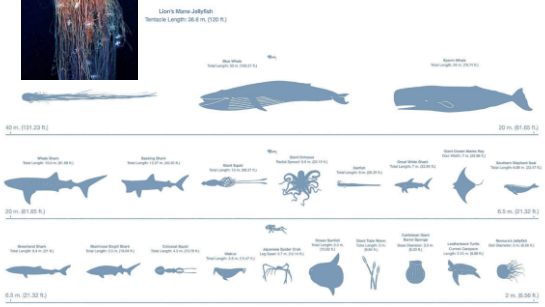


Life in water:
Convergent Evolution and Adaptations

Assoc. Prof. Bojan Lazar, PhD
Department of Biodiversity
Faculty of Mathematics, Natural Sciences and Information Technologies
University of Primorska



Marine Megafauna



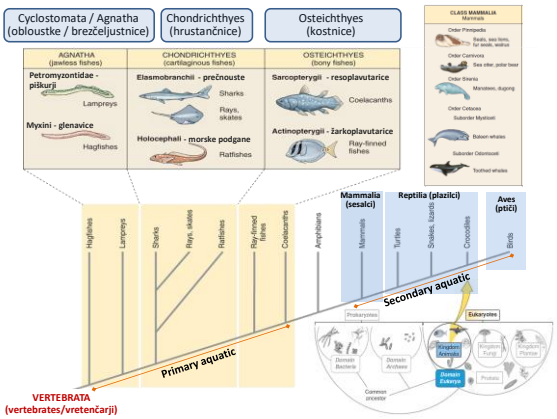
Life history strategies

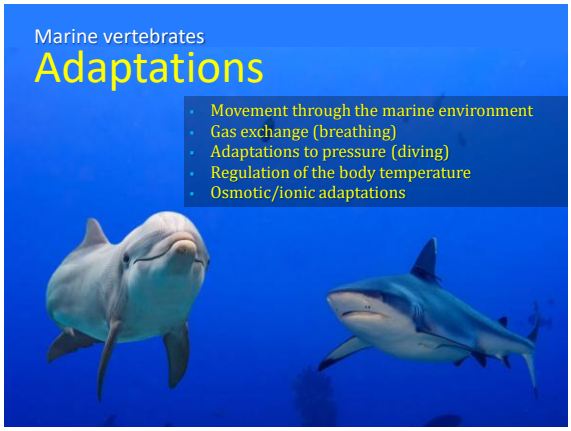
- trade-off in surplus energy allocation



- late maturation
- low reproduction
- long lifespan (decades)

- early maturation
- high reproductive output
- short lifespan





Life in Water

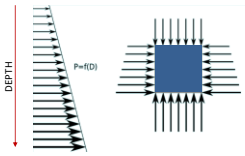
- liquid, gas: fluids (→ the laws of fluid dynamics)
- buoyancy, upthrust: an upward force exerted by a fluid that opposes the weight of a partially or fully immersed object

Movement through the water:

- Energetically demanding
  - ≈ 800x more dense than air

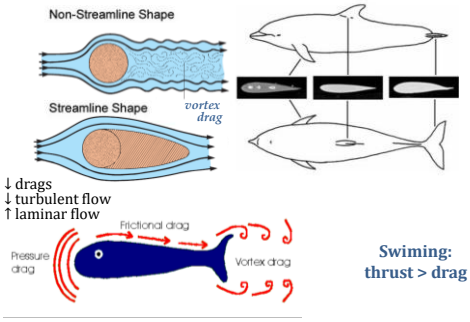
➢ *Drag*

- *Pressure drag*
- *Frictional drag*
- *Vortex drag*



Locomotion in Marine Environment:

