for each organism.
2. Add a microscopic unicellular organism to the list. List the organism's common and scientific names. Include the organism's size details as you did in question 1. Again, include the website addresses that you used to find the size details for each organism.
3. Choose a microscopic multi-cellular organism to add to the list. List the organism's common and scientific names. Include the organism's size details as in question 1. Include the website addresses that you used to find the size details for each organism.
4. Provide an example of a micro super-organism, i.e. organisms that group together to form a massive "wannabe" organism but are able to operate independently. Defend your answer. What is its scientific name? How many individuals makeup the super-organism? Can you find any size details? Explain why it would not qualify as one large organism.
5. Find a *YouTube* ® video of the organisms you added to the listed in questions 2, 3, and 4.
6. Copy the links to those videos in a WORD document and copy your document onto the JUMPDRIVE to present to the class.
7. Micro ranking monitor will collect your size details for blackboard display.

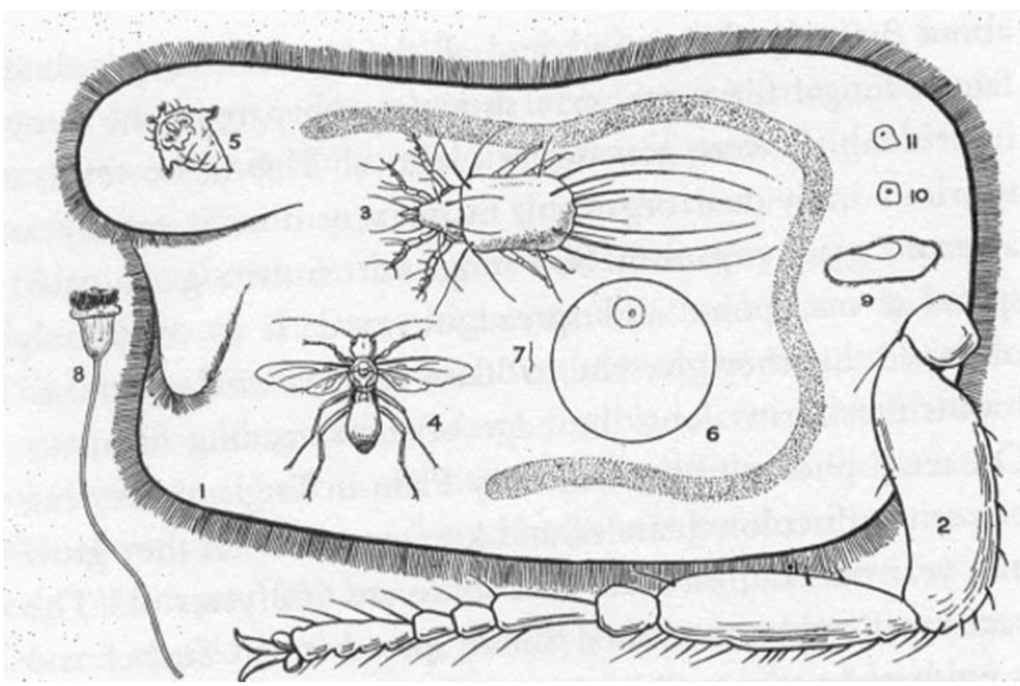

Figure 1. Size comparison of living organisms. 1.*Bursaria* – largest ciliate protozoan, with rope-like nucleus 2. Foreleg of flea – estimate from length of a flea 3. Cheese mite 4. Small wasp 5. Rotifer – small multi-cellular animal 6. Human egg 7. Human sperm 8. *Vorticella* (protozoa) – attached to bottom of pond 9. *Paramecium* 10. *Amoeba* – that causes dysentery 11. Human liver cell. (Image from Bonner's book (2006) but originally from H.G. Wells, J.S .Huxley, and G.P. Wells, *The Science of Life* , 1931.)

B. Macroorganisms

1. If the organism is not named in Fig. 2, then provide the common name. If the scientific name is not listed, provide the scientific name also. Find the size details (dimensions and/or weight) for each organism. Rank the organisms in Fig. 2 from lightest (smallest) to heaviest weight (largest). Include website address that you used to find the size details for each organism.
2. Add an extraordinarily large organism to the list. List the organism's common and scientific names. Include the organism's size details as in question 1. Again, include the website addresses that you used to find the size details for each organism.
3. Add an extraordinarily small macro-organism to the list. (Think smaller than a human but bigger than a microorganism.) List the organism's common and scientific names. Include the organism's size details as in question 1. Include the website addresses that you used to find the size details for each organism.
4. Provide an example of a macro super-organism, i.e. organisms that group together to form a massive "wannabe" organism but are able to operate independently. Defend your answer. What is its scientific name? How many individuals makeup the super-organism? Can you find any size details? Explain why it would not qualify as one large organism.
5. Find a *YouTube* ® video of the organisms you added to the listed in questions 2, 3, and 4.
6. Copy the links to those videos in a WORD document and copy your document onto the JUMPDRIVE to present to the class.
7. Macro ranking monitor will collect your size details for blackboard display.

