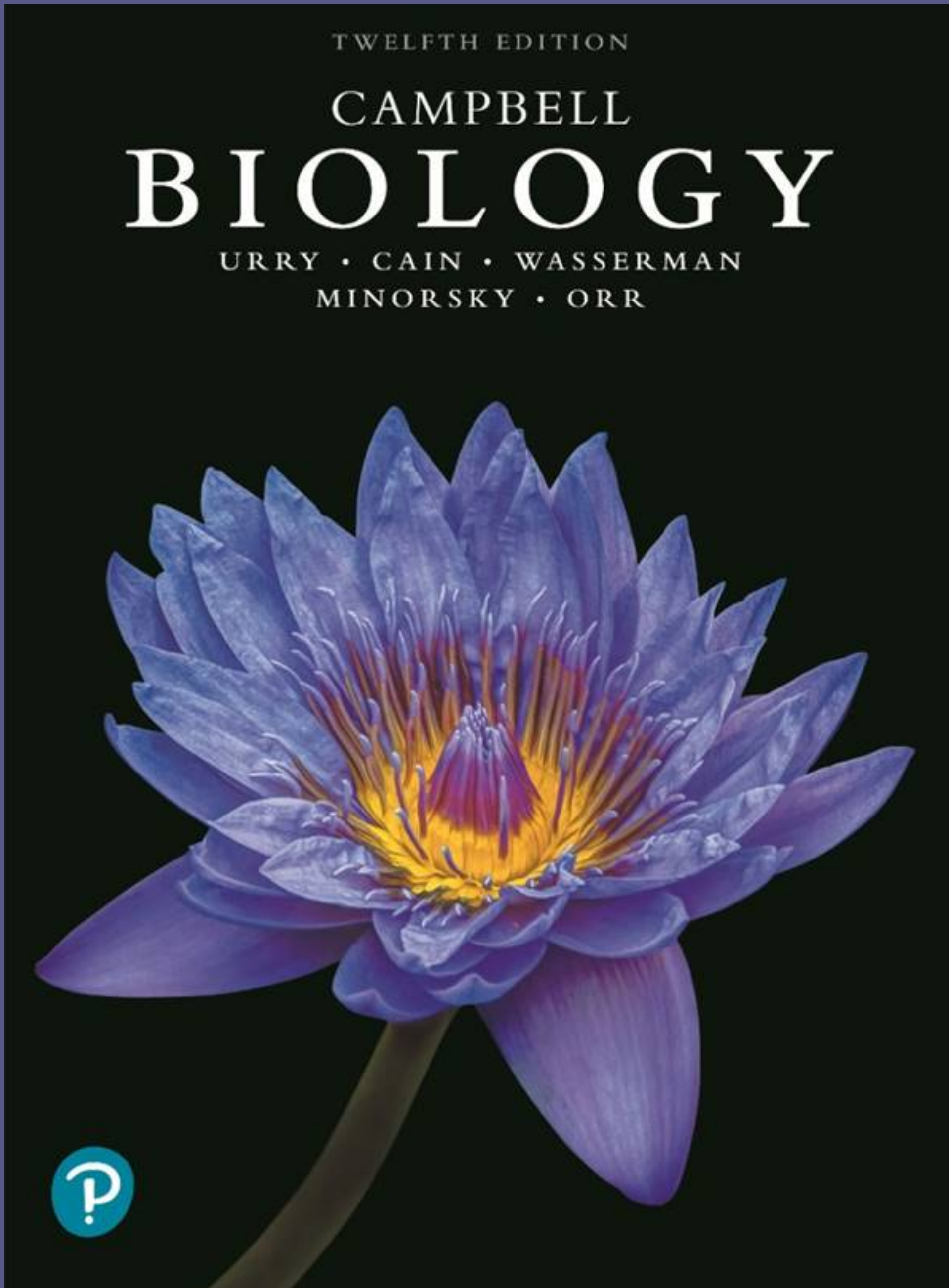


Chapter 40

Basic Principles of Animal Form and Function

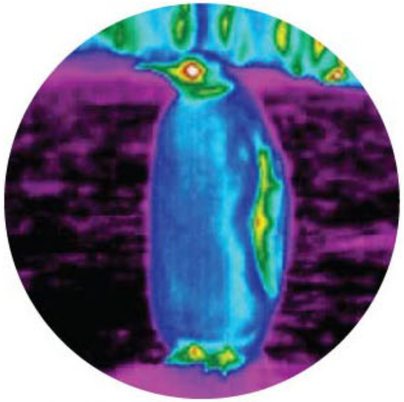
Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

Figure 40.1a

How do animals regulate their internal state even in changing or harsh environments?

Adaptations in form, function, and behavior help maintain an animal's internal environment. Adaptations that limit variation in temperature and other internal variables are widespread and diverse.

Form (anatomy): Insulating reduces heat loss.



Function (physiology): Shivering produces heat.

Behavior: Packing together reduces exposure.

CONCEPT 40.1: Animal form and function are correlated at all levels of organization

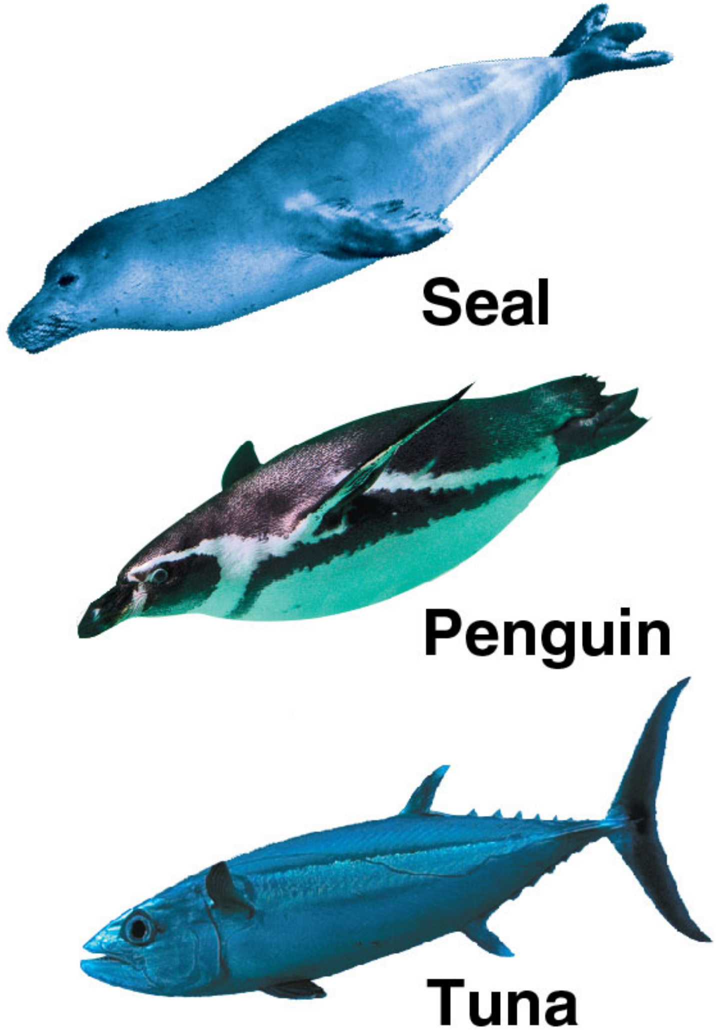
- All animals must obtain nutrients and oxygen, fight off infection, and survive to produce offspring
- Animals’ form including **anatomy**—biological structure—varies widely
- Because structure and function are correlated, examining anatomy often provides clues to **physiology**—biological function

- Size and shape affect the way an animal interacts with its environment
- The body plan of an animal is programmed by the genome, itself the product of millions of years of evolution

Evolution of Animal Size and Shape

- Physical laws that govern strength, diffusion, movement, and heat exchange limit the range of animal forms
- Properties of water limit possible shapes for fast swimming animals
- Convergent evolution often results in similar adaptations of diverse organisms facing the same challenge

Figure 40.2



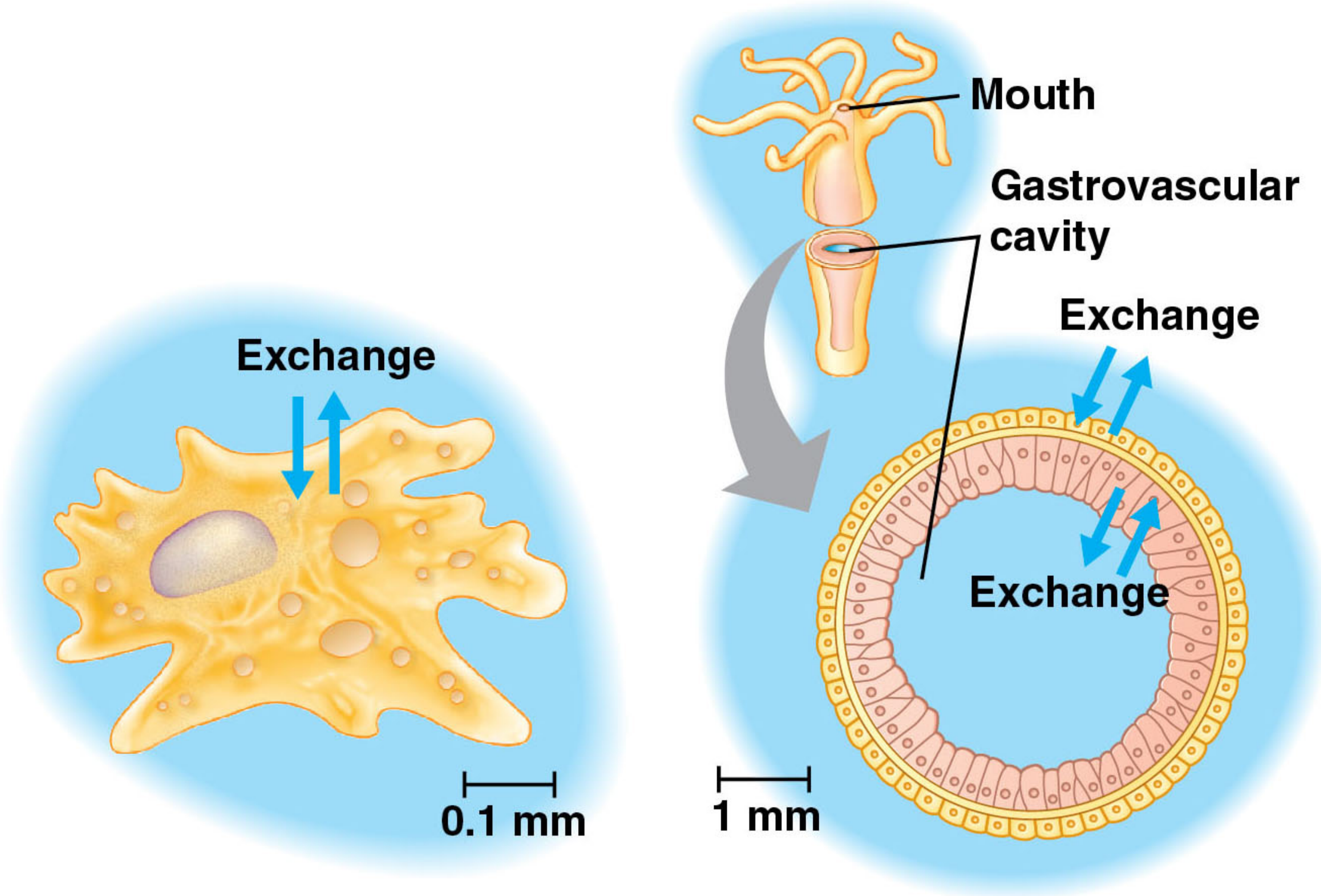
- As animals increase in size, thicker skeletons are required for support
- Muscles required for locomotion represent a larger fraction of the total body mass
- At some point, mobility becomes limited

Exchange with the Environment

- Materials such as nutrients, waste products, and gases must be exchanged across the plasma membranes of animal cells
- Rate of exchange is proportional to a cell's surface area, while amount of material that must be exchanged is proportional to a cell's volume
- A single-celled organism living in water has sufficient surface area to carry out all necessary exchange

- A multicellular organization only works if every cell has access to a suitable aqueous environment
- Multicellular organisms with a saclike body plan have body walls that are only two cells thick, facilitating diffusion of materials

