Chapter 41

Animal Nutrition

Lecture Outline

Overview: The Need to Feed

- All animals eat other organisms—dead or alive, whole or by the piece (including parasites).
- Animal **nutrition** includes the ingestion, breakdown, and absorption of food.
- In general, animals fit into one of three dietary categories.
  1. **Herbivores,** such as cattle, sea slugs, and termites, eat mainly plants or algae.
  2. **Carnivores,** such as sharks, hawks, and spiders, eat other animals.
  3. **Omnivores,** such as cockroaches, crows, bears, and humans, consume animal and plant or algal matter.
- The terms *herbivore*, *carnivore*, and *omnivore* represent the kinds of food that an animal usually eats, but most animals are opportunistic, occasionally eating foods that are outside their main dietary category.
  - For example, cattle and deer, which are herbivores, occasionally eat small animals or bird eggs.
  - All animals consume bacteria along with other types of food.
- To survive and reproduce, animals must balance their consumption, storage, and use of food.

Concept 41.1 An animal's diet must supply chemical energy, organic molecules, and essential nutrients

- An animal's diet must satisfy three nutritional needs: chemical energy for cellular processes, organic building blocks for macromolecules, and essential nutrients.
- Chemical energy from an animal's diet is converted to ATP to power living processes.
  - To meet the continuous need for ATP, animals ingest and digest nutrients for use in cellular respiration and energy storage.
- In addition to fuel for ATP production, an animal's diet must supply the raw materials needed for biosynthesis.
  - Animals require a source of organic carbon (such as sugar) and a source of organic nitrogen (such as protein) in order to construct their own organic molecules.

Materials that an animal's cells require but cannot synthesize are called essential nutrients.

- **Essential nutrients**, which must be obtained from an animal's diet, include both minerals and preassembled organic molecules.

    - Some nutrients are essential for all animals, whereas others are required for only certain species.

- There are four classes of essential nutrients: essential amino acids, essential fatty acids, vitamins, and minerals.

- **Essential amino acids** are those an animal cannot synthesize.
    - Most animals require eight amino acids in their diet.
    - Infants also require a ninth: histidine.

- A diet that does not provide sufficient amounts of one or more essential amino acids leads to protein deficiency, the most common type of malnutrition.
- Animal proteins are "complete," providing all the essential amino acids in their proper proportions.
- Most plant proteins are "incomplete," deficient in one or more essential amino acids.
    - Corn (maize), for example, is deficient in tryptophan and lysine, whereas beans are lacking in methionine.

- Animals produce the enzymes to synthesize most of the fatty acids they need.
- **Essential fatty acids**, the ones that animals cannot synthesize, are unsaturated.
    - For example, humans require linoleic acid to make some membrane phospholipids.

- **Vitamins** are organic molecules that have diverse functions and are required in the diet in relatively small quantities.
    - Although vitamins are required in tiny amounts (from about 0.01 mg to 100 mg per day depending on the vitamin), vitamin deficiency (or overdose in some cases) can cause serious problems.
    - So far, 13 vitamins essential to humans have been identified.
- Vitamins can be grouped into water-soluble vitamins and fat-soluble vitamins.

- Water-soluble vitamins include the B vitamins, which are compounds that function as coenzymes in key metabolic processes.
- Vitamin C, also water-soluble, is required for the production of connective tissue.
- Excessive amounts of water-soluble vitamins are excreted in urine, and moderate overdoses are probably harmless.

- The fat-soluble vitamins are A, K, and D. They have a wide variety of functions.
    - Vitamin A is incorporated in the visual pigments of the eye.
    - Vitamin K is required for blood clotting.
    - Vitamin D aids in calcium absorption and bone formation. This vitamin can be synthesized from other molecules when skin is exposed to sunlight.
- Excess amounts of fat-soluble vitamins are not excreted but are deposited in body fat.
    - Overconsumption may lead to toxic accumulations of these compounds.

