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Higher School of Biological Sciences of Oran
Department of Preparatory Classes

Educational Handout

Subject : Zoology
Zoology Course

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Level: 2nd Year of Preparatory Classes.
Field: Natural and Life Sciences.

Subject taught during the Academic Year:

- 2024/2025
- 2025/2026

Academic Year : 2025/2026

Preamble

Zoology is a fundamental discipline of biological sciences that studies animals, their diversity, their organization, their lifestyles, and their relationships with the environment. This subject plays an essential role in the education of **second-year preparatory** class students, as it provides the necessary foundation for understanding many applied fields, such as ecology, physiology, evolutionary biology, and environmental sciences.

In this module, students will learn about the following topics:

Chapter 1: Introduction to zoology

This first chapter introduces zoological science, its history, objectives, and different branches. It helps students understand the importance of studying the animal world and the methods used to analyse and classify living beings.

Chapter 2: The Protista Kingdom

This chapter covers single-celled or colonial eukaryotic organisms grouped within the Protista kingdom. Students will study their main characteristics, classification, modes of reproduction and ecological importance.

Chapter 3: The Animal Kingdom

The last chapter of the module introduces the great diversity of the animal kingdom. It presents the main zoological groups, their organisational criteria, their evolution and the basic concepts relating to the anatomy, physiology and classification of animals.

Through these three chapters, this course aims to provide students with a general, structured and progressive overview of the animal world, in order to prepare them for the specialised teaching they will encounter in the rest of their scientific studies.

Module details

Institution : Higher School of Biological Sciences of Oran

Department : Department of Preparatory Classes

Domain: Natural and life sciences

Semester : 03

Credits : 06

Rating : 04

Semester Hours : 82h 30

Personal work : 22h 30

Module Leader : Dr. TABECHE Ali

Subject: Zoology

Prerequisites: General Biology, Cell Biology and Basic Gentics.

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Part 02: Subkingdom of Metazoans, Vertebrates

I- General Introduction to the Zoology Module

Zoology is one of the fundamental disciplines within the biological sciences, dedicated to the study of animals in all their diversity. It encompasses the analysis of their organization, anatomy, physiology, behaviors, reproduction, development, and interactions with the environment. Studying animals goes beyond mere observation; it requires a deep understanding of their internal structures, functional mechanisms, and ecological relationships. This integrative approach makes zoology a key discipline for scientific training, especially for second-year preparatory students, as it provides the conceptual and methodological foundations necessary for understanding many other areas of biology, including ecology, physiology, evolutionary biology, ethology, and environmental sciences.

The history of zoology dates back to antiquity, with early systematic observations of animals conducted by Aristotle and his successors, who attempted to classify living organisms according to their morphological and behavioral characteristics. Over the centuries, zoology evolved through the development of the scientific method and the incorporation of concepts from cell biology, genetics, and evolutionary theory. Modern zoology is no longer limited to descriptive studies of species; it also includes the analysis of phylogenetic relationships, the exploration of adaptive mechanisms, and the evaluation of animals' roles within ecosystems and the biosphere. This modern, multidisciplinary perspective allows students to understand that every animal, from unicellular organisms to complex vertebrates, plays a specific role in maintaining ecological balance.

Zoology is also essential in scientific education because it develops fundamental skills such as careful observation, classification, comparative analysis, experimentation, and logical reasoning. These skills are crucial not only for understanding animals themselves but also for mastering biological concepts applicable to other scientific fields. For instance, understanding the physiological mechanisms and behavioral adaptations of animals is vital in ecotoxicology, which examines the environmental impacts on living organisms, and in biodiversity conservation.

This zoology module for second-year students consists of three main chapters, each covering a central aspect of the discipline and allowing students to progressively acquire knowledge and scientific skills. The first chapter, Introduction to Zoology, presents the foundations of the discipline. It traces its history, defines its objectives, and describes its main branches, including descriptive zoology, experimental zoology, systematics, phylogeny, and evolutionary biology. This chapter also highlights the methods used to study animals, from direct observation and laboratory experiments to modern tools such as electron microscopy, genomics, and bioinformatic analysis. Students will learn to apply scientific criteria to identify, classify, and describe living organisms, while developing an understanding of the complexity and diversity of animal life.

The second chapter, The Protista Kingdom, focuses on unicellular or colonial eukaryotic organisms. Although microscopic, these organisms play a major role in both aquatic and terrestrial ecosystems, particularly in nutrient cycles, primary production, and microbial population regulation. Studying Protists helps students understand cell biology, asexual and sexual reproduction, and adaptation to different environments. Moreover, this chapter provides an essential link to evolutionary concepts, as Protists represent a key group for understanding the origin and evolution of multicellular eukaryotes, including animals.

The third chapter, The Animal Kingdom, explores the remarkable diversity of animals, from the simplest organisms to the most complex forms. It presents major phyla, their organizational criteria, morphological and functional characteristics, and the fundamentals of comparative anatomy and physiology. This chapter emphasizes evolutionary processes, showing how specific structures and behaviors have enabled animals to adapt to various environments, whether aquatic, terrestrial, or aerial. A comparative approach across animal groups helps students develop analytical thinking, linking structure, function, and adaptation, and appreciating the continuity of evolutionary processes across the animal kingdom.

This module is not limited to theoretical knowledge; it is also designed to develop practical and experimental skills. Students will engage in activities such as microscopic observation, dissections, data collection, and analysis, drawing scientific conclusions from their observations. These practical exercises are essential for understanding the complexity of animal life and for applying theoretical concepts in real-world contexts, including ecology, natural resource management, and applied scientific research.

In conclusion, the zoology module provides students with a comprehensive and progressive introduction to the animal world. It combines theoretical knowledge, scientific methods, and practical applications, enabling students to gain an in-depth understanding of biological diversity and the interactions between organisms and their environment. Mastery of these concepts provides a solid foundation for specialized studies in ecology, physiology, evolutionary biology, ethology, and environmental sciences. Ultimately, this module aims to prepare students to become scientists capable of analyzing, understanding, and preserving the richness of animal life, which remains a vital component of the biosphere and life on Earth.

II- Chapter 1: Introduction to Zoology

1- Specific Objectives of Chapter 1: Introduction to Zoology

By the end of this chapter, students should be able to:

➢ **Define Zoology and its scope**

- Understand the etymology of the term “zoology” and its historical origins (Sperling, 1661; Mayr, 1982).
- Explain the main areas of study in zoology, including animal diversity, structure, physiology, behavior, reproduction, development, distribution, and ecological interactions.

➢ **Describe the historical development of zoological knowledge**

- Recognize major contributions from ancient civilizations, including prehistoric cave art, Egyptian documentation of fauna, and classical Greek and Roman scholars (Aristotle, Pliny the Elder).
- Analyze the advances in zoology during the Medieval period through Arab and European scholars (Al-Jahiz, Avicenna, Albertus Magnus, Thomas de Cantimpré).
- Explain the scientific contributions of early modern zoologists, including John Ray, Malpighi, Linnaeus, Buffon, and others, emphasizing the shift from empirical observation to systematic study.
- Identify significant developments in the 19th and 20th centuries, including the emergence of experimental zoology, microscopy techniques, and molecular approaches.

➢ **Understand the principles and evolution of zoological classification**

- Explain classical classification systems and their hierarchical taxonomic ranks (kingdom, phylum, class, order, family, genus, species).
- Discuss the limitations of classical systems and the importance of phylogenetic and evolutionary approaches.
- Compare major zoological classifiers, including Linnaeus, Cuvier, Lamarck, Claus, Perrier, and others.
- Describe modern phylogenetic concepts, including monophyletic groups, homologous and analogous traits, and the use of molecular markers.

- **Apply criteria for the classification of living organisms**
  - Identify external, internal, developmental, and genetic traits used in scientific taxonomy.
  - Distinguish between vertebrates and invertebrates based on structural characteristics.
  - Interpret phylogenetic trees, including the three domains of life: Bacteria, Archaea, and Eukarya.
  - Understand the concept of LUCA (Last Universal Common Ancestor) and its relevance to evolutionary classification.

- **Recognize the major organizational plans in the animal kingdom**
  - Differentiate between Parazoans and Eumetazoans based on the presence or absence of true tissues.
  - Distinguish between diploblastic and triploblastic animals according to embryonic germ layers.
  - Understand the different types of body cavities in triploblastic animals: acoelomates, pseudocoelomates, and coelomates.
  - Relate embryological and anatomical features to systematic classification.

- **Develop critical thinking and practical skills**
  - Apply historical and modern classification principles to analyze animal diversity.
  - Compare and contrast classical and phylogenetic approaches to zoological classification.
  - Interpret diagrams and examples of classification, such as the hierarchical taxonomy of *Panthera leo* and *Panthera tigris*.
  - Appreciate the dynamic and evolving nature of zoological science, including modern experimental and molecular approaches.

2- Definition of Zoology

The term zoology was used for the first time in a scientific context although in a very broad sense by the German scholar Johannes Sperling (1603–1658) (Sperling, 1661). It appears in his posthumous Latin work, *Symbolae Physicae* (1661), where he defined the discipline as "the science of animals studied as natural bodies." This definition remains valid today, even though the scope of zoology has expanded considerably since then (Mayr, 1982).

Derived from the Greek words *ζῷον* (zôon, animal) and *λόγος* (lógos, discourse or study), zoology is the science concerned with the animal world. It examines animal diversity, structure, behavior, reproduction, development, origins, distribution, and their interactions with the environment. To do so, it draws upon various disciplines, including morphology, anatomy, histology, ecology, ethology, and genetics (Mayr, 1982).

3- History of zoology

- **Prehistory and antiquity**

During prehistoric and protohistoric periods, and later in Antiquity, human knowledge of the animal world was primarily practical. It was limited to identifying animals and observing the behaviour of species that were part of daily life.

People mainly recognized:

- Domestic animals (horses, cattle, sheep),
- Animals they could use for work or transport (pack animals, draft animals),
- Species they hunted or fished for food (herbivores, fish),
- Their predators (large carnivores),
- Competitors for resources (such as the fox),
- Animals from which they collected useful products (bee honey),
- And, more generally, all species present in their immediate environment.

At that time, zoology was not yet a structured science; it was an empirical form of knowledge, based on direct observation and the necessities of survival (Mayr, 1982).

During the Late Paleocene, humans created numerous cave paintings and sculptures. These artistic representations, likely with ritual purposes, demonstrate that our ancestors closely observed wildlife, often depicting details that reflect a strong knowledge of the animals in their environment (Polkowski, 2018; Yeakel et *al*., 2014).

Archaeological evidence from ancient Egyptian civilization shows that animals were omnipresent across the various dynasties. From a biogeographical perspective, these documents indicate that some species that have since disappeared from Egypt were still present during the Pharaonic period, notably the ostrich and the Nile crocodile, the latter having even returned to the Nile Valley following recent restoration and management projects (Metropolitan Museum of Art, 1995).

Regarding the knowledge of wild fauna, the ancient inhabitants of Upper Egypt were familiar with various large mammals, which they depicted on multiple media, including antelopes and elephants as early as 4000 BCE. During the Old Kingdom (2635-2140 BCE, era of Khufu, Khafre, and Menkaure), around twenty fish species were represented on mosaics and tile surfaces, and locusts were depicted during the New Kingdom (1539-1069 BCE, era of Ramses II and Tutankhamun) (Polkowski, 2018).

Drawings from the 5th and 6th millennia BCE also include small rodents, fennecs, hippopotamuses, mongooses, porcupines, turtles, catfish, and frogs (with toads appearing rarely), alongside representations of domestic birds and donkeys from around 3000 BCE. Scorpions are depicted since the 5th millennium BCE, while flamingos, swans, and lapwings appear from the Predynastic period (around 3000 BCE) (Yeakel et *al*., 2014).

Aristotle (384-322 BCE) distinguished between animals "with blood" and "without blood," as well as between sensitive and insensitive creatures, and between those that were spontaneously mobile and those that were immobile. He provided brief and sometimes superficial descriptions of various species and major zoological groups, including mammals, other quadrupeds, birds, insects, higher crustaceans, cetaceans, fish, shelled animals, and cephalopods. Aristotle also distinguished insects from myriapods and showed interest in the behavior of bees, although he did not produce a fully synthetic or comprehensive work (Aristotle, ca. 350 BCE/1984).

Pliny the Elder (23-79 BCE), who died while observing the eruption of Mount Vesuvius, largely expanded on the observations of his predecessor. He used the collective term "fish" to describe all aquatic animals, including cetaceans, crustaceans, echinoderms, and mollusks, without making the distinctions recognized today (Pliny, 77 CE/1961).

- **<u>Medieval Period</u>**

It was through the Arab civilization that the observation of animals developed during the Middle Ages. Notable examples include Al-Jahiz's Book of Animals, published in 868 CE, and the work of Abdellatif Ben Youssef (1161–1231), who authored the first account of Egypt's vertebrate fauna and conducted studies on the development of the chicken egg (Nasr, 2007; Al-Jahiz, 868/1968).

In Christian Europe, from the 7th to the 14th centuries, most scholars and intellectuals were clerics, especially monks, who accessed Aristotle's works primarily through Arabic translations. Ibn Sina (Avicenna, 980–1037), a Muslim physician, introduced Aristotle's ideas to the Western world and is associated with discoveries concerning blood circulation, the liver, the functioning of the heart, and the recognition that sexuality is a natural and common phenomenon (Nasr, 2007). Additionally, Isidore, bishop of Seville, published a synthetic work in the early 7th century summarizing contemporary knowledge of the physical and natural world (Isidore of Seville, ca. 600 CE).

Western civilization gradually opened to knowledge from the East during the Crusades and through the work of 12th- and 13th-century compilers. Among them, Thomas de Cantimpré (1186–1263), a morphologist and the first major classifier of animal species, cataloged the known animals of his time, distinguishing apodal organisms, blooded bipeds, and many-legged bloodless species, totaling 283 species (Cantimpré, 1220/1908).

The German Dominican Albertus Magnus (1200–1280), known in France as Albert the Great and a translator of Aristotle, published *De Animalibus* around 1280 in 26 volumes. He described the embryos of fishes and birds and subdivided marine invertebrates into major categories corresponding to today's sea urchins, other echinoderms, actinias, jellyfish, sponges, corals, pennatulids, crustaceans, and mollusks (Albertus Magnus, 1280/1967).

- **Modern Period**

John Ray (1627-1705) was the first to propose a classification of animals based on anatomical rather than behavioral or environmental criteria. His classification, particularly of birds, remained the most advanced until Linnaeus' work. The premature death of Francis Willughby (1635-1672) prevented him from completing several works, which Ray later enriched and published under Willughby's name, including *Ornithologia* (London, 1676) and *De Historia Piscium* (Oxford, 1686). Among Ray's main works are *Synopsis Animalium Quadrupedum et Serpentini Generis* (London, 1693), with several posthumous publications such as *Historia Insectorum* (London, 1710) and *Synopsis Avium et Piscium* (London, 1713) (Ray, 1693/1713; Willughby & Ray, 1686).

Marcello Malpighi (1628-1694), considered the father of microscopic anatomy (histology), has his name attached to numerous structures in the human body and in insects. Girolamo Fabrizi d'Acquapendente (1533-1619) focused on embryonic development in animals, a research area further developed by his student Hieronymus Fabricius (1537–1619), particularly in chickens (Malpighi, 1675; Fabricius, 1600).

The first works on insects appeared at the beginning of the 17th century. Thomas Muffet (1553-1604), an English physician and naturalist, posthumously published *Theatrum Insectorum* in 1634, entirely dedicated to insects and other invertebrates. Charles Butler (1559-1647) published in 1609 the first book entirely devoted to bees (Muffet, 1634; Butler, 1609).

The invention of the microscope at the start of the 18th century opened new avenues for naturalists. The most famous micrographer of this period was Antonie van Leeuwenhoek

(1632-1723), who built his own microscopes and advanced anatomy and physiology by discovering microscopic animals and plants, initially called infusoria (Leeuwenhoek, 1702). Joseph Guichard Duverney (1648-1730) published important papers before the French Academy of Sciences on the circulatory and respiratory systems of cold-blooded vertebrates such as frogs and snakes. In 1720, Michael Bernhard Valentini (1657-1729) published a comparative study of vertebrate anatomy. Jacob Theodor Klein (1685-1759) published *Naturalis Dispositio Echinodermatum* in 1734, a pioneering work on sea urchins (Duverney, 1710; Valentini, 1720; Klein, 1734).

Martin Lister (c. 1638–1712), a British physician and naturalist, worked on many invertebrates, including mollusks and spiders. Anna Maria Sibylla Merian (1647-1717) holds a unique place in entomology, studying insects and particularly metamorphosis, following Jan Goedart (1620-1668). She observed butterfly collections from the Americas in the Netherlands and traveled to Surinam in 1699 to study them in situ, illustrating various stages of insect development (larva, pupa, adult) (Merian, 1705; Goedart, 1662).

From 1696 to 1700, Antonio Vallisneri (1661-1730) published Dialoghi sopra la curiosa origine di molti insetti in La Galleria di Minerva, presenting experiments on insect reproduction that, together with the observations of Francesco Redi (1626-1697) and Malpighi, helped refute spontaneous generation. Pierre Lyonnet (1708-1789) published his first anatomical observations of insects in 1750 in Traité anatomique de la chenille qui ronge le bois de saule (Vallisneri, 1700; Redi, 1684; Lyonnet, 1750).

Moses Harris (1731-1785), British entomologist and illustrator, was the first to use butterfly wing venation for classification. Entomology was further advanced by René-Antoine Ferchault de Réaumur (1683-1757), member of the French Academy of Sciences, who conducted experiments on various subjects and published six volumes of Mémoires pour servir à l'histoire des insectes (1734-1742). The 18th century also saw the emergence of studies on crop pests, exemplified by Giovanni Targioni Tozzetti (1712-1783).

Carl Linnaeus (1707-1778), a Swedish naturalist, laid the foundations for modern binomial nomenclature and is considered the father of modern taxonomy, contributing significantly to zoology despite being primarily a botanist.

Buffon (1707-1788), a French naturalist, published *Histoire Naturelle*, focusing mainly on animals and having a major influence on natural history (Linnaeus, 1758; Buffon, 1749-1788).

- **19th Century**

The 19th and 20th centuries saw zoology expand and subdivide into numerous specialized disciplines as knowledge increased.

John James Audubon (1785-1851) traveled extensively across North America for thirty-five years, from Labrador to Louisiana, collecting notes, drawings, and watercolors. His monumental work, The Birds of America, was published in four volumes between 1827 and 1838, providing an unprecedented visual and scientific record of American avifauna (Audubon, 1827-1838).

Karl Ernst von Baer (1792-1876) made pioneering contributions to the study of mammalian embryology, laying the foundations for modern developmental biology (Von Baer, 1828).

4- Zoological Classifiers

Carl Linnaeus (1707-1788) was one of the first major classifiers in modern zoology. He formalized the binomial nomenclature system, based on the concepts of genus and species, which had existed previously but was systematized in the successive editions of *Systema Naturae* published between 1735 and 1774. The 12th edition, published posthumously by his student Gmelin in 10 volumes (1788-1798), represents the culmination of this work. Linnaeus divided the animal kingdom into six classes: mammals, birds, amphibians, fishes, insects, and worms. Each class was subdivided into orders, which grouped genera and the species then known (Linnaeus, 1758/1788).

Georges Cuvier (1769-1832) ushered in a truly new era for zoology. From 1795 onward, he restructured previously confused classes of insects and worms, creating an essentially anatomical classification. By 1812, he had divided the animal kingdom into four major branches: vertebrates, mollusks, articulated animals (arthropods), and radiates (Cuvier, 1812/1830).

Rudolph Claus (1889) later expanded the number of branches to nine, beginning with the simplest animals: protozoans, coelenterates, echinoderms, worms, arthropods, mollusks, molluscoids, tunicates, and vertebrates. These classifications all derived from Cuvier's system (Claus, 1889).

In contrast, Jean-Baptiste Lamarck (1744-1829), the first transformist, sought not only to describe living beings but also to explain their origins. While his classification (1815-1822) ultimately produced results similar to Cuvier's, it introduced vague categories such as "apathetic," "sensitive," and "intelligent" to organize animal classes, revealing its conceptual weaknesses (Lamarck, 1815-1822). Soon afterward, Barbançois proposed the first genealogical tree of life, aligning systematic classification with an evolutionary perspective that would later be expanded by Darwin.

With the growing understanding of embryology, classifications increasingly incorporated developmental data. Koelliker (1844), Karl Vogt, and Thomas Huxley (1874) created systems dividing animals into three groups: monostomes, with a single mouth; deuterostomes, including vertebrates, arthropods, mollusks, and echinoderms; and archæostomes, including worms and anthozoans.

One of the last major 19th-century classifications was Edmond Perrier's (Traité de Zoologie, 1890), which recognized three levels of organization protozoans, mesozoans, and metazoans encompassing 19 phyla (Perrier, 1890).

5- Modern Zoology

By the end of the 19th century, zoology ceased to be primarily descriptive. It was succeeded by experimental zoology, founded by the French biologist Henri de Lacaze-Duthiers (1821–1901), who recognized that zoology at his time had become a static science. To facilitate his own studies and those of his students, he established France's two most important marine biology stations, in Roscoff and Banyuls-sur-Mer, inspired by earlier European examples such as the marine stations of Manger in Norway (1825) and Ostend in Belgium (1842) (Lacaze-Duthiers, 1880).

The first International Congress of Zoology was organized in Paris in 1889, on the occasion of the centenary of the French Revolution and the Universal Exposition. Hosted by the Société Zoologique de France under the honorary presidency of Alphonse Milne-Edwards, the congress adopted the first consensual International Code of Zoological Nomenclature, drafted by Raphaël Blanchard, then Secretary General of the Society (Blanchard, 1889).

Zoology entered a new era in the 20th century, fueled by advances in microscopy. High-resolution transmission microscopy, emerging in the 1960s, allowed cytological observations far beyond the limits of optical microscopes. By the late 1960s, scanning electron microscopy (SEM) became particularly valuable to systematists. By coating zoological specimens with a fine metallic layer that reflected electrons in a vacuum, SEM provided highly magnified, three-dimensional images, revealing subtle morphological and systematic characters invisible to the naked eye (Bozzola & Russell, 1999). This technology proved essential for analyzing specimens collected during major oceanographic expeditions, revealing unexpected faunas and unique biological types.

Modern zoology integrates approaches from other scientific disciplines, including instruments for sound, high-speed imaging, radiation, and particle flux measurements. Organotypic and cellular tissue cultures are now employed in both zoological and medical research. Biochemical methods, such as enzymatic electrophoresis, were later complemented by molecular biology techniques, including nucleic acid electrophoresis for ribosomal RNA, DNA microsatellites, and conserved molecular domains, which have elucidated phylogenetic, environmental, and speciation processes, as well as clinal variations under genetic, ecological, and biogeographic perspectives (Avise, 2004).

Molecular phylogenetics has gained widespread popularity, particularly with the development of Restriction Fragment Length Polymorphism (RFLP) techniques. DNA molecules are cleaved by specific enzymes into fragments of varying lengths, separated by electrophoresis, and computational methods are used to reconstruct the sequence of nucleotides in the native molecule (Nei & Kumar, 2000).

Zoology remains a dynamic and forward-looking science. New animal groups, species, and organizational types are discovered almost annually, prompting zoologists to propose novel biological and evolutionary hypotheses and to continually reconsider phylogenetic relationships among both minor and major taxonomic groups. As a result, increasingly complex and precise terminology is being introduced (Mayr & Bock, 2002).

6- Principles of Classification

There are various ways to organize the diversity of life. In ecology, organisms are often classified according to their roles and positions within an ecosystem, such as their feeding habits (e.g., herbivores, carnivores, omnivores) (Begon, Townsend, & Harper, 2006).

Similarities observed among living organisms are usually explained by common ancestry (homologous traits) or by adaptations to similar environmental conditions (analogous traits), and more rarely, they may arise by chance (traits that appear independently multiple times throughout evolution) (Futuyma & Kirkpatrick, 2017).

The classification relevant here focuses on reconstructing the evolutionary relationships among organisms. Studies of both living and fossil organisms reveal the appearance of new or derived traits over time. Organisms sharing a derived trait inherited it from a common ancestor. This common ancestor is usually hypothetical and often unknown but is assumed to have been the first to acquire the trait. Scientists group organisms based on the possession of these derived characters, a method central to modern phylogenetic systematics (Hennig, 1966).

➢ **Traits Used in Classification and Scientific Classification Methods**

Classification relies on various traits that can be observed at different biological levels:

- External traits: the organization and morphology of body parts.
- Internal traits: skeletal structures, organs, and other internal anatomical features.
- Developmental traits: characteristics observed during embryonic or larval stages.
- Genetic traits: DNA sequences and molecular markers (Futuyma & Kirkpatrick, 2017; Hennig, 1966).

➢ **How to classify in scientific taxonomy?**

Scientific classification is a systematic method used to organize and group living organisms based on their similarities.
The principle is to create groups in which all species share at least one common trait. For example, animals possessing a backbone are classified as vertebrates, while those without a backbone are grouped as invertebrates (Raven et *al*., 2017).

7- Classical Classification

In the classical system of biological classification, living organisms are organized into seven hierarchical levels, called taxonomic ranks or taxa. This system was inspired by Linnaeus and is largely considered outdated in modern taxonomy (Linnaeus, 1758/1788).

The highest rank is the kingdom, which includes:

1. Bacteria
2. Archaea
3. Protists
4. Fungi
5. Plants
6. Animals

Within each kingdom, organisms are further subdivided into:

- Phyla (2nd rank)
- Classes (3rd rank)
- Orders (4th rank)
- Families (5th rank)
- Genera (6th rank)
- Species (7th rank)

Sometimes species are further divided into subspecies, also referred to as races or varieties. Beyond the kingdom level, broader taxa such as super-kingdoms or empires can also be recognized (Mayr & Bock, 2002).

A limitation of this classical system is its reliance on the presence versus absence of specific traits. For example, vertebrates (animals with a backbone) are contrasted with invertebrates, giving the misleading impression that organisms without a backbone are "less evolved." In reality, all living organisms are equally evolved, each adapted to their ecological niche (Raven et *al*., 2017).

The seven taxonomic ranks of the scientific classification of living organisms are presented below, with two species used as examples: Lion (*Panthera leo*) and Tiger (*Panthera tigris*) **(Fig. 1)**.

Kingdom: Animalia
└── Phylum: Chordata
└── Class: Mammalia
└── Order: Carnivora
└── Family: Felidae
└── Genus: Panthera
└── Species: Panthera leo (Lion)
└── Species: Panthera tigris (Tiger)

Fig. 1: Summary diagram of classical classification (Campbell & Reece, 2020).

8- Phylogenetic Classification

Phylogenetic classification is based on the concept of evolution and the idea of common ancestry, meaning that all living organisms are related and share a single common ancestor, known as LUCA (Last Universal Common Ancestor) (Campbell et *al*., 2020). This classification only works with monophyletic groups (an ancestor and all of its descendants), which allows for a clearer visualization of relationships among living organisms. These groups, regardless of their size, are referred to as taxa (Campbell et *al*., 2020).

Phylogenetic classification recognizes three domains **(Fig. 2)**:

a. Bacteria: unicellular organisms without a nucleus (Campbell et *al*., 2020).

b. Archaea: unicellular organisms without a nucleus, often found in extreme environments. They differ from bacteria mainly in the composition of their cell walls (Campbell et *al*., 2020).

c. Eukaryotes: organisms composed of one (unicellular) or multiple (multicellular) cells with a nucleus. This domain includes animals, plants, fungi, and, more broadly, all organisms visible to the naked eye (Campbell et *al*., 2020).

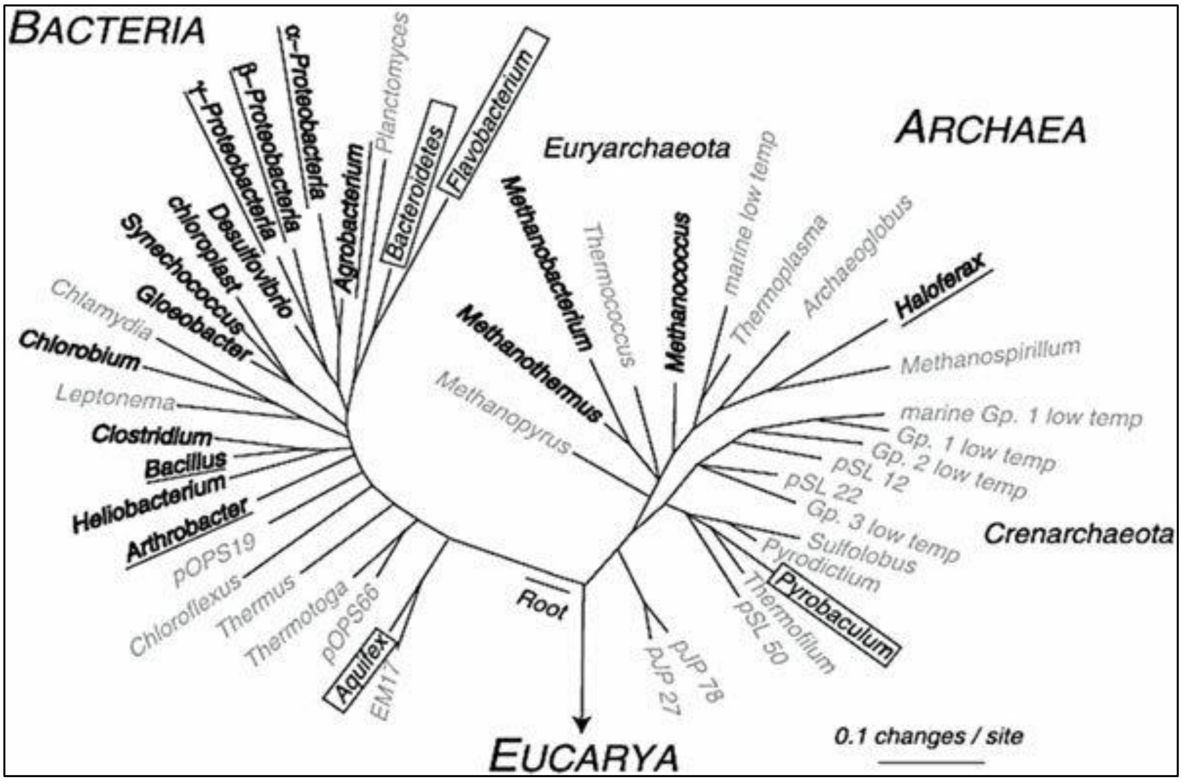


Fig. 2: Phylogenetic tree of the three domains of life (Bacteria, Archaea, and Eucarya) (Barns et *al*. (1996).

9- Organisational plans for the animal kingdom

The major organizational plans of the animal kingdom are defined using several successive criteria.

- **Presence or absence of true tissues.**

Animals are first divided according to whether they possess true tissues. Parazoans lack genuine tissues, while Eumetazoans possess well-defined tissues (Hickman et *al*., 2017).

- **Number of embryonic germ layers.**

Some animals stop their embryonic development at the gastrula stage and develop only two germ layers: the ectoderm and the endoderm. These animals are known as diploblastic. In many other animals, development continues after gastrulation with the formation of a third germ layer, the mesoderm, situated between the ectoderm and the endoderm. These animals are described as triploblastic (Campbell et *al*., 2020).

- **Presence and type of body cavities.**

According to the fate of the mesoderm, triploblastic animals are divided into three major groups:

- Acoelomates: The mesoderm remains compact and forms a solid mass known as parenchyma, without forming any enclosed cavity. The digestive tract is the only internal cavity (Hickman et *al*., 2017).

- Pseudocoelomates: The mesoderm does not form parenchyma; instead, the primitive blastocoel persists between the digestive tract and the body wall, forming a more or less developed cavity called the pseudocoel or "false coelom" (Campbell et *al*., 2020).

