LECTURE PRESENTATIONS
For CAMPBELL BIOLOGY, NINTH EDITION

Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 44

Osmoregulation and Excretion

Lectures by
Erin Barley
Kathleen Fitzpatrick

Overview: A Balancing Act

- Physiological systems of animals operate in a fluid environment
- Relative concentrations of water and solutes must be maintained within fairly narrow limits
- **Osmoregulation** regulates solute concentrations and balances the gain and loss of water

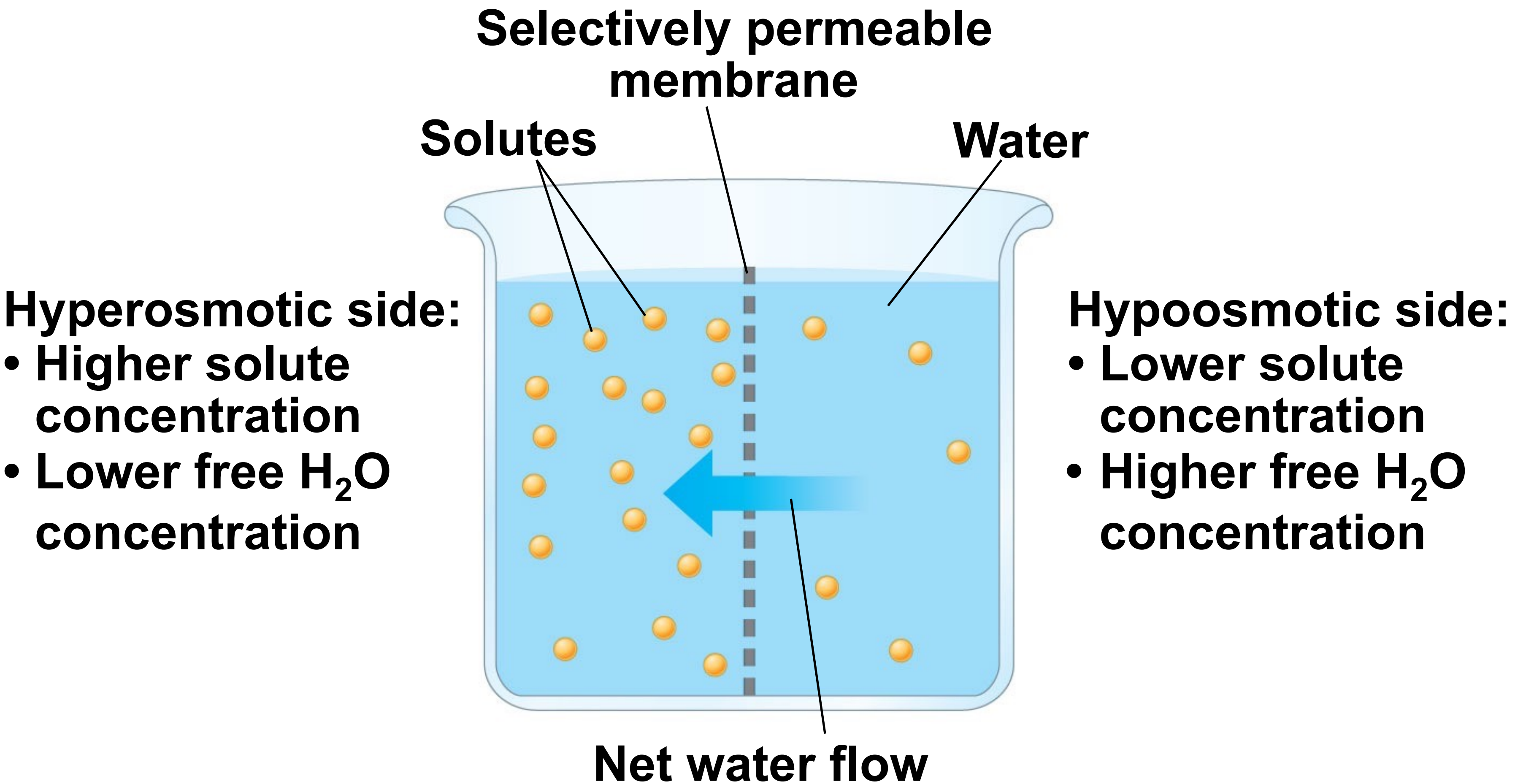
- Freshwater animals show adaptations that reduce water uptake and conserve solutes
- Desert and marine animals face desiccating environments that can quickly deplete body water
- **Excretion** gets rid of nitrogenous metabolites and other waste products

Figure 44.1

Concept 44.1: Osmoregulation balances the uptake and loss of water and solutes

- Osmoregulation is based largely on controlled movement of solutes between internal fluids and the external environment

Figure 44.2



Selectively permeable membrane
Solutes
Water
Hyperosmotic side:
• Higher solute concentration
• Lower free H_2O concentration
Hypoosmotic side:
• Lower solute concentration
• Higher free H_2O concentration
Net water flow

Osmotic Challenges

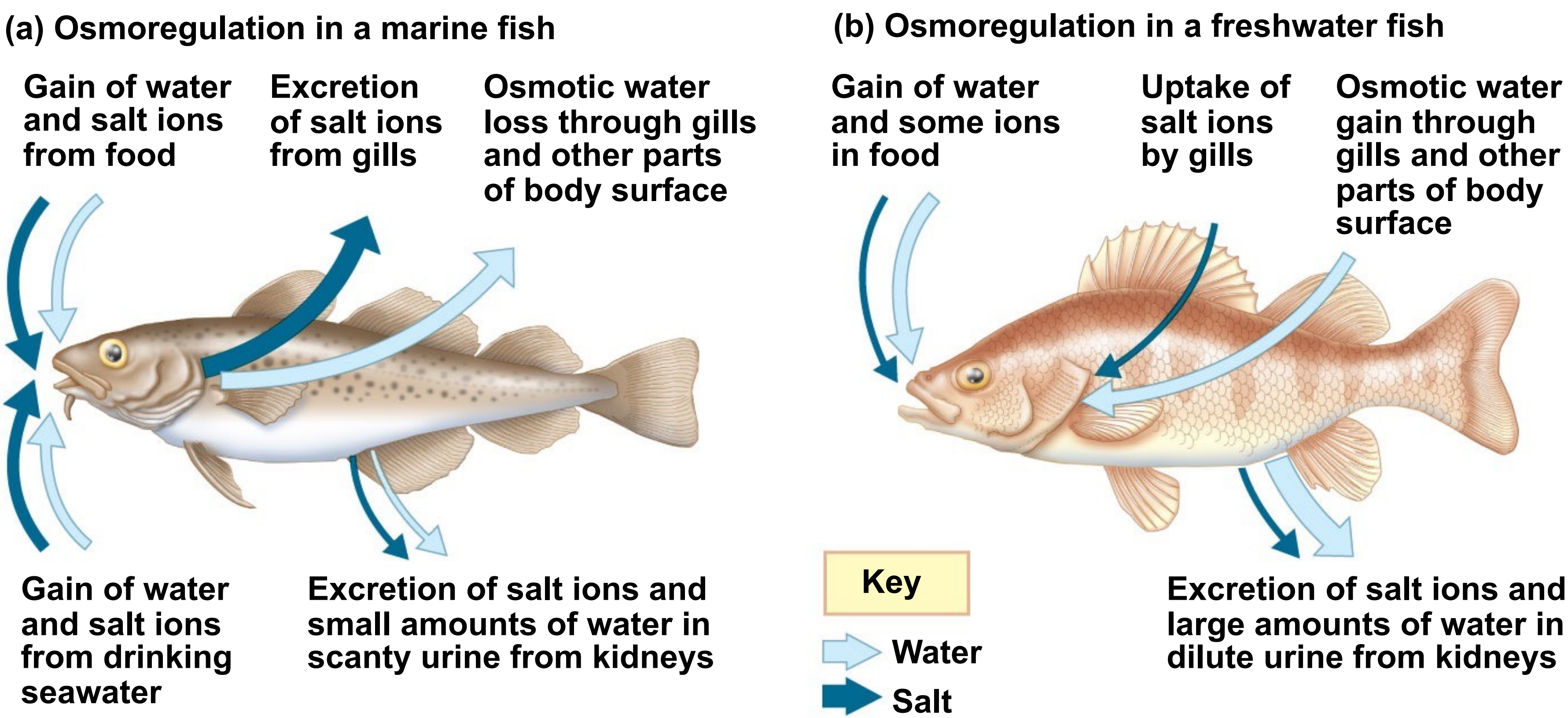
- **Osmoconformers**, consisting only of some marine animals, are isoosmotic with their surroundings and do not regulate their osmolarity
- **Osmoregulators** expend energy to control water uptake and loss in a hyperosmotic or hypoosmotic environment

- Most animals are stenohaline; they cannot tolerate substantial changes in external osmolarity
- Euryhaline animals can survive large fluctuations in external osmolarity

Marine Animals

- Most marine invertebrates are osmoconformers
- Most marine vertebrates and some invertebrates are osmoregulators
- Marine bony fishes are hypoosmotic to seawater
- They lose water by osmosis and gain salt by diffusion and from food
- They balance water loss by drinking seawater and excreting salts

Figure 44.3


(a) Osmoregulation in a marine fish
Gain of water and salt ions from food
Excretion of salt ions from gills
Osmotic water loss through gills and other parts of body surface
Gain of water and salt ions from drinking seawater
Excretion of salt ions and small amounts of water in scanty urine from kidneys
(b) Osmoregulation in a freshwater fish
Gain of water and some ions in food
Uptake of salt ions by gills
Osmotic water gain through gills and other parts of body surface
Excretion of salt ions and large amounts of water in dilute urine from kidneys
Key
Water
Salt

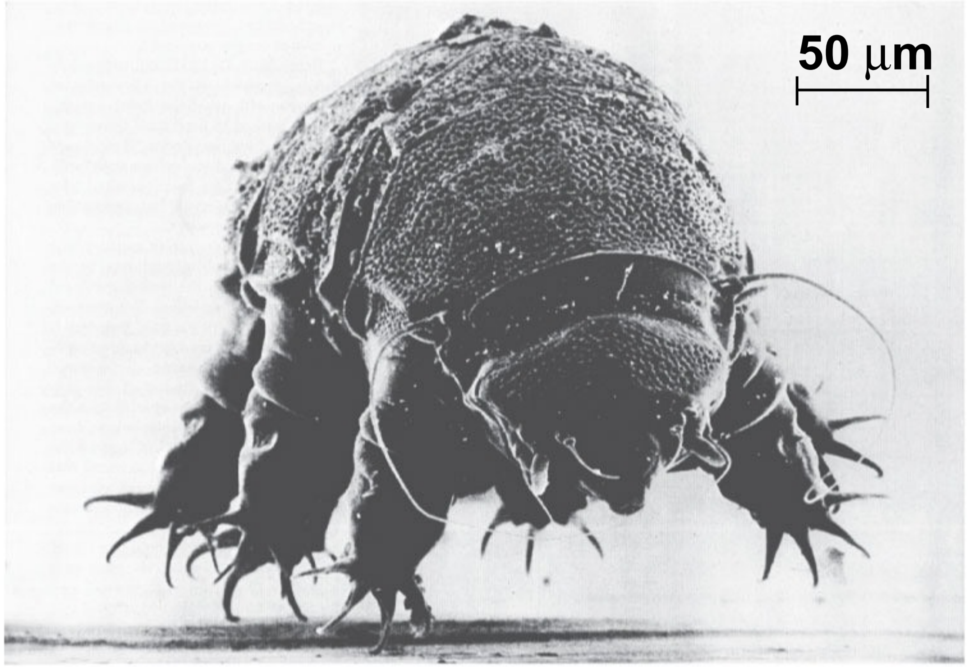
Freshwater Animals

- Freshwater animals constantly take in water by osmosis from their hypoosmotic environment
- They lose salts by diffusion and maintain water balance by excreting large amounts of dilute urine
- Salts lost by diffusion are replaced in foods and by uptake across the gills

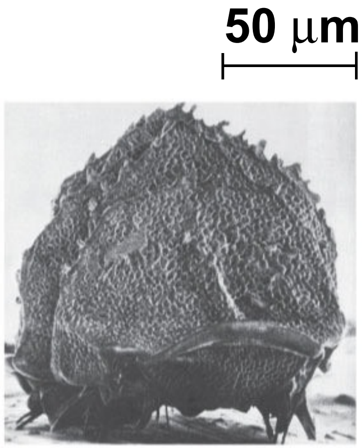
Animals That Live in Temporary Waters

- Some aquatic invertebrates in temporary ponds lose almost all their body water and survive in a dormant state
- This adaptation is called **anhydrobiosis**

