I. RESPIRATION: GAS EXCHANGE
- Supplies oxygen for cellular respiration (metabolism) and 
disposes of waste (CO₂)
- gas travels through resp surface via diffusion
- vertebrates are large, so must have a complex 
system of respiration
-Aquatic animals: Gills
-Terrestrial animals: Lungs

A. Gills – fish and amphibians
- outfolding of body surface exposed to water
- low oxygen levels in water, so fish must expend energy to 
get enough oxygen (to have water pass through gills)
- Answer? Ventilation: in fish water is “swallowed” and 
passes through gills
- gas exchange is facilitated by:
  1. counter-current flow
  2. diffusion gradient

A. Lungs – Terrestrial Vertebrates
- Gills are efficient in water: 
  large surface area, with thin filaments
- On land, gills will collapse and will lose water quickly
So, terrestrial organisms had to evolve respiratory surfaces within the body cavity to reduce water loss
1. Amphibians: relatively small lungs that do not provide a large surface (many lack lungs altogether) – rely on diffusion across other body surfaces, especially their moist skin, for gas exchange.
2. Reptiles, Mammals and Birds: rely entirely on lungs for gas exchange.
3. Some turtles: supplement lung breathing with gas exchange across moist epithelial surfaces in their mouth and anus.
4. Some fish (“lung fish”) have lungs for adaptations to living on oxygen-poor water or to spending time exposed to air.
I. RESPIRATION: GAS EXCHANGE

A. Lungs – An Overview
- evolved from swim bladders
- ventilation through breathing
- passive diffusion of oxygen and CO₂

ADAPTATION

A. Lungs – The Diaphragm

increases ventilation

ADAPTATION

A. Lungs – Actual Gas Exchange

Hb + O₂ = HbO₂

Size and complexity of lungs is related to metabolic rate.
e.g., Birds: Air sacs
help in efficient respiration
I. RESPIRATION: GAS EXCHANGE
A. Lungs

Size and complexity of lungs is related to metabolic rate.

e.g., Birds

Air sacs – how they work

What about deep-seas divers!
(some elephant seals can dive for 1500 m and stay for 2 hours!)

e.g., Deep-diving air breathers: Weddel Seal

Routinely plunges 200-500 m for 20 – 60 min

How:

1. storage of oxygen: in blood and muscle (compared to humans – 2 times as much)
2. twice the volume of blood (compared to humans)
3. most oxygen in blood (70%) vs lungs (5%)
   in humans: blood (51%) and lungs (36%)
II. CARDIOVASCULAR SYSTEM

- Blood with oxygen or CO₂ circulated throughout body for cellular respiration
- Heart pumps oxygen rich and oxygen poor blood systemically (throughout body) and pulmonary (to and fro the lungs)
- Other functions:
  1. Circulate oxygen and remove CO₂
  2. Deliver fuel: glucose and fatty acids
  3. Remove waste (bring to renal system)
  4. Cooling
  5. Immune response
  6. Hormone transport

Heart comparison: Aquatic vertebrates

- Fish:
  - STORAGE OF OXYGEN: IN BLOOD AND MUSCLE (COMPARED TO HUMANS – 2 TIMES AS MUCH)
  - TWICE THE VOLUME OF BLOOD (COMPARED TO HUMANS)
  - MOST OXYGEN IN BLOOD (70%) VS LUNGS (5%)
  - LARGE SPLEEN WHICH CAN STORE 24 L OF BLOOD – WHEN NEEDED RELEASES BLOOD, STORES WHEN NOT
  - HIGH CONCENTRATION OF MYOGLOBIN IN MUSCLES. THIS STORES OXYGEN (SO CAN STORE 25% OF OXYGEN IN MUSCLE VS. 13% IN HUMANS)
  - REDUCE METABOLIC RATE WHEN DIVING (OXYGEN CONSUMPTION)
III. DIGESTION
- Food has to be broken down for energy
- Structural adaptations of digestive systems are often associated with diet
A. Food acquisition and first break-down

Teeth in mammals, some reptiles & amphibians

A. Food acquisition – beak
- vary according to diet

Teeth in mammals, some reptiles & amphibians

A. Food acquisition – Snakes
- specialized fangs (Viperidae) that deliver venom which kills prey, as well as starts digestion
- other venomous snakes, teeth are less derived but can deliver venom
- some lizards (gila monster) deliver neurotoxin; others have bacteria that takes down prey (komodo dragon)
ADAPTATION