- Coelomates: On each side of the digestive tract, the mesoderm splits into two layers that enclose a cavity. These cavities become closed vesicles that together form the coelom, a true body cavity completely lined by mesodermal tissue (Hickman et *al*., 2017).

III- Chapter 2: The reign of protists

1- Specific Objectives of Chapter 2: The Reign of Protists

- **Understand Protists and their Classification**
  - Explain the origin and modern definition of the kingdom Protista.
  - Differentiate protists from plants, animals, and fungi.

- **Recognize Protist Diversity**
  - Describe their morphological, structural, and nutritional diversity (unicellular vs. multicellular, heterotrophic vs. autotrophic).
  - Understand adaptations to different environments.

- **Explore Protozoan Structure and Function**
  - Identify key organelles (nucleus, Golgi, cilia, flagella, cytoskeleton, trichocysts).
  - Explain how their structure supports movement, feeding, and survival.

- **Understand Protozoan Reproduction and Life Cycles**
  - Compare asexual (binary fission, budding, schizogony) and sexual reproduction (gametogamy, conjugation).
  - Explain encystment as a survival strategy.

- **Appreciate Ecological Roles and Distribution**
  - Identify habitats and ecological functions of protozoa.
  - Explain how adaptive radiation contributes to their diversity.

- **Learn Protozoan Classification and Examples**
  - Recognize major protozoan subphyla: Rhizoflagellata, Actinopoda, Sporozoa, Myxozoa, Ciliophora.
  - Understand the biological or medical significance of representative species (e.g., *Trypanosoma, Amoeba, Plasmodium, Paramecium, Foraminifera, Radiolaria*).

- **Analyze Parasitic Protozoan Life Cycles**
  - Describe complex life cycles and host interactions (e.g., *Plasmodium falciparum* in malaria).

- Understand structural and physiological adaptations to parasitic or symbiotic lifestyles.

2- Introduction

The term Protista was introduced by Ernst Haeckel in 1866 to designate two types of organisms: lower protists (prokaryotes) and higher protists (eukaryotes) (Haeckel, 1866). However, in modern biological classification, the kingdom Protista is retained only for eukaryotic organisms other than plants, animals, and fungi (Margulis & Schwartz, 1998).

3- Overview of the Kingdom

The kingdom Protista is highly heterogeneous and includes eukaryotic organisms, most of which are unicellular, although some are multicellular (Bold et *al*., 2000). Protists may be heterotrophic (e.g., protozoa) or autotrophic (e.g., microalgae).

4- Classification

The kingdom Protista is traditionally subdivided into three major groups:

- Protozoa
- Fungus-like protists
- Algae

In some modern classifications, algae are considered a separate kingdom due to their unique characteristics.

Within Protista, algae are notable for being autotrophic, and some species are multicellular (Simpson, 2020).

5- The Phylum Protozoa

5-1 Introduction

Protozoa are unicellular, mobile organisms that reproduce sexually or asexually (Hausmann et *al*., 2003). They are polymorphic and occur in nearly all environments. As heterotrophic organisms, they obtain nitrogen from other organisms or from their environment, often in the form of decaying organic matter (Lynn, 2008).

Nutrients may be absorbed in dissolved form (osmotrophic protozoa) or as particulate matter through phagocytosis (phagotrophic protozoa), using either pseudopodia or a specialized feeding structure known as the cytostome (Kudo, 1966).

Many protozoa are parasitic causing diseases such as leishmaniasis, giardiasis, balantidiasis, and malaria while others form symbiotic associations (Roberts & Janovy, 2010).

Their size ranges from 1–500 µm, occasionally reaching up to 4 mm, although certain foraminifera can grow to several centimeters (Lee et *al*., 1991).

5-2 Morphology and Structure of Protozoa

A. Size

Protozoa range in size from 1 to 600 µm. The smallest forms include sporozoans and certain intracellular parasites, whereas the largest, such as amoebae, may reach up to 5 mm (Kudo, 1966; Lynn, 2008).

B. Structure

Protozoa possess the typical components of a eukaryotic cell, including specialized organelles (Hausmann et *al*., 2003).

- **Plasma Membrane**

Protozoa have a thin lipoprotein membrane called the plasmalemma. In some species, this membrane is reinforced by a superficial envelope that protects the organism from environmental stress and dehydration (Corliss, 2002). When well-developed, this outer layer may include cellulosic, calcareous, or siliceous structures, commonly referred to as a test, shell, lorica, or case.

- **Golgi Apparatus**

The Golgi complex functions primarily in membrane synthesis. In protozoa, it forms stacked sacs known as dictyosomes, which are particularly prominent in flagellates, where the parabasal apparatus plays a major role in secretion and packaging (Hausmann et al., 2003).

- **Nucleus**

Protozoan nuclei show considerable diversity. Many species become temporarily multinucleated during cytokinesis, when the cytoplasm divides into as many individuals as there are nuclei. Some protozoa, however, such as ciliates, consistently possess two nuclei: a macronucleus and a micronucleus (Lynn, 2008).

- **Cilia and Flagella**

Cilia and flagella share the same structural organization as those found in metazoans (e.g., sperm cells). Cilia are short and numerous (5–15 µm), whereas flagella are longer and fewer (150–200 µm) (Lee et *al*., 2000).

Their beating movement includes:

- Effective stroke: The cilium stiffens and bends at the base, generating a forceful push.

- Recovery stroke: The cilium becomes flexible and returns to its original position with minimal water resistance.

Functional types include:

- Buccal cilia, which drive food particles toward the oral region.

- Somatic cilia, used for locomotion.

- **Cytoskeleton**

The protozoan cytoskeleton is well-developed and consists of microfilaments (actin) and microtubules, which play essential roles in cell movement and structural support. Some species possess a rigid microtubular structure called the axostyle, extending along the longitudinal axis (Roberts & Janovy, 2010).

- **Trichocysts**

Found mainly in ciliates, trichocysts are defensive and offensive organelles. These toxin-filled darts eject rapidly to immobilize prey (Lynn, 2008).

- **Sexual and Reproductive Processes**

Protozoa exhibit several reproductive modes:

Gametogamy: Formation of gametes that are either identical (isogamy, e.g., in foraminifera) or morphologically distinct (anisogamy, in some sporozoans).

Gamontogamy: Fusion of gamonts (male and female forms), which subsequently produce gametes (Hausmann et *al*., 2003).

During sexual conjugation in ciliates, the following steps occur:

1. Association at the peristome, followed by degeneration of the macronucleus.
2. The micronucleus undergoes:

One mitotic-like division → two diploid nuclei.

One reductional division → four haploid nuclei (pronuclei).

3. Three pronuclei degenerate, and the remaining one divides mitotically to produce:

One male nucleus

One female nucleus

4. Male nuclei are exchanged between the two conjugating cells.

5. Fusion of male and female pronuclei results in a zygote **(syncaryon)**.
6. The organism forms a cyst, divides into two gamonts, which later form gametes. Fusion of gametes yields a new individual (Corliss, 2002).

5-3 Respiration and Circulation

Protozoa rely exclusively on diffusion for respiration and for the transport of oxygen throughout the cell (Lynn, 2008). Their pellicle must remain permeable, which limits their ability to colonize terrestrial environments (Hausmann, Hülsmann, & Radek, 2003).
Oxygen demand increases with rising temperature; however, the solubility of oxygen in water decreases as temperature increases. Locomotion helps protozoa maintain an adequate oxygen supply: their movement renews the water in contact with the external pellicle, while cytoplasmic streaming within the cell maintains a concentration gradient across the membrane. This gradient facilitates continuous passive diffusion of oxygen into the cell (Corliss, 2002).

5-4 Reproduction

Protozoans exhibit two main reproductive strategies: asexual reproduction (multiplication) and sexual reproduction **(Fig. 3)** (Cox, 2002; Roberts & Janovy, 2013).

5-4-1 Asexual reproduction (agamogony)

This is the most common mode of reproduction, and includes several forms.

- **Binary fission**

Binary fission consists of a series of mitotic divisions producing two daughter cells, which may be identical or slightly different from the parent cell (Roberts & Janovy, 2013).

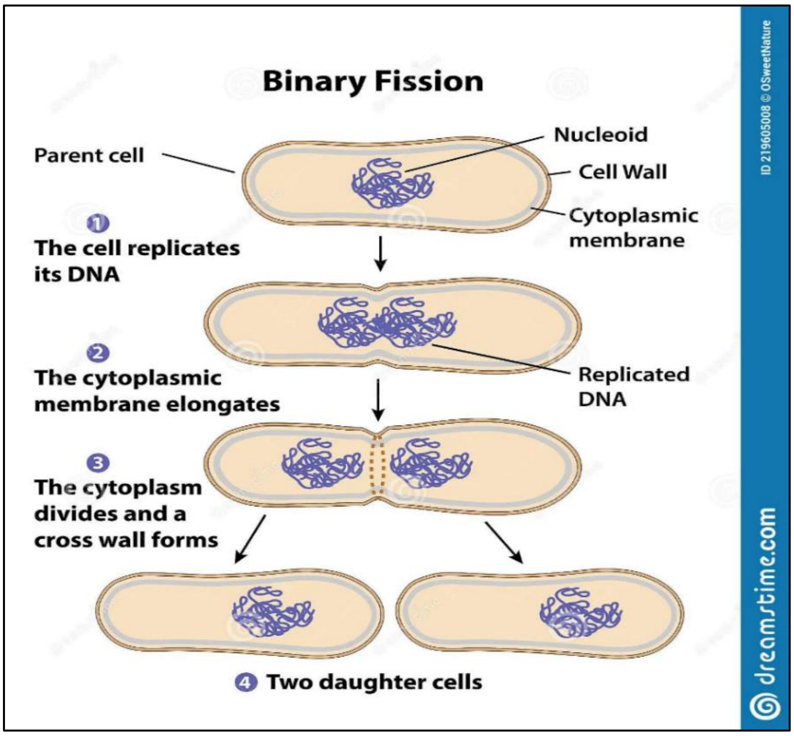


Fig. 3: Binary fission process of cell reproduction in the division stages. Diagram of nucleus, parent cell, daughter cells, cytoplasmic membrane, DNA, chromosome copying, and division steps (Madigan, 2012).

A small exogenous bud may appear on the cell surface **(Fig. 4)**, followed by nuclear division, forming a complete individual that eventually separates from the parent. This is a form of unequal binary fission.

When budding occurs inside the cytoplasm, it is referred to as endogenous budding **(Fig. 4)** (Cox, 2002).

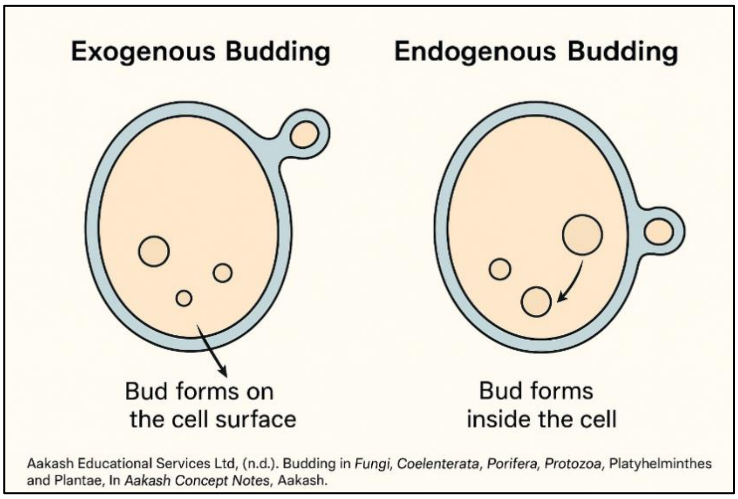


Fig. 4: Exogenous and endogenous budding.

- **Multiple fission (schizogony)**

This process is common among parasitic protists.

The nucleus undergoes several rounds of mitosis within a single cell.

Once multiple daughter nuclei are formed, the cytoplasm is divided into segments, each containing one daughter nucleus. These newly formed cells are called schizonts or merozoites (Levine et *al*., 1980).

- **Budding (gemmiparity)**

One or more buds develop on the maternal cell following a specific pattern.

They detach and form complete individuals.

This type of reproduction occurs mainly in ciliates, where a fragment of the macronucleus enters the bud before it separates from the parent cell (Lynn, 2008).

5-4-2 Sexual reproduction

Sexual reproduction consists of the fusion of two haploid gametes (male and female).

The reproductive mode is determined by the timing of meiosis in the life cycle.

Examples:

- **Sporozoans:**

Meiosis is zygotic, occurring immediately after zygote formation.

Most of the life cycle remains haploid → Haplontic organisms (Cox, 2002).

Haplobiontic cycle:

Alternation between several haploid generations and several diploid generations.

- **Ciliates:**

Meiosis is gametic, occurring just before gamete formation.

Most of the life cycle is diploid → Diplontic organisms (Lynn, 2008).

Diplobiontic cycle:

One phase tends to be reduced, usually the diploid one, with only the zygote being 2n before undergoing meiosis.

- **Foraminifera:**

Meiosis occurs “mid-cycle,” producing an alternation between diploid and haploid generations → **Haplodiplontic organisms** (Sen Gupta, 1999).

Forms of resistance (Encystment): To survive unfavorable environmental conditions, some protozoans form cysts, which serve as protective structures.

When conditions improve, the cyst opens, releasing a cell that regenerates its lost organelles and resumes growth, multiplication, and sexual reproduction (Roberts & Janovy, 2013).

5-5 Distribution and Ecological Importance of Protozoa

Despite their relatively simple organization, protozoans exhibit a remarkably successful structural design, as they are present in all climates and across nearly every type of habitat (Barnes, 1987). They may occur:

- Freely living, in aquatic or moist environments,
- As parasites, causing various diseases, or
- As symbionts in association with other organisms (Hickman et *al*., 2018).

The modification of a basic structural plan that enables protozoans to occupy diverse habitats and adopt multiple lifestyles is known as adaptive radiation (Barnes, 1987). This adaptive radiation reduces competition among organisms sharing a common ancestral origin, thereby promoting an overall increase in biological diversity (Hickman et *al*., 2018).

5-6 Classification of Protozoa

The systematics of protozoa is primarily based on the nature of the locomotory apparatus and on specific characteristics of the developmental cycle. These criteria allow the distinction of five subphyla (Hickman et *al*., 2018).

5-6-1 Subphylum Rhizoflagellata

This subphylum includes protozoans that, during at least part of their vegetative stage, possess flagella, pseudopodia, or both either simultaneously or successively (Barnes, 1987).

5-6-1-1 Class: Flagellates (Zooflagellates) **Examples:** *Trypanosoma* (sleeping sickness)

Flagellates, often referred to as “whip bearers,” inhabit moist environments and marine waters. Their bodies are typically elongated—broad in the middle and tapering at both ends, giving them a spindle- or rocket-shaped form. At the anterior end, a depression is present where one or several flagella are inserted. The number of flagella varies widely, from one to four, but may reach eight or more, as in Euglena (Hickman et *al*., 2018).

Flagellates represent the only group among both the plant and animal kingdoms capable of using all three major nutritional modes: Photosynthesis, Saprophytism, and Ingestion of solid food particles (Barnes, 1987). Photosynthetic flagellates contain the green pigment chlorophyll. Parasitic flagellates are entirely saprozoic, absorbing dissolved organic molecules through their body surface or phagocytosing prey. Non-parasitic forms ingest solid food particles. Flagellates reproduce mainly asexually through binary fission, although sexual reproduction can occur but remains rare (Levine et *al*., 1980). **Example:** *Trypanosoma gambiense* **(Fig. 5)**.

Trypanosoma gambiense, the causative agent of human African sleeping sickness, measures approximately 15–20 µm in length. It possesses a single anterior flagellum that allows active swimming within the host's bloodstream and cerebrospinal fluid (Hickman et *al*., 2018). It reproduces by longitudinal binary fission (mitosis). Transmission to humans occurs through the bite of the tsetse fly, *Glossina palpalis*. The fly becomes infected when it ingests the blood of an infected human host (Levine et *al*., 1980).

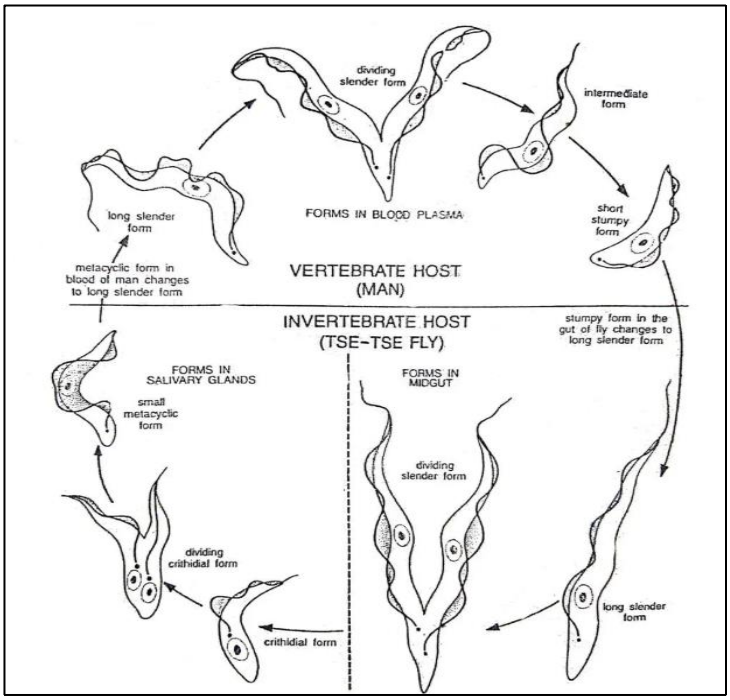


Fig. 5: Life Cycle of Trypanosoma gambiense (Bhuiyan, 2023).

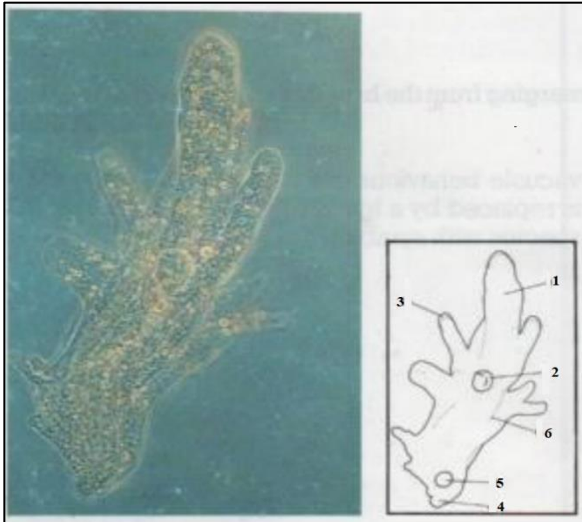
5-6-1-2 Class Rhizopoda (Examples: Amoebae and Foraminifera)

Rhizopods are detritivorous and bacterivorous organisms commonly found in environments rich in organic matter, such as soil and all types of aquatic habitats—particularly freshwater ecosystems (Hickman et *al*., 2018). These protozoans lack permanent locomotory organelles. Instead, they are characterized by the presence of pseudopodia, temporary protoplasmic extensions that function both in locomotion and in heterotrophic feeding (Kotpal, 2012).

Rhizopods do not exhibit a fixed body shape. Their cytoplasm consists of a granular endoplasm, rich in inclusions, and a transparent ectoplasm. They may possess one or several nuclei, each with a central nucleolus. Many species can form cysts when environmental conditions become unfavorable (Lynn, 2008).

Example: The Amoeba *Entamoeba histolytica.*

Amoebae are highly variable in shape. They may appear inactive, forming a rounded contracted mass, or actively moving by extending digitiform pseudopodia **(Fig. 6)** (Kotpal, 2012).



Amoeba. The name *Amoeba* is restricted to those species that have a number of broad, rounded pseudopodia (1) and a single prominent nucleus (2). In the past the name was used for many other species. The nucleus is easily seen because it has a strengthened envelope. The surface of the nucleus is folded. Moving cells typically have watery hyaline caps (3) at the progressing tips of pseudopodia. The posterior end of the cell (uroid) (4) has a crumpled appearance As contractile vacuoles (5) become larger, they tend to accumulate in this part of the cell. The surface of the cell is frequently thrown into longitudinal folds (6). Cells are often opaque because of food vacuoles (more or less absent from the cell illustrated), lipid droplets, and crystals inside the cytoplasm. The species seen here is *A. proteus*. It is large in comparison with most amoebae. Generally similar in appearance is *Chaos*, which has multiple nuclei. *Phase contrast.* (Scale bar 100 µm.)

Fig. 6: Organization of an Amoeba (Patterson, 1999).

Amoebae feed using their pseudopodia: the organism emits lobose pseudopodia in multiple directions to surround its prey commonly algae, rotifers, bacteria, yeasts, ciliates, flagellates, other amoebae (cannibalism), or even small metazoans (macrophagous predation) (Cavalier-Smith, 2004).

The prey becomes enclosed within a food vacuole (phagosome). Digestive vacuoles gradually become alkaline during the digestion and assimilation process. Although the mechanisms of prey capture vary widely, they always result in the formation of a gastrolia, a structure sometimes resembling a true mouth (Lynn, 2008) **(Fig. 7)**.

Phagocytosed material must be broken down into simple molecules for use by the cell. Digestion occurs intracellularly inside the phagosome, formed by the fusion of the ingested particle with lysosomal vesicles. Waste materials accumulate in a vacuole and are eliminated through exocytosis (Hickman et *al.*, 2018).

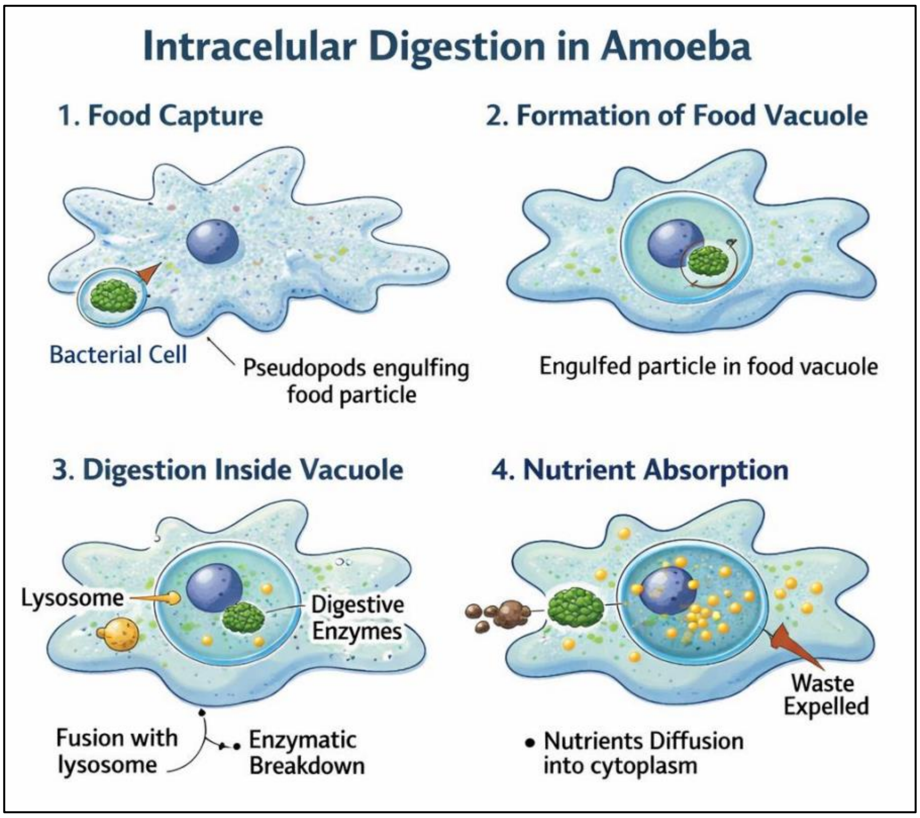


Fig. 7: Intracellular digestion in an amoeba. Diagram illustrating the capture of food by pseudopodia, formation of the food vacuole, digestion by lysosomal enzymes, and absorption of nutrients into the cytoplasm. Diagram inspired by Wiser (2024).

The contractile vacuole (also called pulselle) is present in most freshwater protozoans. Its primary function is osmoregulation, although it may also play a minor role in excretion (Hickman et *al*., 2018; Kotpal, 2012).

Amoeboids, such as amoebae, and most other protozoans can form cysts of various types. These include rare digestive cysts, but primarily cysts for reproduction and dormancy (resting or latent cysts), which enable the organism to survive unfavorable environmental conditions (Lynn, 2008).

Example of Foraminifera: **Morphology, Ecology, and Life Cycle**

Morphology and General Characteristics: Foraminifera are primarily marine protists, either benthic (living on or within the sea floor sediment) or planktonic (floating in the water column) (Sen Gupta, 2003; Murray, 1991). Most species live attached to rocks or algae. They are named after their porous shells, called "tests," which are generally composed of calcium carbonate ($CaCO_3$) (Jones, 2013).

Foraminifera are typically small, ranging from 0.1 to 1 mm, although some exceptional species may reach up to 10-20 cm (Sen Gupta, 2003). The cytoplasm occupies all chambers of the test and extends outward through openings called foramina. Fine, reticulated pseudopodia emerge from the cytoplasm, allowing the organism to move slowly and capture food such as diatoms and other unicellular algae (Kitazato & Bernhard, 2014). Pseudopodia also participate in the construction of new chambers.

Foraminifera display different ecological modes depending on the species:

- Benthic species, which may be epibiontic (resting on the substrate) or endobiontic (buried in the sediment), such as fusulinids and nummulites (Murray, 1991).
- Planktonic species, which can be free-floating or passively drifting, e.g., genera such as Globigerina, Globorotalia, and Globotruncana (Sen Gupta, 2003).

Life Cycle: Foraminifera exhibit a haplo-diplophasic life cycle **(Fig. 8)**, alternating between a haploid, uninucleate generation (gamogony) and a diploid, multinucleate generation (schizogony) (Sen Gupta, 2003; Murray, 1991).

The haploid forms, called gamonts, produce gametes through nuclear division. The fusion of two gametes produces a diploid, multinucleate individual, called a schizont, which reproduces by mitosis. Following meiosis and cytoplasmic division around each nucleus (schizogony), schizonts give rise to new gamonts (Kitazato & Bernhard, 2014).

Morphologically, gamonts and schizonts often differ in overall size and especially in the size of the initial central chamber. In such cases, gamonts are referred to as megalospheric forms, while schizonts are called microspheric forms. However, in some species, the sexual phase (gamogony) is absent (Jones, 2013).

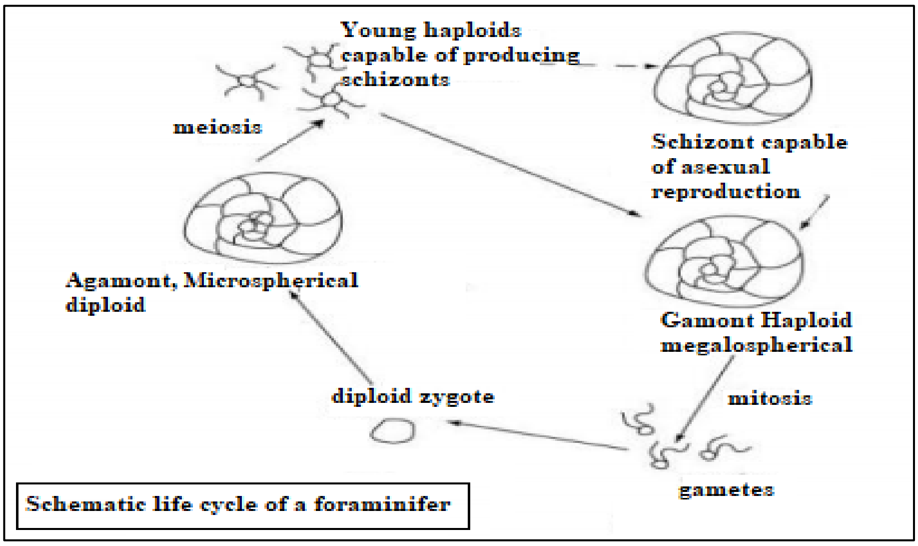


Fig. 8: Schematic Life Cycle of Foraminifera (Goldstein, 1999).

5-6-2 Subphylum of Actinopods: Example Radiolarians

The Actinopoda are so named for their "ray-foot," referring to the thin pseudopodia called axopodia radiating from the cell. These axopodia increase surface area in contact with surrounding water, promoting buoyancy and enabling the organism to capture small protists and other microorganisms, which become trapped among the axopodia and are phagocytosed by the thin cytoplasmic layer. Most actinopods are planktonic. In particular, radiolarians (often referred to under the groups Polycystina and Phaeodaria) possess elaborate siliceous skeletons and a cellular organization with a central capsule dividing endoplasm and ectoplasm. The cytoplasm supports axopodia for feeding, and many species use these for prey capture (Boltovskoy & Anderson, 2010; Suzuki & Aita, 2011).

5-6-3 Subphylum of Sporozoans (Apicomplexans): Example *Plasmodium falciparum*

The Apicomplexa are protozoan parasites lacking locomotive organelles; they are typically immobile or move very slowly. *Plasmodium falciparum*, the agent responsible for malaria in humans, is one example. In these organisms, the life cycle includes both a sexual phase (gamogony) and an asexual phase (schizogony) (Francia & Striepen, 2014; White & Suvorova, 2018).

During schizogony inside red blood cells, *P. falciparum* undergoes repeated asynchronous rounds of DNA replication and nuclear division within a shared cytoplasm, without intervening cytokinesis, resulting in a multinucleated schizont. Only at the end of schizogony does a mass cytokinesis occur, producing numerous daughter merozoites, which then egress and infect new erythrocytes (Gubbels et *al*., 2020).

Furthermore, some parasites differentiate into gametocytes (sexual forms), enabling transmission to the mosquito vector a critical step in the parasite's life cycle (Jeninga, Quinn, & Baum, 2023; Josling, van Biljon, & Llinás, 2024). Mature gametocytes develop in the human bloodstream and are ingested by the mosquito during a blood meal, ensuring continuation of the parasite's complex life cycle.

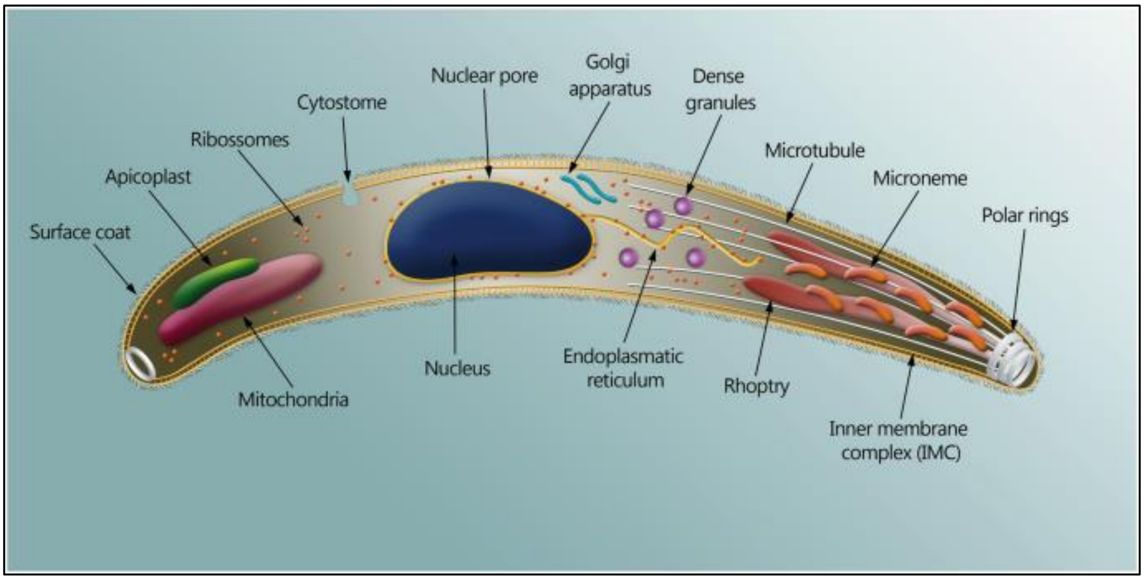


Fig. 9: Structure of a Plasmodium sporozoite. Diagram illustrating the main organelles and structures, including the nucleus, mitochondrion, apicoplast, rhoptries, micronemes, inner membrane complex, and plasma membrane (Miranda et *al*., 2022).