Figure 44.5



(a) Hydrated tardigrade

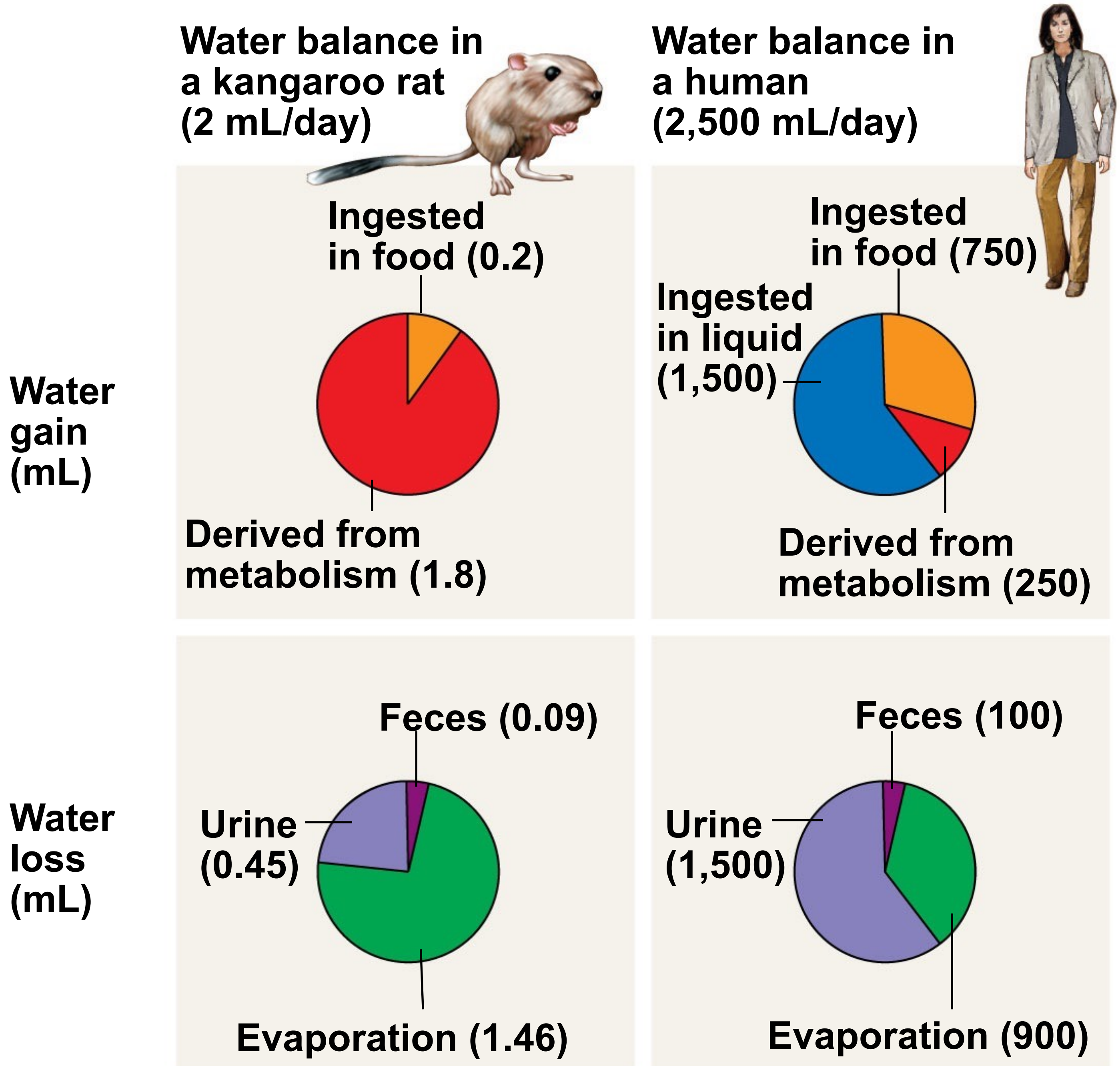


(b) Dehydrated tardigrade

Land Animals

- Adaptations to reduce water loss are key to survival on land
- Body coverings of most terrestrial animals help prevent dehydration
- Desert animals get major water savings from simple anatomical features and behaviors such as a nocturnal lifestyle
- Land animals maintain water balance by eating moist food and producing water metabolically through cellular respiration

Figure 44.6


Water balance in a kangaroo rat (2 mL/day)
Water balance in a human (2,500 mL/day)
Water gain (mL)
Ingested in food (0.2)
Derived from metabolism (1.8)
Ingested in food (750)
Ingested in liquid (1,500)
Derived from metabolism (250)
Water loss (mL)
Feces (0.09)
Urine (0.45)
Evaporation (1.46)
Feces (100)
Urine (1,500)
Evaporation (900)

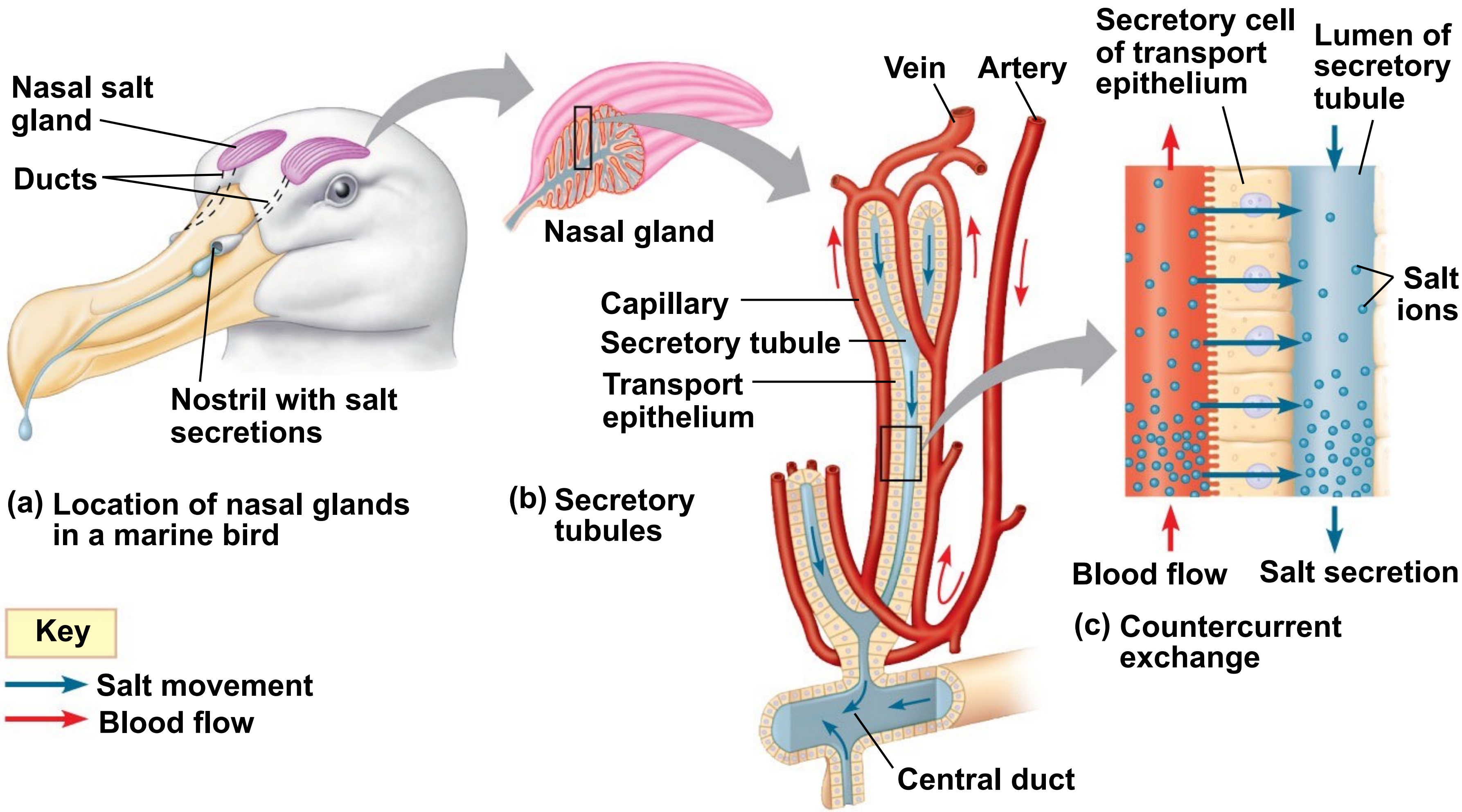
Energetics of Osmoregulation

- Osmoregulators must expend energy to maintain osmotic gradients
- The amount of energy differs based on
  - How different the animal’s osmolarity is from its surroundings
  - How easily water and solutes move across the animal’s surface
  - The work required to pump solutes across the membrane

Transport Epithelia in Osmoregulation

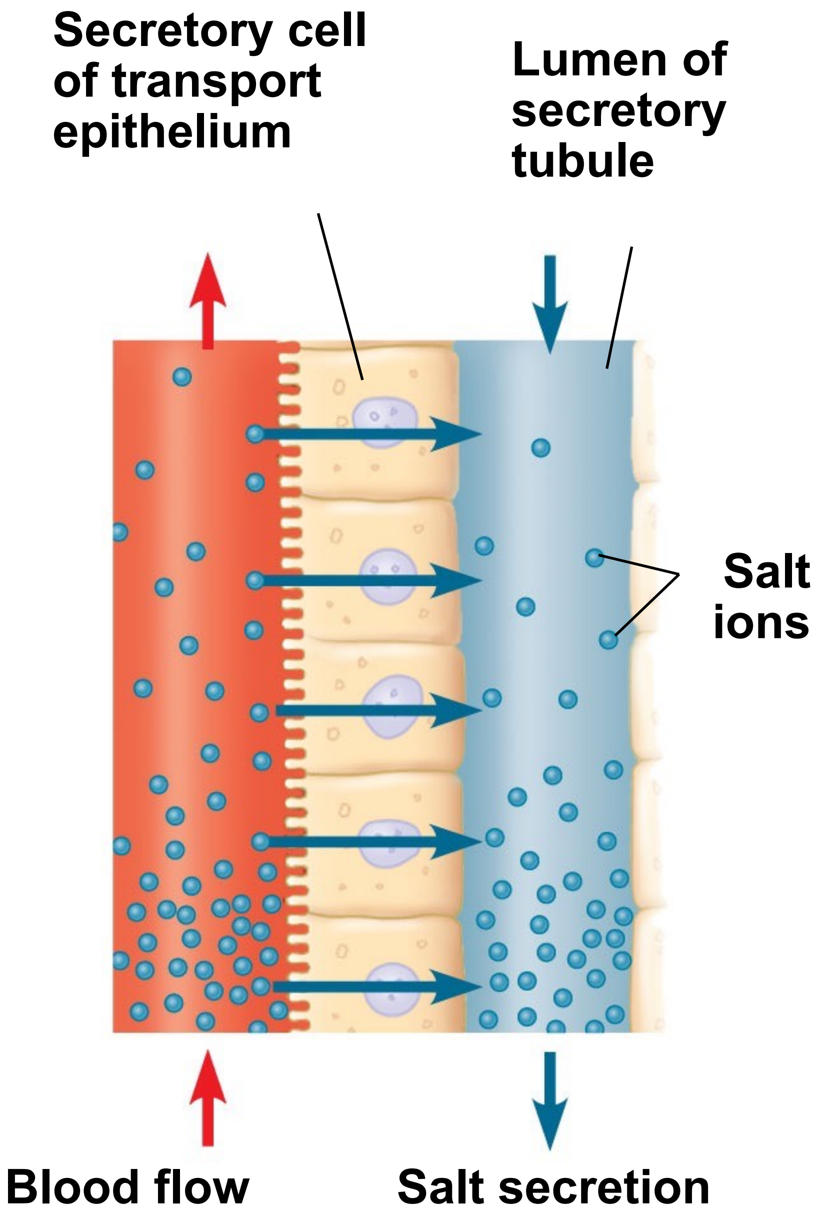
- Animals regulate the solute content of body fluid that bathes their cells
- **Transport epithelia** are epithelial cells that are specialized for moving solutes in specific directions
- They are typically arranged in complex tubular networks
- An example is in nasal glands of marine birds, which remove excess sodium chloride from the blood

Figure 44.7



Nasal salt gland
Ducts
Nostril with salt secretions
(a) Location of nasal glands in a marine bird
Nasal gland
Capillary
Secretory tubule
Transport epithelium
(b) Secretory tubules
Vein
Artery
Central duct
Secretory cell of transport epithelium
Lumen of secretory tubule
Salt ions
Blood flow
Salt secretion
(c) Countercurrent exchange
Key
Salt movement
Blood flow

Figure 44.7c

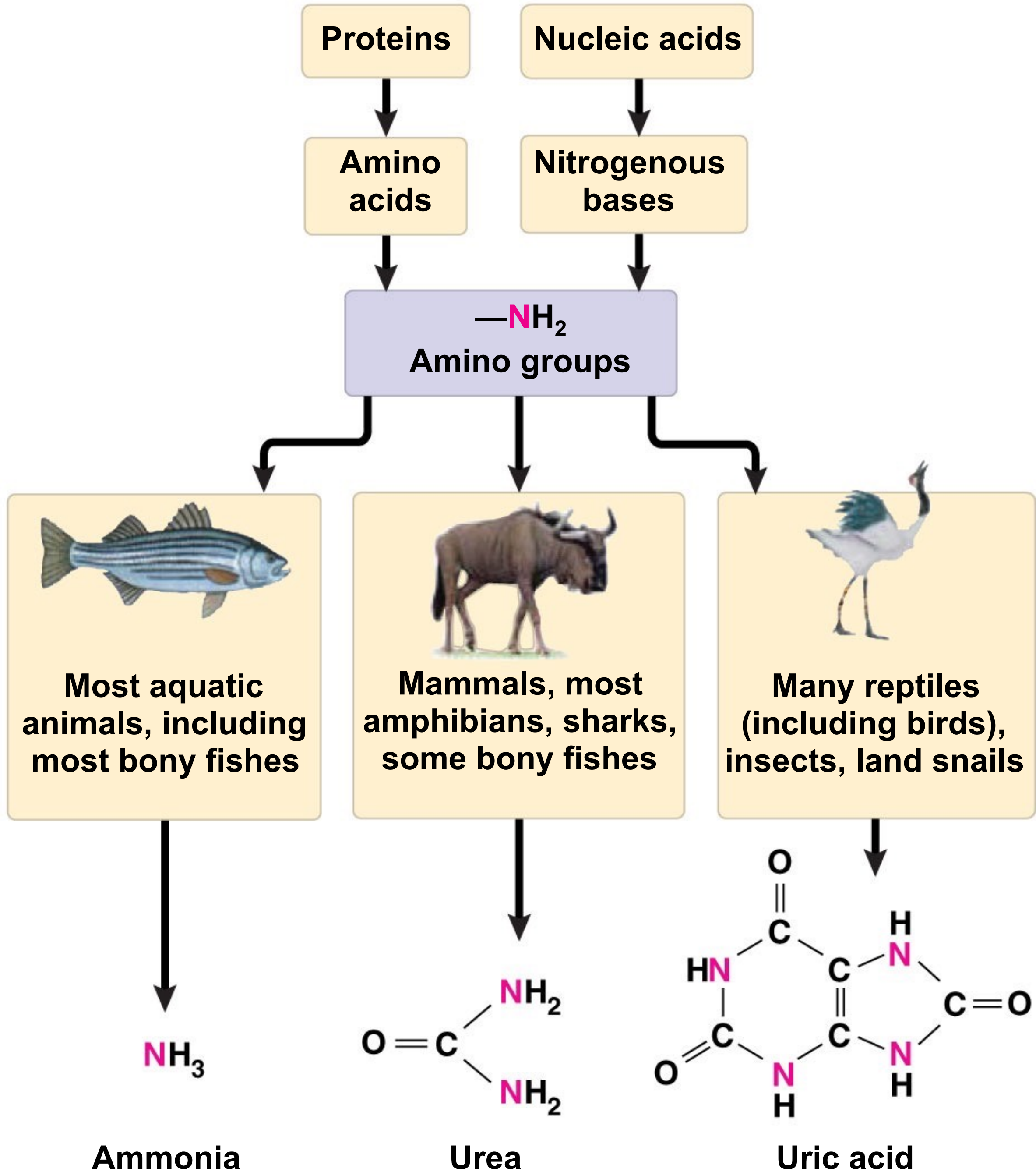


(c) Countercurrent exchange

Concept 44.2: An animal's nitrogenous wastes reflect its phylogeny and habitat

- The type and quantity of an animal's waste products may greatly affect its water balance
- Among the most significant wastes are nitrogenous breakdown products of proteins and nucleic acids
- Some animals convert toxic **ammonia** (NH_3) to less toxic compounds prior to excretion

