Principles of Animal Physiology: Mechanistic & Evolutionary Approaches

ZCT – 434 [Topic No: 1] Lecture No: 1
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In the words of the renowned physiologist Knut Schmidt- Nielsen, animal physiology is **"*the study of how animals work*."** Animal physiologists study the structure and function of the various parts of an animal, and how these parts work together to allow animals to perform their normal behaviors and to respond to their environments.

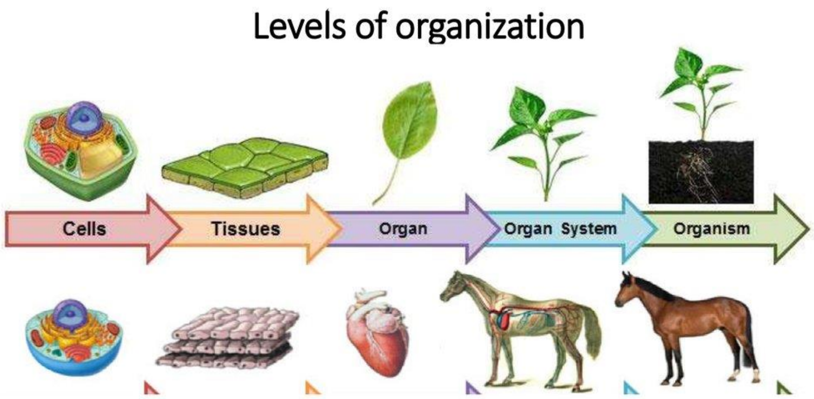
One hallmark of animal physiology is diversity. More than a million different species of animals live on Earth, each of which has acquired through evolution countless unique properties. Each physiological process is a product of the activities of complex tissues, organs, and systems that can arise through complex patterns of genetic regulation of countless cells.

Despite this great diversity, there are many commonalities within physiology unifying themes that apply to all physiological processes.

- First of all, physiological processes obey physical and chemical laws.
- Second, physiological processes are regulated to maintain internal conditions within acceptable ranges. This internal constancy, known as *homeostasis*, is maintained though feedback loops that sense conditions and trigger an appropriate response.
- Third, the physiological state of an animal is part of its *phenotype*, which arises as the product of the genetic makeup, or *genotype*, and its interaction with the environment.

- Fourth, the genotype is a product of evolutionary change in a group of organisms—populations or species—over many generations.

Most physiological studies examine how various processes affect the physiological phenotype of an animal. Both the genotype of an organism and its environment interact through development to produce the phenotype of the adult organism. The phenotype is itself the product of processes at many levels of biological organization, including the biochemical, cellular, tissue, organ, and organ system levels. Together these processes interact to produce complex behaviors and physiological responses.



The environment can, in turn, influence the adult phenotype. Organisms may change their behavior as a result of learning, or alter their physiological responses through modification of their phenotypes. Ultimately, the phenotype (morphology, physiology, and behavior) of an animal influences its reproductive success. Differential survival of organisms with distinct phenotypes may result in evolutionary change in the genotype of a population over many generations.

Modern animal physiology is a discipline concerned with the whole range of processes that affect animal function. Although animal physiology is an experimental science that can trace its roots back more than two millennia to the ancient Greeks, it plays an important role in modern biology as the intellectual glue that holds disparate biological fields together.

A Brief History of Animal Physiology

- Although Greek thinkers such as Hippocrates (460–*circa* 377 B.C., the father of medicine) and Aristotle (384–322 B.C., the father of natural history) were not primarily experimental physiologists, Hippocrates' emphasis on the importance of careful observation in the treatment of disease and Aristotle's emphasis on the relationship between structure and function make them important figures in the history of physiology.
- Claudius Galenus (A.D. 129–*circa* 199), known as Galen, was the first to use systematic and carefully designed experiments to probe the function of the body. Galen made extensive use of dissection and vivisection of nonhuman primates such as Barbary apes and other mammals to test his physiological ideas. For example, Galen performed experiments in which he tied off the ureters (the tubes leading from the kidney to the bladder), and observed that the kidneys swelled. From this observation he concluded that the kidneys play a role in the formation of urine. Similarly, he tied off the laryngeal nerve (which leads to the vocal cords) of a living pig, at which point the pig stopped squealing. From this experiment, he concluded that the brain and nerves regulate the voice. This experimental work, combined with his practice as a physician to the Roman gladiators, allowed him to formulate detailed descriptions of anatomy and elucidate the basis of many physiological processes. Although much of Galen's work was fundamentally incorrect when viewed from a modern perspective, his emphasis on careful observation and experimentation makes him the founder of physiology.
- During the Middle Ages the medical traditions of the ancient Greeks were practiced and further developed by physicians in the Muslim world, most notably Ibn al-Nafis (1213–1288), who was the first to correctly describe the

anatomy of the heart, the coronary circulation, the structure of the lungs, and the pulmonary circulation. He was also the first to describe the relationship between the lungs and the aeration of the blood.

- The Renaissance brought a new flowering of physiological research in the Western world. Jean- Francois Fernal (1497–1558) outlined the current state of knowledge of human health and disease.
- Andreas Vesalius (1514–1564), author of the first modern anatomy textbook, demonstrated that Galen had made many errors in both anatomy and physiology. Because Galen was thought to have done everything that was necessary to understand the workings of the body, many medical practitioners of the time shunned physiological research. Thus, by showing that Galen was not entirely correct, Vesalius's work triggered the modern study of anatomy and physiology.
- William Harvey (1578–1657) identified the path of blood through the body, and showed that contractions of the heart power this movement. Although Harvey could not see the fine capillaries that connect arteries and veins using the crude magnifying glasses that were available at the time, he postulated that they must exist to form a closed circulation for the blood around the body. Harvey showed how dissections, close observation of living organisms, and careful experiments could be combined to teach us about the functions of the body.
- Prior to the 18th century, physiologists fell into one of two camps. The ***iatrochemists*** believed that body function involved only chemical reactions, whereas ***iatrophysicists*** believed that only physical processes were involved.
- In the late 17th and early 18th centuries a Dutch physician, Hermann Boerhaave, and his Swiss pupil, Albrecht von Haller, proposed that bodily

functions were a combination of both chemical and physical processes. By uniting these two approaches, these researchers were among the earliest proponents of physiology as we understand it today.