Apicomplexans (or Sporozoa) are intracellular parasites or endosymbionts whose nutrition is osmotrophic. The best-known apicomplexan is Plasmodium falciparum, the causative agent of human malaria, a disease transmitted by female mosquitoes of the genus Anopheles (Roberts & Janovy, 2023). Once injected into the human host **(Fig. 10)**, the sporozoite invades liver cells—where it is referred to as a cryptozoite and up to 5,000 parasites may develop within a single hepatocyte. Inside these cells, the parasite multiplies through schizogony before being released following hepatocyte rupture (White et *al*., 2014).

After differentiation into merozoites, the parasites infect red blood cells, in which they undergo repeated cycles of asexual multiplication that eventually cause erythrocyte lysis. Within the bloodstream, some merozoites differentiate into gametocytes, the sexual stages responsible for transmission to mosquitoes (Kafsack et *al*., 2014). When an Anopheles mosquito takes a blood meal, it ingests these gametocytes, which then undergo fertilization within the mosquito midgut, forming an encysted ookinete and subsequently an oocyst. The sporozoites produced in the oocyst migrate from the midgut wall to the mosquito's salivary glands, from which they can be inoculated into a new human host (Roberts & Janovy, 2023; White et *al*., 2014).

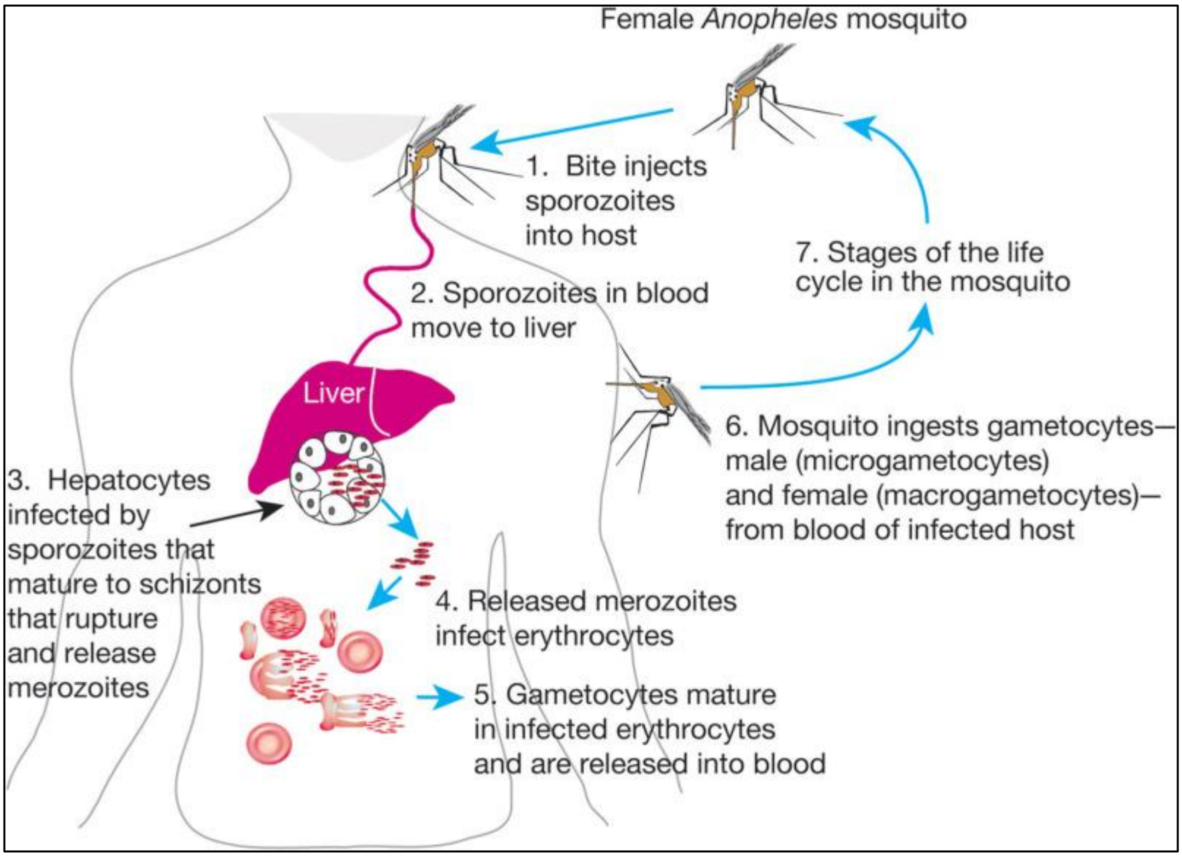


Fig. 10: Life cycle of Plasmodium falciparum, a parasitic protozoan that causes the most severe form of malaria in humans. The bite of the female Anopheles mosquito introduces sporozoites into the human host, which mature as they travel to the liver and ultimately the bloodstream. After a blood meal from an infected person, the malarial gametocytes enter the midgut of the mosquito where they transform into male microgametes and female macrogametes. Their union leads to a zygote, which transforms into an ookinete, penetrates the intestinal wall of the mosquito, and is transformed into a circular oocyst. Inside the oocyst, the sporozoites develop from germinal cells known as sporoblasts. The sporozoites emerge from the oocysts and migrate to the salivary gland where they enter the human hosts during the blood meal of the mosquito (Varki et *al*., 2022).

5-6-4 Subphylum Myxozoa (or Cnidosporidia)

Comprises protozoan parasites of invertebrates and fish that were historically grouped with the Sporozoa. Their developmental cycle begins with a small amoeboid germ cell known as the sporoplasm, whose growth leads to the formation of a large spore-bearing structure equipped with a polar filament. This process gives rise to multinucleated plasmodia that may induce tumor-like lesions in the host tissues (Lom & Dyková, 2006). Within these plasmodia, complex multicapsular spores are produced, each containing polar capsules and infectious sporoplasms responsible for host-to-host transmission (Okamura et *al*., 2015; Foissner, 2016).

5-6-5 Subphylum Ciliophora (or Ciliates) includes protozoans such as Paramecium

Characterized by the presence of vibratile cilia during at least one stage of their life cycle. Their cytoplasm exhibits a high degree of structural differentiation, and their nuclear apparatus is composed of two types of nuclei: a macronucleus and a micronucleus (Lynn, 2008). Asexual reproduction occurs through transverse binary fission, whereas sexual reproduction involves a distinctive fertilization process known as conjugation (Corliss, 2002).

Most ciliates are free-living heterotrophs, but some species exist as commensal symbionts within the rumen of ruminant mammals. Symbiosis refers to the intimate association between two organisms of different species. When one partner benefits without affecting the other, the relationship is termed commensalism for example, sea anemones attached to the shells of certain mollusks (Brusca et *al*., 2016). When both partners benefit, the association is mutualistic, as in lichens formed by algae and fungi. Conversely, when one organism benefits at the expense of the other, the interaction is parasitic, with one partner serving as the parasite and the other as the host **(Fig. 11 and 12)** (Lynn, 2008).

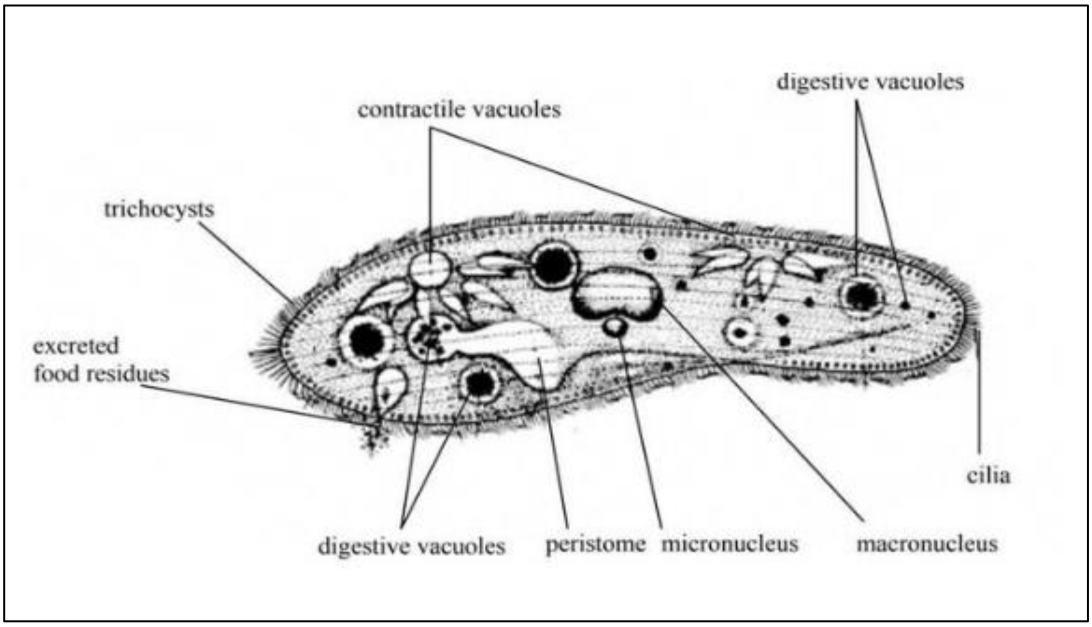


Fig. 11: Structure of *Paramecium* (Hausmann, 1985).

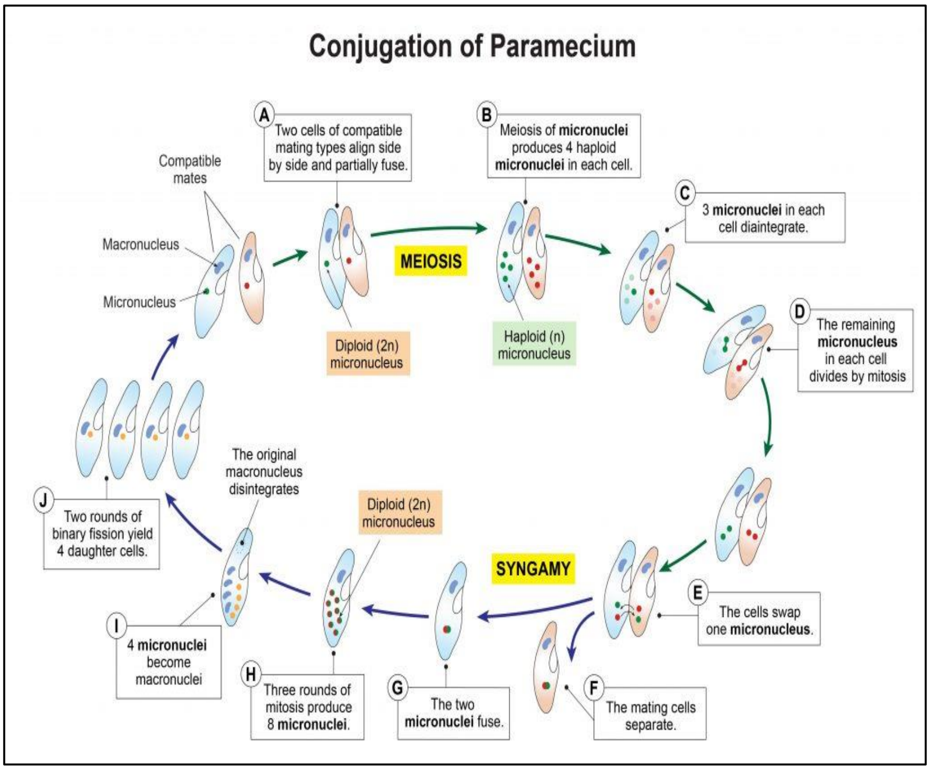


Fig. 12: Conjugation of *Paramecium caudatum* (Campbell, 2020).

IV- Chapter 3: The Animal Kingdom

***Part 01: Subkingdom of Metazoans, Invertebrates*.**

1- Specific Objectives of Part 01, Chapter 3: Subkingdom of Metazoans, Invertebrates

- Understand the diversity and evolutionary relationships of invertebrate animals.
- Recognize the transition from simple to complex body plans (diploblastic → triploblastic).
- Learn key structural and functional concepts: coelom, metamerism, protostomes vs. deuterostomes.
- Identify major invertebrate phyla and understand their morphology, physiology, reproduction, and ecological roles.
- Develop the ability to classify invertebrates based on their characteristics and adaptations.

2- General Overview

2-1 Introduction

Metazoans are characterized by the production of gametes through meiosis. They exhibit a cellular organization in which differentiated cells can aggregate to form tissues (Campbell et *al*., 2018) **(Fig. 13)**.

Key features include:

- **Epithelium:** This layer is in contact with the external environment and delineates the internal space, even when the external medium is internalized. Epithelial cells are often ciliated and secrete a cuticle (Gilbert, 2016).
- **Extracellular matrix (ECM):** Anchored to the basal lamina, the ECM contains integrins, which ensure cohesion between cells and the basal lamina, and cadherins, which mediate cell–cell adhesion (Alberts et *al*., 2015).
- **Connective tissue:** This consists of free, non-junctional cells embedded in a protein polymer matrix, such as collagen, which provides structural stability (Hall, 2015).

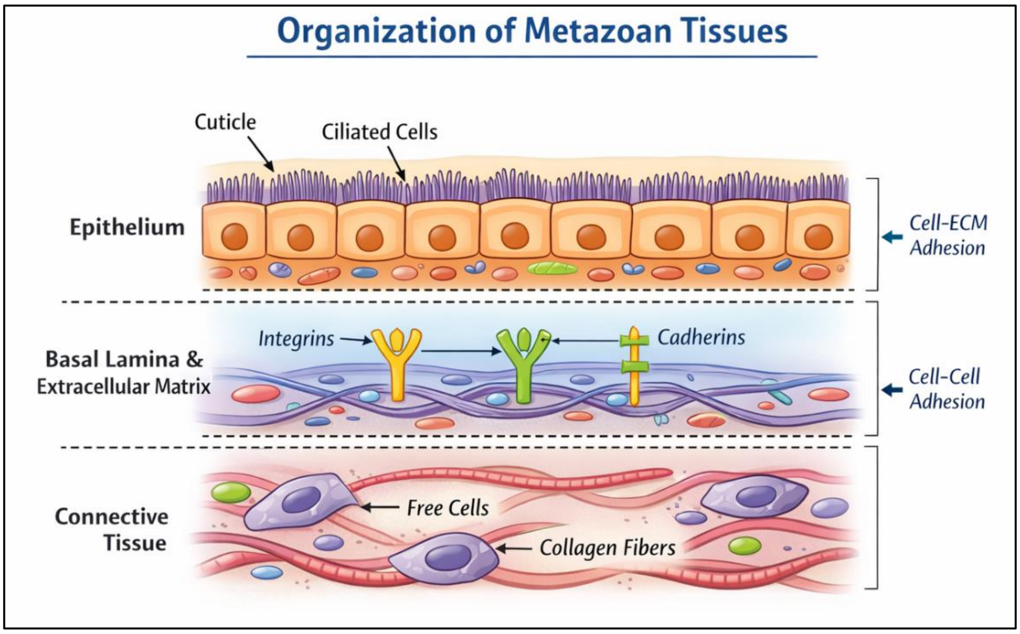


Fig. 13: Organization of metazoan tissues. Adapted from (Alberts et *al*., 2015).

2-2 Transition from Diploblastic to Triploblastic Animals

- **Appearance of the Mesoderm**

- The mesoderm is the third embryonic germ layer, located between the ectoderm and endoderm in eumetazoans, excluding cnidarians.

- It appears at the end of gastrulation.

This is associated with the establishment of bilateral symmetry in the Bilateria.

- **Synapomorphies of Bilaterians**

- Presence of the mesoderm
- Bilateral symmetry
- Digestive tube with two openings: mouth and anus
- Centralized nervous system
- Presence of an excretory system
- Hox gene complex controls the regionalization of the body along the anterior–posterior axis (Gilbert, 2016; Nielsen, 2012).

2-3 The Coelom

- The coelom is a body cavity formed by the mesoderm.
- It can develop in two ways:

- Schizocoely: solid mesodermal masses gradually hollow out to form a central cavity.

- Enterocoely: mesoderm emerges as hollow vesicles at the top of the archenteron (Campbell et al., 2018; Gilbert, 2016).

2-4 Metamerism

In many eumetazoans (but not all), the mesoderm fragments into repetitive units during development. Metamerism (or segmentation) refers to the posterior division of the body into repetitive anatomical units called metameres (or segments). Each metamere contains a pair of coelomic sacs formed within the mesoderm. Morphologically and anatomically, metamerism is reflected by the repetition of various organs within these metameres (Nielsen, 2012; Gilbert, 2016).

2-5 Protostomes and Deuterostomes

The primary synapomorphies distinguishing these groups are based on the fate of the blastopore:

- **Protostomes:** The blastopore becomes the mouth; the mesoderm forms through schizocoely.
- **Deuterostomes:** The blastopore becomes the anus first; the mesoderm forms via enterocoely (Campbell et *al*., 2018).

Coelom status in Bilateria:

- Some bilaterians lack a true coelom.
- Traditionally, the absence of a coelom was considered primitive, leading to the distinction of acoelomates / pseudocoelomates from coelomates.
- Modern phylogenetic analyses suggest that the absence of a coelom in some taxa is secondary loss, and the coelom is a synapomorphy of Bilateria. Consequently, coelom absence/presence is no longer a reliable criterion for bilaterian systematics, and the acoelomate and pseudocoelomate grades are discarded (Nielsen, 2012).

Synapomorphies of Protostomes:

- Mouth forms first at the blastopore site
- Coelom formed via schizocoely
- Ventral nervous system

Lophotrochozoa

- Includes numerous and highly diverse taxa.
- Phylogenetic relationships remain largely unresolved.
- Larvae of the trochophore type.
- Spiralians: exhibit spiral cleavage, in which cell division planes are oblique relative to the anterior-posterior axis; divisions are unequal, producing macromeres and micromeres.
- Determinate cleavage: the fate of each blastomere is fixed early; cell fate is generally consistent across taxa (Gilbert, 2016).

Ecdysozoa

- A more coherent group; phylogenetic relationships among taxa are better resolved.
- Characterized by a cuticle and growth via molting (ecdysis).

3- Diploblastic Metazoans

3-1 Phylum Porifera (Sponges)

3-1-1 General Characteristics

Sponges are multicellular, diploblastic organisms with an extremely primitive organization (Nielsen, 2012; Brusca & Brusca, 2003). Their various cell types lack fixed arrangement and permanent cohesion, and at any point in the body, the microscopic structure is identical, a condition known as the atissular state (Campbell et *al*., 2018; Hooper & Van Soest, 2002).

Sponges are devoid of defined organs or organ systems, including circulatory, respiratory, excretory, and reproductive systems (Bell, 2008; Wilkinson, 1983).

The inner cell layer is composed of collar cells (choanocytes), morphologically similar to protozoans called **choanoflagellates** (Nielsen, 2012; Leys & Ereskovsky, 2006). This similarity led some authors to classify sponges as an intermediate subkingdom, Parazoa, between protozoans and metazoans (Campbell et *al*., 2018).

Most sponges are marine, although some freshwater species exist (Bell, 2008). They are sessile and lack well-defined symmetry. Their forms vary from **tubular**, **massive (branching)**, **to encrusting**, depending on the substrate (Hooper & Van Soest, 2002) **(Fig. 14)**.

Sponges vary in size from a few millimeters up to one meter, yet all share an identical water canal system that connects the external environment to **the gastral cavity (spongocoel)**, facilitating water flow for **respiration and feeding** (Brusca & Brusca, 2003; Wilkinson, 1983).

Despite their simple organization, sponges possess a skeleton of spicules, composed of dense networks of calcium carbonate, silica, or organic material, providing structural support (Hooper & Van Soest, 2002; Nielsen, 2012).

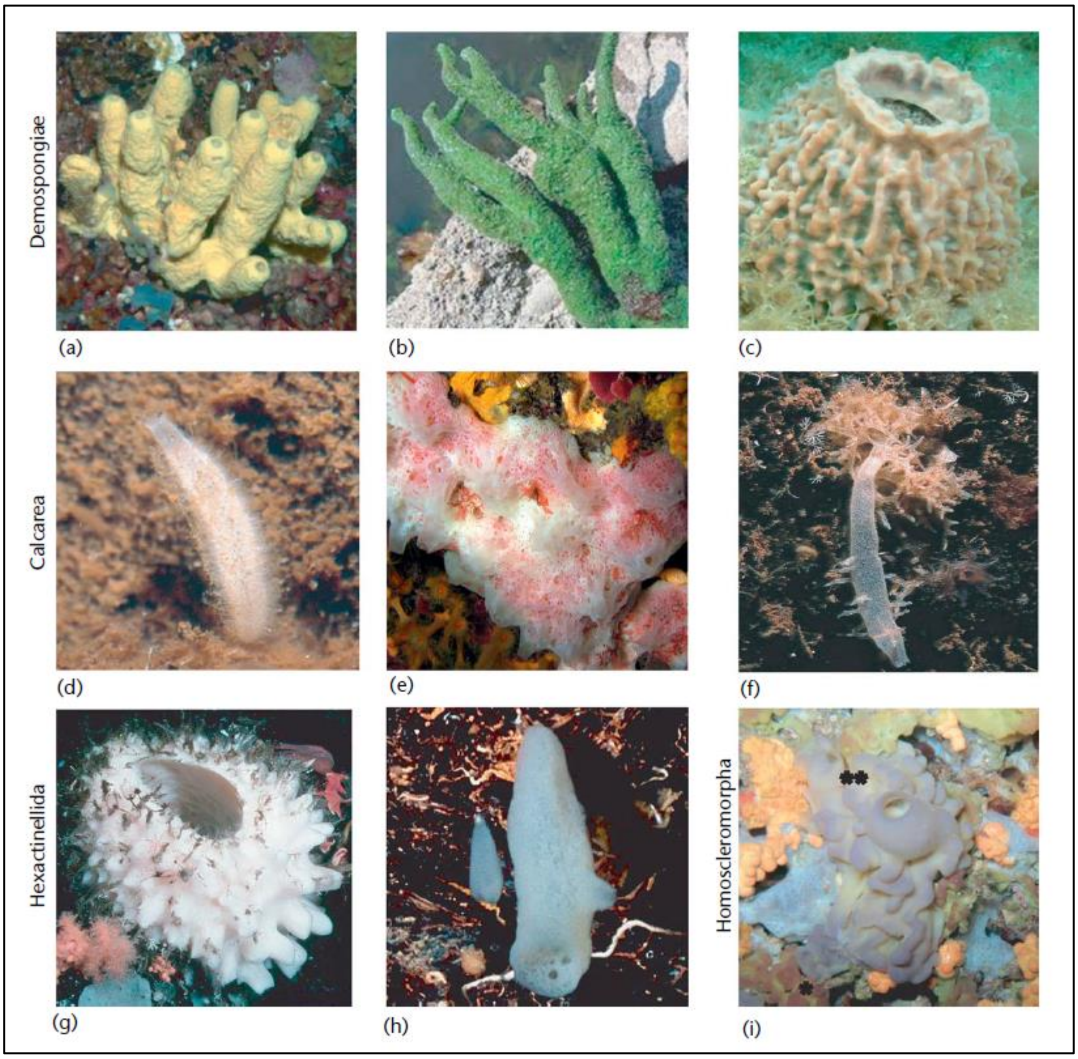


Fig. 14: Pictures illustrating the diversity of forms, colours and sizes in Porifera, with a few chosen examples from the four clades. (a) *Aplysina cavernicola*, (b) *Ephydatia fluviatilis*, (c) *Xestospongia muta*, (d) *Sycon ciliatum*, (e) *Clathrina contorta*, (f) *Leucosolenia complicata*, (g) *Rosella nuda*, (h) *Oopsacas minuta* and (i) *Oscarella species* (*Oscarella tuberculata* and *Oscarella lobularis*) (Renard et *al*., 2013).

3-1-2 Structure of Sponges

To better understand the structure of a sponge, we focus on the Olynthus type, which represents the juvenile stage of calcareous sponges and exhibits a simple organization (Brusca & Brusca, 2003; Nielsen, 2012).

The organism is hollow, small (approximately 1 cm), and urn-shaped, attached at its base, with a large opening at the opposite pole called **the osculum** (Hooper & Van Soest, 2002). This opening leads into the spacious gastral cavity, or spongocoel (Leys & Ereskovsky, 2006).

The body wall contains numerous small pores, arranged irregularly. Seawater continuously enters through these **inhalant pores** and exits through the osculum (Wilkinson, 1983) **(Fig. 15)**.

The sponge's survival depends **on this constant water flow**, which provides oxygen and food particles necessary for nutrition (Bell, 2008; Brusca & Brusca, 2003).

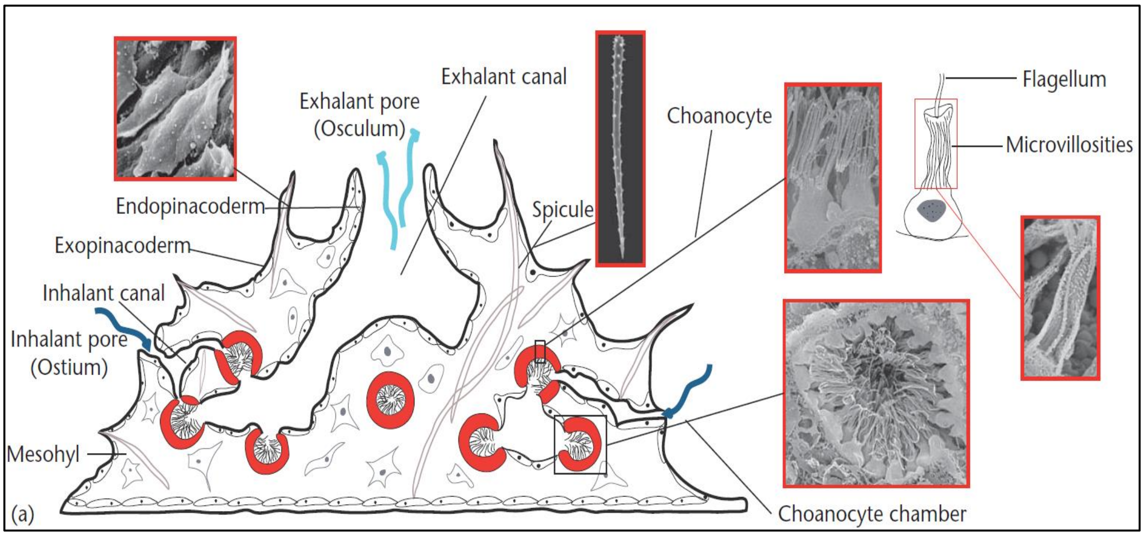


Fig. 15: General organisation of sponges (Renard et *al*., 2013).

The body wall of sponges is relatively thick and interrupted by numerous pores **(Fig. 16)** (Brusca & Brusca, 2003; Nielsen, 2012). It is organized into three main layers:

- **Ectoblast (outer layer / dermal layer):**

- Composed of pinacocytes, which are flattened, tightly connected cells covered by a thin cuticle.

- Inhalant pores open between these cells, allowing water to enter the sponge (Hooper & Van Soest, 2002).

- **Endoblast (inner layer / gastral layer):**

- Made up of flagellated collar cells (choanocytes).

- Choanocytes play a crucial role in maintaining strong water flow throughout the sponge, which brings nutrient particles, such as microplankton (Wilkinson, 1983).

- The arrangement of choanocytes determines the sponge's overall shape. These cells line either a large single cavity or smaller chambers connected by canals (Leys & Ereskovsky, 2006).

- **Mesoglea (middle layer):**

A gelatinous layer containing several specialized cell types:

- Porocytes: tubular "drain" cells that traverse the mesoglea and connect the outer and inner layers.

- Collencytes: more or less star-shaped, branched cells that interconnect and secrete the mesogleal gel.

- Amoebocytes: mobile cells that move by cytoplasmic deformation (similar to amoebae). They differentiate into specialized cell types such as gonocytes, phagocytes, and myocytes, the latter being contractile cells grouped around the osculum.

- Scleroblasts: cells that secrete spicules, forming the sponge skeleton.

- Nerve cells: fixed, spindle-shaped or pyramidal cells forming a rudimentary nervous system that establishes connections between pinacocytes and choanocytes (Brusca & Brusca, 2003; Hooper & Van Soest, 2002).

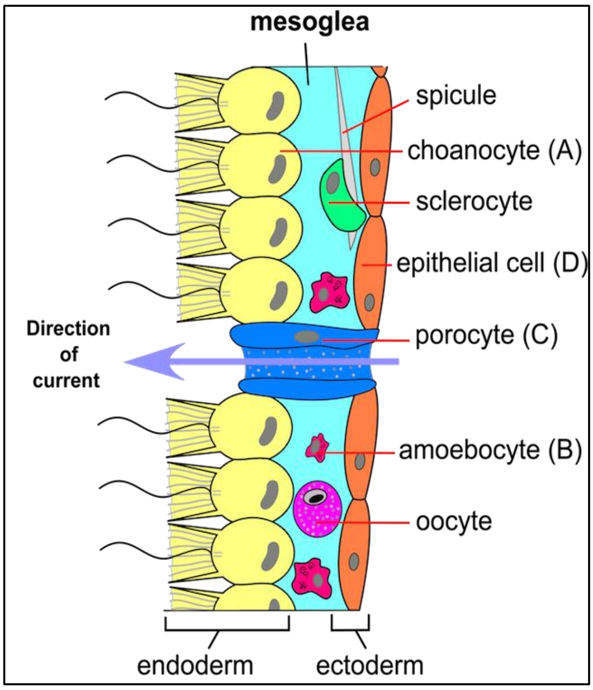


Fig. 16: Structure of the sponge body wall (Porifera), showing the pinacoderm, choanoderm, mesohyl, ostia (incurrent pores), osculum (excurrent opening), and specialized cells such as choanocytes, amoebocytes, porocytes, and sclerocytes (Brusca & Brusca, 2003).

3-1-3 Nutrition

Sponges are sessile, immobile, and active filter feeders. The choanocytes (endodermal cells) possess a flagellum whose beating ensures continuous water flow, supplying both oxygen and food particles, such as bacteria and unicellular algae (Brusca & Brusca, 2003; Nielsen, 2012; Maldonado & Riesgo, 2009).

Food particles carried by the water are **captured by pseudopodia or lobopodia**, cytoplasmic extensions at the base of the choanocyte collar. Captured prey is enclosed in **digestive vacuoles**, which are then transferred to underlying **amoebocytes** for distribution throughout the sponge (Hooper & Van Soest, 2002; Yahel et al., 2003).

Digestion is **intracellular**, beginning in the choanocytes and continuing within the amoebocytes (Leys & Ereskovsky, 2006; Wilkinson, 1983; Vacelet, 1991) **(Fig. 17)**. Filter feeding by sponges also plays a **key ecological role**, cycling nutrients and particulate matter in benthic ecosystems (Gili & Coma, 1998).