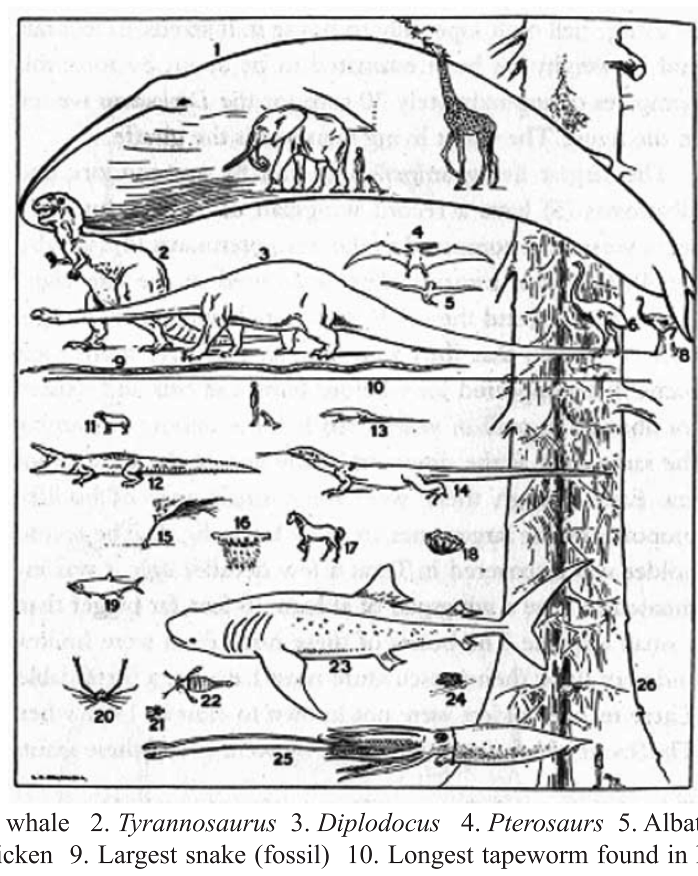

Figure 2. 1. Blue whale 2. *Tyrannosaurus* 3. *Diplodocus* 4. *Pterosaurs* 5. Albatross 6. *Aepyornis* 7. Ostrich 8. Chicken 9. Largest snake (fossil) 10. Longest tapeworm found in humans 11. Sheep (domestic) 12. West African (Nile) crocodile 13. Komodo dragon 14. Largest Lizard (extinct) 15. Largest polyp 16. *Cynaea*, largest jellyfish 17. Horse 18. Giant Clam 19. Large Tarpon 20. Japanese spider crab 21. Large Atlantic lobster 22. Eurypterid (extinct sea scorpion) 23. Whale shark 24. *Rafflesia*, largest flower 25. Giant squid (mollusk) 26. *Sequoia* (w/100 ft branch). (Image from Bonner's book (2006) but originally from HG Wells, JS Huxley, and GP Wells, *The Science of Life,* 1931.)

C. Complexity Exercise Part 1

Formulating a hypothesis using microscopy & imaging:

- View various volvocine microscopic slides using the low-power objective initially. Locate a green ball of cell/s. Switch to the higher-power objective and observe more closely. (**Do not use the oil immersion objective!**)
- Make observations of the various Volvocales viewed; i.e. color, morphology, cluster size, etc.
- Identify the unknown volvocales by using the dichotomous key.
- Image each type of volvocales using the light microscope and cameras. Then save the image. Email yourself the photos which will be included in your project assignment.

Questions:

1. If you were to only use your images, how would you be able to differentiate between the different volvocales? By cell types? Explain. (Base your answer on your observations of the different volvocines.)
2. How and why is quorum sensing involved in the division of labor? Find a scientific paper that explains this phenomenon. Include in your lab report one figure in the paper that illustrates this phenomenon.
3. In *Volvox*, what is the advantage gained by producing somatic cells that are incapable of reproduction? Find a scientific paper about *Volvox*, summarize the study, and explain a figure in the paper that depicts your answer.

Conclusions:

1. What can you hypothesize about the relationship between complexity and weight (size) based on the above exercise? Give a detailed explanation and use the images you collected to reinforce your answer.
2. How would you test your hypothesis?
3. What would be the significance if your hypothesis is supported?

Volvocales Dichotomous Key*

1\. Cells grouped into a colony. **2**

1\. Cells not grouped into a colony; single, round. ***Chlamydomonas***

2\. Colony one cell thick; flat or cup shaped. **7**

2\. Colony a round ball or sphere. **3**

3\. Colony composed of less than 100 cells. **4**

3\. Colony hollow round ball of more than 500 cells; new colonies can be seen forming inside the mature colony. ***Volvox***

4\. All cells in a colony are the same size; seldom more than 32 cells. **5**

4\. Cells in a colony of two different sizes. **6**

5\. Under high power (400X) the cells are round, mostly 16 cell colonies, never triangular or wedge shaped; cells separated from each other and not tightly packed. ***Gonium pectorale***

5\. Under high power (400X) the cells are triangular or wedge shaped; cells are very tightly packed and close together. ***Pandorina***

6\. Cells round in shape; mostly 16 but sometimes 64-100 cells in mainly hollow spheres. ***Eudorina***

6\. Cells when viewed from the side are spindle shaped; usually 4 or 8 cells in a colony; under low power the colony looks like a doughnut or crown. ***Stephanosphaera***

7\. Colony like a flattened horseshoe with several projections from the posterior; 16 to 32 cells in colony. ***Platydorina***

7\. Colony a square or rectangle; mostly 4 cells in a colony. ***Gonium sociale***

(*Modified from a dichotomous key by Carolina Biological Supply Company)

D. Complexity Exercise Part 2

Graphing data to uncover the Size Rule:

Generate a graph on Excel™ using the cell type diversity table (Table 1) from Bell & Mooers, 1997). Remember the following log a = b; the fourth column in Table 1 provides you the 'b'; solve for 'a' by using 10^b = a; 'a' is your x-axis value. Use the third column in Table 1 for your y-axis.

Questions:

4. What can you hypothesis about the relationship between complexity and weight based on this exercise? Explain in detail using the images you collected.
5. How and why is quorum sensing involved in the division of labor? Find a scientific paper that discusses this phenomenon and explain a figure in the paper.

Conclusions:

1. Summarize the lab exercise.
2. Explain the hypothesis that you developed by imaging different size volvocales.
3. How would you test your hypothesis?
4. What would be the significance if your hypothesis is supported?
5. Examine Table 1 from from Bell & Mooers, 1997. What can you conclude about the relationship between complexity and weight?

Fill-in the box with α or 1/α. Recall that (α) is directly and (1/α) is indirectly proportional to size.

Complexity $\boxed{}$ Weight

TABLE 1. Estimates of cell type diversity. The first two columns are phylum and species. The third column is the estimated number of cell types. The fourth column is $\log_{10}$ nominal total cell number, calculated by assuming cell volume to be 1000 μm^3. The fifth column is a code identifying phyla on plots. The authority is given in the final column; if more than one publication was consulted, that giving most information is cited