In the 19th century physiological knowledge began to accumulate at a rapid rate.

- For example, in 1838 Matthias Schleiden and Theodor Schwann formulated the “cell theory,” which states that organisms are made up of units called cells, a discovery that paved the way for modern physiology.
- Claude Bernard (1813–1878) discovered that hemoglobin carries oxygen, that the liver contains glycogen, that nerves can regulate blood flow, and that ductless glands produce internal secretions (hormones) that are carried in the blood and influence distant tissues. One of Bernard’s most important contributions was his concept of the **milieu interieur** (internal environment); he postulated that living organisms preserve a distinct internal environment despite changes in the external environment.
- This concept—the ability to maintain a constant internal environment—was later developed more fully by the American physiologist Walter B. Cannon (1871–1945), who **coined the term *homeostasis*.**

Until the 20th century, physiologists made little distinction between animal physiology and medical physiology. Most physiological experiments on animals were performed with the goal of improving the understanding of the human body both in health and in illness. But in the 20th century biologists became interested in applying the newly emerging physiological knowledge to animals living in diverse environments, and in trying to understand the nature of physiological diversity.

- Per Scholander (1905–1980) was one of the first and most influential of these comparative physiologists. Scholander studied a remarkable diversity of physiological responses, including the mechanisms involved in diving vertebrates, the responses of warm-blooded animals to cold environments, and how fish fill their swim bladders (air-filled organs that fish use for buoyancy). Scholander also organized the influential **expeditions of the *Alpha Helix*** in the research program.

- The contributions of C. Ladd Prosser (1907–2002) include the discovery of so-called **central pattern generators**. These groups of neurons coordinate many rhythmic behaviors, including breathing and walking. Prosser also discovered the relationship between muscle diameter and conduction speed, and during World War II he worked on the effects of radiation on animal life as part of the Manhattan Project.
- Knut Schmidt-Nielsen (1915–2007) devoted his career to understanding how animals live in harsh and unusual environments. In his classic early work on the adaptations of the camel to desert life, he showed that the camel's nose contains a countercurrent exchanger that allows it to recapture moisture from exhaled air, resulting in an almost 60% reduction in water loss compared to other mammals.
- George Bartholomew (1923–2006) is the founder of the field of ecological physiology, or the study of how an organism interacts with its environment. Bartholomew combined the study of animal behavior, ecology, and physiology to assess the evolutionary significance of adjustments or adaptations in animals to their environments. He identified the individual as the principal unit of natural selection, and emphasized the importance of variation in physiology.
- Peter Hochachka (1937–2002) and George Somero (1941–) founded the field of adaptational biochemistry. By applying the concepts and techniques of biochemistry to the questions of comparative physiology, they have extended to the subcellular level our understanding of how animals adapt to hostile

environments, providing insights into the biochemical mechanisms that allow animals to live in habitats as diverse as the deep sea, the Antarctic oceans, high mountain peaks, and tropical rain forests. Any attempt to survey the major figures in the history of animal physiology excludes countless other researchers who have made important contributions to the field.

Subdisciplines in Physiological Research

Modern physiological knowledge is the product of the efforts of multitudes of scientists with diverse interests and expertise. Typically, an animal physiologist specializes in one or two subdisciplines of physiology, with an awareness of the central issues in other, related subdisciplines. There are three main ways to categorize physiological subdisciplines:

- By the biological level of organization,
- By the nature of the process that causes physiological variation, and
- By the ultimate goals of the research.

Physiological subdisciplines can be distinguished by the biological level of organization

Since physiology is concerned with biological function at many levels of organization, one of the most common ways to distinguish branches of physiology is by reference to these levels.

- **Cell and molecular physiologists** study phenomena that occur at the cellular level, although these effects have important consequences for higher levels of organization. Cell and molecular physiologists might include researchers studying molecular genetics, signal transduction, metabolic biochemistry, or membrane biophysics.

- Many physiologists focus their efforts on specific physiological systems. A **systems physiologist** is concerned with how cells and tissues interact to carry out specific responsibilities within the whole animal. Thus, there are respiratory physiologists, sensory physiologists, and so on.
- An **organismal physiologist** is most often concerned with the way an intact animal undertakes a specific process or behavior. For example, an organismal physiologist might study changes in animal metabolic rate in response to a stressor, such as temperature. An organismal characteristic such as metabolic rate is the product of multiple physiological systems interacting in complex ways. Some organismal physiologists specialize in particular groups of animals: thus, there are marine mammal physiologists, avian physiologists, fish physiologists, and so on.
- An **ecological physiologist** studies how the physiological properties of an animal influence the distribution and abundance of a species or population. For example, an ecological physiologist may study how the nutrient distribution in the environment influences the growth rate of an animal. While organismal physiologists may focus their research on an interesting group of animals, ecological physiologists are more concerned with how an interesting environment affects diverse animals within that environment.
- An **integrative physiologist** attempts to understand physiological processes at a variety of levels of biological organization and across multiple physiological systems. For example, an integrative physiologist might study how variation in hemoglobin genes contributes to differences in oxygen delivery and how those differences in the ability to extract oxygen from the environment contribute to the geographical distribution of the species.

Of course, there is a great deal of overlap among these subdisciplines, and making distinctions among them is often difficult. In fact, few physiological researchers confine themselves exclusively to investigating a single level of biological organization.