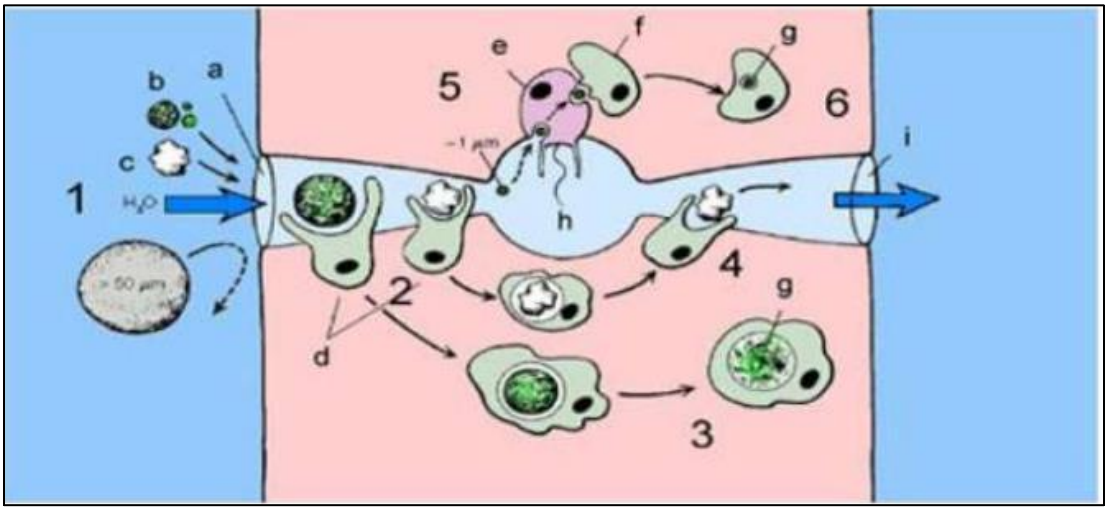


Fig. 17: Nutrition by Water Filtration in Syconoid and Leuconoid Sponges.
a: incurrent pore; b: organic particle; c: inorganic particle; d and f: amoebocyte (phagocyte); e: choanocyte; g: digestive vacuole; h: choanocyte chamber (vibratile basket); i: excurrent pore (Vacelet, 2016).

3-1-4 Reproduction

The majority of sponges are **hermaphroditic**, particularly **siliceous** sponges, whereas **calcareous** sponges are typically **gonochoric** (separate sexes) (Brusca & Brusca, 2003; Hooper & Van Soest, 2002). **Oocytes** and **sperm** fuse to produce a **swimming larva**, which eventually settles on a new substrate to develop into a mature sponge (Leys & Ereskovsky, 2006; Maldonado & Riesgo, 2009).

Sponges also reproduce asexually through small budding structures called **gemmules**. Each gemmule can develop into a **new sponge**, allowing the species to persist under unfavorable environmental conditions (Wilkinson, 1983; Vacelet, 1991).

3-1-5 Classification of Sponges

Sponges belong to the phylum Porifera. Their classification is primarily based on the composition and structural organization of the skeletal supporting elements (Brusca & Brusca, 2003; Hooper & Van Soest, 2002). Sponges typically produce a free-swimming larva that later settles on a substrate, and they are also capable of asexual reproduction by budding.

3-1-5-1 Calcareous sponges or Calcisponges

Calcareous sponges constitute an important group of **small-sized forms**, characterized by a relatively light skeleton composed of **calcite spicules**. These sponges are **exclusively marine**, occurring from the surface down to approximately **100 meters depth**. Their classification is mainly based on **the distribution of choanocytes**, allowing the distinction of **two subclasses** (Ruppert et *al*., 2004; Brusca & Brusca, 2003):

- **Homocoelous sponges:**

Choanocytes line the **entire gastral cavity**, corresponding to a simple organization known as the **asconoid type (Fig. 18)**.

These sponges exhibit an **asconoid organization**, often **urn-shaped**, in which the gastral cavity represents **the only flagellated chamber**.

Examples include: *Leucosolenia* and *Clathrina* (Hooper & Van Soest, 2002).

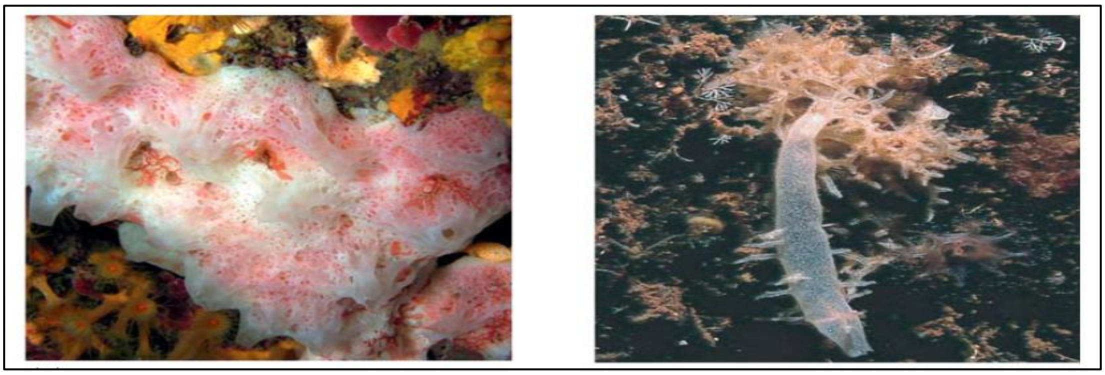


Fig. 18: Pictures illustrating calcareous sponges, for example: *Clathrina contorta*, and *Leucosolenia complicata*, (Renard et *al*., 2013).

➢ **Heterocoelous sponges:**

Choanocytes are localized within **diverticula of the gastral cavity**, resulting in more complex organizations of **the syconoid** and **leuconoid types (Fig. 19)**.

These sponges display increasingly complex body plans:

- Syconoid stage:

Choanocytes are confined to **tubular diverticula**, known as **flagellated chambers**, which open through small apertures called **apopyles** into a central axial cavity, **the atrium**, lined with pinacocytes (e.g., *Sycon raphanus*) (Ruppert et *al*., 2004).

- Leuconoid stage:

Each primary diverticulum is subdivided into **secondary diverticula**, forming numerous **small flagellated** chambers where choanocytes are located. These chambers open into a complex network of **exhalant canals**, lined with pinacocytes and connected to the atrium, greatly increasing filtration efficiency (Brusca & Brusca, 2003; Maldonado et *al*., 2012).

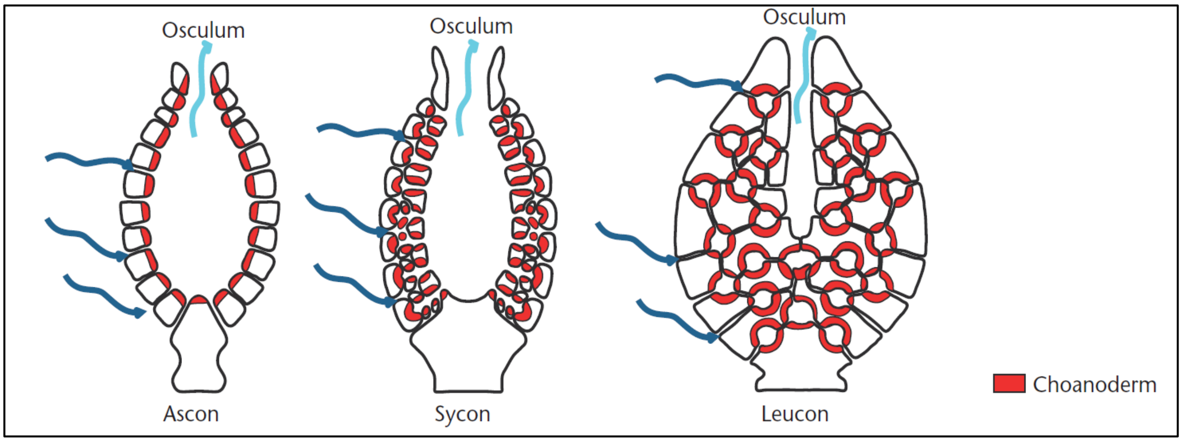


Fig. 19: The three main levels of complexity of the aquiferous system (Renard et *al*., 2013).

3-1-5-2 Demosponges or corneous–siliceous sponges

Demosponges represent **the largest class of Porifera**, including **the few freshwater species** known among sponges (Hooper & Van Soest, 2002). Their skeleton is mainly composed of **spongin**, a flexible proteinaceous material, and generally **lacks hard calcareous spicules**, although many species also possess **siliceous spicules** for additional support (Ruppert et *al*., 2004).

The simplest organizational form in demosponges corresponds to **the rhagon stage**, which resembles a **flattened syconoid structure** and is considered a key developmental form **(Fig. 20)**.

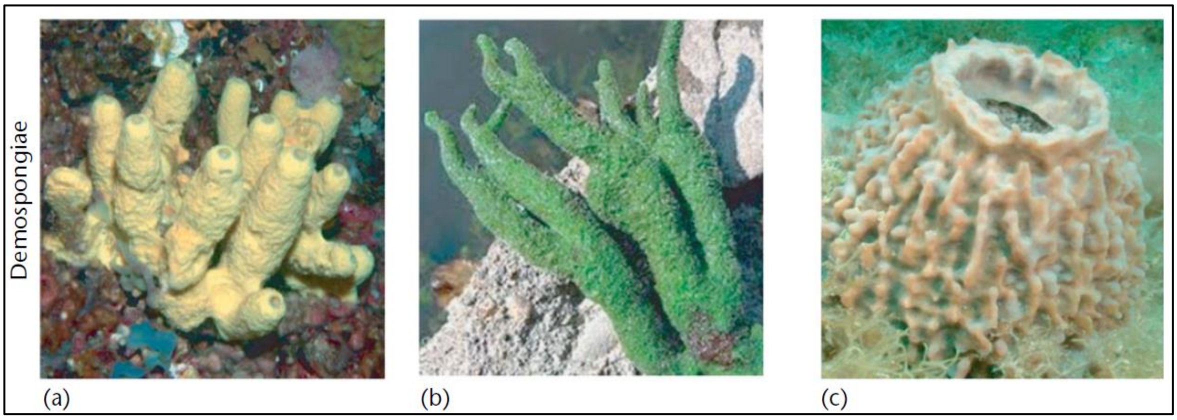


Fig. 20: Pictures illustrating desmosponges, for example: (a) *Aplysina cavernicola*, (b) *Ephydatia fluviatilis*, (c) *Xestospongia muta* (Renard et *al*., 2013).

3-1-5-3 Hexactinellids (glass sponges)

Hexactinellids, commonly referred to as **glass sponges**, are characterized by a skeleton composed **exclusively of silica**. Their spicules are arranged in elaborate geometric patterns and are typically **hexactine (triaxon) spicules**, consisting of **three perpendicular axes** forming six rays. This distinctive skeletal architecture provides rigidity and lightness and is particularly adapted to **deep-sea environments** (Leys et *al*., 2007; Brusca & Brusca, 2003) **(Fig. 21)**.

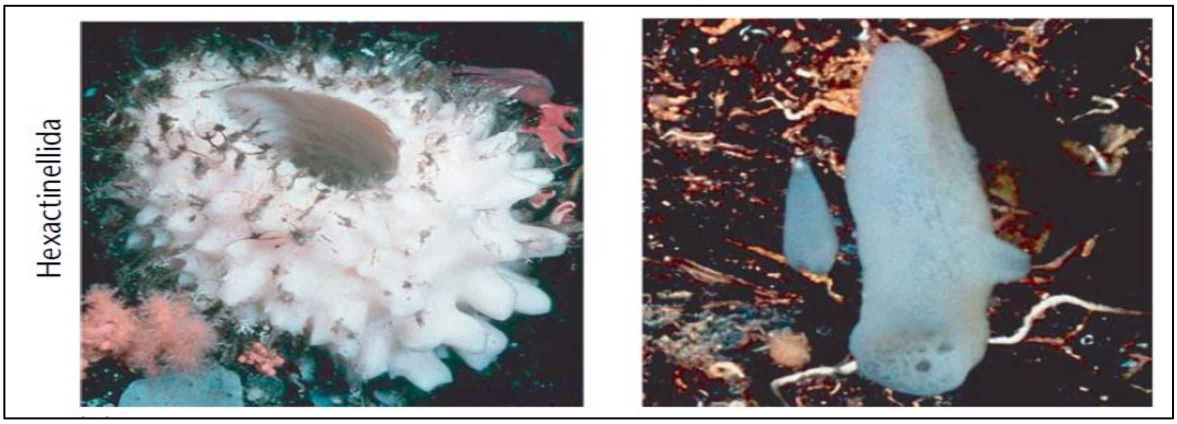


Fig. 21: Pictures illustrating Hexactinellids, for example: *Rosella nuda* and *Oopsacas minuta* (Renard et *al*., 2013).

3-2 Phylum Cnidaria

3-2-1 General Characteristics

The phylum Cnidaria represents a pivotal evolutionary lineage positioned between the earliest multicellular organisms and the more complex metazoans that emerged subsequently. This group is of particular biological interest due to several distinctive morphological and developmental features (Brusca et *al*., 2016; Ruppert et *al*., 2004).

Cnidarians exhibit a fundamentally radial body symmetry, a structural organization that imposes significant ecological and functional constraints on their mode of life. Radial symmetry is generally associated with a sessile or planktonic existence, in which interaction with the environment occurs in all directions rather than along a defined anterior–posterior axis. Consequently, cnidarians lack a centralized nervous system and instead possess a diffuse nerve net distributed throughout the body wall (Brusca et *al*., 2016; Hickman et *al*., 2017).

Members of this phylum are diploblastic, developing from two primary embryonic germ layers: the ectoderm and the endoderm, separated by a non-cellular mesoglea. They represent the earliest metazoans to reach a true tissue level of organization (cell–tissue grade), marking a key step in animal evolution (Ruppert et *al*., 2004). The emergence of radial symmetry appears to have occurred concurrently with diploblasty, and no diploblastic organisms exhibiting true bilateral symmetry are recognized among extant metazoans (Brusca et *al*., 2016).

Cnidarians are exclusively predatory organisms that capture and subdue their prey using highly specialized stinging cells known as cnidocytes (historically termed cnidoblasts). These cells contain intracellular organelles called nematocysts, which function in prey adhesion, penetration, envenomation, or entanglement. The discharge of nematocysts is one of the most rapid cellular processes known in animals and represents a key synapomorphy of the phylum (Brusca et *al*., 2016; Ruppert et *al*., 2004).

The cnidarian life cycle is also distinctive and typically exhibits metagenesis (alternation of generations), resulting in a dimorphic life cycle that includes two morphologically and functionally different stages: the polyp and the medusa **(Fig. 22)**. The polyp stage is generally sessile and reproduces asexually (e.g., by budding), whereas the medusa stage is usually free-swimming and responsible for sexual reproduction. The relative dominance and development of these two stages vary among the different cnidarian classes, providing important taxonomic and evolutionary distinctions within the phylum (Hickman et *al*., 2017; Ruppert et *al*., 2004).

3-2-2 Architecture and Classification of Cnidarians

The term *Cnidaria* derives from the Greek knidē (nettle) and the Latin suffix -aria ("resembling"), referring to the presence of specialized stinging cells cnidocytes (also called cnidoblasts) distributed over the body surface. These cells are diagnostic of the phylum and contain nematocysts used in prey capture and defense (Brusca et *al*., Moore, & Shuster, 2016; Ruppert et *al*., 2004).

Cnidarians are radially or biradially symmetrical animals whose body wall is composed of two primary germ layers: an outer ectoderm (epidermis) and an inner endoderm (gastrodermis), separated by a gelatinous extracellular matrix known as the mesoglea (sometimes referred to as mesenchyme or mesohyl in broader invertebrate contexts). This diploblastic organization reflects an early evolutionary stage in metazoan tissue differentiation (Hickman et *al*., 2017; Ruppert et *al*., 2004).

The general architecture of cnidarians superficially resembles that of asconoid sponges in that the body can be described as a double-layered sac enclosing a central cavity. However, unlike sponges (Porifera), cnidarians possess true tissues, including nerve cells and muscle-like contractile cells, marking a higher level of structural organization (Brusca et *al*., 2016). The mouth is typically surrounded by tentacles armed with cnidocytes and opens into a gastrovascular cavity (coelenteron), which functions in both digestion and distribution of nutrients. Most cnidarians exhibit two distinct morphological stages during their life cycle: a generally planktonic medusa stage and a typically benthic, sessile polyp stage. The relative development and predominance of these stages form the basis for classification within the phylum (Hickman et *al*., 2017; Ruppert et *al*., 2004).

- **Medusae** are free-swimming (nektonic or planktonic) forms characterized by **an umbrella-shaped body** (bell) **(Fig. 22)**. The mouth is oriented downward and is borne on a tubular structure known as the manubrium, which hangs from the center of the subumbrellar surface. This mouth opens into a centrally located gastrovascular cavity.

The gastrovascular cavity extends into radial canals distributed throughout the bell, ensuring both digestion and internal nutrient distribution. The margin of the bell is typically lined with tentacles armed with numerous cnidocytes (cnidoblasts), which are especially concentrated along these appendages and play a primary role in prey capture and defense (Brusca et *al*., 2016; Ruppert et *al*., 2004).

In most cnidarian groups, sexual reproduction occurs predominantly during the medusa stage. Gametes are generally produced in specialized gonads, and fertilization leads to the formation of a ciliated planula larva, which eventually settles and develops into a polyp stage, thereby completing the life cycle (Hickman et *al*., 2017; Ruppert et *al*., 2004).

- **Polyps** generally exhibit a cylindrical body form and are typically sessile, attaching to the substrate by means of a **pedal disc** (basal disc) **(Fig. 22)**. This attachment structure anchors the organism firmly to rocks, shells, or other benthic surfaces.

The oral region is usually oriented upward and is surrounded by a crown of tentacles armed with cnidocytes. These tentacles encircle the mouth and play a central role in prey capture and food transfer to the gastrovascular cavity. The polyp body wall, like that of other cnidarian forms, is diploblastic and encloses a single gastrovascular cavity that functions in digestion and internal nutrient distribution (Brusca et *al*., 2016; Hickman et *al*., 2017; Ruppert et *al*., 2004).

In many cnidarian classes, the polyp stage is responsible primarily for asexual reproduction (e.g., budding), although in some groups it may also contribute to sexual reproduction. The structural organization of the polyp reflects the typical radial symmetry and tissue-level organization characteristic of the phylum.

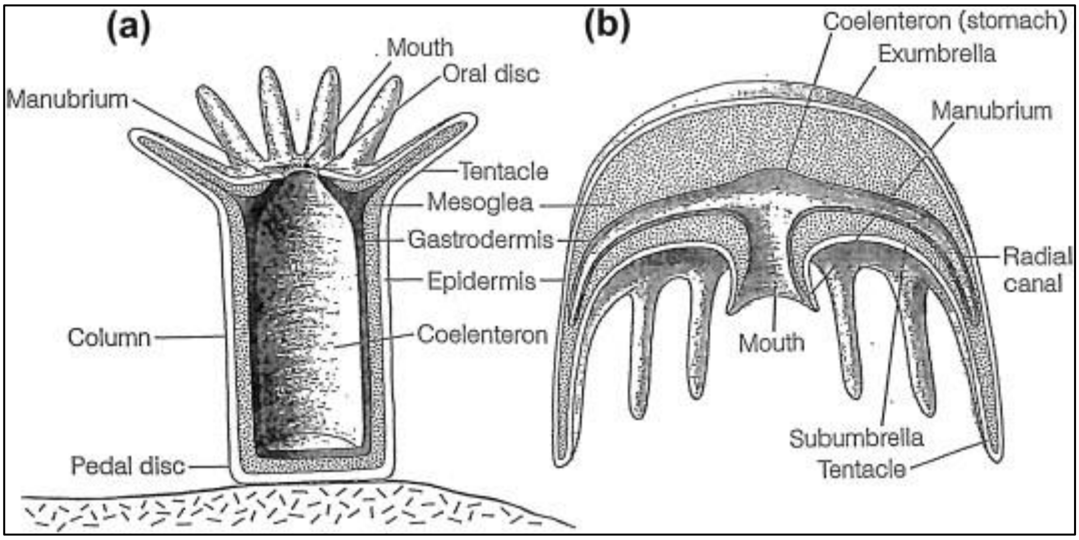


Fig. 22: Schematics of the two body forms present in the phylum Cnidaria: (a) represents the sessile polyp and (b) represents the motile medusa (Rupert et *al*., 2004).

The principal classes of cnidarians are distinguished, among other criteria, by the relative importance and developmental predominance of the polyp and medusa forms within the life cycle (Brusca et *al*., 2016; Hickman et *al*., 2017) **(Fig. 23)**.

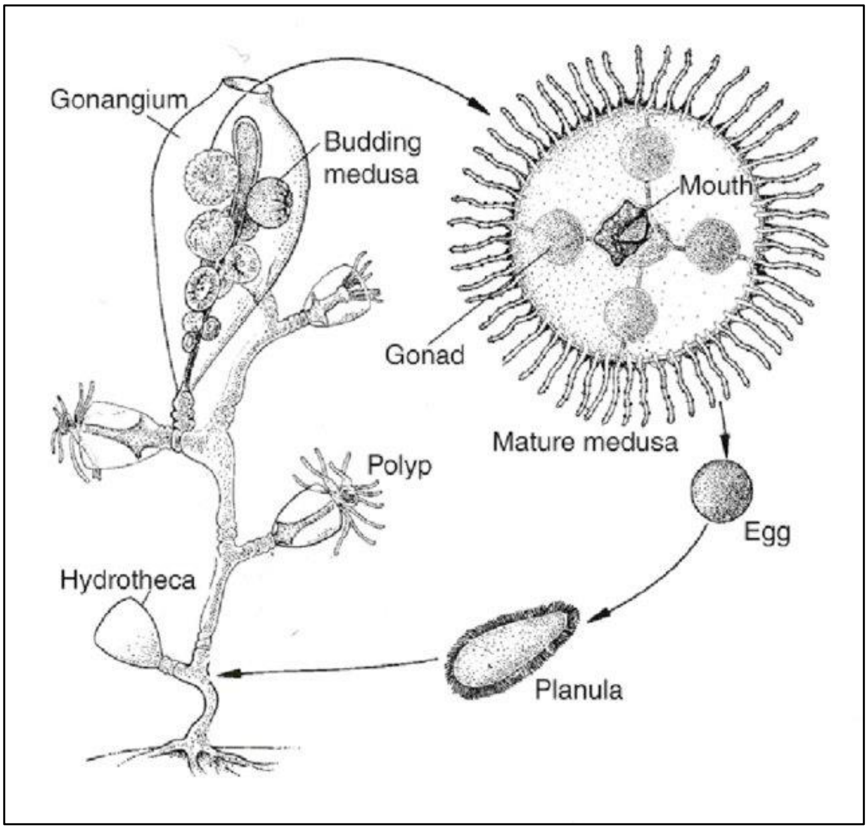


Fig. 23: Life cycle of a Leptomedusae *Obelia geniculata* (Telesh et *al*., 2008).

- **Hydrozoa:** In hydrozoans, both body forms are generally present and are of approximately equal importance in the life cycle. The polyp stage is often colonial and may reproduce asexually by budding, whereas the medusa stage is typically smaller. An important exception is the freshwater genus Hydra, in which the medusa stage is absent and the polyp form is dominant (Ruppert et *al*., 2004).
- **Scyphozoa:** In scyphozoans (the "true jellyfish"), the medusa stage is dominant and represents the most conspicuous phase of the life cycle. The polyp stage (scyphistoma) is usually small, short-lived, and often overlooked. Sexual reproduction typically occurs in the medusa, followed by the development of a planula larva and subsequent polyp formation.
- **Anthozoa:** The name Anthozoa derives from the Greek anthos **("flower")**, reflecting the flower-like appearance of many species. In this class, the polyp stage is dominant and permanent, and there is generally no medusa stage. Members include corals and

sea anemones, which reproduce sexually and/or asexually exclusively in the polyp form (Brusca et *al*., 2016).

A fourth class, **Cubozoa** (box jellyfish), is recognized by most modern classifications, although some earlier zoologists considered it an order within Scyphozoa. Cubozoans are characterized by a cube-shaped bell and tentacles grouped at the four lower corners of the umbrella. They possess comparatively complex sensory structures and are often highly active swimmers (Hickman et *al*., 2017).

Thus, variation in the dominance, reduction, or absence of either the polyp or medusa stage constitutes a fundamental basis for cnidarian classification and reflects evolutionary diversification within the phylum.

3-2-3 Locomotion and Support in Cnidarians

Medusae are relatively weak swimmers, and ocean currents constitute their principal means of dispersal. Nevertheless, they must maintain their position within the water column. This is achieved through both passive and active mechanisms.

Passively, medusae possess a body density close to that of seawater, causing them to sink slowly. Their umbrella-shaped bell increases surface area and hydrodynamic resistance, thereby reducing the rate of descent.

Actively, medusae swim by rhythmic contraction of the bell. Contraction of the subumbrellar musculature expels water downward, generating jet propulsion that moves the animal upward. This pulsatile locomotion allows limited directional control, although most displacement remains current-driven (Brusca et *al*., 2016; Hickman et *al*., 2017).

In certain colonial cnidarians, such as the Portuguese man-of-war, *Physalia physalis*, the colony is not sessile but instead drifts at the sea surface. This organism is a siphonophore composed of a highly integrated colony of specialized polyps (zooids). Some zooids are specialized for reproduction (gonozooids), whereas others perform somatic functions such as feeding or defense (autozooids).

The Portuguese man-of-war possesses a gas-filled float (pneumatophore) that enables buoyancy and also functions as a sail, facilitating wind-driven movement across the ocean surface (Ruppert, Fox, & Barnes, 2004).

The presence of a gastrovascular cavity and a mouth capable of closing (unlike the permanently open osculum of sponges) allows cnidarians to function with a hydrostatic skeleton. This skeletal system consists of the fluid-filled gastrovascular cavity enclosed by muscular body walls. Because water is incompressible, the body volume remains constant when the mouth is closed.

Contraction of epitheliomuscular cells in the epidermis forms longitudinal muscles, which shorten the body and retract the tentacles. In contrast, circular muscles located primarily in the gastrodermis elongate the body when contracted.

The presence of antagonistic muscle groups (longitudinal versus circular muscles) permits active extension following contraction, rather than relying solely on passive elastic recoil of muscle fibers. This antagonistic arrangement enhances movement efficiency and provides controlled changes in body shape (Brusca et *al*., 2016; Hickman et *al*., 2017) **(Fig. 24)**.

In certain anthozoans, such as sea anemones, the gastrovascular cavity is subdivided by internal septa (mesenteries). This compartmentalization enhances the efficiency of the hydrostatic skeleton because antagonistic muscle contractions can be localized within specific regions of the body rather than involving the entire musculature simultaneously. As a result, movements become more precise and mechanically controlled (Brusca et *al*., 2016; Ruppert et *al*., 2004).

Gland cells located in the pedal disc of polyps secrete adhesive substances that enable firm attachment to the substrate. Nevertheless, many species including hydras and sea anemones are capable of detaching and relocating. Hydras commonly move by a characteristic "somersaulting" motion, alternately attaching the tentacles and pedal disc. Sea anemones may slowly glide or detach entirely.

In some cases, these organisms accumulate a gas bubble within the gastrovascular cavity, allowing temporary flotation in the water column and passive dispersal by currents. Certain sea anemones are even capable of limited swimming movements by coordinated rowing motions of their tentacles (Hickman et *al*., 2017).

Corals combine two supportive systems: a hydrostatic skeleton that facilitates tentacular movement and a rigid calcareous endoskeleton (composed primarily of calcium carbonate) that provides structural support to the colony. This mineralized skeleton is fundamental to reef formation and colony stability (Ruppert et *al*., 2004).

3-2-4 Respiration and Circulation

Cnidarians rely primarily on diffusion for gas exchange. Because their body wall typically consists of only two cellular layers an outer epidermis (ectoderm) and an inner gastrodermis (endoderm) lining the gastrovascular cavity most cells are in close proximity to either the external environment or the internal cavity. This short diffusion distance eliminates the need for specialized respiratory or circulatory systems (Brusca et *al*., 2016; Hickman et *al*., 2017). Nutrient distribution is similarly accomplished without a true circulatory system. Amoeboid cells within the mesoglea facilitate the transport of nutrients from gastrodermal cells to epidermal tissues. In addition, the gastrovascular cavity itself plays a dual role in digestion and internal distribution of dissolved nutrients (Ruppert et *al*., 2004).

3-2-5 Feeding and Digestion

Most cnidarians are carnivorous predators that feed on plankton, protozoans, and small fish. Prey is captured and immobilized using cnidocytes located on the tentacles. These cells often contain toxins capable of paralyzing or killing prey. Once subdued, the prey is transported to the mouth by coordinated tentacular movements (Brusca et *al*., 2016).

Digestion in cnidarians is both extracellular and intracellular. Gastrodermal cells secrete mucus and digestive enzymes into the gastrovascular cavity, where extracellular digestion begins. The gastrodermal cells are flagellated, and the beating of their flagella circulates water, food particles, and enzymes within the cavity, enhancing digestive efficiency.

Partially digested food particles are subsequently taken up by phagocytosis into gastrodermal cells, where digestion is completed intracellularly within membrane-bound digestive vacuoles. Undigested material is eventually expelled through the mouth, as cnidarians possess a single opening that serves both ingestion and egestion (Hickman et *al*., 2017; Ruppert et *al*., 2004) **(Fig. 24)**.

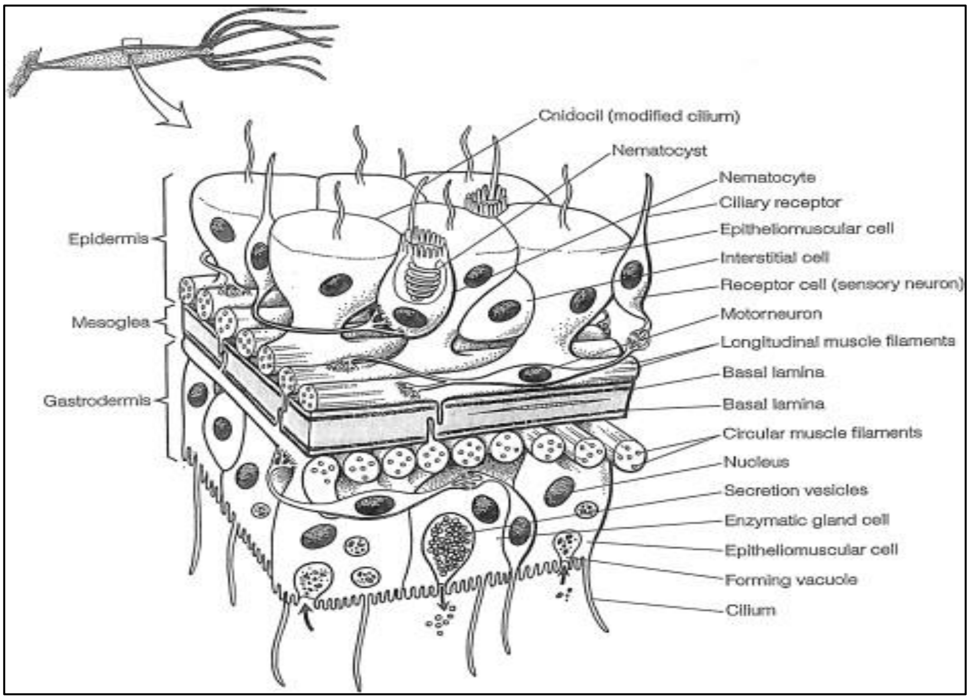


Fig. 24: A cross-section of Hydra representing the two tissue layers typical of Cnidaria, the outer epidermis and inner gastrodermis. The mesoglea is a gelatinous non-tissue layer between the two (Rupert et *al*., 2004).

In anthozoans, a unique structure called **the siphonoglyph** is present. This is a ciliated groove located at each end of the elongated mouth. The ciliary beating within the siphonoglyph circulates water into the gastrovascular cavity, facilitating internal flow and enhancing contact between food particles and gastrodermal cells. Additionally, the cells of the siphonoglyph secrete mucus, which lubricates the mouth and pharynx, easing the passage of prey into the cavity (Brusca et *al*., 2016; Hickman et *al*., 2017).