AMOEBAS, CILIATES AND BROWN SEAWEEDS					
Acrasiomycota	*Acrasis rosea*	2	2.85	X	Raper, 1984
Acrasiomycota	*Dictyostelium minutum*	2	3.15	X	Raper, 1984
Acrasiomycota	*Dictyostelium discoideum*	3	4.1	X	Raper, 1984
Ciliata	*Zoothamnion alterans*	4	2.15	I	Summers, 1938
Phaeophyta	*Ectocarpus siliculosus*	4	5.5	P	Knight, 1931
Phaeophyta	*Chordaria linearis*	6	10	P	Searles, 1980
Phaeophyta	*Chordaria flagelliformis*	6	9.6	P	Kornmann, 1962
Phaeophyta	*Leathesia difformis*	6	10.6	P	Bold & Wynne, 1978
Phaeophyta	*Elachista fucicola*	5	7.2	P	Koeman & Cortel-Breeman, 1976
Phaeophyta	*Haplogloia andersonii*	7	8.6	P	Peters, 1992
Phaeophyta	*Papenfussiella callitricha*	7	8.1	P	Wilce, 1969
Phaeophyta	*Kurogiella saxatilis*	7	10.4	P	Kawai, 1993
Phaeophyta	*Colpomenia sinuosa*	5	9.3	P	Wynne, 1972
Phaeophyta	*Scytosiphon lomentaria*	4	8.9	P	Clayton, 1976
Phaeophyta	*Haplospora globosa*	4	10.4	P	Kuhlenkamp & Muller, 1985
Phaeophyta	*Asperococcus fistulosus*	5	10.0	P	Bold & Wynne, 1978
Phaeophyta	*Dictyosiphon hirsutus*	6	10.6	P	Peters, 1992
Phaeophyta	*Isthmoploea sphaerophora*	3	4.2	P	Rueness, 1974
Phaeophyta	*Hummia onusta*	5	8.0	P	Fiore, 1977
Phaeophyta	*Cutleria* sp	7	9.5	P	Bold & Wynne, 1978
Phaeophyta	*Ralfsia verrucosa*	8	8.8	P	Loiseaux, 1968
Phaeophyta	*Heteroralfsia saxicola*	9	8.9	P	Kawai, 1989
Phaeophyta	*Zeacarpa leiomorpha*	8	9.9	P	Anderson *et al.*, 1988
Phaeophyta	*Syringoderma phinneyi*	6	5.3	P	Henry & Müller, 1983
Phaeophyta	*Carpomitra cabrecae*	7	9.4	P	Motomura *et al.*, 1985
Phaeophyta	*Sphacelaria bipinnata*	9	9.1	P	Clint, 1927
Phaeophyta	*Cladostephus verticillatus*	8	8.1	P	Sauvageau, 1907
Phaeophyta	*Dictyota binghamiae*	4	11.4	P	Foster et al., 1972
Phaeophyta	*Fucus vesiculosus*	7	12.5	P	McCully, 1966
Phaeophyta	*Ascophyllum nodosum*	6	11.8	P	Rawlence, 1973
Phaeophyta	*Desmarestia antarctica*	7	11.8	P	Moe & Silva, 1989
Phaeophyta	*Himantothallus grandifolius*	14	12.2	P	Wiencke & Clayton, 1990
Phaeophyta	*Alaria marginata*	14	12.0	P	Kain, 1979.
Phaeophyta	*Laminaria dentigera*	14	11.1	P	Kain, 1979
Phaeophyta	*Durvillea antarctica*	6	12.0	P	Naylor, 1949
GREEN ALGAE AND PLANTS					
Chlorophyta	*Astrephomène gubernaculum*	2	1.65	C	Stein, 1958
Chlorophyta	*Eudorina illinoisensis*	2	2	C	Iyengar & Desikachary, 1981
Chlorophyta	*Fritschiella tuberosa*	5	2.3	C	McBride, 1970
Chlorophyta	*Microthamnion kutzingianus*	3	1.8	C	Bold & Wynne, 1978
Chlorophyta	*Pleodorina sphaerica*	2	2.55	C	Iyengar & Desikachary, 1981
Chlorophyta	*Ulothrix zonata*	3	1.5	C	Floyd *et al.*, 1972
Chlorophyta	*Volvox aureus*	2	2.75	C	Iyengar & Desikachary, 1981
Bryophyta	*Anthoceros himalayensis*	12	4.6	B	Hehra & Handoo, 1953
Bryophyta	*Cyathodium barodae*	13	7.7	B	Chavran, 1937
Bryophyta	*Cyathodium foetidissimus*	15	8.8	B	Lang, 1905
Bryophyta	*Fegatella conica*	15	6.5	B	Maybrook, 1914
Bryophyta	*Funaria hygrometrica*	20	8.4	B	Puri, 1981
Bryophyta	*Monoclea forsteri*	13	6.5	B	Shuster, 1984
Bryophyta	*Polytrichum commune*	26	9	B	Puri, 1981
Bryophyta	*Pogonatum stevensii*	21	8.85	B	Chopra & Sharna, 1958
Bryophyta	*Sphagnum recurvum*	11	8.95	B	Puri, 1981
Bryophyta	*Symphogyna brogniarti*	13	5.65	B	Puri, 1981
Gymnospermata	*Pinus monophylla*	30	10	G	Foster & Gifford, 1974
Psilophyta	*Psilotum nudum*	17	11	B	Sporne, 1975
Pteridophyta	*Azolla pinnata*	20	9	T	Konar & Kapoor, 1974
Pteridophyta	*Helminthostachys zeylandica*	5	7.85	T	Lang, 1902
Pteridophyta	*Hymenophyllum tunbridgensis*	15	9.85	T	Boodle, 1900
Pteridophyta	*Ophioglossum palmatum*	14	9.8	T	Chrysler, 1941
Pteridophyta	*Trichomanes rigidum*	5	3	T	Bower, 1928
Spermatophyta	*Croomia pauciflora*	42	10.2	A	Tomlinson & Ayensu, 1968
Spermatophyta	*Fuirena ciliaris*	44	10.4	A	Govindarajalu, 1969
Spermatophyta	*Lemna minor*	18	5.9	A	Daubs, 1965
Spermatophyta	*Lomandra hermaphroditicum*	36	10.55	A	Fahn, 1954
Spermatophyta	*Mamillaria elongata*	27	10.8	A	Darbishire, 1904