Figure 40.3

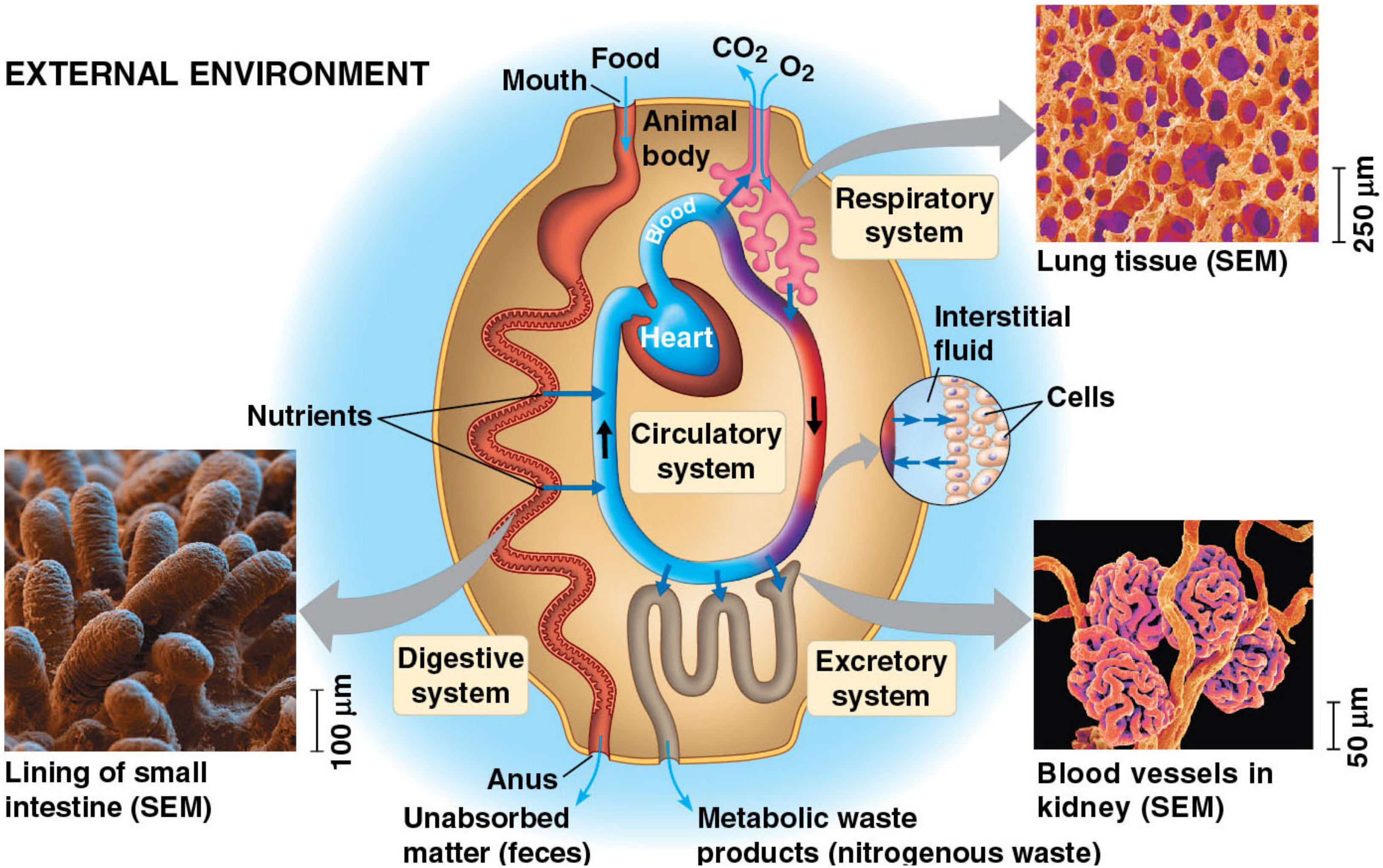


(a) An amoeba, a single-celled organism

(b) A hydra, an animal with two layers of cells

- In flat animals such as tapeworms, most cells are in direct contact with their environment
- More complex organisms are composed of compact masses of cells with a more complex internal organization
- Evolutionary adaptations such as specialized, extensively branched or folded structures enable sufficient exchange with the environment

Figure 40.4



EXTERNAL ENVIRONMENT
Food
Mouth
CO_2
O_2
Animal body
Blood
Respiratory system
Lung tissue (SEM)
250 µm
Heart
Interstitial fluid
Cells
Nutrients
Circulatory system
Lining of small intestine (SEM)
100 µm
Digestive system
Excretory system
Blood vessels in kidney (SEM)
50 µm
Anus
Unabsorbed matter (feces)
Metabolic waste products (nitrogenous waste)

- In animals, the space between cells is filled with **interstitial fluid**, which links exchange surfaces to body cells
- A complex body plan helps an animal living in a variable environment to maintain a relatively stable internal environment

Hierarchical Organization of Body Plans

- Most animals are composed of cells organized into **tissues,** groups of cells with a similar appearance and a common function
- Tissues make up **organs**, which together make up **organ systems**
- Some organs, such as the pancreas, belong to more than one organ system

Table 40.1

Table 40.1 Organ Systems in Mammals

Organ System	Main Components	Main Functions
Digestive	Mouth, pharynx, esophagus, stomach, intestines, liver, pancreas, anus (See Figure 41.8.)	Food processing (ingestion, digestion, absorption, elimination)
Circulatory	Heart, blood vessels, blood (See Figure 42.5.)	Internal distribution of materials
Respiratory	Lungs, trachea, other breathing tubes (See Figure 42.24.)	Gas exchange (uptake of oxygen; disposal of carbon dioxide)
Immune and lymphatic	Bone marrow, lymph nodes, thymus, spleen, lymph vessels (See Figure 43.7.)	Body defense (fighting infections and virally induced cancers)
Excretory	Kidneys, ureters, urinary bladder, urethra (See Figure 44.12.)	Disposal of metabolic wastes; regulation of osmotic balance of blood
Endocrine	Pituitary, thyroid, pancreas, adrenal, and other hormone-secreting glands (See Figure 45.8.)	Coordination of body activities (such as digestion and metabolism)
Reproductive	Ovaries or testes and associated organs (See Figures 46.9 and 46.10.)	Gamete production; promotion of fertilization; support of developing embryo
Nervous	Brain, spinal cord, nerves, sensory organs (See Figure 49.6.)	Coordination of body activities; detection of stimuli and formulation of responses to them
Integumentary	Skin and its derivatives (such as hair, claws, sweat glands) (See Figure 50.5.)	Protection against mechanical injury, infection, dehydration; thermoregulation
Skeletal	Skeleton (bones, tendons, ligaments, cartilage) (See Figure 50.37.)	Body support, protection of internal organs, movement
Muscular	Skeletal muscles (See Figure 50.26.)	Locomotion and other movement

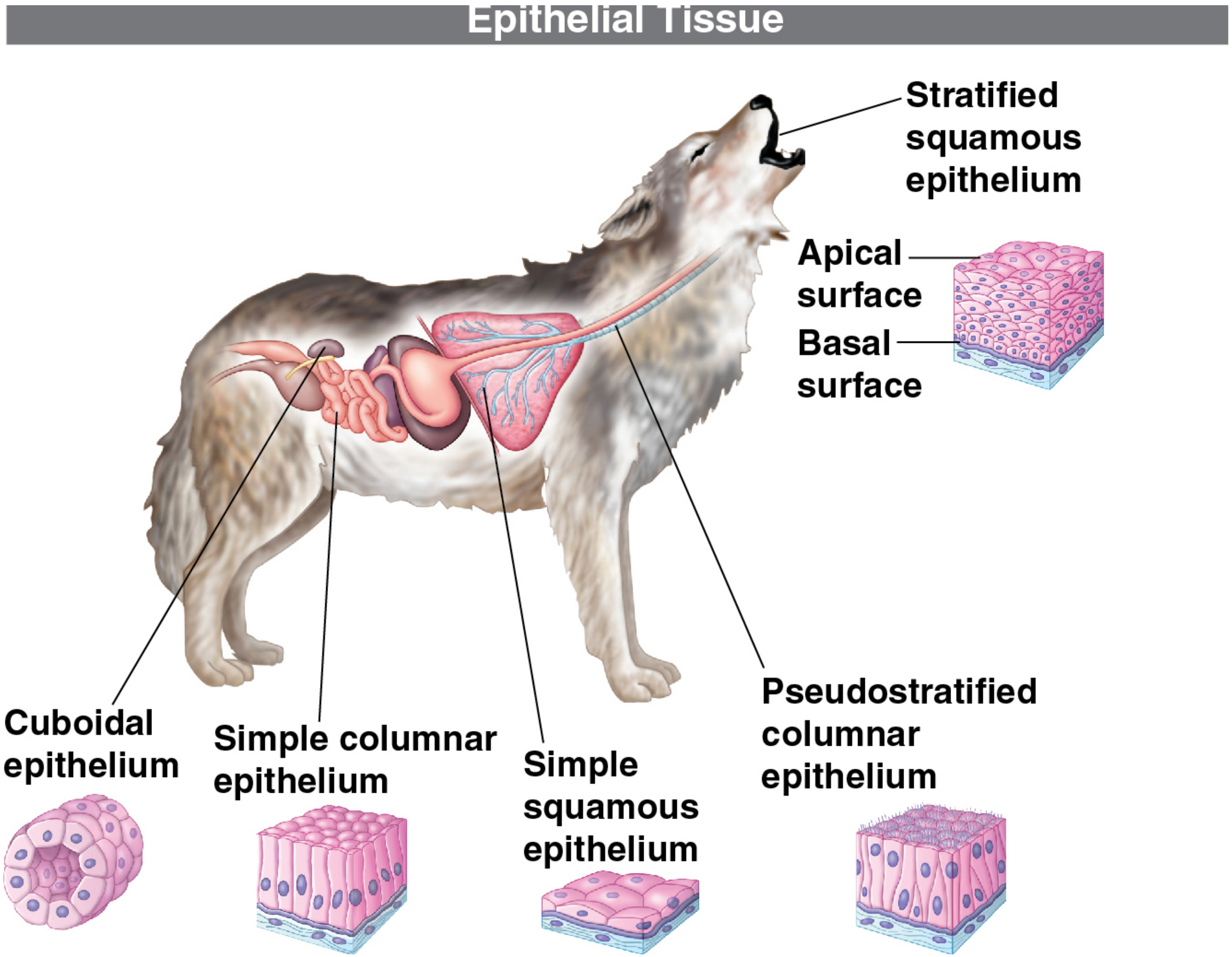
- There are four main types of animal tissues:
  - Epithelial
  - Connective
  - Muscle
  - Nervous

Figure 40.5 Exploring structure and function in animal tissues

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 packed
- The shape of epithelial cells may be cuboidal (like dice), columnar (like bricks on end), or squamous (like floor tiles)

Figure 40.5a


Epithelial Tissue
Stratified squamous epithelium
Apical surface
Basal surface
Cuboidal epithelium
Simple columnar epithelium
Simple squamous epithelium
Pseudostratified columnar epithelium

Connective Tissue

- **Connective tissue** holds many tissues and organs together and in place
- It contains sparsely packed cells scattered throughout an extracellular matrix
- The matrix consists of fibers in a liquid, jellylike, or solid foundation

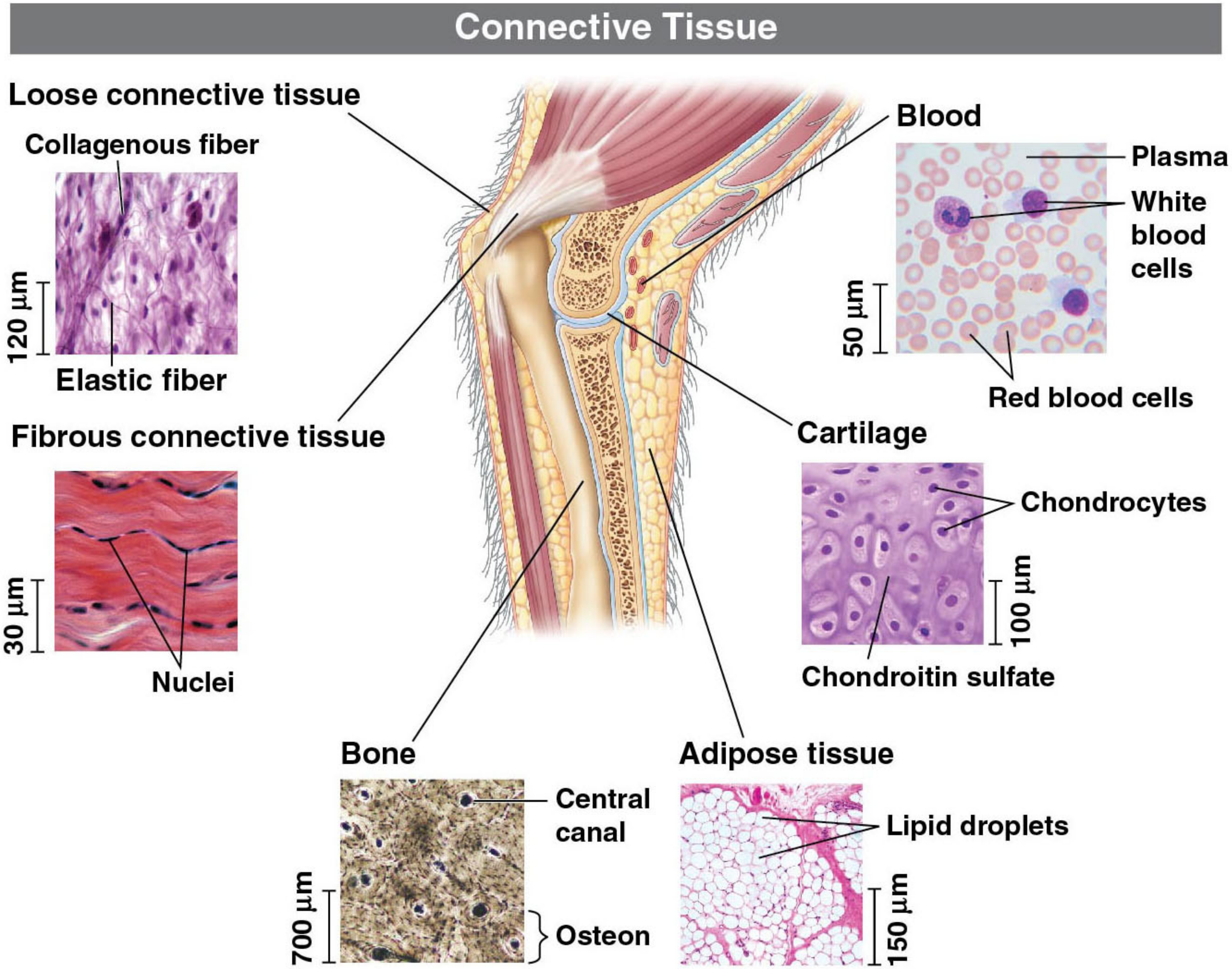
- Connective tissue contains cells, including
  - **Fibroblasts**, which secrete fiber proteins
  - **Macrophages**, which engulf foreign particles and cell debris by phagocytosis