- **Minerals** are simple inorganic nutrients, such as iron and sulfur, which are usually required in small amounts—from less than 1 mg to about 2,500 mg per day.
- Minerals have diverse functions in animal physiology.
    - Some are cofactors built into the structure of enzymes. For example, magnesium is present in enzymes that split ATP.
    - Sodium, potassium, and chloride are important in nerve function and have a major influence on the osmotic balance between cells and interstitial fluids.

- Iodine is required for thyroid hormones, which regulate metabolic rate.
- Vertebrates require relatively large quantities of calcium and phosphorus for the construction and maintenance of bone.

- Excess consumption of some minerals can upset the homeostatic balance and cause toxic effects.
  - Excess consumption of salt (sodium chloride) may contribute to high blood pressure.
  - The average U.S. citizen eats enough salt to provide about 20 times the required amount of sodium.
  - Liver damage due to iron accumulation affects up to 10% of the population in regions of Africa that have an iron-rich water supply.

Dietary deficiencies can have negative impacts on health and survival.

- A diet that lacks one or more essential nutrients or supplies less chemical energy than the body requires results in *malnutrition,* a failure to obtain adequate nutrition.
- The potential effects of malnourishment include deformities, disease, and even death.
  - Cattle, deer, and other herbivores may develop fragile bones if they graze in areas where soils and plants are deficient in phosphorus.
  - Some grazing animals obtain the missing nutrients by consuming concentrated sources of salt or other minerals.
- Recent experiments with spiders have found that carnivores can adjust for dietary deficiencies by switching to prey that restores their nutritional balance.
- Humans may suffer from diets lacking in essential nutrients.
  - A diet that provides insufficient amounts of one or more essential amino acids causes protein deficiency, the most common type of malnutrition among humans.
  - If protein deficient children survive infancy, they may have impaired physical and mental development.
  - People subsisting on a rice diet may suffer from vitamin A deficiency, which can cause blindness or death.
  - A genetically engineered strain of "Golden Rice" synthesizes beta-carotene, a source of vitamin A.
- A diet that fails to provide adequate sources of chemical energy results in *undernutrition.*
- When an animal is undernourished, it uses up stored fat and carbohydrates, and the body begins breaking down its own proteins for fuel.
  - Muscles begin to decrease in size, and the brain can become protein-deficient.
  - If energy intake remains less than energy expenditure, death will eventually result.
  - Even if a seriously undernourished person survives, some damage may be irreversible.
- Undernourishment is most common when drought, war, or another crisis severely disrupts the food supply.
  - In sub-Saharan Africa, where the AIDS epidemic has crippled communities, 200 million people are undernourished.
- Another cause of undernourishment is anorexia nervosa, an eating disorder associated with compulsive starvation despite food availability.

It is important – but difficult – to determine an ideal human diet.

- Humans are genetically diverse and live in varied settings.

- Ethical concerns preclude experimenting on the nutritional needs of children.
- Researchers study genetic defects that disrupt food uptake, storage, or use.
  - Hemochromatosis causes a buildup of iron in the absence of excess iron consumption.
  - By studying this disease, scientists have learned about the genes that regulate iron absorption.
- Insights into human nutrition have come from *epidemiology*, the study of human health and disease at the population level.
  - Epidemiologists aim to identify nutritional strategies for the prevention and control of diseases and disorders.
- In the 1970s, researchers found that women of low socioeconomic status are more likely to have children with neural tube defects, which occur when tissue fails to enclose the developing brain and spinal cord.
  - Richard Smithells of the University of Leeds found that folic acid (vitamin B_9) supplements greatly reduce the risk of neural tube defects.
  - In 1998, the FDA began to require that folic acid be added to the enriched grain used to make bread and cereal.
  - The frequency of neural tube defects has been significantly reduced as a result.

