Chapter 40
Basic Principles of Animal Form and Function
Overview: Diverse Forms, Common Challenges

- **Anatomy** is the study of the biological form of an organism.
- **Physiology** is the study of the biological functions an organism performs.
- The comparative study of animals reveals that form and function are closely correlated.
Concept 40.1: Animal form and function are correlated at all levels of organization

- Size and shape affect the way an animal interacts with its environment
- Many different animal body plans have evolved and are determined by the genome
Evolution of Animal Size and Shape

• Physical laws constrain strength, diffusion, movement, and heat exchange
• As animals increase in size, their skeletons must be proportionately larger to support their mass
• Evolutionary convergence reflects different species’ adaptations to a similar environmental challenge
Figure 40.2

- Seal
- Penguin
- Tuna
Exchange with the Environment

- Materials such as nutrients, waste products, and gases must be exchanged across the cell membranes of animal cells.
- Rate of exchange is proportional to a cell’s surface area while amount of exchange material is proportional to a cell’s volume.
• A single-celled protist living in water has a sufficient surface area of plasma membrane to service its entire volume of cytoplasm
• Multicellular organisms with a saclike body plan have body walls that are only two cells thick, facilitating diffusion of materials
Figure 40.3

(a) Single cell

(b) Two layers of cells
• In flat animals such as tapeworms, the distance between cells and the environment is minimized.
• More complex organisms have highly folded internal surfaces for exchanging materials.
Figure 40.4

External environment
- Food
- CO$_2$, O$_2$
- Animal body

Respiratory system
- Lung tissue (SEM)
- Blood vessels in kidney (SEM)
- Cells
- Interstitial fluid

Digestive system
- Lining of small intestine (SEM)
- 100 μm

Circulatory system
- Nutrients
- Blood
- Heart

Excretory system
- Anus
- 50 μm
- Unabsorbed matter (feces)
- Metabolic waste products (nitrogenous waste)

Nutrients
- Cells
- Interstitial fluid

Metabolic waste products
- Nitrogenous waste

Unabsorbed matter (feces)
- 250 μm
Figure 40.4a

External environment

Food

Mouth

Animal body

CO₂

O₂

Respiratory system

Cells

Interstitial fluid

Digestive system

Nutrients

Circulatory system

Heart

Unabsorbed matter (feces)

Metabolic waste products (nitrogenous waste)

Excretory system

Anus
• In vertebrates, the space between cells is filled with **interstitial fluid**, which allows for the movement of material into and out of cells.

• A complex body plan helps an animal living in a variable environment to maintain a relatively stable internal environment.
Most animals are composed of specialized cells organized into **tissues** that have different functions.

- Tissues make up **organs**, which together make up **organ systems**.
- Some organs, such as the pancreas, belong to more than one organ system.
<table>
<thead>
<tr>
<th>Organ System</th>
<th>Main Components</th>
<th>Main Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digestive</td>
<td>Mouth, pharynx, esophagus, stomach, intestines, liver, pancreas, anus</td>
<td>Food processing (ingestion, digestion, absorption, elimination)</td>
</tr>
<tr>
<td>Circulatory</td>
<td>Heart, blood vessels, blood</td>
<td>Internal distribution of materials</td>
</tr>
<tr>
<td>Respiratory</td>
<td>Lungs, trachea, other breathing tubes</td>
<td>Gas exchange (uptake of oxygen; disposal of carbon dioxide)</td>
</tr>
<tr>
<td>Immune and lymphatic</td>
<td>Bone marrow, lymph nodes, thymus, spleen, lymph vessels, white blood cells</td>
<td>Body defense (fighting infections and cancer)</td>
</tr>
<tr>
<td>Excretory</td>
<td>Kidneys, ureters, urinary bladder, urethra</td>
<td>Disposal of metabolic wastes; regulation of osmotic balance of blood</td>
</tr>
<tr>
<td>Endocrine</td>
<td>Pituitary, thyroid, pancreas, adrenal, and other hormone-secreting glands</td>
<td>Coordination of body activities (such as digestion and metabolism)</td>
</tr>
<tr>
<td>Reproductive</td>
<td>Ovaries or testes and associated organs</td>
<td>Reproduction</td>
</tr>
<tr>
<td>Nervous</td>
<td>Brain, spinal cord, nerves, sensory organs</td>
<td>Coordination of body activities; detection of stimuli and formulation of responses to them</td>
</tr>
<tr>
<td>Integumentary</td>
<td>Skin and its derivatives (such as hair, claws, skin glands)</td>
<td>Protection against mechanical injury, infection, dehydration; thermoregulation</td>
</tr>
<tr>
<td>Skeletal</td>
<td>Skeleton (bones, tendons, ligaments, cartilage)</td>
<td>Body support, protection of internal organs, movement</td>
</tr>
<tr>
<td>Muscular</td>
<td>Skeletal muscles</td>
<td>Locomotion and other movement</td>
</tr>
</tbody>
</table>
Exploring Structure and Function in Animal Tissues