The presence of **septa** (mesenteries) in sea anemones increases the surface area for absorption and digestion, improving interaction between the gastrodermal cells and the contents of the cavity.

Cnidarians have a single opening serving as both mouth and anus, forming an **incomplete digestive system**. This arrangement is less efficient than a complete digestive tract because partially digested food, digestive waste, and newly ingested prey are mixed within the gastrovascular cavity. Consequently, it is difficult to maintain concentration gradients of nutrients and metabolic wastes across the gastrodermal cell membranes, which limits the efficiency of digestion and nutrient absorption (Ruppert et *al*., 2004).

3-2-6 Excretion and Osmoregulation

Marine cnidarians are **isosmotic** with seawater, and therefore generally face no challenges in osmoregulation. Nitrogenous wastes are primarily excreted as **ammonia**, which diffuses directly into the surrounding water (Brusca et *al*., 2016; Hickman et *al*., 2017).

Freshwater cnidarians, such as hydras, are hypertonic relative to their environment. Excess water enters the body by osmosis and must be eliminated actively. Water is expelled through the gastrodermal cells, while membrane-bound proteins actively transport ions to compensate for diffusive losses, maintaining ionic balance in a hypotonic medium (Ruppert et *al*., 2004).

3-2-7 Sensory and Nervous System

Cnidarians lack a head and brain. Their sessile or planktonic lifestyle means they can encounter prey or predators from any direction, making centralized nerve concentrations less advantageous.

They possess a **primitive nerve net**, composed of approximately 100,000 neurons in some species. These neurons are in contact with contractile cells of the epidermis and gastrodermis and extend processes across both layers. The nerve net coordinates muscle responses, which are classified as slow or fast, depending on the diameter of the nerve fibers involved (Brusca et *al*., 2016).

Cnidarians also have **sensory cells** that detect chemical and tactile stimuli in the epidermis and gastrodermis. Polyps usually lack specialized sensory organs, whereas medusae often possess **photoreceptor cells** and gravity-sensing structures called **statocysts**. A simple statocyst consists of a small sac of ciliated sensory cells containing fluid and calcium sulfate statoliths. The cilia detect orientation, allowing the animal to distinguish the direction of the substrate from that of the water surface (Hickman et *al*., 2017; Ruppert et *al*., 2004).

3-2-8 Reproduction

Cnidarians typically exhibit both **sexual** and **asexual reproduction**. Meiosis occurs during gamete production, so both medusae and polyps are diploid.

- **Asexual reproduction (polyp stage):** Polyps reproduce by budding, binary fission, or regeneration. In some species, specialized cells can revert to earlier forms, allowing flexibility in colony growth.

- **Sexual reproduction (medusa stage):** Medusae produce gametes that are released into the water for **external fertilization**. The resulting zygote develops into a ciliated, planktonic **planula larva**, which eventually settles and develops into a new polyp, completing the life cycle (Brusca et *al*., 2016; Hickman et *al*., 2017; Ruppert et *al*., 2004).

3-2-9 Defense Mechanisms

Cnidarians possess highly effective **defense mechanisms**. Their **cnidocytes** release toxins capable of producing painful stings, deterring predators and potential threats. Divers familiar with the discomfort of cnidarian stings sometimes use **proteolytic enzymes** (similar to meat tenderizers) to neutralize these toxins (Brusca et *al*., 2016; Ruppert et *al*., 2004).

In corals, the rigid **calcareous endoskeleton** provides mechanical protection against predatory fish, reducing damage to the colony.

3-2-10 Ecology

Cnidarians are generally **carnivorous**, preying on plankton, protozoans, and small fish. However, some sea anemones produce **cellulases**, enabling partial digestion of plant material.

They themselves serve as prey for various fish, mollusks, and crustaceans. Polyps secrete large amounts of **mucus** to remove sediment particles from their surface, which also serves as a food source for many coral reef fishes. Certain flatworms can consume polyps without triggering cnidocyte discharge and incorporate the stinging cells into their own epidermis for protection, a process called **kleptocnidae**.

A classic example of symbiosis is **the sea anemone** and **clownfish** association. The fish is coated in the anemone’s mucus, preventing recognition as prey. The anemone provides protection, while the fish consumes waste from the anemone and acts as a lure, attracting additional prey (Brusca et *al*., 2016; Hickman et *al*., 2017).

Many corals host **photosynthetic algae** (zooxanthellae) within vacuoles. These algae supply sugars that nourish the coral and assist in the removal of nitrogenous wastes, establishing a mutualistic relationship critical for coral reef productivity.

3-3 Phylum Ctenophora

3-3-1 Introduction

Ctenophores are small, **marine predatory organisms** that superficially resemble jellyfish but differ in key anatomical and functional traits. They constitute a significant portion of the **planktonic biomass** in the world's oceans. Their name derives from the comb-like rows of locomotory cilia, called **ctenes**, arranged in quasi-symmetrical longitudinal rows along the body (Brusca et *al*., 2016; Ruppert et *al*., 2004).

Unlike cnidarians, ctenophores lack stinging cnidocytes. Instead, they capture prey using colloblasts, specialized adhesive cells that secrete a sticky substance to immobilize prey. Well-known species include **the sea gooseberry (*Pleurobrachia*)** and **the Venus girdle (*Cestum veneris*)**. All ctenophores are hermaphroditic, producing both male and female gametes (Hickman et *al*., 2017).

3-3-2 Lifestyle and Locomotion

Although ctenophores are largely **drifted by ocean currents**, they are capable of active swimming. Locomotion is achieved by coordinated beating of **the comb-like ciliary rows** along the body. Their translucent bodies have a gelatinous, often iridescent appearance, which can produce **bioluminescent light** or reflect ambient light in flashes of color during movement.

Ctenophores inhabit **all oceans**, from surface waters down to approximately 4,000 meters depth, including both marine and brackish environments. They are particularly abundant in **tropical regions** as well as near both the Arctic and Antarctic poles (Brusca et *al*., 2016; Hickman et *al*., 2017; Ruppert et *al*., 2004) **(Fig. 25)**.

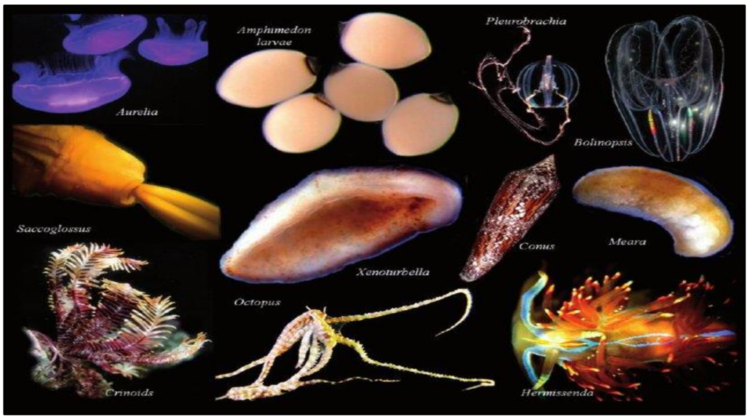


Fig. 25: These are illustrative examples of species representing the phylum Ctenophora (Moroz, 2015).

3-3-3 Morphology of Ctenophores

Ctenophores exhibit **diverse body morphologies**, including ovoid, ribbon-like, pear-shaped, or bell-shaped forms. Most species possess approximately **eight rows of ciliary plates** (ctenes) along the base of the body, which function as the primary means of propulsion.

The majority of ctenophores have **two long tentacles**, which are retracted into specialized sheaths while swimming. These tentacles are exclusively used for **prey capture**, often coated with adhesive colloblasts.

Ctenophores demonstrate an extraordinary **regenerative capacity**. Even when severely damaged, the organism can fully regenerate its body. Certain structures, such as statocysts (balance organs), are capable of complete regeneration even after total destruction (Brusca et *al*., 2016; Hickman et *al*., 2017).

Morphologically, ctenophores are generally **biradial**, but they display localized asymmetries in structures such as pores, the anal region, ctenes, and statocysts. The statocysts consist of **calcified cells resting on ciliated structures**, which exert pressure according to the orientation of the organism. Sensory stimulation from these organs is transmitted to the ectoderm, allowing the ctenophore to restore horizontal balance by adjusting the beat of its locomotory cilia (Ruppert et *al*., 2004).

Although formidable predators, ctenophores are among **the most graceful creatures of the oceans**. Their unusual shapes, delicate bodies, and shimmering iridescent colors produced by reflected light along the ciliary rows give them an almost **alien appearance**, evoking the impression of "marine extraterrestrials."

4- Triploblastic Metazoans

4-1 Phylum Platyhelminthes

4-1-1 Introduction

Platyhelminthes are among **the most primitive triploblastic acoelomates**, inhabiting marine, freshwater, or terrestrial environments. They may be free-living or parasitic. These flatworms exhibit a **dorso-ventrally flattened body**, and their general body cavity is a **gastrocoel** filled with parenchyma (Brusca et *al*., 2016; Ruppert et *al*., 2004) **(Fig. 26)**.

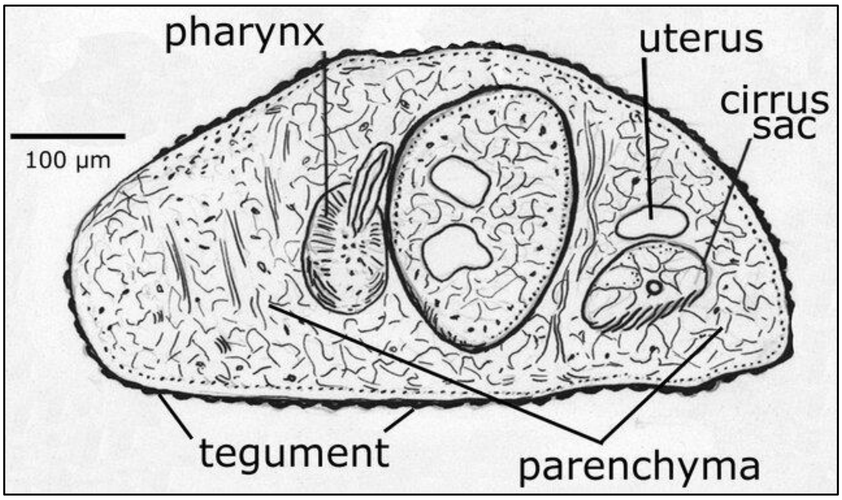


Fig. 26: Cross section of a parasitic trematode showing the lack of ciliated epithelium (Gardner & Gardner, 2024).

Platyhelminthes **lack both a circulatory** and **respiratory system**; gas exchange occurs directly across **the tegument**. The digestive system is **incomplete**, with only one opening serving as both mouth and anus. The excretory system is of **the protonephridial type**, consisting of flame cells connected to tubules that regulate osmotic balance and remove nitrogenous wastes **(Fig. 27)**.

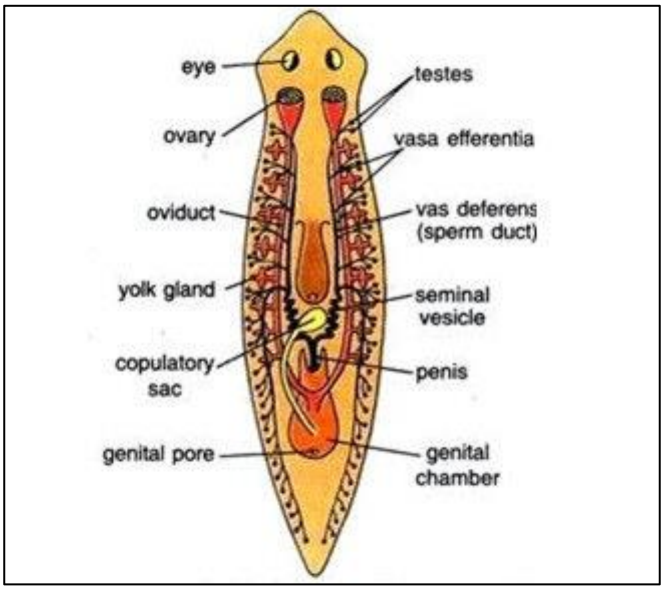


Fig. 27: Excretory system of Planaria (Nishimura et *al*, 2010).

Locomotion in free-living flatworms is achieved through the coordinated activity of **ciliated epidermal cells** and **musculature**, enabling gliding and directional movement.

The nervous system is rudimentary, typically consisting of a pair of anterior ganglia connected to longitudinal nerve cords, forming a simple ladder-like arrangement that controls sensory input and muscle contraction (Hickman et *al*., 2017) **(Fig. 28)**.

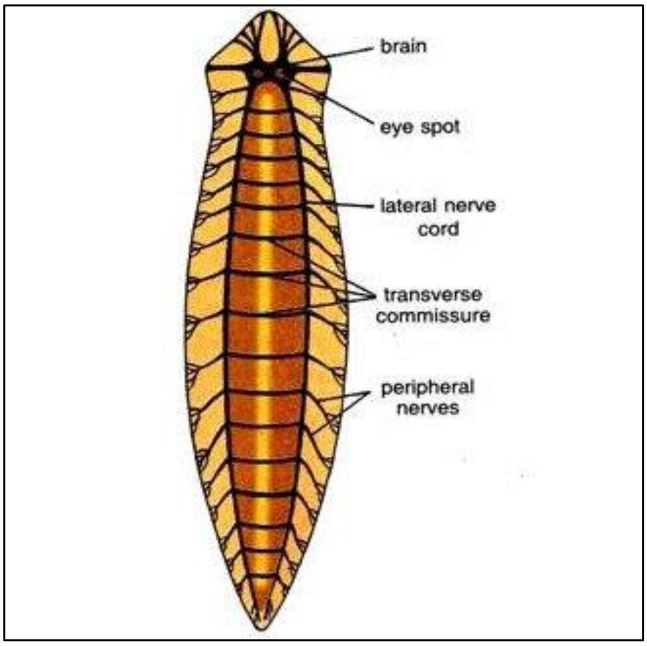


Fig. 28: Nervous system of Planaria (Sluys et *al*, 2009).

4-1-2 Reproduction

Most members of the phylum Platyhelminthes are simultaneous hermaphrodites, possessing both male and female reproductive organs within the same individual. Fertilized eggs are typically enclosed within protective cocoons that contain numerous vitelline (yolk) cells, which provide nutritional support for the developing embryo. Development in free-living forms is generally direct, although indirect development may occur in some taxa (Brusca et *al*., 2016; Ruppert et *al*., 2004).

4-1-3 Systematics

Platyhelminthes are traditionally divided into four major classes: Turbellaria, Trematoda, Monogenea, and Cestoda (Ruppert et *al*., 2004).

A. Class Turbellaria

Turbellarians are mostly small, free-living flatworms that inhabit primarily freshwater environments, although marine and terrestrial (humid habitat) species also occur. They are non-segmented worms with a dorsoventrally flattened, often leaf-shaped body. The anterior region commonly bears two or more eyespots (ocelli) and may present sensory tentacles (Brusca et *al*., 2016).

The body covering consists of a ciliated epidermal epithelium. Locomotion is achieved by the coordinated beating of cilia over the epithelial surface. Beneath the epidermis lies a basal lamina followed by several layers of musculature, typically arranged as circular, oblique, and longitudinal muscle fibers (Ruppert et *al*., 2004).

Turbellarians are hermaphroditic, and development is generally simple and direct.

Based on the morphology and organization of the digestive system, four principal orders are traditionally recognized:

- **Order Acoela (Acoels):** The digestive system is highly reduced. A mouth and a simple digestive cavity are present, but there is no pharynx or true intestine.
- **Order Rhabdocoela:** Characterized by a mouth, a pharynx, and a simple, straight intestine.
- **Order Polycladida:** The intestine is highly developed and extensively branched, with radial extensions throughout the body.
- **Order Tricladida:** The intestine consists of three main branches one anterior and two posteriors. A well-known example is the planarian (Brusca et *al*., 2016; Ruppert et *al*., 2004).

- **Example : Les planaires (Planarians)**

Planarians are small free-living flatworms belonging to the phylum Platyhelminthes, traditionally placed in the class Turbellaria and mainly within the order Tricladida. They are generally scavengers and, in some cases, carnivorous. Aquarium species are typically white-beige, yellowish, or light brown, extremely thin, and measure approximately 2-10 mm in length. They move by creeping along surfaces.

Approximately 200 freshwater species have been described, but planarians inhabit marine, freshwater, and even very moist terrestrial environments. Marine forms are often larger and more brightly colored than the small freshwater species commonly found in aquaria (Brusca et *al*., 2016; Ruppert et *al*., 2004).

- **Reproduction**

Planarians reproduce both sexually and asexually. They are simultaneous hermaphrodites in sexual reproduction.

They are particularly well known for their asexual reproduction by transverse fission. In this process, the body divides into fragments, and each fragment regenerates the missing parts to form a complete new individual. Thus, the entire organism can regenerate from a body piece, demonstrating remarkable regenerative capacity (Ruppert et *al*., 2004; Brusca et *al*., 2016).

- **Respiration and Circulation**

Platyhelminthes lack specialized respiratory and circulatory systems.

Oxygen required for cellular metabolism and carbon dioxide produced by cells diffuse directly through the thin body surface (tegument). The dorsoventrally flattened body increases the surface-area-to-volume ratio, facilitating efficient gas exchange by diffusion (Brusca et *al*., 2016).

- **Locomotion**

Planarians possess circular, longitudinal, and transverse muscle layers that allow contraction of the body tissues and enable movement. Locomotion also involves ciliary gliding over a thin mucus layer.

This movement is generally less efficient than that of nematodes, which possess a pressurized hydrostatic skeleton (pseudocoelomic cavity) that enhances locomotor efficiency (Ruppert et *al*., 2004).

B. Class Trematoda

Trematodes are **internal parasites of vertebrates**. Their body is dorsoventrally flattened, leaf-like, and non-segmented. Unlike Turbellaria, the epithelium lacks cilia, so these worms are immobile. The body surface (tegument) is covered by a protective cuticle, often bearing scales or spines. Trematodes possess **attachment organs**, typically an anterior oral sucker and a ventral sucker, which facilitate adhesion to host tissues (Brusca et *al*., 2016; Eiras et *al*., 2012).

- **Development and Life Cycle**

Trematodes exhibit **indirect development**, often involving multiple hosts. The subclass **Digenea** includes species that require a vertebrate definitive host and one or more intermediate hosts, usually mollusks, where larval stages develop. A classical example is *Fasciola hepatica* (the liver fluke), which parasitizes both sheep and humans (Smyth, 1994; Roberts & Janovy, 2018) **(Fig. 29)**.

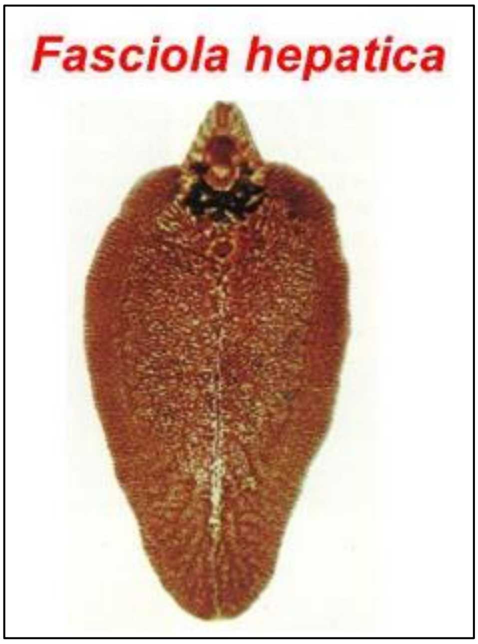


Fig. 29: Morphology of *Fasciola hepatica* lifecycle (Abdisa, 2017).

The life cycle is complex, consisting of multiple developmental stages:

- Larval stages are often aquatic and can infect plants, freshwater mollusks (snails), or freshwater fish, which serve as intermediate hosts. Some species may require a third host depending on the developmental stage (Eiras et *al*., 2012).

- The complete life cycle typically spans about 6 months: approximately 3 months are spent in the definitive host (from ingestion of metacercariae to the maturation of adult flukes in the bile ducts), and 3 months in the external environment and intermediate hosts (egg to metacercaria) (Smyth, 1994).

The intermediate host is highly specific. For example, *Lymnaea truncatula*, a freshwater snail, is required for the life cycle of *F. hepatica*. The snail's habitat must meet strict conditions (water chemistry, temperature, depth, current, and associated vegetation). Eggs must first reach water to hatch into larvae searching for a suitable snail host. If the precise snail species is absent, the larva dies, regardless of the presence of other snail species, making successful infection rare (Roberts & Janovy, 2018) **(Fig. 30)**.

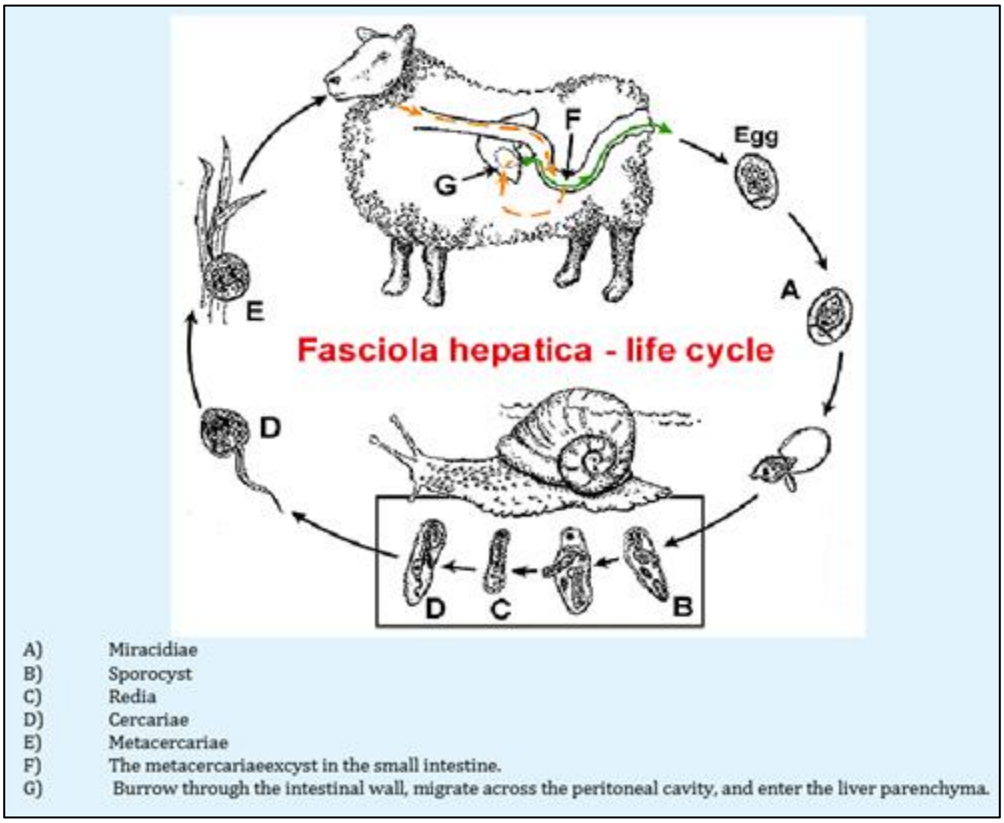


Fig. 30: *Fasciola hepatica* lifecycle (Abdisa, 2017).

- **Trematodes of Medical Importance**

Two main groups are important in human pathology:

Hermaphroditic flukes (e.g., liver flukes and *Clonorchis spp*.): Infection usually occurs through the ingestion of raw or undercooked freshwater fish containing metacercariae.

Schistosomes (blood flukes): These species have separate sexes. Infection occurs when cercariae penetrate human skin during contact with contaminated water during domestic, recreational, or agricultural activities (Colley et *al*., 2014).

C. Class Monogenea

Monogeneans are **ectoparasitic flatworms** with a **direct life cycle**, meaning they require only a single vertebrate host. They produce a free-swimming larval stage, called **the oncomiracidium**, which locates and attaches to the host. Monogeneans typically parasitize fish, attaching to gills, skin, or fins using specialized posterior attachment organs called **haptors**.

A well-known example is *Diplozoon paradoxum* **(Fig. 31)**, which parasitizes freshwater fish and exhibits permanent fusion of two individuals as adults (Brusca et *al*., 2016; Rohde, 2005).

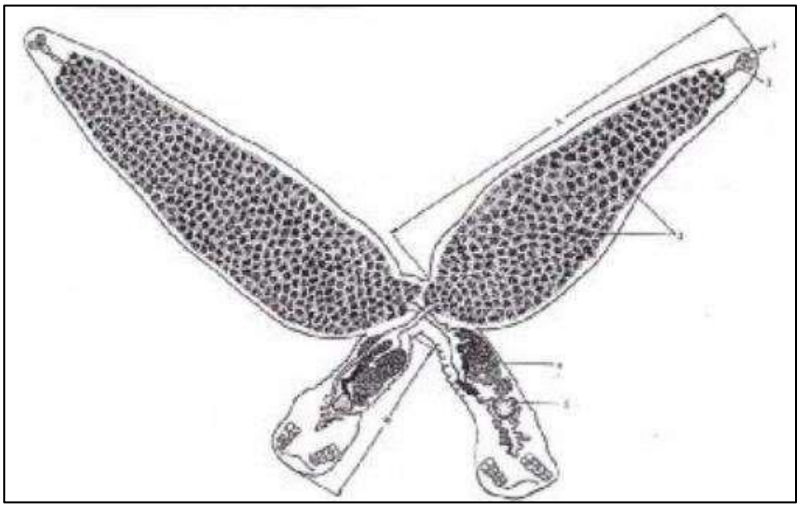


Fig. 31: Illustration of *Diplozoon paradoxum* showing the typical cross of two fused diplozoid specimens (Mhaisen & Abdul-Ameer, 2014).

D. Class Cestoda

Cestodes are **endoparasites of the digestive tract of higher vertebrates**. Their bodies are dorsoventrally flattened, ribbon-like, segmented, and lack cilia. They have neither a digestive tract nor a respiratory system.

The body is divided into three main regions:

- **Scolex:** The anterior attachment organ, which may bear suckers and/or a crown of hooks.
- **Neck (Proliferation Zone):** Region where new body segments (proglottids) are produced.
- **Strobila:** A chain of segments (proglottids) that compose the main body (Brusca et *al*., 2016; Roberts & Janovy, 2018).

The tegument is thick and aciliated, protecting the parasite from host digestive enzymes. Nutrients are absorbed directly through the tegument by **osmosis ("osmotrophy")**, allowing cestodes to survive without a digestive, circulatory, or respiratory system, functioning under anaerobic conditions (Brusca et *al*., 2016).

Cestodes are **hermaphroditic** and usually have a **complex life cycle** involving at least two hosts. Classification is based on scolex morphology, genital system features, and the parasitic cycle. Two main subclasses are recognized:

- **Cestodaria:** Lacking a scolex (e.g., some Nemerteans).
- **Eucestoda:** Possess a scolex, further divided into two orders:
  - ✓ **Pseudophyllidea:** Scolex has two shallow grooves (dorsal and ventral), e.g., Bothriocephalus.
  - ✓ **Cyclophyllidea:** Scolex with four suckers, e.g., Taenia spp. (Brusca et *al*., 2016; Roberts & Janovy, 2018) **(Fig. 32)**.

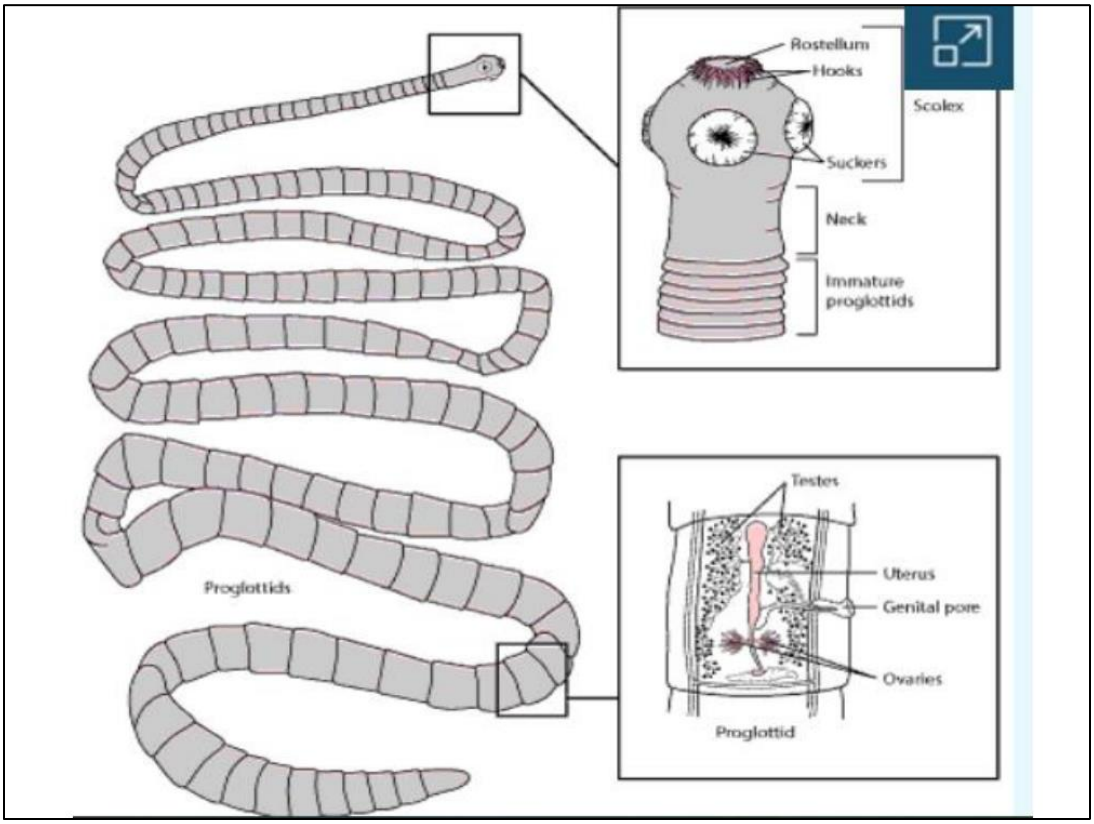


Fig. 32: Representative structure of a tapeworm, based on *Taenia solium* (Ravishankar & Kumar, 2021).

- **Life Cycle of Taenia**

The eggs are excreted by the definitive host (human) and develop into **oncospheres (hexacanth embryos)**. When ingested by intermediate hosts (pigs or cattle), the oncosphere penetrates the intestine, enters the bloodstream, and migrates to various organs where it develops into a **cysticercus**. The definitive host becomes infected by consuming raw or undercooked meat containing the cysticercus, which then develops into an adult tapeworm in the intestine (Smyth, 1994; Roberts & Janovy, 2018) **(Fig. 33)**.