COMPLEXITY OF ORGANISMS

Spermatophyta	*Petermannia cirrhosa*	39	10.4	A	Tomlinson & Ayensu, 1969
Spermatophyta	*Sagittaria lancifolia*	42	11	A	Stant, 1964
Spermatophyta	*Selenipedium palmifolium*	35	10.1	A	Rosso, 1966
Spermatophyta	*Wolffia arrhiza*	5	4	A	Luandolt, 1986
Spermatophyta	*Wolffia microscopica*	7	4.85	A	Maheshwari, 1954
Spermatophyta	*Wolfiella welwitschii*	8	5.6	A	Maheshwari, 1954
Sphenophyta	*Equisetum palustre*	16	10.75	B	Eames, 1936
RED SEAWEEDS					
Rhodophyta	*Beckerella scalaramosa*	12	10.5	R	Kraft, 1976
Rhodophyta	*Botryocladia wynnei*	6	6.6	R	Ballantine, 1985
Rhodophyta	*Farlowia mollis*	7	9.5	R	Abbott, 1962
Rhodophyta	*Gloeophycus koreanum*	12	10.8	R	Lee & Yoo, 1979
Rhodophyta	*Halymenia asymmetrica*	13	10.8	R	Gaetano, 1986
Rhodophyta	*Membranoptera subtropica*	12	6.8	R	Schneider & Eiseman, 1979
Rhodophyta	*Neodilsea natashae*	12	10.3	R	Linstrom, 1984
Rhodophyta	*Sarconema scinaioides*	13	9.4	R	Papenfuss & Edelstein, 1974
Rhodophyta	*Schimitzia hiscockiana*	14	11.3	R	Maggs & Guiry, 1985
Rhodophyta	*Schimmelmannia dawsonii*	11	11.4	R	Acleto, 1972
Rhodophyta	*Yamadaella cenomyce*	7	9.6	R	Abbott, 1970
Rhodophyta	*Yamadaphycus carnosa*	11	9	R	Mikami, 1973
FUNGI					
Ascomycota	*Gymnoascus reessii*	5	4.2	F	Gaümann, 1928
Ascomycota	*Leptosphaeria* sp	9	4.05	F	Gaümann, 1928
Basidiomycota	*Sphaerolobus stellatus*	9	6.1	B	Buller, 1933
Zygomycota	*Rhizopus nigricans*	3	2.8	Z	Gaümann, 1928
Zygomycota	*Mucor mucedo*	3	2.3	Z	Buller, 1931
ANIMALS					
Annelida	*Lumbricus terrestris*	57	10	W	Stephenson, 1930
Annelida	*Apodotrocha progenerans*	16	3.8	W	Westheide & Rieger, 1983
Annelida	*Hirudo medicinalis*	26	10.3	W	Mann, 1962
Annelida	*Aelosoma tenebrarum*	12	4.7	W	Brace, 1901
Annelida	*Nais variabilis*	13	5.4	W	Stephenson, 1908
Annelida	*Diurodrilus westheidi*	14	3.55	W	Kristensen & Niilon, 1982
Annelida	*Pomatoceros triqueter larva*	12	4.85	W	Segrove, 1941
Annelida	*Dasybranchus caducus larva*	10	4.5	W	Bookhaut, 1957
Annelida	*Pisione remota larva*	11	4.65	W	Akesson, 1961
Annelida	*Dinophilus conklinii*	23	4	W	Nelson, 1907
Arthropoda	*Callinectes sapidus*	69	11.5	O	Johnson, 1980
Arthropoda	*Periplaneta americana*	50	9.5	O	Smith, 1968
Chordata	*Canis familiaris*	99	13.7	V	Adam *et al.*, 1983
Chordata	*Morone saxatilis*	122	11.4	V	Groman, 1982
Chordata	*Salmo gairdneri*	116	11.4	V	Yasutake, 1983
Chordata	*Mus musculus*	102	11.3	V	Gude *et al.*, 1982
Cnidaria	*Hydra attenuata*	15	4.8	J	Campbell & Bode, 1983
Cnidaria	*Microhydra rideri*	3	2.1	J	Spoon & Blanquet, 1978
Cnidaria	*Haliclystus haliclystus*	22	7.5	J	Wietrzykowski, 1910
Cnidaria	*Cyanea cyanea*	22	13	J	Hyman, 1940
Ctenophora	*Pleurobrachia* sp	13	4	O	Hyman, 1940
Entoprocta	*Loxosoma sultana*	16	3.55	E	Harmer, 1885
Entoprocta	*Pedicillina echinata larva*	10	4.6	E	Hatschek, 1877
Gastrotricha	*Turbanella cornuta*	18	3.85	H	Teuchert, 1977
Gastrotricha	*Chordodasys antennatus*	15	3.1	H	Rieger, *et al.*, 1974
Gnathostomulida	*Rastrognathia macrostoma*	13	3.5	G	Kristensen & Norrevang, 1977
Gnathostomulida	*Valvognathia pogonostoa*	15	3.25	G	Kristensen & Norrevang, 1978
Kinorhyncha	*Pycnophyes frequens*	16	3.9	K	Hyman, 1951
Mesozoa	*Dicyemmenea lameerei*	3	2.35	M	Dougherty, 1963
Mesozoa	*Dicyema typhus*	3	3.2	M	Nouvel, 1947
Mesozoa	*Conocyema polymorpha*	3	1.45	M	Nouvel, 1947
Mesozoa	*Dicyemmenea abelis*	6	1.3	M	Nouvel, 1947
Mesozoa	*Rhopalura granosa*	3	3.15	M	Atkinson, 1933
Mollusca	*Amphibola crenata larva*	9	4.3	U	Farnie, 1924
Mollusca	*Neomenia carinata larva*	7	3	U	Thompson, 1960
Nematoda	*Rhabditis monhystera*	23	2.65	N	White, 1988
Nematoda	*Caenorhabditis elegans*	24	2.95	N	White, 1988
Placozoa	*Trichoplax adhaerens*	4	2.5	L	Grell & Benwitz, 1971
Platyhelminthes	*Dugesia mediterranea*	14	6.25	Y	Castle, 1928
Platyhelminthes	*Anaperus sulcatus*	9	8.1	Y	Beklemischew, 1914
Platyhelminthes	*Macrostomum gigas*	14	5.7	Y	Hyman, 1951
Platyhelminthes	*Enterostomula graffi*	12	5.55	Y	Ruffin, 1941
Porifera	*Spongilla lacustris*	16	4	S	Brien, 1932
Rotifera	*Apsilus vorax*	16	5.15	F	Gast, 1900
Rotifera	*Notholca acuminata*	13	3.5	F	Pejlar, 1958
Sedes incertis	*Salinella salve*	3	1.95	?	Frenzel, 1892

E. Strength Exercise

Examine the femurs of various primates. Show all your calculations!

1. Measure the length (height) and width (diameter) from the handout of each femur in cms.
2. Using the scale bar shown on the handout, calculate the approximate actual height and diameter in cms. (Hint: Use a proportion.)
3. Match the bones (A-J) to the primates: adult human, *Australopithecus afarensis, Bonobo*, chimpanzee, gorilla, *Homo ergaster*, five-year old child, mandrill baboon, orangutan, siamang based on the actual height you calculated in question #2.

Figure 3. Primate femurs. Actual Primate Femur Bones Handout is 11 x 17 inches.

4. Calculate the estimated strength of each femur by squaring the actual diameter values that were calculated in question #2.
5. Calculate the approximate weight (size) of each organism by multiplying the estimated strength (which was calculated in question #4) by the approximate height (which was calculated in question #2).
6. Place the values in weight (size) order on an Excel ™spreadsheet.
7. From these values, create a graph (plot strength vs. weight; weight should be the x axis). Determine the slope of the line; the slope of the line is the exponent for weight below. (Hint: $y = mx + b$).

Questions:

1. What is the relationship between strength and weight? Show and describe your graph in detail, including the significance of your slope.
2. Find three organisms (obtain from reliable sources and/or scientific papers) that depict the special relationship between strength and weight. Explain fully.
3. From among your examples, choose one and refer to a figure in the scientific paper. Describe the figure from that paper that illustrates the size rule. (Include a copy of the paper in your lab report.)

Conclusion:

1. In a logical and organized manner, write a summary of the lab and your examples.
2. Describe the significance of the size rule. (Don't forget to reference appropriately!)
3. What is the relationship between strength and weight? As strength increase, does weight? Or is strength the inverse of weight? Fill-in the box with α (directly)or 1/α (indirectly) proportional.

Strength $\boxed{}$ Weight

Speed Exercise

1. Observe living *Paramecium* and *E. coli* under the compound light microscope. Note and characterize any movement of these organisms as well as any moving organelles, i.e. flagella.
2. Using the data found in Table 2 about swimming, running and flying organisms construct a log-log graph on Excel™ where speed (cm/sec) is the x-axis and length (m) is the y-axis
3. In order to plot the three modes of locomotion on the same graph, first plot one mode of locomotion, then right click on a data point, choose the 'select data' option, add a series for the other 2 modes of locomotion, and highlight the appropriate cells. Be resourceful and figure it out!