Figure 44.8



Proteins
Nucleic acids
Amino acids
Nitrogenous bases
—NH2
Amino groups
Most aquatic animals, including most bony fishes
Mammals, most amphibians, sharks, some bony fishes
Many reptiles (including birds), insects, land snails
NH3
Ammonia
Urea
Uric acid

Forms of Nitrogenous Wastes

- Animals excrete nitrogenous wastes in different forms: ammonia, urea, or uric acid
- These differ in toxicity and the energy costs of producing them

Ammonia

- Animals that excrete nitrogenous wastes as ammonia need access to lots of water
- They release ammonia across the whole body surface or through gills

Urea

- The liver of mammals and most adult amphibians converts ammonia to the less toxic **urea**
- The circulatory system carries urea to the kidneys, where it is excreted
- Conversion of ammonia to urea is energetically expensive; excretion of urea requires less water than ammonia

Uric Acid

- Insects, land snails, and many reptiles, including birds, mainly excrete **uric acid**
- Uric acid is relatively nontoxic and does not dissolve readily in water
- It can be secreted as a paste with little water loss
- Uric acid is more energetically expensive to produce than urea

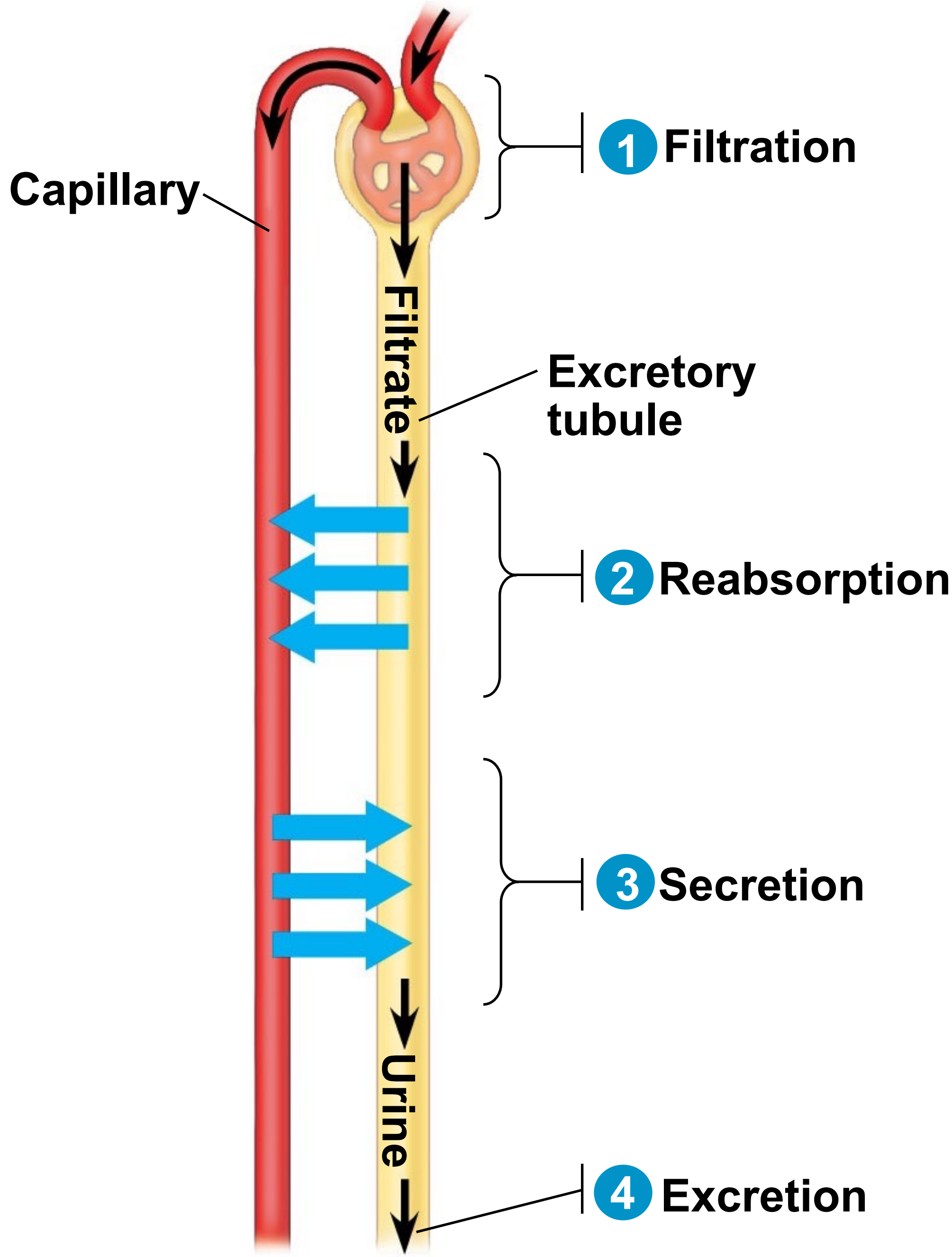
Concept 44.3: Diverse excretory systems are variations on a tubular theme

- Excretory systems regulate solute movement between internal fluids and the external environment

Excretory Processes

- Most excretory systems produce urine by refining a **filtrate** derived from body fluids
- Key functions of most excretory systems
  - **Filtration**: Filtering of body fluids
  - **Reabsorption**: Reclaiming valuable solutes
  - **Secretion**: Adding nonessential solutes and wastes from the body fluids to the filtrate
  - **Excretion**: Processed filtrate containing nitrogenous wastes, released from the body

Figure 44.10

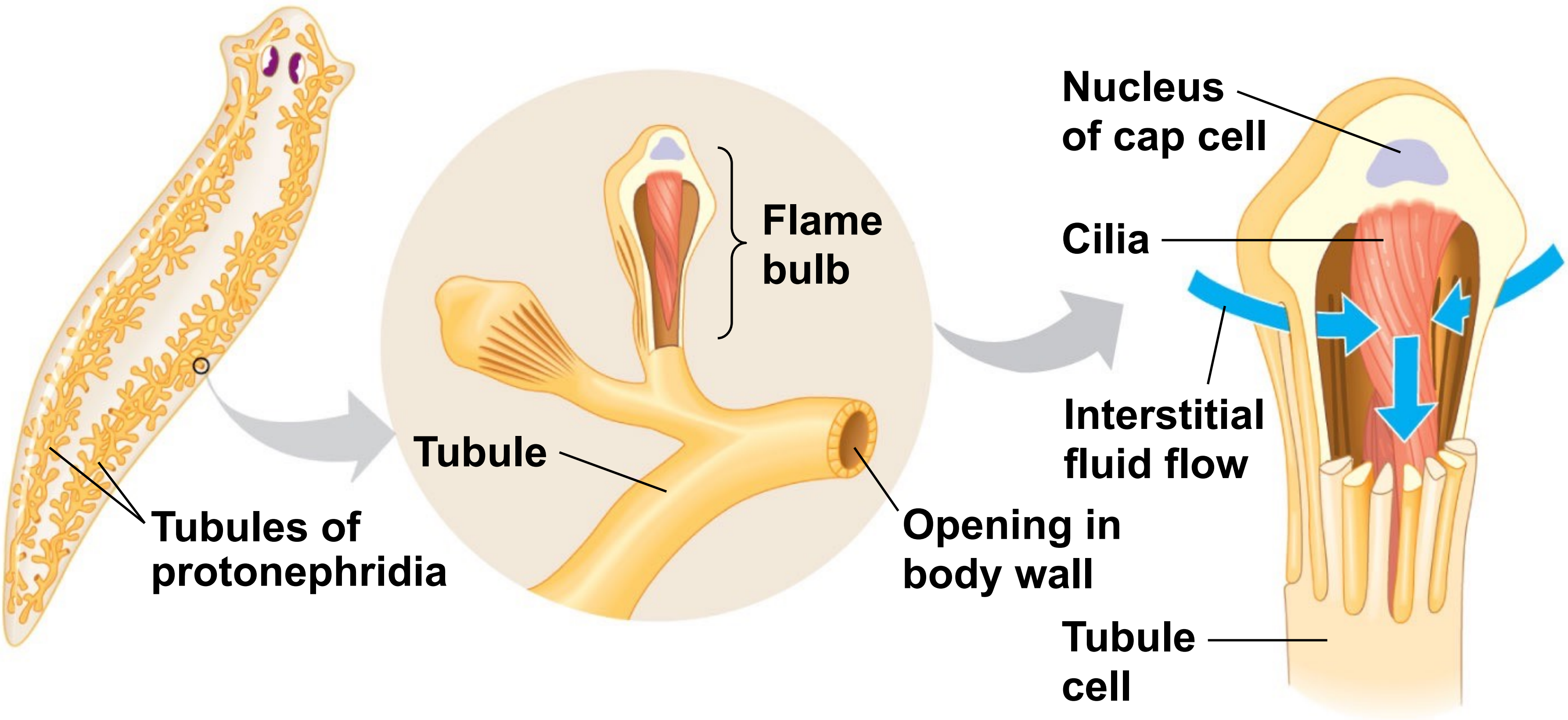


Capillary
Filtrate
Excretory
tubule
1 Filtration
2 Reabsorption
3 Secretion
Urine
4 Excretion

Protonephridia

- A **protonephridium** is a network of dead-end tubules connected to external openings
- The smallest branches of the network are capped by a cellular unit called a flame bulb
- These tubules excrete a dilute fluid and function in osmoregulation

Figure 44.11

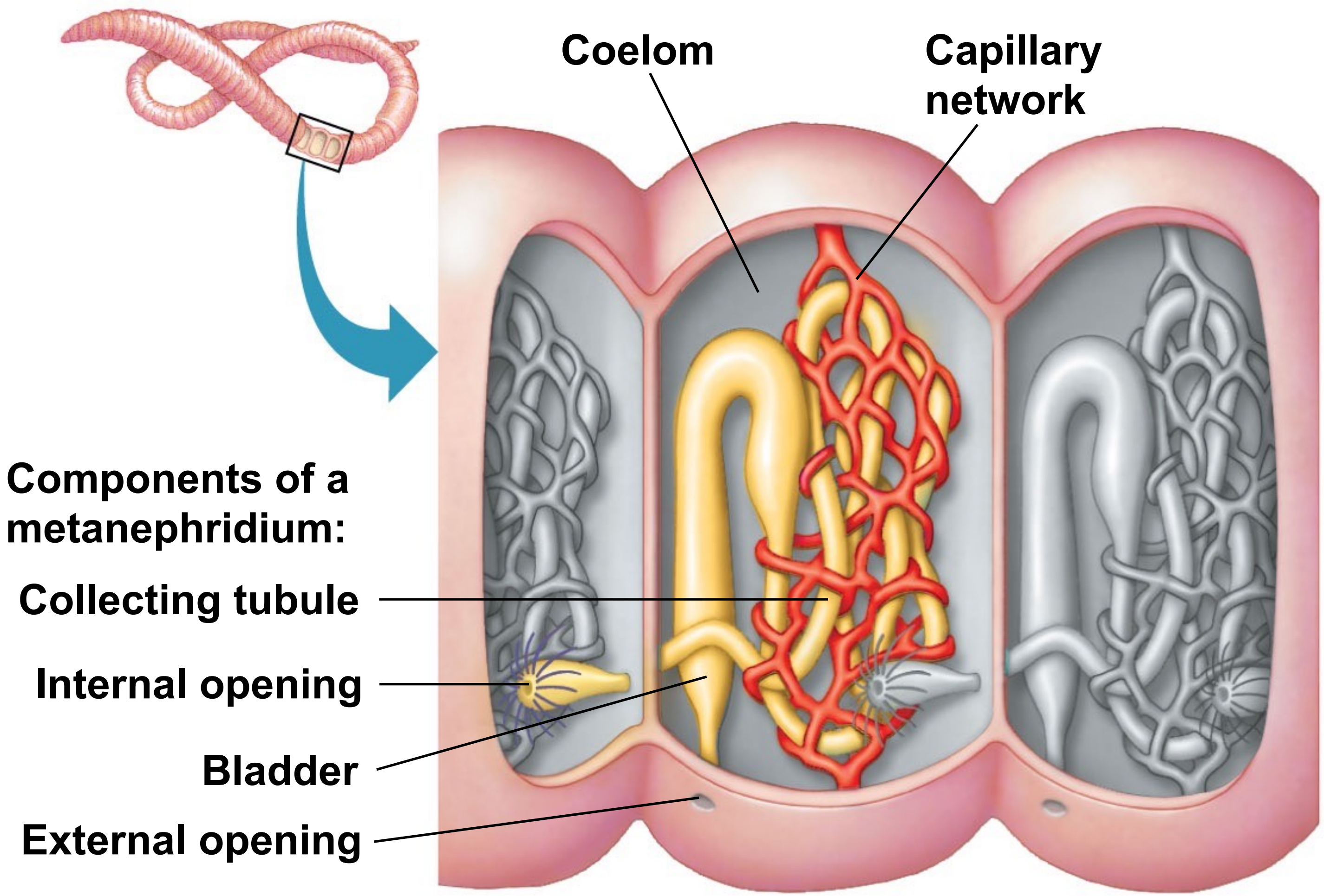


Tubules of protonephridia
Tubule
Flame bulb
Opening in body wall
Nucleus of cap cell
Cilia
Interstitial fluid flow
Tubule cell

Metanephridia

- Each segment of an earthworm has a pair of open-ended **metanephridia**
- Metanephridia consist of tubules that collect coelomic fluid and produce dilute urine for excretion

