12. Osmoregulation & Excretion

We are slightly salty bags of water in the environment

What do we regulate to maintain volume, function?

- Water Content
- Ions (salts)
  - total concentration (osmolarity/osmolality)
  - specific types: [Na+], [K+], etc.

What are the major different types of environments?

Terrestrial	Not enough water
Marine	Too much salt
Fresh Water	Too little salt

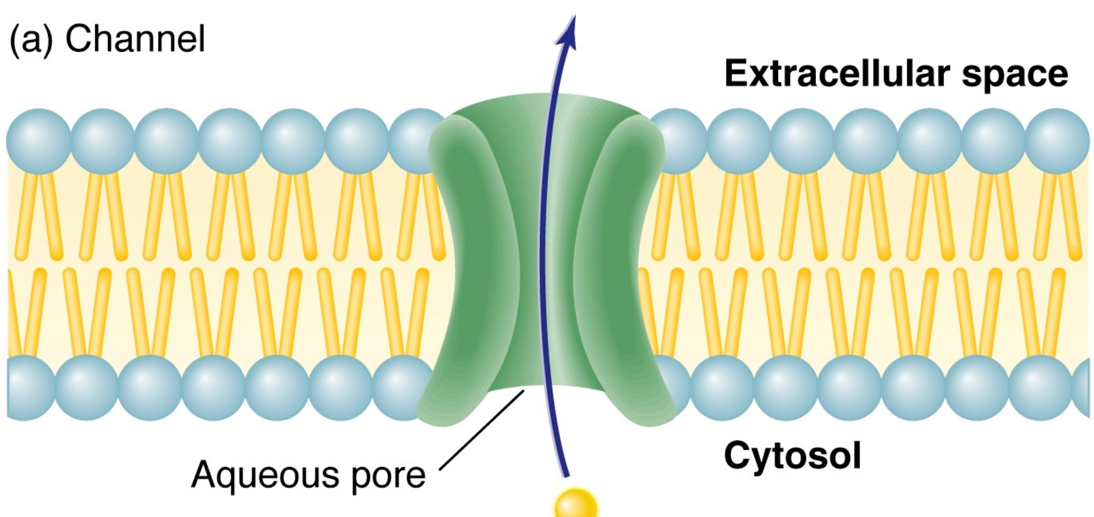
Water flows freely through cell membranes

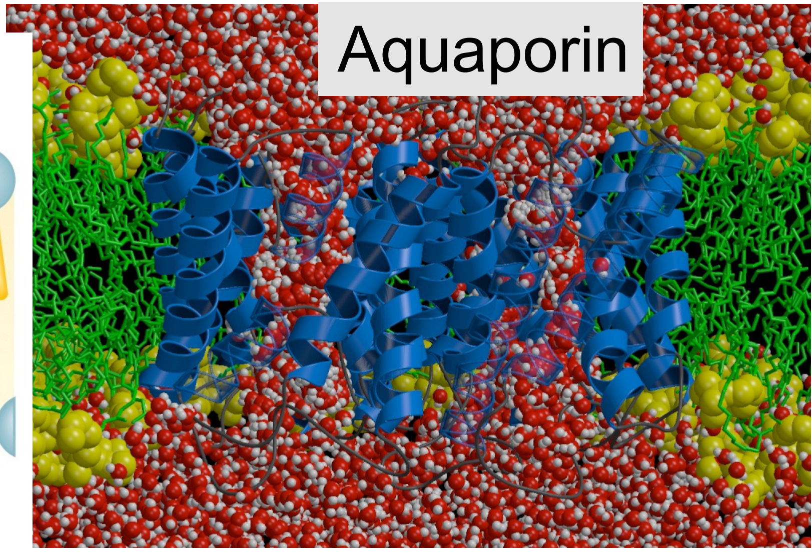
Aquaporin is a channel protein: Big pukas letting H_2O through (image below)

Channels do not require/use any energy equivalents (ATP)

Ions have a harder time getting through membrane (Semi permeable membrane)

In general: Ions “trapped” in cells, water flows through to balance concentration gradient





Body Solids and Fluids

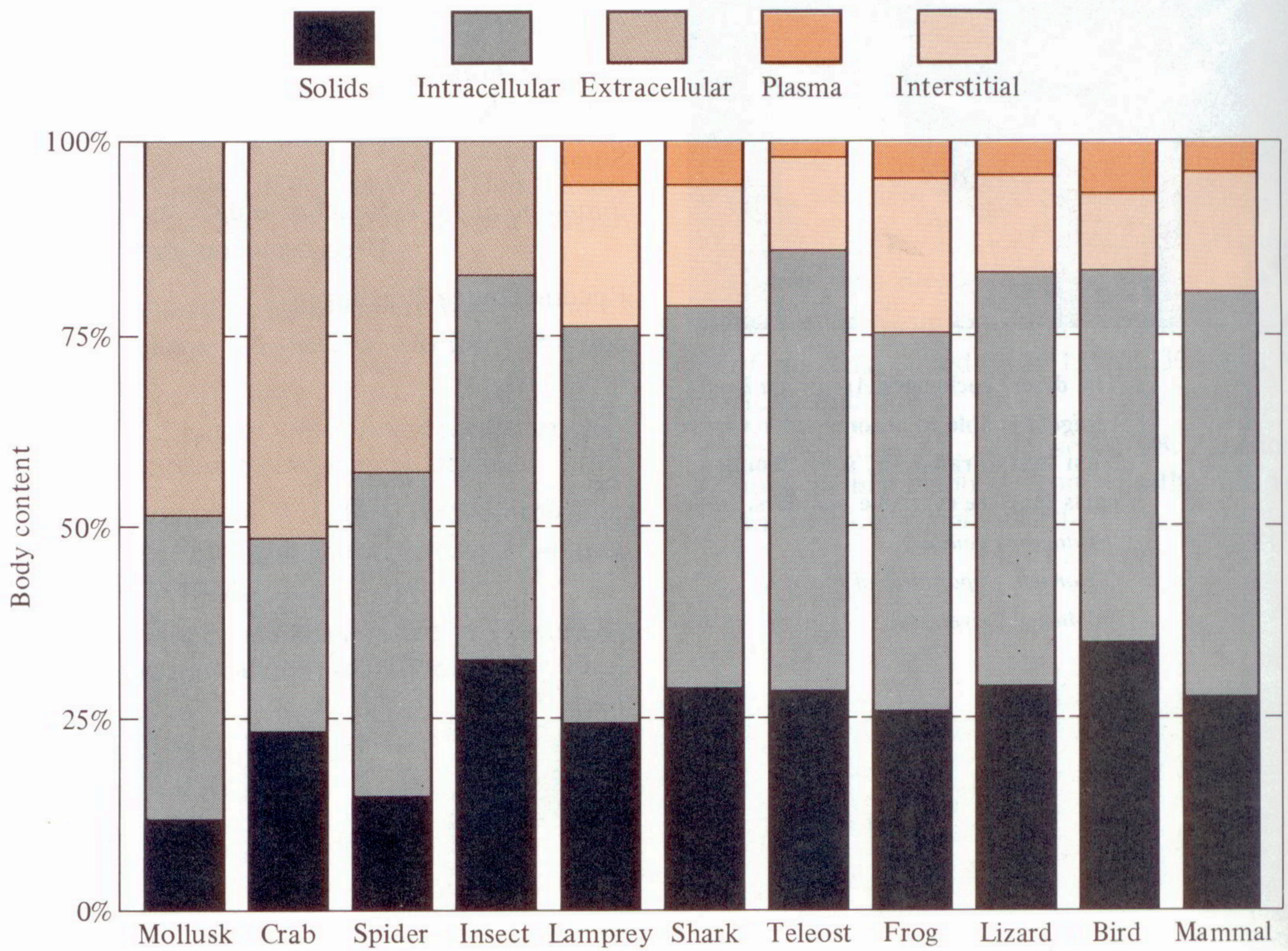
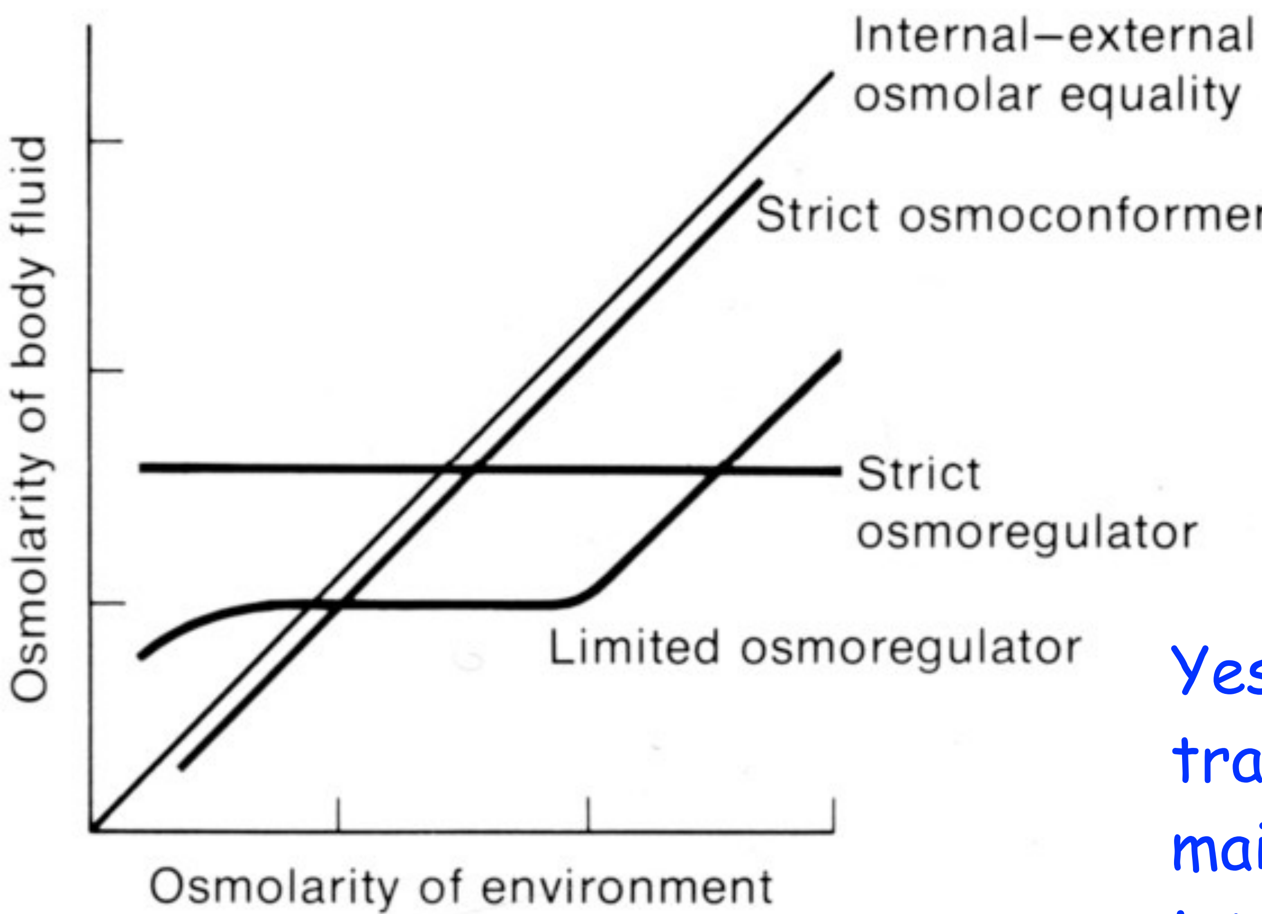


FIGURE 16–1 Distribution of body solids and water in various fluid compartments for a variety of animals.