Concept 41.2 The main stages of food processing are ingestion, digestion, absorption, and elimination

- Food processing by animals can be divided into four distinct stages: ingestion, digestion, absorption, and elimination.
- **Ingestion,** the act of eating or feeding, is the first stage of food processing.
- **Digestion,** the second stage of food processing, is the process of breaking food down into molecules small enough for the body to absorb.
- Mechanical digestion, such as chewing, precedes chemical digestion. This breaks the food into smaller pieces, increasing the surface area available for chemical digestion.
- Chemical digestion is necessary because animals cannot directly use the macromolecules in food. They are too large to pass through the cell membranes to enter the cells of the animal.
  - In addition, the proteins, carbohydrates, nucleic acids, fats, and phospholipids in food are not identical to those an animal makes itself.
- Chemical digestion cleaves macromolecules into their component monomers, which the animal then uses to make its own molecules or as fuel for ATP production.
- Chemical digestion reverses the process that a cell uses to link together monomers to form macromolecules.
  - Rather than removing a molecule of water for each new covalent bond formed, digestion breaks bonds with the addition of water via **enzymatic hydrolysis**.
- A variety of hydrolytic enzymes catalyze the digestion of each of the classes of macromolecules found in food.
  - Polysaccharides and disaccharides are split into simple sugars. Fats are digested to glycerol and fatty acids. Proteins are broken down into amino acids. Nucleic acids are cleaved into nucleotides.

- After the food is digested, the animal's cells take up small molecules such as amino acids and simple sugars from the digestive compartment, a process called **absorption**.
- During **elimination**, undigested material passes out of the digestive compartment.

Most organisms carry out digestion in specialized compartments.

- The simplest digestive compartments are food vacuoles, organelles in which hydrolytic enzymes break down food without digesting the cell's own cytoplasm, a process termed **intracellular digestion**.
  - This process begins after a cell has engulfed food by phagocytosis or pinocytosis.
- Newly formed food vacuoles fuse with lysosomes, which are organelles containing hydrolytic enzymes.
- A few animals, such as sponges, digest their food entirely by this mechanism.
- In most animals, at least some hydrolysis occurs by **extracellular digestion,** the breakdown of food outside cells.
  - Extracellular digestion occurs within compartments that are continuous with the outside of the animal's body.
  - Thus, organisms can devour much larger pieces of food than can be ingested by phagocytosis.
- Many animals with simple body plans have digestive sacs with single openings, called **gastrovascular cavities.**
- Gastrovascular cavities function in both the digestion and distribution of nutrients throughout the body.
  - For example, the cnidarians called hydras capture their prey with nematocysts and use tentacles to stuff the prey through the mouth into the gastrovascular cavity.
  - The prey is then partially digested by enzymes secreted by specialized gland cells of the gastrodermis.
  - Nutritive muscular cells in the gastrodermis engulf the food particles.
  - Most of the actual hydrolysis of macromolecules occurs intracellularly.
  - Undigested materials are eliminated through the mouth.
- In contrast to cnidarians and flatworms, most animals have digestive tubes extending between a mouth and anus.
- These digestive tubes are called **complete digestive tracts,** or **alimentary canals**.
- Because food moves in one direction, the tube can be organized into specialized regions that carry out digestion and nutrient absorption in a stepwise fashion.
- In addition, animals with alimentary canals can eat more food before the earlier meal is completely digested.

Concept 41.3 Organs specialized for successive stages of food processing form the mammalian digestive system

- The general principles of food processing are similar for a diversity of animals, including mammals. We will use the mammalian system as a representative example.
- The mammalian digestive system consists of the alimentary canal and various accessory glands that secrete digestive juices into the canal through ducts.

- The accessory glands include the salivary glands, the pancreas, the liver, and the gallbladder.

- **Peristalsis,** rhythmic waves of contraction by smooth muscles in the walls of the canal, pushes food along the alimentary canel.
- **Sphincters**, muscular ring-like valves, regulate the passage of material between specialized chambers of the canal.