Figure 44.12

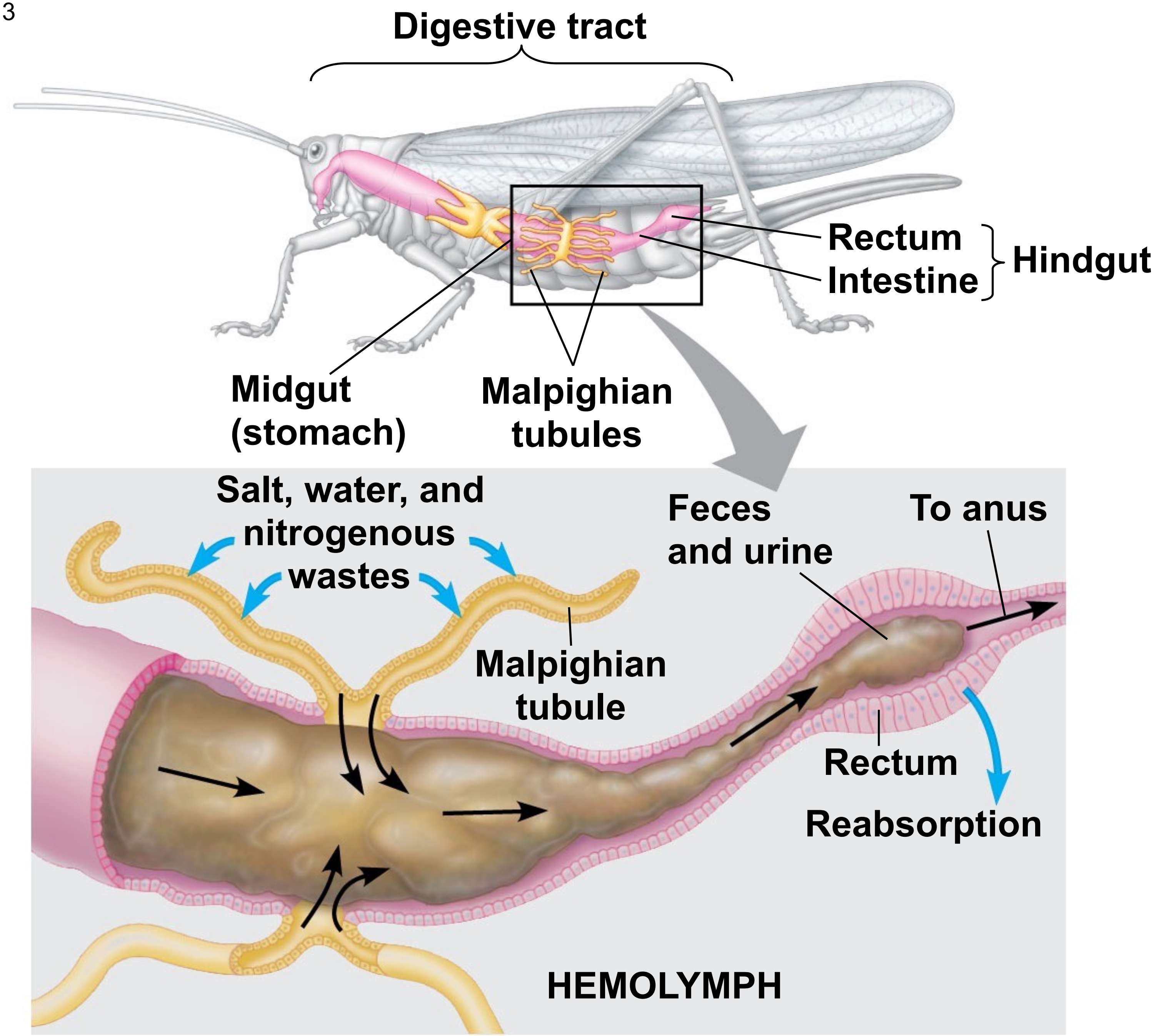


Coelom
Capillary network
Components of a metanephridium:
Collecting tubule
Internal opening
Bladder
External opening

Malpighian Tubules

- In insects and other terrestrial arthropods, **Malpighian tubules** remove nitrogenous wastes from hemolymph and function in osmoregulation
- Insects produce a relatively dry waste matter, mainly uric acid, an important adaptation to terrestrial life
- Some terrestrial insects can also take up water from the air

Figure 44.13


Digestive tract
Rectum
Intestine
Hindgut
Midgut (stomach)
Malpighian tubules
Salt, water, and nitrogenous wastes
Feces and urine
To anus
Malpighian tubule
Rectum
Reabsorption
HEMOLYMPH

Kidneys

- Kidneys, the excretory organs of vertebrates, function in both excretion and osmoregulation

Figure 44.14-a

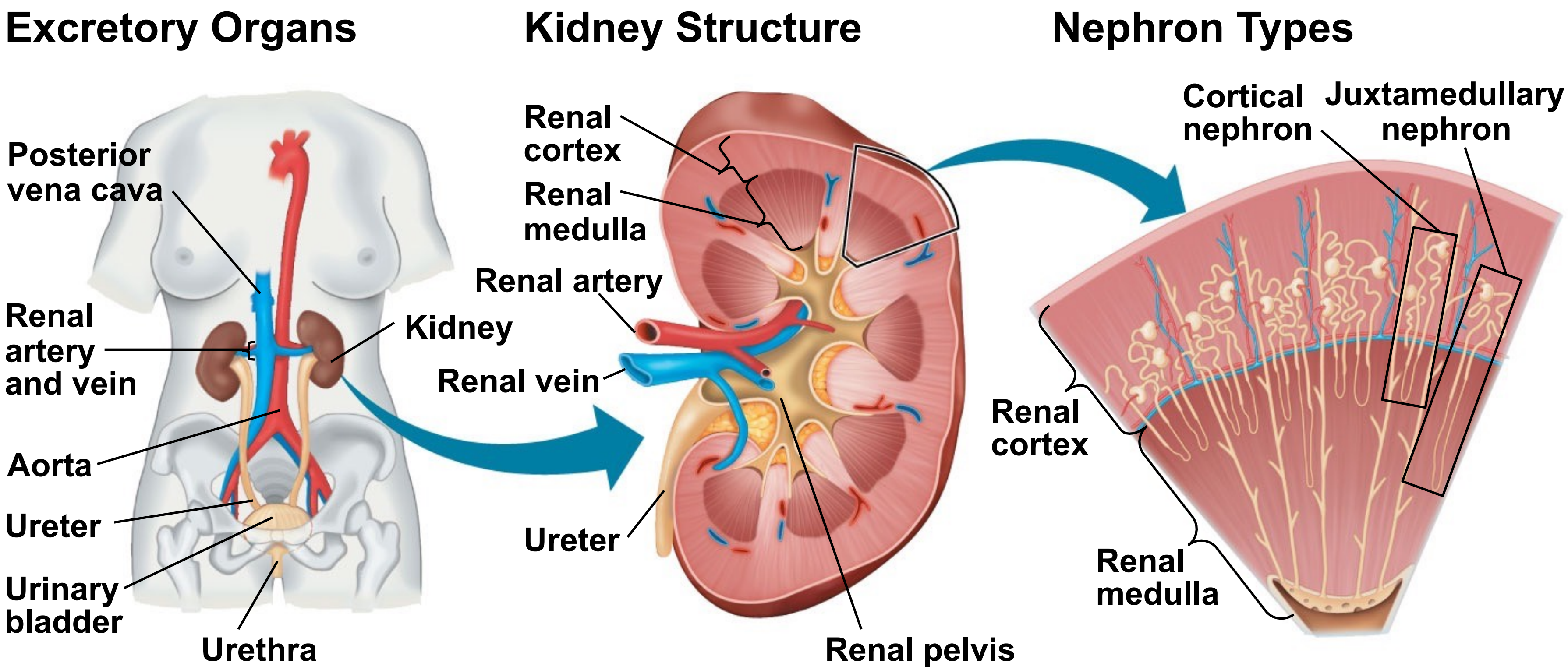
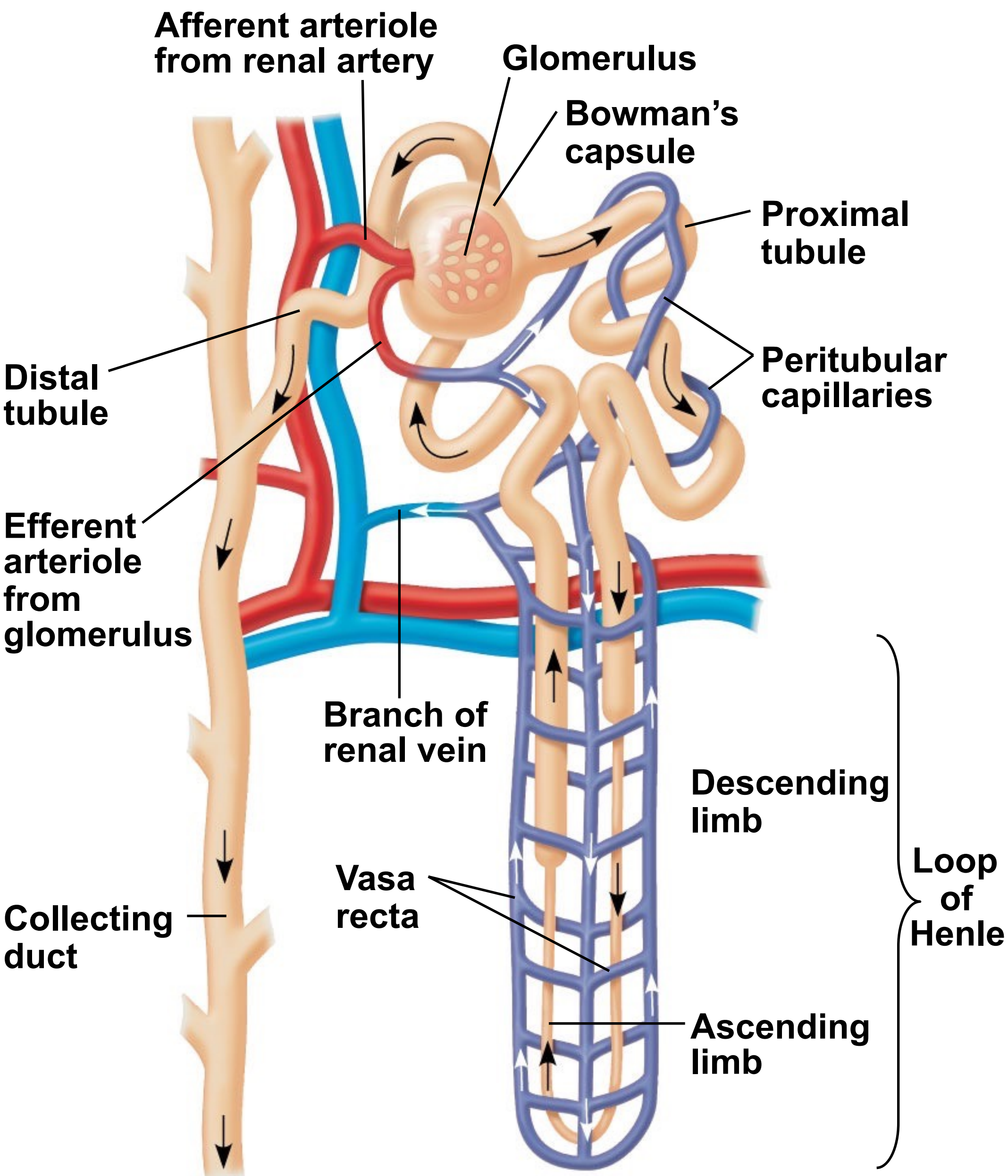
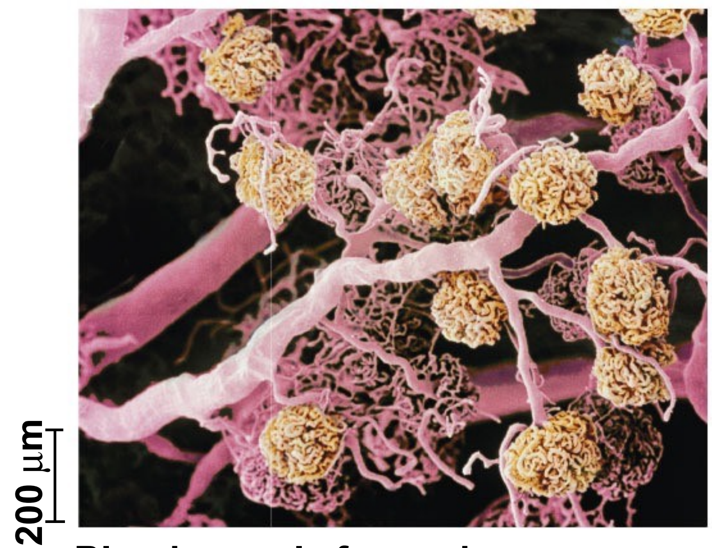


Figure 44.14-b

Nephron Organization





Blood vessels from a human kidney. Arterioles and peritubular capillaries appear pink; glomeruli appear yellow.