Osmoregulatory strategies



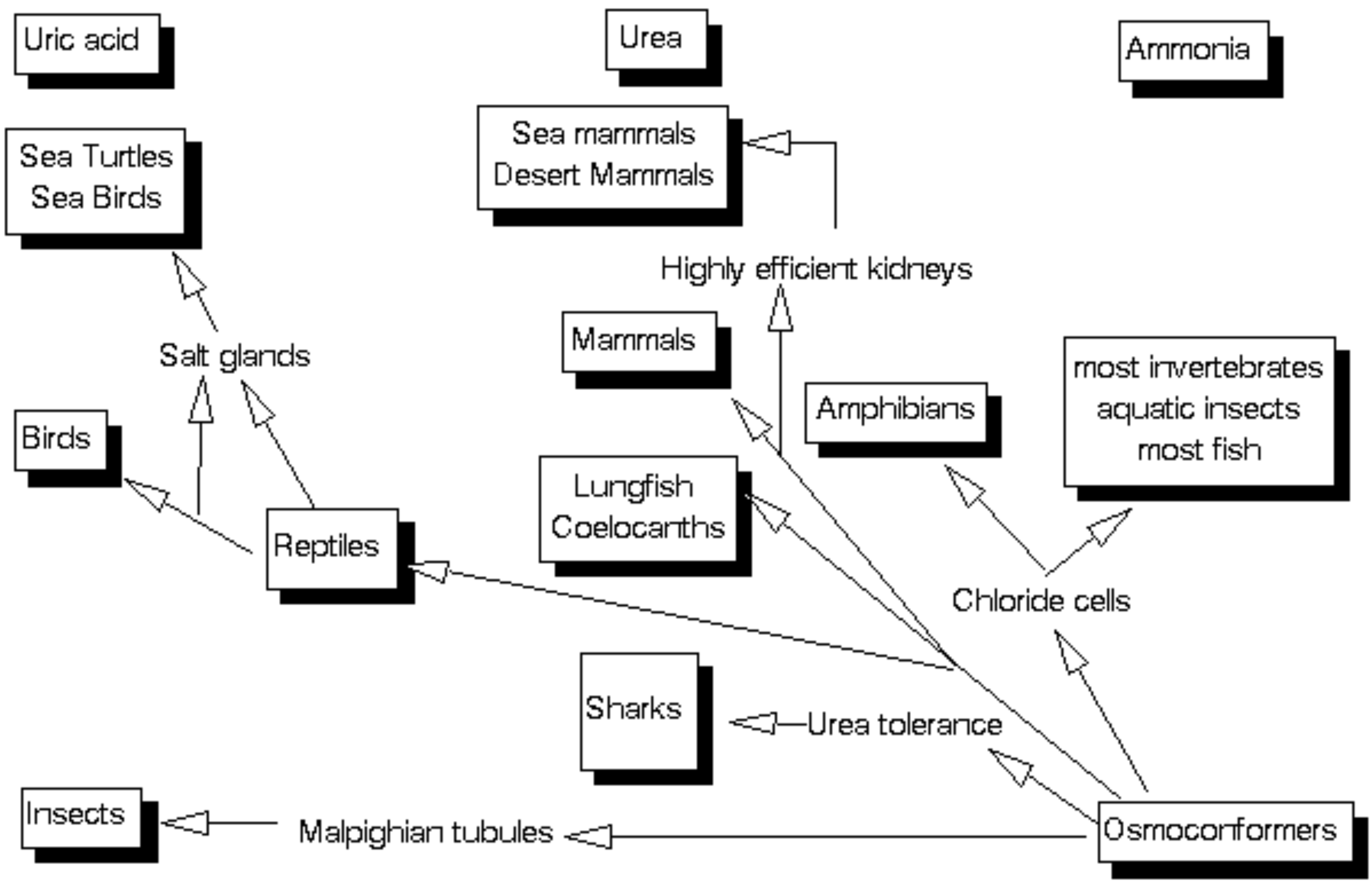
Free ride?

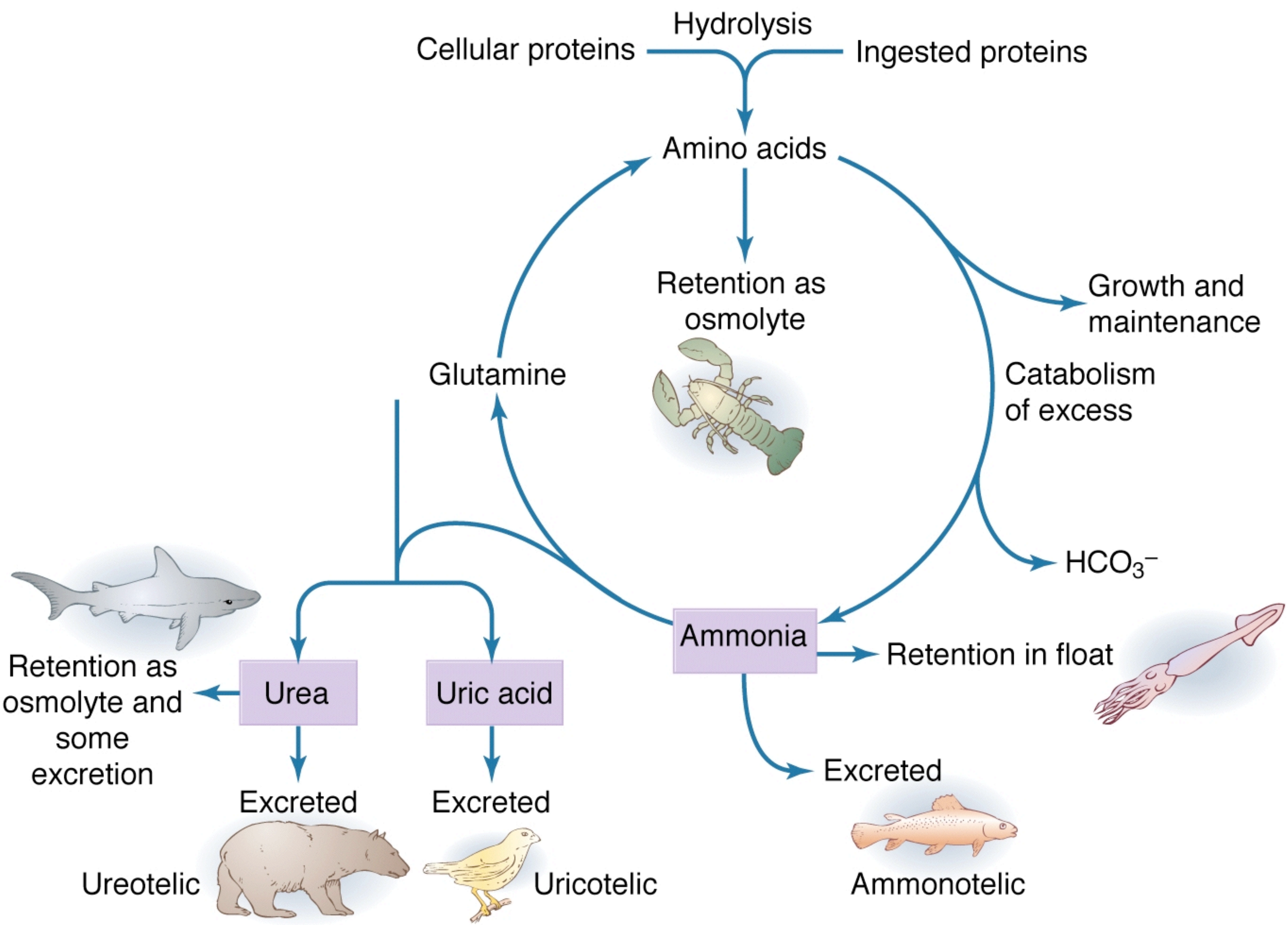
No - must maintain intracellular function - balance.