Questions:

1. What observations about movement can be made for the *Paramecium* and *E. coli*?
2. Where are mounting preparations described?
3. What are the differences between bacterial flagella and eukaryotic flagella? What flagellar arrangement did your E. coli have?
5. Using the graph designed above, what is the relationship between speed and size? Why? Explain your graph in detail.
6. Find a scientific paper that calculates the Reynolds number of an organism and explain the study.
7. Find a scientific paper that calculates the speed of an organism. Pick an organisms which is no bigger than a fox. Explain a figure in the study that illustrates the size rule discussed today.

Conclusion:

1.Summarize the lab exercises and evaluate their effectiveness.
2. Explain the size rule and its significance (use the model organisms from lab as examples).
3. Fill-in the box with α (directly) or 1/α (indirectly) proportional to summarize the relationship between speed and weight.

Strength $\boxed{}$ Weight

Materials

- Student access to computers with Microsoft Excel® and Internet access
- Centimeter rulers
- Printed copies of Volvocine dichotomous key, Bell & Mooers data, speed data, and primate bone image

Notes for the Instructor

Student handouts may or may not include some background information. They also provide students with the exercise of the day, some follow-up questions, and instructions on how to write the conclusions for the lab assignment. The format used by the author includes a title page, objective(s), exercise(s) which depending on the lab may include observations, answers to questions, a conclusion, and references. While the author uses an unorthodox format for a lab report, the reader may redesign the handout to suit their preferences.

All exercises (with the exception of the Size of Living Things) start with an introduction and significance of the topic. Students are encouraged to participate and develop a hypothesis of the size rule that will be examined. After making graphs, students explain why they would accept or reject their hypothesis.

Size of Living Things Exercise

The main objective of this exercise is to teach students what constitutes a reliable source. Another benefit of this exercise is that it serves as an introductory lab to the size rule labs that follow.

Students are placed in groups of two or three, who will be assigned some of the 26 macroscopic and some of the 13 microscopic organisms. First assign the macroscopic organisms. Then assign the microscopic organisms. Students must look up size information (i.e. length, width, height, and/or weight) on their assigned organisms from trustworthy websites or sources, e.g. PubMed for primary literature, foundations, zoos or aquariums, are also acceptable. Ask for a volunteer to help collect and size order the macroscopic organisms. Do the same for the microscopic organisms. Some of the problems students run into include- some of the organisms only have weight or length information available, ranges of size information are provided at one source but specific sizes are provided at another source, sometimes less reputable websites (e.g. Petland, Roger's Rabbit Ranch, etc.) have more details on the organism's size but students may partially confirm/support the less reliable source with a less detailed scientific article. The exercise isn't as much about accuracy as it is about getting students used to searching for credible sources.

As students collect the size data on their organisms, have your volunteers list the macroscopic and microscopic organisms in size order on the board for all to see how their contributions fit into the bigger picture. Ask students to explain what they considered reliable and unreliable sources.

Key to Figure 1.

1. Bursaria – largest ciliate protozoan, rope-like nucleus
2. Foreleg of flea – estimate from length of a flea
3. Cheese mite
4. Small wasp
5. Rotifer – small multi-cellular animal
6. Human egg
7. Human sperm
8. Vorticella (protozoa) – attached to bottom of pond
9. Paramecium
10. Amoeba – that causes dysentery
11. Human liver cell

Key to Figure 2.

1. Blue whale
2. Tyrannosaurus
3. Diplodocus
4. Pterosaurs
5. Albatross
6. Aepyornis
7. Ostrich
8. Chicken
9. Largest snake (fossil)
10. Longest tapeworm found in humans
11. Sheep (domestic)
12. West African (Nile) crocodile
13. Komodo dragon
14. Largest Lizard (extinct)
15. Largest polyp
16. Cynaea, largest jellyfish
17. Horse
18. Giant Clam
19. Large Tarpon
20. Japanese spider crab
21. Large Atlantic lobster
22. Eurypterid (extinct sea scorpion)
23. Whale shark
24. Rafflesia, largest flower
25. Giant squid (mollusk)
26. Sequoia (w/100 ft branch)

Table 2. The maximum speed of organisms in swimming, running or flying according to size. (Images of data taken from Dr. Bonner's 1965 book entitled *Size and Cycling: An Essay on the Structure of Biology.*)

Table 2. The maximum speed of organisms of different size. The table is subdivided into 3 types of locomotion: swimming, running, and flying. This table is the basis for Figure 22.

Swimming

Species	*Length*	*Speed in cm/sec*	*Reference*
1. *Bacillus subtilus*	2.5 μ	1.5×10^{-3}	Tabulae Biologicae
2. *Spirillum volutans*	13 μ	1.1×10^{-2}	idem
3. *Euglena* sp.	38 μ	2.3×10^{-2}	idem
4. *Paramecium* sp.	220 μ	1×10^{-1}	idem
5. *Unionicola ypsilophorus* (water mite)	1.3 mm	4×10^{-1}	Welsh (1932, J. Gen. Physiol. *16*: 349)
6. *Pleuronectes platessa* (plaice; larva)	7.6 mm	6.4	Boyar (1961, Trans. Amer. Fish. Soc. *90*:21)
7. idem	9.5 mm	11.5	idem
8. *Carassius auratus* (Goldfish)	7 cm	75	Bainbridge (1961, Sympos. Zool. Soc. London *5*:13)
9. *Leuciscus leuciscus* (dace)	10 cm	130	idem
10. idem	15 cm	175	idem
11. idem	20 cm	220	idem
12. *Pomolobus pseudoharengus* (river herring)	30 cm	440	Dow (1962, J. Conseil Intern. Explor. de la mer *27*:77)
13. *Pygoscelis adeliae* (Adelie penguin)	75 cm	380	Meinertzhagen (1955, Ibis *97*:81)
14. *Thunnus albacares* (yellowfin tuna)	98 cm	2080	Walters and Firestone (1964, Nature *202*: 208)
15. *Acanthocybium solandri* (wahoo)	1.1 M	2150	idem
16. *Delphinus delphis* (dolphin)	2.2 M	1030	Hill (1950, Sci. Progress, *38*:209)
17. *Balaenoptera musculus* (blue whale)	26 M	1030	idem