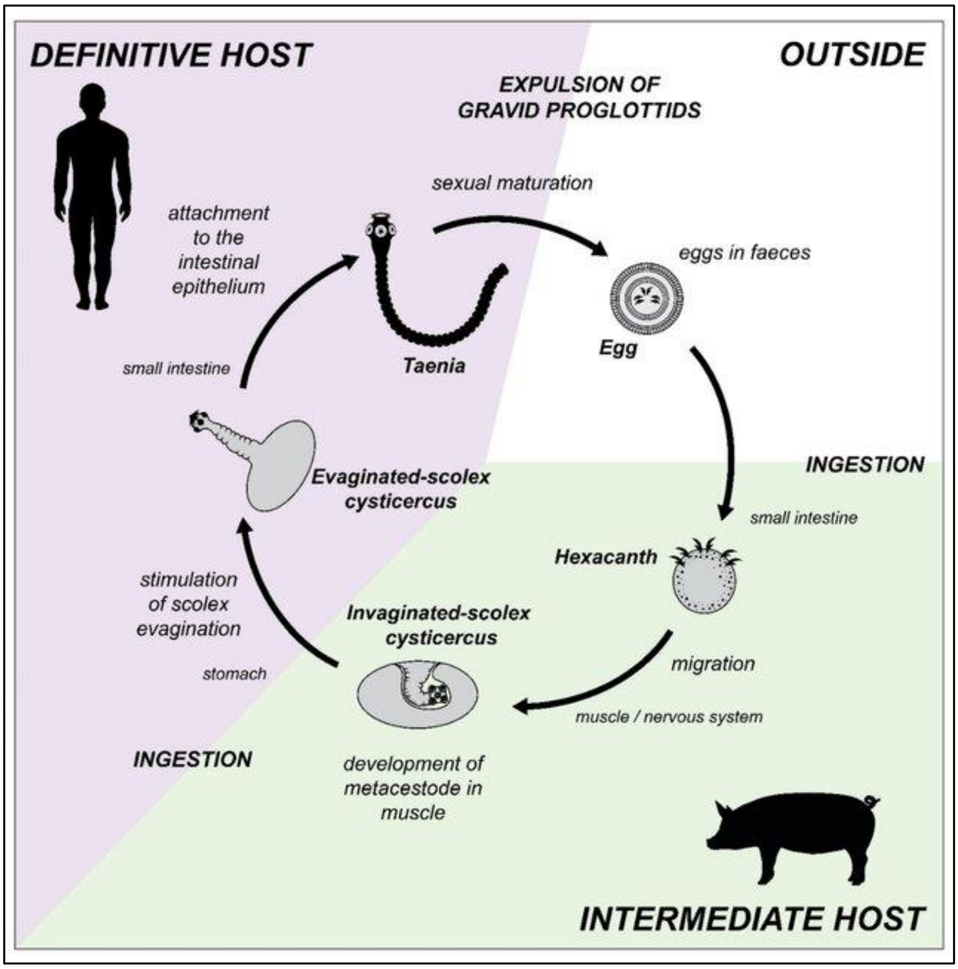


Fig. 33: Life cycle of *Taenia solium*. Parasite stages and its migration through the interior of its intermediate host (e.g., pig, in green) and its definitive host (e.g., man, in purple), is illustrated (Martínez-González et *al*., 2022).

- **Reproduction**

Proglottids are **protandrous hermaphrodites**:

- Male reproductive tissues are functional first, then cease activity.
- Female tissues mature afterward, allowing fertilization.

Fertilization occurs when proglottids of different sexual maturity come into contact. Each fertilized proglottid can contain millions of eggs (up to ~80,000). Smaller cestode species may compensate for lower fecundity by asexual multiplication during larval stages (Roberts & Janovy, 2018; Brusca et *al*., 2016).

4-2 Phylum Nemathelminths

4-2-1 Introduction

Nemathelminths, commonly known as nematodes (roundworms), are triploblastic, bilaterally symmetrical, pseudocoelomate metazoans with an elongated, cylindrical, and non-segmented body (Brusca & Brusca, 2003; Ruppert et *al*., 2004)). They include numerous free-living species inhabiting marine, freshwater, and soil environments, as well as many parasitic forms infecting animals (e.g., *Ascaris, Trichinella, Enterobius*) and plants (e.g., *Anguina tritici*) (Roberts et *al*., 2013).

It is estimated that approximately 500,000 nematode species may exist, making them one of the most diverse animal groups after insects (Hugot et *al*., 2001). Their body is circular in cross-section and tapered at both ends **(Fig. 34)**. The anterior end bears a mouth usually surrounded by three lips, whereas the posterior end carries an anus in females and a cloacal opening with two copulatory spicules in males (Ruppert et *al*., 2004).

The body is covered by a thick, multilayered cuticle containing structural proteins (often described as chitin-like), which is impermeable except to respiratory gases. Because the cuticle is inextensible, growth occurs through periodic molting (ecdysis or exuviation) (Brusca & Brusca, 2003). This cuticle also provides resistance to digestive enzymes in parasitic species (Roberts et *al*., 2013).

Sexes are usually separate (gonochoric), with marked sexual dimorphism: females are generally larger, and males often have a curved posterior end (Ruppert et *al*., 2004).

Nematodes are pseudocoelomates; their organs lie within a fluid-filled primary body cavity (pseudocoel), partially lined by mesoderm. The digestive tract and gonads are suspended in this cavity, which contains perivisceral fluid and amoeboid cells (Brusca & Brusca, 2003).

The body wall consists of:

- An ectoderm forming a single-layered epidermis that produces four longitudinal cords:
  - Two (dorsal and ventral) containing nerve cords.
  - Two lateral cords containing excretory canals.
- A mesoderm differentiated into myoepithelial muscle cells forming four longitudinal muscle fields.
- An endoderm forming a single-layered intestinal epithelium (Ruppert et *al*., 2004).

Traditionally grouped under "Nemathelminthes," modern taxonomy separates Nematodes and Nematomorphs into distinct phyla (Brusca & Brusca, 2003).

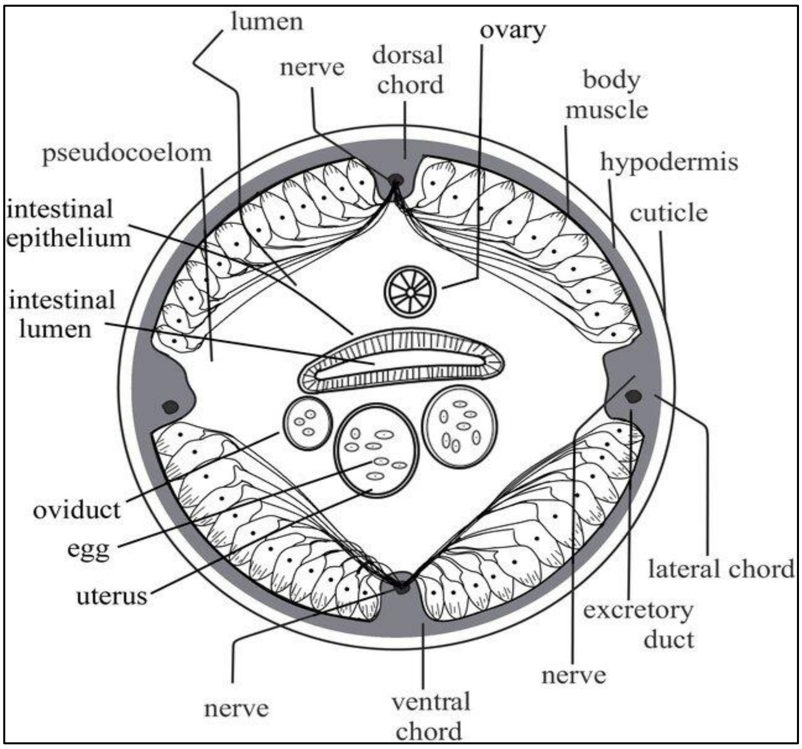


Fig. 34: Cross-section of a nematode showing cuticle, muscles and internal organs in pseudocoelom cavity (Mashela et *al*., 2020).

4-2-2 Respiratory System

Nematodes lack specialized respiratory organs. Gas exchange occurs by simple diffusion across the body surface (Ruppert et *al*., 2004).

4-2-3 Nervous System

The nervous system consists of a circumpharyngeal (periesophageal) nerve ring associated with paired lateral ganglia (cerebroid ganglia) and ventral ganglia. From this nerve ring arise anterior nerves supplying the lips and sensory organs, and longitudinal nerve cords extending posteriorly (Brusca & Brusca, 2003).

Sensory structures include (**Fig. 35)**:

- Peribuccal papillae.
- Chemoreceptors:
  - Amphids (anterior sensory organs near the mouth).
  - Phasmids (posterior sensory structures near the tail).

These structures play key roles in environmental perception, especially in parasitic and free-living forms (Ruppert et *al*., 2004).

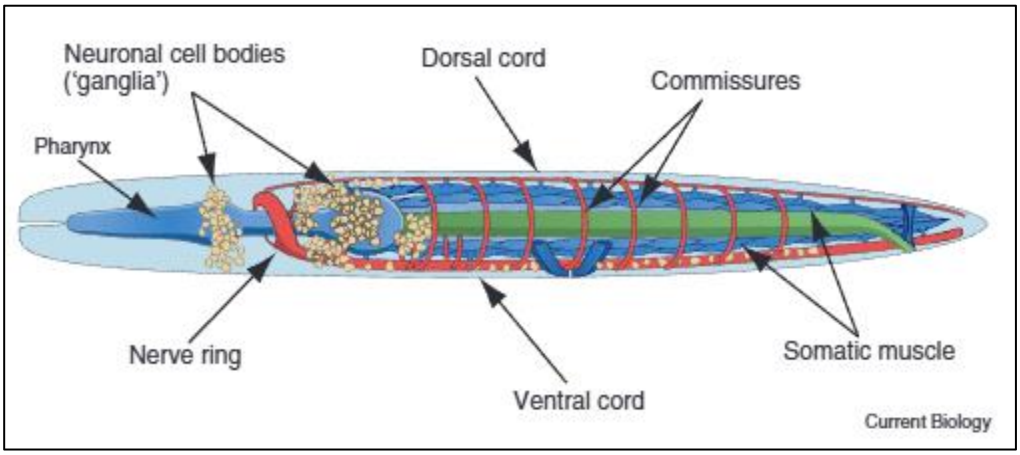


Fig. 35: Overview of nematode nervous systems.
Key features include a circumoral brain or nerve ring, composed of axonal and dendritic processes, clusters of cephalic neuronal cell bodies ('ganglia'), a ventral nerve cord containing processes and motor neuron cell bodies, and a dorsal nerve cord and circumferential commissures consisting exclusively of processes. The neuropil (comprising nerve ring and cords) is shown in red, neuronal cell bodies in yellow, muscles in blue, gut in green (Schafer, 2016).

4-2-4 Excretory System (Fig. 36)

Two main types are described:

- **Glandular type:** Consists of one or two large renette cells located ventrally, opening to the exterior via a median excretory pore in the esophageal region.
- **Tubular type:** Composed of lateral excretory canals within the epidermal cords, joining anteriorly and opening through a single anterior excretory pore (Brusca & Brusca, 2003).

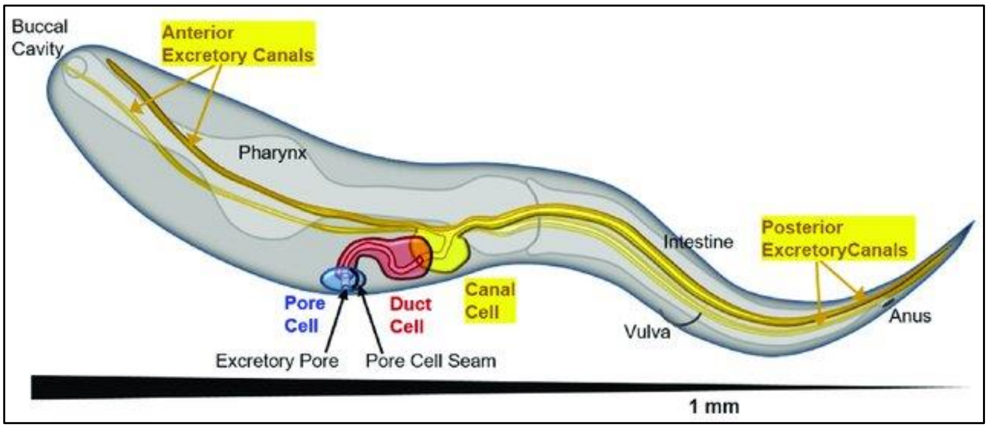


Fig. 36: Perspective diagram (anterior close, posterior far) showing position of the cells of the excretory system, and the long tubular canals stretching the length of the nematode (1 mm total length, about 50 μm in diameter). The excretory pore cell (seamed) is in blue, excretory duct cell (seam present at birth, then removed to become seamless) in red, and excretory canal cell in yellow. The canals can collect excess liquid from the entire length of the animal to transport to the duct and pore cells for removal (Buechner et *al*., 2020).

4-2-5 Digestive System

The digestive tract is straight, complete, and open at both ends **(Fig. 37)**. It includes:

- A mouth (often with three lips or specialized hooks/teeth).
- A buccal capsule (stomodeum), sometimes armed with teeth or denticles.
- A muscular pharynx lined with cuticle.
- A simple intestine formed by a single layer of epithelial cells.
- A rectum (proctodeum) of ectodermal origin, lined with cuticle (Ruppert et *al*., 2004).

In parasitic forms, esophageal glands may secrete anticoagulant substances (Roberts et *al*., 2013).

Several buccal cavity types are recognized in marine nematodes:

- Simple, unarmed (liquid feeders).
- Conical, unarmed (microphagous species).
- Reduced armature (algae feeders or omnivores).
- Strongly armed (predatory species) (Ruppert et *al*., 2004).

Feeding involves a muscular pharyngeal pump with a valve mechanism that compensates for internal hydrostatic pressure (Brusca & Brusca, 2003).

4-2-6 Reproductive System

Nematodes reproduce sexually (amphimixis), and some species may reproduce by parthenogenesis. Fertilization is internal (Roberts et *al*., 2013) **(Fig. 37)**.

Most species are gonochoric with sexual dimorphism:

- **Male:** Usually smaller; reproductive system includes one (rarely two) long testis, a seminal vesicle, a cloaca, and copulatory spicules within a spicular pouch. Sperm are aflagellate and move amoeboidly (Ruppert et *al*., 2004).
- **Female:** Typically has two ovaries, two oviducts, and two uteri that join into a short vagina opening at the vulva (ventral, often in the anterior third of the body). The upper uterus may function as a seminal receptacle (Brusca & Brusca, 2003).

Egg formation, shell development, and early embryogenesis occur in the uterus. Some species are ovoviviparous (Roberts et *al*., 2013).

Development includes five larval stages separated by four molts. The third larval stage (L3) is often the infective stage in parasitic species and the most resistant stage in free-living forms (Roberts et *al*., 2013).

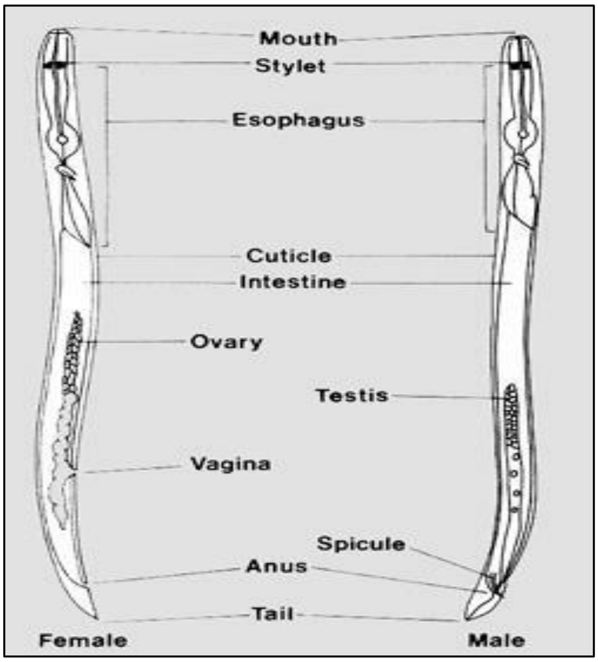


Fig. 37: Diagram of the digestive and reproductive systems in male and female nematodes (Jibril et *al*., 2016).

4-2-7 Ecology

Free-living nematodes (often called "eelworms") are abundant in marine sediments, freshwater, and moist soils. They are generally small and may be carnivorous or detritivorous (Ruppert et *al*., 2004).

Parasitic nematodes infect invertebrates (especially arthropods) and all classes of vertebrates, inhabiting body cavities, blood vessels, digestive tracts, kidneys, or tissues (Roberts et *al*., 2013).

Example: Class Nematomorpha (Gordiacea)

Nematomorphs are long, slender worms (up to 1.5 m) resembling nematodes. Larvae are parasitic (usually in arthropods), whereas adults are free-living and aquatic (Brusca & Brusca, 2003).

The adult intestine is reduced; adults do not feed, and the mouth and anus are non-functional. Larvae absorb nutrients through the tegument (Ruppert et *al*., 2004).

The nervous system is intra-epidermal; excretory canals and protonephridia are absent. Only one ventral muscle field is present. Sexes are separate with internal fertilization (Brusca & Brusca, 2003).

Approximately 250 species are known, grouped into:

- **Gordiida** (freshwater species; larvae parasitize insects).
- **Nectonematoida** (marine species; parasites of crustaceans) (Ruppert et *al*., 2004).

4-3 Phylum Annelida

4-3-1 Introduction

Annelids are **multicellular**, **triploblastic** animals exhibiting bilateral symmetry (Brusca et *al*., 2016; Hickman et *al*., 2017).

During embryonic development, the mesoderm splits to form fluid-filled cavities entirely lined by mesodermal tissue; therefore, annelids are classified as **true coelomates** (Ruppert et *al*., 2004; Brusca et *al*., 2016).

The name **Annelida** (from the Latin *annellus*, meaning "little ring") refers to their characteristic body organization, which consists of a **series of repeated units arranged sequentially along the anterior-posterior axis** (Hickman et *al*., 2017).

This structural organization is known as **metamerism**, and each repeated body unit is called a **metamere** (segment) (Ruppert et *al*., 2004; Brusca et *al*., 2016) **(Fig. 38)**.

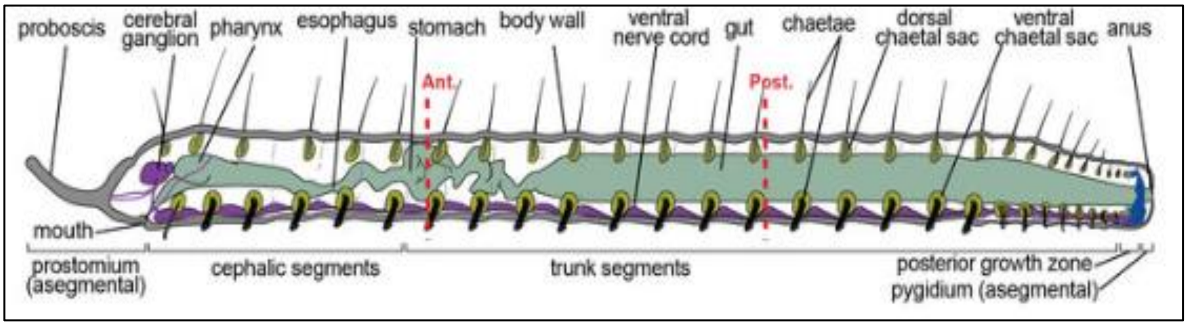


Fig. 38: General Diagram of an Annelid (Zattara & Bely, 2011).

4-3-2 Systematics

Traditionally, the phylum **Annelida** is divided into three major classes (Brusca et *al*., 2016; Ruppert et *al*., 2004).

➢ **Oligochaeta**

The class **Oligochaeta** (from Greek *oligos* = few) includes earthworms such as *Lumbricus* (Hickman et *al*., 2017).

They are characterized by:

- Reduced or very small chaetae (setae) (Ruppert et *al*., 2004)
- Absence of parapodia (Brusca et *al*., 2016)
- Presence of a clitellum in most species (Hickman et *al*., 2017)

Oligochaetes are mainly terrestrial or freshwater annelids (Ruppert et *al*., 2004).

➢ **Hirudinea (Achaeta)**

The class **Hirudinea** (from Latin *hirudo* = leech) includes leeches such as Hirudo (Brusca et *al*., 2016).

They are characterized by:

- Dorso-ventrally flattened body (Ruppert et *al*., 2004)
- Complete absence of chaetae and parapodia (Brusca et *al*., 2016)
- Presence of anterior and posterior suckers (Hickman et *al*., 2017)

Many species are temporary ectoparasites of marine, freshwater, and terrestrial animals (Ruppert et *al*., 2004). They attach to the host using suckers, pierce tissues with jaws bearing small chitinous teeth, and suck blood (Brusca et *al*., 2016).

Leeches secrete enzymes that facilitate skin penetration and produce an anticoagulant substance called hirudin, which prevents blood clotting and allows continuous blood flow (Ruppert et *al*., 2004; Hickman et *al*., 2017).

- **Polychaeta**

The class Polychaeta (from Greek *polys* = many, **chaete** = bristle) includes species such as *Nereis* (Brusca et *al*., 2016).

They are characterized by:

- Numerous chaetae (Ruppert et *al*., 2004)
- Well-developed parapodia of variable forms (Brusca et *al*., 2016)
- A distinct head region bearing sensory organs (Hickman et *al*., 2017)

Most polychaetes are marine and exhibit gonochorism (separate sexes) (Ruppert et *al*., 2004).

- **Orders within Polychaeta**
- **Order Errantia**

Free-living species characterized by:

- A highly developed locomotory system (Brusca et *al*., 2016)
- Well-developed jaws and a carnivorous diet (Ruppert et *al*., 2004)
- Numerous sensory organs (Hickman et *al*., 2017)

Example: Family Nereididae.

- **Order Sedentaria**

Species that:

- Live in tubes (Ruppert et *al*., 2004)
- Feed on sediments or filter suspended particles (Brusca et *al*., 2016)
- May possess a well-developed respiratory apparatus (Hickman et *al*., 2017)

In these forms, parapodia and sensory organs are reduced in relation to their sedentary lifestyle (Ruppert et *al*., 2004).

Annelids are relatively advanced invertebrates, representing a decisive evolutionary step in animal organization. Their body is typically divided into three main regions: **head** (prostomium and peristomium), **trunk** (segmented region), and **posterior end** (pygidium) (Brusca et *al*., 2016; Ruppert et *al*., 2004).

The annelid structural level introduces a major innovation compared with earlier diploblastic animals and triploblastic acoelomates: the organization of cells into **true organs and organ systems** with specialized structures and precise physiological functions (Hickman et *al*., 2017; Ruppert et *al*., 2004).

One of the most important evolutionary advances in annelids is the presence of a **complete and highly specialized digestive tract**, with both a mouth and an anus. This through-gut allows regional specialization (e.g., pharynx, esophagus, crop, gizzard, intestine) and more efficient digestion and nutrient absorption (Brusca et *al*., 2016; Hickman et *al*., 2017).

Annelids also possess a **closed circulatory system**, in which blood remains within vessels and circulates throughout the body. In many species, the blood contains respiratory pigments such as hemoglobin dissolved in the plasma, making annelids among the first invertebrates to possess true blood and an efficient oxygen transport system (Ruppert et *al*., 2004; Brusca et *al*., 2016).

Finally, annelids have a **segmentally organized ganglionic nervous system**, consisting of a dorsal cerebral ganglion (brain) connected to a ventral nerve cord with paired segmental ganglia. This arrangement enables coordinated control of each body segment and contributes to their advanced locomotor abilities (Hickman et *al*., 2017; Ruppert et *al*., 2004).

4-3-3 Nervous system

The nervous system of annelids consists of a complex neural mass located in the cephalic lobe, **the brain (cerebral or supraesophageal ganglion)**, positioned entirely above the esophagus (Brusca et *al*., 2016; Ruppert et *al*., 2004).

From this brain arise **two circumesophageal connectives** that surround the esophagus and connect to the first pair of **subesophageal ganglia** (Hickman et *al*., 2017; Ruppert et *al*., 2004).

From the subesophageal ganglia originates **the ventral nerve cord**, typically double (paired) in structure, extending longitudinally along the body. Each segment contains **a pair of segmental ganglia**, forming a metamerically organized ganglionic chain that coordinates segmental activities (Brusca et *al*., 2016; Hickman et *al*., 2017) **(Fig. 39)**.

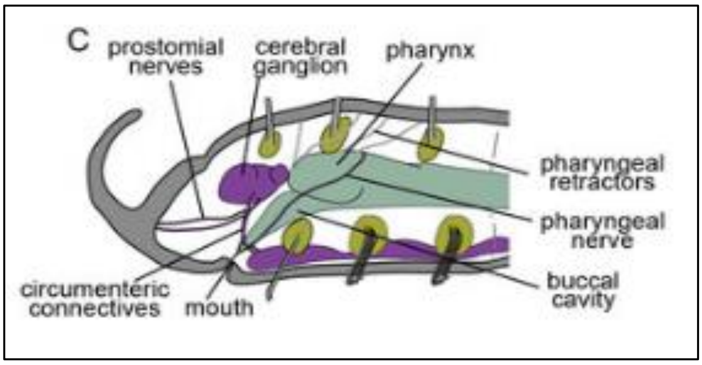


Fig. 39: Diagram of the nervous system in annelids (Zattara & Bely, 2011).

Example: Study of a Typical Polychaete: *Nereis*

The body of a typical polychaete such as Nereis is divided into three main regions (Brusca et *al*., 2016; Ruppert et *al*., 2004) **(Fig. 40)**:

1. Head region

The head is composed of two elements:

- **Prostomium:** a sensory cephalic region bearing sensory structures such as antennae, palps, and eyes.
- **Peristomium:** a specialized segment surrounding the mouth and bearing **four tentacular cirri**.

2. Main body region (Soma or trunk)

This is the largest portion of the body and consists of numerous similar segments (metameres).

Each segment typically bears:

- A pair of **parapodia** (lateral appendages)
- Numerous **chaetae (setae)** used for locomotion

The trunk represents the truly segmented region of the animal and contains coelomic compartments in each metamere.

3. Caudal region (Pygidium)

The posterior region, or **pygidium**, bears:

- The anus
- Two slender tentacle-like extensions called anal (caudal) cirri

It does not bear parapodia. New segments arise anterior to the pygidium from a posterior growth zone.

Importantly, **the prostomium** and **pygidium do not contain coelomic cavities**, and therefore they are not considered true metameres (Ruppert et *al*., 2004; Hickman et *al*., 2017).

The Head of a Typical Polychaete (*Nereis*)

The head **(Fig. 40)** of a typical polychaete such as Nereis is highly specialized and bears well-developed sensory and feeding structures (Brusca et *al*., 2016; Ruppert et *al*., 2004).

- **Prostomium**

The prostomium carries highly developed sensory organs:

- Two pairs of eyes (ocelli): The first pair is more developed than the second and is involved in light perception (vision).
- One pair of short, filiform antennae: Primarily tactile organs (touch).
- Two biarticulated palps, thick and swollen: Mainly involved in tactile and sensory perception.

- **Peristomium**

At the level of the peristomium:

- A powerful eversible proboscis (pharynx) is inserted internally.

When protruded, the proboscis displays:

- ✓ Two strong jaws at its anterior end.
- ✓ Numerous chitinous denticulations called **paragnaths**, which assist in prey capture and feeding.

- Four tentacular cirri: These structures function in sensitivity and chemoreception (including olfaction).

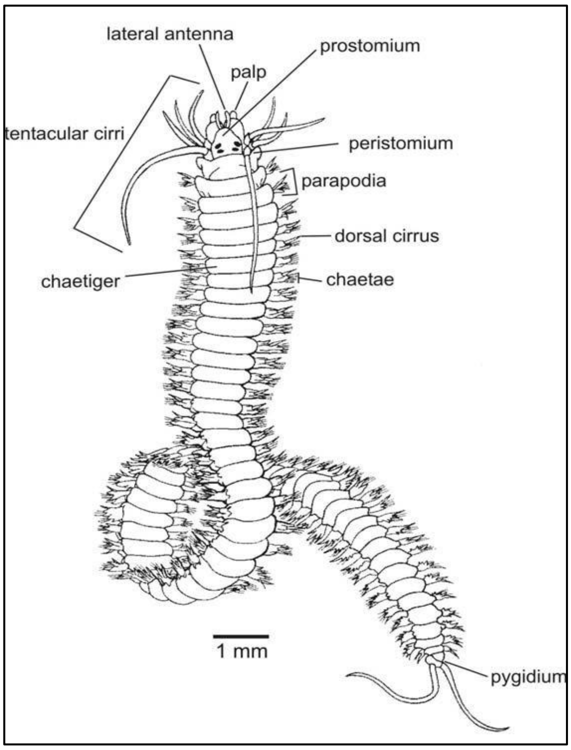


Fig. 40: Diagram of a Polychaete (*Nereis*) (Loo et *al*.,2006).

Structure of Each Metamere in a Typical Polychaete (*Nereis*)

Each metamere **(Fig. 41)** bears two lateral extensions called parapodia (Brusca et *al*., 2016; Ruppert et *al*., 2004).

A single parapodium is composed of two branches (rami):

- The dorsal ramus (notopodium)
- The ventral ramus (neuropodium)

Each ramus carries a short tentacle: **the dorsal cirrus** and **the ventral cirrus**.

Numerous **compound chaetae (setae)** are attached to the rami.

Each ramus is supported internally by a rigid cuticular rod called **an acicula**.

➢ **Internal Organization of a Metamere**

Observation **(Fig. 41)** shows that each metamere consists of:

- An epidermis covered by a very thin **chitinous cuticle**.
- **Circular**, **longitudinal**, and **transverse muscles**.
- A pair of **coelomic vesicles** (true coelomic cavities).
- A pair of **nephridia** (primitive kidneys) that filter coelomic fluid and excrete waste products; the excretory system consists of small tubules allowing elimination of metabolic wastes (Hickman et *al*., 2017).
- **Vascular elements** forming a closed circulatory system with:

✓ A **dorsal blood vessel**, located above the digestive tract, where blood flows from posterior to anterior.

✓ A **ventral blood vessel**, located below the digestive tract, where blood flows in the opposite direction (Ruppert et *al*., 2004).

- **Reproductive cells (gametes)**, often temporarily stored within the coelom.

Coelomic Linings

- The outer walls of the coelomic vesicles lining the body wall musculature form **the somatopleure**.
- The inner walls, adjacent to the dorsal and ventral vessels, digestive tract, and nervous system, form **the splanchnopleure**.
- The walls of the two coelomic vesicles within the same metamere meet in the sagittal plane to form **the mesentery**.

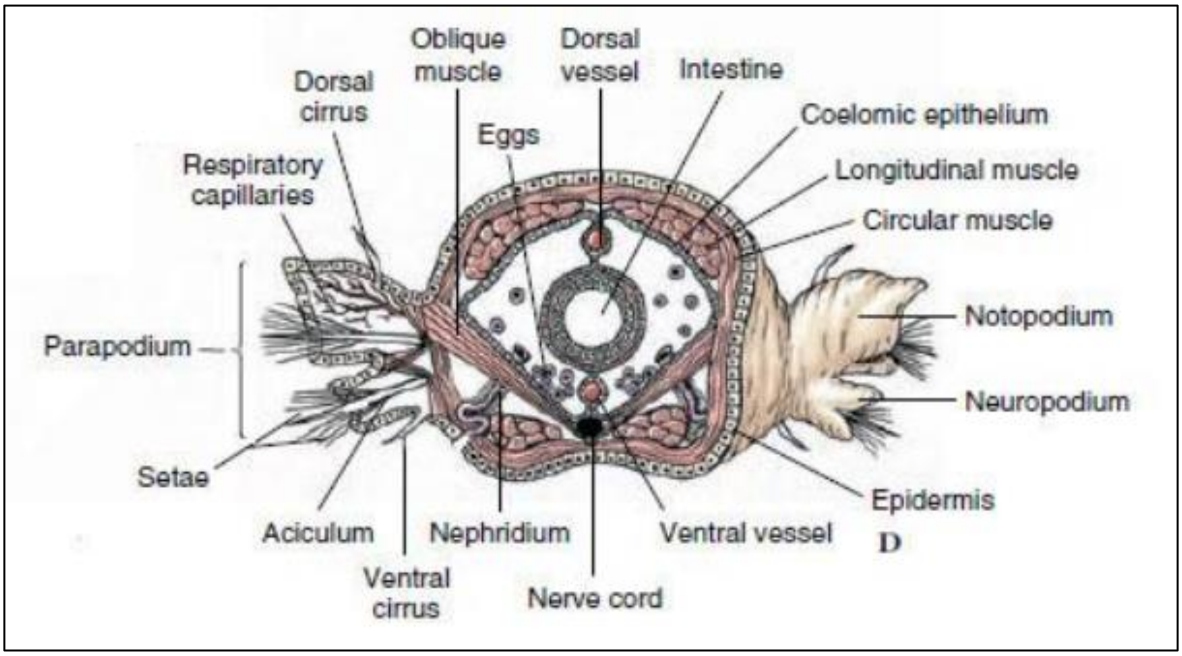


Fig. 41: Diagram of transverse Section of a *Nereis* Metamere (Kumar, 2018).