Often a physiologist interested in a process at one level of organization also studies its function at the next lower level. This approach, known as **reductionism**, assumes that we can learn about a system by studying the function of its parts. Although a reductionist approach can be extremely illuminating, and has been the basis of many important biological discoveries, ultimately many processes have characteristics that are not apparent simply by examining the component parts. This feature of complex systems is called **emergence (Wholism)**, which is just another way of saying that the whole is often more than the sum of its parts. The emergent properties of a system are due to the interactions of the component parts of the system, and can be difficult to predict by studying each part in isolation. Physiologists are usually interested in these emergent properties, and thus physiologists study how molecules, cells, and tissues interact to produce the complex system that is an organism.

Physiological subdisciplines can be distinguished by the process that generates variation

Many physiologists are interested in how biological functions change over time or in response to changes in the environment. Thus, physiology can also be divided on the basis of the mechanism by which changes or differences in physiological processes arise.

- A **developmental physiologist** studies how structures and functions change as animals grow through the various life stages from embryo to reproductive maturity, to senescence and death. These developmental pathways transform omnipotent stem cells into specialized cells, forming multicellular tissues and physiological systems. To understand the diversity in animal morphology and function, it is important to appreciate how these structures arise in development.

- An **environmental physiologist** assesses how animals mount physiological responses to environmental challenges. For example, changes in temperature have the potential to affect many physiological systems in complex ways. An environmental physiologist is concerned with the way an individual animal organizes or reorganizes its physiology to survive the environmental challenge.
- An **evolutionary physiologist** is primarily concerned with explaining how specific physiological traits arise within lineages over the course of multiple generations. Thus, evolutionary physiologists may be interested in the origins of variation within populations of a single species, or the basis of differences between closely related groups of animals.

Animal physiology can be a pure or an applied science

Physiological research can be distinguished on the basis of the ultimate goal.

The research of an **applied physiologist** is intended to achieve a specific, practical goal. For example, physiologists study some animals because of their economic importance.

- Thus, **veterinary medicine** relies on physiological research to improve the health of agricultural animals and household pets.
- Similarly, much physiological research is aimed at understanding the human body. Although the ultimate goal of **medical physiology** is to understand human disease, medical physiology relies on other species as model systems.
- In contrast to a medical physiologist, who uses animals to understand the human condition, a **comparative physiologist** studies animals to explore the origins and nature of physiological diversity. Comparative animal physiology

thrives on the breadth of physiological diversity, all the while searching for unifying themes.

Unifying Themes in Physiology

In spite of the vast and diverse nature of animal physiology, several unifying themes and principles apply to all of its subdisciplines:

Table 1 Unifying themes in animal physiology.

Unifying theme	Examples
Physiological processes obey the laws of physics and chemistry.	Mechanical engineering rules apply to physical properties of animals. Chemical laws, including the effects of temperature, govern interactions between biological molecules. Electrical laws describe membrane function of all cells, including excitable cells. Body size affects many physiological processes.
Physiological processes are usually regulated.	Homeostasis is the maintenance of internal constancy. Negative feedback loops help maintain homeostasis. Positive feedback loops generate an explosive response.
The physiological phenotype is a product of the genotype and the environment.	Even identical genotypes can result in different phenotypes. Phenotype changes with normal development. Phenotype changes with environmental and physiological challenges. Phenotypic plasticity is the ability of a phenotype to change in response to environmental conditions.
A genotype is the product of evolution, acting through natural selection and other evolutionary processes.	The definition of adaptation is context dependent. In the strictest evolutionary sense, adaptation refers to a trait that confers an increase in reproductive success. Adaptation can also refer to phenotypic changes that improve the performance of a physiological system, without underlying evolutionary change. Not all physiological differences are adaptations.

Physics and Chemistry: The Basis of Physiology

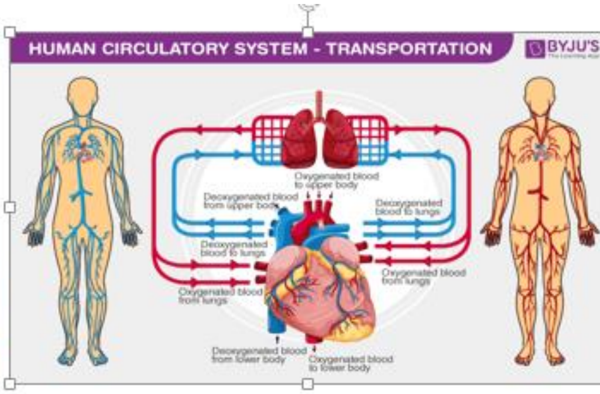
To understand physiology you need a basic understanding of chemistry and physics. Animals are constructed from natural materials and thus obey the same physical and chemical laws that apply to everything that we see around us. Temperature, for example, exerts its effects on physiology by altering the nature of chemical bonds in biomolecules or solubility of gases in solution. Physiologists often borrow concepts and techniques from the physical and chemical sciences, including engineering, to help them understand how animals work.

Mechanical theory helps us understand how organisms work

Each material has physical properties that are useful in some contexts but not others. It would be a mistake for an engineer to design a skyscraper from Styrofoam, or a kite of concrete. Likewise, biological materials, or biomaterials—proteins, carbohydrates, and lipids—also have characteristic physical properties that make them useful for some processes but not others.

- For example, some proteins are rigid and inflexible whereas others readily deform. The physicochemical characteristics of these biomaterials are determined by their molecular properties.
- For example, a network of proteins can be made more rigid by additional bonds that cross-link proteins together. Cells use enzymatic reactions to fine-tune the physical properties of macromolecules. The macromolecules combine to form cells, which are collected together to form tissues.

