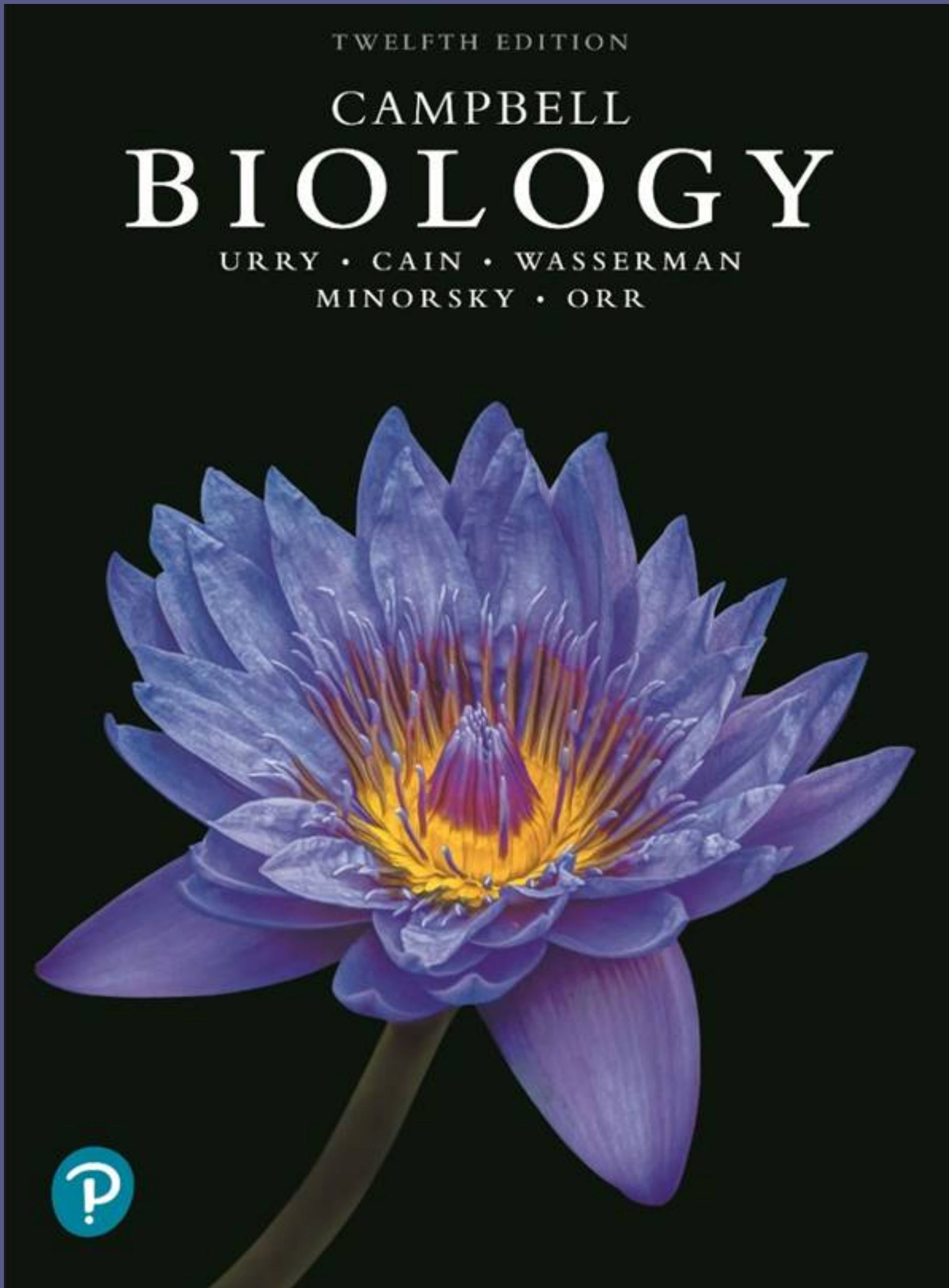


Chapter 44

Osmoregulation and Excretion

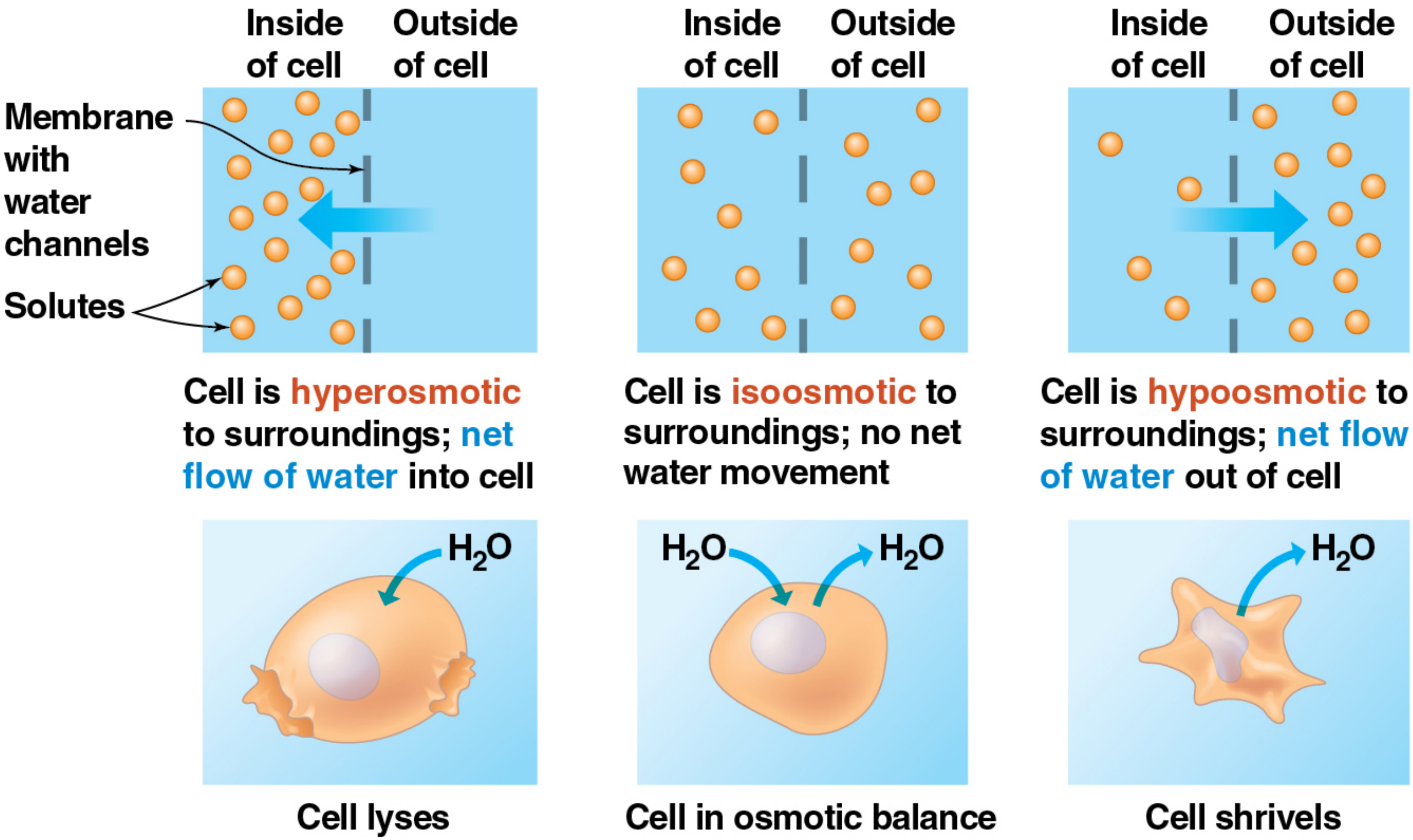
Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

Figure 44.1a

Figure 44.1b

How do animals regulate water and salt concentrations in their tissues?

Animals transport salts and thereby direct water movement into or out of cells by osmosis.



A Balancing Act

- Maintaining fluid balance requires that the relative concentrations of solutes and water be kept within narrow limits
- **Osmoregulation** controls solute concentrations and balances water gain and loss
- Several mechanisms have evolved for ridding the body of nitrogenous metabolites and other metabolic waste products, a process called **excretion**

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

- Osmoregulation requires controlled movement of water and solutes across plasma membrane
- The driving force for this movement is a concentration gradient of one or more solutes across the membrane

Osmosis and Osmolarity

- Water enters and leaves cells by osmosis
- **Osmolarity**, the solute concentration of a solution, determines the movement of water across a selectively permeable membrane
- If two solutions are isoosmotic, water molecules will cross the membrane at equal rates in both directions
- In this case, there is no net movement of water between the isoosmotic solutions

- If two solutions differ in osmolarity, the net flow of water is from the hypoosmotic (less concentrated) to the hyperosmotic (more concentrated) solution

Osmoregulatory Challenges and Mechanisms

- Animals can maintain water balance in one of two ways
- **Osmoconformers** 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
- Osmoregulation allows animals to live in environments that are uninhabitable for osmoconformers

Figure 44.2

- 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
- However, they actively transport specific solutes that they maintain at levels different from those of the ocean
- Marine bony fishes are hypoosmotic to seawater
- They balance water loss by drinking large amounts of seawater and eliminating the ingested salts through their gills and kidneys

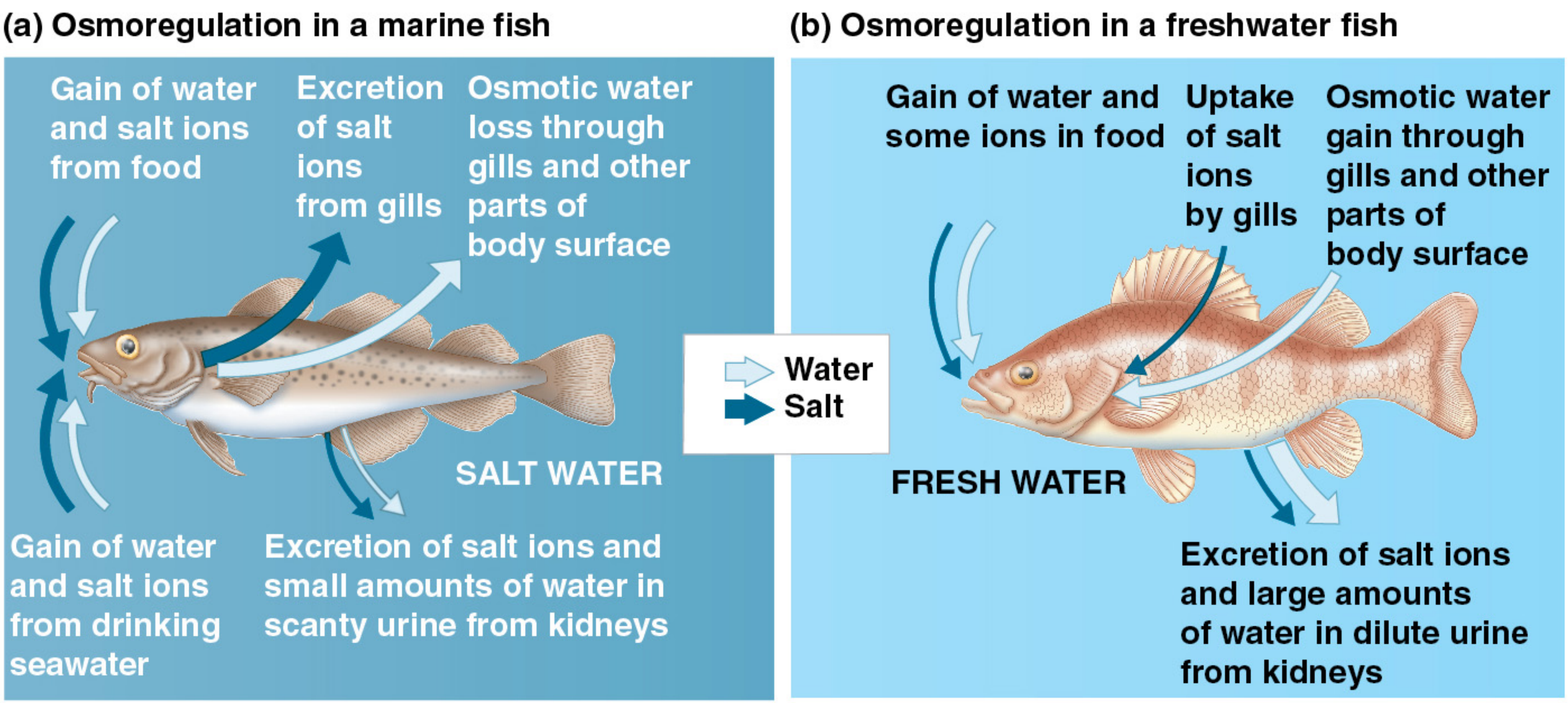
- Osmoregulation is frequently coupled to elimination of nitrogenous waste products, such as urea
- Sharks have a high concentration of urea in their bodies, but trimethylamine oxide (TMAO) protects them from its denaturing effect
- Sharks take in water by osmosis and in their food; the excess water is disposed of in urine
- The urine also removes some of the salt that diffuses into the shark’s body

