and stored smears are later stained after the "Breed method," and the bacteria counted. The resulting numbers of bacteria per field are plotted against time (see Fig. 1, an actual example from class data). Interpretation of the resulting curves, and their comparison with a curve based on the class' average data, provide insight into such varied matters as evaluation of statistics, dairy products examinations, and the ecology of "closed systems."

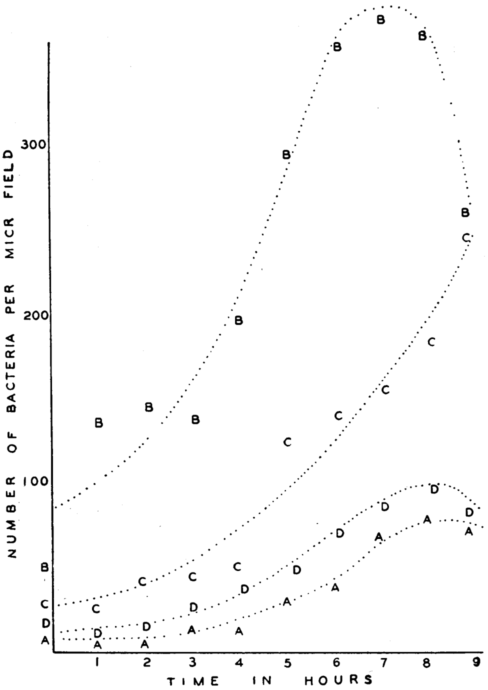

Fig. 1. Student determinations of growth rates of bacteria in milk samples. Since the Breed method of counting bacteria in milk does not distinguish between living and dead bacteria, the "maximum stationary phase" on the above curves should appear to continue indefinitely. The data, contradicting this expectation in curves A, B and D, may perhaps be explained as due to actual destruction of dead bacteria, agglutination, or similar phenomena in the rapidly changing medium.

Some Simple Physical Principles in General Biology

PAUL A. MEGLITSCH
Drake University, Des Moines, Iowa

and

JOHN P. WESSEL
Chicago City Junior College, Herzl Branch

Many students in introductory biology courses lack an adequate background in the physical sciences. This deficiency poses an important problem, namely, *the selection of material for illustrating quantitative principles.* This material should be of such a nature that it can be understood with a minimum knowledge of the physical sciences. This paper has a dual purpose: 1) to stimulate other teachers to aid in the solution of this problem and 2) to contribute some material for the teaching of quantitative concepts in an introductory course.

Some simple physical laws can be shown to have a direct bearing on the determination of the form and function of organisms. These cases serve to emphasize the importance of the quantitative viewpoint in interpreting the phenomena observed in biological studies.

RELATION OF SURFACE TO MASS

One of the simplest relationships—that of surface to mass—is one of the most rewarding. That surface and mass will increase at different rates is simply demonstrated and can be understood without any background in the physical sciences. A discussion such as the following will, by analogy, explain this relationship not only for cubes, but for other geometrical figures.

Assuming that two solids have the same shape, their surfaces are to each other as the square of their linear dimensions, while their masses are to each other as the cubes of their linear dimensions. For example, a cube 1 inch on each side has 6 square inches of surface and a volume of 1 cubic inch. If we double the linear dimensions to 2 inches on each side, the surface is now 24 square inches and the volume 8 cubic inches. The surface has increased 4 times (2 squared) while the volume has increased 8 times (2 cubed).

The cell membrane, the absorptive surfaces of the intestine and the respiratory surfaces of gill and lung are examples of physiologically active surfaces. There are many such surfaces which play an essential role in the dynamics of the organism. The rate at which materials pass through these surfaces is dependent upon the *area* exposed and the *efficiency* of the structure for its particular function. The requirements of an organism for oxygen, food, or water, on the other hand, depends directly on the mass of the protoplasm, all other things being equal. It is evident, therefore, that the surface-mass ratio has a determining effect on form and function whenever a dynamic imbalance of surface and mass develops.

Surface-mass relationships operate at the cellular level as well as at higher levels. There is considerable evidence to indicate that in any given type of cell there is a certain more or less constant ratio between the size of the nucleus and the cytoplasmic mass. Since materials can enter or leave the nucleus only by passing through the nuclear membrane, the surface area of the membrane limits the rate with which materials enter and leave the nucleus. Among larger protozoa, for example, the macronucleus is elongated, beaded, or irregular, thus exposing a greater surface to the cytoplasm than would be the case if it were spherical or oval as in most of the smaller protozoa. In the same manner the area of the plasma membrane acts as a limiting factor in the rate of absorption of substances required by the cytoplasmic mass, and so tends to limit the maximum size which the cell or protozoan can attain. In a cylindrical organism, increase in length without concomitant increase in diameter permits growth in size without materially altering the surface-mass relationship, a fact which may be correlated with the common occurrence of very greatly elongated ciliates, some of which attain a length of several millimeters. When the organism is greatly flattened, an increase in mass does not materially change the surface-mass ratio if growth occurs only in length and breadth without effecting thickness. Several species of Myxosporidia attain a considerable size, measuring from five to ten millimeters in length and breadth, while they are only one hundred microns or less in thickness.