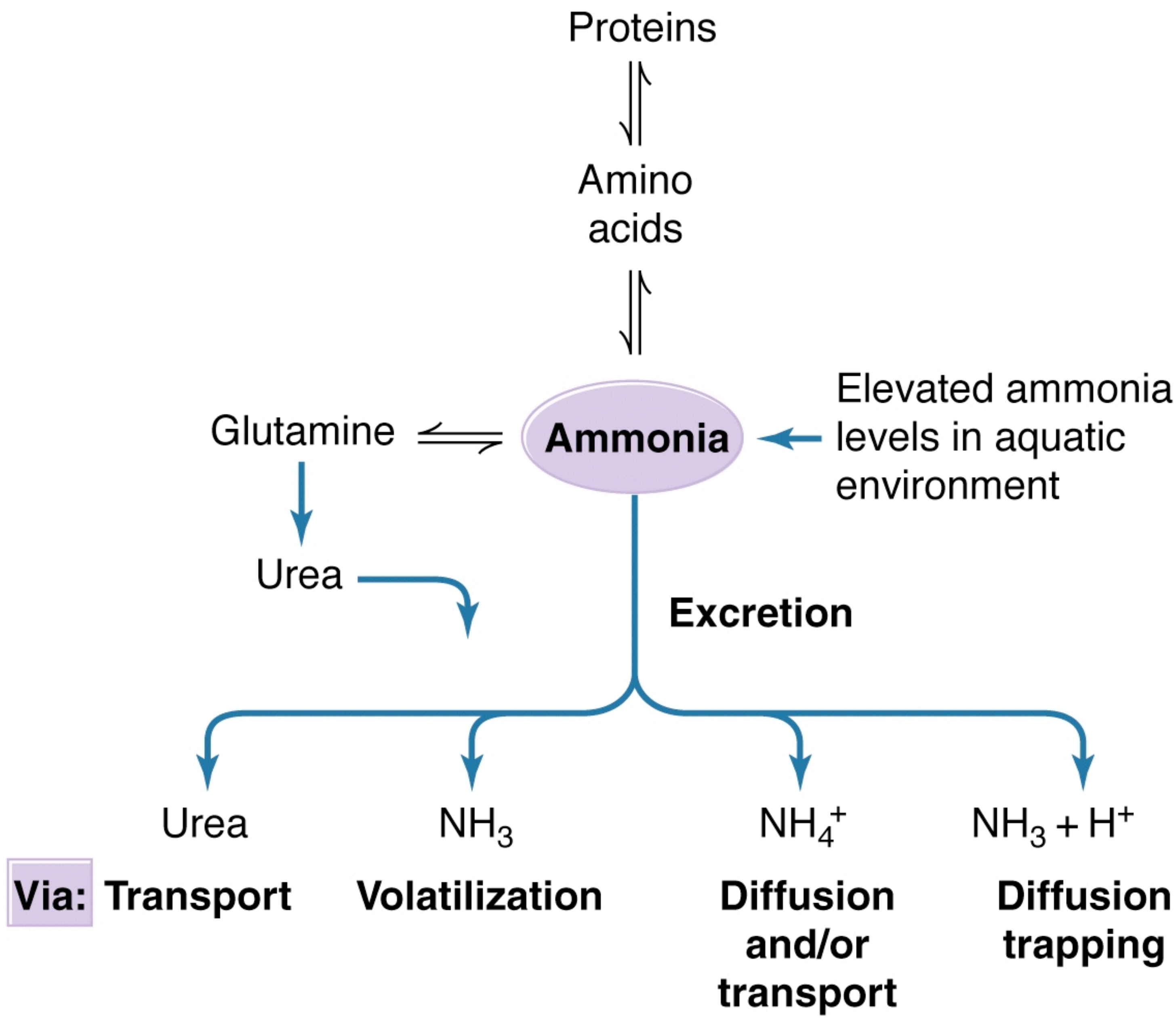
Expensive?

Yes - done by active transport= **ATP!**, but maintains stable internal environment

Evolution of excretory and osmoregulatory strategies




Hydrolysis
Cellular proteins
Ingested proteins
Amino acids
Retention as osmolyte
Growth and maintenance
Glutamine
Catabolism of excess
HCO_3^-
Ammonia
Retention in float
Urea
Uric acid
Retention as osmolyte and some excretion
Excreted
Excreted
Excreted
Ureotelic
Uricotelic
Ammonotelic


Proteins
Amino acids
Glutamine
Ammonia
Elevated ammonia levels in aquatic environment
Urea
Excretion
Urea
NH_3
NH_4^+
$NH_3 + H^+$
Via: Transport
Volatilization
Diffusion and/or transport
Diffusion trapping

Extracellular and Intracellular Ions

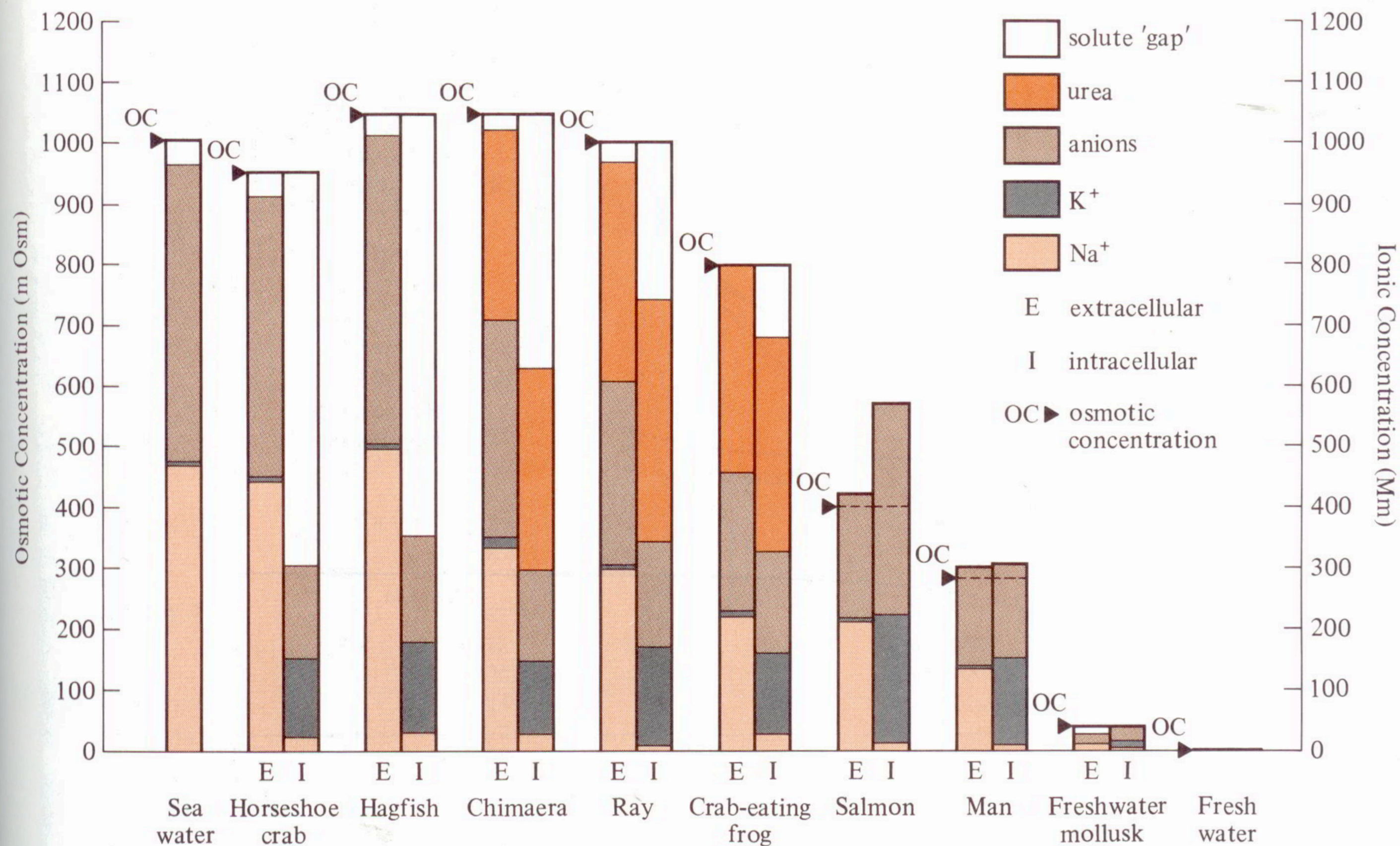


FIGURE 16–3 Extracellular and intracellular ion, urea, and osmotic concentrations of selected invertebrates and vertebrates compared with seawater and freshwater and showing the total osmotic concentration, major cation concentrations (Na^+, K^+), anions accompanying Na^+ and K^+, urea concentration, and the "osmotic gap" that is filled by various other solutes (divalent cations, other anions, amino acids, TMAO, etc.). Abbreviations are as follows: E, extracellular; I, intracellular; and OC, osmotic concentration.

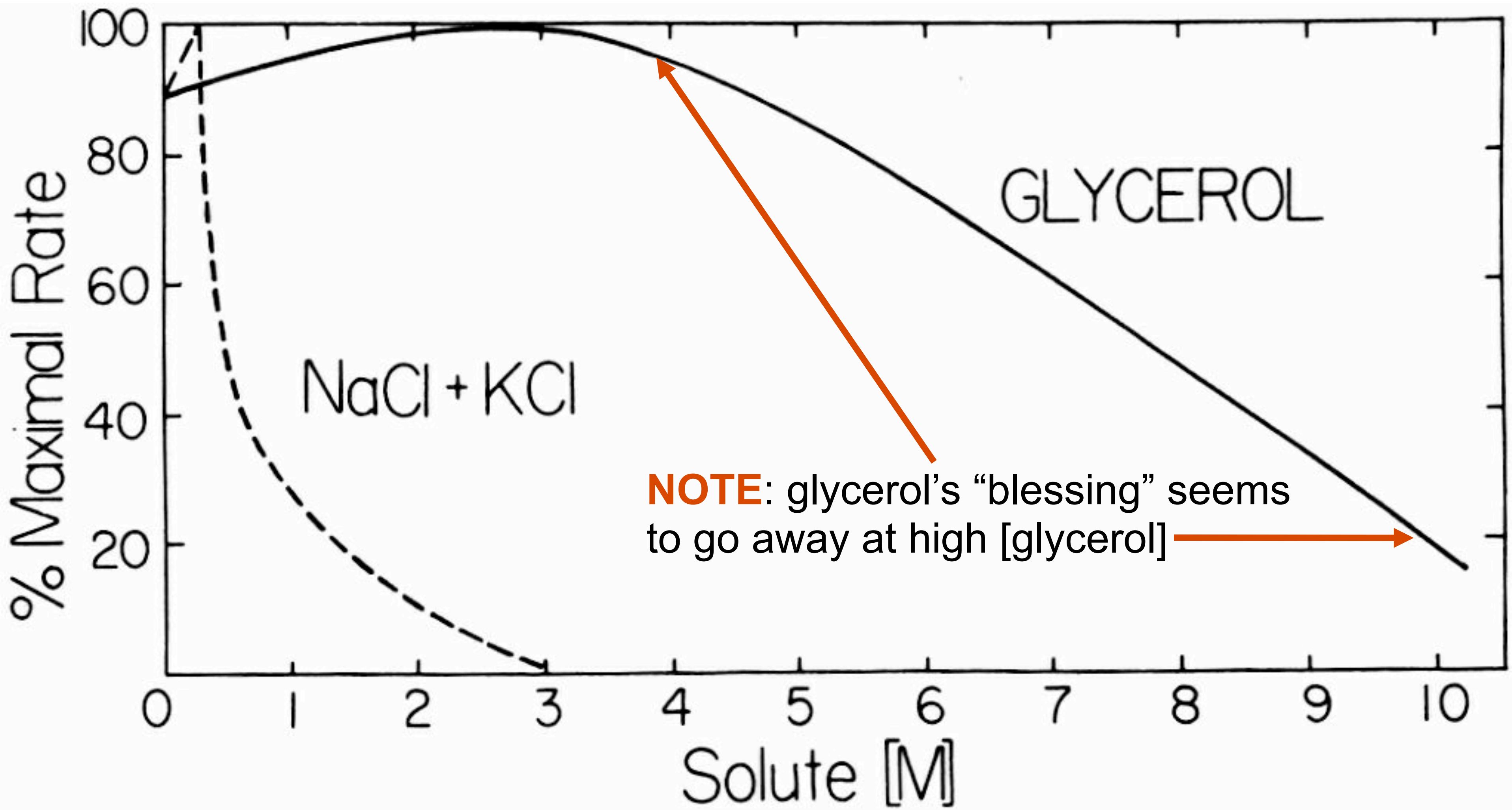
Two basic strategies in design of osmolyte systems:

- "Compatible osmolytes": minimal effect on k_{cat}, K_m and stability (at physiological concentrations).
  - Sugars and polyols, e.g., glycerol
  - Free amino acids
  - Methylammonium & methylsulfonium compounds
- "Counteracting osmolyte systems": opposing influences lead to no *net* effect on k_{cat}, K_m and stability.
  - Urea:TMAO (tri methyl amine oxide)

Solute "compatibility": rate of reaction

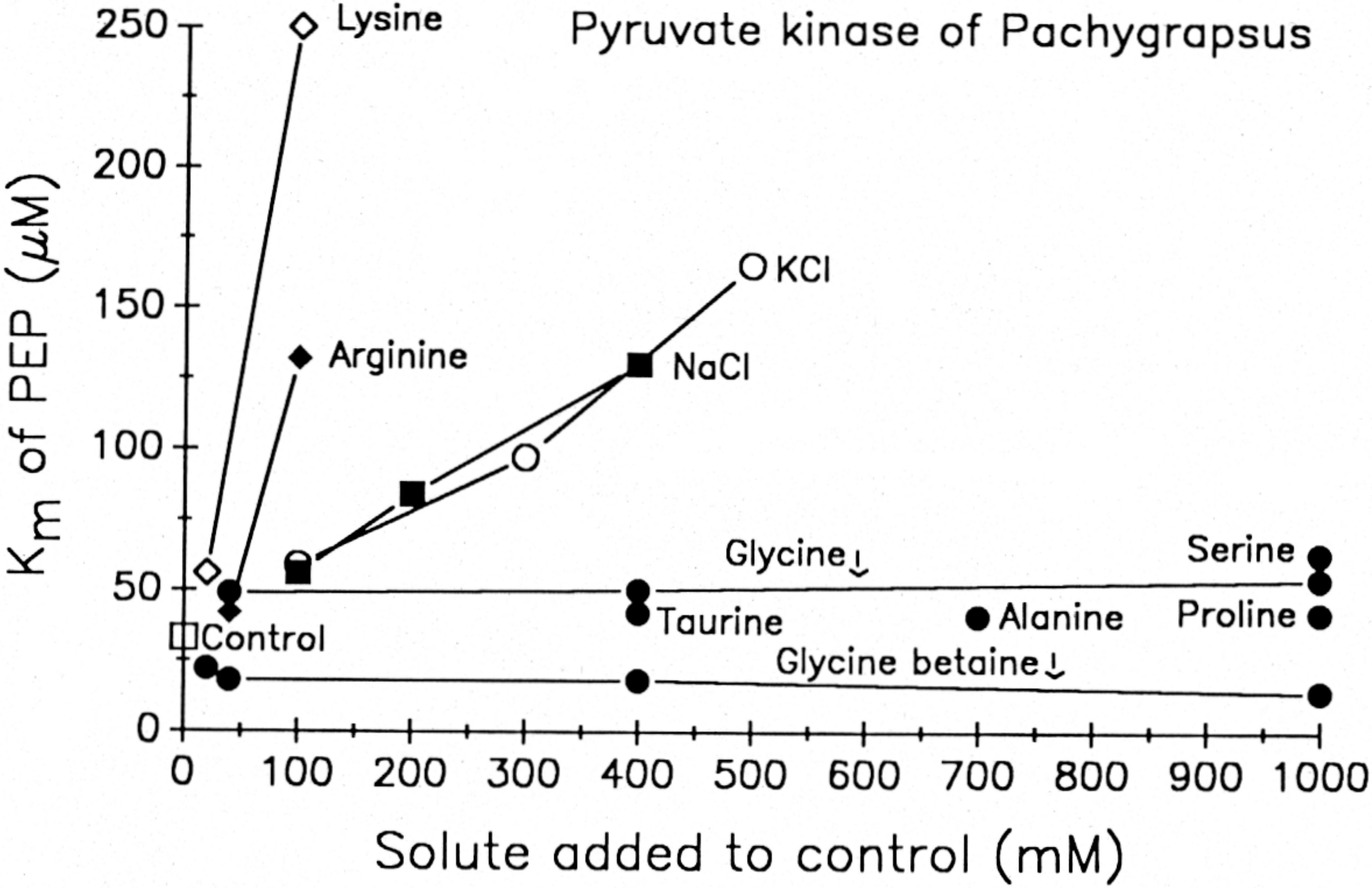
"Glycerol may be regarded as God's gift to solute-stressed eukaryotes"

A.D. Brown (1990)



L. Borowitzka & A. D. Brown (1974) *Arch. Microbiol.* 96:37-52.

Compatible osmolytes: Minimal effects on K_m



Bowlus & Somero (1979) J. Exp. Zool. 208: 137-152

Major intracellular osmolytes of marine animals

Marine Invertebrates

Muscle [solutes] mOsmol l^{-1}

Σosmolality: **1050**

[K+]: **160**
[Cl-]: 80
[Urea]: 0
[TMAO]: 50
[Betaine]: 80
[Free AA]: **420**

Marine Teleosts

Muscle [solutes] mOsmol l^{-1}

Σosmolality: **430**

[K+]: **165**
[Cl-]: 25
[Urea]: ~0
[TMAO]: 10-20
[Betaine]: 10-20

Marine Elasmobranchs

Muscle [solutes] mOsmol l^{-1}

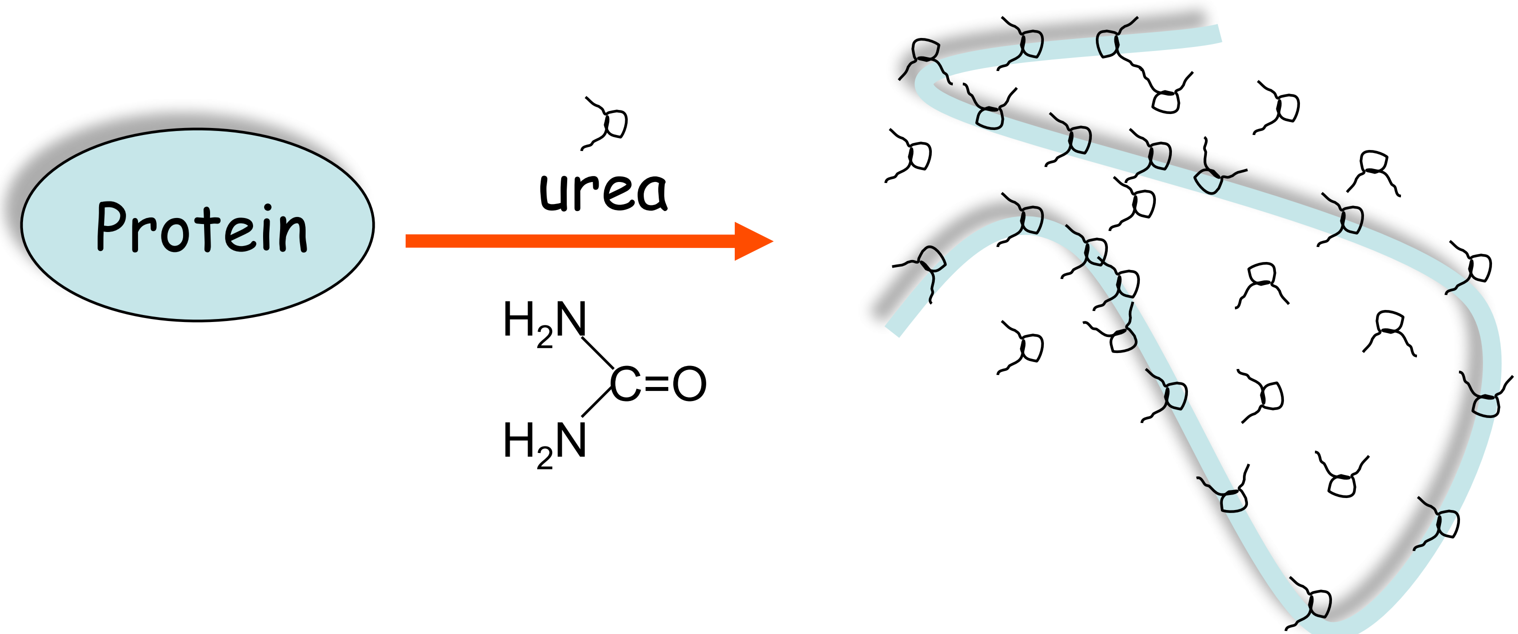
Σosmolality: **1070**

[K+]: **170**
[Cl-]: 30
→ [Urea]: **440**
→ [TMAO]: **210**

Urea

- Common waste product from protein degradation (protein turnover) in organisms that produce concentrated urine
  - Less toxic than ammonia (NH_3^+)
  - However, urea is still toxic at high concentrations
    - Denatures proteins by favoring interactions with amino acids
  - Costly synthesis: 5 ATP/urea

Urea-induced denaturation: Preferential binding of solute → unfolding

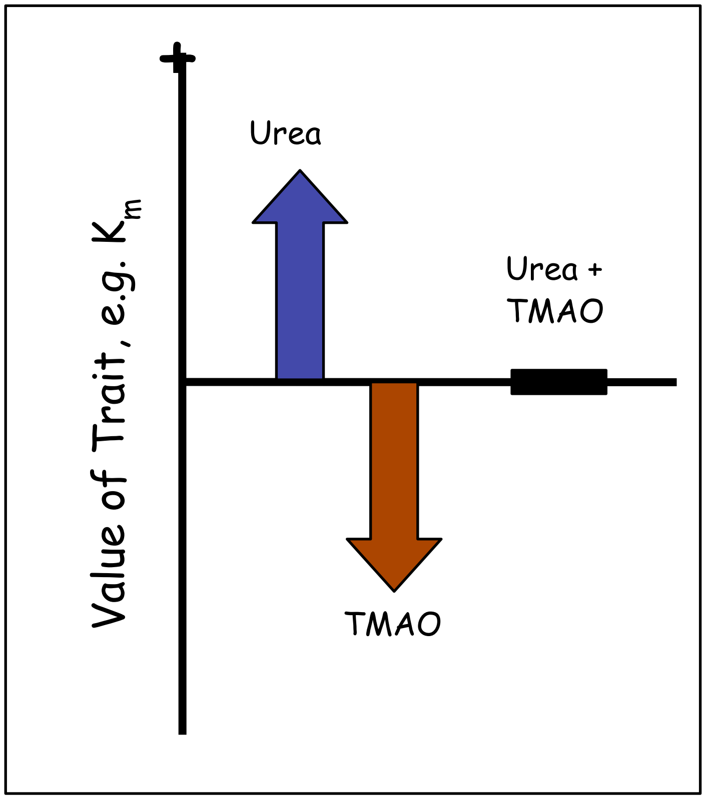


- Urea binds to amino acid residues (exergonic)
- Energetically favorable binding → exposure of maximal number of binding sites → unfolding (denaturation)
- Alters water structure