The oral cavity, pharynx, and esophagus initiate food processing.

- Both physical and chemical digestion of food begins in the mouth, or **oral cavity**.
- During chewing, teeth of various shapes cut, smash, and grind food, making it easier to swallow and increasing its surface area.
- The presence of food in the oral cavity triggers a nervous reflex that causes the **salivary glands** to deliver saliva through ducts to the oral cavity.
  - Salivation may occur in anticipation of food because of learned associations between eating and the time of day, cooking odors, or other stimuli.
- Chemical digestion of carbohydrates, a main source of chemical energy, begins in the oral cavity.
- Saliva contains **amylase,** an enzyme that hydrolyzes starch and glycogen into smaller polysaccharides and the disaccharide maltose.
- Saliva contains **mucus**, a viscous mixture of water, salts, and slippery glycoproteins called mucins.
  - Mucus protects the soft lining of the mouth from abrasion and lubricates the food for easier swallowing.
- Saliva also contains buffers that help prevent tooth decay by neutralizing acid in the mouth.
- Antibacterial agents in saliva, such as lysozyme, kill microbes that enter the mouth with food.
- The tongue tastes food, manipulates it during chewing, and helps shape the food into a ball called a **bolus.**
- During swallowing, the tongue pushes a bolus back into the oral cavity and into the pharynx.
- The **pharynx,** also called the throat, is a junction that opens to both the esophagus and the trachea (windpipe).
- When we swallow, the top of the trachea moves up so that its opening, the *glottis*, is blocked by a cartilaginous flap, the *epiglottis*.
  - This mechanism normally ensures that a bolus will be guided into the entrance of the esophagus and not directed down the trachea.
  - If food or liquid enters and blocks the trachea, the material can be dislodged by vigorous coughing or a forced upward thrust of the diaphragm (the Heimlich maneuver).
- The esophagus contains both striated and smooth muscle.
  - The striated muscle at the top of the esophagus is active during swallowing.
  - In the rest of the esophagus, smooth muscle functions in peristalsis, as rhythmic cycles of contraction move the bolus to the stomach.

The stomach stores food and performs preliminary digestion.

- The **stomach** is in the upper abdominal cavity, just below the diaphragm.

- With accordion-like folds and a very elastic wall, the stomach can stretch to accommodate about 2 L of food and fluid, storing an entire meal.
- The stomach secretes a digestive fluid called **gastric juice** and mixes this secretion with the food by the churning action of the smooth muscles in the stomach wall.
  - The mixture of ingested food and digestive juices is called **chyme**.
- Two components of gastric juice carry out chemical digestion in the stomach.
- One component of gastric juice is hydrochloric acid (HCl), which disrupts the extracellular matrix that binds cells together.
  - With a high concentration of hydrochloric acid, the gastric juice has a pH of about 2—acidic enough to digest iron nails.
  - This low pH kills most bacteria that are swallowed with food.
  - It also denatures proteins in food, increasing exposure of their peptide bonds.
- The second component of gastric juice is **pepsin**, an enzyme that begins the hydrolysis of proteins.
  - Pepsin, which works well in strongly acidic environments, is a **protease** that breaks peptide bonds adjacent to specific amino acids, producing smaller polypeptides.
- Cells in the gastric glands of the stomach produce the components of gastric juice.
  - *Parietal cells* secrete hydrochloric acid in the form of hydrogen and chloride ions, using an ATP-driven pump.
  - Meanwhile, *chief cells* release pepsin into the lumen in an inactive form called **pepsinogen**.
  - HCl in the lumen of the stomach converts pepsinogen to active pepsin by clipping off a small portion of the molecule to expose its active site.
  - In a positive-feedback system, activated pepsin activates more pepsinogen molecules.
- Because HCl and pepsin form in the lumen of the stomach, not within the cells of the gastric glands, the stomach's cells are protected from self-digestion.
- The stomach's second line of defense against self-digestion is a coating of mucus, secreted by the epithelial cells, that protects the stomach lining.
  - Still, the epithelium is continuously eroded, and the epithelium is completely replaced by mitosis every three days.
- Gastric ulcers, lesions in the stomach lining, are caused by the acid-tolerant bacterium *Helicobacter pylori*.
  - Ulcers are often treated with antibiotics.
  - The discovery that ulcers are caused by a bacterial infection, not by stress, earned Barry Marshall and Robin Warren the Nobel Prize in 2005.
- About every 20 seconds, the stomach contents are mixed by the churning action of smooth muscles.
- As a result of mixing and enzyme action, what begins in the stomach as a recently swallowed meal becomes nutrient-rich chyme.
- Most of the time, the stomach is closed off at both ends.
- The opening from the esophagus to the stomach normally dilates only when a bolus driven by peristalsis arrives.
  - The occasional backflow of acid chyme from the stomach into the lower esophagus—known as acid reflux—causes the irritation of the esophagus called "heartburn."