- There are three types of connective tissue fiber, all made of protein:
  - Collagenous fibers provide strength and flexibility
  - Reticular fibers join connective tissue to adjacent tissues
  - Elastic fibers stretch and snap back to their original length

- 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
  - Fibrous connective tissue is found in **tendons**, which attach muscles to bones, and **ligaments**, which connect bones at joints
  - **Bone** is mineralized and forms the skeleton

- **Adipose tissue** stores fat for insulation and fuel
- **Blood** is composed of blood cells and cell fragments in blood plasma
- **Cartilage** is a strong and flexible support material

Figure 40.5b



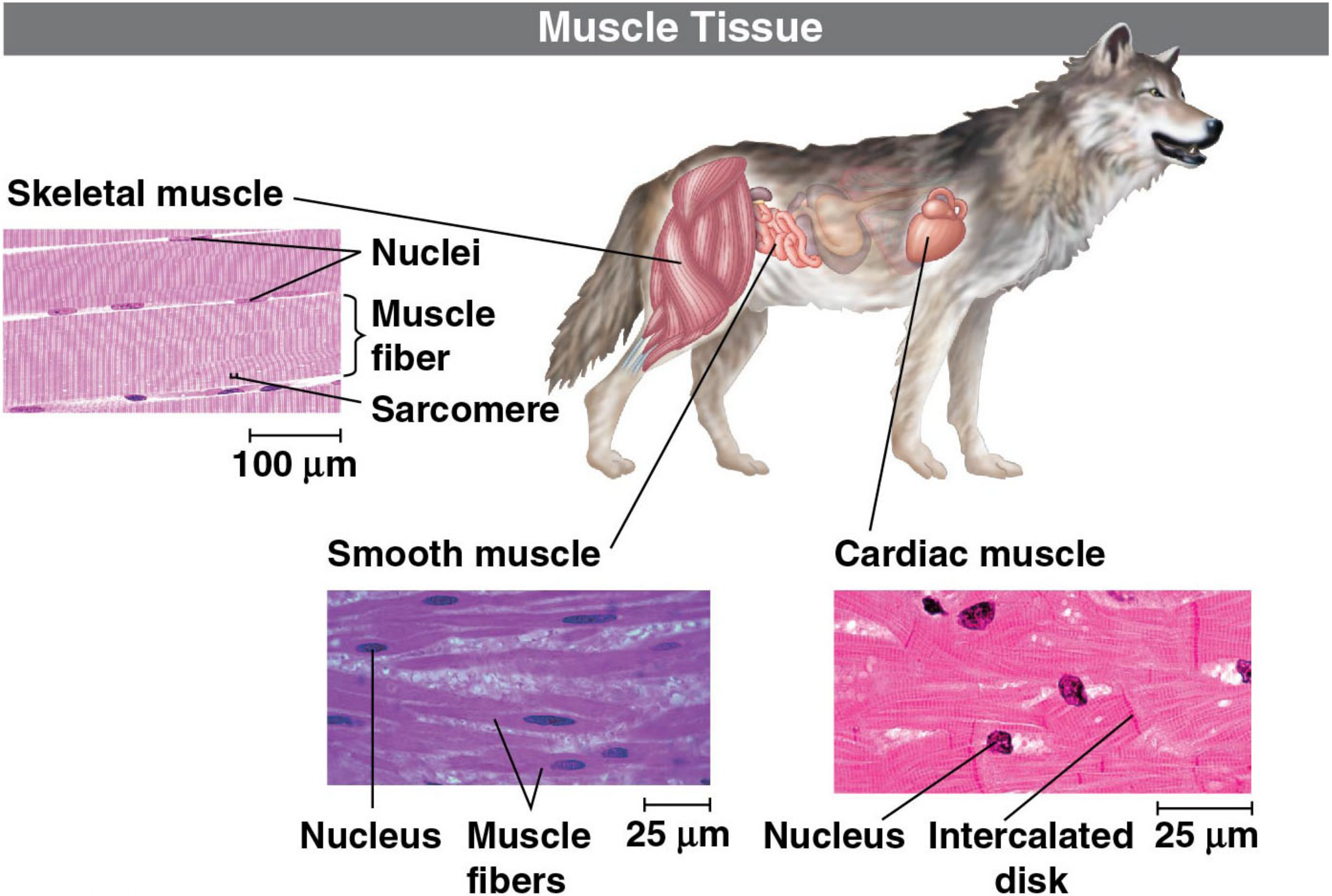
Connective Tissue
Loose connective tissue
Collagenous fiber
120 µm
Elastic fiber
Fibrous connective tissue
30 µm
Nuclei
Bone
Central canal
700 µm
Osteon
Adipose tissue
Lipid droplets
150 µm
Blood
Plasma
White blood cells
50 µm
Red blood cells
Cartilage
Chondrocytes
100 µm
Chondroitin sulfate

Muscle Tissue

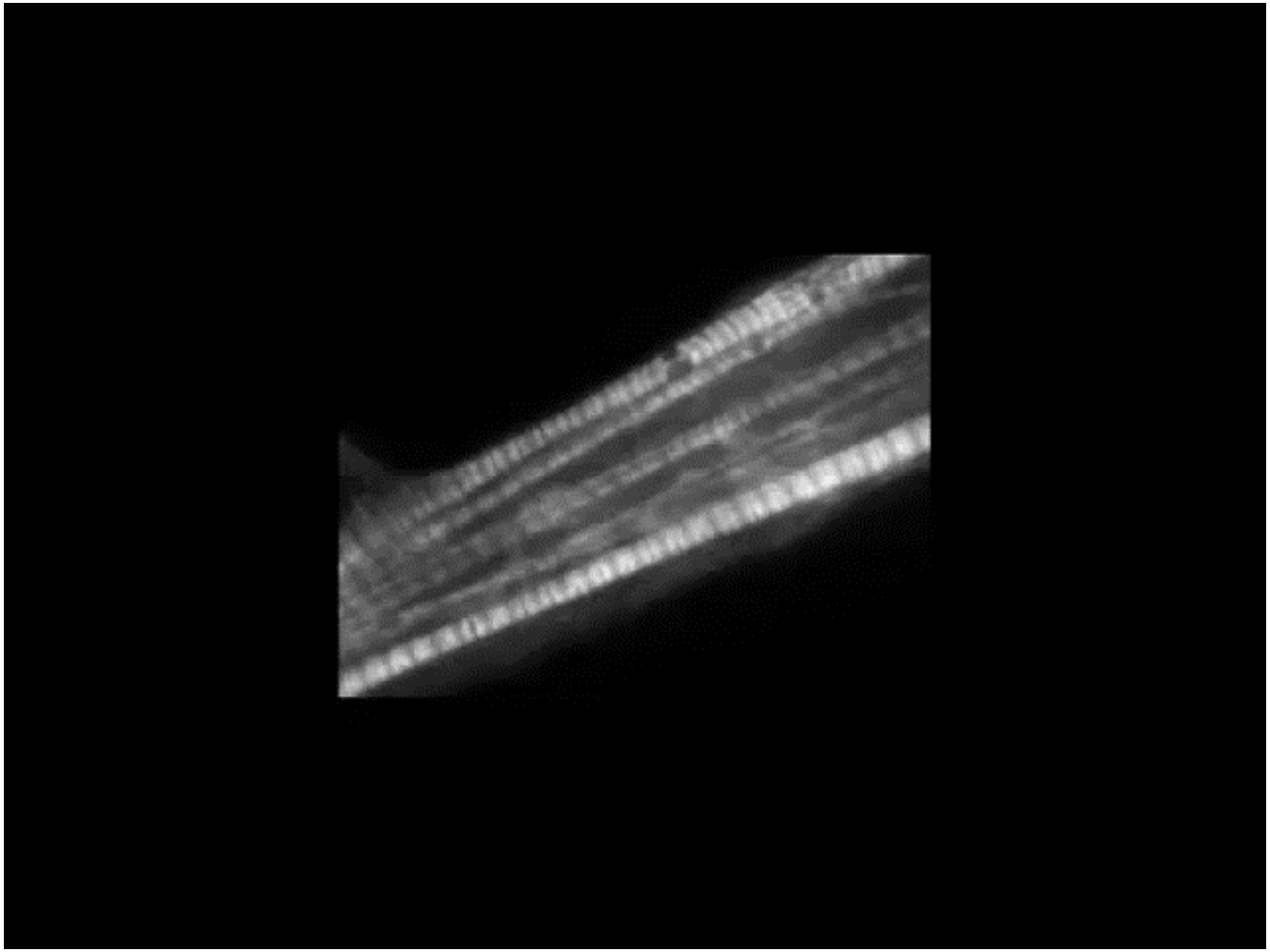
- **Muscle tissue** is responsible for nearly all types of body movement
- Muscle cells consist of filaments of the proteins actin and myosin, which together enable muscles to contract

- Muscle tissue in the vertebrate body is divided 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 40.5c


Muscle Tissue
Skeletal muscle
Nuclei
Muscle fiber
Sarcomere
100 µm
Smooth muscle
Nucleus
Muscle fibers
25 µm
Cardiac muscle
Nucleus
Intercalated disk
25 µm

Video: Cardiac Muscle Contraction



Nervous Tissue

- **Nervous tissue** functions in the receipt, processing, and transmission of information
- Nervous tissue contains
  - **Neurons**, or nerve cells, which transmit nerve impulses
  - **Glial cells**, or **glia**, which support cells

Coordination and Control

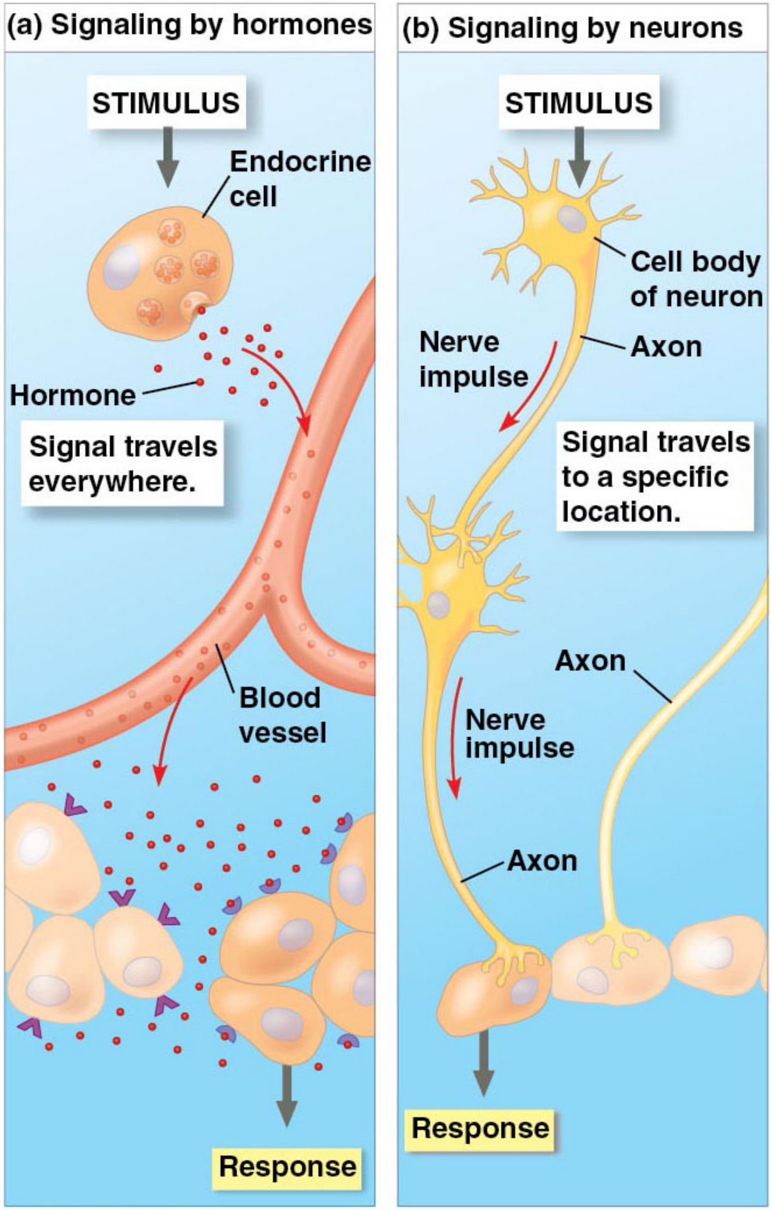
- Animals have two major systems for coordinating and controlling responses to stimuli: the endocrine and the nervous systems
- The **endocrine system** releases signaling molecules that are carried to all locations in the body
- The **nervous system** transmits information along dedicated routes, connecting specific locations in the body