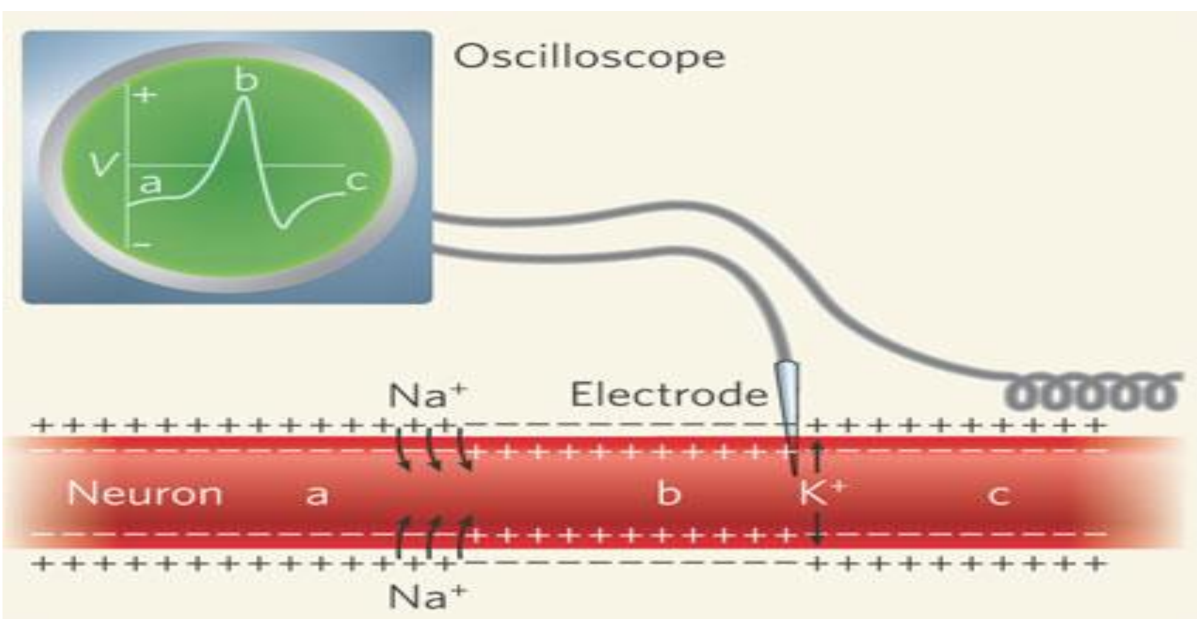
Thus, the **mechanical properties** of a tissue, such as bone, are conferred by the molecular properties of the components of the bone-forming cells, the nature of the connections between cells, and the interactions between tissues.



In addition to **mechanical properties, other engineering concepts such as flow, pressure, resistance, stress, and strain play important roles in physiology.** An engineer designing a system to pump water from a deep well takes into consideration factors such as the pressure gradients, fluid dynamics, the power of the pump, and resistance in the plumbing. A cardiovascular physiologist has the same concerns in trying to understand how the heart delivers blood through the blood vessels.

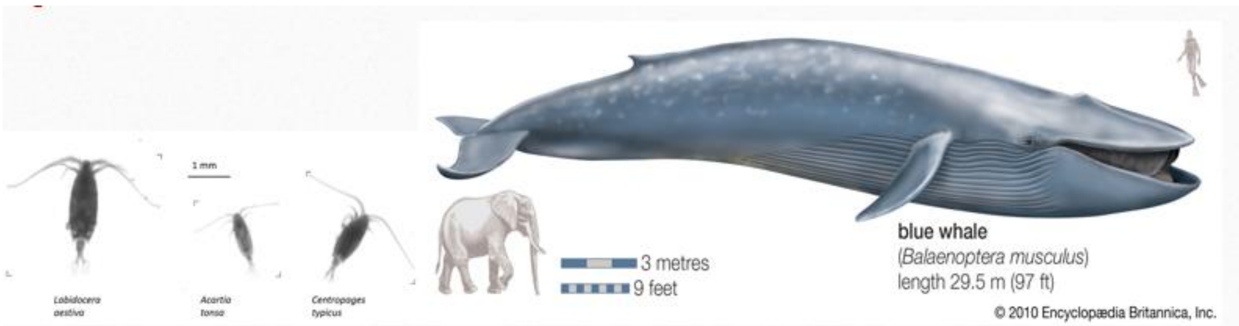
Electrical potentials are a fundamental physiological currency

Just as we use electricity to power many of the machines we use in our daily lives, animals use electricity to power cellular activities. Cells establish a charge difference across biological membranes by moving ions and molecules to create ion and electrical gradients. All cells and many organelles within cells rely on this potential difference, or membrane potential, to drive processes that are needed for survival. Animals also use changes in electrical potentials to send signals within and between cells, helping to coordinate the complex processes of the body. Muscles and neurons, two cell types that are found only in animals, use changes in membrane potential to send signals. Thus, electrical theory has played an important role in helping physiologists to understand the way that neurons and muscles work.