III. DIGESTION

A. Food acquisition – Snakes
- quadrate bone and unfused mandibles allow for swallowing of extremely large prey

B. Stomach and intestine
1. Stomach – strong muscle walls “mash” food; walls also secrete acid for digestion
2. Small intestine – more chemicals break down food; broken down “food” absorbed through walls and circulated throughout body
3. Large intestine – other important minerals and water reabsorbed through walls; waste material collected and formed
4. Rectum – stores feces (waste), which leaves through anus

B. Comparison
- length of digestive system related to diet
- Because plant cells contain hard cell walls, it takes longer for plant matter to digest than meat.
- In general, herbivores and omnivores have longer digestive system than carnivores

C. Symbiotic Relationship to break down cellulose
- vertebrates cannot break down cellulose, but certain bacteria can
- symbiotic relationship in gut (cecum)

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ADAPTATION

III. DIGESTION

C. Symbiotic Relationship to break down cellulose

1. Cow chews and swallows plant matter; bolus is formed and enter the rumen and reticulum.
2. Symbiotic bacteria and protists digest this cellulose-rich meal, secreting fatty acids.
3. Periodically, the cow regurgitates and rechews the cud, which further breaks down the cellulose fibers.
4. The cow then reswallows the cud, which moves to the omasum, where water is removed.

ADAPTATION

IV. WATER BALANCE

- MUST BALANCE THE CHEMICAL COMPOSITION OF BODY FLUIDS: DEPENDS ON UPTAKE AND LOSS OF WATER AND SOLUTES (LIKE SALT) - OSMOREGULATION
- WHEN MACROMOLECULES ARE BROKEN DOWN FOR ENERGY, ONE BY-PRODUCT IS NITROGENOUS WASTE – TOXIC MOLECULE
- METABOLIC WASTE (EXCEPT CO₂) MUST BE REMOVED FROM THE BODY THROUGH BODY FLUIDS. SO PRODUCTION AND SECRETION OF WASTE PRODUCT DIRECTLY INFLUENCES WATER BALANCE.
- TO DO SO, VERTEBRATES MUST ADJUST THE COMPOSITION OF BLOOD. VERTEBRATES HAVE KIDNEYS, AND OTHER ORGANS, THAT PROCESS BLOOD
- WATER AND SOLUTE BALANCE OF INDIVIDUAL CELLS IS INTEGRAL

HOW AN ANIMAL GETS RID OF NITROGENOUS WASTE DEPENDS ON EVOLUTIONARY HISTORY AND ECOLOGY

ADAPTATION

AMMONIA: Very soluble in water and easily diffuses through epithelial walls. But very toxic so has to be diluted. Common in fresh water vertebrates. In fish, most ammonia removed by gills, with help of kidney.

UREA: CO₂ BOUND TO AMMONIA.
- advantage: not as toxic as ammonia (100000 times less toxic)
- disadvantage: cost energy to produce in liver.

URIC ACID: not as toxic, but insoluble in water. Excreted as semisolid waste with very little water loss. Common in birds, many reptiles
- disadvantage: more expensive to process than urea
- advantage: low water requirement, so great for organisms with little water

Some animals can change which compound to secrete depending on water supply. Some tortoises secrete urea but shift to uric acid when water supplies are low.
IV. WATER BALANCE

B. WATER BALANCE IN FRESH WATER

Environment has fewer solutes than internal environment, so gaining water and losing salt -produce very dilute urine, and regain salts through food and gills.

What about organisms that live part of their lives out at sea and in rivers?

Salmon – when at sea, “drink” salt water and lose salt through gills and concentrated urine. when in fresh water, minimize drinking and produce dilute urine, and uptake salt through gills.

C. WATER BALANCE ON LAND

1. IMPERMEABLE SKIN TO PREVENT WATER LOSS
MANY VERTEBRATES HAVE MULTIPLE LAYERS OF DEAD, KERATINIZED SKIN WHICH IS WATER IMPERMEABLE (LIKE REPTILIAN SCALES)

2. BEHAVIORAL MODIFICATION
DESERT ANIMALS ARE ACTIVE MOSTLY AT NIGHT

3. EFFICIENT ORGANS THAT PREVENT WATER LOSS – KIDNEY, SALT GLANDS.
- BLOOD IS PROCESSED VIA SELECTIVE REABSORPTION (REMOVE WATER OR SOLUTES FROM BLOOD TO TISSUE) OR SECRETION (REMOVE WATER OR SOLUTES FROM TISSUE TO BLOOD)