- The signaling molecules broadcast through the body by the endocrine system are called **hormones**
- A hormone may remain in the bloodstream for minutes or even hours
- Different hormones cause distinct effects and may affect a single location or sites throughout the body

- In the nervous system, signals called nerve impulses travel to specific target cells along communication lines consisting mainly of axons
- Nerve signal transmission is very fast, and lasts only a fraction of a second
- The information conveyed by the nervous system depends on the pathway the signal takes
- Communication in the nervous system usually involves more than one type of signal

- The endocrine system is well adapted for coordinating gradual changes that affect the entire body
- The nervous system is suited for directing immediate and rapid responses to the environment
- The endocrine and nervous systems often work in close coordination; both help maintain a stable internal environment

Figure 40.6



(a) Signaling by hormones
STIMULUS
Endocrine cell
Hormone
Signal travels everywhere.
Blood vessel
Response
(b) Signaling by neurons
STIMULUS
Cell body of neuron
Nerve impulse
Axon
Signal travels to a specific location.
Axon
Nerve impulse
Axon
Response

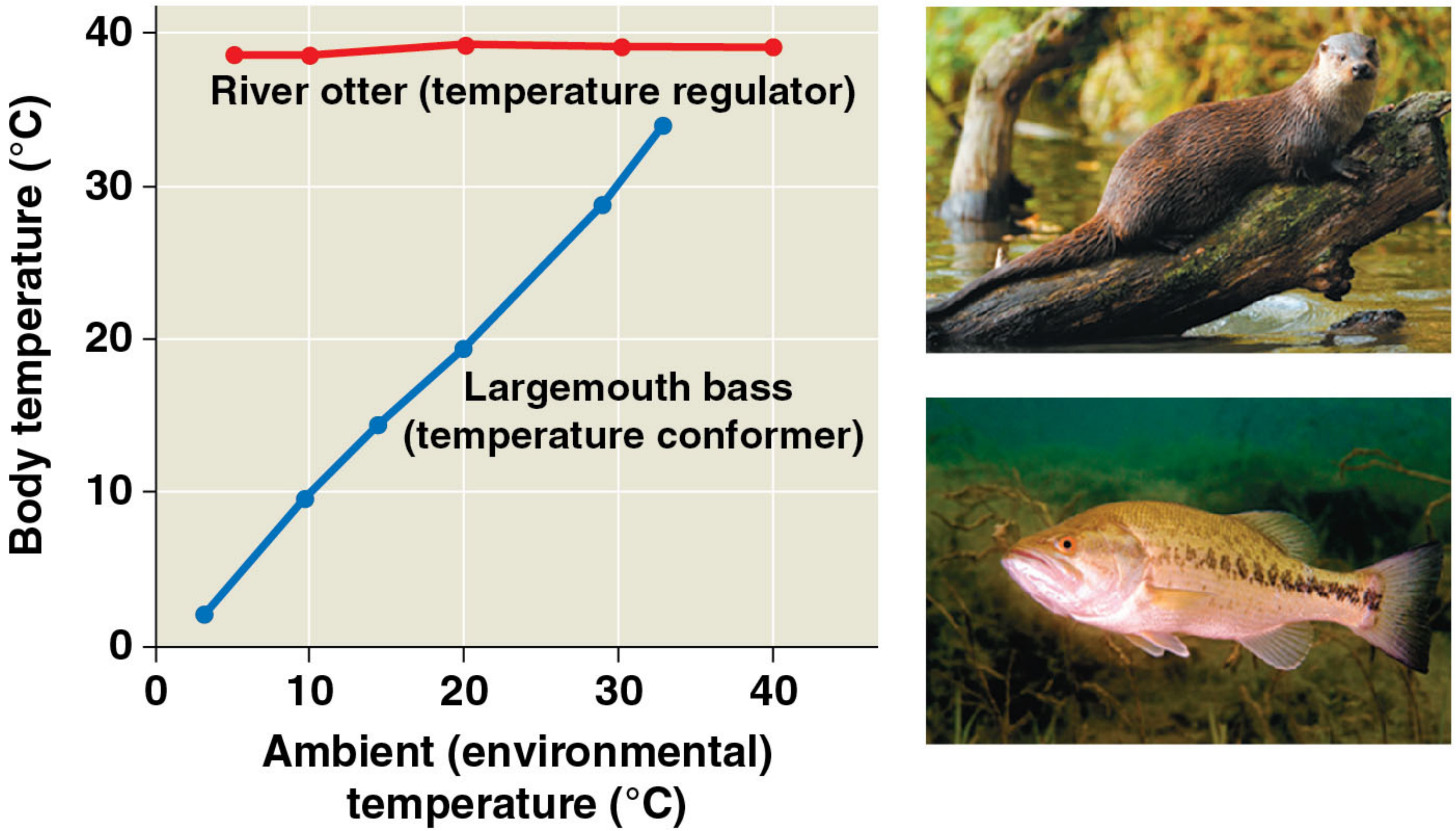
CONCEPT 40.2: Feedback control maintains the internal environment in many animals

- Faced with environmental fluctuations, animals manage their internal environment by either regulating or conforming

Regulating and Conforming

- An animal that is a **regulator** uses internal control mechanisms to control internal change in the face of external fluctuation
- A **conformer** allows its internal condition to vary with certain external changes
- Animals may regulate some environmental variables while conforming to others

Figure 40.7



River otter (temperature regulator)
Largemouth bass
(temperature conformer)
Body temperature (°C)
Ambient (environmental)
temperature (°C)
0
10
20
30
40

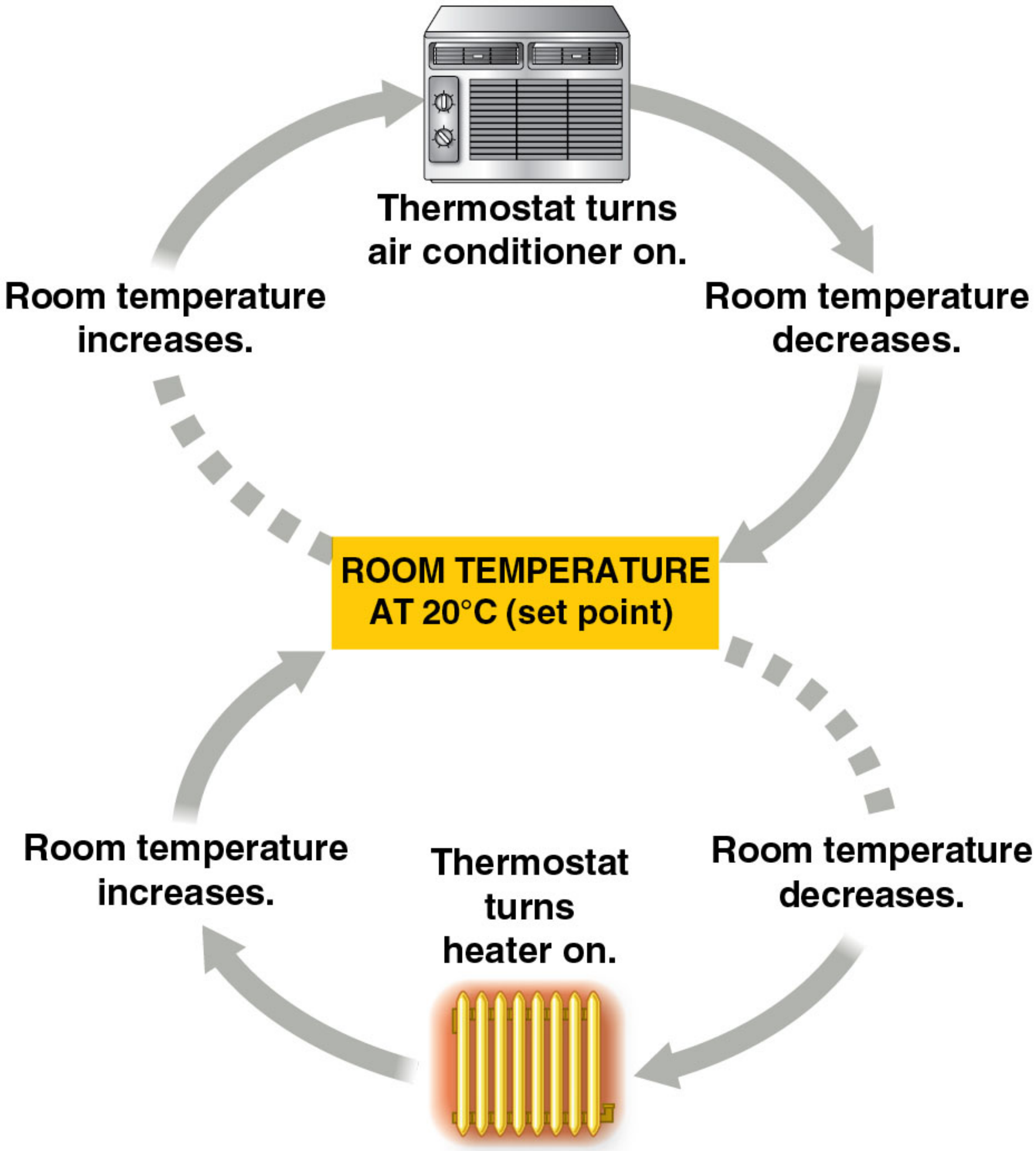
Homeostasis

- Organisms use **homeostasis** to maintain a "steady state"—a relatively constant internal environment—regardless of external environment
- In humans, body temperature, blood pH, and glucose concentration are each maintained at a fairly constant level

Mechanisms of Homeostasis

- The homeostatic control system in animals maintains a variable at or near a particular value, or **set point**
- A fluctuation above or below the set point serves as a **stimulus**, which is detected by a **sensor**
- A control center then generates output that triggers a **response**
- The response helps return the variable to the set point

Figure 40.8

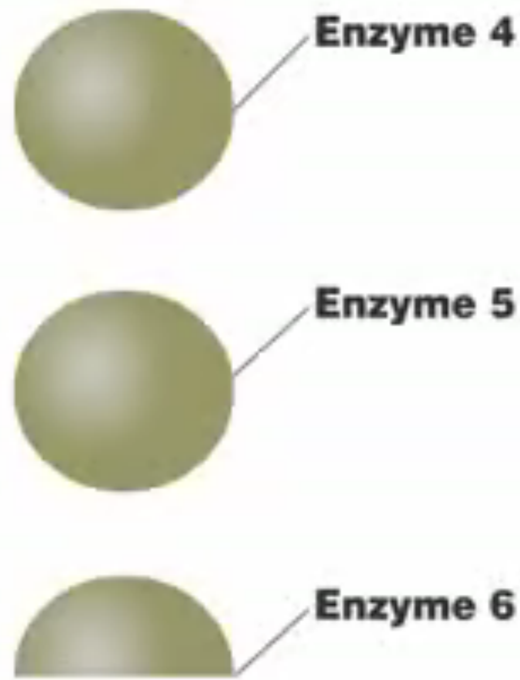

Thermostat turns
air conditioner on.
Room temperature
increases.
Room temperature
decreases.
ROOM TEMPERATURE
AT 20°C (set point)
Room temperature
increases.
Thermostat
turns
heater on.
Room temperature
decreases.