- Different tissues have different structures that are suited to their functions
- Tissues are classified into four main categories: epithelial, connective, muscle, and nervous
Epithelial Tissue

- Epithelial tissue covers the outside of the body and lines the organs and cavities within the body.
- It contains cells that are closely joined.
- The shape of epithelial cells may be cuboidal (like dice), columnar (like bricks on end), or squamous (like floor tiles).
• The arrangement of epithelial cells may be simple (single cell layer), stratified (multiple tiers of cells), or pseudostratified (a single layer of cells of varying length)
Epithelial Tissue

- Cuboidal epithelium
- Simple columnar epithelium
- Simple squamous epithelium
- Pseudostratified columnar epithelium
- Stratified squamous epithelium
Figure 40.5ab

Polarity of epithelia

Apical surface
Basal surface
Basal lamina

40 μm
Connective Tissue

- **Connective tissue** mainly binds and supports other tissues
- It contains sparsely packed cells scattered throughout an extracellular matrix
- The matrix consists of fibers in a liquid, jellylike, or solid foundation
There are three types of connective tissue fiber, all made of protein:

- Collagenous fibers provide strength and flexibility
- Elastic fibers stretch and snap back to their original length
- Reticular fibers join connective tissue to adjacent tissues
Connective tissue contains cells, including:

- **Fibroblasts** that secrete the protein of extracellular fibers

- **Macrophages** that are involved in the immune system
In vertebrates, the fibers and foundation combine to form six major types of connective tissue:

- Loose connective tissue binds epithelia to underlying tissues and holds organs in place
- Cartilage is a strong and flexible support material
- Fibrous connective tissue is found in tendons, which attach muscles to bones, and ligaments, which connect bones at joints
- **Adipose tissue** stores fat for insulation and fuel
- **Blood** is composed of blood cells and cell fragments in blood plasma
- **Bone** is mineralized and forms the skeleton
Connective Tissue

Loose connective tissue
- Collagenous fiber
- Elastic fiber
- Nuclei

Fibrous connective tissue
- Bone
- Central canal
- Osteon
- Chondrocytes
- Chondroitin sulfate

Blood
- Plasma
- White blood cells
- Red blood cells

Adipose tissue
- Fat droplets
Figure 40.5bb

Loose connective tissue

Collagenous fiber

Elastic fiber

120 µm
Fibrous connective tissue

Nuclei

30 μm
Figure 40.5bd

Bone

Central canal

Osteon

700 μm

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Figure 40.5be

Adipose tissue

Fat droplets

150 μm

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Figure 40.5bf

Cartilage

Chondrocytes

100 μm

Chondroitin sulfate

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Blood

Plasma

White blood cells

Red blood cells

55 μm

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Muscle Tissue

- **Muscle tissue** consists of long cells called muscle fibers, which contract in response to nerve signals.
It is divided in the vertebrate body into three types:

- **Skeletal muscle**, or striated muscle, is responsible for voluntary movement
- **Smooth muscle** is responsible for involuntary body activities
- **Cardiac muscle** is responsible for contraction of the heart
Figure 40.5ca

Muscle Tissue

Skeletal muscle

Nuclei
Muscle fiber
Sarcomere

Smooth muscle

Cardiac muscle

Nucleus
Muscle fibers

Nucleus
Intercalated disk
Skeletal muscle

Nuclei

Muscle fiber

Sarcomere

100 μm
Smooth muscle

Nucleus  Muscle fibers  25 μm
Cardiac muscle

Nucleus    Intercalated disk    50 µm

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Nervous Tissue

- **Nervous tissue** senses stimuli and transmits signals throughout the animal

- Nervous tissue contains
  - **Neurons**, or nerve cells, that transmit nerve impulses
  - **Glial cells**, or glia, that help nourish, insulate, and replenish neurons
Nervous Tissue