Streamlined Body Shape

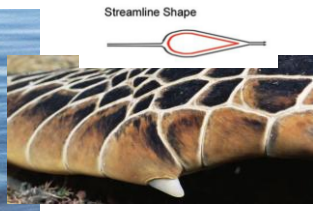


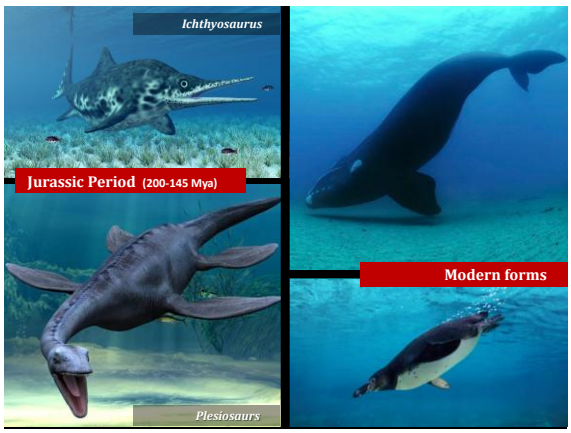
Swiming: thrust > drag









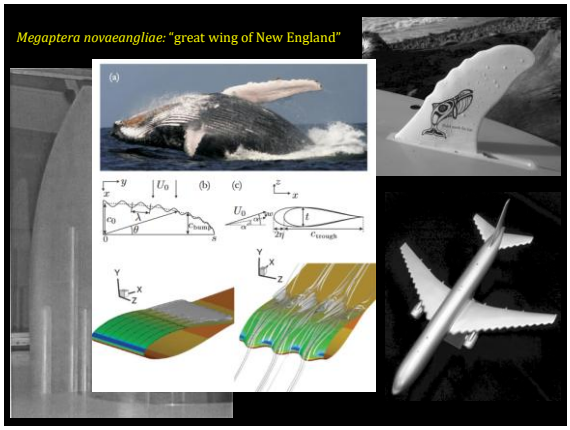


Convergent Evolution

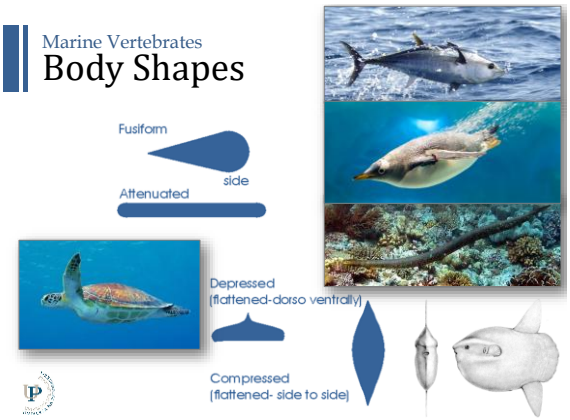
- Independent evolution of similar features in species/taxonomic groups of different evolutionary lineages
- Results of universal physical and physiological principles
  - common biological (evolutionary) solutions in evolutionary distant taxonomic clades

  ⇒ analogous structures (organs): similar form or function but different evolutionary origin





Marine Vertebrates
Body Shapes

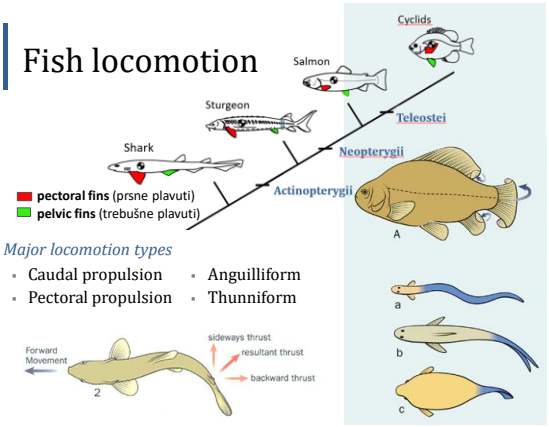


Large Marine Vertebrates:

Locomotion in Marine Environment

1) Anatomical & morphological adaptations
   - hydrodynamic body shape (*streamlined body shape*)
   - locomotory limbs with large surfaces (fins, flippers)
   - changes in buoyancy (due to compression of air in lungs, swimming bladder, fur...)
2) Behavioural adaptations
   - intermittent locomotion
   - selective use of sea currents
   - travelling in a formation

Fish locomotion



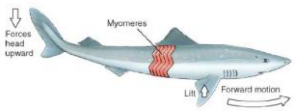
Major locomotion types

- Caudal propulsion
- Pectoral propulsion
- Anguilliform
- Thunniform



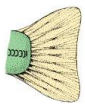
Chondrichthyes

HETEROCERCAL CAUDAL FIN



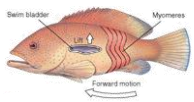
Body density > Sea water density

- *negative bouyancy*
- no swim bladder
- heterocercal caudal fin
- ventral position of pectoral fins
- cartilaginous skeleton
- large "oily liver"
- urea and 3-methylamin oxide in muscles and blood



Osteichthyes

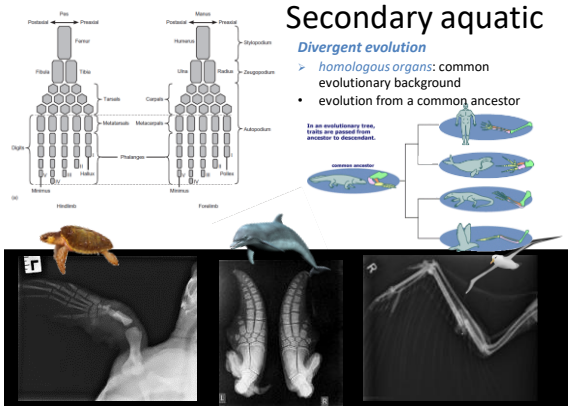
HOMOCERCAL CAUDAL FIN



Avg. body density: variable...

- *most fishes: neutral buoyancy*
- swim bladder, lungs
- homocercal caudal fin
- position of paired fins
- benthic/deep sea and large pelagic fishes: *reduction or loss of swim bladder*

Secondary aquatic



Divergent evolution

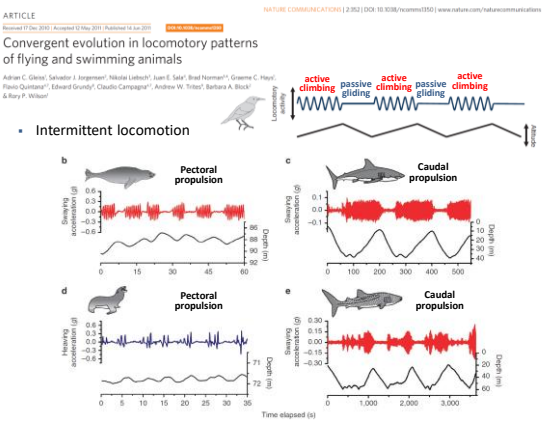
- *homologous organs*: common evolutionary background
- evolution from a common ancestor

Buoyancy control



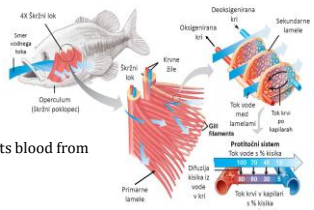
- neutral buoyancy: average body density = density of sea water
- increase of hydrostatic pressure with depth → increase in buoyancy force

1) Anatomically-morphological solutions
   - structure and position of locomotor organs (fins)
   - regulation of air retention in the body
     - compression/retention of air in the lungs, air bladder, fur, feathers...
   - decrease in tissue density
     - incorporation of oil (e.g. in the liver) and fat
     - lighter skeletal elements (cartilage, air bones of birds…)
2) Behevioral solutions
   - *intermittent locomotion*



- Intermittent locomotion

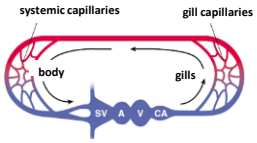
Circulation and gas exchange



Heart:

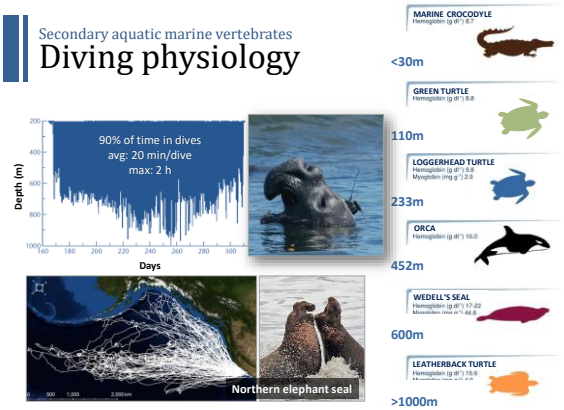
- venous, three-chambered:
  - *Sinus venosus* (SV): collects blood from the body
  - *Atrium* (A)
  - *Ventriculum* (V)
- *Conus arteriosus* (CA): maintains blood pressure in the short aorta, which carries blood to the gills



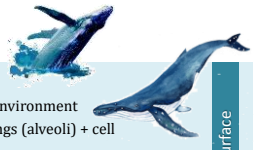


Secondary aquatic marine vertebrates

Diving physiology



What is hapening in the process of diving?



- Intake of air (oxygen storage)
- *Apnea* (stop of breathing)
  - No gas exchange btw. animal and environment
  - Exchange of gasses *continues* in lungs (alveoli) + cell metabolism
  - Voluntary and forced
- *Bradycardia* (reduction of heart frequency)
- *Hypoperfusion* (redistribution and reduction of the blood flow)
- *Tachycardia* (increase of heart frequency)
  - During ascendant phase

Bellow sea surface

- Surfacing: Expiration (brake down of lactates)

Secondary aquatic marine vertebrates

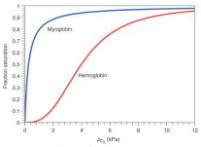
Diving adaptations

1) Adaptations to oxygen storage
   - Where/how to store oxygen
   - Changes in blood flow (distribution of gasses)
   - Changes in metabolism (oxygen consumption rates)
2) Adaptations to pressure
   - Mechanical effects of pressure
   - Changes in solubility of gasses (N_2, O_2)
     - N_2 : nitrogen narcosis (euphoria, disorientation)
     - O_2 : blackout and death in partial pressure >1 atm

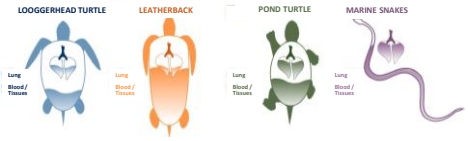
- Convergent evolution in different evolutionary lineages of *breath-hold divers*

Secondary aquatic marine vertebrates

Oxygen storage



- Lungs (air)
- Blood (Hemoglobin, Hb)
  - Higher hematocrit concentrations
  - Higher relative volume of blood in comparison to related terrestrial species
    - Humans: blood ≈ 7% body mass
    - Marine mammals: blood ≈ 10-20% body mass
- Muscles (Myoglobin, Mb)
  - Much higher affinity for oxygen
  - Muscle Mb conc. 10-30x higher than in related terrestrial species



Secondary aquatic marine vertebrates

Diving metabolism

- Aerobic: 1 molecule of glucose → CO_2 + H_2O + 38 ATP
- Anaerobic: glucose → lactate + 2 ATP
  - 1/19 of energy
  - Lactate: toxic

➢ **ADL** – *Aerobic Dive Limit*



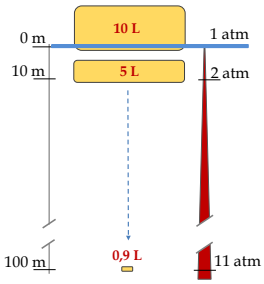
Adaptations:

- Increased tolerance to lactates (high conc. of enzyme lactat -dehydrogenase) → increased tolerance of tissues to hypoxia
- *Body size*

Biophysics

Diving depts & pressure

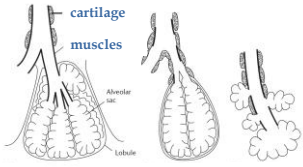
- Boyle's Law
  $P_1 V_1 = P_2 V_2$
- Changes in air volume most dramatic in the shallow dives: 10-20m
- Direct effects on cellular processes (nervous tissue, organs, membranes…): 500-1000m



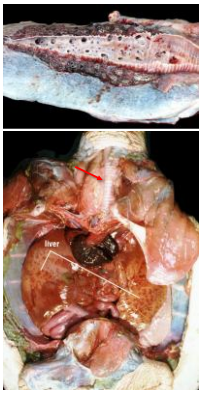
Secondary aquatic marine vertebrates

Adaptations to pressure

- Adaptations of respiratory system
  - strengthened terminal airways (trachea, bronchi)
  - Lung collapse (alveoli)
    (air in tracheas, no absorption in alveoli)
- Oxygen stored in tissues (Mb)

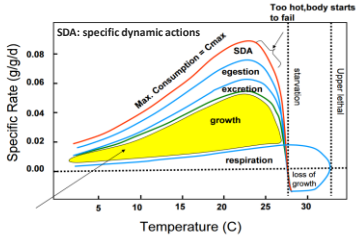


Seal Sea lion Walrus

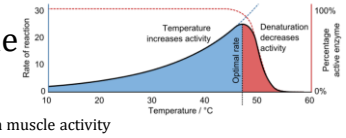


Thermal biology

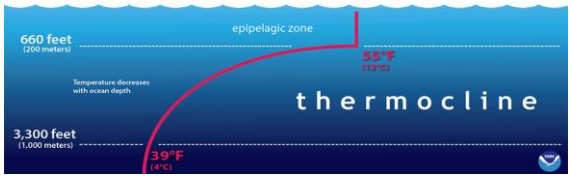
thermocomformer → thermoregulator



Q_{10} principle



- Biochemical principle
- Δ10°C: ~50% decrease in muscle activity
- Elevated body temperature:
  - Faster contraction of muscles
  - Faster transfer of oxygen from blood to muscles (aerobic metabolism)
  - Faster decomposition of lactates (muscle relaxation)



Regulation of body temperature

1. Acording *steadiness of body temperature*

- *Poikilothermy* - temperature regulation characterized by wide variations in body temperature as a result of changing environmental conditions.
- *Homeothermy* - stable body temperature

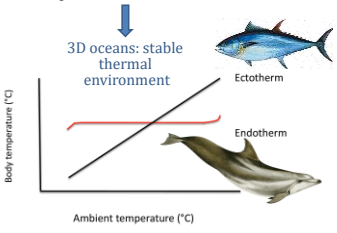
2. Acording to the *energy source*

- *Ectothermy* – mode of thermoregulation in which body temperature primarily dependent on the absorption of heat energy from the environment.
- *Endothermy* - body temperature depends on the cell metabolism of the organism

Thermobiology

Regulation of T_b

- High thermal capacity of water: fast and constant heat loss
  - thermal conductivity 25x higher than air
- Thermal capacity of water ≈3,200x higher than air per unit volume





Thermobiology: Adaptations *I*



Anatomical - physiological

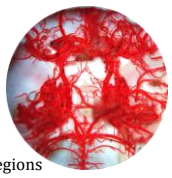
- Reduced *surface-to-volume* ratio (→ *going big*: large body size)
- Dark body colour → faster heat absorption
- Alternative enzyme systems
  - enable physiological processes at different temperatures
- Elevated salt (ions) concentration in the body
  - ➢ decreases freezing temperature
- "Antifreeze" – glycoproteins
  - ➢ prevents crystallization
- Metabolic heat production
  - *Endothermy*
  - *Regional endothermy (heterothermy)*
- Body isolation
  - subcutaneous fat layer, oil, hair…