HOW KIDNEYS WORK
humans as an example:
- kidney secretes urine that is 4x more concentrated than our body fluid
- production of highly concentrated urine (urea and salt) done by:
  1. active transport of solute through membrane in kidney
  2. passive transport via diffusion gradient

filtrate removed from blood enter nephron
filtrate travels through tubules
descending loop: water passively leaves filtrate because of gradient – filtrate more dilute than kidney tissue
filtrate becomes more concentrated as it descends
ascending loop: important minerals reabsorbed actively, creating a highly concentrated area outside the loop and making dilute urine
final “collecting duct”: body releases antidiuretic hormone, which makes the collecting duct walls very permeable to water so water is reabsorbed making urine more concentrated

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IV. WATER BALANCE

C. WATER BALANCE ON LAND: variation in kidney structure linked to ecology

1. Desert mammals: Really long loop of Henle's
   - kangaroo rat urine 17x more concentrated than body fluid
   - Australian hopping mouse: 25x
   - humans 3-4x

2. Reptiles have short nephrons, so reabsorb water through cloaca

3. More terrestrial frogs reabsorb water directly through urinary bladder

V. TEMPERATURE

B. Ectothermy vs. Endothermy

1. Ectothermy: low metabolic rate, so relies on environment for heat
   - Fish, amphibians and reptiles

2. Endothermy: high metabolic rate, so produces own heat not relying on the environment
   - Mammals and Birds (probably dinosaurs too)

   Costly:
   - Human at rest – 1300 to 1800 kcal/day
   - Alligator at rest – 60 kcal/day
   - Although costly, endothermy has many advantages:
     1. sustain activity for longer period
     2. active at low temperatures
     3. live in extreme environments

   Many of our biological activities (e.g., enzymes breaking down food) is mediated by temperature
   - Thermoregulation: animals maintain an “optimal” body temperature for proper cellular function

A. Processes of heat loss or gain

1. conduction: transfer of heat when objects are in direct contact
2. convection: transfer of heat from moving air or liquid
3. radiation: emission of heat from an object
4. evaporation: heat removal by a liquid when it turns to gas
V. TEMPERATURE

C. Mechanisms of Temperature Control

b. Cooling by Evaporation
   - water is lost through skin and when breathing via evaporation
   - water absorbs heat during evaporation, so excellent way to cool
   1. Panting: increases evaporation through breathing
   2. Sweating: increases heat loss through skin

c. change metabolic rate
   - endotherms can produce more heat when cold
   - shivering in mammals and birds (but some snakes, like python, can use shivering to produce heat for egg incubation)

d. Behavioral Response
   - most ectothermic organisms rely on this
   1. basking or seeking shelter

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D. Extreme Adaptations to Temperature

1. Freezing

   How do vertebrates, especially ectotherms, cope with freezing temperatures?

   a. Antifreeze in blood

      e.g., Antarctic fish *Trematomus borchgrevinki*

      Blood contains glycoproteins which lower the freezing point of blood, so fish can swim at -1.8 C

      e.g., tree frogs (*Hyla versicolor*) have glycerol (3%) in its body fluids

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VI. CHANGING CONDITIONS: DAILY AND SEASONAL PATTERNS

- CONDITIONS CHANGE LIKE FOOD SUPPLY, TEMPERATURE
- ESPECIALLY IMPORTANT IN WINTER WHEN FOOD IS SCARCE AND TEMPERATURE LOW

A. HIBERNATION AND TORPOR

TORPOR: low metabolic rate for low periods of activity

HIBERNATION: extended torpor in low temperatures (winter)

ESTIVATION: extended torpor in higher temperatures (summer) and low water supply

But Hibernation and Estivation are the same phenomenon

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Torpor is common in animals with high metabolic rates and require large intake of food.
VI. CHANGING CONDITIONS: DAILY AND SEASONAL PATTERNS

A. HIBERNATION AND TORPOR

2. Hibernation in ground squirrels

- High elevation
- Hibernate during winter to reduce energy requirements
- 150 kcal vs 5 kcal per day

Why is this adaptive?

VI. CHANGING CONDITIONS: SEASONS

B. MIGRATION

HOW DO BIRDS NAVIGATE?

1. VISUAL LANDMARKS
   - Local and long-distance orientation/travel
   - Waterfowl: follow watercourse
   - Raptors: coasts of Central America (and Bay Area)

2. SOLAR COMPASS
   - Navigate by sun position

KRAMER’S WORK ON EUROPEAN STARLINGS

- Starlings placed in pavilion cages, where the sun and sky are visible during zugunruhe
- When sun is visible, oriented NE for spring migration
- When cloudy, no direction
VI. CHANGING CONDITIONS: SEASONS

B. MIGRATION

HOW DO BIRDS NAVIGATE?