Feedback Control in Homeostasis

- **Negative feedback** is a control mechanism that "damps" a stimulus
- It plays a major role in homeostasis in animals
- Homeostasis moderates but doesn't eliminate changes in the internal environment
- **Positive feedback** amplifies a stimulus and does not play a major role in homeostasis
- Instead, it helps drive a process (such as childbirth) to completion

Animation: Regulation: Negative Feedback

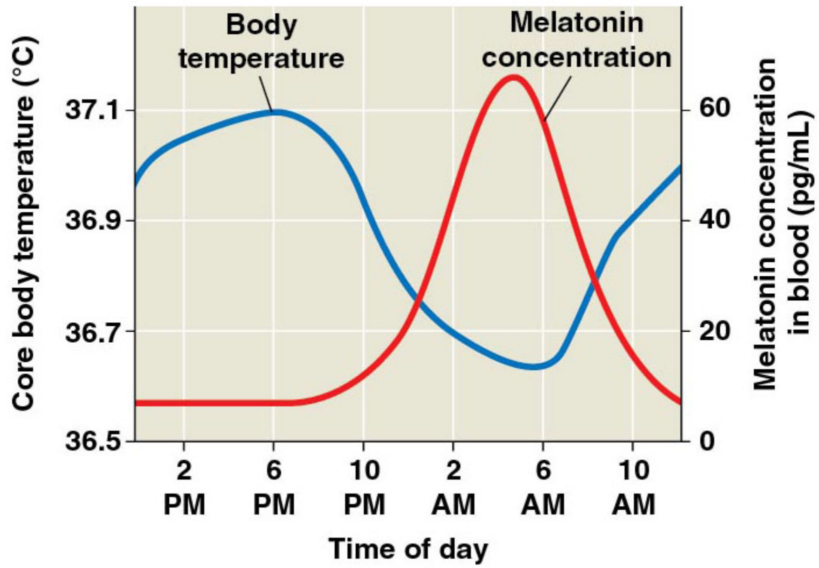
Animation: Regulation: Positive Feedback



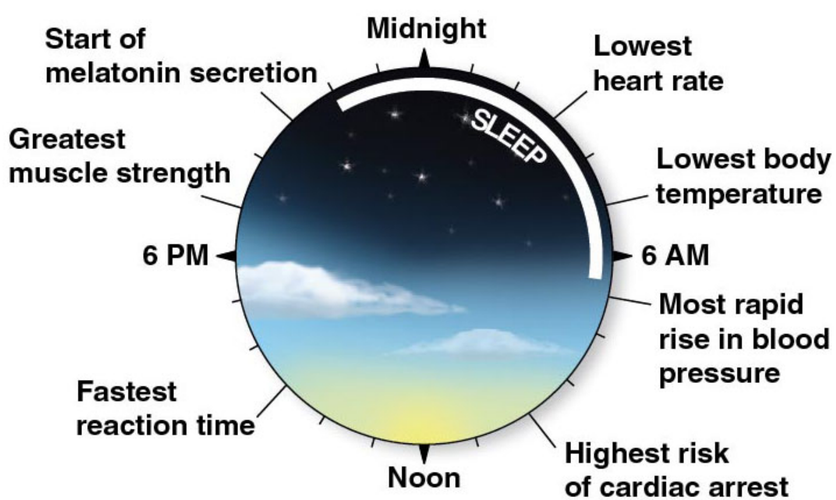
Alterations in Homeostasis

- 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

Figure 40.9



(a) Variation in core body temperature and melatonin concentration in blood



(b) The human circadian clock

- Homeostasis is sometimes altered by **acclimatization**
- This is a change in an animal's physiology as it adjusts to changes in its external environment
- An example is adaptation to changes in altitude

Figure 40.10

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 normal range

Endothermy and Ectothermy

- **Endothermic** animals generate heat by metabolism; birds and mammals are endotherms
- **Ectothermic** animals gain heat from external sources; ectotherms include fishes, amphibians, nonavian reptiles, and most invertebrates

- Endotherms can maintain a stable body temperature even in the face of large fluctuations in environmental temperature
- Endothermy is more energetically expensive than ectothermy; ectotherms need to consume less food than equally sized endotherms
- In general, ectotherms tolerate greater variation in internal temperature

Figure 40.11

(a) King penguins (*Aptenodytes patagonicus*), endotherms

(b) Florida red-bellied turtles (*Pseudomys nelsoni*), ectotherms

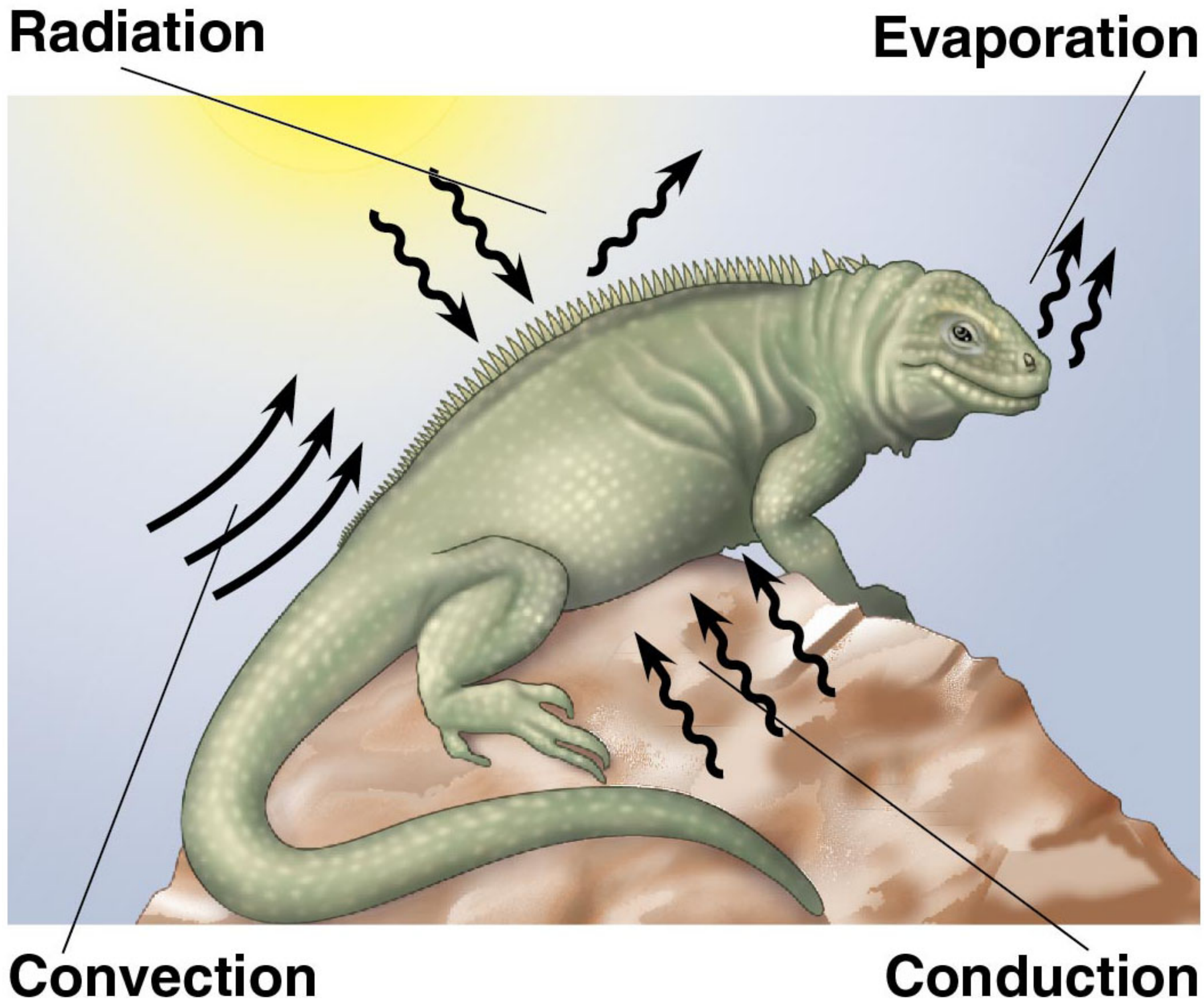
Variation in Body Temperature

- 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
  - Conduction

Figure 40.12



- 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

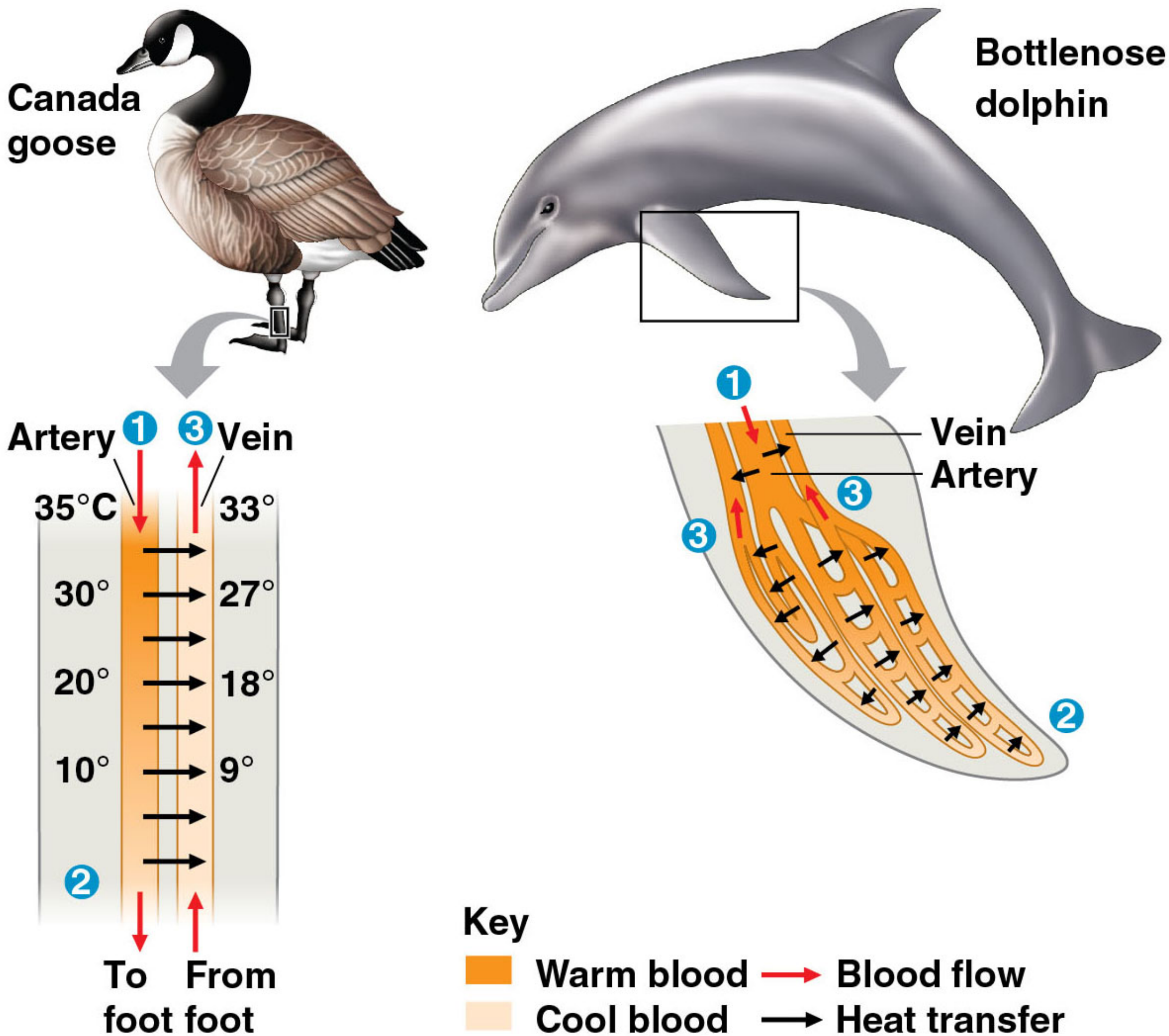
- Insulation is a major thermoregulatory adaptation in mammals and birds
- It reduces the flow of heat between an animal’s body and its environment
- Skin, feathers, fur, and blubber reduce heat flow between an animal and its environment
- Insulation is especially important in marine mammals such as 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 thereby reduce heat loss

Figure 40.13



Canada
goose
Bottlenose
dolphin
Artery
1
3
Vein
35°C
33°
30°
27°
20°
18°
10°
9°
2
To
foot
From
foot
1
Vein
Artery
3
3
2
Key
Warm blood
Cool blood
Blood flow
Heat transfer

- Certain sharks, fishes, and insects 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 mammals and birds live in places where regulating the body temperature requires cooling in addition to warming the body
- When the environmental temperature is above that of the body, evaporation can keep the body temperature from rising
- Sweating or bathing moistens the skin, helping to cool an animal down
- Panting increases the cooling effect in birds and many mammals