Neurons

Neuron:
- Dendrites
- Cell body
- Axon

Glia

- Axons of neurons
- Blood vessel

Figure 40.5da

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Figure 40.5db

Neuron:

Dendrites

Cell body

Axon

(Fluorescent LM)
Figure 40.5dc

- **Glia**
- **Axons of neurons**
- **Blood vessel**

(Confocal LM)

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Coordination and Control

• Control and coordination within a body depend on the endocrine system and the nervous system.
• The endocrine system transmits chemical signals called **hormones** to receptive cells throughout the body via blood.
• A hormone may affect one or more regions throughout the body.
• Hormones are relatively slow acting, but can have long-lasting effects.
Figure 40.6a

(a) Signaling by hormones

Stimulus

Endocrine cell

Hormone

Signal travels everywhere.

Blood vessel

(b) Signaling by neurons

Stimulus

Cell body of neuron

Axon

Nerve impulse

Signal travels to a specific location.
• The nervous system transmits information between specific locations
• The information conveyed depends on a signal’s pathway, not the type of signal
• Nerve signal transmission is very fast
• Nerve impulses can be received by neurons, muscle cells, endocrine cells, and exocrine cells
Figure 40.6b

(a) Signaling by hormones

- Blood vessel

- Response

(b) Signaling by neurons

- Nerve impulse

- Axons

- Response
Concept 40.2: Feedback control maintains the internal environment in many animals

- Animals manage their internal environment by regulating or conforming to the external environment
Regulating and Conforming

• A **regulator** uses internal control mechanisms to moderate internal change in the face of external, environmental fluctuation

• A **conformer** allows its internal condition to vary with certain external changes

• Animals may regulate some environmental variables while conforming to others
Homeostasis

- Organisms use **homeostasis** to maintain a “steady state” or internal balance regardless of external environment.
- In humans, body temperature, blood pH, and glucose concentration are each maintained at a constant level.
Mechanisms of Homeostasis

- Mechanisms of homeostasis moderate changes in the internal environment.
- For a given variable, fluctuations above or below a set point serve as a stimulus; these are detected by a sensor and trigger a response.
- The response returns the variable to the set point.
Figure 40.8

Response: Heating stops.

Sensor/control center: Thermostat turns heater off.

Stimulus: Room temperature increases.

Room temperature decreases.

Set point: Room temperature at 20°C

Response: Heating starts.

Stimulus: Room temperature decreases.

Room temperature increases.

Sensor/control center: Thermostat turns heater on.
Feedback Control in Homeostasis

• The dynamic equilibrium of homeostasis is maintained by **negative feedback**, which helps to return a variable to a normal range
• Most homeostatic control systems function by negative feedback, where buildup of the end product shuts the system off
• **Positive feedback** amplifies a stimulus and does not usually contribute to homeostasis in animals
Alterations in Homeostasis

- Set points and normal ranges can change with age or show cyclic variation
- In animals and plants, a **circadian rhythm** governs physiological changes that occur roughly every 24 hours
(a) Variation in core body temperature and melatonin concentration in blood

(b) The human circadian clock
(a) Variation in core body temperature and melatonin concentration in blood
Figure 40.9b

(b) The human circadian clock

- Start of melatonin secretion
- Greatest muscle strength
- Fastest reaction time
- Noon
- Midnight
- Lowest heart rate
- Lowest body temperature
- Most rapid rise in blood pressure
- Highest risk of cardiac arrest

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• Homeostasis can adjust to changes in external environment, a process called **acclimatization**
Concept 40.3: Homeostatic processes for thermoregulation involve form, function, and behavior

- Thermoregulation is the process by which animals maintain an internal temperature within a tolerable range
Endothermy and Ectothermy

- **Endothermic** animals generate heat by metabolism; birds and mammals are endotherms.
- **Ectothermic** animals gain heat from external sources; ectotherms include most invertebrates, fishes, amphibians, and nonavian reptiles.
• In general, ectotherms tolerate greater variation in internal temperature, while endotherms are active at a greater range of external temperatures
• Endothermy is more energetically expensive than ectothermy
(a) A walrus, an endotherm