Flying

Species	*Length*	*speed in cm/sec*	*Reference*
1. *Drosophila melanogaster* (fruit fly)	2 mm	190	Hocking (1953, Roy. Ent. Soc. *104*:223)
2. *Tabanus affinis* (horse fly)	1.3 cm	660	idem
3. *Archilochus colubris* (ruby-throated hummingbird)	8.1 cm	1120	Pearson (1961, dor, *63*:506)
4. *Anax* sp. (dragon fly)	8.5 cm	1000	Wigglesworth (Prin. Insect Ph
5. *Epesticus fuscus* (big brown bat)	11 cm	690	Hazard and Da (1964, J. Mam *45*:236)
6. *Phylloscopus trochilus* (willow warbler)	11 cm	1200	Meinertzhagen Ibis, *97*:81)
7. *Apus apus* (swift)	17 cm	2550	idem
8. *Cypsilurus cyanopterus* (flying fish)	34 cm	1560	Idem and Schul Stern (1948, Th of Fishes)
9. *Numenius phaeopus* (whimbrel)	41 cm	2320	Meinertzhagen Ibis, *97*:81)
10. *Anas acuta* (pintail duck)	56 cm	2280	idem
11. *Cygnus bewicki* (Bewick's swan)	1.2 M	1880	idem
12. *Pelicanus onochrotalus* (white pelican)	1.6 M	2280	idem

Running

Species	*Length*	*Speed in cm/sec*	*Reference*
1. *Bryobia* sp. (clover mite)	0.8 mm	8.5×10^{-1}	Pillai, Nelson, and Winston (Pers. comm.)
2. Species of Anyestidae (mite)	1.3 mm	4.3	idem
3. *Iridomyrmex humilis* (Argentine ant)	2.4 mm	4.4	Shapley (1920 PNAS, *6*:204; 1924, *10*:436)
4. *Liometopum apiculatum* (ant)	4.2 mm	6.5	idem
5. *Peromyscus M. bairdii* (deermouse)	9 cm	250	Layne and Benton, (1954, J. Mammal. *35*:103)
6. *Callisaurus draconoides* (zebra tailed lizard)	15 cm	720	Belkin (1961 Copeia, p. 223)
7. *Tamias striatus lysterii* (chipmunk)	16 cm	480	Layne and Benton (1954, J. Mammal. *35*:103)
8. *Diposaurus dorsalis* (Desert crested lizard)	24 cm	730	Belkin (1961, Copeia, p. 223)
9. *Sciurus carolinensis leucotis* (grey squirrel)	25 cm	760	Layne and Benton (1954, J. Mammal. *35*:103)
10. *Vulpes fulva* (red fox)	60 cm	2000	Hill (1950, Sci. Progress, *38*:209)
11. *Acinonyx jubatus jubatus* (cheetah)	1.2 M	2900	idem
12. *Struthio camelus* (ostrich)	2.1 M	2300	idem

Complexity Lab

Introduce the concepts of complexity, division of labor, multicellularity, and quorum sensing. (In another exercise, students identified volvocine species using a dichotomous key. They made observations and developed a hypothesis about the relationship between complexity and size. They then accepted or reject their hypothesis making the graph.)

Explain the benefits of using a model, like the Volvox, when examining division of labor. The author acquired 7 different volvocine species (labeled A-G), which students identified using a dichotomous key (Carolina Biological). Students practiced their microscope and imaging skills. The images they collected were included in the lab report, where they were labeled with the correct volvocine species name. Students received full credit on that part of the report if they properly identified each volvocine.

The second part of the lab entailed graphing the relationship between the total number of cells and the number of cell types (see Table 1 in Bell and Mooers, 1997). As long as students follow the exercise instructions, they will have no problem designing the graph.

Strength Lab

Discuss the physical constraints imposed by nature on living organisms, e.g. animals have muscles to overcome the force of gravity. This would be a good lab to introduce students to allometry; highlighting how in order to maintain functionality, organisms must have a design that can be altered as its length and area and mass grow at different rates. One example is how human shape changes with developmental stages; i.e. an infant's head-to-body ratio is greater than an adult's. This is also a great lab to reintroduce students to the concept of scaling factors. John Tyler Bonner uses an exponent in for weight here that is obtained from the slope. Thus, an explanation of the significance of $y = mx + b$ and the information that the slope reveals is in order- y is the strength; x is the "weight"; b is the y-intercept but we are not concerned with that here; and m is the slope, which shows how proportional the relationship is. If the slope is 1, then the relationship is perfectly proportional. If the slope is greater than 1, then the relationship is out of proportion. And if the slope is less than 1, then the relationship is slower than proportional, which is the case here.

Key to Primate Femur Heights

a. *Bonobo* 28.4 cm

b. *Homo ergaster* 44.2 cm

c. Mandrill baboon 25.6 cm

d. Five-year old child 22.1 cm

e. Siamang 18.9 cm

f. Chimpanzee 28.1 cm

g. Gorilla 38.2 cm

h. *Australopithecus afarensis* 26.5 cm

i. Orangutan 34.1 cm

j. Adult human. 48 cm

Speed Lab

Describe the modes of locomotion that organisms of various sizes employ. *Paramecium* and *E. coli* are used as examples of how microorganisms move in an aqueous environment and to describe the differences between prokaryotic and eukaryotic flagella. Note that smaller organisms are governed by surface tension forces, larger organisms are limited by gravity. This is what prompted the development of the Reynolds number. You may decide to use different organisms or even select a different mode of locomotion to compare and contrast.

We used several types of mounting preparations- (1) the hanging drop slide preparation uses a drop of water on each of the four corners of a coverslip, then turns the coverslip drop-side down into the specimen for viewing under the microscope (this can done using a dimpled slide if you wish), (2) the traditional wet mount uses Vaseline or nail polish to enclose the coverslip over the specimen, and (3) the 3 coverslip method uses two coverslips as the walls and one to cover the specimen. Add a variant of methods these or use only two.

Designing the graph for this lab is tricky. Perhaps it would not be a bad idea if this were one of the last labs, as there is a learning curve for proper Excel ™ usage.

Instructions for creating a speed vs size graph

1. Open Excel™
2. Enter Speed (cm/sec) in first column (A) then enter length (M) in the second column (B) for Swimmers
3. Repeat step 2 for Runners using columns D & E
4. Repeat step 2 for Flyers using columns G & H
5. Make a graph, one locomotion at a time
    a. Select data for swimmers

    b. Click Insert Tab, Charts, then Scatter Plot

    c. Right click on X-axis, select Format Axis, under Axis Options check logarithmic scale (leaving it in base 10, leave everything else alone), & click close

    d. Repeat step c for Y-axis

    e. Right click on any data point, Add Trendline, Select the Trend/Regression Type that produces a line through the data

    f. Right click on chart, Click Select Data, Click on Series 1, Click Edit, name series *Swimming*, then hit Enter

g. Now, click Add Series, name series Running, Click Select Range Button in the Series X values, from excel cells select only the speed data, hit Enter, Next in the Series Y values delete =*{1}*, then click Select Range Button go to the excel cells and select only the length column for runners data, click enter

h. Repeat step g for Flyers

i. Repeat Step e for Swimmers

j. Repeat Step e for Flyers

6. Edit graph in order to optimize display of data

   a. Find the lowest data value on the axis

   b. Set X- & Y-axis intercept at the lowest value

   c. To do this, Right click X-axis, click on Format Axis, under Axis Options go to Axis value, type in the lowest value, then Click Close

   d. Repeat for Y-axis

7. Add Axis and Chart titles

Sample Results

Keys to Size of Living Things Exercise

Macro-organisms

1. Cyanea
2. Tapeworm found in human
3. Largest polyp
4. Large Atlantic lobster
5. Chicken
6. Rafflesia, largest flower
7. Albatross
8. Japanese spider crab
9. Eurypterid
10. West African Crocodile
11. Domestic Sheep
12. Komodo dragon
13. Ostrich
14. Pterosaurs
15. Large tarpon
16. Giant clam
17. Aepyorniss
18. Giant squid
19. Horse
20. Largest snake (fossil)
21. Largest lizard (fossil)
22. Tyrannosaurus
23. Whale shark
24. Diplodocus
25. Blue Whale
26. Sequoia