Figure 44.14c

Nephron Types

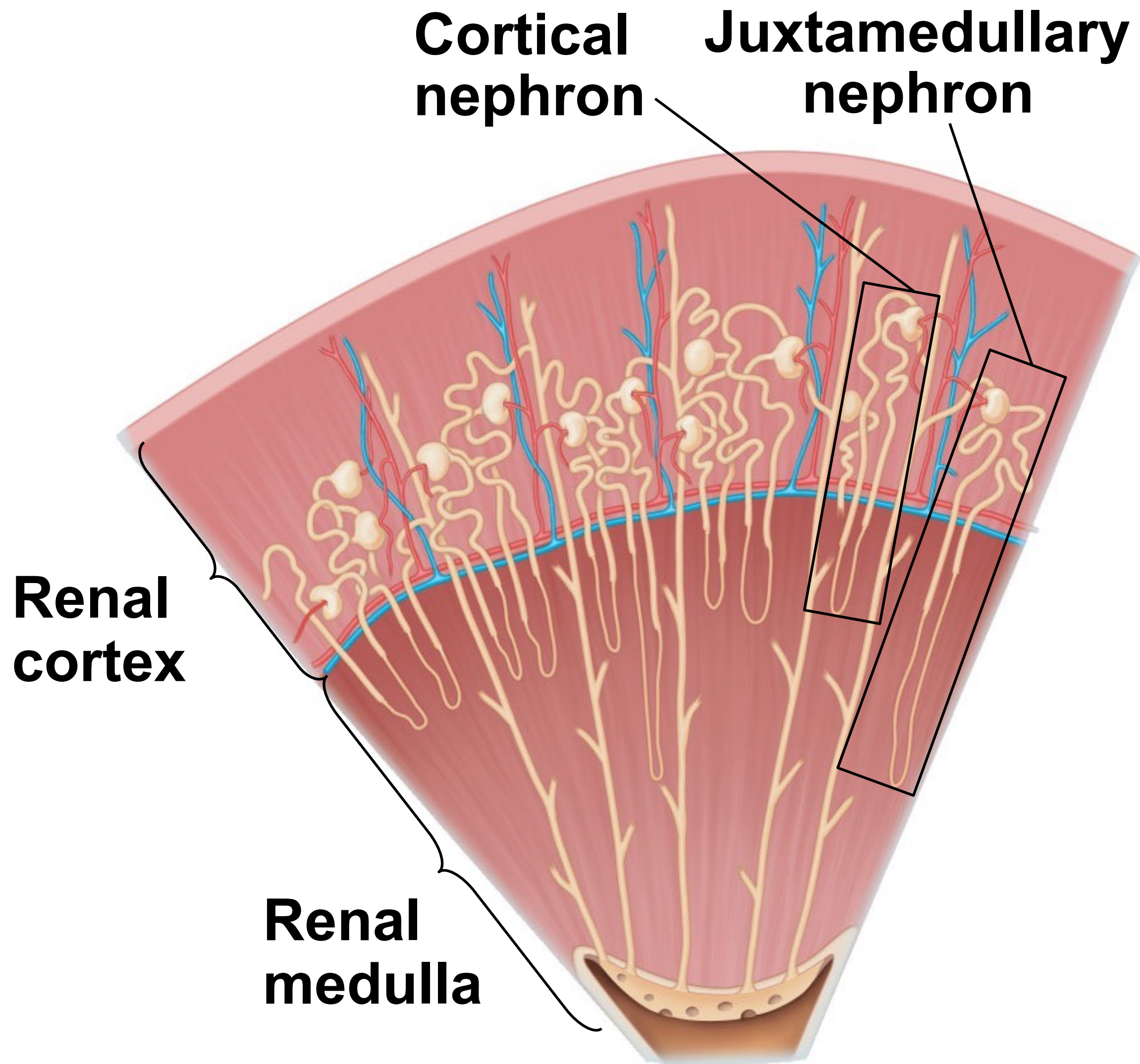
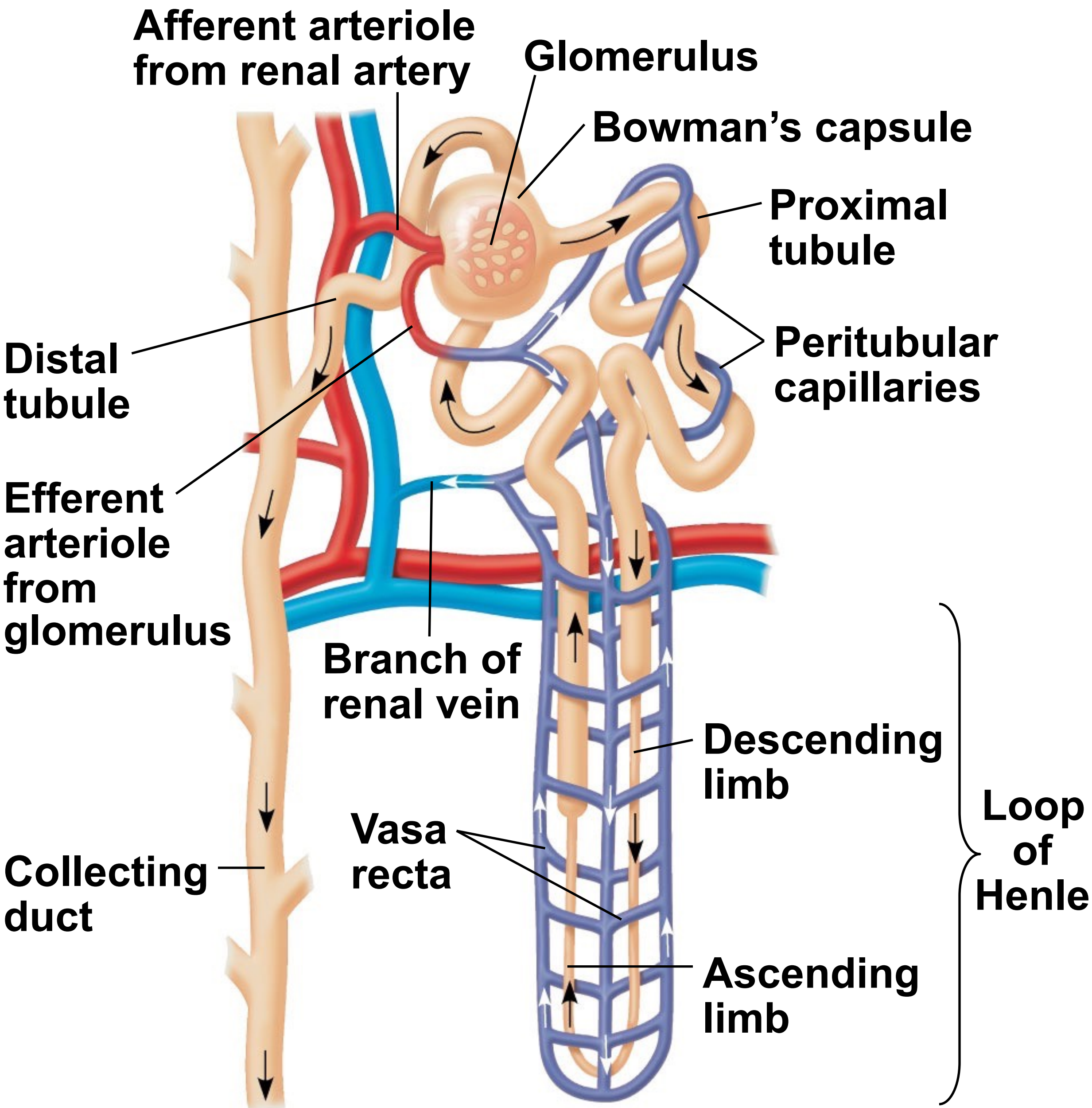


Figure 44.14d

Nephron Organization



Concept 44.4: The nephron is organized for stepwise processing of blood filtrate

- The filtrate produced in Bowman's capsule contains salts, glucose, amino acids, vitamins, nitrogenous wastes, and other small molecules

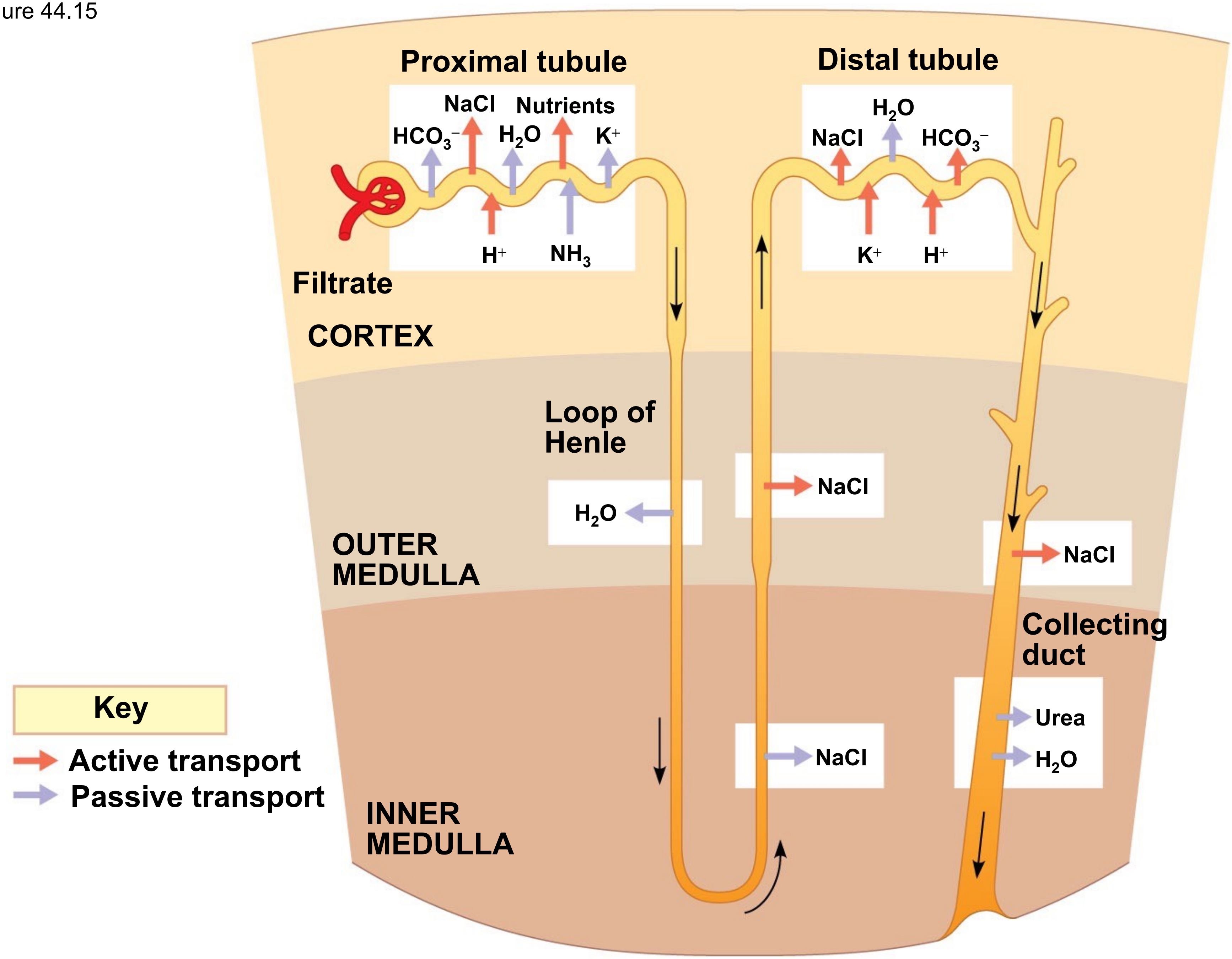
From Blood Filtrate to Urine: *A Closer Look*

Proximal Tubule

- Reabsorption of ions, water, and nutrients takes place in the proximal tubule
- Molecules are transported actively and passively from the filtrate into the interstitial fluid and then capillaries
- Some toxic materials are actively secreted into the filtrate
- As the filtrate passes through the proximal tubule, materials to be excreted become concentrated

PLAY Animation: Bowman's Capsule and Proximal Tubule

Figure 44.15



Proximal tubule
NaCl
Nutrients
HCO_3^-
H_2O
K^+
H^+
NH_3
Distal tubule
H_2O
NaCl
HCO_3^-
K^+
H^+
Filtrate
CORTEX
Loop of Henle
H_2O
NaCl
OUTER MEDULLA
NaCl
Collecting duct
Urea
H_2O
NaCl
INNER MEDULLA
Key
Active transport
Passive transport

Descending Limb of the Loop of Henle

- Reabsorption of water continues through channels formed by **aquaporin** proteins
- Movement is driven by the high osmolarity of the interstitial fluid, which is hyperosmotic to the filtrate
- The filtrate becomes increasingly concentrated

Ascending Limb of the Loop of Henle

- In the ascending limb of the loop of Henle, salt but not water is able to diffuse from the tubule into the interstitial fluid
- The filtrate becomes increasingly dilute

Distal Tubule

- The distal tubule regulates the K^+ and NaCl concentrations of body fluids
- The controlled movement of ions contributes to pH regulation

PLAY Animation: Loop of Henle and Distal Tubule

Collecting Duct

- The collecting duct carries filtrate through the medulla to the renal pelvis
- One of the most important tasks is reabsorption of solutes and water
- Urine is hyperosmotic to body fluids