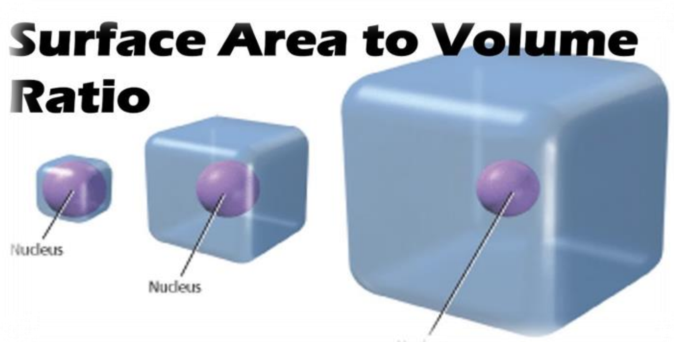


Biochemical and physiological patterns are influenced by body size

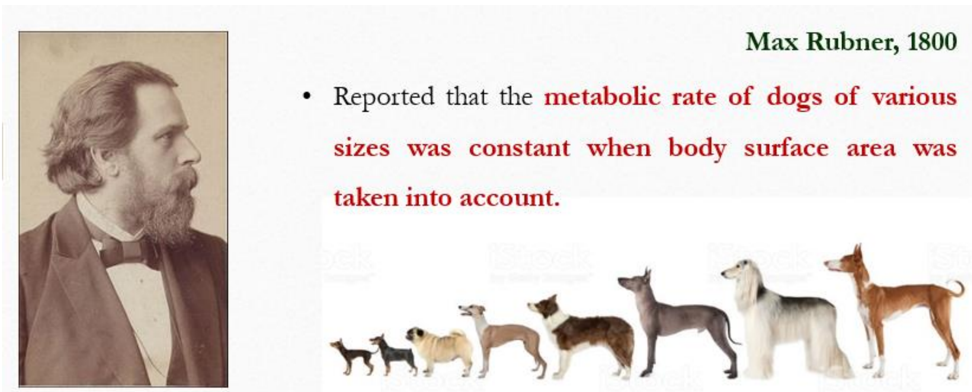
From tiny zooplankton weighing less than a milligram to blue whales weighing over 100,000 kg, animals vary greatly in body size, and these differences have profound effects on physiological processes.



One reason is that the ratio of the surface area to volume changes with body size. Consider an animal shaped like a sphere. With a radius *r*, its mass, or rather its volume (V) = $(4/3)\pi r3$ and its surface area (A) = $4\pi r2$.



Since surface area increases by the power of two, and volume increases by the power of three, the surface area is proportional to the volume to the 2/3 power, or $V0.67$. This relationship between surface area and volume has an important influence on thermal biology. Heat is produced by tissue metabolism, and thus the metabolic rate of the animal as a whole depends on the mass of tissues. Metabolic heat is lost across the surface of the body. Since heat production varies with body mass and heat loss varies with body surface area, a larger animal has more difficulty shedding metabolic heat than does a smaller animal. It has long been known that metabolic rate of animals does not increase proportionately with body mass. That is, animals differing 10-fold in body size differ less than 10-fold in metabolic rate. In the late 1800s, Max Rubner reported that the metabolic rate of dogs of various sizes was constant when body surface area was taken into account. For many years, it was thought that the relationship between body mass and metabolic rate was related to the ratio of surface area to volume.



In the 1930s, Max Kleiber examined the influence of body size on metabolic rate of birds and mammals. Based on these data, he formulated the **allometric scaling** equation, relating body mass (*M*) and metabolic rate (*y*)

$$y = aM^b$$

where *a* is the normalization coefficient and *b* the **scaling coefficient**. Kleiber's work suggested the value for *b* was closer to 0.75 (3/4) rather than the value of 0.67 (2/3) expected from Rubner's studies.

These data, and many studies since, suggest that allometric scaling of metabolism is not easily explained by simple differences in ratio of surface area to volume. Despite the complexity of size dependent physiological properties, or perhaps because of the complexity, allometric scaling remains one of the dominant themes in comparative animal physiology. Normally reticent physiologists have been inspired to engage in animated, and sometimes vitriolic arguments about both the exact value of *b* and the underlying mechanisms.

Physiological Regulation

Most organisms are faced with environmental variation. Temperature, food availability, and the physiochemical environment around an animal may change with the time of day, the season, or the movement of an animal across the landscape. Multicellular animals can be classified according to the strategies they use to cope with changing conditions.

- **Conformers** allow internal conditions to change when faced with variation in external conditions.

  For example, the body temperature of a fish will be low in cold water and high in warm water. Thus, each of the cells in a fish's body must cope with the effects of changes in external temperature.

- **Regulators** maintain relatively constant internal conditions regardless of the conditions in the external environment.

  For example, human body temperature is likely to be approximately 37°C whether the person are in a warm room or standing outside on a very cold day. Human body has mechanisms to maintain its internal temperature, and thus the vast majority of the cells in your body do not have to cope with the effects of changes in ambient temperature.

Each strategy has its benefits and costs. Because physiological responses demand metabolic energy, conforming is much less expensive than regulating. However, environmental changes can have deleterious effects on physiology, so regulating provides a much more stable internal environment.

Animals may be regulators with respect to one internal parameter, but conformers with respect to another parameter. For example, lizards conform to external temperature but regulate their internal salt concentrations within a narrow range.

Homeostasis is the maintenance of internal constancy

The maintenance of internal conditions in the face of environmental perturbations (deviation of a system) is referred to as **homeostasis**. The word *homeostasis* does not imply that there is no change in the organism, only that the animal initiates specific responses to control or regulate a particular variable.

- For example, your body temperature remains relatively constant only because numerous physiological processes actively change, adjusting the rates of heat production and heat loss.
- For example, when you stand in the cold air, your muscles may shiver to produce heat that replaces the heat lost to the environment. Thus, muscle activity changes in order to maintain constant body temperature.

The nature of the physiological response to an environmental change depends on many factors. Short-term challenges can often be dealt with using existing physiological systems.

- When a dog is too hot, it can move to a cooler location or pant to shed heat in its breath. These are effective short-term behavioral and physiological approaches to reducing thermal stress. However, they are not effective long-term strategies. A dog hiding in the shade cannot hunt for food, and panting conflicts with oxygen delivery during running. Instead, dogs cope with long-term changes in temperature, such as seasonal cycles, by growing fur in the autumn and shedding fur in the spring.

This example illustrates several **principles that govern physiological changes**.