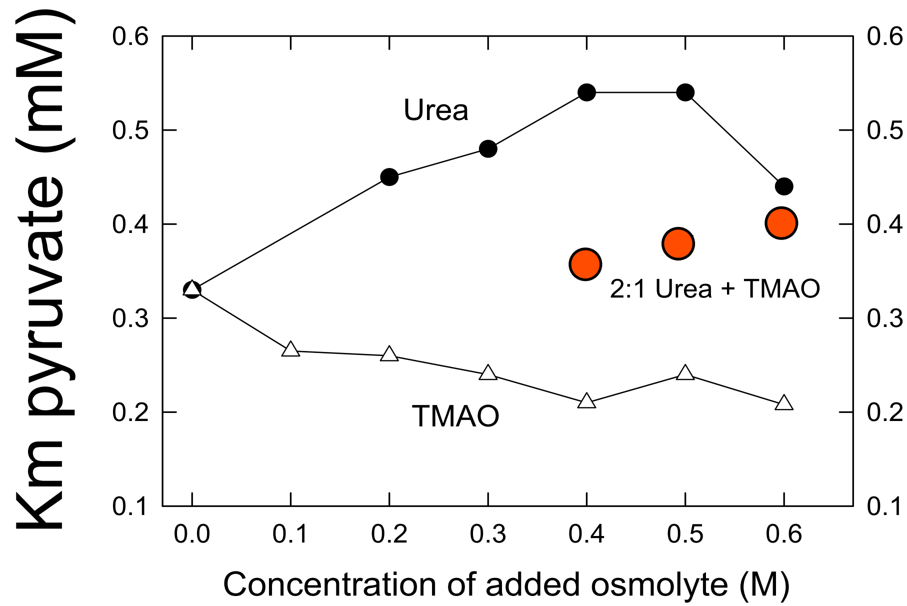
Counteracting osmolytes:

Urea + TMAO: offsetting effects on K_m^{pyr}

(after Baskakov *et al*. 1998. *Biophys. J.* 74: 2666)



"Counteracting Solutes"



Marine Elasmobranchs

Muscle [solutes] mOsmol l^{-1}

Σosmolality: **1070**

[Urea]: **440**

[TMAO]: **210**

Extracellular and Intracellular Ions

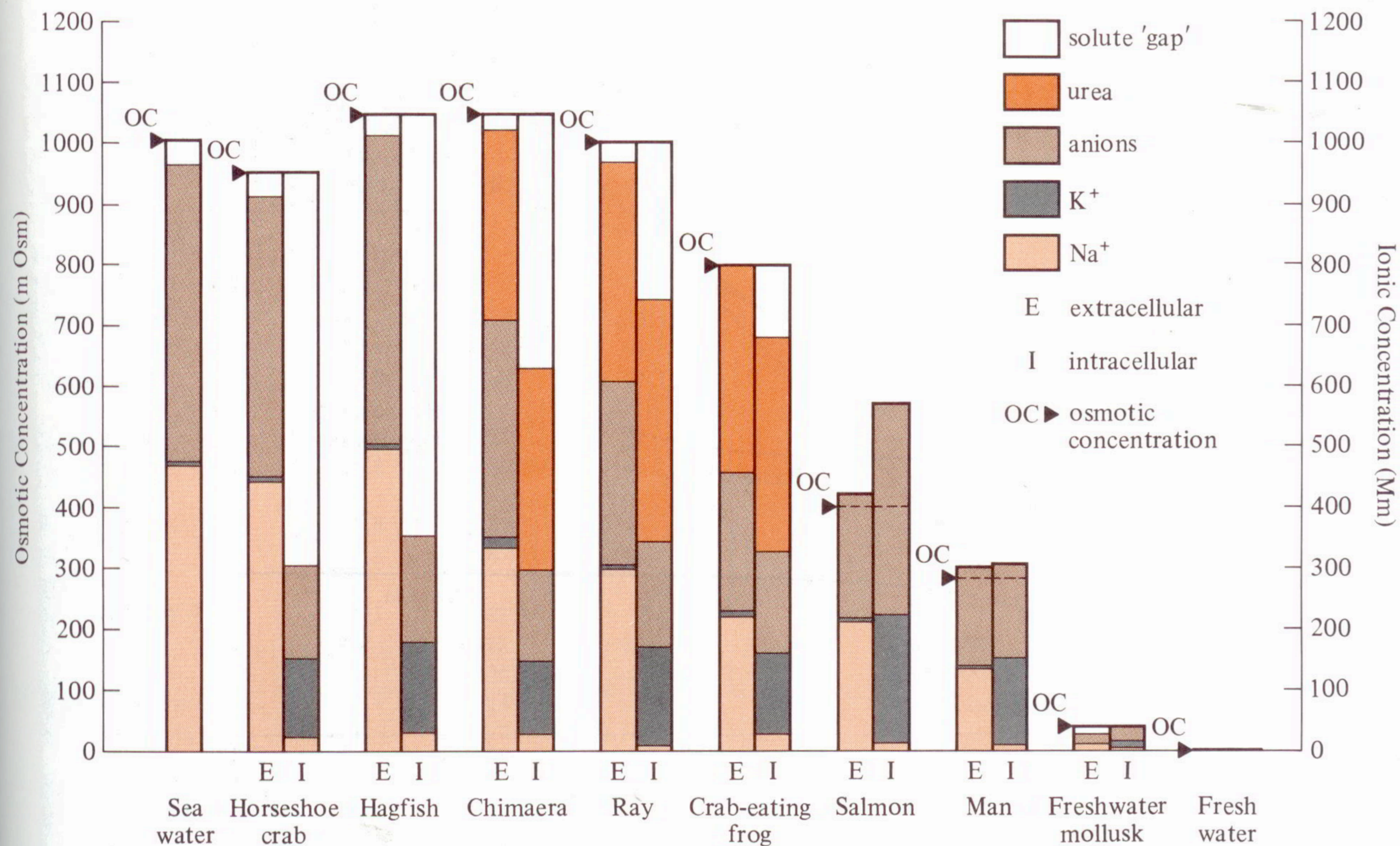


FIGURE 16–3 Extracellular and intracellular ion, urea, and osmotic concentrations of selected invertebrates and vertebrates compared with seawater and freshwater and showing the total osmotic concentration, major cation concentrations (Na^+, K^+), anions accompanying Na^+ and K^+, urea concentration, and the "osmotic gap" that is filled by various other solutes (divalent cations, other anions, amino acids, TMAO, etc.). Abbreviations are as follows: E, extracellular; I, intracellular; and OC, osmotic concentration.

Table 14-1 Composition of extracellular fluids of representative animals*

	Habitat*	Osmolarity (mosM)	Ionic concentrations (mM) Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HPO_4^{2-}	Urea
Seawater†		1000	460	10	10	53	540	27		
Coelenterata	Freshwater	10-50								
Aurelia (jellyfish)	SW		454	10.2	9.7	51.0	554	14.6		
Echinodermata										
Asterias (starfish)	SW		428	9.5	11.7	49.2	487	26.7		
Annelida										
Arenicola (lugworm)	SW		459	10.1	10.0	52.4	537	24.4		
Lumbricus (earthworm)	Ter.		76	4.0	2.9		43			
Mollusca										
Aplysia (sea slug)	SW		492	9.7	13.3	49	543	28.2		
Liligo (squid)	SW		419	20.6	11.3	51.6	522	6.9		
Anodonta (clam)	FW		15.6	0.49	8.4	0.19	11.7	0.73		
Crustacea										
Cambarus (crayfish)	FW		146	3.9	8.1	4.3	139			
Homarus (lobster)	SW		472	10.0	15.6	6.7	470			
Insecta										
Locusta	Ter.		60	12	17	25				
Periplanta (cockroach)	Ter.		161	7.9	4.0	5.6	144			
Cyclostomata										
Eptatretus (hagfish)	SW	1002	554	6.8	8.8	23.4	532	1.7	2.1	3
Lampetra (lamprey)	FW	248	120	3.2	1.9	2.1	96	2.7		0.4

* The osmolarity and composition of seawater vary, and the values given here are not intended to be absolute. The composition of body fluids of osmoconformers will also vary, depending on the composition of the seawater in which they are tested.
† SW = seawater; FW = freshwater; Ter. = terrestrial.
Sources: Schmidt-Nielsen and Mackay, 1972; Prosser, 1973.

Table 14-1 Composition of extracellular fluids of representative animals*

	Habitat*	Osmolarity (mosM)	Ionic concentrations (mM) Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}	Cl^{-}	SO_4^{2-}	HPO_4^{2-}	Urea
Seawater†		1000	460	10	10	53	540	27		
Chondrichthyes										
Dogfish shark	SW	1075	269	4.3	3.2	1.1	258	1	1.1	376
Carcharhinus	FW		200	8	3	2	180	0.5	4.0	132
Coelacantha										
Latimeria	SW		181	51.3	6.9	28.7	199			355
Teleostei										
Paralichthys (flounder)	SW	337	180	4	3	1	160	0.2		
Carassius (goldfish)	FW	293	142	2	6	3	107			
Amphibia										
Rana esculenta (frog)	FW	210	92	3	2.3	1.6	70			2
Rana cancrivora	FW	290	125	9			98			40
	80% SW	830	252	14			227			350
Reptilia										
Alligator	FW	278	140	3.6	5.1	3.0	111			
Aves										
Anas (duck)	FW	294	138	3.1	2.4		103		1.6	
Mammalia										
Homo sapiens	Ter.	260	142	4.0	5.0	2.0	104	1	2	
Lab rat	Ter.		145	6.2	3.1	1.6	116			

* The osmolarity and composition of seawater vary, and the values given here are not intended to be absolute. The composition of body fluids of osmoconformers will also vary, depending on the composition of the seawater in which they are tested.
† SW = seawater; FW = freshwater; Ter. = terrestrial.
Sources: Schmidt-Nielsen and Mackay, 1972; Prosser, 1973.