Freshwater Animals

- Freshwater animals constantly take in water by osmosis from their hypoosmotic environment
- They lose salts by diffusion and maintain water balance by drinking almost no water and excreting large amounts of dilute urine
- Salts lost by diffusion are replaced in foods and by uptake across the gills

- Euryhaline fishes, such as salmon, undergo dramatic changes in osmoregulatory status
- When in rivers and streams, they osmoregulate like other freshwater fishes
- When they migrate to the ocean, they acclimatize
- They produce more of the steroid hormone cortisol, which increases the number and size of specialized salt-secreting cells
- This enables them to excrete excess salt from the gills and produce very little urine

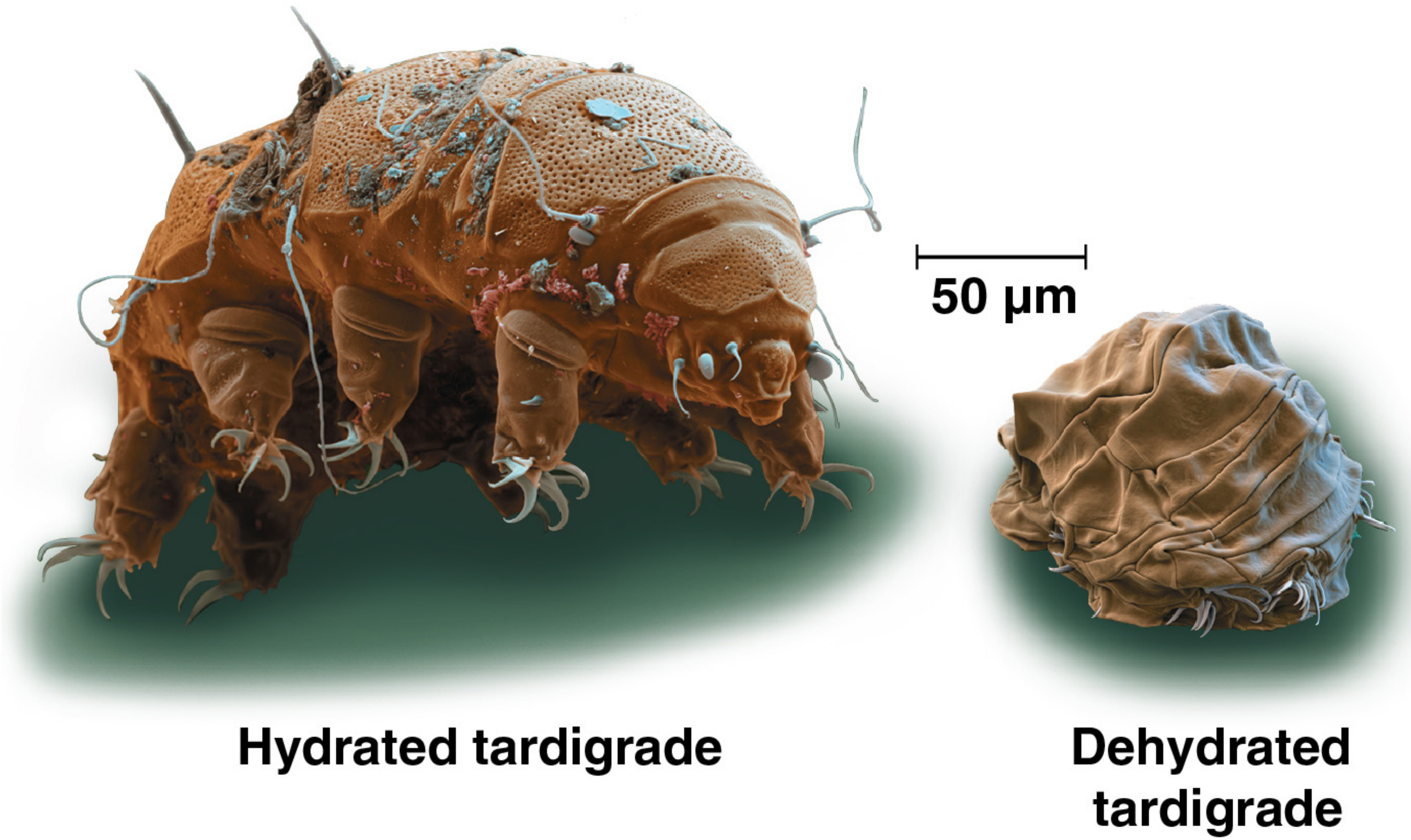
Figure 44.3


(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
SALT WATER
Gain of water and salt ions from drinking seawater
Excretion of salt ions and small amounts of water in scanty urine from kidneys
Water
Salt
(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
FRESH WATER
Excretion of salt ions and large amounts of water in dilute urine from kidneys

Animals That Live in Temporary Waters

- Extreme dehydration, or desiccation, is fatal for most animals
- However, some aquatic invertebrates in temporary ponds lose almost all their body water and survive in a dormant state
- This adaptation is called **anhydrobiosis**
- Tardigrades (water bears) can dehydrate from about 85% water to 2% water in the dehydrated, inactive state, easily reversible when water is added

Figure 44.4



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

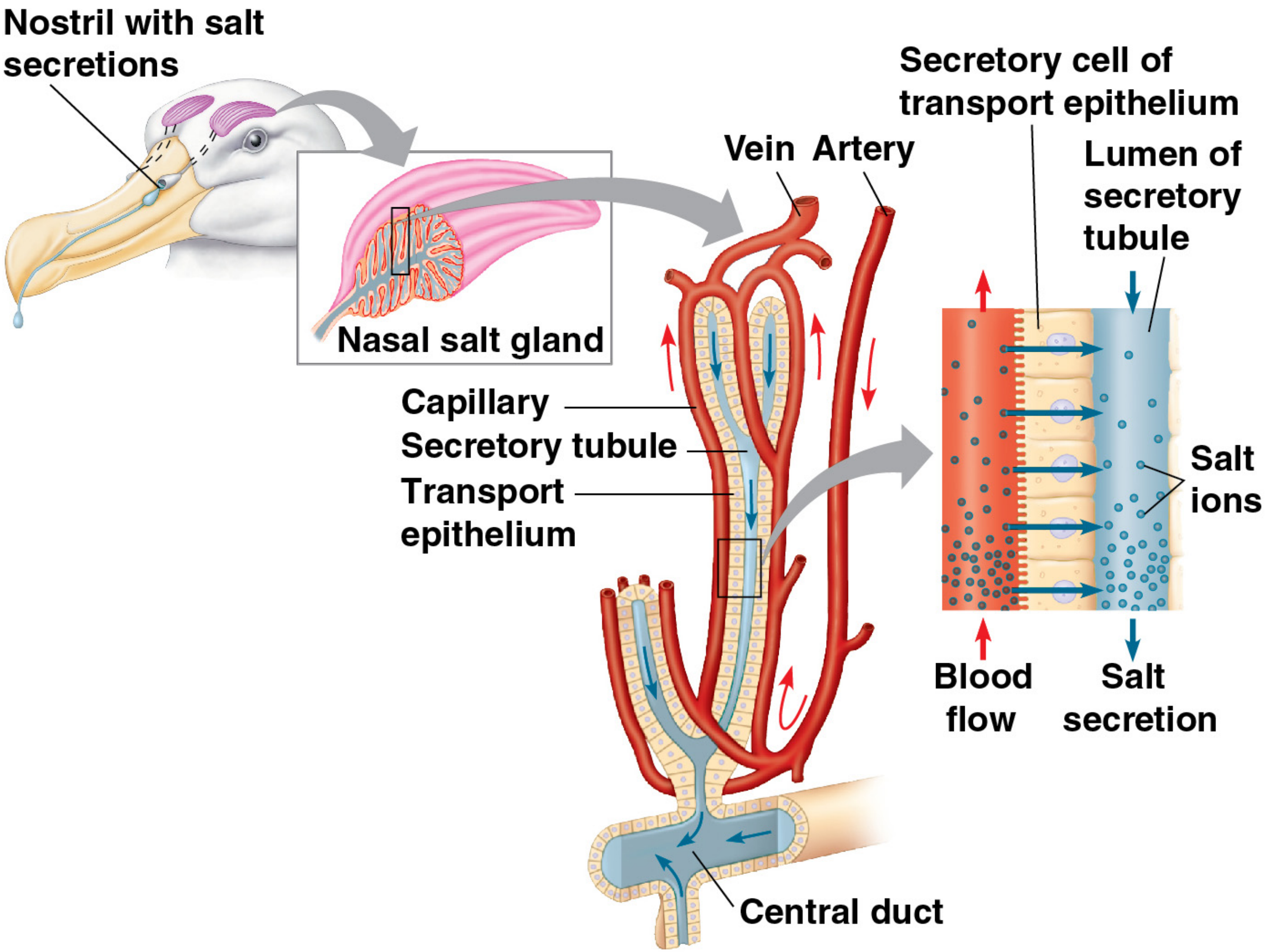
Energetics of Osmoregulation

- 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 specialized for controlled movement of solutes in specific directions
- They are typically arranged into tubular networks with extensive surface areas
- An example is in the nasal glands of marine birds, which remove excess sodium chloride from the blood

Figure 44.5



Nostril with salt secretions
Nasal salt gland
Vein
Artery
Secretory cell of transport epithelium
Lumen of secretory tubule
Capillary
Secretory tubule
Transport epithelium
Salt ions
Blood flow
Salt secretion
Central duct

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

- In regulating and safeguarding their internal fluids, animals must deal with **ammonia**, a toxic metabolite produced by breakdown of nitrogenous molecules
- Ammonia and other metabolic waste products are removed from the body by **excretion**
- Most metabolic wastes must be dissolved in water for excretion, so the type and quantity or waste products have a large impact on water balance

Forms of Nitrogenous Waste

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

Ammonia

- Ammonia is very toxic
- Animals that excrete nitrogenous wastes as ammonia need access to lots of water
- In many invertebrates, ammonia release occurs across the whole body surface

Urea

- Most terrestrial mammals and many marine species excrete **urea**, which is less toxic than ammonia
- In vertebrates, urea is produced in the liver
- Advantages of urea are its low toxicity and high solubility in water
- 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 even more energetically expensive to produce than urea