THE CRITICAL POINT

In the evolution of organ systems, the order in which they appear is made more comprehensible when it is kept in mind that the proportion of surface area to mass is decreasing with the increase in the size of the organism. A point is eventually reached when the surface area is inadequate to support the mass of protoplasm. At this *critical point,* the surface-mass ratio becomes a vital factor limiting the maximum size which the organism can attain without a change in form. For various important physiological processes the critical point is reached at a different stage of evolution, a fact which may be correlated with the evolutionary order of the appearance of the various systems.

The molecular size of foods is larger than that of oxygen or of carbon dioxide and therefore are absorbed at a slower rate. Simple organisms may require a specialized digestive system although the body surface is sufficient to take care of the respiratory needs. We encounter this situation in coelenterates and flatworms. In general, molecules of nitrogenous wastes are of an intermediate size and the critical point for excretion is reached before that for respiration. Although the surface of the body of flatworms is adequate for respiratory needs, special excretory adaptations, such as flame cells and excretory tubules have been evolved. It is only among the larger invertebrates that such specializations as tracheal tubes, gills, and respiratory pigments are found.

As new psysiological interrelationships evolve, the ratio of surface to mass at which a critical point is reached may be greatly changed. Among annelids, the fluid-filled coelom and the haemolymph system facilitates the distribution of food substances. The movement of these body fluids carries foods away from the absorptive surface, resulting in the stepping-up of the diffusion gradient. The rate of diffusion is thus accelerated and a relatively smaller absorptive surface suffices in these forms. However, in larger annelids, e.g. *Lumbricus,* the surface of the digestive tube may be increased by a typhlosole, possibly indicating that the surface-mass ratio is again approaching a critical point.

Annelids provide other excellent examples of the physiological consequences of increased bulk. The elongation and coiling of the nephridial tubules is a specialization which increases surface area. The slow diffusion rate of oxygen in water and the low oxygen concentration in the tubes in which some of the aquatic annelids dwell is correlated with various adaptations for increasing the respiratory surface, such as external gills and the development of respiratory pigments.

THE EXOSKELETON

"In arthropods the exoskeleton is composed of dead material and encases the soft tissues. This type of skeleton interferes with continuous growth. The growth period in such forms is relatively short and periodic, that is, it occurs only during the periods when a new skeleton is being formed following the shedding of the old one. In vertebrates the living endo-skeleton does not in any way interfere with the growth of the organism; consequently many of these forms become massive. As a group the vertebrates are the largest of all animals. The difference in size between vertebrates and higher invertebrates in largely due to differences in the amount of muscular tissue. There is a relationship between the amount of muscular tissue and the amount of skeletal surface for muscle attachment. The increased amount of muscle and skeletal tissue imposes increased nervous, nutritive, respiratory, excretory, and circulatory requirements."* It is thus among vertebrates that changing surface-mass ratios are most strikingly illustrated.

THE VERTEERATES

The absorptive and secretory surfaces of vertebrates exhibit a variety of adaptations which are correlated with the decreased ratio of surface to mass imposed upon the organisms by their large size. In all vertebrates there is some form of internal folding which increases the total

---

* MEGLITSCH, P. A. and J. P. WESSEL, *An Introduction to Biological Principles,* Burgess Publishing Co., Minneapolis, Minn., pp. 63–64. 1948.

surface of the gastro-intestinal tract. Among the elasmobranchs the spiral valve adds to the absorptive surface, while among other groups the elongation and coiling of the ileum serves the same purpose. Increased diameter of the colon slows the rate of movement of its contents, thus increasing the time for absorption of water, bile salts, and vitamin K.

Among fishes an adequate respiratory surface is attained through the agency of a pharyngeal gill system. Modern amphibia, all relatively small and capable of exchanging respiratory gases through the body surface, have a poorly developed lung with incomplete and sparse partitioning. Reptiles are provided with a lifeless, impermeable outer covering of scales. Their increased size and their loss of cutaneous respiration is compensated for by an increase in lung surface and a more effective separation of systemic and pulmonary blood streams.