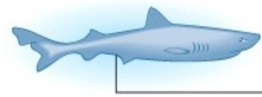
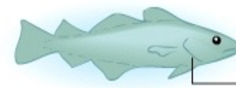
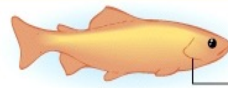
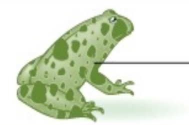
Intracellular Ions

Intracellular solutes - K^+ and organic solutes

Table 14-2 Electrolyte composition of the human body fluids

Electrolytes	Serum ($meq \cdot kg^{-1}\ H_2O$)	Interstitial fluid ($meq \cdot kg^{-1}\ H_2O$)	Intracellular fluid (muscle) ($meq \cdot kg^{-1}\ H_2O$)
Cations			
Na^+	142	145	10
K^+	4	4	156
Ca^{2+}	5		3
Mg^{2+}	2		26
Totals	153	149	195
Anions			
Cl^-	104	114	2
HCO_3^-	27	31	8
HPO_4^{2-}	2		95
SO_4^{2-}	1		20
Organic acids	6		
Proteins	13		55
Totals	153	145	180

Note: Some of the ions contained within cells are not completely dissolved within the cytosol, but may be partially sequestered within cytoplasmic organelles. Thus, the true free Ca^{2+} concentration in the cytosol is typically below the overall value given in the table for intracellular Ca^{2+}. Failure of anion and cation totals to agree reflects incomplete tabulation.

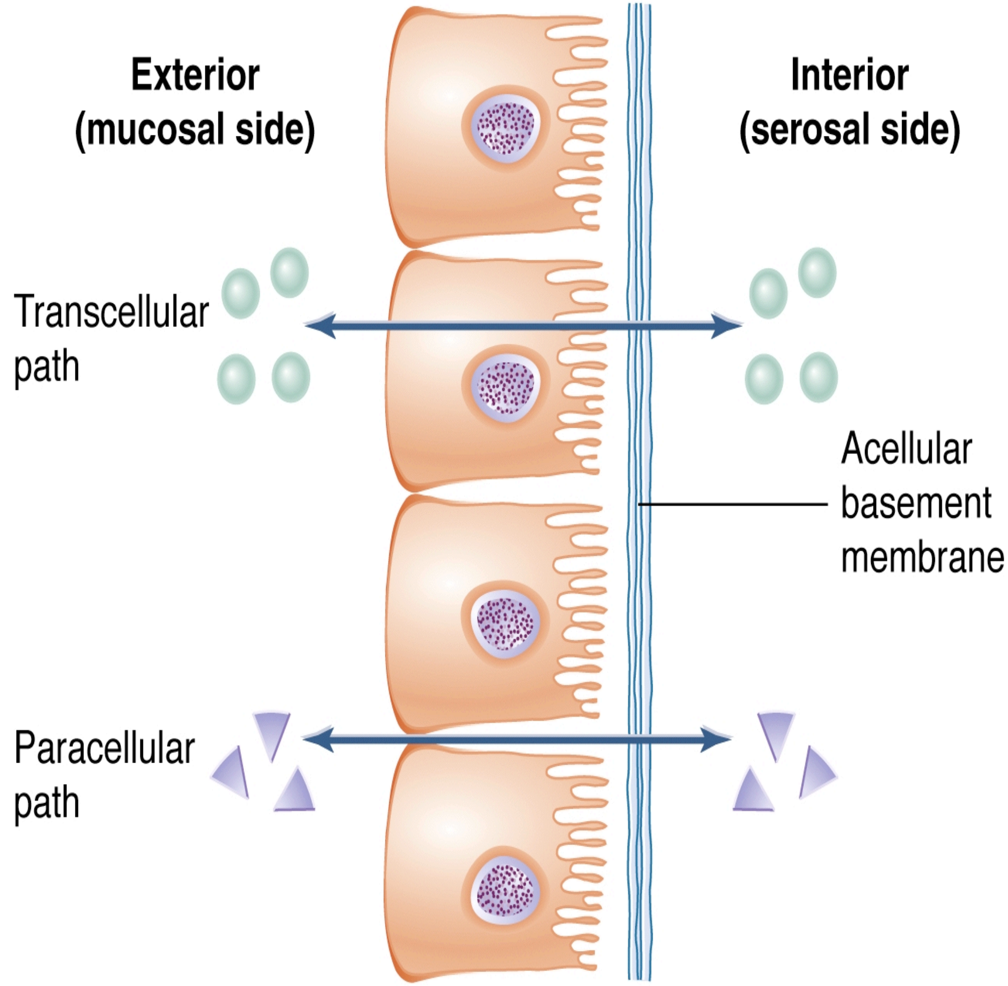
Type of animal	Blood concentration relative to environment	Urine concentration relative to blood	Osmoregulatory mechanisms
Marine elasmobranch	Slightly hyperosmotic	Iso-osmotic	 Does not drink seawater Hyperosmotic NaCl from rectal gland
Marine teleost	Hypo-osmotic	Iso-osmotic	 Drinks seawater Secretes salt from gills
Freshwater teleost	Hyperosmotic	Hypo-osmotic	 Drinks no water Absorbs salt with gills
Amphibian	Hyperosmotic	Hypo-osmotic	 Absorbs salt through skin
Marine reptile	Hypo-osmotic	Iso-osmotic	 Drinks seawater Hyperosmotic salt-gland secretion
Desert mammal	–	Hyperosmotic	 Drinks no water Depends on metabolic water
Marine mammal	Hypo-osmotic	Hyperosmotic	 Does not drink seawater
Marine bird	–	Hyperosmotic	 Drinks seawater Hyperosmotic salt-gland secretion
Terrestrial bird	–	Hyperosmotic	 Drinks freshwater

Too little water, has to drink salty water

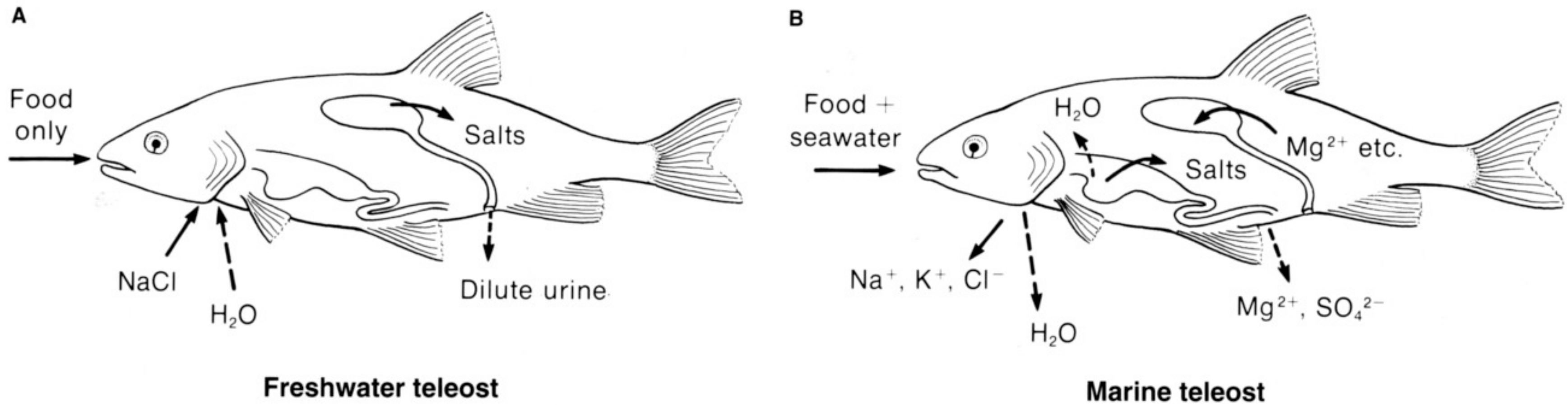
Too much water, has to absorb salt

Sites of Water exchange : Where?

- Gills
- Lungs REWL
- Skin CEWL
- Gut
- Kidneys



Environmental gradients are critical!



Water and Ion Budgets

Water Gain: drinking, eating performed water, **metabolic water**, osmotic absorption, water vapor absorption

Water Loss: urine and feces, osmotic loss across the gills and skin, **evaporation**

Ion Gain: food and water, cutaneous uptake, gill uptake

Ion Loss: urine and feces, diffusion across body surface, saliva, sweat, salt glands