Behavioral Responses

- Ectotherms, and sometimes endoderms, use behavioral responses to control body temperature
- They may seek warm places when cold and orient themselves toward heat sources
- When hot, they bathe, move to cooler areas, or change orientation to minimize heat absorption

Figure 40.14

- Social behavior contributes to thermoregulation in both endotherms and ectotherms
- Endotherms such as Emperor penguins may huddle together to conserve heat
- Individuals move between the cooler outer edges of the huddle and the warmer center
- In hot weather, honeybees transport water to the hive and fan with their wings, promoting evaporation and convection

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 mammals have a tissue called brown fat that is specialized for rapid heat production
- It is found in the infants of many mammals and in adult mammals that hibernate
- The amount of brown fat in human adults has been found to vary depending on the temperature of the surrounding environment
- Birds and some nonavian reptiles can also raise body temperature through shivering

Figure 40.15

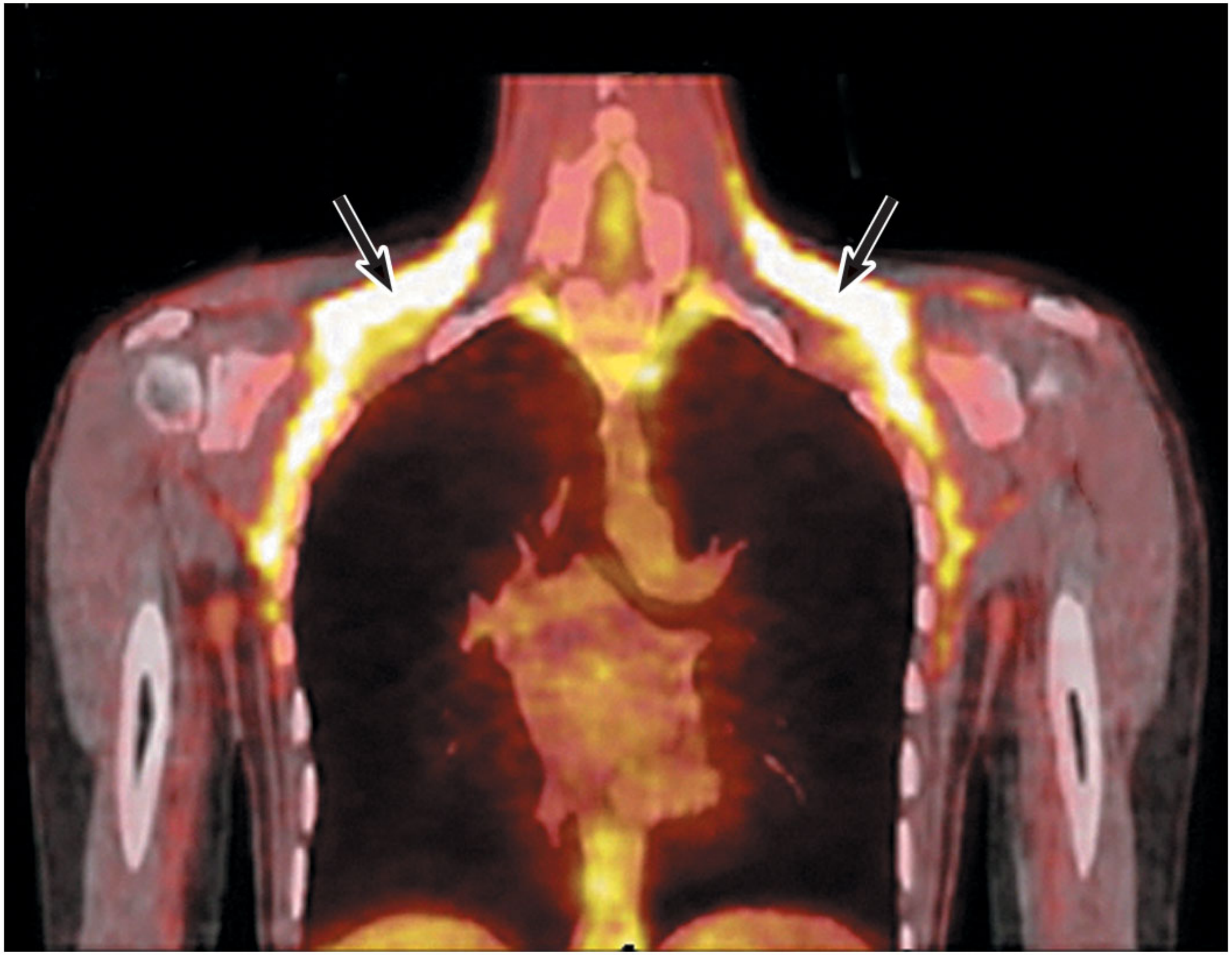
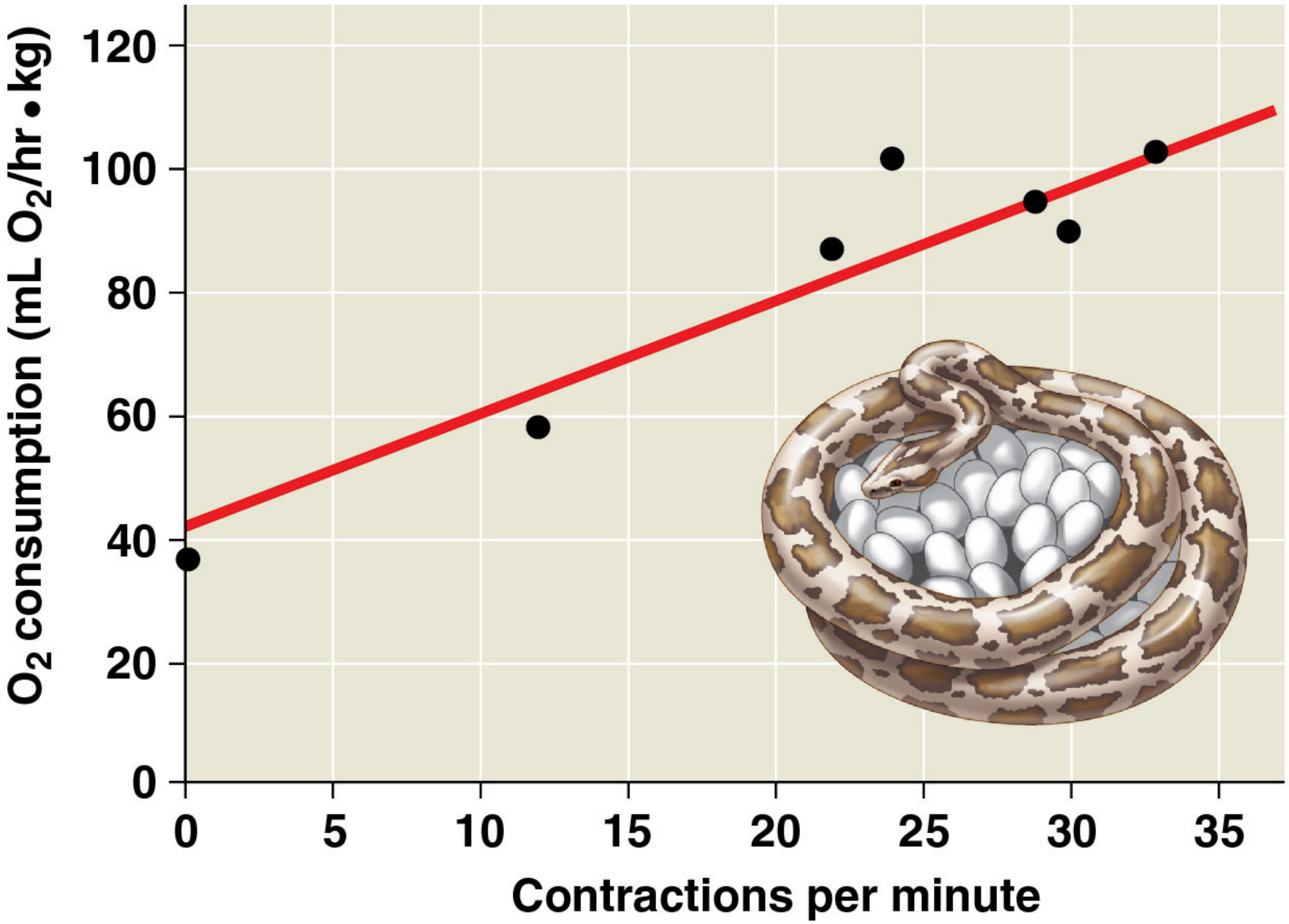


Figure 40.16

Results



Data from V. H. Hutchison, H. G. Dowling, and A. Vinegar, Thermoregulation in a brooding female Indian python, *Python molurus bivittatus, Science* 151:694–696 (1966).

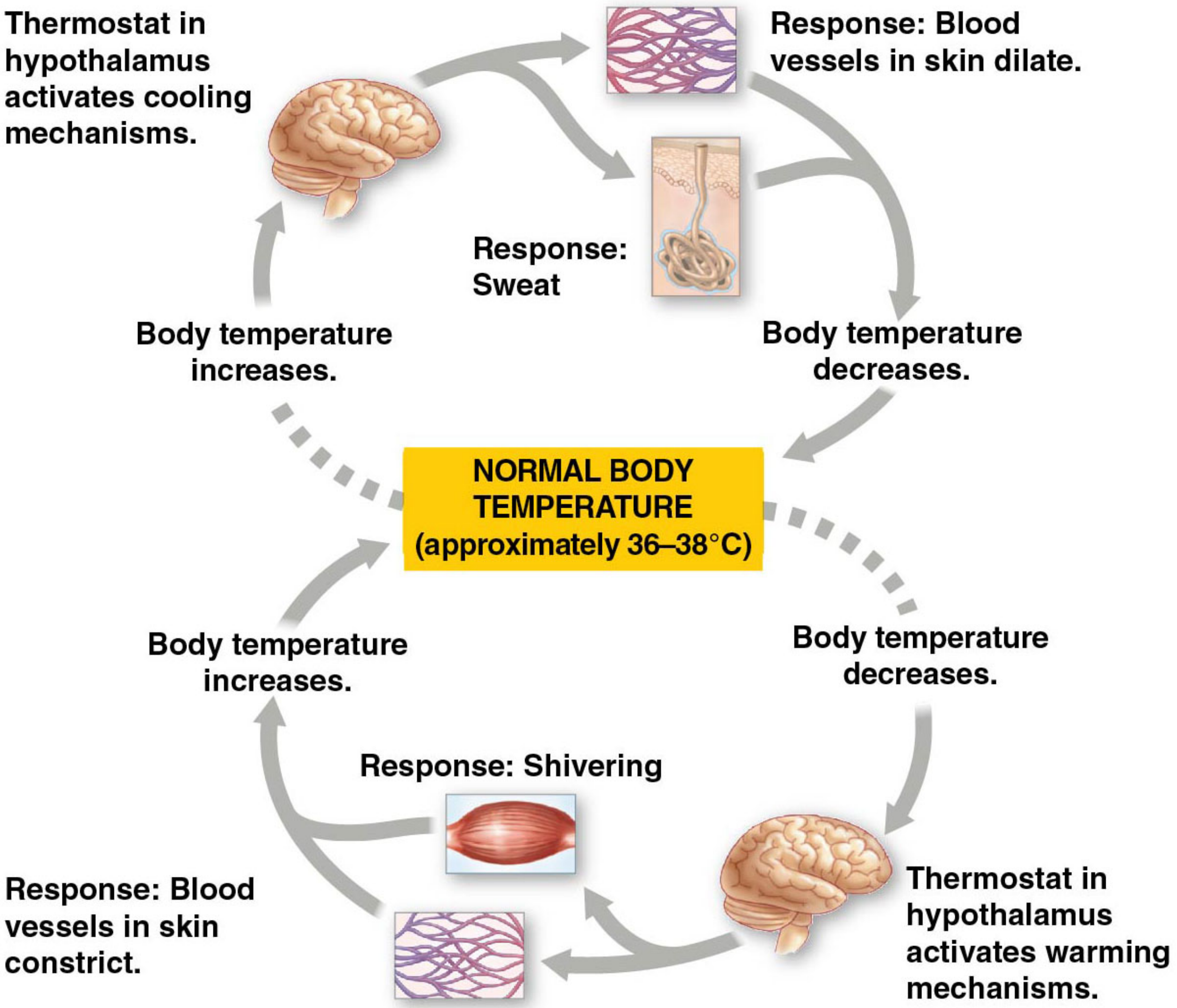
Acclimatization in Thermoregulation

- Birds and mammals can adjust their insulation to acclimatize to seasonal temperature changes
- Lipid composition of cell membranes may change with temperature
- When temperatures are subzero, some ectotherms produce “antifreeze” compounds to prevent ice formation in their cells

Physiological Thermostats and Fever

- In mammals, the sensors responsible for thermoregulation are concentrated in a region of the brain called the **hypothalamus**
- The hypothalamus triggers heat loss or heat-generating mechanisms
- Fever, a response to some infections, reflects an increase in the normal range for the biological thermostat
- Some ectothermic organisms seek warmer environments to increase their body temperature in response to certain infections

Figure 40.17


Thermostat in hypothalamus activates cooling mechanisms.
Response: Blood vessels in skin dilate.
Response: Sweat
Body temperature increases.
Body temperature decreases.
NORMAL BODY TEMPERATURE (approximately 36–38°C)
Body temperature increases.
Body temperature decreases.
Response: Shivering
Response: Blood vessels in skin constrict.
Thermostat in hypothalamus activates warming mechanisms.