- The sphincter at the opening from the stomach to the small intestine helps regulate the passage of chyme into the intestine.
  - A squirt at a time, it takes about 2 to 6 hours after a meal for the stomach to empty.

The small intestine is the major organ of digestion and absorption.

- With a length of more than 6 m in humans, the **small intestine** is the longest section of the alimentary canal.
- Most of the enzymatic hydrolysis of food macromolecules and most of the absorption of nutrients into the blood occur in the small intestine.
- In the **duodenum,** the first 25 cm or so of the small intestine, chyme from the stomach mixes with digestive juices from the pancreas, liver, gallbladder, and gland cells of the intestinal wall.
- Hormones released by the stomach and duodenum control the digestive secretions into the alimentary canal.
- The **pancreas** produces several enzymes and an alkaline solution rich in bicarbonate that acts as a buffer to neutralize the acidity of chyme from the stomach.
  - Pancreatic enzymes include trypsin and chymotrypsin, proteases that are secreted into the duodenum in inactive form.
  - The pancreatic proteases are activated once they are in the lumen within the duodenum.
- The **liver** performs a wide variety of important functions in the body, including the production of **bile.**
  - Bile contains bile salts that act as detergents that aid in the digestion and absorption of fats.
  - Bile is stored and concentrated in the **gallbladder**.
- The liver also breaks down toxins that enter the body and helps balance nutrient utilization.
  - Bile also contains pigments that are by-products of red blood cell destruction in the liver.
  - These bile pigments are eliminated from the body with the feces.
- The epithelial lining of the duodenum produces several digestive enzymes.
  - Some enzymes are secreted into the lumen, while others are bound to the surface of the epithelial cells.
- Enzymatic digestion is completed as peristalsis moves the mixture of chyme and digestive juices along the small intestine.
- Most digestion is completed while the chyme is still in the duodenum.
- The remaining regions of the small intestine, the *jejunum* and *ileum,* function mainly in the absorption of nutrients and water.
- To enter the body, nutrients in the lumen must pass the lining of the digestive tract.
- A few nutrients are absorbed in the stomach and large intestine, but most absorption takes place in the small intestine.
- The enormous surface area of the small intestine is an adaptation that greatly increases the rate of nutrient absorption.
  - The small intestine has a surface area of 300 m^2, roughly the size of a tennis court.
- Large circular folds in the lining bear fingerlike projections called **villi**.