Figure 44.6

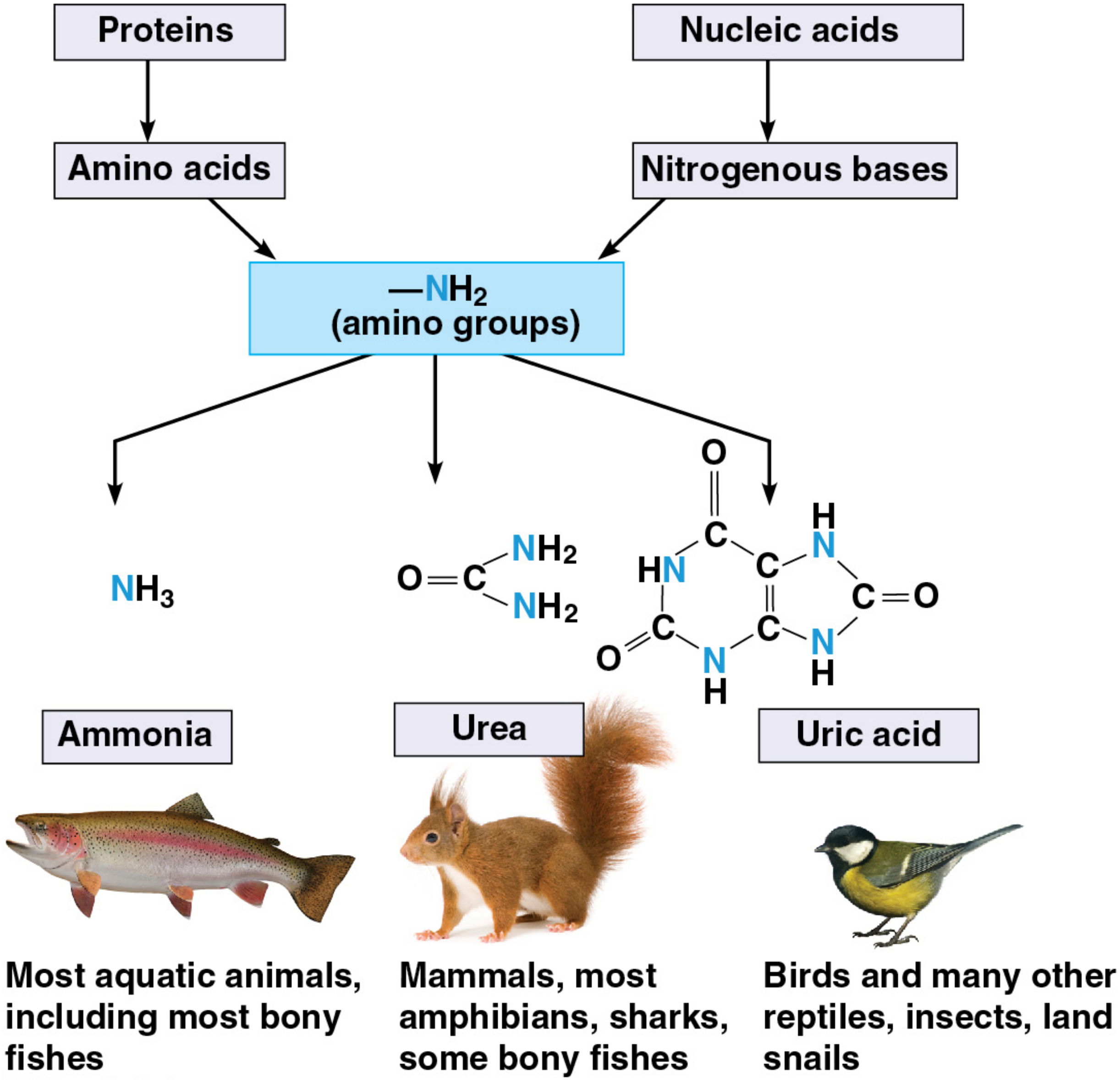

Proteins
Nucleic acids
Amino acids
Nitrogenous bases
—NH2
(amino groups)
NH3
Ammonia
Urea
Uric acid
Most aquatic animals, including most bony fishes
Mammals, most amphibians, sharks, some bony fishes
Birds and many other reptiles, insects, land snails

Figure 44.7

The Influence of Evolution and Environment on Nitrogenous Wastes

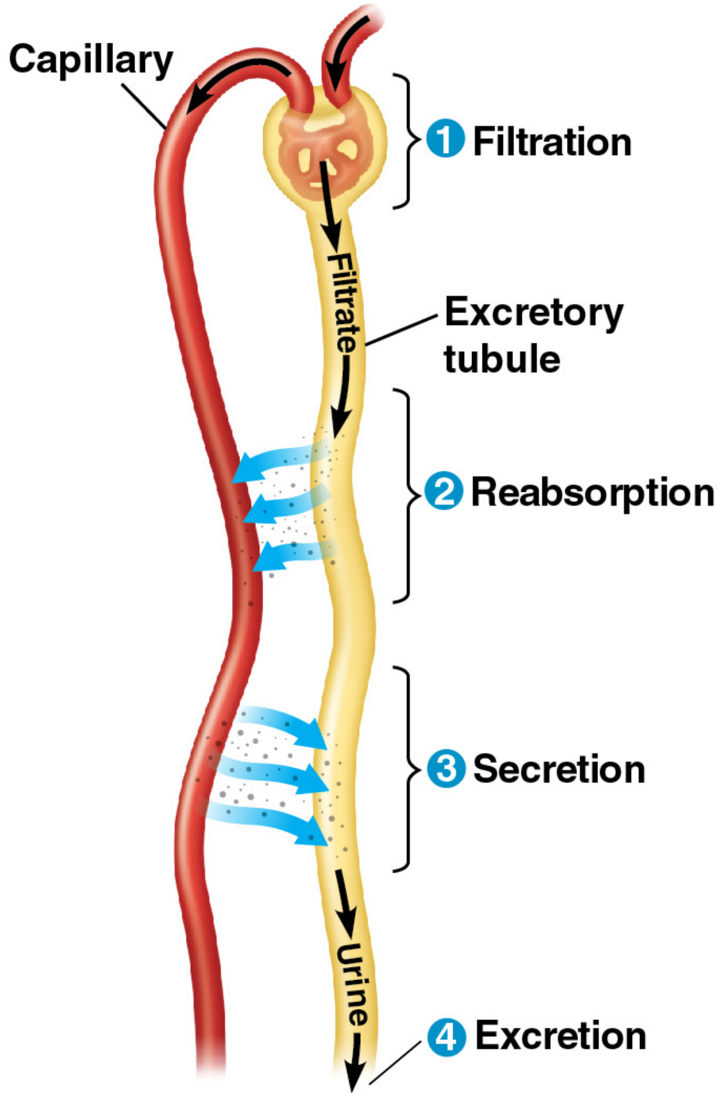
- The kind of nitrogenous wastes excreted depends on an animal’s habitat, especially water availability
- Another factor is the immediate environment of the animal egg
- The amount of nitrogenous waste is coupled to the animal’s energy budget
- It is also linked to diet

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

- Excretory systems dispose of metabolic wastes and control body fluid composition
- They thus play a central role in homeostasis

- 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**: Recovering valuable solutes
  - **Secretion**: Adding nonessential solutes and wastes to the filtrate
  - Excretion: Processed filtrate containing nitrogenous wastes is released from the body

Figure 44.8



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

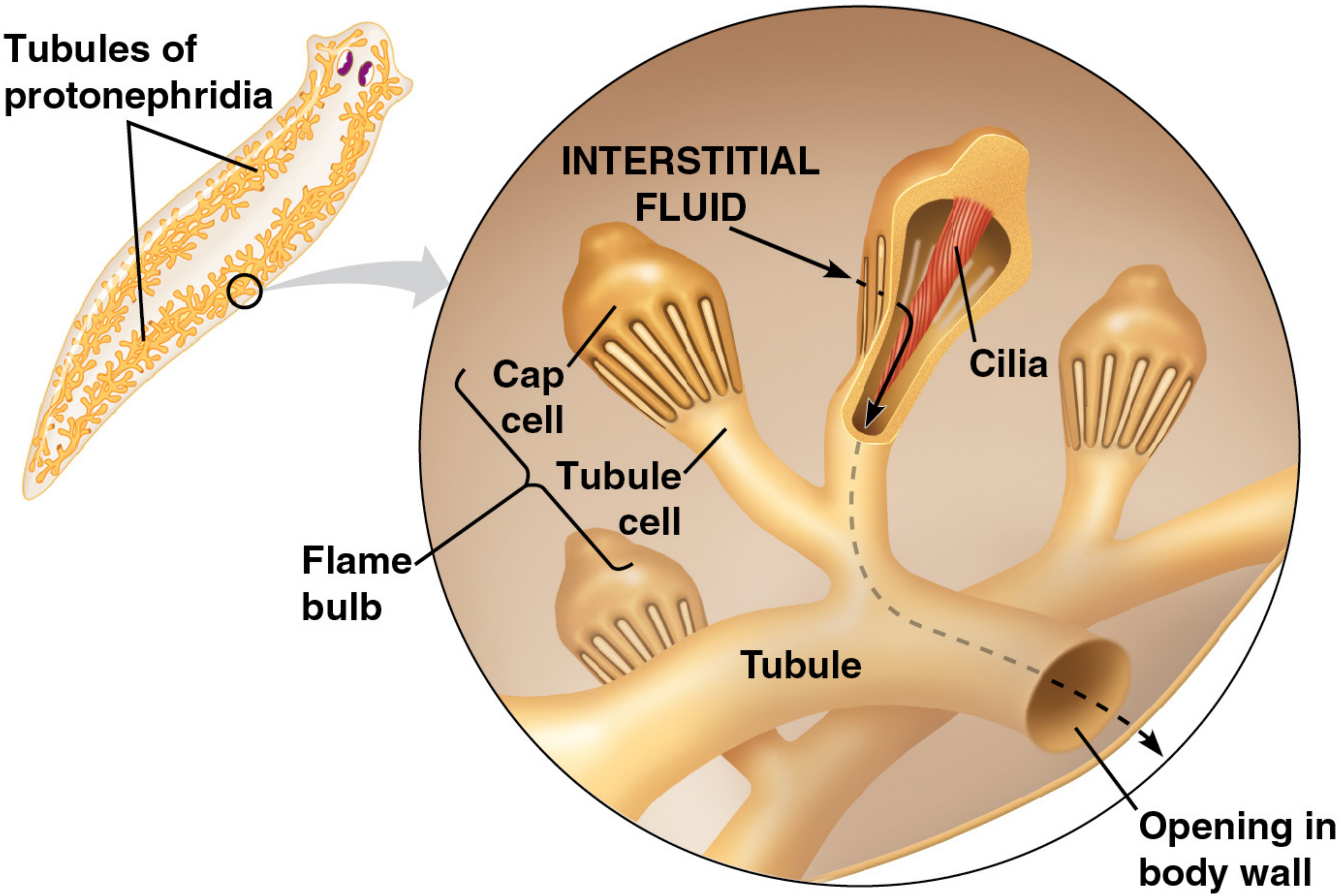
Survey of Excretory Systems

- Systems that perform basic excretory functions vary widely among animal groups
- They are generally built on a complex network of tubules

Protonephridia

- A **protonephridium** is a network of dead-end tubules that branch throughout the body
- 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

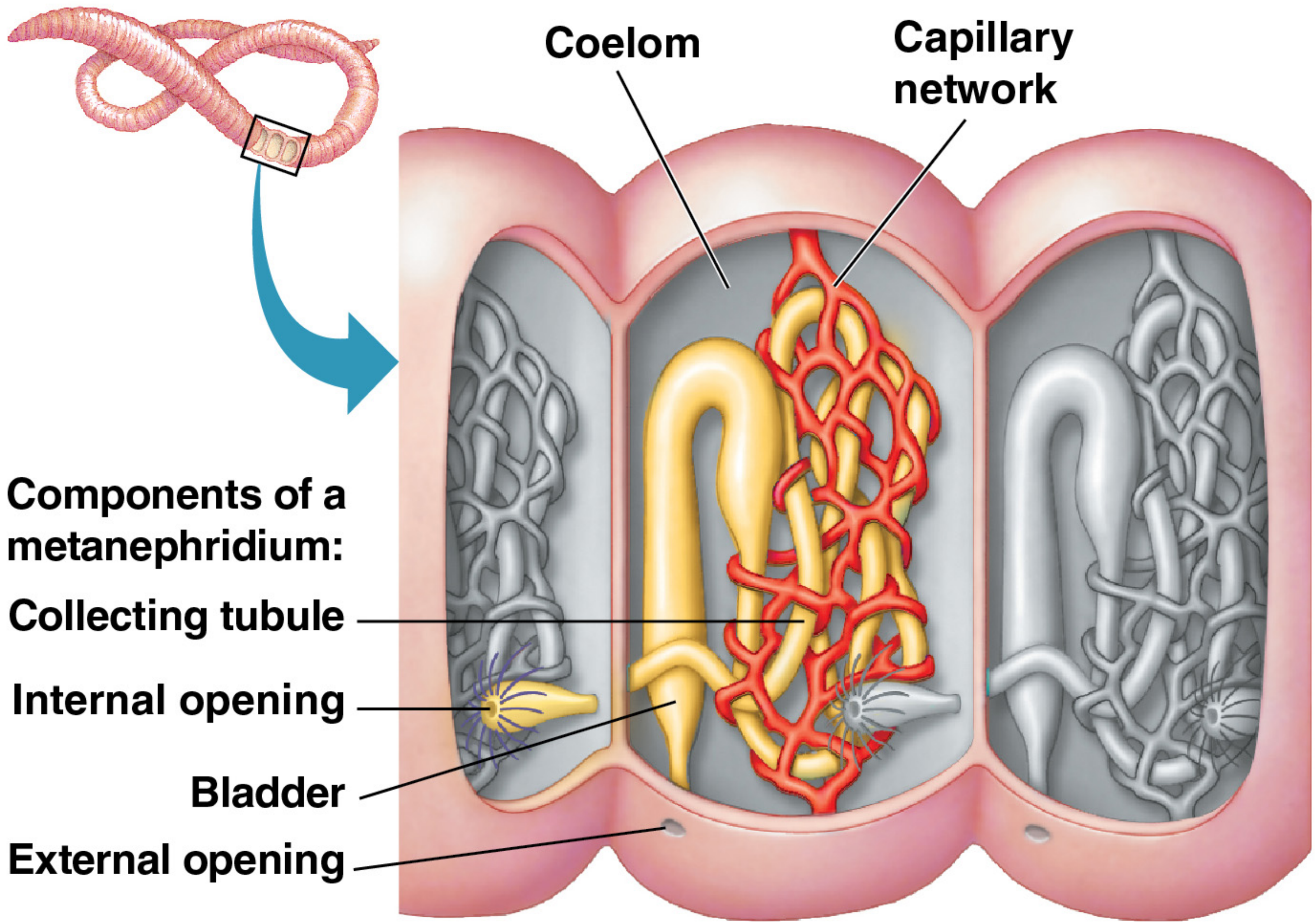
Figure 44.9


Tubules of protonephridia
INTERSTITIAL FLUID
Cap cell
Cilia
Tubule cell
Flame bulb
Tubule
Opening in body wall