CONCEPT 40.4: Energy requirements are related to animal size, activity, and environment

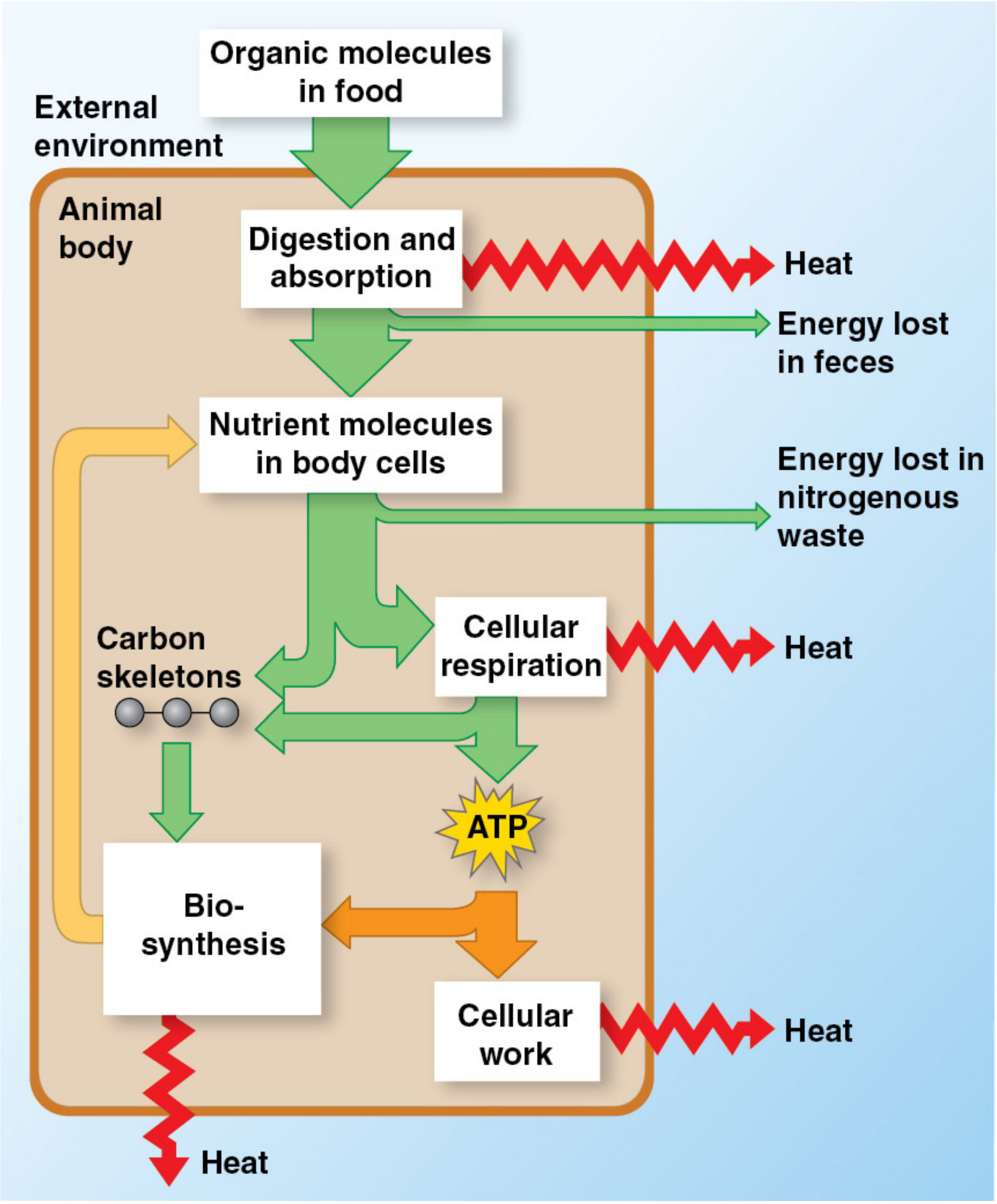
- **Bioenergetics** is the overall flow and transformation of energy in an animal
- It determines an animal's nutritional needs, and it relates to an animal's size, activity, and environment

Energy Allocation and Use

- Organisms can be classified by how they obtain chemical energy
- Autotrophs, such as plants, harness light energy to build energy-rich molecules
- Heterotrophs, such as 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

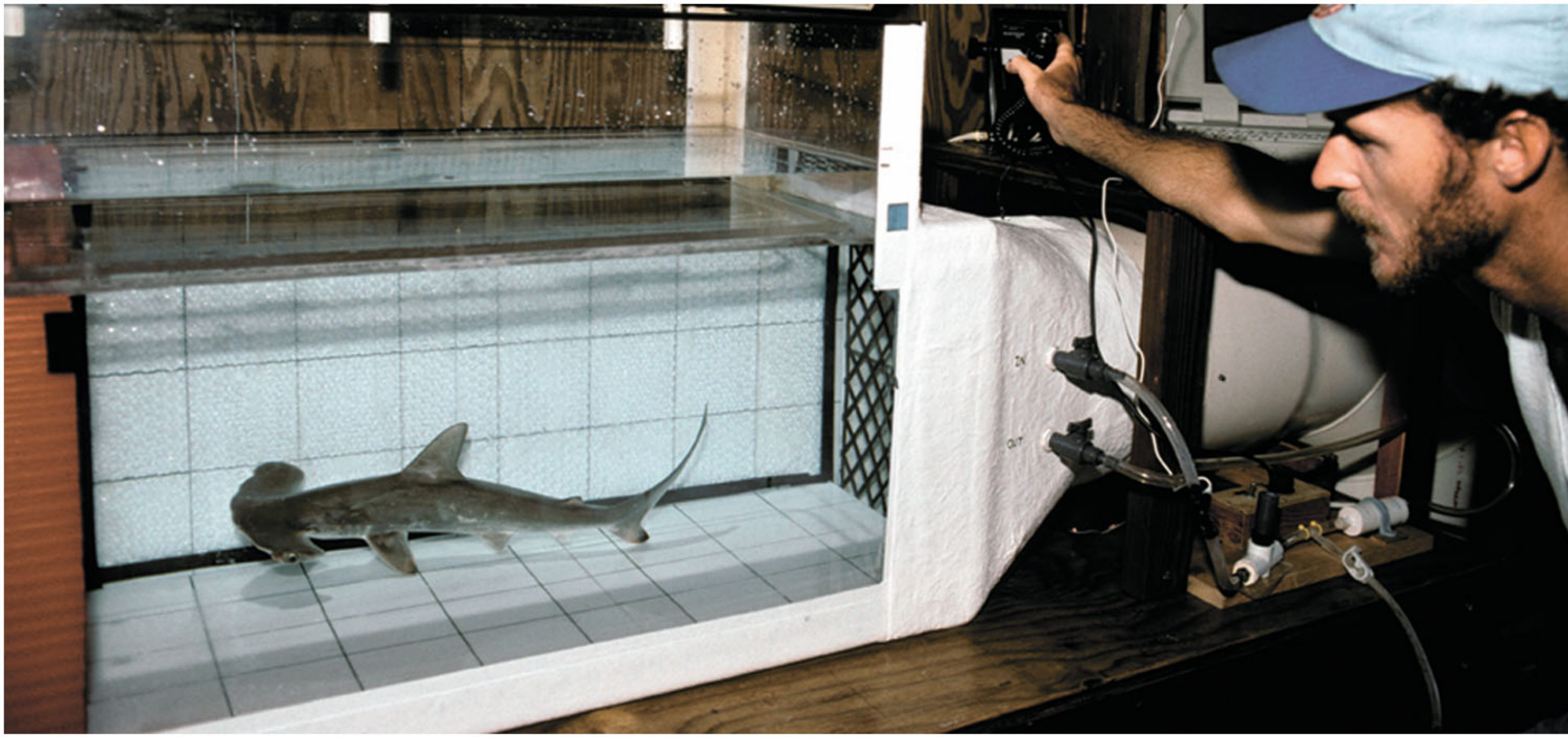
Figure 40.18


Organic molecules in food
External environment
Animal body
Digestion and absorption
Heat
Energy lost in feces
Nutrient molecules in body cells
Energy lost in nitrogenous waste
Carbon skeletons
Cellular respiration
Heat
ATP
Bio-synthesis
Cellular work
Heat
Heat

Quantifying Energy Use

- **Metabolic rate** is the sum of all the 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
  - Measuring energy content of food consumed and energy lost in waste products

Figure 40.19



Minimum Metabolic Rate and Thermoregulation

- **Basal metabolic rate** (**BMR**) is the metabolic rate of an endotherm at rest, with an empty stomach, and not experiencing stress
- BMR is measured under a comfortable temperature range

- **Standard metabolic rate** (**SMR**) is the metabolic rate of a fasting, non-stressed ectotherm at rest at a specific temperature
- Ectotherms have much lower metabolic rates than endotherms of a comparable size

Influences on Metabolic Rate

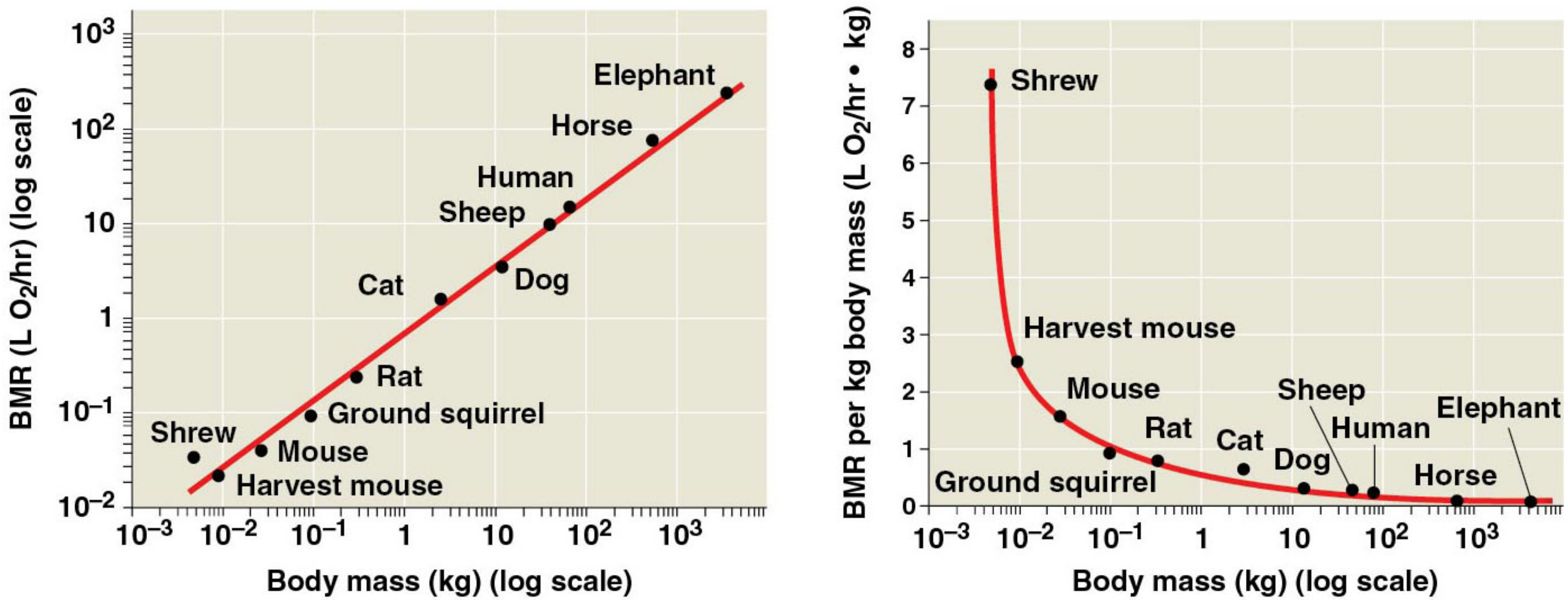
- Metabolic rates are affected by many factors besides whether an animal is an endotherm or ectotherm
- Some key factors are age, sex, size, activity, temperature, and nutrition

Size and Metabolic Rate

- Metabolic rate is roughly 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

- Trade-offs shape the evolution of body plans
- As body size increases, energy costs per gram of tissue decrease but a larger fraction of body tissue is needed for exchange, support, and locomotion