Eating & Drinking: Easy! Direct Gain

Metabolic Water

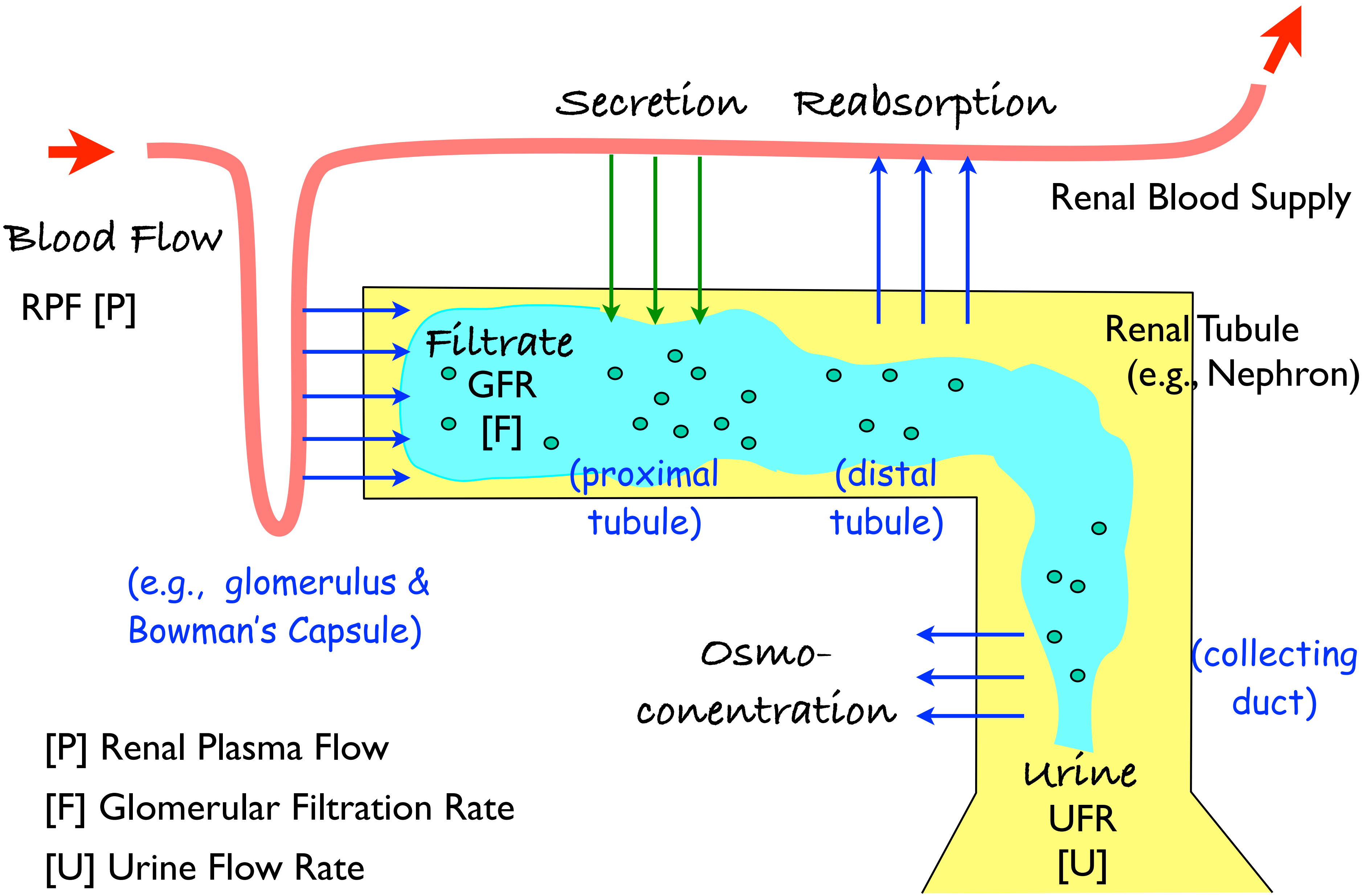
Osmosis, Ion Diffusion

Active Transport

Excretion

Cutaneous/Respiratory Exchange

Tubular Excretion



[P] Renal Plasma Flow

[F] Glomerular Filtration Rate

[U] Urine Flow Rate

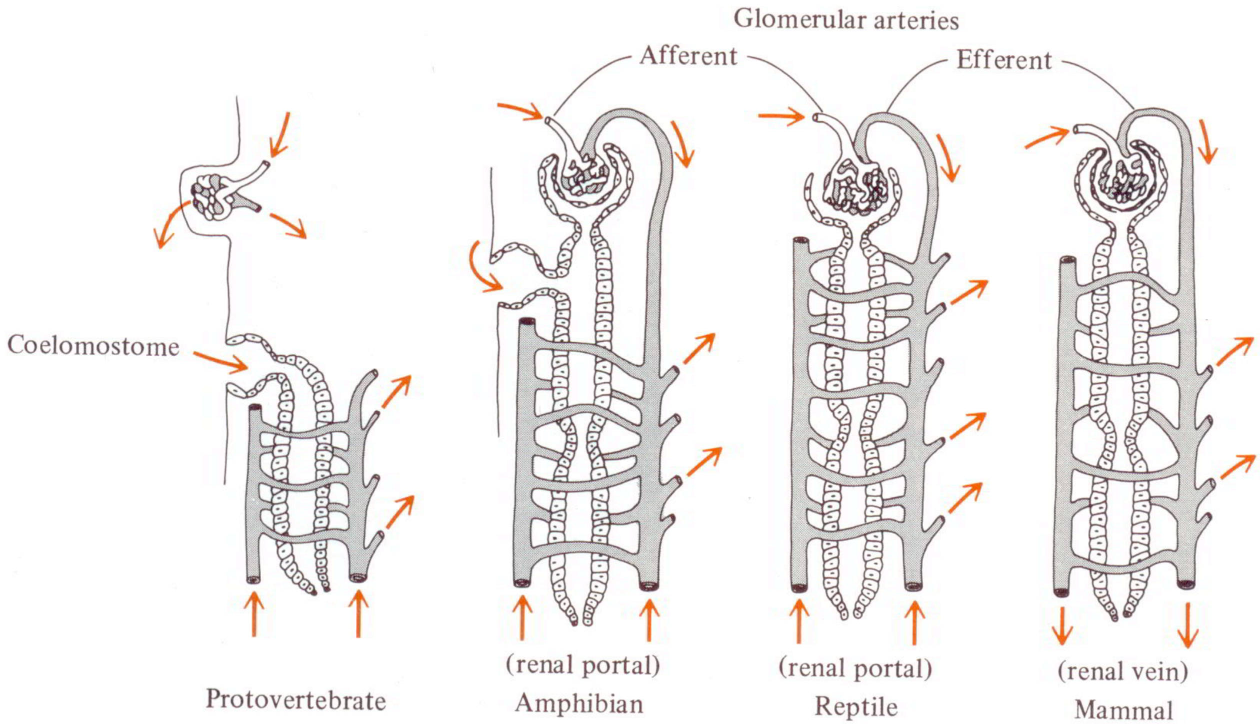


FIGURE 17–21 Highly schematic scenario for the evolution of the vertebrate nephron from a coelomoduct. In protovertebrates, fluid is secreted into the coelom by a capillary network distant from the coelomostome opening; the renal tubule has a separate capillary supply. In vertebrates such as amphibians, there is a glomerular capillary network associated with the renal tubule and the coelomostome persists; the glomerular network also supplies blood to the renal tubule in association with a separate renal portal supply. In reptiles, birds, and mammals, the renal tubule lacks a coelomostome; in mammals, there is only a glomerular blood supply to the renal tubule (i.e., no renal portal system). *(Modified from Smith 1959.)*

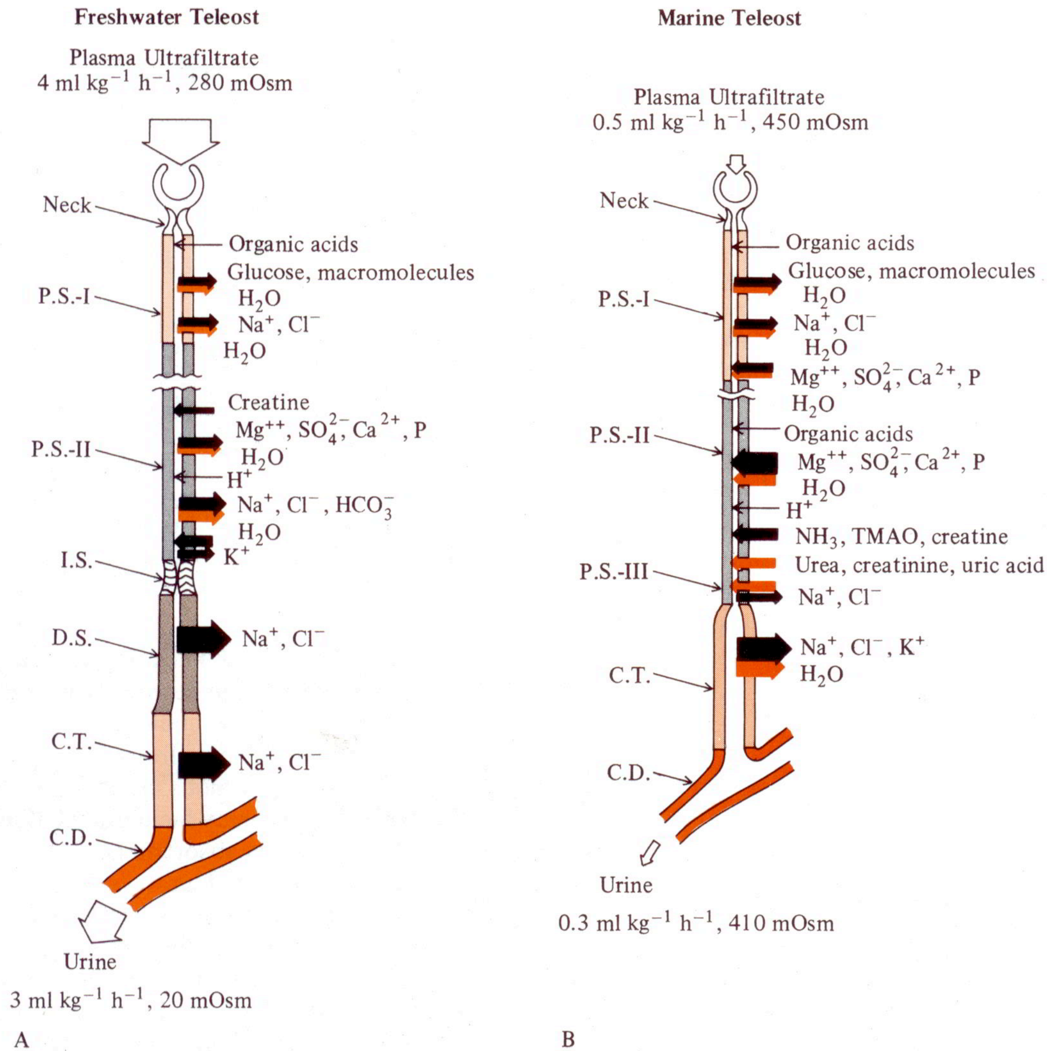


FIGURE 17–23 Representation of the structure and function of the nephron in freshwater teleosts (**A**) and marine teleosts (**B**). Indicated are the major morphological segments of the

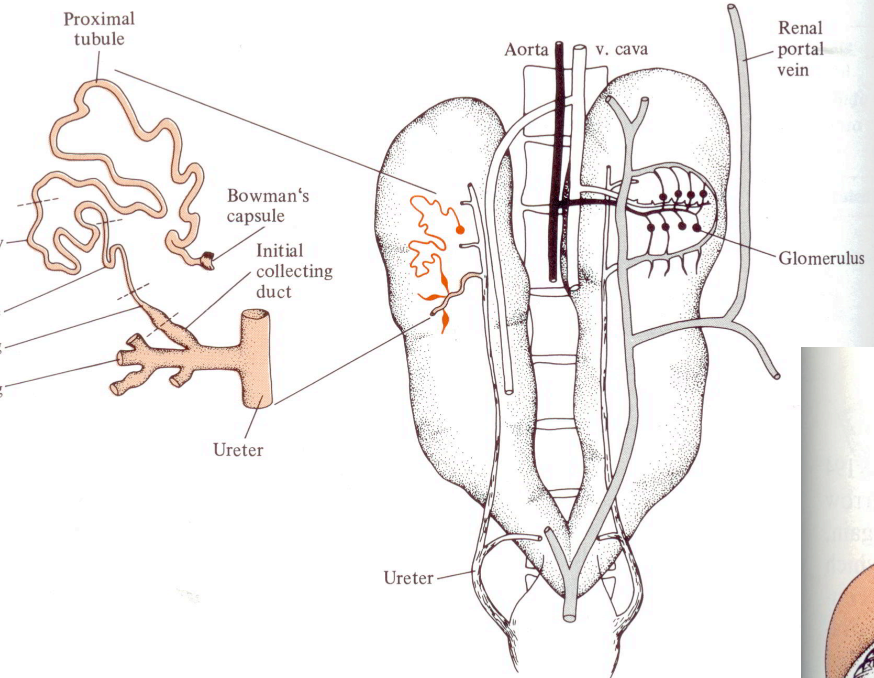


FIGURE 17–25 General structure of the kidney of a lizard showing (on the left) the ureter with one collecting duct, associated collecting tubules, and one complete nephron and (on the right) the renal and renal portal blood supply to the glomeruli and peritubular capillary bed. The detailed structure of a typical nephron is also shown. *(From Davis, Schmidt-Nielsen, and Stolte 1976.)*