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
- Metanephridia of earthworms function in excretion and osmoregulation

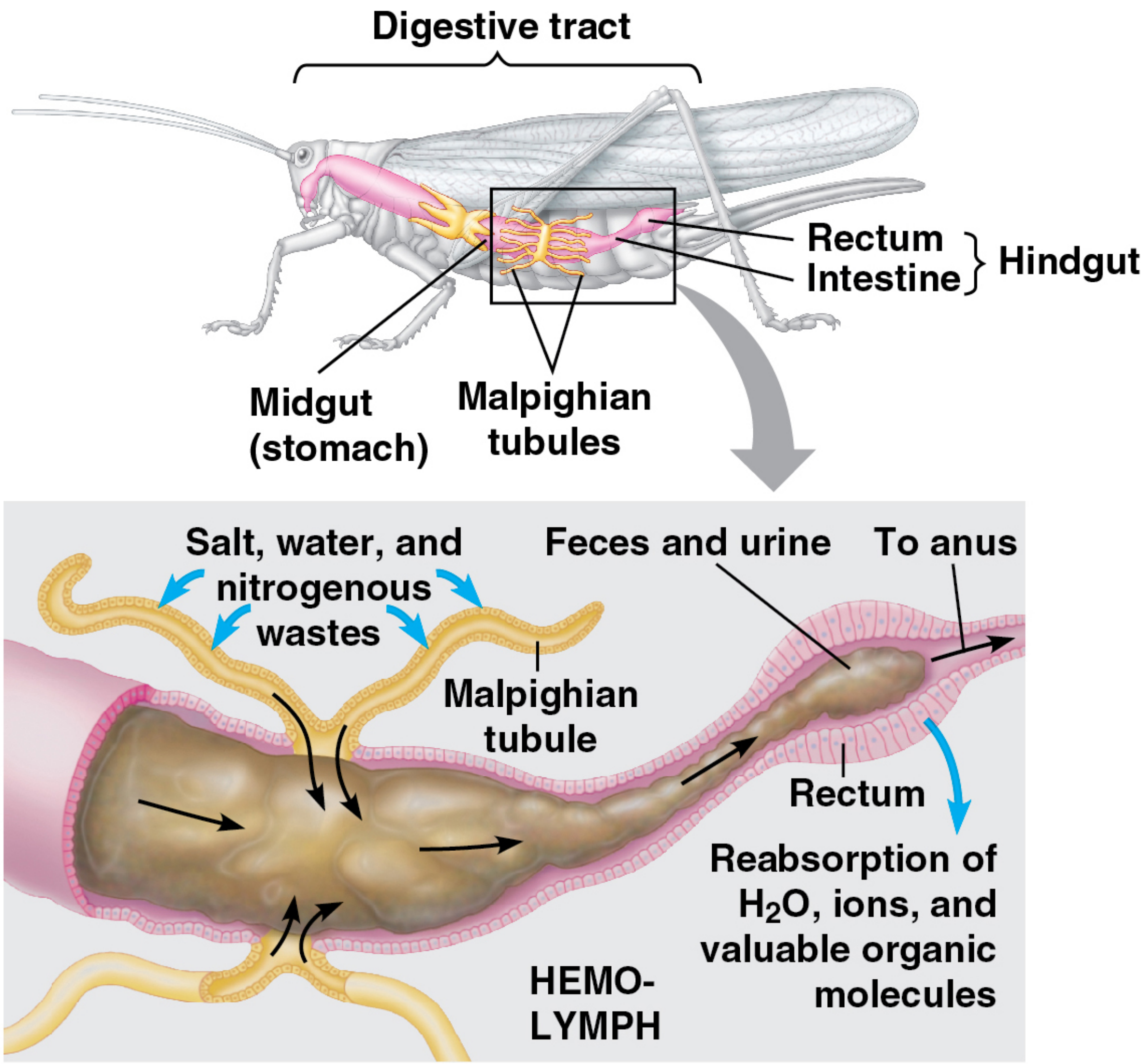
Figure 44.10


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
- The filtration step is absent in these systems
- The nitrogenous wastes are mainly insoluble uric acid, eliminated as nearly dry matter
- This system is capable of conserving water very effectively

Figure 44.11



Digestive tract
Rectum
Intestine
Hindgut
Midgut
(stomach)
Malpighian
tubules
Salt, water, and
nitrogenous
wastes
Feces and urine
To anus
Malpighian
tubule
Rectum
Reabsorption of
H_2O, ions, and
valuable organic
molecules
HEMO-
LYMPH

Kidneys

- **Kidneys**, the excretory organs of vertebrates and some other chordates, function in both excretion and osmoregulation
- The numerous tubules of kidneys are highly organized
- The vertebrate excretory system also includes ducts and other structures that carry urine from the tubules out of the kidney and out of the body

- Urine produced by each kidney exits the renal pelvis through a duct called the **ureter**
- The ureters drain into a common sac called the **urinary bladder**
- Urine is expelled from the bladder through a tube called the **urethra**

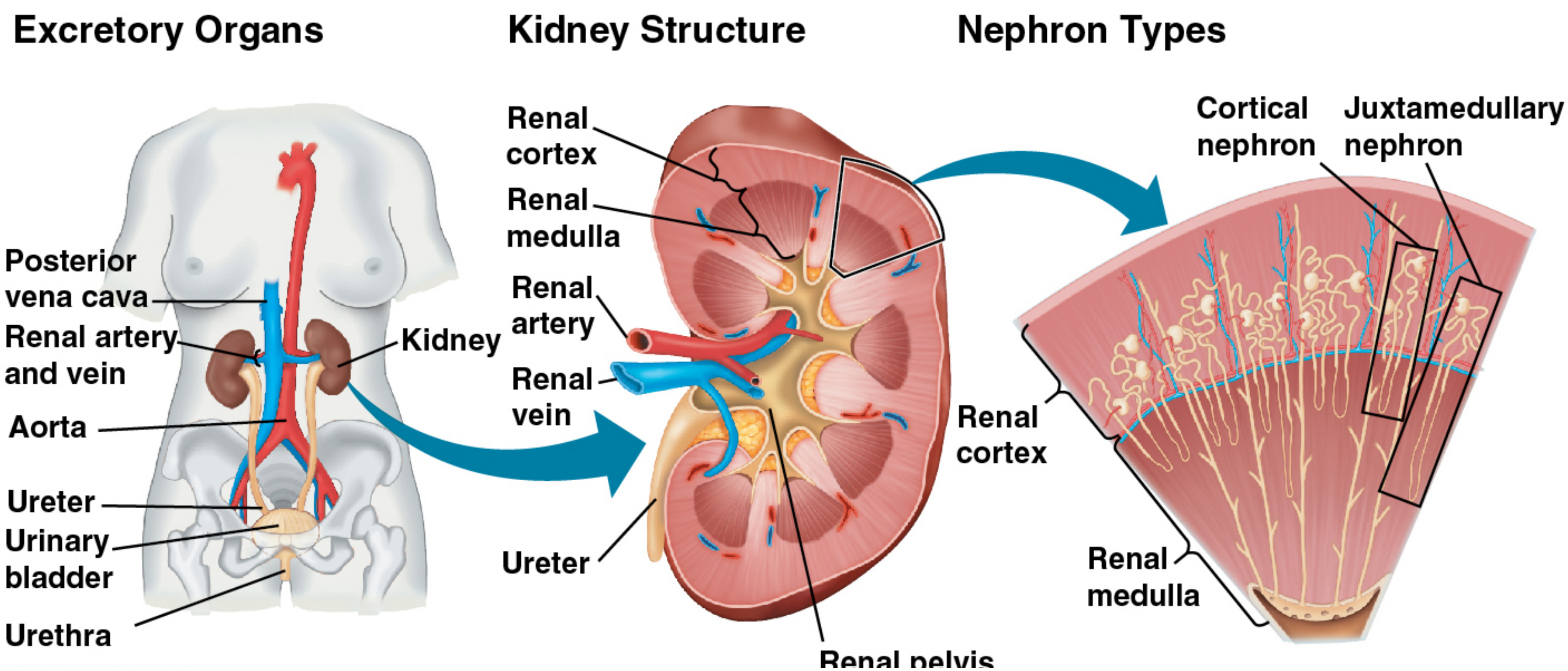
- Each kidney has an outer **renal cortex** and an inner **renal medulla**
- Within these lie tightly packed excretory tubules and associated blood vessels
- The tubules carry and process a filtrate produced from blood entering the kidney; nearly all the fluid is reabsorbed
- The remaining fluid exits as urine, collects in the **renal pelvis**

- **Nephrons** are the functional units of the vertebrate kidney
- Of the ~1 million nephrons in a human kidney, 85% are **cortical nephrons** which extend only a short distance into the medulla
- The remainder, the **juxtamedullary nephrons**, extend deep into the medulla
- These are essential for production of urine that is hyperosmotic to body fluids, key for water conservation

- Nephrons consist of a long tubule and a ball of capillaries called the **glomerulus**
- The **Bowman's capsule** surrounds the glomerulus
- Processing of the filtrate occurs as it passes through three major regions of the nephron:
  - The **proximal tubule**
  - The **loop of Henle**
  - The **distal tubule**

- A **collecting duct** receives the processed filtrate from many nephrons and transports it to the renal pelvis
- **Peritubular capillaries** surround the proximal and distal tubules, while other branches form the **vasa recta**, serving the renal medulla

Figure 44.12


Excretory Organs
Kidney Structure
Nephron Types
Posterior vena cava
Renal artery and vein
Aorta
Ureter
Urinary bladder
Urethra
Kidney
Renal cortex
Renal medulla
Renal artery
Renal vein
Ureter
Renal pelvis
Cortical nephron
Juxtamedullary nephron
Renal cortex
Renal medulla

Animation: Nephron Introduction

Nephron Function

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
- Under normal conditions, ~1,600 L of blood flows through a pair of human kidneys each day
- Only about 1.5 L of urine is transported to the bladder for excretion

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
- As the filtrate passes through the proximal tubule, materials to be excreted become concentrated
- Some toxic materials are actively secreted into the filtrate