2. SOLAR COMPASS

NAVIGATE BY SUN POSITION

-BIRDS HAVE TO COMPENSATE FOR THE CHANGING POSITION OF THE SUN (15 DEG / HOUR)

-BILOGICAL CLOCKS

HOFFMAN'S EXPERIMENTS ON EUROPEAN STARLINGS

-TRAINED BIRDS TO FIND FOOD AT SPECIFIC COMPASS DIRECTION

-SET BIOL CLOCKS 6 HOURS BEHIND

-BIRDS OFF BY 90 DEG, SUN IS IN THE S, BIRDS THINK THIS IS E

2. SOLAR COMPASS

-SOLAR COMPASS NAVIGATE BY SUN POSITION

ADAPTATION

VI. CHANGING CONDITIONS: SEASONS

B. MIGRATION

HOW DO BIRDS NAVIGATE?

3. STELLAR COMPASS

-STAR POSITION (NOCTURNAL MIGRANTS)

EMLEN'S WORK ON INDIGO BUNTINGS

SPRING NIGHT SKY: ORIENT N

WINTER NIGHT SKY: ORIENT S

4. OLFACTATION

PAPI'S WORK ON HOMING PIGEONS

-BIRDS FORM AN OLFACTORY MENTAL MAP

KIEPENHEUER'S WORK ON HOMING PIGEONS

-RAISED NAIVE PIGEONS

GRP A - BLACK DOTS: EXPOSED TO BENZYLALDEHYDE BLOWN IN FROM NW

GRP B - WHITE DOTS: NOT EXPOSED TO SPECIFIC SCENTS

-TRAVELED W AND RELEASED BIRDS, GRP A HAD BA BLOWN IN FROM NW DURING TRAVEL AND AT RELEASE, GRP B CONTROL AIR

-GRP B HOMED IN FINE

-GRP A "THOUGHT" THEY HAVE BEEN TRAVELING NW (TOWARDS THE SCENT) AND SO ORIENTED SE TO GO HOME

REPLICATED WITH RELEASE SITE S OF HOME
5. GEOMAGNETISM

Earth has a weak N-S magnetic field:
   Map of horizontal space

Keeton's work on homing pigeons:
- Attached magnets to the back
- Should disrupt perception of magnetic field
- In sunny days, birds do ok – use vision or sun position
- In cloudy days, when sun is not visible:
  Controls -- homed
  Treatments -- did not orient

V. CHANGING CONDITIONS: SEASONS

B. MIGRATION

How do birds navigate?

5. GEOMAGNETISM

Walcott and Green's work on homing pigeons:
- Attached Helmholtz coils (creates own magnetic field)
- Clear day, bird oriented
- Cloudy day: reversal of current, resulted in opposite orientation

HOW?

Photopigments (rhodopsin) that can convert both light and magnetic fields into nerve impulses

VI. LOCOMOTION

AQUATIC: SWIMMING

Most animals are buoyant in water, so gravity is not an issue but water is denser than air so friction is greater.

Problem of overcoming friction:
1. Fusiform (torpedo-like) body to reduce drag

Locomotion requires energy, and each type differs in its requirement
ADAPTATION

VII. LOCOMOTION

B. ON LAND

- GRAVITY IS IMPORTANT, BUT LITTLE (AIR) FRICTION
- SO SUPPORT (SKELETON) AND MUSCLES ARE KEY

1. RUNNING

- must overcome inertia of body (motionless) to set body in motion
- must overcome deceleration due to friction (ground and air)
- speed = product of stride length and stride rate

2. HOPPING

- Landing: impact force and weight of the kangaroo is absorbed by active stretching of the muscle and elastic stretch of the Achilles tendon.

- Jumping: the weight is accelerated by a recoil force due to active muscle contraction and elastic recoil of the Achilles tendon.

ADAPTATION

VII. LOCOMOTION

B. Avian Flight

Four forces to balance:

1. gravity
2. lift
3. thrust
4. drag

How do birds achieve lift?

1. Airfoil and powered flaps
VII. LOCOMOTION
B. Avian Flight

ADAPTATION

AERODYNAMICS OF FLIGHT

1. Bernoulli’s Principle

Drag: opposes lift and thrust

1. Pressure (or induced) drag
2. Friction drag

Countering Drag
1. Shape of wing – reduces friction drag
VII. LOCOMOTION
B. Avian Flight

Countering Drag
2. Alula – 3-4 feathers attached to the first digit

- reduces induced drag

3. Slots – reduces pressure/counters induced drag

WING TYPES
aspect-ratio: LENGTH TO WIDTH RATIO

long, narrow and pointed (large aspect ratio) e.g., albatross
long, broad. eg. hawks
(slots allow for reduced drag)
short, rounded (small aspect ratio)
e.g., pheasant
small, narrow and tapering. e.g. swallow
long primaries, short secondaries