Functional Significance

The circular and longitudinal muscles attach both to the cuticle and to the coelomic fluid contained within the coelomic vesicles situated between the digestive tract and the body wall muscles **(Fig. 42)**.

This arrangement creates a **hydrostatic skeleton**, enabling effective locomotion through coordinated muscular contractions (Brusca et *al*., 2016).

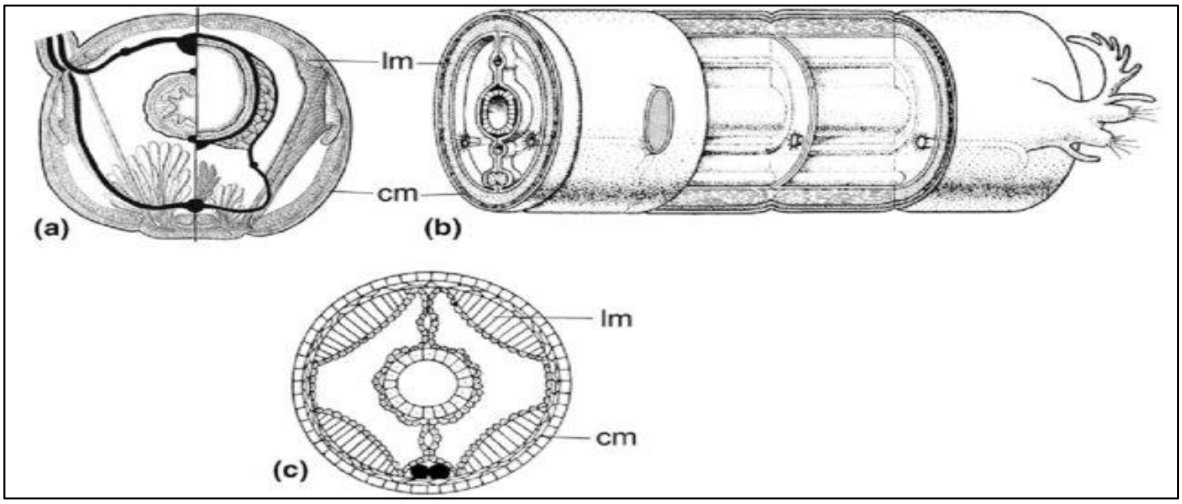


Fig. 42: General arrangement of body wall musculature. (a) Amphitrite rubra, diagram of transversal section through midbody region. (b) Schematic organisation of segments in Annelida. (c) Annelid body plan. cm-circular muscles, lm-longitudinal muscles (Tzetlin & Filippova, 2005).

4-4 Phylum Mollusca

4-4-1 Introduction

The phylum Mollusca **(Fig. 43)** consists of soft-bodied invertebrates, most of which are aquatic, though some inhabit moist terrestrial environments. The name *Mollusca* derives from the Latin *molluscus*, meaning (soft), reflecting this fundamental characteristic (Brusca & Brusca, 2003). With approximately 100,000 described living species, the vast majority are members of the classes **Gastropod**a and **Bivalvia** (Ruppert et *al*., 2004).

Despite their wide range of forms and life histories, all molluscs share a common suite of anatomical features that are believed to have originated from a single ancestral form sometimes referred to as **the archimollusc**. This hypothetical ancestor possessed a muscular foot used for locomotion, a dorsal visceral mass, a mantle, ctenidia (gills), and a through-gut with a mouth at the anterior and anus posteriorly (Ponder & Lindberg, 2008).

Typically, modern molluscs exhibit three main body regions: a head, a ventral muscular foot, and a dorsal visceral mass. The nervous system is relatively simple and consists of a ventral nerve cord with paired ganglia (Brusca & Brusca, 2003). The dorsal visceral mass is covered by a protective mantle, which secretes a calcareous shell in most taxa.

Although molluscs are predominantly marine, several groups have successfully colonized freshwater and terrestrial habitats. The scientific discipline devoted to the study of molluscs is known as malacology, and the study of shells alone is referred to as conchology (Gosling, 2003).

Ancestral characteristics of molluscs include a shell and mantle that encapsulate the visceral mass, a ciliated ventral foot, a radula for feeding (present in most classes except bivalves), and ctenidia located within the mantle cavity (Ruppert et *al*., 2004).

In phylogenetic terms, molluscs are considered a highly derived invertebrate lineage. They possess well-developed organ systems, including a defined head, centralized nervous structures, a complete digestive tract, respiratory structures such as gills or lungs, and a circulatory system with a heart (Ponder & Lindberg, 2008).

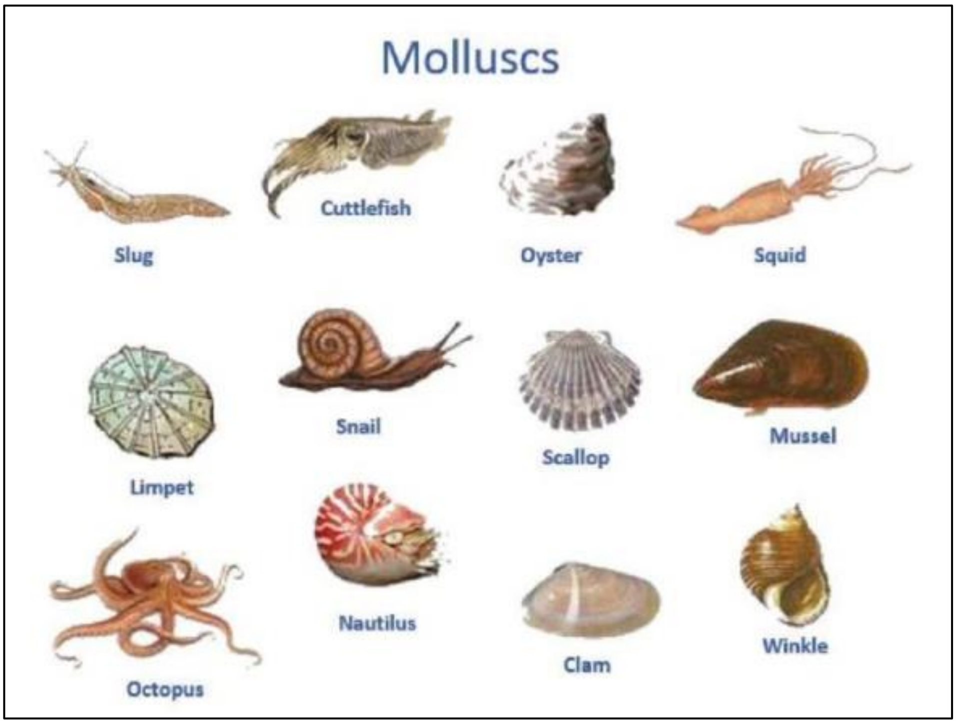


Fig. 43: Illustration depicting multiple mollusk species (Khan et *al*., 2019).

4-4-2 Systematics

The phylum Mollusca is traditionally divided into **seven classes (Fig. 44)**:

- Aplacophora
- Polyplacophora
- Monoplacophora
- Gastropoda
- Scaphopoda
- Bivalvia (also called Pelecypoda or Lamellibranchia)
- Cephalopoda

Currently, approximately 99% of living mollusc species belong to the Bivalvia (e.g., oysters, mussels, clams) and Gastropoda (e.g., snails, slugs), which represent the most diverse and widespread groups within the phylum (Brusca & Brusca, 2003; Ruppert et *al*.,2004).

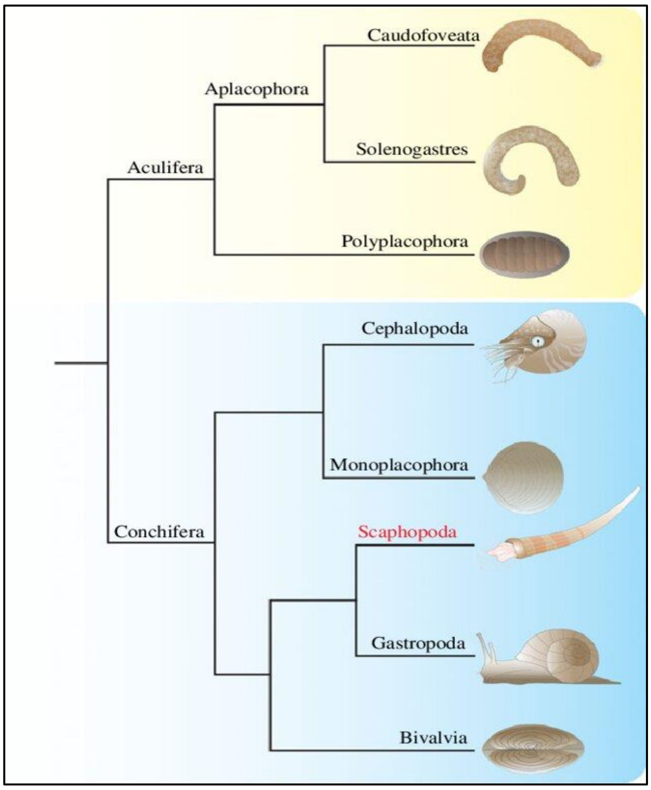


Fig. 44: Phylogeny of Mollusks (Wollesen et *al*.,2018).

4-4-3 External Morphology

The shell is composed of a single piece that protects the animal's soft body. The body is soft, segmented, and divided into three main regions **(Fig. 45)**:

- **Head:** The head bears a pair of retractable tentacles, with eyes located at their base in aquatic mollusks. The mouth typically contains a chitinous jaw on the dorsal side and a radula, a rasping tongue-like organ, on the ventral side (Ruppert et *al*., 2004).
- **Foot:** The foot is a muscular organ, often well-developed, which functions in locomotion (Pechenik, 2015).
- **Visceral mass:** Enclosed by the mantle, a specialized membrane, the visceral mass contains the main internal organs and is responsible for secreting the shell (Barnes, 1982).

In gastropods, a pallial cavity is formed by a fold of the mantle. The anus and urinary opening open into this cavity. In *Prosobranchia*, the pallial cavity contains a gill, whereas *Pulmonata* lack gills but have a highly vascularized pulmonary cavity that functions as a lung (Fretter & Graham, 1994; Ponder & Lindberg, 2008).

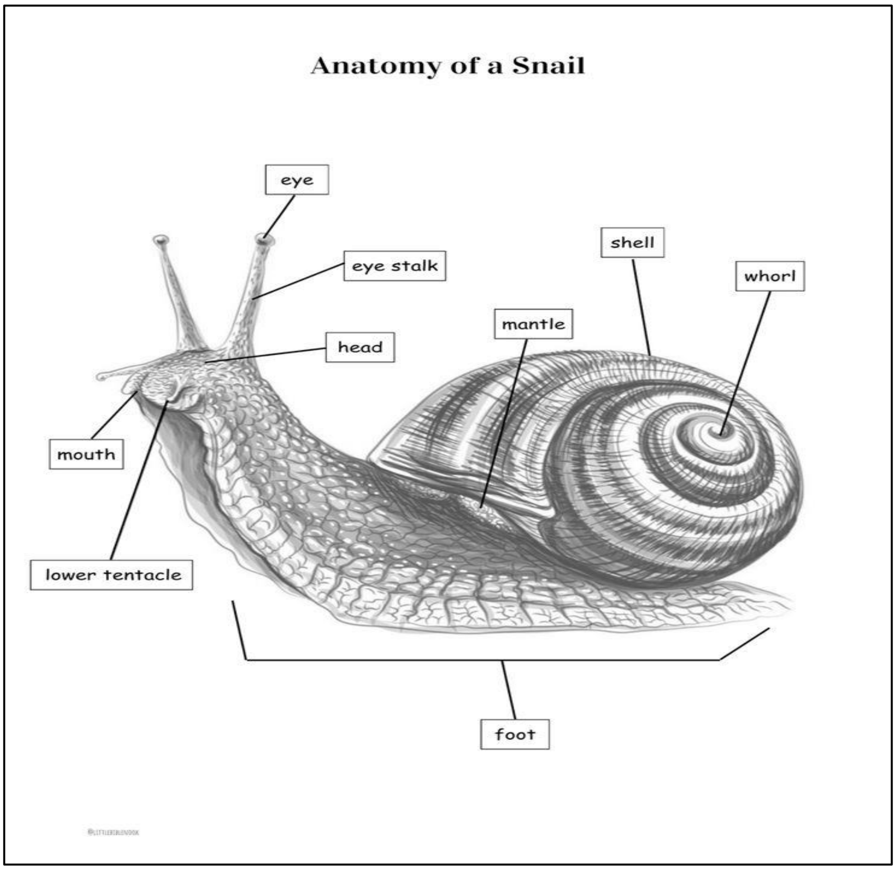


Fig. 45: Illustration of the external morphology of a gastropod (snail) (Barnes ,1982).

The shell (or test) of mollusks is composed primarily of calcium carbonate, in the forms of calcite and aragonite. It is secreted by the mantle as the animal grows (Ruppert et *al*., 2004). In living mollusks, the shell is covered externally by a thin layer of organic material called periostracum, composed of conchiolin, which protects the underlying calcareous layers (Pechenik, 2015).

The inner surface of the shell is lined with nacre, giving it a smooth, iridescent appearance (Barnes, 1982).

In gastropods, the single-piece shell is schematically formed by the coiling of a very elongated cone around a central axis called **the columella** (Ruppert et *al*., 2004).

A shell is described as dextral when the coiling, viewed from the apical pole (apex), proceeds clockwise, and sinistral when it coils in the opposite direction (Pechenik, 2015) **(Fig. 46)**.

Except in the Ancylidae, the shell consists of several whorls separated by sutures (Barnes, 1982).

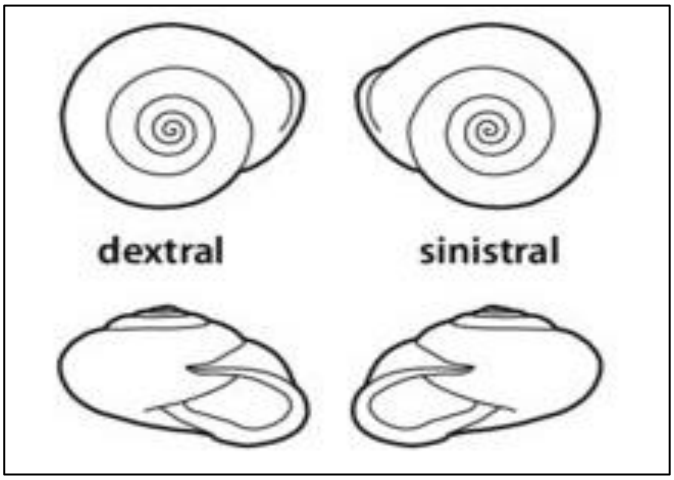


Fig. 46: Illustration of the shells: Dextral and sinistral (Barnhart, 2019).

4-4-4 Internal Morphology

- **Respiratory System:** The respiratory system consists of a single gill located in the pallial cavity on the right side. The gill is composed of small, fleshy triangular extensions that project from the inner surface of the mantle and are arranged in a single row, like the teeth of a comb; this type of gill is referred to as monopectinate (Ruppert et *al*., 2004). These lamellae are perforated with numerous blood spaces where gas exchange occurs and are covered with vibratile cilia. Some species, such as *Fissurella* and *Haliotis*, which are closely related to lamellibranchs in general organization, possess bipectinate gills, each formed by two rows of triangular lamellae (Pechenik, 2015) **(Fig. 47)**.
- **Circulatory System:** The circulatory system features a heart enclosed in a pericardium, consisting of a single ventricle and a single auricle. It is located slightly posterior to the gill, along the pathway of arterial blood coming from the gill. The auricle receives blood first and passes it to the ventricle, which then pumps it into a single aorta. The aorta is very short and immediately divides into an anterior aorta, supplying the cephalopod–pedal region, and a visceral aorta, which runs into the coiled visceral mass. The terminal branches open into lacunae or blood spaces between cellular elements, allowing direct tissue perfusion. Venous blood then accumulates in irregular cavities or sinuses, also lacking defined walls, before returning to the gill; a true venous system is therefore absent (Barnes, 1982; Fretter & Graham, 1994) **(Fig. 47)**.

The anterior position of the gill relative to the heart classifies Littorina as a prosobranch gastropod (Ponder & Lindberg, 2008).

- **Nervous System (Fig. 47):** The nervous system of gastropods consists primarily of three types of **ganglia**:
  - **Cerebral ganglia:** Two ganglia located above the esophagus, connected by a short commissure. They innervate the eyes, tactile tentacles, and otocysts (Ruppert, Fox, & Barnes, 2004).
  - **Pedal ganglia:** Two ganglia located below the esophagus, connected by a commissure and linked to the cerebral ganglia via two connectives, forming **the first esophageal ring**. They innervate the foot and also support two otocysts, which are primarily innervated by the cerebral ganglia (Pechenik, 2015).
  - **Visceral ganglia:** Three to five ganglia located below and posterior to the esophagus, connected to the cerebral ganglia by two long connectives forming **the second esophageal** ring, also called **the large visceral commissure**. This commissure is much longer than the first and coordinates the innervation of the visceral organs (Barnes, 1982; Fretter & Graham, 1994).

Beyond the basic arrangement, similar to lamellibranchs, two additional pairs of ganglia are present along the two long connectives linking the cerebral ganglia to the pedal ganglia:

- **Pallial ganglia:** These innervate the mantle and are connected to the pedal ganglia by two small connectives (p and p'). Together with the cerebral and pedal ganglia on the same side, they form a triangular arrangement on each side of the esophagus, known as **the lateral triangle of gastropods** (Ruppert et *al*., 2004).
- **Intestinal ganglia:** These innervate the intestine. The two long connectives linking the cerebral ganglia to the visceral ganglia each carry two ganglia along their path (visceral and pallial). This arrangement is called **the orthoneurous nervous system** and is observed only in **opisthobranchs**, in which the viscera have not undergone torsion (Pechenik, 2015; Fretter & Graham, 1994).

In **prosobranch gastropods**, such as Littorina, all the same ganglia are present, but the orientation of the long commissure connecting the cerebral and visceral ganglia is modified due to a 180° **torsion of the visceral mass**. This torsion displaces the middle region of the commissure: the right intestinal ganglion moves to the left above the intestine, and the left intestinal ganglion moves to the right below the intestine, creating a crossover in the shape of an "X." The right intestinal ganglion is called the supraintestinal ganglion, and the left is called **the subintestinal ganglion** (Barnes, 1982).

Because torsion affects only the visceral mass, the ganglia in the head region remain unchanged, as do the visceral ganglia beneath the intestine.

This X-shaped crossing of the commissure classifies the prosobranch nervous system as chiastoneurous (Ponder & Lindberg, 2008).

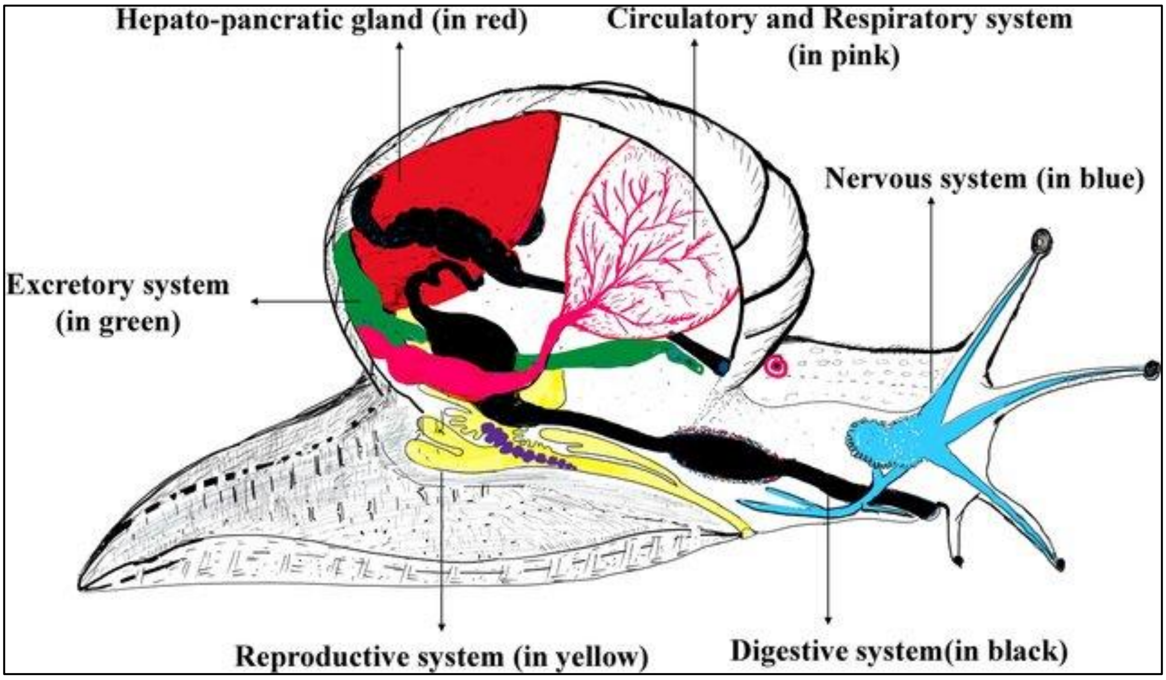


Fig. 47: The major physiological systems of the snail. Nervous system in blue, circulatory and respiratory systems in pink, excretory system in green, reproductive system in yellow, digestive system in black, and digestive glands in red color. Adapted and modified from published literature (Ponder et *al*. 2019)

4-5 Phylum Arthropoda

4-5-1 Introduction

Arthropods are bilaterally symmetrical invertebrates characterized by a segmented body organized into two or three distinct tagmata (head, thorax, and abdomen, or cephalothorax and abdomen) **(Fig. 48)**. They possess a thick, rigid cuticle forming a chitinous exoskeleton that provides protection and structural support (Brusca et *al*., 2016; Ruppert et *al*., 2004). Each segment (metamere) is typically composed of several sclerotized plates: a dorsal tergite, a ventral sternite, and two lateral pleurites. A defining feature of the phylum is the presence of jointed appendages (from Greek *arthron* = joint; *podos* = foot). Arthropods exhibit heteronomous segmentation, meaning that different body regions and their appendages are specialized for specific functions. The body cavity is a hemocoel, which functions as the main internal cavity filled with hemolymph (Brusca et *al*., 2016).

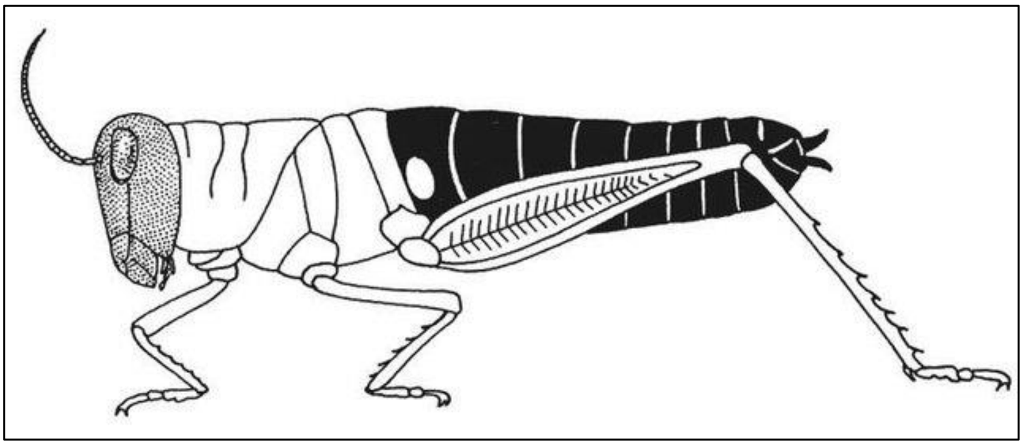


Fig. 48: General arthropod body plan, in the case of insects consisting of the three tagmata: head (shaded), thorax (unshaded), and abdomen (darkened) (Brusca & Brusca, 2003).

- **The digestive system** consists of a complete and differentiated alimentary canal associated with digestive glands, including salivary glands and hepatopancreatic structures. The gut is divided into three main regions: the stomodeum (foregut), mesenteron (midgut), and proctodeum (hindgut) (Ruppert et *al*., 2004).
- **The excretory system** is typically metanephridial in origin and is commonly represented by Malpighian tubules, especially in terrestrial forms such as insects and arachnids (Brusca et *al*., 2016).
- **Respiration** occurs through specialized organs depending on the group: gills in crustaceans, tracheae in myriapods and hexapods, and book lungs and/or tracheae in arachnids (Ruppert et *al*., 2004).
- **The circulatory system** is open, with a dorsal tubular heart that pumps hemolymph into the hemocoel. The blood (hemolymph) is generally colorless or bluish due to the presence of respiratory pigments such as hemocyanin in some groups (Brusca et *al*., 2016).
- **The nervous system** is well developed; cephalic ganglia are fused to form a brain, connected to a ventral nerve cord with segmental ganglia (Ruppert et *al*., 2004).

4-5-2 Reproduction

In arthropods, sexes are generally separate (dioecious), meaning that males and females are distinct individuals (Brusca et *al*., 2016). Fertilization is typically internal, occurring through direct copulation or via the transfer of spermatophores, depending on the group (Ruppert et *al*., 2004). Sexual dimorphism is common in many arthropod taxa, with males and females differing in size, morphology, coloration, or specialized reproductive structures (Chapman, 2013).

Arthropods characteristically exhibit development involving metamorphosis, which includes significant morphological and physiological transformations between immature and adult stages (Brusca et *al.*, 2016). Growth occurs through a series of molts (ecdysis), during which the rigid chitinous exoskeleton is periodically shed and replaced to allow body enlargement and developmental progression (Ruppert et *al.*, 2004; Chapman, 2013).

4-5-3 Systematics of Arthropods

Arthropoda is divided into five subphyla:

A. Subphylum Trilobitomorpha (Trilobites)

- This subphylum consists of a single class, the Trilobites. They are extinct marine arthropods, considered the most primitive, often living in sand or shallow waters (Brusca et *al.*, 2016) **(Fig. 49)**.
- Trilobites ranged in size from a few centimeters to several tens of centimeters.
- Their body exhibited three longitudinal lobes: a central axial lobe and two lateral lobes.
- Their biramous appendages had an inner branch for locomotion and an outer branch for swimming (Ruppert et *al.*, 2004).

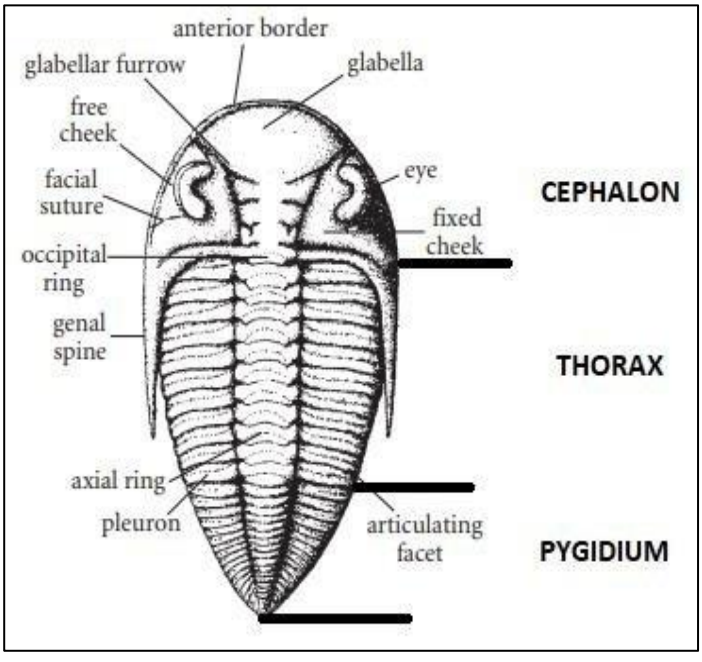


Fig. 49: Trilobite morphology (Kowalewska, 2020).

B. Subphylum Crustacea (Crustaceans)

- Crustaceans are mainly marine, rarely freshwater or terrestrial; many forms are parasitic (Boxshall & Halsey, 2004).
- The body is divided into a cephalothorax and abdomen, with each segment bearing appendages that are often biramous **(Fig. 50)**.
- They typically have one or two pairs of sensory antennae, followed by mandibles and one or two pairs of feeding appendages, along with locomotory legs.
- The exoskeleton is reinforced with calcium salts.
- Respiration occurs through gills, even in terrestrial species.
- Development can be either:
- **Indirect (dilated):** multiple larval and adult stages with metamorphosis (e.g., shrimp).
- **Direct (condensed):** the egg hatches into a juvenile resembling the adult (e.g., crayfish).
- Crustaceans are classified into several classes:
- **Branchiopoda:** free-living, often with a carapace and two large biramous antennae for swimming (e.g., *Daphnia pulex*).
- **Ostracoda:** small, fast-swimming aquatic crustaceans enclosed in a bivalve-like carapace (e.g., *Cythereis* sp.).
- **Maxillopoda:** reduced abdomen and appendages; includes free-living or sessile aquatic forms, some parasitic on fish (e.g., *Cyclops* sp., *Argulus foliacens*, *Balanus sp.*).
- **Malacostraca:** largest marine, freshwater, and terrestrial crustaceans; thorax with 8 segments, abdomen with 6, head fused to thorax forming a cephalothorax (e.g., shrimp, lobsters, crabs) (Brusca et *al.*, 2016).

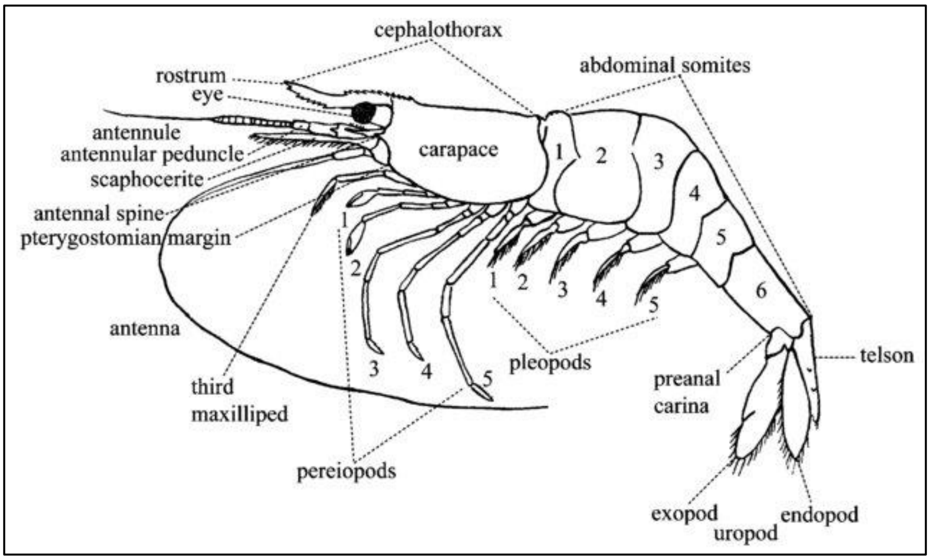


Fig. 50: General morphology of Shrimp (Von Rintelen & Cai, 2009).