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

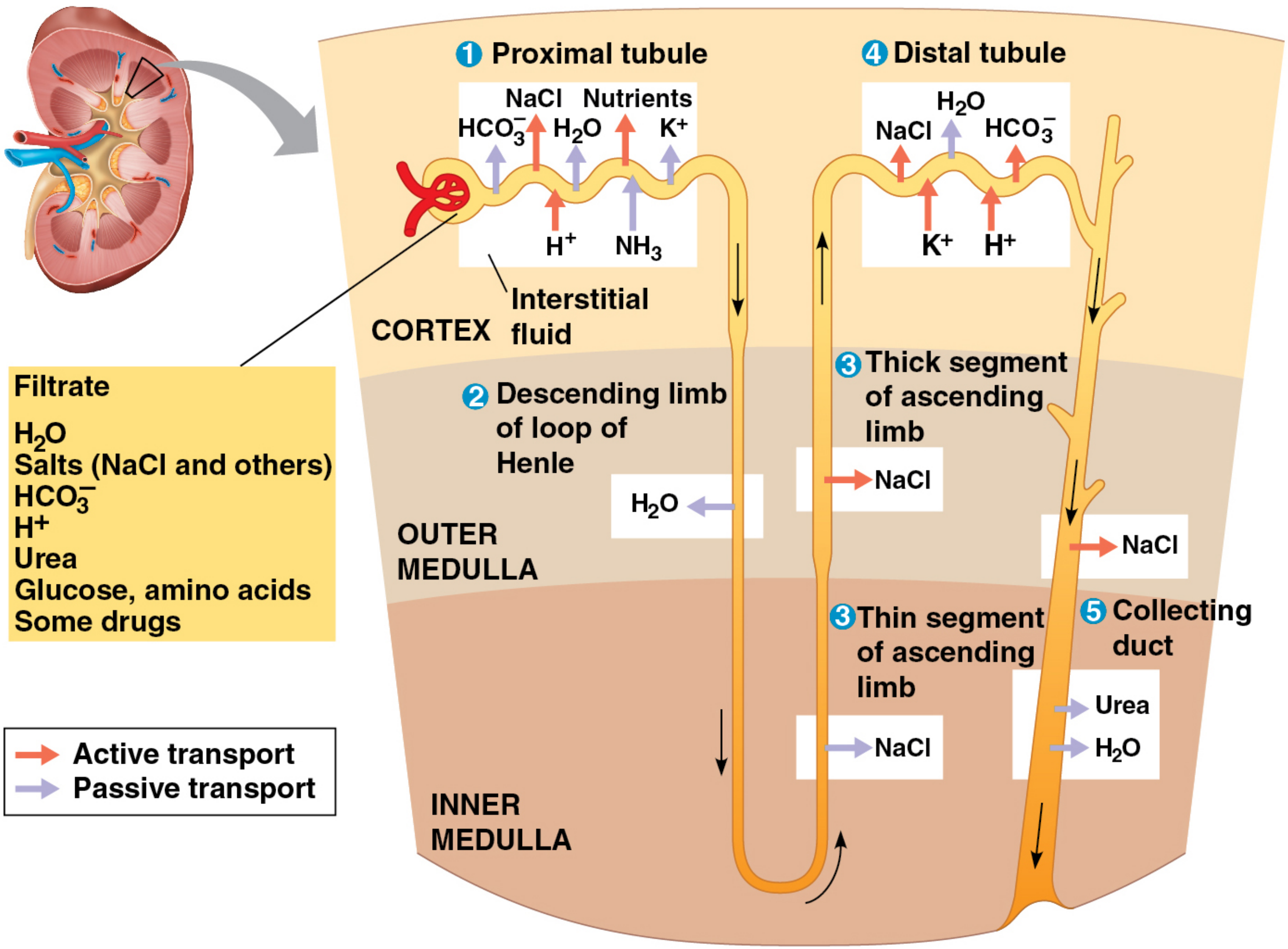
Distal Tubule

- The distal tubule regulates the K^+ and NaCl concentrations of body fluids
- The controlled movement of ions (H^+ and HCO_3^-) contributes to pH regulation

Collecting Duct

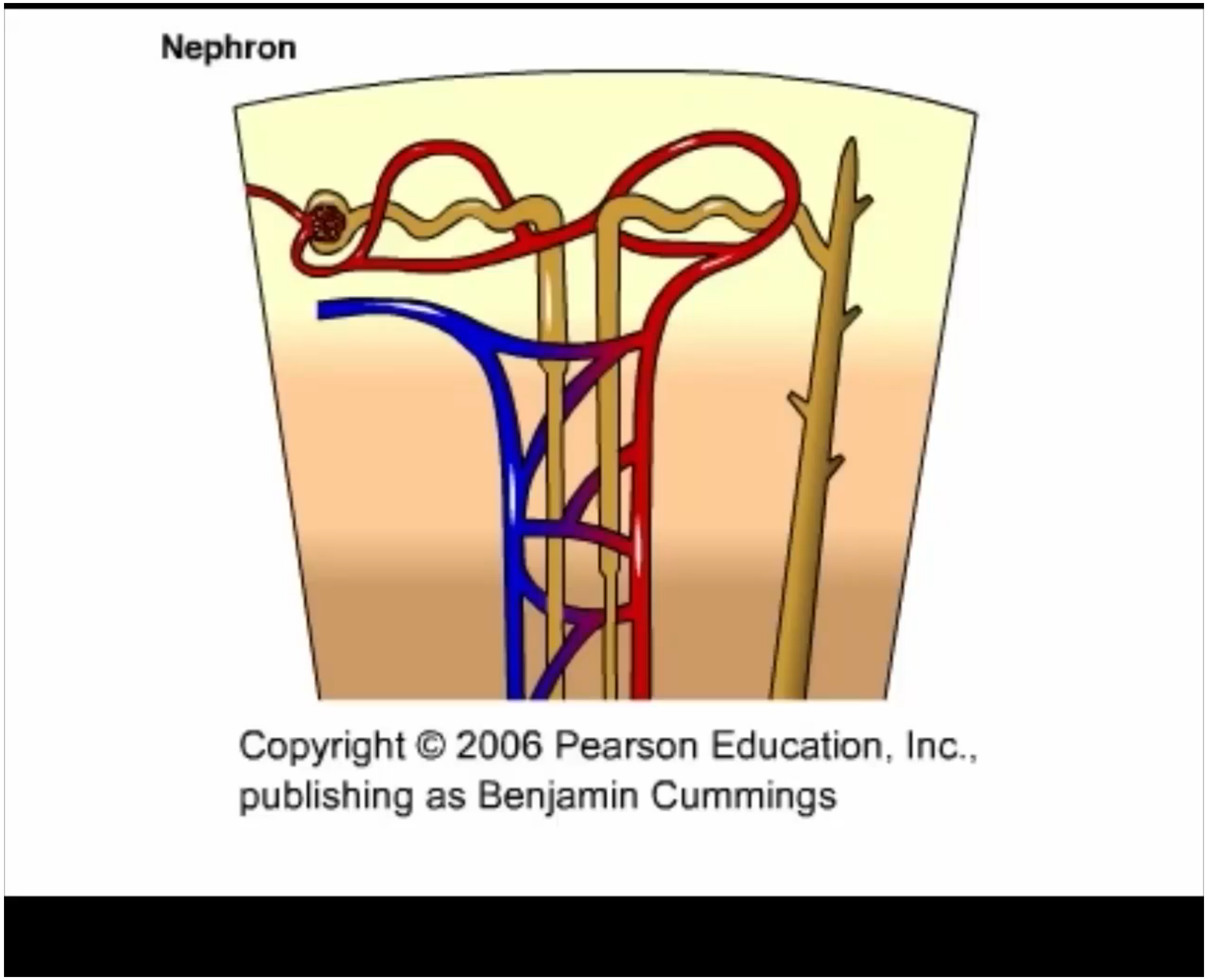
- The collecting duct carries filtrate through the medulla to the renal pelvis
- One of the most important tasks is reabsorption of solutes and water
- Urine is hyperosmotic to body fluids

Figure 44.13

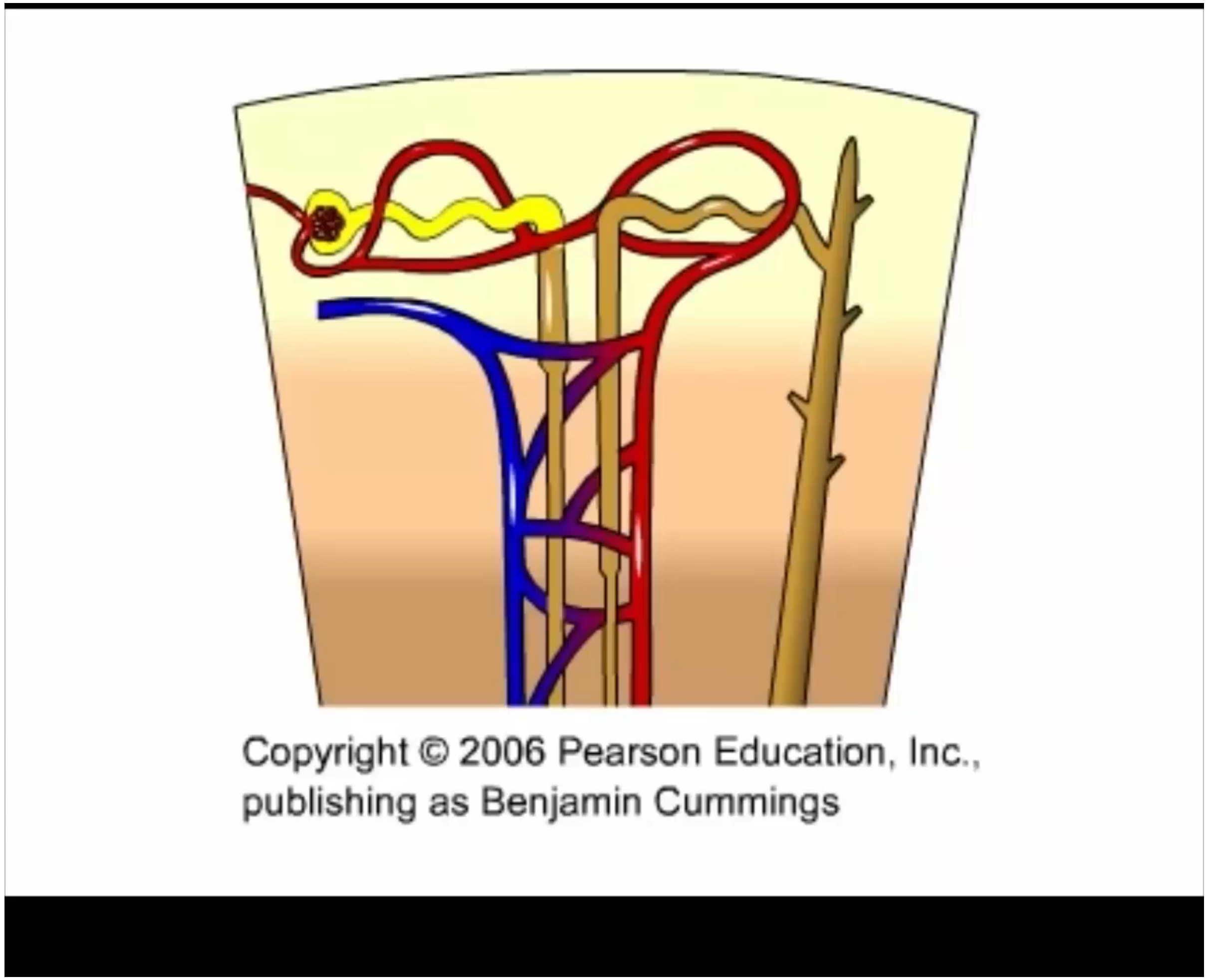


1 Proximal tubule
NaCl Nutrients
HCO3− H2O K+
H+ NH3
Interstitial fluid
CORTEX
4 Distal tubule
H2O
NaCl HCO3−
K+ H+
Filtrate
H2O
Salts (NaCl and others)
HCO3−
H+
Urea
Glucose, amino acids
Some drugs
2 Descending limb of loop of Henle
H2O
3 Thick segment of ascending limb
NaCl
NaCl
OUTER MEDULLA
3 Thin segment of ascending limb
NaCl
5 Collecting duct
Urea
H2O
INNER MEDULLA
Active transport
Passive transport