Micro-organisms

1. Human sperm
2. Human liver cell
3. Amoeba
4. Rotifer
5. Paramecium
6. Human egg
7. Small wasp
8. Cheese mite
9. Vorticella
10. Bursaria
11. Foreleg of flea

Strength Exercise

Table 4. Class data obtained from *Strength Exercise*.

Weight (cm^3)	Strength (cm^2)
23.75	1.08
207.84	4.33
185.06	4.33
115.31	4.33
92.25	3.31
60.94	2.43
36.12	1.69
175.68	6.1
325.47	9.73
500.59	13.25

Complexity Exercise

Table 5. Cell type number and log.

10^(log of total cell #)	Cell Type #
707.9457844	2
1412.537545	2
12589.25412	3
141.2537545	4
316227.766	4
10000000000	6
3981071706	6
39810717055	6
15848931.92	5
398107170.6	7
125892541.2	7
25118864315	7
1995262315	5
794328234.7	4
25118864315	4
10000000000	5
39810717055	6
15848.93192	3
100000000	5
3162277660	7
630957344.5	8
794328234.7	9
7943282347	8
199526.2315	6
2511886432	7
1258925412	9
125892541.2	8
2.51189E+11	4
3.16228E+12	7
6.30957E+11	6
6.30957E+11	7
1.58489E+12	14
1E+12	14
1.25893E+11	14
1E+12	6
44.66835922	2
100	2
199.5262315	5
63.09573445	3
354.8133892	2
31.6227766	3
562.3413252	2
39810.71706	12
50118723.36	13
630957344.5	15
3162277.66	15
251188643.2	20
3162277.66	13
1000000000	26
707945784.4	21
707945784.4	11
446683.5922	13
10000000000	30
1E+11	17
1000000000	20
70794578.44	5
7079457844	15
6309573445	14
1000	5
15848931925	42
25118864315	44
794328.2347	18
35481338923	36
63095734448	27
25118864315	39
1E+11	42
12589254118	35
10000	5
70794.57844	7
398107.1706	8
56234132519	16
31622776602	12
3981071.706	6
3162277660	7
63095734448	12
63095734448	13
6309573.445	12
19952623150	12
2511886432	13
1.99526E+11	14
2.51189E+11	11
3981071706	7
1000000000	11
15848.93192	5
11220.18454	9
1258925.412	9
630.9573445	3
199.5262315	3
10000000000	57
6309.573445	16
19952623150	26
50118.72336	12
251188.6432	13
3548.133892	14
70794.57844	12
31622.7766	10
44668.35922	11
10000	23
3.16228E+11	69
3162277660	50
5.01187E+13	99
2.51189E+11	122
2.51189E+11	116
1.99526E+11	102
63095.73445	15
125.8925412	3
31622776.6	22
1E+13	22
10000	13
3548.133892	16
39810.71706	10
7079.457844	18
1258.925412	15
3162.27766	13
1778.27941	15
7943.282347	16
223.8721139	3
1584.893192	3
28.18382931	3
19.95262315	6
1412.537545	3
19952.62315	9
1000	7
446.6835922	23
891.2509381	24
316.227766	4
1778279.41	14
125892541.2	9
501187.2336	14
354813.3892	12
10000	16
141253.7545	16
3162.27766	13
89.12509381	3

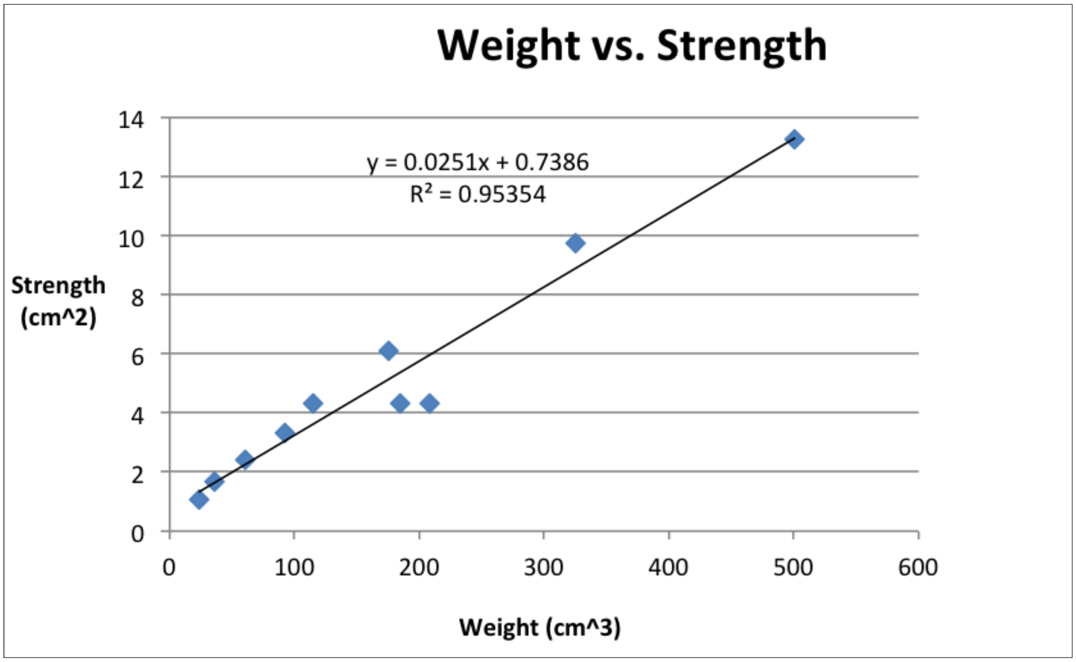

Figure 4. Plot of strength vs. weight data.