(b) A lizard, an ectotherm
(a) A walrus, an endotherm
(b) A lizard, an ectotherm

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Variation in Body Temperature

- The body temperature of a poikilotherm varies with its environment.
- The body temperature of a homeotherm is relatively constant.
- The relationship between heat source and body temperature is not fixed (that is, not all poikilotherms are ectotherms).
Balancing Heat Loss and Gain

- Organisms exchange heat by four physical processes: radiation, evaporation, convection, and conduction
Heat regulation in mammals often involves the **integumentary system**: skin, hair, and nails.

Five adaptations help animals thermoregulate:

- Insulation
- Circulatory adaptations
- Cooling by evaporative heat loss
- Behavioral responses
- Adjusting metabolic heat production
Insulation

- Insulation is a major thermoregulatory adaptation in mammals and birds
- Skin, feathers, fur, and blubber reduce heat flow between an animal and its environment
- Insulation is especially important in marine mammals such as whales and walruses
Circulatory Adaptations

- Regulation of blood flow near the body surface significantly affects thermoregulation.
- Many endotherms and some ectotherms can alter the amount of blood flowing between the body core and the skin.
- In vasodilation, blood flow in the skin increases, facilitating heat loss.
- In vasoconstriction, blood flow in the skin decreases, lowering heat loss.
• The arrangement of blood vessels in many marine mammals and birds allows for **countercurrent exchange**

• Countercurrent heat exchangers transfer heat between fluids flowing in opposite directions and reduce heat loss
Figure 40.12

Canada goose

Bottlenose dolphin

Key
- Warm blood
- Blood flow
- Cool blood
- Heat transfer

Vein

Artery

35°C
33°C
30°C
27°C
20°C
18°C
10°C
9°C

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• Some bony fishes and sharks also use countercurrent heat exchanges
• Many endothermic insects have countercurrent heat exchangers that help maintain a high temperature in the thorax
Cooling by Evaporative Heat Loss

- Many types of animals lose heat through evaporation of water from their skin.
- Panting increases the cooling effect in birds and many mammals.
- Sweating or bathing moistens the skin, helping to cool an animal down.
Behavioral Responses

- Both endotherms and ectotherms use behavioral responses to control body temperature
- Some terrestrial invertebrates have postures that minimize or maximize absorption of solar heat
Adjusting Metabolic Heat Production

- Thermogenesis is the adjustment of metabolic heat production to maintain body temperature.
- Thermogenesis is increased by muscle activity such as moving or shivering.
- Nonshivering thermogenesis takes place when hormones cause mitochondria to increase their metabolic activity.
- Some ectotherms can also shiver to increase body temperature.
Experiment

Figure 40.14

The graph shows the relationship between oxygen consumption (mL O₂/hr·kg) and contractions per minute. The data points are plotted on a linear scale, with oxygen consumption on the y-axis and contractions per minute on the x-axis. A linear trend line indicates a positive correlation between the two variables. The graph includes an image of a snake, possibly indicating that the experiment involves snake behavior or physiology.
Acclimatization in Thermoregulation

- Birds and mammals can vary their insulation to acclimatize to seasonal temperature changes.
- When temperatures are subzero, some ectotherms produce “antifreeze” compounds to prevent ice formation in their cells.
Physiological Thermostats and Fever

- Thermoregulation is controlled by a region of the brain called the hypothalamus.
- The hypothalamus triggers heat loss or heat generating mechanisms.
- Fever is the result of a change to the set point for a biological thermostat.
Figure 40.16

Response: Sweat

Sensor/control center: Thermostat in hypothalamus

Response: Blood vessels in skin dilate.

Body temperature decreases.

Stimulus: Increased body temperature

Homeostasis: Internal body temperature of approximately 36–38°C

Body temperature increases.

Stimulus: Decreased body temperature

Response: Blood vessels in skin constrict.

Response: Shivering

Sensor/control center: Thermostat in hypothalamus
Figure 40.16a

Response: Sweat

Sensor/control center: Thermostat in hypothalamus

Response: Blood vessels in skin dilate.