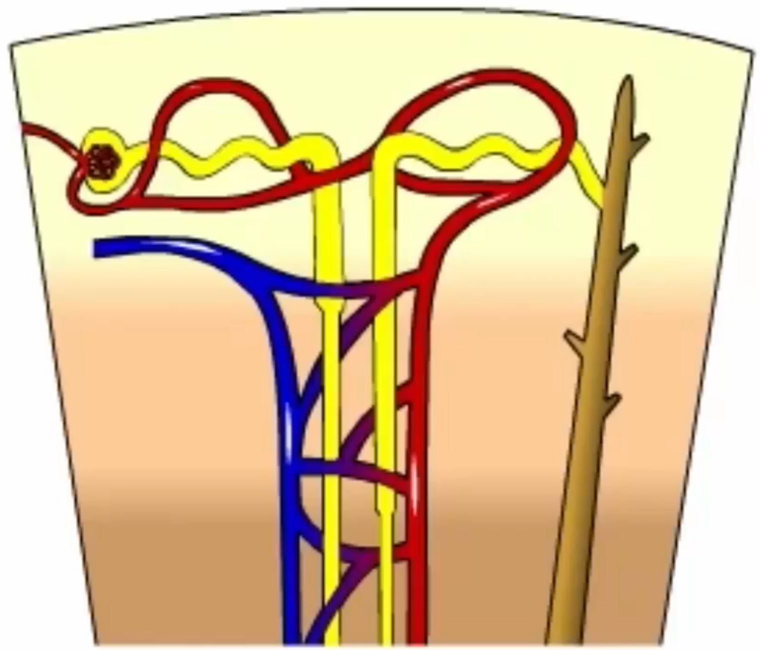
Animation: Bowman's Capsule



Animation: Loop of Henle



Animation: Collecting Duct



Solute Gradients and Water Conservation

- The mammalian kidney's ability to conserve water is a key terrestrial adaptation
- Hyperosmotic urine can be produced only because considerable energy is expended to transport solutes against concentration gradients
- The two primary solutes affecting osmolarity are NaCl and urea

Concentrating Urine in the Mammalian Kidney

- In the proximal tubule, filtrate volume decreases as water and salt are reabsorbed, but osmolarity remains the same
- As the filtrate flows to the descending limb of the loop of Henle, solutes become more concentrated due to water leaving the tubule by osmosis
- NaCl diffusing from the ascending limb maintains a high osmolarity in the interstitial fluid of the renal medulla

- Energy is expended to actively transport NaCl from the filtrate in the upper part of the ascending limb
- The **countercurrent multiplier system** in the loop of Henle maintains a high salt concentration in the kidney
- This system allows the vasa recta to supply the kidney with nutrients without interfering with the osmolarity gradient

- In the collecting duct, osmosis extracts water from the filtrate as it passes from cortex to medulla and encounters interstitial fluid of increasing osmolarity
- Urine produced is isoosmotic to the interstitial fluid of the inner medulla, but hyperosmotic to blood and interstitial fluids elsewhere in the body

Video: How the Human Kidney Concentrates Urine

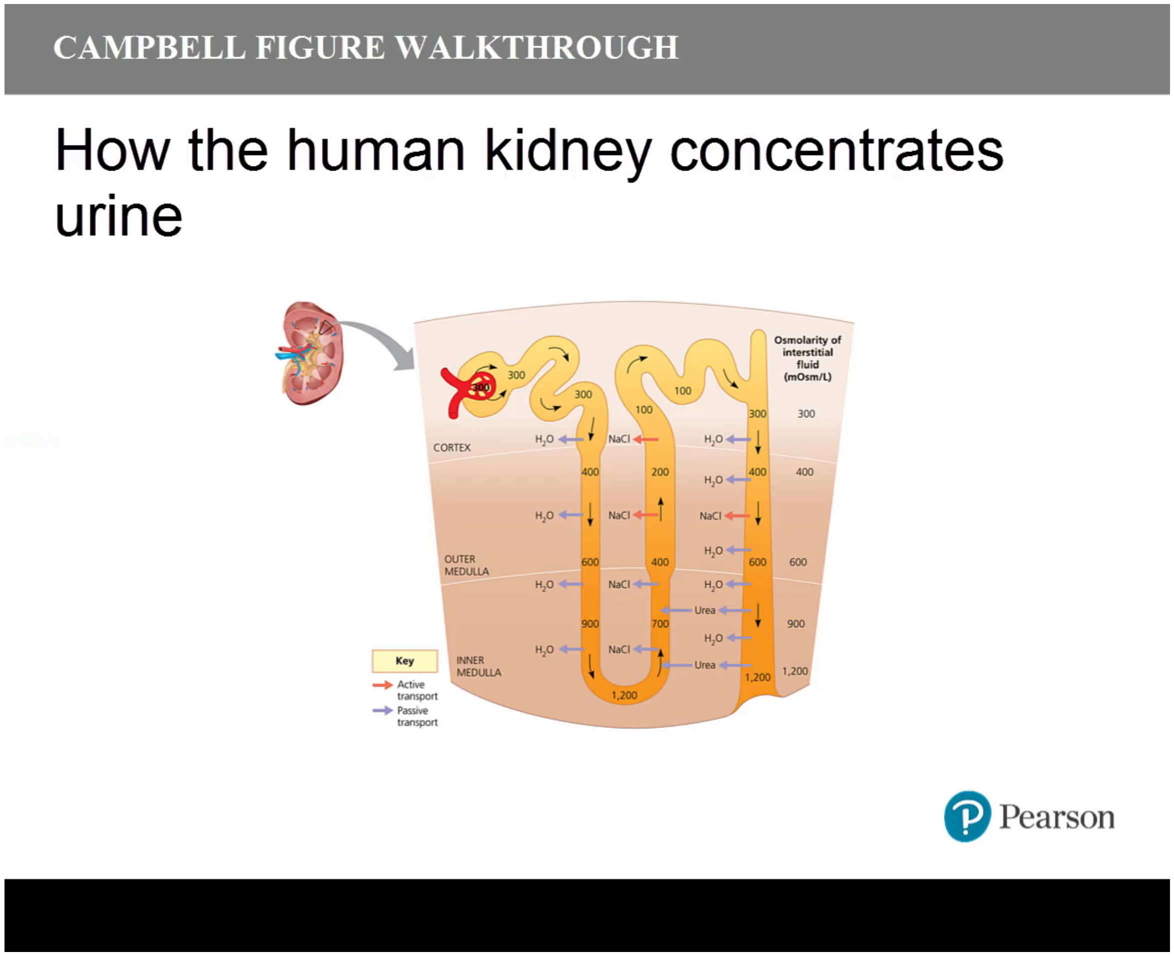
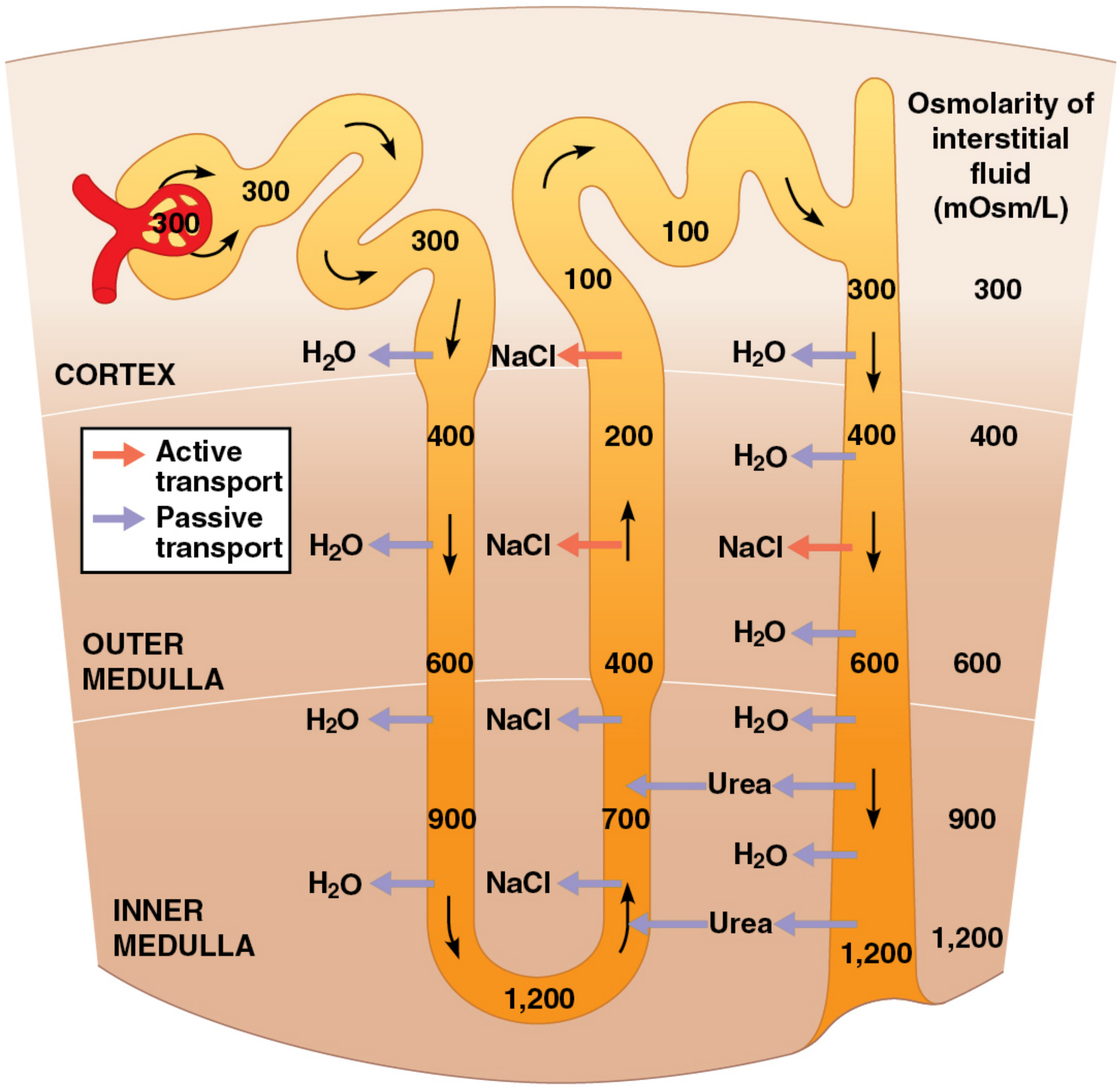


Figure 44.14



Osmolarity of interstitial fluid (mOsm/L)
300
300
300
300
100
100
300
300
CORTEX
H_2O
NaCl
H_2O
400
200
400
400
Active transport
Passive transport
H_2O
H_2O
NaCl
NaCl
OUTER MEDULLA
H_2O
600
400
600
600
H_2O
NaCl
H_2O
Urea
900
700
900
H_2O
INNER MEDULLA
H_2O
NaCl
Urea
1,200
1,200
1,200

Adaptations of the Vertebrate Kidney to Diverse Environments

- Variations in nephron structure and function equip the kidneys of different vertebrates for osmoregulation in various habitats

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

Case Study: *Kidney Function in the Vampire Bat*

- The South American vampire bat, which feeds at night on the blood of large birds and mammals, illustrates the versatility of the mammalian kidney
- The vampire bat can alternate rapidly between producing large amounts of dilute urine as it feeds and small amounts of very hyperosmotic urine when roosting
- This adaptation is an essential adaptation to an unusual food source

Figure 44.15

Birds and Other Reptiles

- Birds have shorter loops of Henle than mammals do, but conserve water by excreting uric acid instead of urea
- Other reptiles have only cortical nephrons but reabsorb water from wastes in the cloaca
- Reptiles also excrete nitrogenous waste as uric acid

Figure 44.16

Freshwater Fishes and Amphibians

- Freshwater fishes excrete large volumes of very dilute urine
- Salt concentration relies on reabsorption of ions from filtrate in the distal tubules
- Kidney function in amphibians is similar to freshwater fishes
- Amphibians conserve water on land by reabsorbing water from the urinary bladder

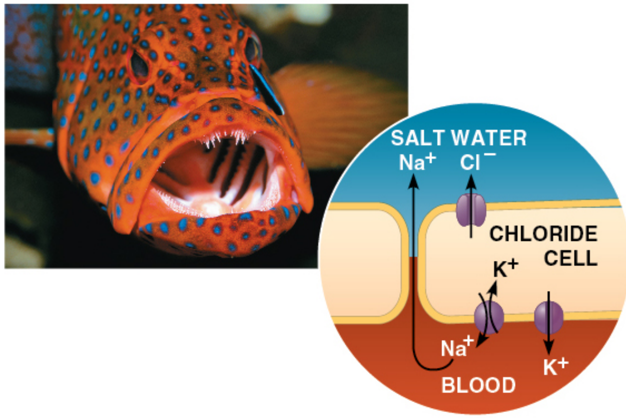
Marine Bony Fishes

- Marine bony fishes have fewer and smaller nephrons than freshwater fishes, and their nephrons lack a distal tubule
- Their kidneys have small glomeruli; some lack glomeruli entirely
- Filtration rates are low, and very little urine is excreted
- Osmoregulation relies on specialized chloride cells in the gills