- **First, some physiological strategies are effective in the short term but less useful for the long term.** Holding your breath may be fine for diving to the bottom of a lake, but it will not help you cope with low oxygen levels while you climb Mount Everest.

- **Second, some strategies require a significant investment in resources and need longer to take effect.** Hair growth, for instance, is a relatively slow process that requires metabolic energy.
- **Third, some stressors are sufficiently predictable that animals remodel physiology in anticipation of the stress, and often in predictable cycles.** Many physiological processes change daily, showing a **circadian rhythm**. Some changes are seasonal, such as the growth and shedding of fur. Other patterns, such as human reproductive cycles, are linked to the lunar cycle. In some cases, cyclical physiological changes proceed without any environmental input, but generally they arise in response to specific environmental cues, such as temperature or photoperiod.

Feedback loops control physiological pathways

To maintain homeostasis, animals must

- Detect external conditions and
- If necessary initiate compensatory responses that keep vital areas buffered against unfavorable change.
- Animals most often maintain homeostasis using a **reflex control pathway**.

A change in the internal or external environment provides a stimulus. The stimulus then causes a response.

- For instance, when you depress the gas pedal of your car (the stimulus), the car accelerates (the response). If you take your foot off the gas (remove the stimulus), the car will slow down.

Animals fine-tune physiological responses by using **antagonistic controls**: independent regulators that exert opposite effects on a step or pathway.

(Antagonist = a substance which interferes with or inhibits the physiological action of another)

In the car analogy above, the gas pedal and the brake are examples of antagonistic controls.

You can cause the car to decelerate by taking your foot off the gas or depressing the brake, but the car's response will be greater if you use both in combination. Animals control body temperature by regulating both heat production and heat dissipation. Hormones mediate many antagonistic controls. Insulin and glucagon are antagonistic controllers of glucose levels.

Negative feedback loops maintain homeostasis

In a **negative feedback loop**, the response sends a signal back to the stimulus, reducing the intensity of the stimulus.

- For example, when you eat, the incoming food causes the stomach to swell. The change in stomach volume and early digestion products trigger a negative feedback loop, acting through your brain, to reduce your appetite.

Many physiological systems have a **set-point**, a preferred physiological state defended through feedback loops.

Set-point is the level or **point** at which a variable **physiological** state (as body temperature or weight) tends to stabilize.

- Your body temperature has a set point of approximately 37°C. When temperature rises, your body may sweat to cool you down, whereas a decrease in body temperature may trigger shivering to warm you back to your set-point.

Although the set-point for human body temperature is near 37°C, the exact body temperature set-point varies between individuals and changes throughout the day.

Positive feedback loops cause explosive responses

Some physiological systems are controlled by **positive feedback loops**. Unlike negative feedback, which minimizes changes in the regulated variable, **positive feedback loops maximize changes in the regulated variable.**

- For example, the muscles in the stomach are normally regulated to contract and relax in a regular pattern to gently mix food. However, when a toxin is detected, a positive feedback loop is triggered to induce forceful contractions that propel the food back up the esophagus to induce vomiting.

Pathways involving positive feedback loops begin slowly but rapidly increase in intensity. In a positive feedback loop there must also be a signal that allows the animal to stop the process at the proper time, so that the action does not spiral out of control.

Phenotype, Genotype, and the Environment

The physiological properties of an animal are aspects of the animal's **phenotype**. Physiological traits, like other characteristics of animals, are determined in large part by the genes of the genome—the **genotype**—but are also influenced by the way the genes are regulated, particularly in response to external conditions.

An individual genotype has the capacity to produce considerable variation in cellular properties.

Although the same genes are found in each cell, they are regulated in combinations to allow animals to develop distinct tissues. During this process of tissue formation, called ***morphogenesis***, networks of genes are turned on and off in precise patterns to create the appropriate phenotype.

- For example, when the fertilized egg of a frog develops into a tadpole, a developmental program is turned on to produce the gills and a tail. When the tadpole undergoes metamorphosis, another program is triggered that results in the formation of the lungs and legs, and death of the cells in the gills and tail.

In addition to orchestrating the normal developmental program, the genotype controls the way animals can alter their phenotype in response to physiological and environmental conditions.

- For example, changes in the expression of genes allow your muscles to change in size and strength in relation to exercise training.

The differences in genotype among animals are central to the phenotypic variation upon which natural selection acts. Every individual genotype has a capacity to differ in complex, often unpredictable ways because of the way the genes respond to external conditions.

A single genotype results in more than one phenotype

A single genotype can result in multiple phenotypes, depending on the environmental conditions that the animal experiences.

- For example, if identical twins were raised in different places, it is possible that one twin might grow taller than the other due to differences in diet. This ability of a single genotype to generate more than one phenotype, depending on environmental conditions, is called **phenotypic plasticity**.

We observe this phenomenon most commonly at the population level, where individuals with similar genotypes can have different phenotypes depending on environmental conditions. The term *phenotypic plasticity* encompasses a wide range of changes in phenotype, some reversible and some irreversible.

Developmental plasticity, or **polyphenism**, is a form of phenotypic plasticity in which development under different conditions results in alternative phenotypes in the adult organism that cannot be reversed by subsequent changes in the environment.

The similar concept of a **reaction norm**, or the range of phenotypes produced by a particular genotype in different environments, applies to phenotypes that exist as a continuum.

- For example, when water fleas (*Daphnia pulex*) are reared in the presence of predators (or even chemical extracts of predators) they develop large, armored, helmet-shaped heads and an elongated spiny tail. When they are reared in the absence of predators, they develop with much smaller heads and a shorter, less spiky tail. Adult water fleas retain these morphologies even if the predator extracts are removed from the water.

Acclimation and acclimatization result in reversible phenotypic changes

Most animals are able to remodel their physiological machinery in response to external conditions.