PLAY Animation: Collecting Duct

Figure 44.16-1

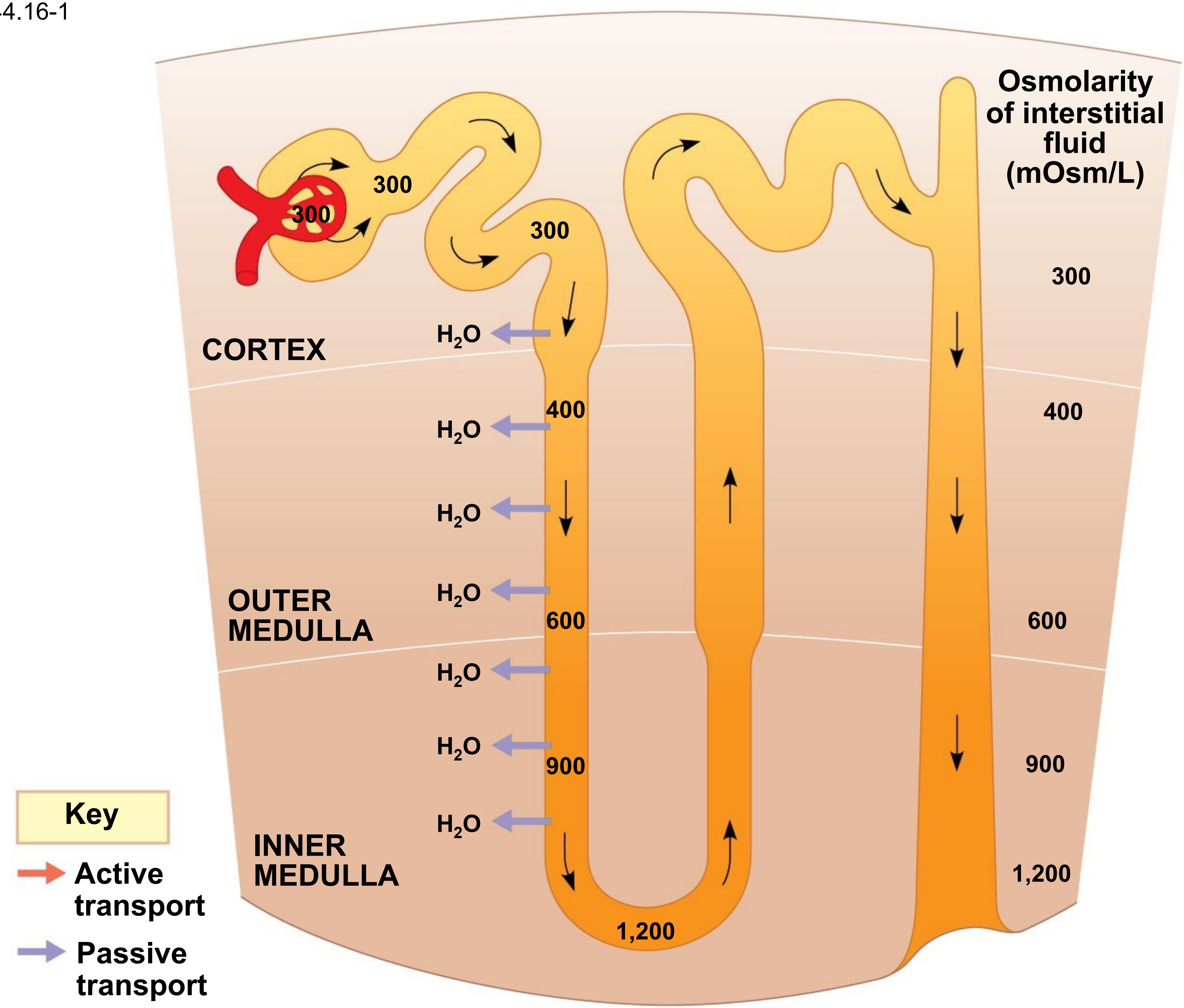


Figure 44.16-2

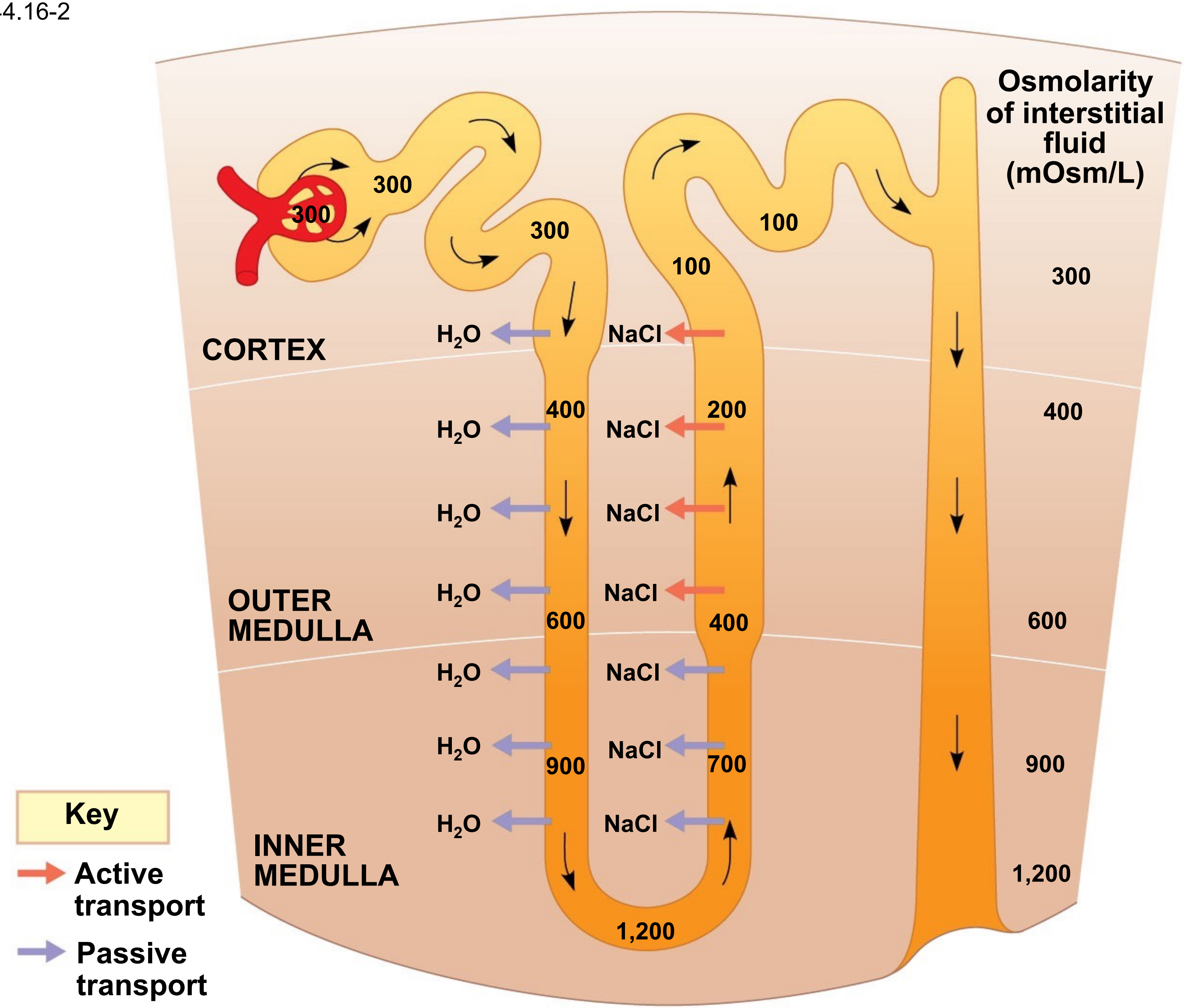
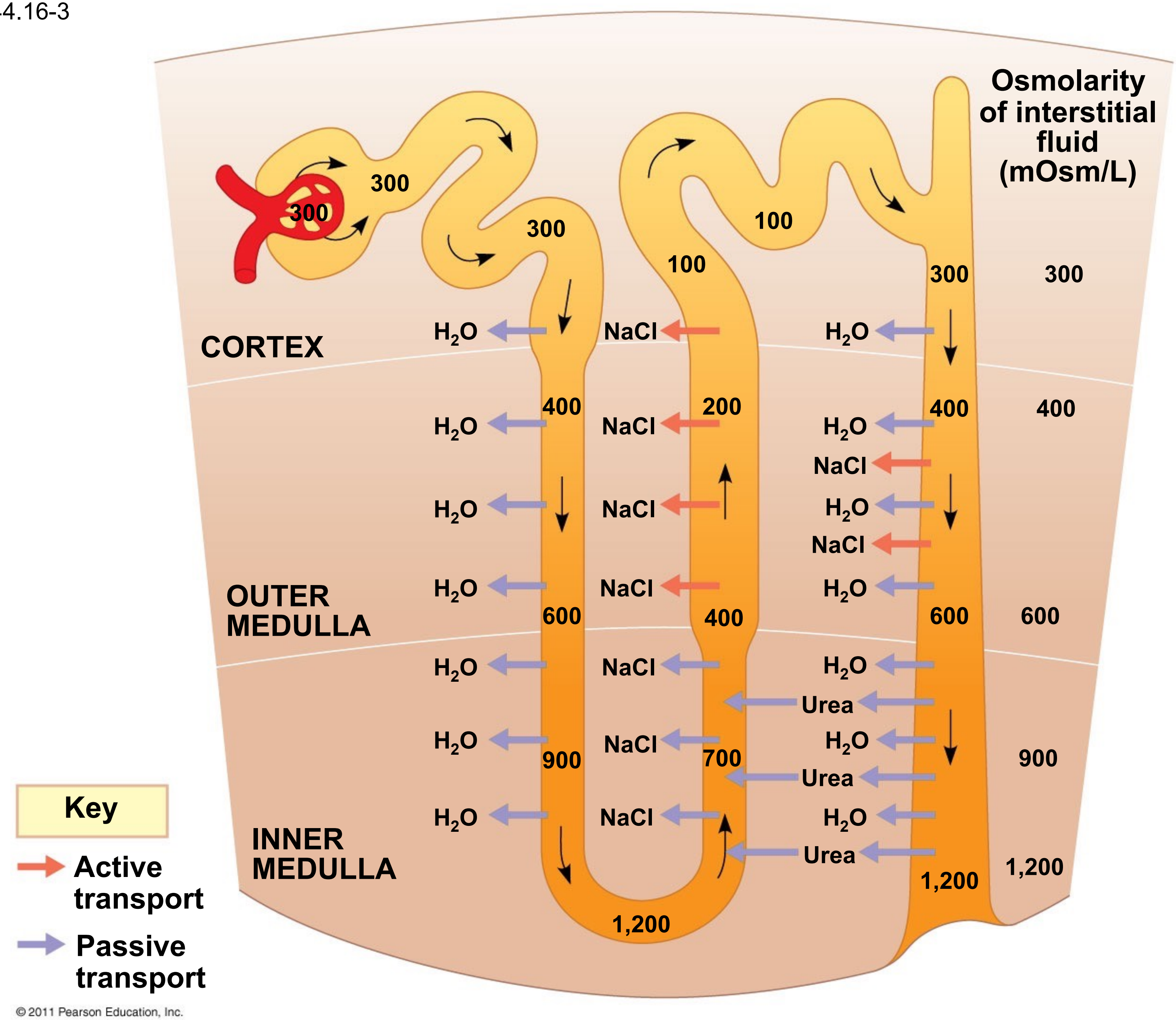


Figure 44.16-3



Adaptations of the Vertebrate Kidney to Diverse Environments

- The form and function of nephrons in various vertebrate classes are related to requirements for osmoregulation in the animal's habitat

Mammals

- The juxtamedullary nephron is key to water conservation in terrestrial animals
- Mammals that inhabit dry environments have long loops of Henle, while those in fresh water have relatively short loops

Birds and Other Reptiles

- Birds have shorter loops of Henle but conserve water by excreting uric acid instead of urea
- Other reptiles have only cortical nephrons but also excrete nitrogenous waste as uric acid

Figure 44.17

Freshwater Fishes and Amphibians

- Freshwater fishes conserve salt in their distal tubules and excrete large volumes of dilute urine
- Kidney function in amphibians is similar to freshwater fishes
- Amphibians conserve water on land by reabsorbing water from the urinary bladder

Marine Bony Fishes

- Marine bony fishes are hypoosmotic compared with their environment
- Their kidneys have small glomeruli and some lack glomeruli entirely
- Filtration rates are low, and very little urine is excreted

Concept 44.5: Hormonal circuits link kidney function, water balance, and blood pressure

- Mammals control the volume and osmolarity of urine
- The kidneys of the South American vampire bat can produce either very dilute or very concentrated urine
- This allows the bats to reduce their body weight rapidly or digest large amounts of protein while conserving water

Figure 44.18

Antidiuretic Hormone

- The osmolarity of the urine is regulated by nervous and hormonal control
- **Antidiuretic hormone (ADH)** makes the collecting duct epithelium more permeable to water
- An increase in osmolarity triggers the release of ADH, which helps to conserve water