Figure 40.20



(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 both endotherms and ectotherms
- In general, the maximum metabolic rate an animal can sustain is inversely related to the duration of the activity

- For most terrestrial animals, the average daily rate of energy consumption is two to four times BMR (endotherms) or SMR (ectotherms)
- The fraction of an animal's energy budget devoted to activity depends on factors such as environment, behavior, size, and thermoregulation

Torpor and Energy Conservation

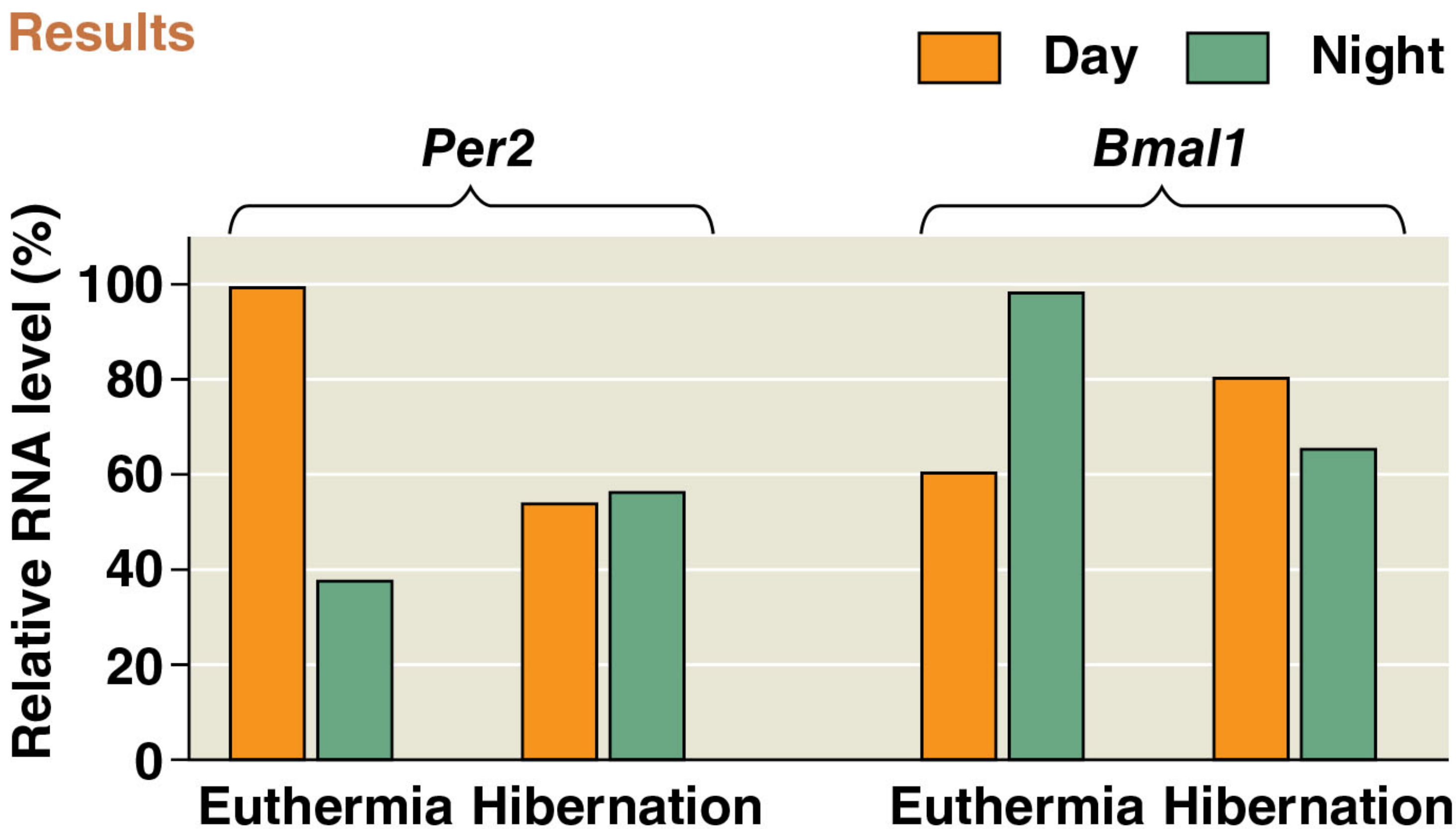
- **Torpor** is a physiological state of decreased activity and metabolism
- Torpor enables animals to save energy while avoiding difficult and dangerous conditions
- Daily torpor is exhibited by many small mammals and birds and seems adapted to feeding patterns
- **Hibernation** is long-term torpor that is an adaptation to winter cold and food scarcity

Figure 40.21

Hibernating dormouse
(*Muscardinus avellanarius*)

- Metabolic rates during hibernation can be 20 times lower than if the animal attempted to maintain normal body temperature (36–38ºC)
- Summer torpor, called estivation, enables animals to survive long periods of high temperatures and scarce water
- In the European hamster, the molecular components of the circadian clock cease operation during hibernation

Figure 40.22



Data from F. G. Revel et al., The circadian clock stops ticking during deep hibernation in the European hamster, *Proceedings of the National Academy of Sciences USA* 104:13816–13820 (2007).

- There are some fundamental similarities in the evolutionary adaptations of plants and animals

Figure 40.23

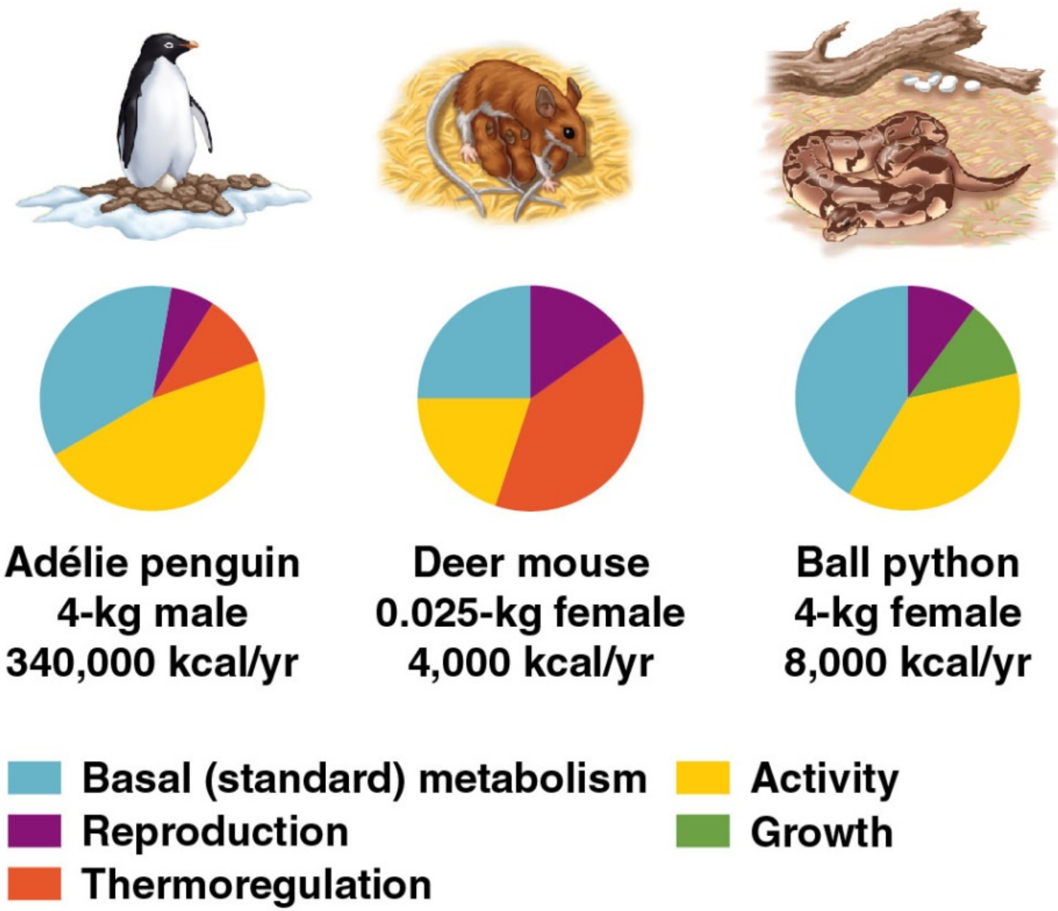
MAKE CONNECTIONS: Life Challenges and Solutions

Environmental Response

Nutritional Mode

Growth and Regulation

Figure 40.UN01



Data from M. A. Chappell et al., Energetics of foraging in breeding Adélie penguins, *Ecology* 74:2450–2461 (1993); M. A. Chappell et al., Voluntary running in deer mice: speed, distance, energy costs, and temperature effects, *Journal of Experimental Biology* 207:3839–3854 (2004); T. M. Ellis and M. A. Chappell, Metabolism, temperature relations, maternal behavior, and reproductive energetics in the ball python (*Python regius*), *Journal of Comparative Physiology B* 157:393–402 (1987).

Figure 40.UN02

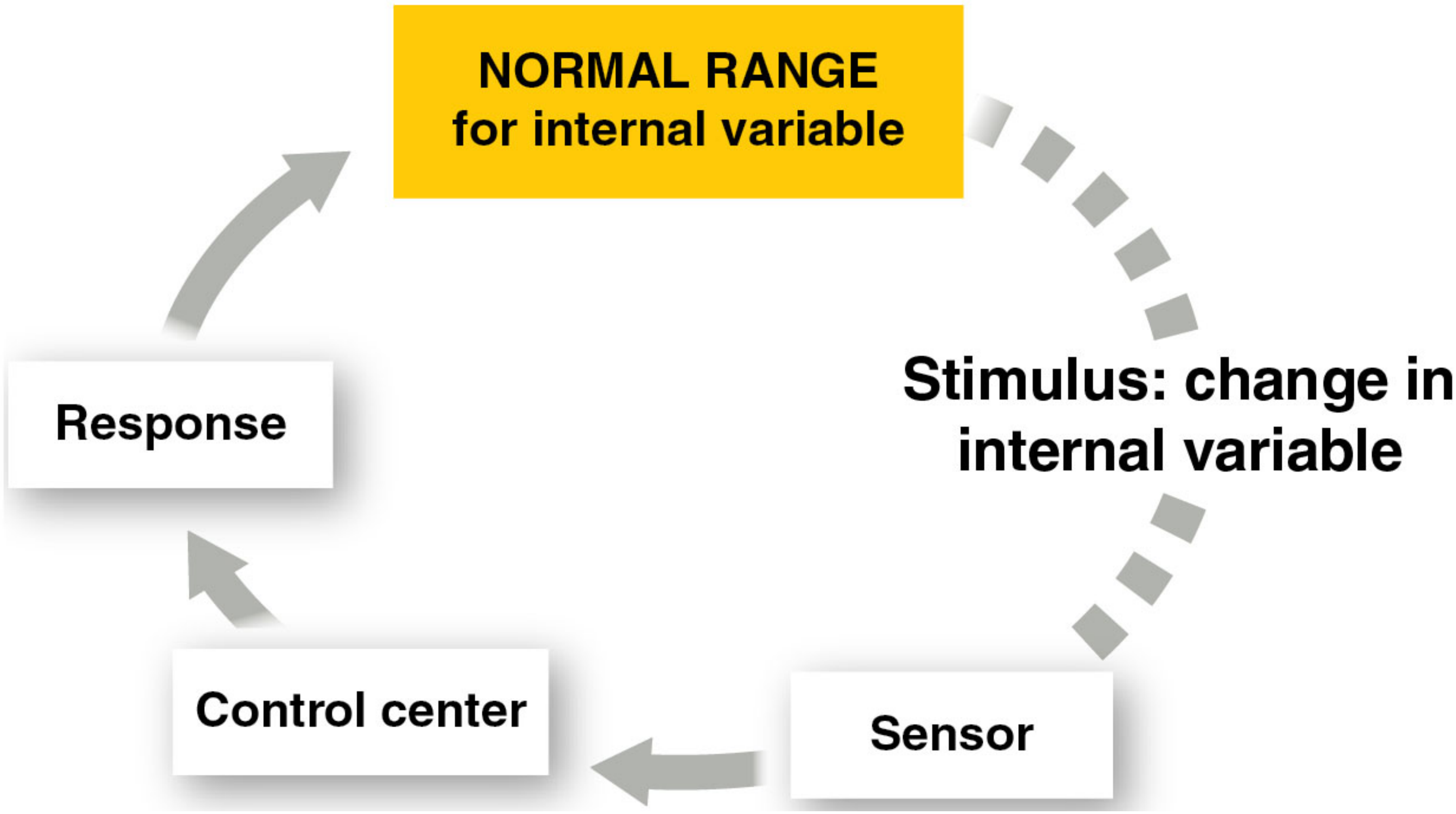


Figure 40.UN03