Physiologists use the related terms **acclimation** and **acclimatization** when referring to processes that cause reversible changes in the phenotype of an organism in response to an environmental change. **The word *acclimation* refers to the process of change in response to a controlled environmental variable (usually in a laboratory setting), while the word *acclimatization* refers to the process of change in response to natural environmental variation.**

- For example, if you take a fish from water at 15°C and leave it in water at 5°C, you will observe a variety of changes in muscle biochemistry, metabolic rate, and other physiological parameters. This process would be referred to as acclimation.
- In contrast, if you compare a fish that you capture in the summer from a lake with a mean temperature of 15°C with a fish that you capture in winter from a lake at 5°C, you will observe many of the same changes, but in this case the process would be termed acclimatization.

Acclimatization may be the result not just of the temperature change, but also of changes in day length, food availability, and any other environmental parameters that vary between summer and winter. In general, both acclimation and acclimatization are reversible physiological changes.

Physiology and Evolution

One of the fundamental challenges of animal physiology is to understand and account for the great diversity of animal body forms and the strategies that animals use to cope with their environments.

- Consider the neck of a giraffe, which, in relation to its body size, is far longer than the neck of its closest living relative, the okapi. When a physiologist thinks about the neck of a giraffe, what question first springs to mind? A respiratory physiologist might wonder: how can a giraffe breathe through such a long neck? A cardiovascular physiologist might wonder: how can a giraffe's heart pump blood all the way up to its head? These mechanistic questions are amenable to the experimental methods of physiology and can be addressed using many of the techniques and conceptual approaches we discuss in this text.

- In contrast, an evolutionary physiologist might wonder: why does a giraffe have a long neck? This question actually encompasses two different kinds of thinking. If we wish to address the **proximate cause** of the giraffe's long neck, we might examine the genes that specify the size or number of vertebrae in the skeleton. Alternatively, we might wish to understand the **ultimate cause** of the giraffe's long neck: whether long necks provided an evolutionary advantage to the ancestors of the giraffe. To address these ultimate questions we need to consider the impact of evolutionary change and the adaptive significance of the physiological traits that we study.

What is adaptation?

Adaptation has two distinct meanings within the context of physiology. The most common usage refers to the product or process of evolution by natural selection, that is, a change in a population or group of organisms over evolutionary time. Many evolutionary biologists argue that the word *adaptation* should *only* be used in this context.

However, physiologists often use the word *adaptation* as a synonym for the word *acclimation*.

One usage is in the context of phenotypic plasticity: a beneficial change in an individual's physiology that occurs over the course of its lifetime.

- For example, a medical physiologist might discuss exercise adaptations: the changes in the muscles and heart that occur during exercise training. In this text, *adaptation* is used in the context of evolutionary adaptation, but it is important that you learn to make the distinction between this definition and the way the term is used by other scientists and the general community.

To an evolutionary physiologist, an adaptation is a trait that arose via a process such as natural selection and conveys an increase in reproductive success. Thus, an evolutionary adaptation is the result of processes that occur over the course of many generations, rather than within the lifetime of a single individual.

- The evolution of insecticide resistance in insects provides an excellent example of the principles of adaptive evolution. Over the last 50 years, chemical insecticides have been used to kill insects that harm crops or carry disease.
- For instance, organophosphates have been used for decades to control populations of insects, such as the common house mosquito *Culex pipiens*.
- Organophosphates kill mosquitoes by inhibiting acetylcholinesterase, an enzyme that is vital for neuronal transmission. The insecticides kill off all or most of the susceptible mosquitoes, but those few rare individuals with beneficial mutations survive and reproduce. This differential survival changes the structure of the population.
- Resistant populations of *Culex pipiens* have evolved in two ways. Some mosquitoes have mutations in the acetylcholinesterase gene, which makes the enzyme more tolerant of the insecticide.
- Other mosquitoes have extra copies of the *esterase* gene, which encodes an enzyme that converts the organophosphate into a less toxic form. These mutations are vital for survival in the presence of the insecticide, but in the absence of insecticide the individuals carrying these mutations are at a disadvantage.
- Those that overproduce esterase use energy that could serve other physiological functions; those with the mutated acetylcholinesterase have an enzyme that does not function quite aswell as the nonmutant (or *wild type*).
- Thus, these genotypes are superior to wild-type genotypes only when the insecticides are present.

We can distill several general principles about the process of evolutionary adaptation from the evolution of insecticide tolerance in mosquitoes:

1. For evolution to occur, there must be variation among individuals in the trait under consideration.

2. The trait must be heritable—genetically determined and passed on to offspring.

3. The trait must increase fitness—the reproductive success of the individuals that have the trait.

4. The relative fitness of the different genotypes depends on the environment. If the environment changes, the trait may no longer be beneficial.

Not all differences are evolutionary adaptations

Not all evolution is adaptive. For example, **genetic drift**, or random changes in the frequency of particular genotypes in a population over time, can result in substantial differences in the phenotype of two populations, independent of any adaptive evolution. Genetic drift is most likely to occur in small populations and is a result of happenstance, not of differences in fitness. If a forest fire kills most of the individuals of a population, the few survivors may happen to display a different genotype frequency than the ancestral population.

After a number of generations, the derived population may differ from the ancestral population, but not for any reason related to natural selection and fitness. This example of genetic drift is known as the **founder effect**.

Evolutionary relationships influence morphology and physiology

Although it is easy to be overwhelmed by the diversity in animal form and function, animal biologists strive to understand the nature of this diversity. One of the best ways to understand how an animal works is to establish in which ways the animal is similar to other organisms.

Some animal traits are shared among all organisms, some among all animals, and some among related animals (lineages). Other traits are truly unique to the species under study.