Water and

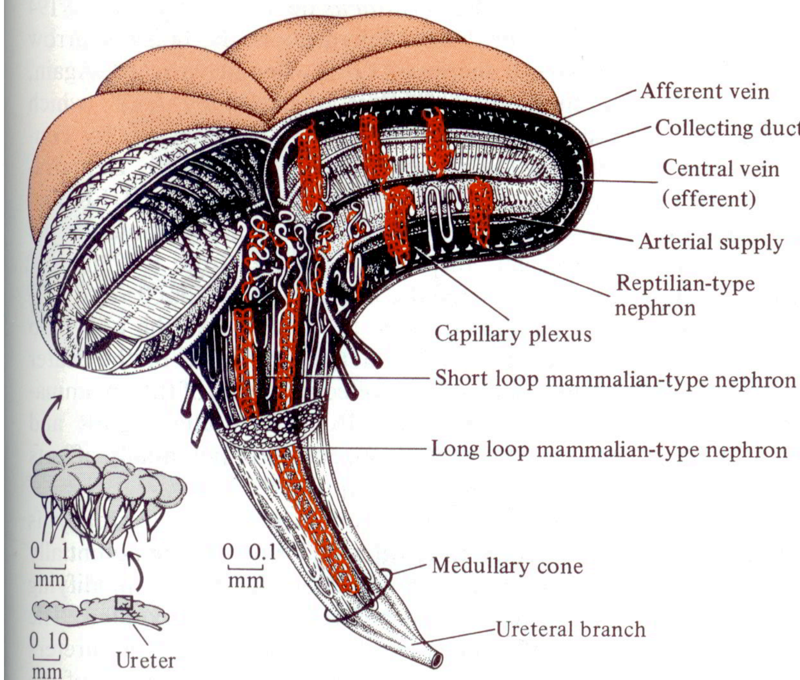


FIGURE 17–
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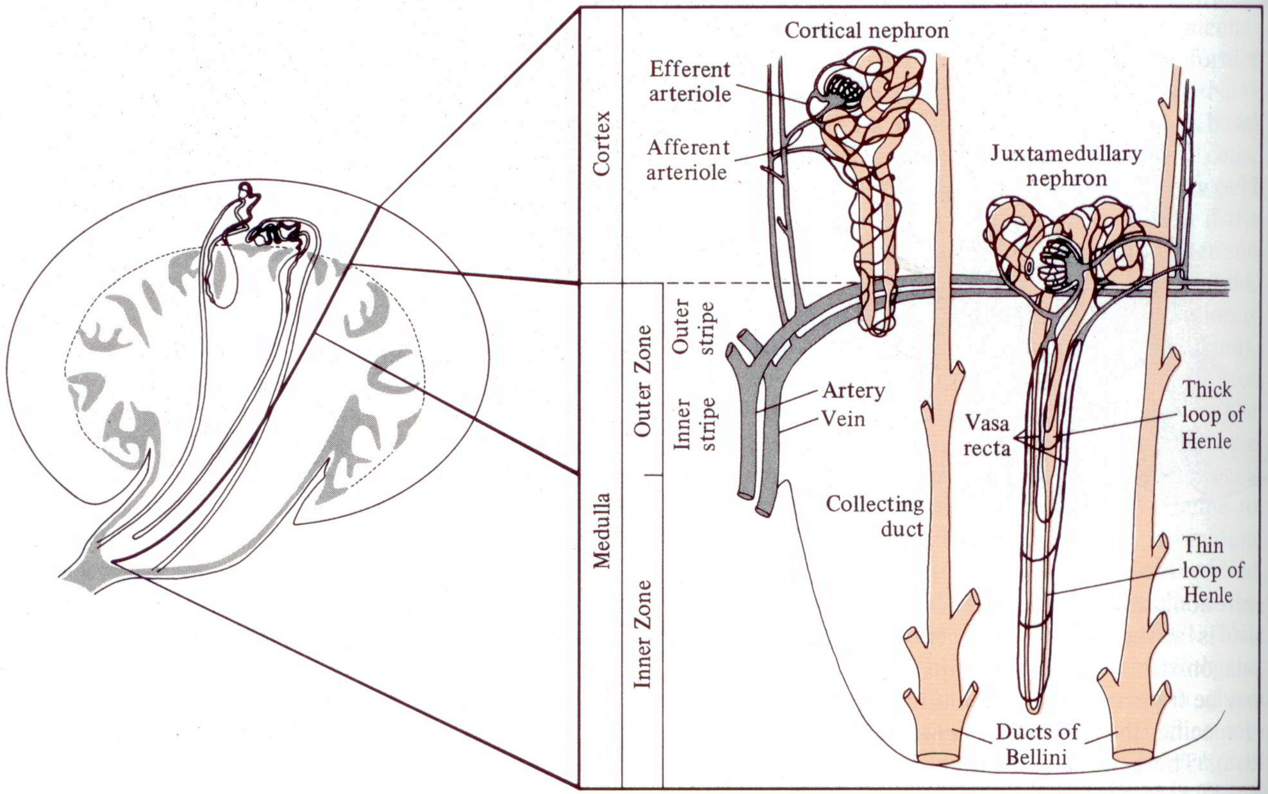

FIGURE 17–31 Schematic cross section (left) of the stucture of a rodent kidney and the detailed anatomical arrangement of the cortical and juxtamedullary nephrons (right). *(Modified from Kaibbling et al. 1975; Pitts 1974.)*

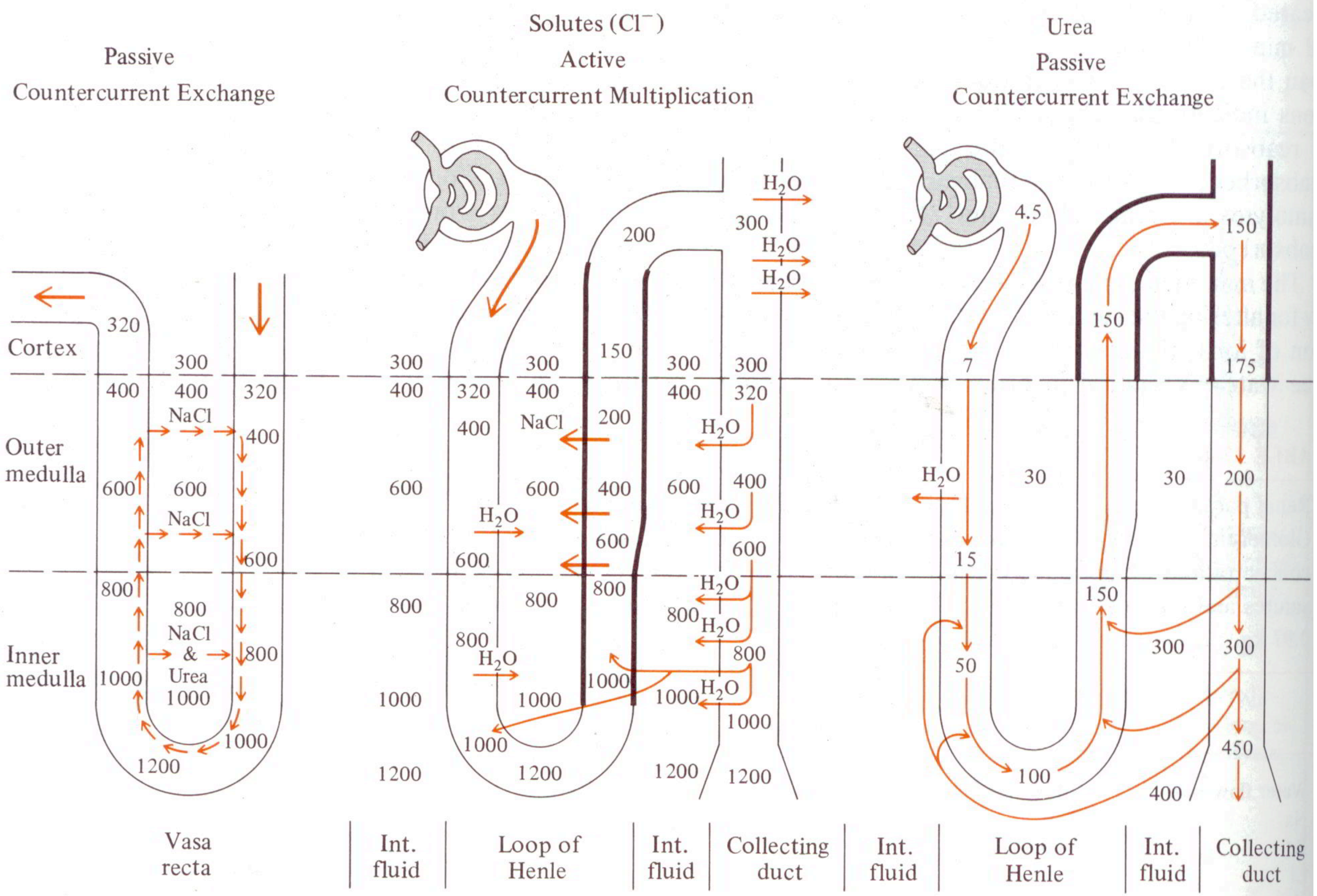

FIGURE 17–32 Mechanism for osmotic concentration of urine by countercurrent multiplication of solute concentration in the loop of Henle and adjacent interstitial fluid (int fluid) by active transport of Cl^- (center). A passive countercurrent exchange of urea contributes to the interstitial osmotic gradient (right). There is a passive countercurrent exchange of solute and urea in the peritubular blood supply (vasa recta) to limit potential dissipation of the interstitial osmotic gradient by peritubular blood flow.