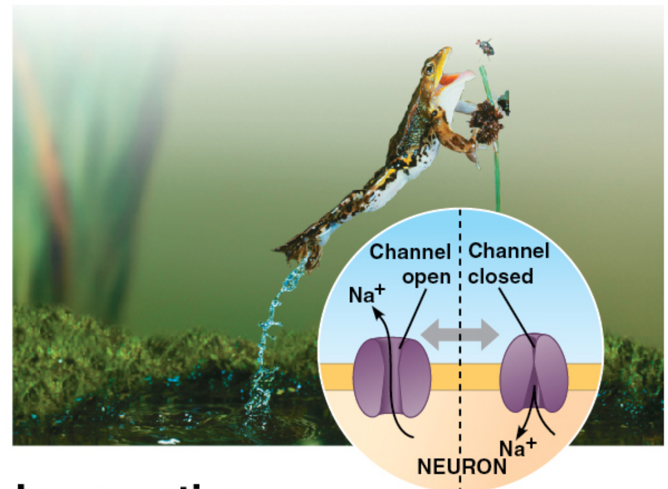
Figure 44.17

MAKE CONNECTIONS: Ion Movement and Gradients

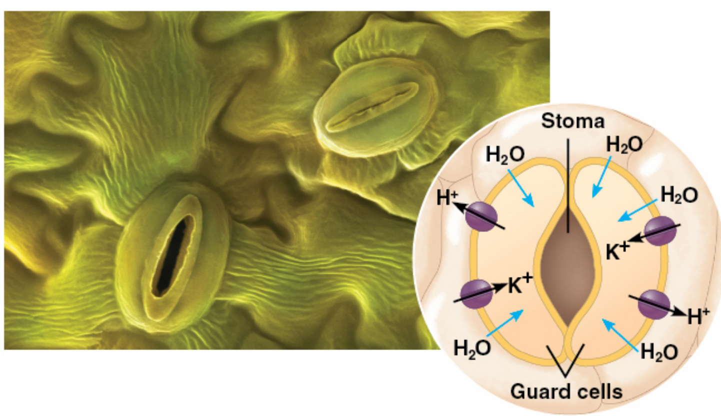
Osmoregulation



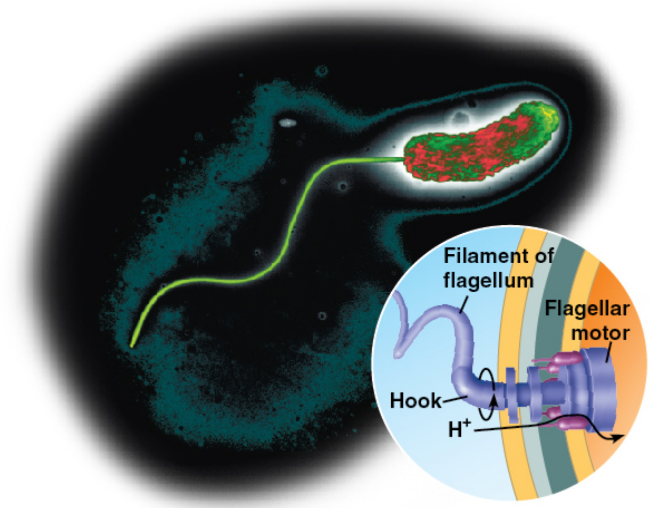
Information Processing



Gas Exchange



Locomotion



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

- Mammals can control the volume and osmolarity of urine in response to changes in salt intake and water availability
- Two major control circuits that respond to different stimuli together restore and maintain normal water and salt balance

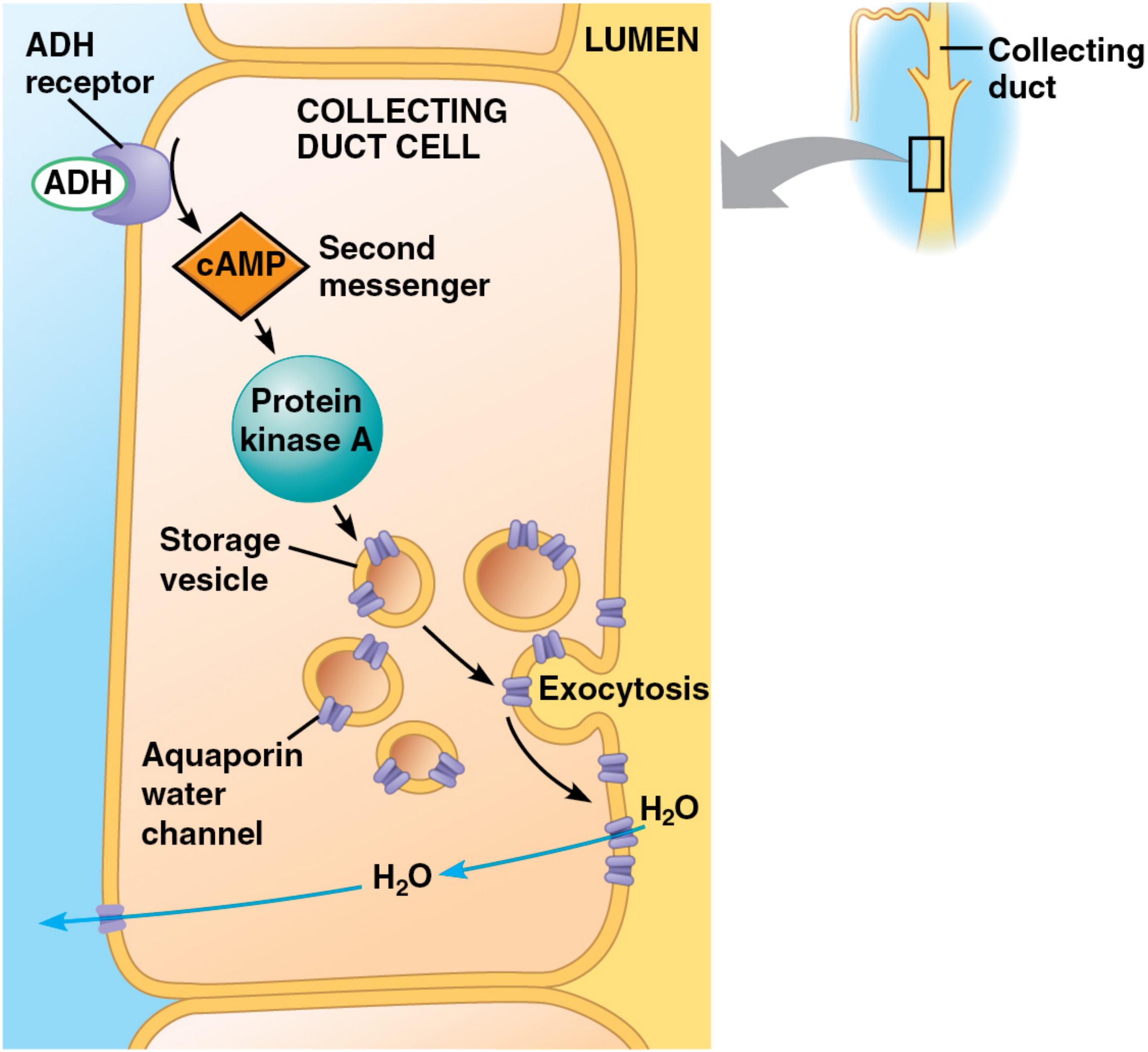
Homeostatic Regulation of the Kidney

- A combination of nervous and hormonal controls manages the osmoregulatory functions of the mammalian kidney
- These controls contribute to homeostasis for blood pressure and blood volume

Antidiuretic Hormone

- **Antidiuretic hormone**, ADH, is also called vasopressin
- ADH molecules released from the posterior pituitary bind to and activate membrane receptors on collecting duct cells
- This initiates a signal cascade leading to insertion of aquaporin proteins into the membrane lining the collection duct
- The increase in water recapture reduces urine volume

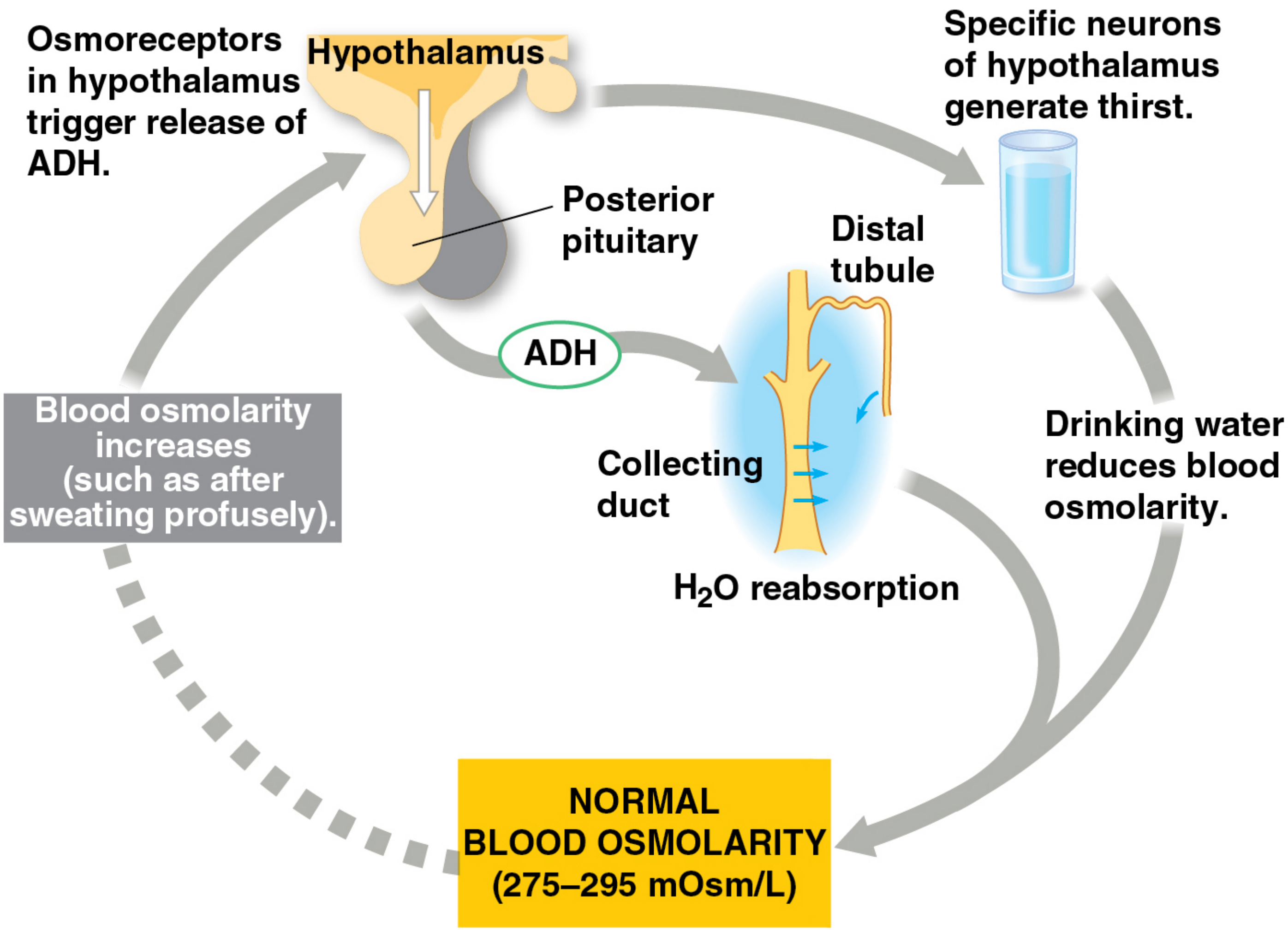
Figure 44.18



ADH receptor
ADH
LUMEN
COLLECTING DUCT CELL
cAMP
Second messenger
Protein kinase A
Storage vesicle
Exocytosis
Aquaporin water channel
H_2O
H_2O
Collecting duct