PLAY Animation: Effect of ADH

Figure 44.19-1

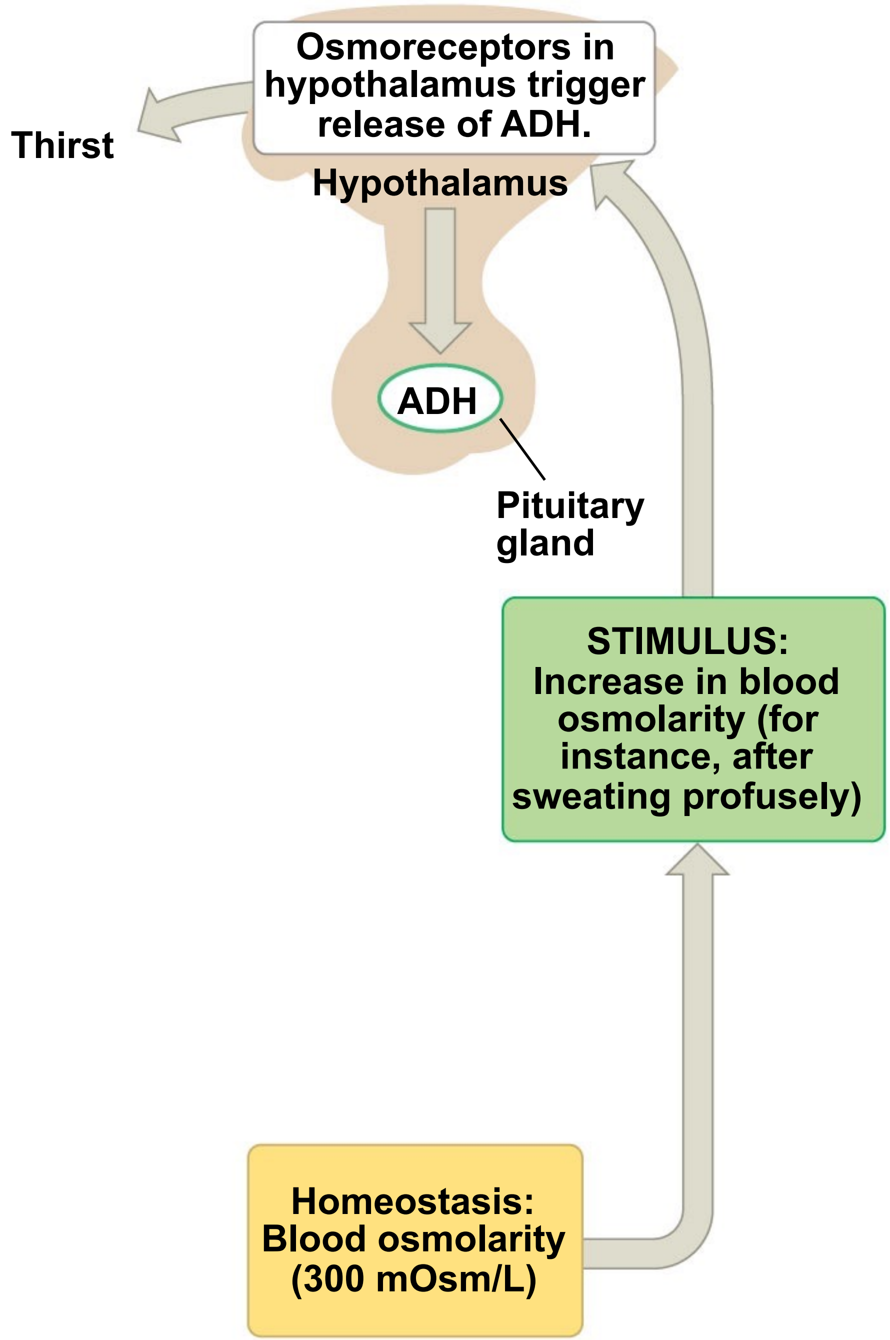
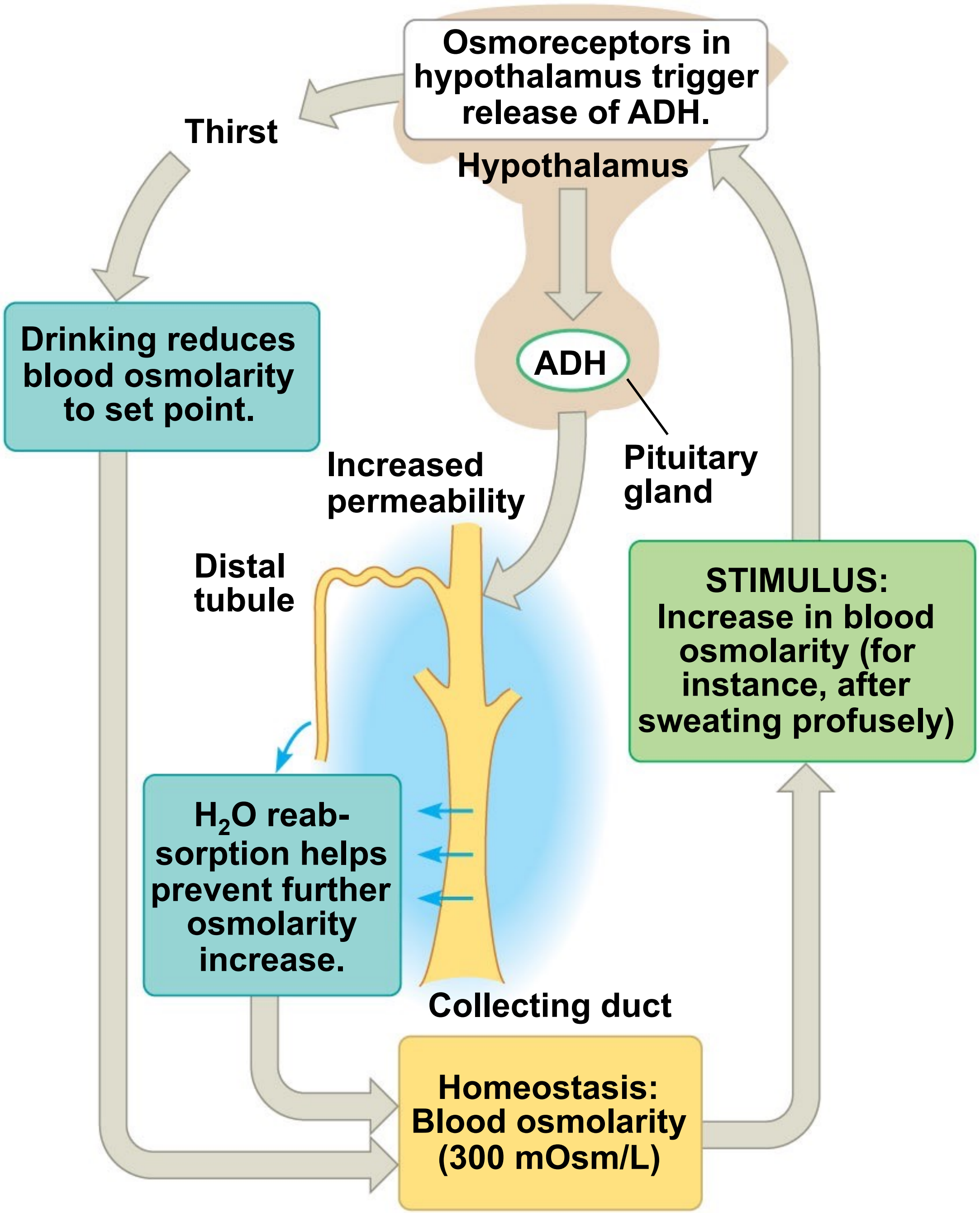
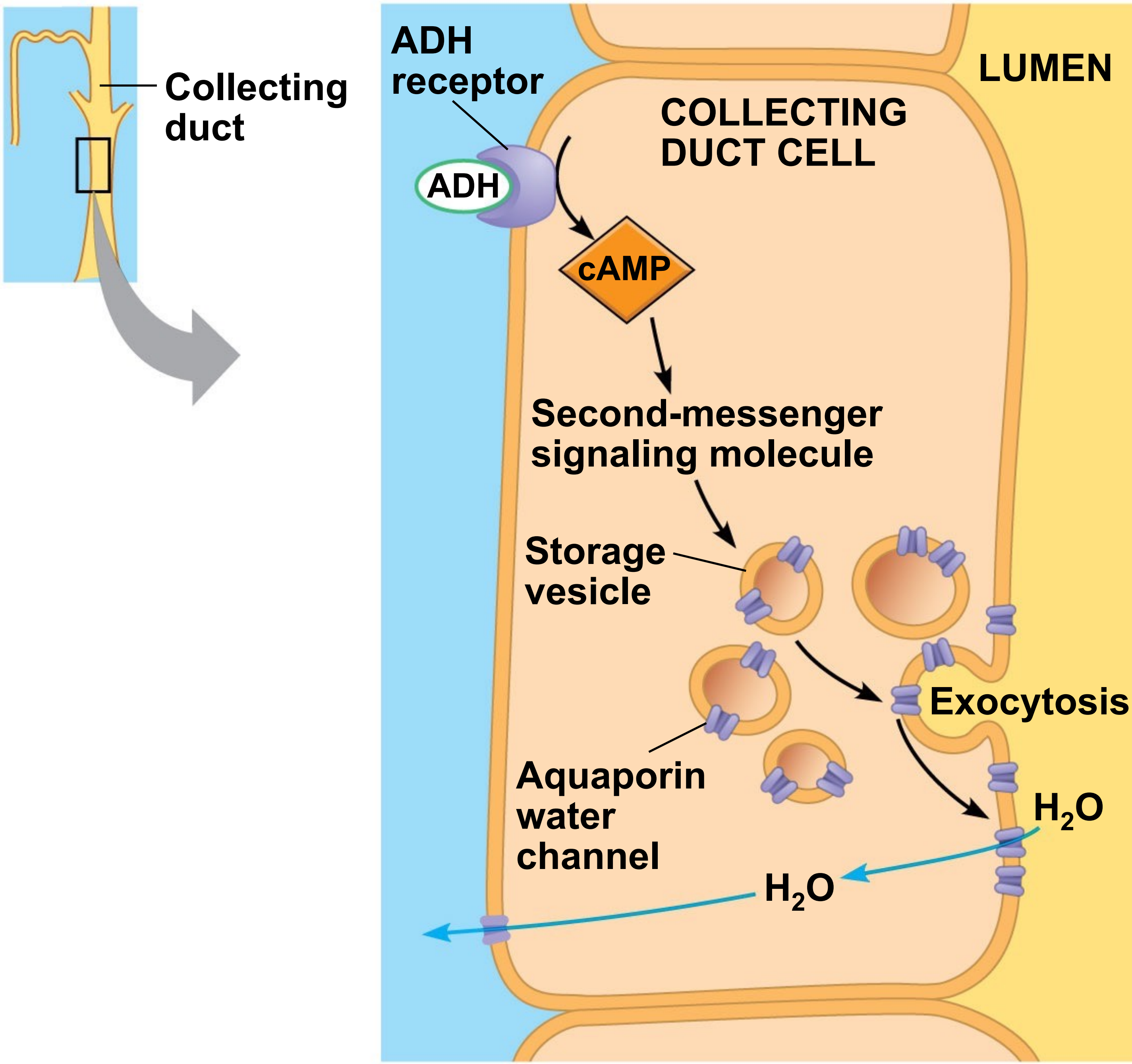


Figure 44.19-2



- Binding of ADH to receptor molecules leads to a temporary increase in the number of aquaporin proteins in the membrane of collecting duct cells

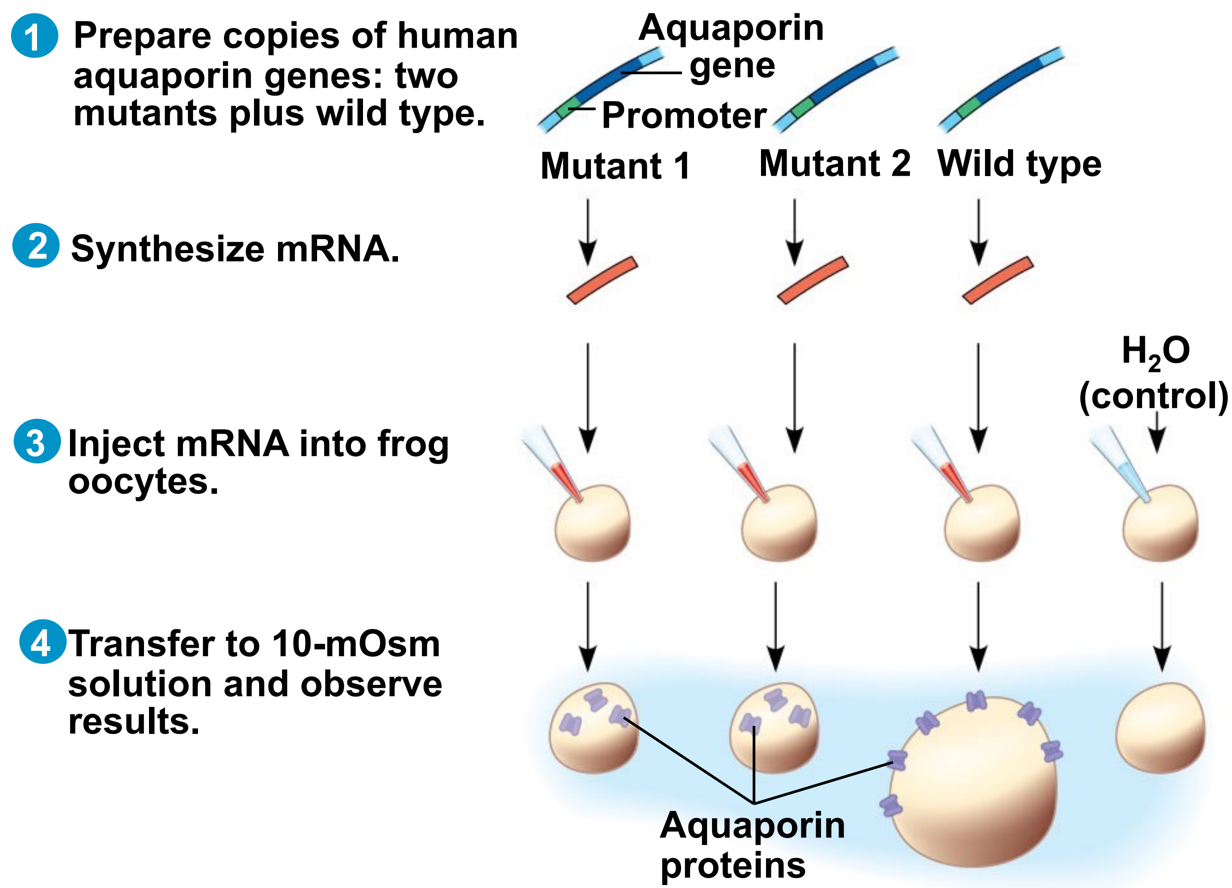
Figure 44.20


Collecting duct
ADH receptor
ADH
LUMEN
COLLECTING DUCT CELL
cAMP
Second-messenger signaling molecule
Storage vesicle
Exocytosis
Aquaporin water channel
H_2O
H_2O

- Mutation in ADH production causes severe dehydration and results in diabetes insipidus
- Alcohol is a diuretic as it inhibits the release of ADH

Figure 44.21

EXPERIMENT



RESULTS

Injected RNA	Permeability (μm/sec)
Wild-type aquaporin	196
None	20
Aquaporin mutant 1	17
Aquaporin mutant 2	18

Figure 44.21a

EXPERIMENT

1 Prepare copies of human aquaporin genes: two mutants plus wild type.

2 Synthesize mRNA.

3 Inject mRNA into frog oocytes.

4 Transfer to 10-mOsm solution and observe results.

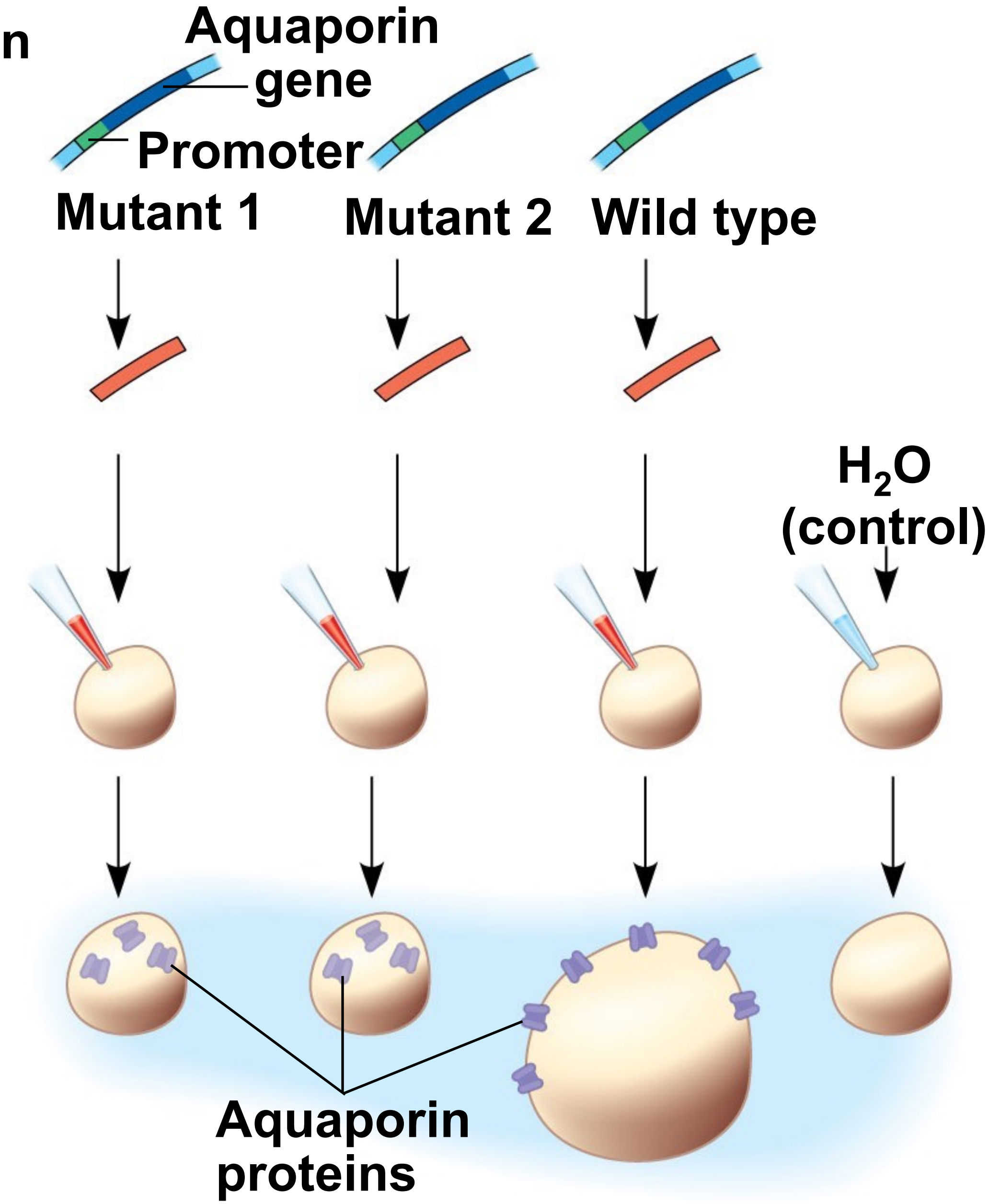


Figure 44.21b

RESULTS

Injected RNA	Permeability (μm/sec)
Wild-type aquaporin	196
None	20
Aquaporin mutant 1	17
Aquaporin mutant 2	18