When a new species of insect is discovered deep in the heart of the Amazon jungle, we already know many of its features. Like all eukaryotic organisms, it will possess a genome of DNA, proteins of the same 20 amino acids, and phospholipid membranes. Like other animals, its cells will be connected to each other with proteins such as collagen and elastin, and it will have nerves and muscles that allow it to sense the world around it and move from place to place. Like other invertebrates, it will lack a spinal cord. Like other arthropods, it will have an exoskeleton of chitin. Like other insects, it will have six legs and paired wings. We can be reasonably certain of these features because the new species of insect has an evolutionary history that included, at some point in the last billion years, ancestors that it shared with other insects, invertebrates, metazoans, and ultimately all eukaryotic organisms. Thus, species that are closely related to each other are likely to share more common features than do species that are distantly related.

METHODS AND MODEL SYSTEMS: August Krogh Models in Animal Physiology

A model species is an organism that is studied by a wide community of researchers because:

- it has features that are conducive to experimentation and
- Understanding a process in the model provides insight into how the process works in other species of interest.

Each model species has been chosen because it demonstrates a combination of features that make it well suited to some studies, though not all studies. This approach of using an animal model with features that are favorable for scientific study is known as the **August Krogh principle**:

For every biological problem there is an organism on which it can be most conveniently studied.

The importance of specific model systems changes over time, as technologies advance and genomic databases expand. An animal that was inconvenient to study in the past may be much easier to study now.

For example, mice became more useful models in developmental physiology when transgenic mouse technologies became readily available.

Knowledge gained from model systems is useful only if that information is relevant to other species. Most commonly, a model was originally chosen because of parallels with human biology. Although the major model animals are quite different in appearance, much of the genetic and structural machinery that underlies development is similar among animals.

The early patterns of embryonic development are similar in most vertebrate models, such as zebra fish, chickens, mice, and humans. However, there are always concerns about the phylogenetic distance between model systems. For this reason, each taxon has one or more species that have been trumpeted as a model.

Some animals are useful models because they have unusual anatomical features.

- Perhaps the most famous example of such a model system is the squid giant axon. Squid are relatively simple animals that have certain axons large enough to be easily seen and readily manipulated.
- The oocytes of the African clawed frog (*Xenopus laevis*) are useful as models for the expression of foreign proteins. *Xenopus* oocytes are large, so scientists can easily introduce foreign RNA by microinjection. The RNA is then translated and the protein sent to the appropriate location. For example, microinjection of RNA coding for membrane proteins causes the oocyte to translate the protein and insert it into the membrane where its functional properties can be assessed.

Many animals are useful models because of their developmental biology. Nematodes are small animals composed of only a few thousand cells. The development from fertilized egg to adult has been studied to the point that the fate of each cell has been mapped. Researchers can microinject substances into a designated cell at a specific developmental stage, knowing that specific cell will divide and differentiate into a specific tissue or organ.

Zebra fish are useful models because the embryo grows quickly and remains transparent for much of its early development. This allows researchers to follow complex cellular changes in living animals. Such studies are aided by transfection of genes encoding fluorescent proteins that can be monitored more easily.

One important factor that determines the utility of a model species is the ease with which genes can be modified. The ability to generate mutations that result in the gain or loss of a function allows physiologists to explore the importance of structural features.

For many years, random mutagenesis was the only way to generate mutants. During this period, invertebrates and small fish were used because it was possible to conduct large-scale screening projects to identify interesting mutants. More recently, genetic approaches to physiology have been facilitated by two trends.

- First, the proliferation of techniques for targeted mutagenesis makes it easier to work on animals with long generation times, because large-scale screening is not needed.
- Second, there is a rapid growth in the number of species for which we have genomic information. Models become a lot more convenient to use in genetic studies when we know their entire genome.

Suggestive Questions:

1. Explain the role of Mechanistic Approaches in understanding physiology.
2. Explain in brief, the Mechanistic properties that underlies the physiological processes occurring in an organism.
3. Justify the statement "electrical potentials are fundamental physiological currency".
4. Justify the statement "biochemical and physiological patterns are influenced by body size".
5. Justify the statement "mechanical theory helps us in understanding how organisms work".
6. Give the classification of multicellular organisms based on the strategies they implement to cope with changing environmental conditions.
7. Write a short note on Conformers and Regulators with suitable examples.
8. Explain the statement with appropriate example "Animals may be regulators with respect to one internal parameter, but conformers with respect to another parameter".
9. Explain the statement "Homeostasis is the maintenance of internal constancy.
10. Comment on the statement that "*homeostasis* does not imply that there is no change in the organism".
11. Explain the multifactorial nature of physiological response to environmental change.
12. Explain the underlying principles that govern physiological modifications in response to environmental changes.
13. Using antagonistic action of Insulin and Glucagon on Glucose level justify the statement that "Feedback Loops control Physiological Pathways".

14. Comment on the statement that "Negative feedback loops maintains homeostasis".
15. Comment on the statement that "Positive feedback loops requires strict regulation".
16. Justify the statement "a single genotype results in more than one phenotype".
17. Explain the concept of **phenotypic plasticity** with relevant example.
18. What do you mean by the term Polyphenism? Explain with possible example.
19. Explain the concept of Reaction Norm with the help of suitable example.
20. Explain the concept of Acclimation and Acclimatization with proper example.
21. Explain the statement with example that both acclimation and acclimatization are reversible physiological changes.
22. Explain the concept of Proximate Cause and Ultimate Cause with proper example.
23. Justify the statement with example that "physiologists often use the word *adaptation* as a synonym for the word *acclimation"*.
24. Give the general principles about the process of evolutionary adaptation.
25. Comment on the statement "not all differences are evolutionary adaptations".
26. Explain the relationship between Genetic Drift and Founder Effect.
27. Why allometric scaling of metabolism is not easily explained by simple differences in ratio of surface area to volume?
28. Write a short note on August Krogh's Models in Animal Physiology.