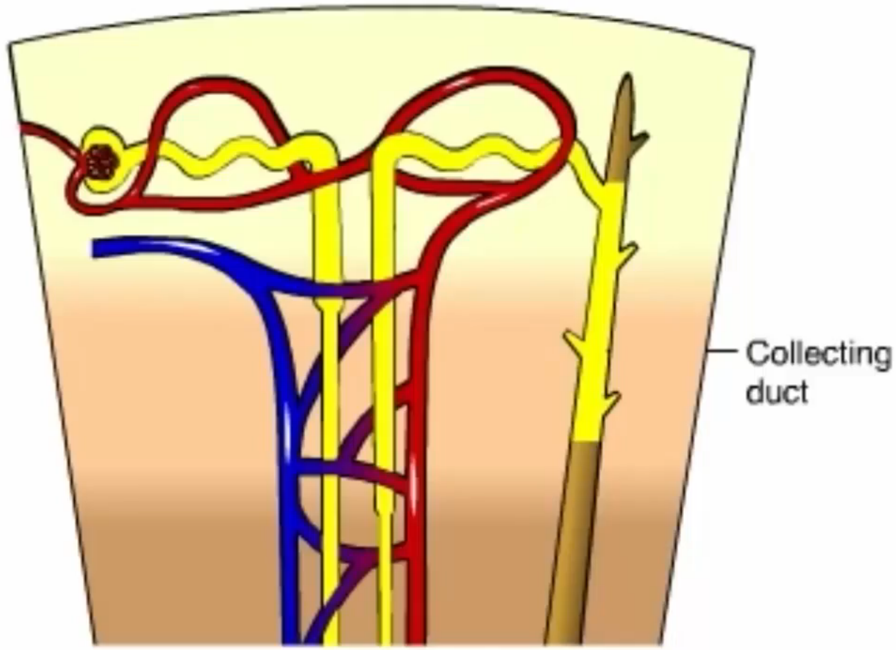
- Osmoreceptor cells in the hypothalamus monitor blood osmolarity and regulate release of ADH from the posterior pituitary
- When osmolarity rises above its set point, ADH release into the bloodstream increases, leading to concentrated urine
- When osmolarity drops below a set point, it causes a reduction in ADH secretion, and leads to more dilute urine

Figure 44.19

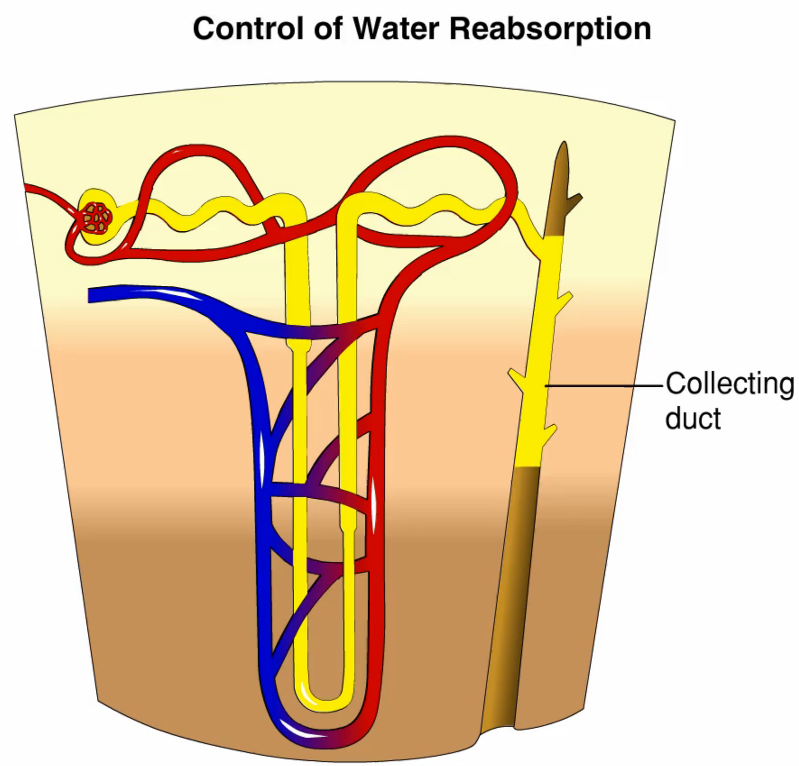


Osmoreceptors in hypothalamus trigger release of ADH.
Hypothalamus
Posterior pituitary
Specific neurons of hypothalamus generate thirst.
Distal tubule
ADH
Collecting duct
H_2O reabsorption
Drinking water reduces blood osmolarity.
Blood osmolarity increases (such as after sweating profusely).
NORMAL BLOOD OSMOLARITY (275–295 mOsm/L)

Animation: Effect of ADH



Animation: Control of Water Reabsorption



- Alcohol is a diuretic, as it inhibits the release of ADH
- The resulting dehydration may cause some symptoms of a hangover
- Mutation in ADH production causes severe dehydration and results in *diabetes insipidus*
- Mutations in an aquaporin gene have a similar effect

Figure 44.20

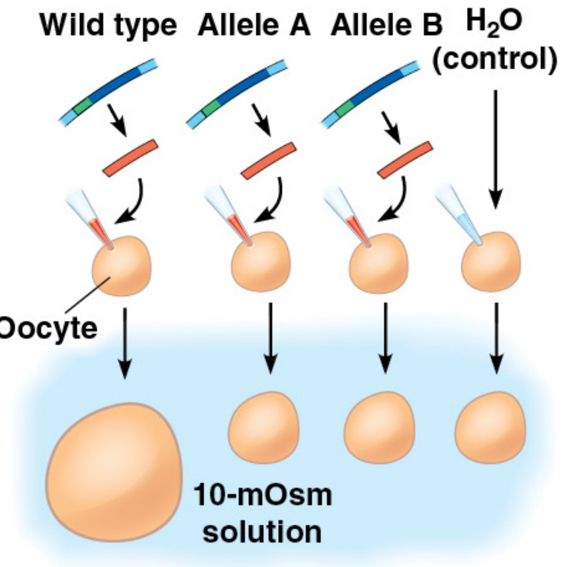
Experiment

Source of Aquaporin-2 Gene Sequence	Amino Acids 183–191* in Encoded Protein	Amino Acids 212–220* in Encoded Protein
Frog (*Xenopus laevis*)	MNPARSFAP	GIFASLIYN
Lizard (*Anolis carolinensis*)	MNPARSFGP	AVVASLLYN
Chicken (*Gallus gallus*)	MNPARSFAP	AAAASIIYN
Human (*Homo sapiens*)	MNPARSLAP	AILGSLLYN
Conserved residues	MNPARS--P	----S--YN
Patient's gene: allele A	MNPACSLAP	AILGSLLYN
Patient's gene: allele B	MNPARSLAP	AILGPLLYN

*The numbering is based on the human aquaporin-2 protein sequence.

1 Inject wild-type and mutant aquaporin mRNA into frog oocytes.

2 Transfer to 10-mOsm solution and measure rate of oocyte swelling.



Results

Source of Injected mRNA	Rate of Swelling (μm/sec)
Human wild type	196
Patient's allele A	17
Patient's allele B	18
None (H_2O control)	20

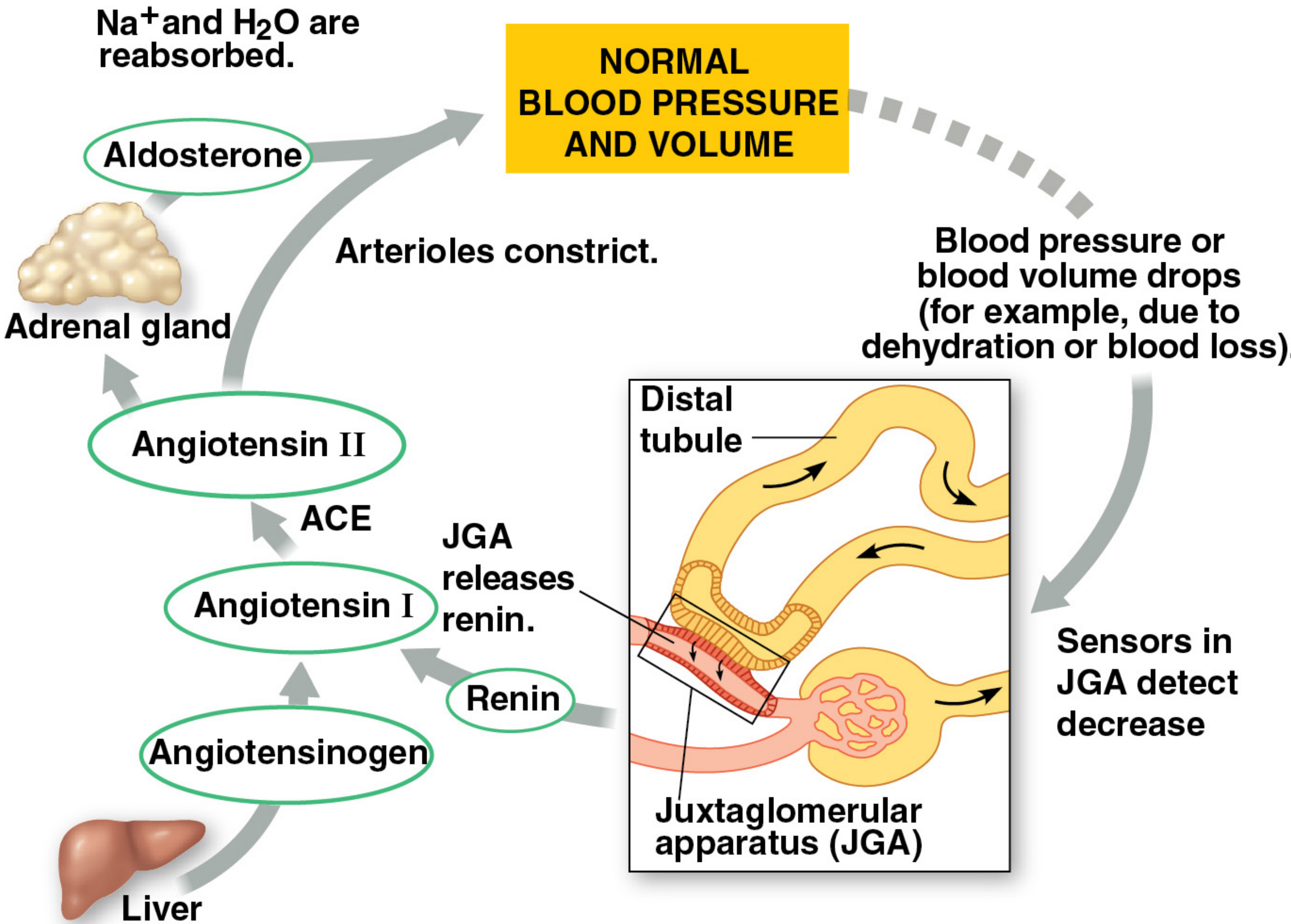
Data from P. M. Deen et al., Requirement of human renal water channel aquaporin-2 for vasopressin-dependent concentration of urine, *Science* 264:92–95 (1994).

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 by triggering vasoconstriction and decreases blood flow to the kidneys
- It also stimulates the release of the hormone aldosterone, which increases blood volume and pressure
- The RAAS operates as a feedback circuit

Figure 44.21



Na+ and H2O are reabsorbed.
NORMAL BLOOD PRESSURE AND VOLUME
Aldosterone
Adrenal gland
Arterioles constrict.
Blood pressure or blood volume drops (for example, due to dehydration or blood loss).
Angiotensin II
ACE
Distal tubule
JGA releases renin.
Angiotensin I
Renin
Sensors in JGA detect decrease
Angiotensinogen
Juxtaglomerular apparatus (JGA)
Liver

Coordinated Regulation of Salt and Water Balance

- ADH and RAAS both increase water reabsorption, but only RAAS maintains body fluid osmolarity by stimulating Na^+ reabsorption
- 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
- Its action lowers blood pressure and volume

- ANP, ADH, and the RAAS provide an elaborate set of checks and balances to control blood osmolarity, salt concentration, volume, and pressure
- Thirst plays an essential role in control of water and salt balance
- Researchers are focused on identifying the cellular and molecular pathways that link the neurons involved in thirst with the behavioral responses

Figure 44.UN01

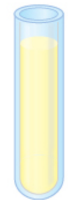
Animal	Inflow/Outflow	Urine
Freshwater fish. Lives in water less concentrated than body fluids; fish tends to gain water, lose salt	Does not drink water Salt in (active transport by gills) H_2O in  Salt out H_2O out	 ▶ Large volume of urine ▶ Urine is less concentrated than body fluids
Marine bony fish. 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