- Each epithelial cell of a villus has many microscopic appendages called **microvilli** that are exposed to the intestinal lumen.
  - The microvilli are the basis of the term *brush border* for the intestinal epithelium.
- In some cases, transport of nutrients across the epithelial cells is passive, as molecules move down their concentration gradients from the lumen of the intestine into the epithelial cells, and then into capillaries.
  - Fructose, a simple sugar, moves by facilitated diffusion down its concentration gradient from the lumen of the intestine into the epithelial cells and then into capillaries.
- Amino acids, small peptides, vitamins, and most glucose molecules are pumped against concentration gradients by the epithelial cells of the villus.
  - This active transport allows much more absorption of nutrients than would be possible with passive diffusion.
- The capillaries and veins that drain nutrients away from the villi converge into the **hepatic portal vein**, which leads directly to the liver.
- The liver, which has the metabolic versatility to interconvert various organic molecules, has first access to the amino acids and sugars absorbed after a meal is digested.
- The liver modifies and regulates this varied mix before releasing materials back into the bloodstream.
  - The liver helps regulate the levels of glucose in the blood, ensuring that the blood exiting the liver usually has a glucose concentration very close to 90 mg per 100 mL, regardless of the carbohydrate content of the meal.
  - The liver also removes toxic substances before the blood circulates broadly.
- From the liver, blood travels to the heart, which pumps the blood and nutrients to all parts of the body.
- Monoglycerides and most fatty acids are absorbed by epithelial cells and recombined into triglycerides within the cells.
- The fats are coated with phospholipids, cholesterol, and proteins to form water-soluble globules called **chylomicrons**.
- Chylomicrons are transported by exocytosis out of epithelial cells and into **lacteals**, lymph vessels at the core of each villus.
- The lacteals converge into the larger vessels of the lymphatic system, eventually draining into large veins that return blood to the heart.

Absorption of water is the major function of the large intestine.

- The **large intestine** includes the colon, cecum, and rectum.
- The large intestine connects to the small intestine at a T-shaped junction where a sphincter controls the movement of materials.
- The main arm of the T is the 1.5 m long **colon**, which leads to the rectum and anus.
- The other arm of the T is a pouch called the **cecum**.
  - The relatively small cecum of humans has a fingerlike extension, the **appendix**, which makes a minor contribution to body defense.
- A major function of the colon is to recover water that has entered the alimentary canal as the solvent in various digestive juices.
  - About 7 L of fluid are secreted into the lumen of the digestive tract of a person each day.

- More than 90% of the water is reabsorbed in the small intestine and the colon.

- Because there is no biological mechanism for the active transport of water, water absorption in the colon occurs by osmotically driven bulk flow as ions, particularly sodium, are pumped out of the lumen.
- Digestive wastes, the **feces**, become more solid as they are moved along the colon by peristalsis.
  - It takes 12 to 24 hours for material to travel the length of the organ.
  - If the lining of the colon is irritated by a viral or bacterial infection, less water than usual is resorbed, resulting in diarrhea.
  - If too much water is absorbed because peristalsis moves the feces too slowly, the result is constipation.
- Living in the large intestine is a rich community of mostly harmless bacteria, which make up approximately one-third of the dry weight of feces.
  - One of the most common inhabitants of the human colon is *Escherichia coli*.
  - Because *E. coli* is so common in human digestive systems, its presence in lakes and streams is an indicator of contamination by untreated sewage.
- As a by-product of their metabolism, many colon bacteria generate gases, including methane and hydrogen sulfide.
- These gases and ingested air are expelled through the anus.
- Some bacteria produce vitamins, including vitamin K, and several B vitamins, including biotin and folic acid, which supplement our dietary intake of vitamins.
- Feces contain masses of bacteria and undigested materials, including cellulose.
  - Although cellulose fibers have no caloric value to humans, their presence in the diet helps move food along the digestive tract.
- The terminal portion of the colon is called the **rectum,** where feces are stored until they can be eliminated.
- Between the rectum and the anus are two sphincters, one involuntary and one voluntary.
- Once or more each day, strong contractions of the colon create an urge to defecate.

Concept 41.4 Evolutionary adaptations of vertebrate digestive systems correlate with diet

The variety of digestive systems correlates with diet.