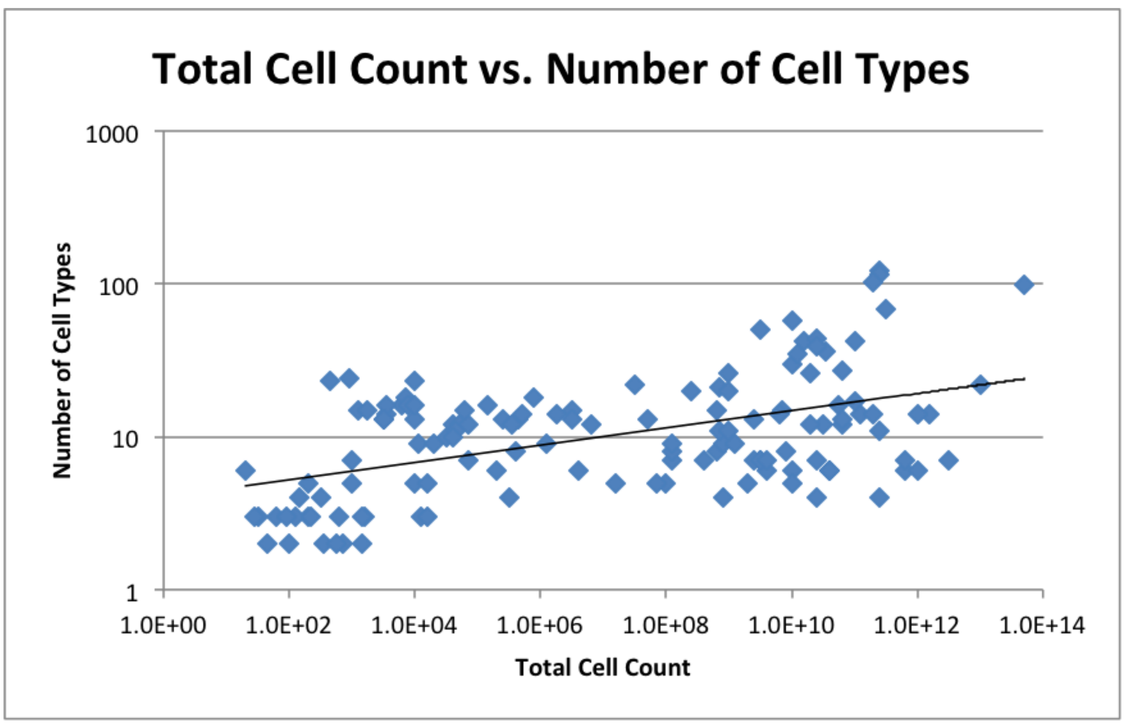

Figure 5. Total cell count vs number of cell types.

Speed Exercise

Table 6. Comparison of locomotion and length.

Swimming		Running		Flying	
Speed in cm/sec	**Length (M)**	**Speed in cm/sec**	**Length (M)**	**Speed in cm/sec**	**Length (M)**
0.0015	0.0000025	0.85	0.0008	190	0.002
0.011	0.000013	4.3	0.0013	660	0.013
0.023	0.000038	3.3	0.0024	1120	0.081
0.1	0.00022	6.5	0.0042	1000	0.085
0.4	0.0013	250	0.09	690	0.11
6.4	0.0076	720	0.15	1200	0.11
11.5	0.0095	480	0.16	2550	0.17
755	0.07	730	0.24	1560	0.34
130	0.1	760	0.25	2320	0.41
175	0.15	2000	0.6	2280	0.56
220	0.2	2900	1.2	1880	1.2
440	0.03	2300	2.1	2280	1.6
380	0.75				
2080	0.98				
2150	1.1				
1030	2.2				
1030	26				

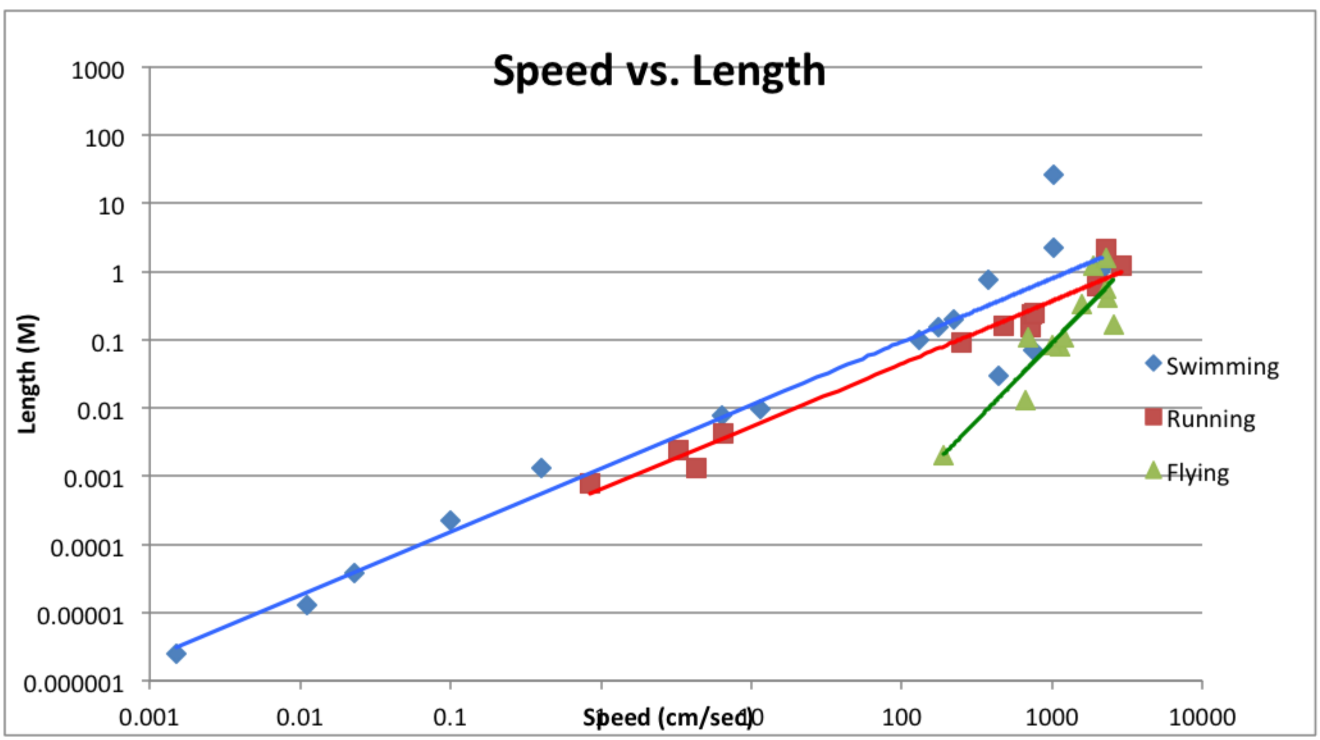

Figure 6. Comparison of speed vs. length for different modes of locomotion.

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About the Author

Ken Sossa is a neuroscientist who predominantly teaches physiology courses. He, however, ventured into new and amazing territory when teaching Unity and Diversity of Life. It is that course that spawned his interest in size issues and thus the labs written about here.

Mission, Review Process & Disclaimer

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