Stimulus: Increased body temperature

Body temperature decreases.

Homeostasis: Internal body temperature of approximately 36–38°C
Figure 40.16b

Homeostasis:
Internal body temperature of approximately 36–38°C

Body temperature increases.

Stimulus:
Decreased body temperature

Response:
Blood vessels in skin constrict.

Response:
Shivering

Sensor/control center: Thermostat in hypothalamus
Concept 40.4: Energy requirements are related to animal size, activity, and environment

- **Bioenergetics** is the overall flow and transformation of energy in an animal
- It determines how much food an animal needs and it relates to an animal’s size, activity, and environment
Energy Allocation and Use

- Animals harvest chemical energy from food.
- Energy-containing molecules from food are usually used to make ATP, which powers cellular work.
- After the needs of staying alive are met, remaining food molecules can be used in biosynthesis.
- Biosynthesis includes body growth and repair, synthesis of storage material such as fat, and production of gametes.
Quantifying Energy Use

- **Metabolic rate** is the amount of energy an animal uses in a unit of time
- Metabolic rate can be determined by
  - An animal’s heat loss
  - The amount of oxygen consumed or carbon dioxide produced
Minimum Metabolic Rate and Thermoregulation

• **Basal metabolic rate (BMR)** is the metabolic rate of an endotherm at rest at a “comfortable” temperature

• **Standard metabolic rate (SMR)** is the metabolic rate of an ectotherm at rest at a specific temperature

• Both rates assume a nongrowing, fasting, and nonstressed animal

• Ectotherms have much lower metabolic rates than endotherms of a comparable size
Influences on Metabolic Rate

- Metabolic rates are affected by many factors besides whether an animal is an endotherm or ectotherm
- Two of these factors are size and activity
Size and Metabolic Rate

- Metabolic rate is proportional to body mass to the power of three quarters \( (m^{3/4}) \)
- Smaller animals have higher metabolic rates per gram than larger animals
- The higher metabolic rate of smaller animals leads to a higher oxygen delivery rate, breathing rate, heart rate, and greater (relative) blood volume, compared with a larger animal
Figure 40.19

(a) Relationship of basal metabolic rate (BMR) to body size for various mammals

(b) Relationship of BMR per kilogram of body mass to body size

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(a) Relationship of basal metabolic rate (BMR) to body size for various mammals
(b) Relationship of BMR per kilogram of body mass to body size
Activity and Metabolic Rate

- Activity greatly affects metabolic rate for endotherms and ectotherms
- In general, the maximum metabolic rate an animal can sustain is inversely related to the duration of the activity
Energy Budgets

• Different species use energy and materials in food in different ways, depending on their environment

• Use of energy is partitioned to BMR (or SMR), activity, thermoregulation, growth, and reproduction
Figure 40.20

Annual energy expenditure (kcal/yr)

<table>
<thead>
<tr>
<th>Species</th>
<th>Energy Expenditure (kcal/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60-kg female human from temperate climate</td>
<td>800,000</td>
</tr>
<tr>
<td>4-kg male Adélie penguin from Antarctica (brooding)</td>
<td>340,000</td>
</tr>
<tr>
<td>0.025-kg female deer mouse from temperate North America</td>
<td>4,000</td>
</tr>
<tr>
<td>4-kg female eastern indigo snake</td>
<td>8,000</td>
</tr>
</tbody>
</table>

Endotherms

- Basal (standard) metabolism
- Reproduction
- Thermoregulation
- Growth
- Activity

Ectotherm

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Figure 40.20b

Ectotherm

Reproduction

Growth

Activity

Annual energy expenditure (kcal/yr)

Basal (standard) metabolism

8,000

4-kg female eastern indigo snake

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Torpor and Energy Conservation

- **Torpor** is a physiological state in which activity is low and metabolism decreases.
- Torpor enables animals to save energy while avoiding difficult and dangerous conditions.
- **Hibernation** is long-term torpor that is an adaptation to winter cold and food scarcity.
RESULTS

![Graph showing relative RNA levels of Per2 and Bmal1 in Euthermia and Hibernation, with data for Day and Night.](image-url)
• Summer torpor, called estivation, enables animals to survive long periods of high temperatures and scarce water
• Daily torpor is exhibited by many small mammals and birds and seems adapted to feeding patterns