- The digestive systems of mammals and other vertebrates are variations on a common plan.
- The many intriguing varieties of digestive systems are often associated with the animal’s diet.
- Dentition, an animal’s assortment of teeth, is one example of structural variation reflecting diet.
- Mammals’ evolutionary adaptation of teeth for processing different kinds of food is one of the major reasons they have been so successful.
- Nonmammalian vertebrates generally have less specialized dentition, but there are exceptions.
  - For example, poisonous snakes, such as rattlesnakes, have fangs, modified teeth that inject venom into prey.

- Some snakes have hollow fangs, like syringes, while others drip poison along grooves in the tooth surface.

- Large, expandable stomachs are common in carnivores, which may go for a long time between meals and, therefore, must eat as much as they can when they do catch prey.
  - For example, a 200-kg African lion can consume 40 kg of meat in one meal.
- The length of the vertebrate digestive system is also correlated with diet.
- In general, herbivores and omnivores have longer alimentary canals relative to their body sizes than do carnivores, providing more time for digestion and more surface areas for absorption of nutrients.
  - Vegetation is more difficult to digest than meat because it contains cell walls. A longer digestive tract allows more time for digestion and more surface area for absorption.

Symbiotic microorganisms help nourish many vertebrates.

- Much of the chemical energy in the diet of herbivorous animals is contained in the cellulose of plant cell walls.
- Animals do not produce enzymes that hydrolyze cellulose, so many vertebrates (and termites) house large populations of symbiotic bacteria and protists in fermentation chambers in their alimentary canals.
  - These microbes have enzymes that can digest cellulose to simple sugars that the animal can absorb.
- The location of symbiotic microbes in herbivores' digestive tracts varies depending on the type of herbivore.
  - The hoatzin, an herbivorous bird that lives in South American rain forests, has a large, muscular crop (an esophageal pouch) that houses symbiotic microbes.
  - Many herbivorous mammals, including horses, house symbiotic microbes in a large cecum, the pouch where the small and large intestines connect.
  - The koala also has an enlarged cecum, where symbiotic bacteria ferment finely shredded eucalyptus leaves.
- The symbiotic bacteria of rabbits and some rodents live in the large intestine and cecum.
  - Since most nutrients are absorbed in the small intestine, these herbivores recover nutrients from fermentation in the large intestine by *coprophagy*, eating some of their feces and passing food through the alimentary canal a second time.
- The most elaborate adaptations for an herbivorous diet have evolved in the **ruminants,** which include deer, cattle, and sheep.

Adaptations related to digestion are widespread among multicellular animals.

- The giant 3 m long tubeworms that live at deep-sea hydrothermal vents thrive at pressures of 260 atmospheres.
- These worms have no mouth or digestive systems. Instead, they rely on mutualistic bacteria to obtain energy and nutrients from the carbon dioxide, oxygen, hydrogen sulfide, and nitrate available at the vents.
- For invertebrates and vertebrates alike, mutualistic symbiosis has evolved as a general strategy for expanding the sources of nutrition available for animals.

Concept 41.5 Feedback circuits regulate digestions, energy storage, and appetite

- Many animals go for long intervals between meals and do not need their digestive systems to be active continuously.
    - Each step in processing is activated as food reaches a new compartment in the alimentary canal.
    - The arrival of food triggers secretion of substances that promote the next stage of chemical digestion, as well as muscular contractions that then propel food farther along the canal.
- A branch of the nervous system called the *enteric division*, which is dedicated to the digestive organs, regulates these events as well as peristalsis in the small and large intestines.
- The endocrine system also plays a critical role in controlling digestion.
- Hormones released by the stomach and duodenum ensure that digestive secretions are present only when needed.
    - Like all hormones, they are transported through the bloodstream. This is true even for the hormone gastrin, whose target (the stomach) is the same organ that secretes it.

Animals regulate energy storage and allocation.