The Renin-Angiotensin-Aldosterone System

- The **renin-angiotensin-aldosterone system (RAAS)** is part of a complex feedback circuit that functions in homeostasis
- A drop in blood pressure near the glomerulus causes the **juxtaglomerular apparatus (JGA)** to release the enzyme renin
- Renin triggers the formation of the peptide **angiotensin II**

- Angiotensin II
  - Raises blood pressure and decreases blood flow to the kidneys
  - Stimulates the release of the hormone **aldosterone**, which increases blood volume and pressure

Figure 44.22-1

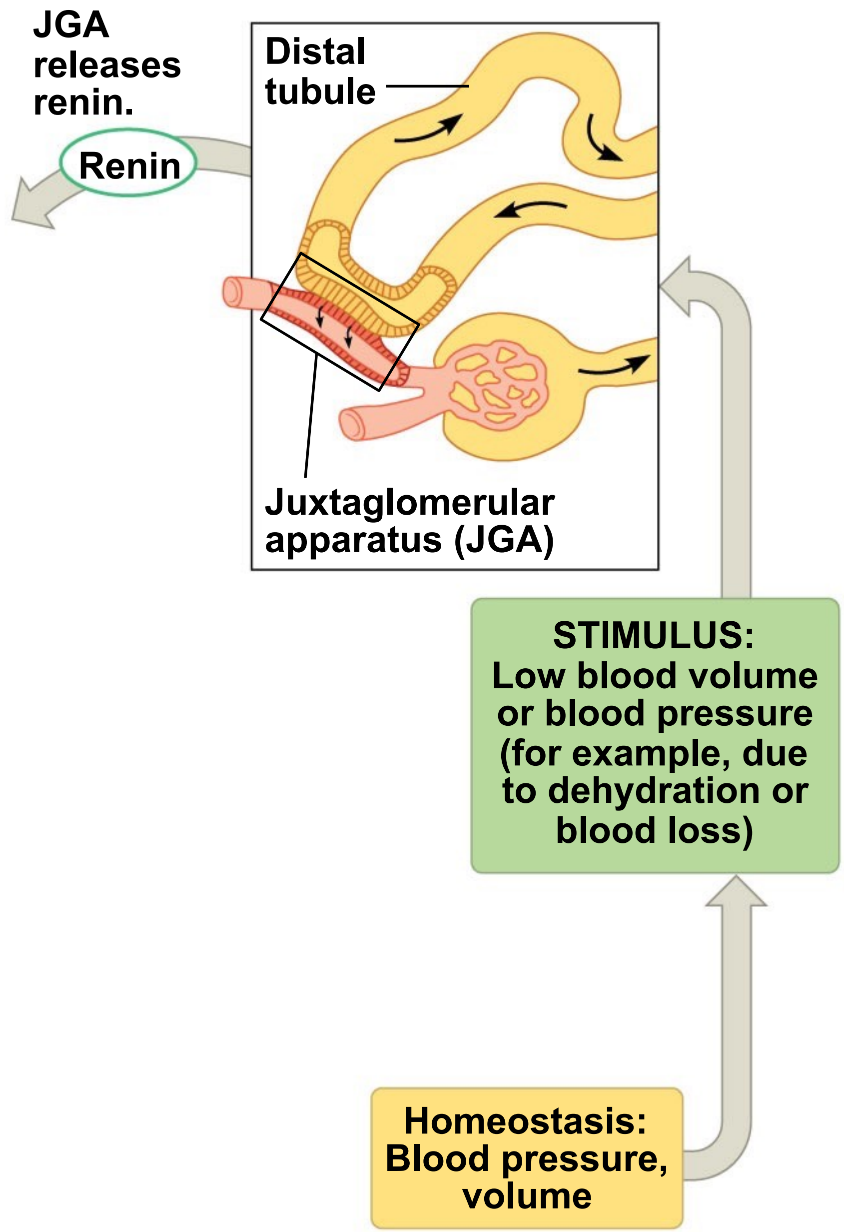


Figure 44.22-2

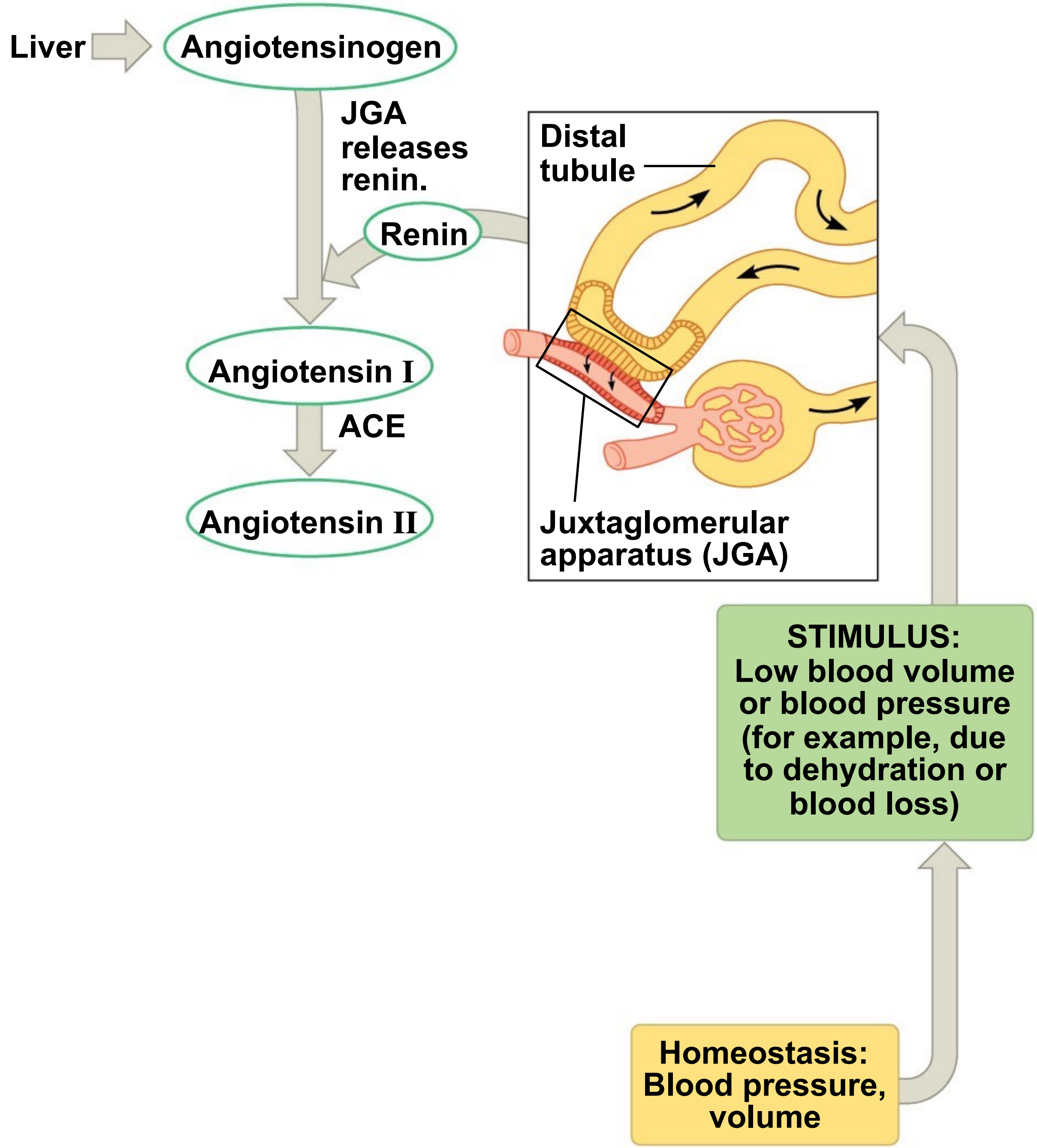
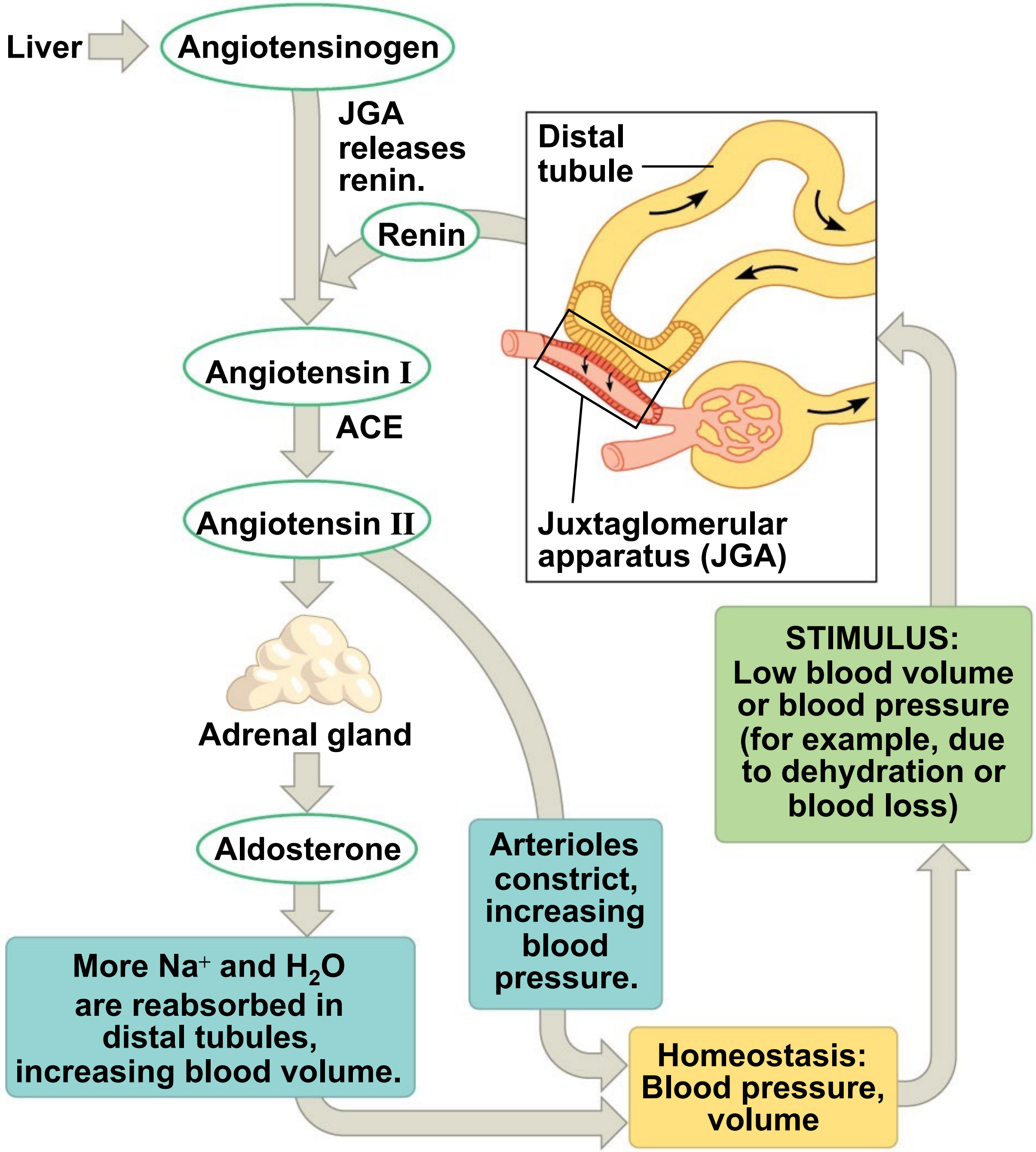


Figure 44.22-3



Homeostatic Regulation of the Kidney

- ADH and RAAS both increase water reabsorption, but only RAAS will respond to a decrease in blood volume
- Another hormone, **atrial natriuretic peptide (ANP)**, opposes the RAAS
- ANP is released in response to an increase in blood volume and pressure and inhibits the release of renin

Figure 44.UN01

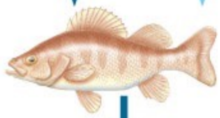
Animal	Inflow/Outflow	Urine
Freshwater fish. Lives in water less concentrated than body fluids; fish tends to gain water, lose salt	**Does not drink water** **Salt in (active transport by gills)** **H_2O in**  **Salt out**	 ▶ **Large volume of urine** ▶ **Urine is less concentrated than body fluids**
Marine bony fish. Lives in water more concentrated than body fluids; fish tends to lose water, gain salt	**Drinks water** **Salt in** **H_2O out**  **Salt out (active transport by gills)**	 ▶ **Small volume of urine** ▶ **Urine is slightly less concentrated than body fluids**
Terrestrial vertebrate. Terrestrial environment; tends to lose body water to air	**Drinks water** **Salt in (by mouth)**  **H_2O and salt out**	 ▶ **Moderate volume of urine** ▶ **Urine is more concentrated than body fluids**

Figure 44.UN02