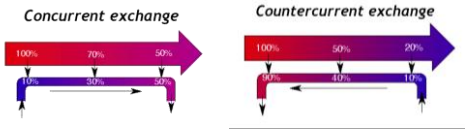
Large Marine Vertebrates

Regional endothermy



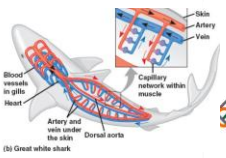
- Heterothermy
- Maintaining of elevated temperatures in body regions important for efficient performance, e.g. muscles

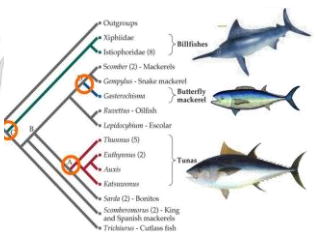
1) *Countercurrent heat exchange*
2) *Rete mirabile*: dense network of small arteries and veins in close contact
   - ➢ increased area for heat exchange

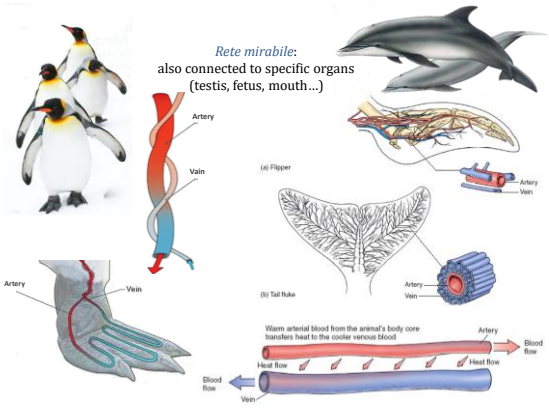


Regional endothermy

- Convergent evolution
  - At least 3x just in evolution of bonny fishes
  - Also in sharks: *fam.* Lamnidae (e.g. great white, mako..)



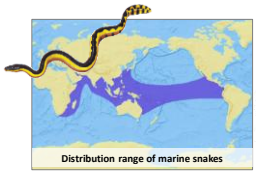


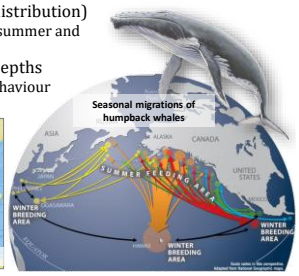


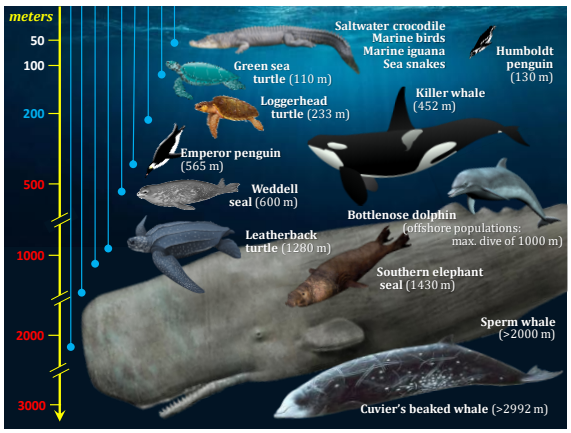
Thermobiology: Adaptations *II*

Distribution ranges and 3D habitat use

- ranges limited to thermally suitable environments
- seasonal habitat use (2D distribution)
  - seasonal migrations btw. summer and wintering habitats
- vertical habitat use: dive depths
  - 3D distribution: diving behaviour







Readings

Diving Physiology of Marine Vertebrates

Daniel P Costa, *Department of Ecology and Evolutionary Biology, University of California-Santa Cruz, Santa Cruz, California, USA*

Pough & Janis 2018: *Vertebrate Life.*

- Chapter 4: *Living in Water*