Although the changing surface-mass ratio undoubtedly influences the development of most organ systems, there are a number of instances in which it must play but a minor role. The change from aquatic to terrestrial life imposes the necessity for a more economical use of water. This is probably correlated with an increase in the reabsorptive power of the urinary tubules, made possible by their increase in numbers and length. Warm-bloodedness increases the metabolic rate and thus demands an increased excretory surface in birds and mammals.

The Warm-blooded Animals

Among warm-blooded animals the high metabolic rate imposes a new strain on digestive, respiratory and excretory systems, as well as on the circulatory system which must distribute materials to the various body parts more rapidly or more efficiently. The four-chambered heart coupled with the relatively rapid pulse rate, the reduction of the renal portal system and the compensating development of the arterial supply to the kidney all serve to increase the efficiency of circulation. The increase in length and internal folding in the alimentary tract; the increase in the partitioning of the lungs and more efficient oscillatory mechanisms; an the increase in the number of renal corpuscles are all factors which have helped to make warm-bloodedness possible.

The maintenance of a constant body temperature depends upon a balance between heat production and heat loss. Many factors influence the rate of heat loss when the environmental temperatures are high. However, as environmental temperatures decrease the percentage of total heat loss through conduction and radiation at the body surface constantly increases. As a result the total surface area of the animal becomes an increasingly significant factor among mammals and birds living in cool or cold climates. Since the smaller animals have a relatively greater ratio of surface to mass, the amount of heat loss at the body surface will be higher per unit of mass than in more bulky forms.

The amount of heat produced depends upon the volume of the tissues, especially muscles, in which oxidative processes occur. In smaller organisms, therefore, there is a relatively greater amount of heat loss and the metabolic rate must be higher. Thus heart rate, body temperature, speed of reproductive cycle, etc., tend to increase in smaller organisms. A mouse is said to consume half its body weight in food in twenty-four hours, while man, for example, takes in about a fiftieth of his body weight in the same period. The net result is to place a limitation on the minimum size of warm-blooded forms. All other things being equal, this minimum size will vary with the external temperature, and in colder climates the smallest warm-blooded animals would freeze. This is undoubtedly correlated with *Bergmann's Rule* which states that races living in cooler climates are larger in body size than races of the same species in warmer climates. Local temperature loss may cause discomfort, and even freezing, in relatively small parts which have a proportionally large surface. Thus fingers, toes and ears are usually the first body part to suffer cold. This is undoubtedly correlated with *Allen's Rule,* which states that the races of mammals living in cooler regions have relatively shorter tails, legs and ears than races of the sames species in warmer regions. It also applies to birds, with respect to relative lengths of beaks, legs and wings.

To Cut or Not to Cut!

DONALD S. LACROIX
Amherst High School, Amherst, Massachusetts

There seem to be several ''schools of thought'' in the matter of dissecting preserved specimens in the high school biology course. There are some secondary school biology teachers who require minute and careful studies of anatomy in worms, frogs, crayfish and what-not—who require the memorizing of bone names, muscle pieces and sundry other portions. Again, there are those teachers who suggest little or no dissecting—simply leaning on the text-book drawings. I suspect that between these extremes we find on the one hand the teacher who has taken several college courses in comparative anatomy and who is steeped in the tradition of memorizing a lot of ''part'' names; and on the other hand the teacher who never had much actual laboratory work with a dissecting kit, and is therefore afraid to tackle any ''dismembering'' with a bunch of high school pupils.

From the average high school (if such exists!) only a few pupils go on to college. Of these, still fewer will undertake any courses of a biological nature. Most of the boys and girls in the high school biology course will join the ranks now occupied by Mr. and Mrs. Average Citizen. Hence it would seem to be a waste of time to require these students to make detailed studies of the anatomy of preserved specimens. The logical procedure is to give the youngsters a chance to do some dissection—enough ''opening up'' of several types to observe the development of digestive systems, respiratory apparatus, reproductive organs, skeletal structures and so on—but without having to study and memorize many parts and minute pieces. Those students who enter institutions of higher learning to pursue medicine, surgery, nursing or other biological courses will get enough of that type of study when the time comes. Those who, upon graduating from high school are to become secretaries, clerks, machinists or ditch-diggers will have gained little from learning the names of all the bones in a cat's skeleton—but they should get a fairly good mental picture of how they themselves ''tick'' if they have had the opportunity to see the insides of several types of animals.

The usual preserved specimens mentioned above have been used from early times in school biology and certainly have a place in the sun. Greater interest