- The first sites used for energy storage in the human body are liver and muscle cells.
    - In these cells, excess energy from the diet is stored in glycogen.
- Once glycogen depots are full, any additional excess energy is usually stored in fat in adipose cells.
- When stored energy is mobilized, the human body generally expends liver glycogen first and then draws on muscle glycogen and fat.
- Fats are especially rich in energy; oxidizing a gram of fat liberates about twice the energy liberated from a gram of carbohydrate or protein.
    - For this reason, adipose tissue provides the most space-efficient way for the body to store large amounts of energy.
    - Most healthy people have enough stored fat to sustain them through several weeks without food.
- The pancreatic hormones insulin and glucagon maintain glucose homeostasis by tightly regulating the synthesis and breakdown of glycogen.
    - When insulin levels rise after a carbohydrate-rich meal, glucose entering the liver in the hepatic portal vein is used to synthesize glycogen.
    - Between meals, when blood in the hepatic portal vein has a much lower glucose concentration, glucagon stimulates the liver to break down glycogen, releasing glucose into the blood.
    - Through the combined action of insulin and glucagon, blood exiting the liver has a glucose concentration of 70–110 mg per 100 mL at nearly all times.

Animals regulate appetite and food consumption.

- *Overnourishment*, the consumption of more calories than the body needs for normal metabolism, causes obesity, the excessive accumulation of fat.
- Obesity contributes to a number of health problems, including the most common type of diabetes (type 2), cancer of the colon and breast, and cardiovascular disease that can lead to heart attacks and strokes.

- Obesity is a factor in about 300,000 deaths per year in the United States alone.

- Several homeostatic mechanisms help regulate body weight. Operating as feedback circuits, these mechanisms control the storage and metabolism of fat.
- Several hormones regulate long-term and short-term appetite by affecting a "satiety center" in the brain.
- In addition, a network of neurons relays and integrates information from the digestive system to regulate hormone release.
- To a large extent, this neuronal network functions independent of inputs from the central nervous system.
- Mutations that cause mice to be chronically obese played a key role in advancing our understanding of the satiety pathway.
  - Mice with mutations in the *ob* or *db* gene eat voraciously and become much heavier than normal.
  - Based on experiments, Doug Coleman deduced that the *ob* gene is required to produce the satiety factor, and the *db* gene is required to respond to the factor.
- Cloning of the *ob* gene led to the demonstration that it codes for the hormone **leptin**.
  - The *db* gene encodes the leptin receptor. Leptin and the leptin receptor are key components of the circuitry that regulates appetite over the long term.
  - Leptin is a product of adipose cells, so levels rise when the amount of body fat increases, cuing the brain to suppress appetite.
  - Loss of fat decreases leptin levels, signaling the brain to increase appetite.
- The feedback signals provided by leptin thus maintain body fat levels within a set range.
- Leptin has complex functions, including a role in how the nervous system develops.
- Most obese people have an abnormally high leptin level, which fails to elicit a response from the brain's satiety center.
  - Clearly, there is much to learn in this important area of human physiology.
- The relationship between fat storage and evolutionary adaptation in animals may be complex.
- Petrels produce plump chicks. These seabirds fly long distances to bring back food that is very rich in lipids.
  - The fact that fat has about twice as many calories per gram as other fuels minimizes the number of foraging trips.
- However, growing petrels get little protein in their oily diet.
  - To get enough protein, young petrels consume many more calories than they burn in metabolism, and consequently become obese.
  - Their fat depots help them survive periods when their parents cannot find enough food.
- When food is plentiful, chicks come to weigh much more than their parents. They must fast for several days before they are capable of flight.
- Fat hoarding is now a health liability, but have been an advantage in our evolutionary past.
- Our ancestors on the African savanna were hunter-gatherers who survived mainly on seeds and other plant products, a diet supplemented by hunting game or scavenging meat from animals killed by other predators.

- Natural selection may have favored individuals with a physiology that induced them to gorge on rich, fatty foods when they were available.
- Individuals with genes promoting the storage of high-energy molecules during feasts may have been more likely to survive famines.
- Our present-day taste for fats may be partly an evolutionary vestige of less nutritious times.