C. Subphylum Myriapoda (Myriapods)

- Terrestrial arthropods with tracheal respiration and a pigmented exoskeleton.
- Appendages are uniramous, with the anterior pair forming antennae; locomotory legs are behind the head (Chapman, 2013) **(Fig. 51)**.
- Classes include:
  - **Diplopoda (Millipedes):** abdominal segments bear two pairs of legs; head has a pair of short antennae and two pairs of mouthparts; herbivorous or detritivorous (e.g., *Spirobolus* sp.).
  - **Chilopoda (Centipedes):** one pair of legs per segment; head with long antennae and three pairs of mouthparts; predatory, venomous with poisonous claws (e.g., *Scolopendra, Lithobius*) (Brusca et *al*., 2016).

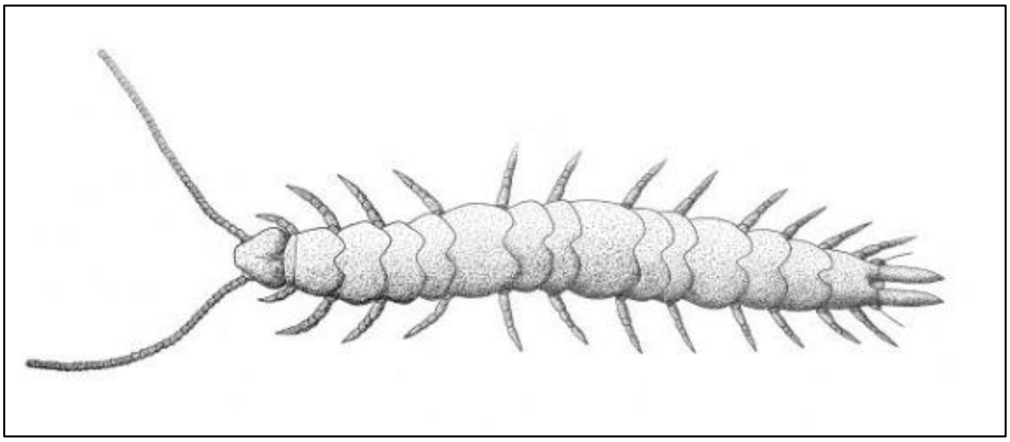


Fig. 51: General morphology of Myriapod (Dohle, 1996).

D. Subphylum Hexapoda (Hexapods)

- Hexapods have three pairs of legs and four classes: Collembola, Diplura, Protura, and Insecta.
- Primitive hexapods (Collembola, Diplura, Protura) are small, wingless, with internal mouthparts; they live in moist environments and develop ametabolously (egg → juvenile → adult) (Chapman, 2013).
- Insects are terrestrial, aerial, or aquatic; the body is divided into head, thorax, and abdomen **(Fig. 52)**:
  - **Head:** simple (ocelli) and compound eyes, a pair of antennae, and external mouthparts (labrum, mandibles, maxillae, labium).
  - **Thorax:** three segments (prothorax, mesothorax, metathorax) with one pair of legs each; wings on meso- and metathorax in winged species.
  - **Abdomen:** typically without appendages, ending in the anus; respiration via tracheae or gills in aquatic species.
- Sexual dimorphism exists; parthenogenesis occurs in some groups (e.g., aphids, bees).
- The digestive tract is differentiated: pharynx, esophagus, crop, gizzard, intestine.
- Development can be:
  - **Incomplete metamorphosis (hemimetaboly):** larva resembles adult (paurometabolous) or differs (hemimetabolous) (e.g., grasshoppers, dragonflies).
  - **Complete metamorphosis (holometaboly):** all larval stages present, including pupal stage (e.g., mosquitoes, butterflies).
- Diapause allows developmental arrest under adverse conditions.
- Insects are divided into:
  - **Apterygote insects:** primitive wingless insects (e.g., silverfish, Lepisma).
  - **Pterygote insects:** winged insects with over 25 orders (Brusca et *al*., 2016).

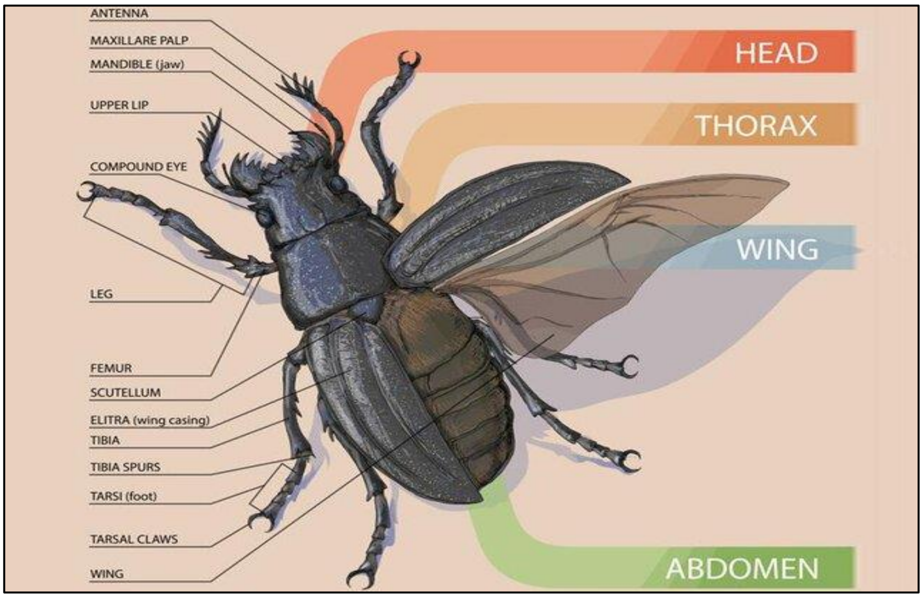


Fig. 52: External morphology of insects (Phauk et *al*., 2019).

E. Subphylum Chelicerata (Chelicerates)

- Mostly terrestrial, lacking antennae, with six pairs of appendages; first two pairs are specialized (chelicerae and pedipalps) while the remaining are locomotory legs.
- Body divided into prosoma and opisthosoma (Brusca et *al*., 2016) **(Fig. 53)**.
- Classes include:
- **Merostomata:** primitive aquatic chelicerates with gill respiration (e.g., horseshoe crab).
- **Pycnogonida:** small, slender marine chelicerates; rudimentary opisthosoma, larvae parasitic on cnidarians.
- **Arachnida:** terrestrial, respiration via lungs or tracheae; notable orders:
- **Scorpiones:** elongated, segmented body; opisthosoma with venomous stinger; pedipalps modified as pincers.
- **Araneae:** prosoma and opisthosoma connected by pedicel; chelicerae with venom glands.
- **Opiliones:** globular body from fused prosoma and opisthosoma; long slender walking legs.
- **Acari:** small, prosoma and opisthosoma fused; larva with three pairs of legs, adults with four; pedipalps modified as piercing structures (e.g., ticks) (Ruppert et *al*., 2004).

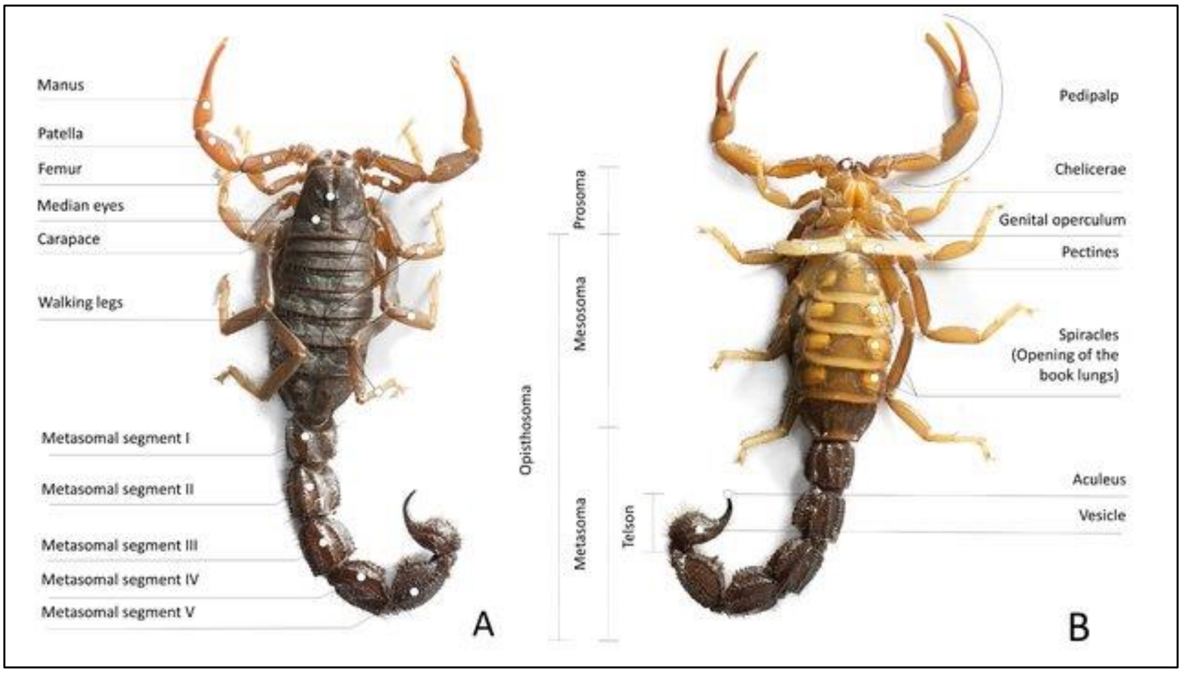


Fig. 53: Overall anatomy of a scorpion (*Parabuthus transvaalicus*, Buthidae). (A) Dorsal view. (B) Ventral view (Simone & Van der Meijden, 2021).

4-6 Phylum Echinodermata

4-6-1 Introduction

Echinoderms represent an ancient and remarkable group of marine animals. Although the starfish and sea urchin are the most well-known examples, they represent only a small portion of the diversity within this phylum (Brusca & Brusca, 2003).

Echinoderms are exclusively marine organisms that first appeared approximately 500 million years ago and were a dominant component of animal faunas around 350 million years ago. Today, only about 6,000 species remain, distributed across six of the 23 classes in this phylum; the remaining 17 classes are extinct and known only from fossils (Hyman, 1955; Smith, 2013) **(Fig. 54)**.

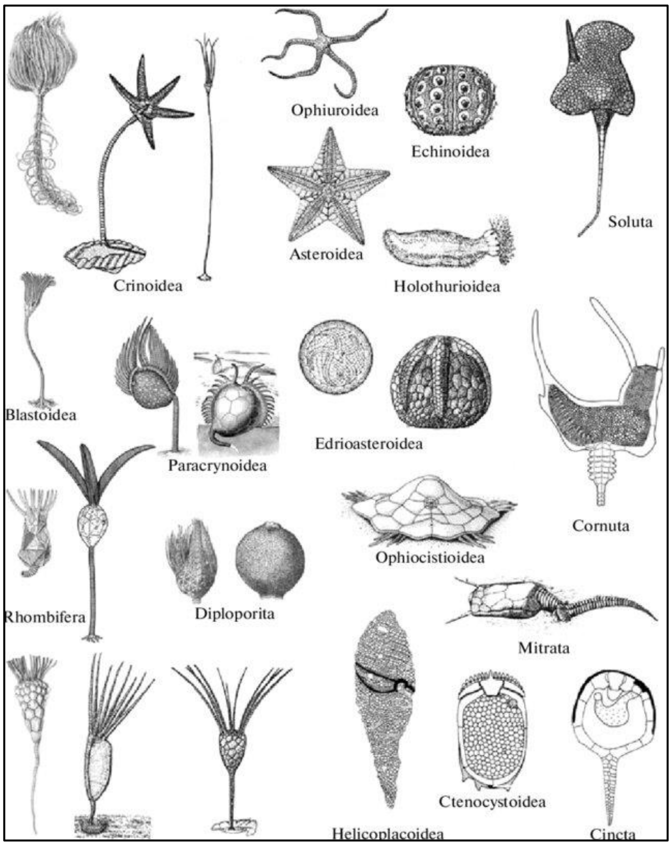


Fig. 54: Diagram of Fossil Echinoderm Species (Rozhnov, 2010).

These animals are named for their spiny skin ("echino" meaning spiny and "derm" meaning skin) and possess an internal calcareous skeleton. Echinoderms are unique among invertebrates in having an internal skeleton composed of calcium carbonate ossicles (Ruppert et *al*., 2004).

Echinoderms also possess a distinctive water vascular system and exhibit a pentaradial symmetry (from Greek *penta*, five). Both the water vascular system and the perivisceral coelomic cavity are derived from the embryonic coelom (Hickman et *al*., 2017).

Unlike other radially symmetric animal phyla such as Cnidaria and Ctenophora, echinoderms are triploblastic and possess a true coelomic cavity (Ruppert et *al*., 2004).

The early development of echinoderms begins with a bilaterally symmetrical, free-swimming larva. Only later in development do larvae transform into adults exhibiting the characteristic radial symmetry (David et *al*., 2000) **(Fig. 55)**.

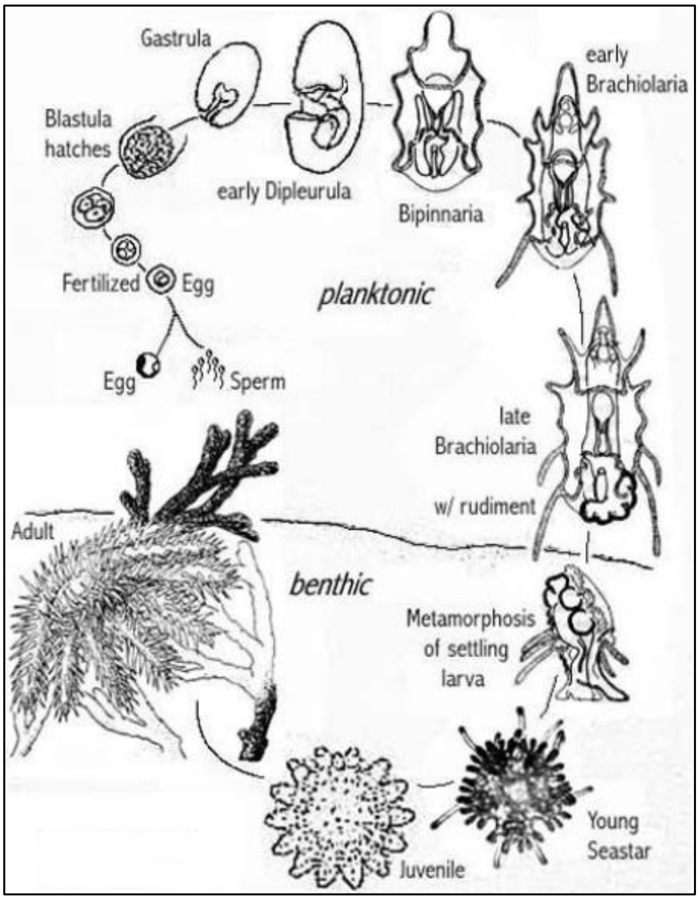


Fig. 55: Diagram of Life cycle of *Acanthaster planci* (De Dios & Sotto, 2015).

The earliest echinoderms were sessile and had their mouth oriented upward with arms spread out in complex fan-like arrangements. At that time, ocean floors were rich in small organic particles; when these died, they settled to the bottom and were trapped by the ambulacral grooves of ancestral echinoderms and funneled toward the mouth (Ubaghs, 1967).
Over the course of evolution, the orientation of the body changed. The appendages became involved in locomotion rather than food capture, and the mouth shifted to face downward toward the substrate. Although the basic body plan was established early on, there remained considerable morphological flexibility (David et *al*., 2000).
Several extant echinoderm species have evolved a degree of bilateral symmetry in adults, but their locomotion remains limited and reliant on the ambulacral system (Brusca & Brusca, 2003).

4-6-2 External Morphology of the Starfish (*Asterias*)

The starfish, Asterias, is the most commonly used echinoderm to illustrate the characteristics of the phylum. Key features include a pentaradial body plan and an endoskeleton composed of ossicles, which also form the spiny projections that protect the animal. Locomotion occurs via tube feet, which are part of the water vascular (ambulacral) system (Ruppert et *al*., 2004). The body is divided into two main regions: a central disc and arms radiating from the disc (Brusca & Brusca, 2003) **(Fig. 56 and 57)**.

- **Oral Surface**

On the oral surface **(Fig. 56 and 57)**, two characteristic features are observed: the central mouth and the five ambulacral grooves, one located at the center of each arm, extending from the arm tips toward the mouth. Each ambulacral groove contains four rows of tube feet (podia), external projections of the water vascular system. These tube feet pass between the ossicles of the endoskeleton and are often difficult to observe due to protective spines.

Each podium functions as a small suction device, capable of attaching to substrates. Tube feet can extend or retract through the contraction of internal muscles. Individually, each podium is a relatively inefficient locomotive organ, but considering that a single starfish possesses over 1,000 podia, locomotion is highly effective. Because suction is essential, starfish are generally restricted to hard substrates (Hyman, 1955).

Alongside the ambulacral grooves are rows of blunt spines, which are specialized dermal ossicles that pierce the epidermis.

- **Aboral Surface**

On the aboral surface **(Fig. 56)**, conical spines are more abundant. Surrounding each large spine is a circle of pedicellariae, small modified spines. Pedicellariae are particularly numerous among the large spines beside the ambulacral grooves. Each pedicellaria consists of a basal stalk and two distal movable elements, functioning like a tiny pair of scissors. Both the spines and pedicellariae prevent fouling by other organisms (David et *al*., 2000).

In well-preserved or live specimens, numerous fine, finger-like projections are visible. These are dermal gills, giving the skin a velvety appearance. They are lined externally by ciliated epidermis and internally by the ciliated perivisceral epithelium. The cilia facilitate diffusion, a critical process for the starfish's survival (Ruppert et *al*., 2004).

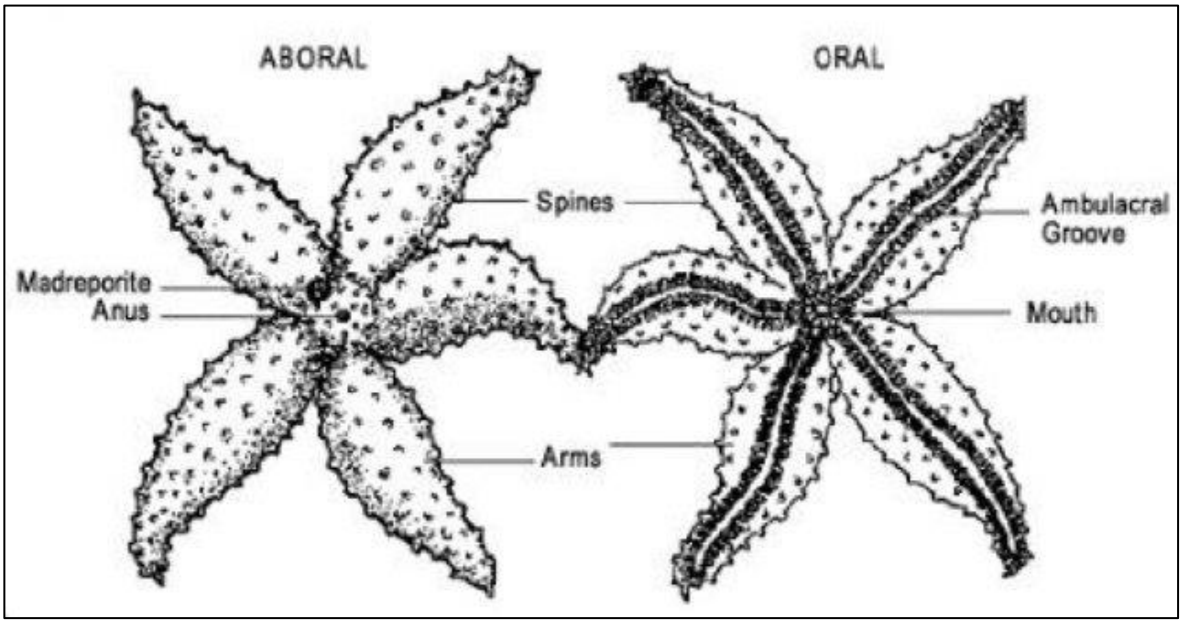


Fig. 56: Diagram of Aboral and oral sides of a generic Asteroid (Daviddi, 2015).

- **Attachment and Water Vascular Openings**

Each arm attaches to the central disc. **The madreporite**, the external opening of the water vascular system, resembles a sieve and is located on one side of the disc, between two arms (the interambulacral region). The two arms flanking the madreporite form **the bivium**, while the other three arms constitute the trivium.

A small, inconspicuous anus is also located on the disc, positioned in the interambulacral region following the madreporite in a clockwise direction (Brusca & Brusca, 2003; Hyman, 1955) **(Fig. 57)**.

4-6-3 Internal Anatomy of the Starfish (*Asterias*)

- **Water Vascular (Ambulacral) System**

The water vascular system consists of a ring canal, a stone canal connecting the madreporite to the ring canal, and five radial canals extending along each arm. The ring canal contains nine Tiedemann's bodies, while the expected tenth is replaced by the junction between the stone canal and the ring canal (Ruppert et *al*., 2004) **(Fig. 57)**.

Polian vesicles, usually located on the ring canal, are absent in species of the genus Asterias. The radial canals, hidden by ambulacral ossicles, run along the center of each arm and connect to the tube feet (podia). The ampullae, bulbous expansions of the tube feet, project into the perivisceral cavity and can be observed along each arm as they cross the ambulacral ridge. The coordinated hydraulic action of these structures enables locomotion and feeding (Hyman, 1955).

- **Digestive System**

The mouth leads to a very short esophagus, which opens into a large stomach. The stomach has cardiac and pyloric regions. The cardiac stomach is larger and eversible through the mouth, allowing many starfish to feed on bivalve mollusks by inserting the stomach between the shells and releasing digestive enzymes for extracorporeal digestion. Other prey, such as small fish and crustaceans, can be ingested whole (Brusca & Brusca, 2003).

The pyloric stomach, located aborally, has a flattened pentagonal shape and is much smaller than the cardiac stomach. At each angle of the pentagon, a large duct leads to a pair of pyloric caeca in each arm. These branched digestive glands occupy most of the perivisceral cavity and terminate in lobules. The inner lining is ciliated, facilitating constant mixing, while the walls secrete digestive enzymes and serve as storage organs. The short rectum extends from the center of the pyloric stomach to the anus, though undigested residues are often regurgitated rather than expelled (Ruppert et *al*., 2004) **(Fig. 57)**.

- **Reproductive System**

The gonads are paired structures located at the base of each arm, varying in size according to reproductive stage. Gametes are released through gonopores on the sides of the central disc (Hyman, 1955) **(Fig. 57)**.

- **Nervous System**

The starfish has a simple nervous system, consisting of a diffuse nerve net. A nerve ring surrounds the central disc, with radial nerves extending into each arm to coordinate feeding and tube foot movements. At the tip of each arm, a modified tube foot functions as a photoreceptor (Brusca & Brusca, 2003) **(Fig. 57)**.

- **Excretory and Respiratory Systems**

Starfish lack dedicated excretory and respiratory organs. Instead, dermal gills (papulae) provide a large surface area for diffusion of gases and waste between the environment and the perivisceral and ambulacral cavities. Both cavities are ciliated, and the constant mixing ensures an effective diffusion gradient for oxygen uptake and waste removal (Ruppert et *al.*, 2004) **(Fig. 57)**.

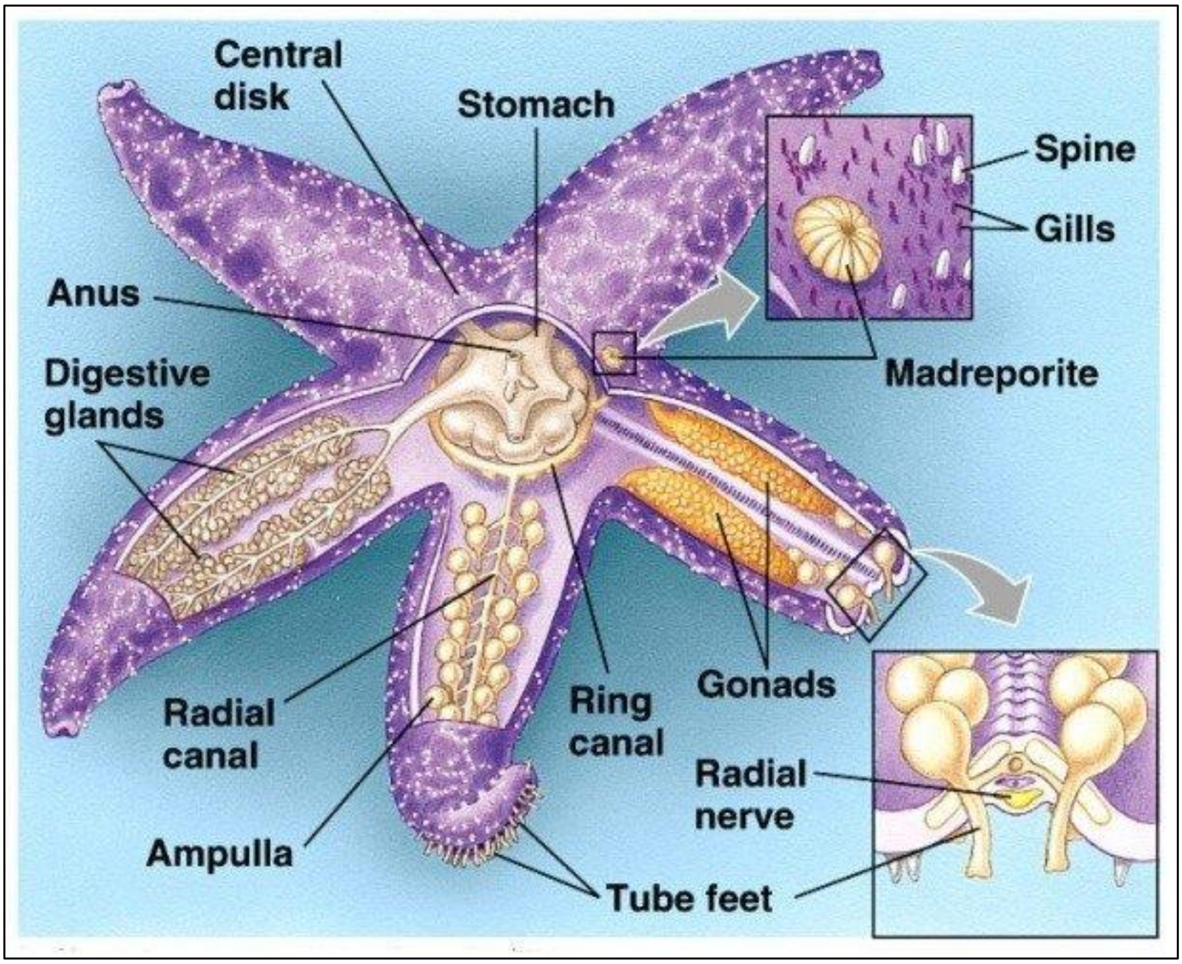


Fig. 57: Diagram of internal structure of a live starfish (Mao et *al*., 2013).

4-6-4 Classification of Echinoderms

Echinoderms (Echinodermata) are a phylum of **benthic marine animals** found at all ocean depths, with fossil records dating back to the Cambrian period. Currently, they are classified into **five extant classes**: starfish *(Asteroidea)*, sea urchins *(Echinoidea)*, sea cucumbers *(Holothuroidea)*, crinoids *(Crinoidea)*, and brittle stars *(Ophiuroidea)* (Ruppert et *al*., 2004).

- **Class Asteroidea (Starfish)**

Starfish are often highly colored and, like all echinoderms, exhibit **pentaradial symmetry**, typically evident in adults. They are recognized by their **star-shaped body**, with **five (or more) arms radiating from a central disc**, which houses most of the organs, including digestive and nervous systems. The size of the central disc relative to the arms varies among species (Brusca & Brusca, 2003) **(Fig. 58)**.

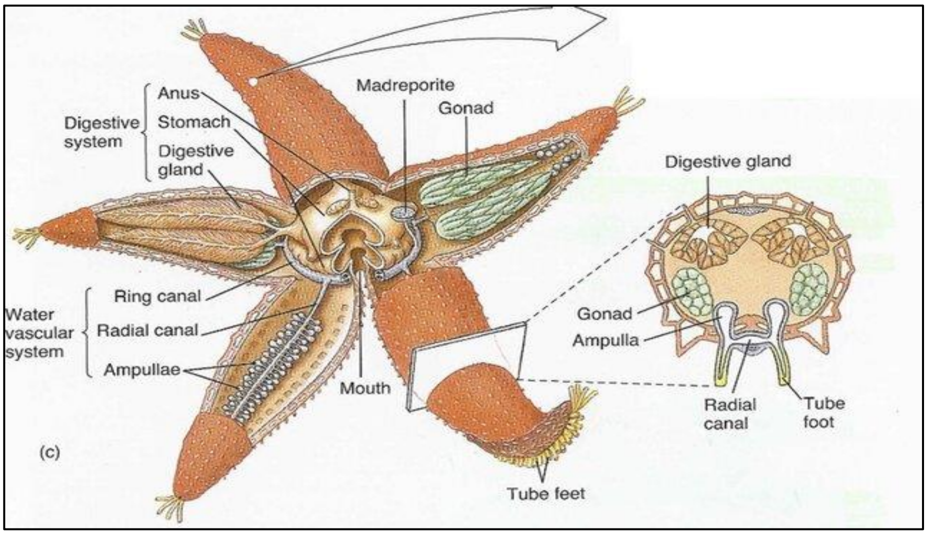


Fig. 58: Diagram of the internal structure of a sea star (Marchiori, 2024).

- **Class Echinoidea (Sea Urchins)**

Sea urchins are **grazers**, feeding primarily on algae in the littoral zones of oceans. Members of this class possess a characteristic **Aristotle's lantern**, located in the mouth and composed of approximately forty ossicles forming **five calcareous teeth** connected by muscles. This structure enables the animal to grind **plant material efficiently** (Hyman, 1955) **(Fig. 59)**.

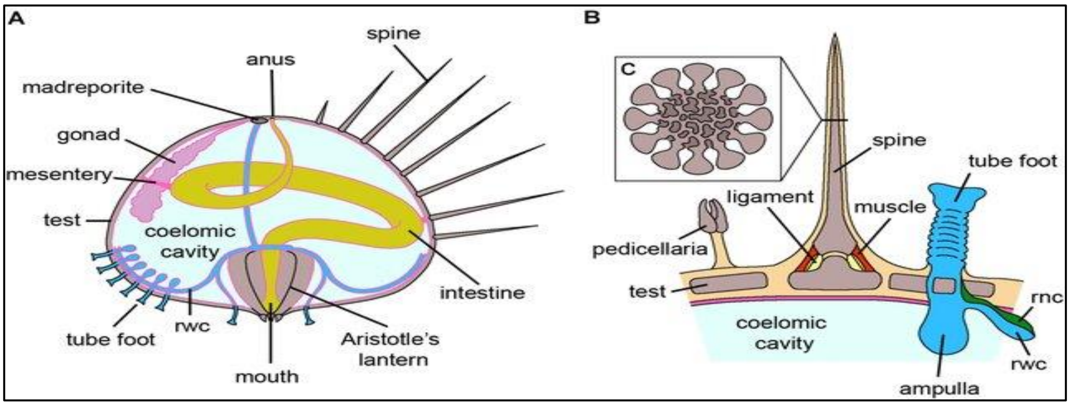


Fig. 59: Diagram Echinoidea. (A) Schematic section through the vertical plane of an adult sea urchin. The oral side, containing the mouth with the Aristotle's lantern, faces the substrate, whereas the aboral side, including madreporite and anus, faces the water column. The digestive tube is anchored to the internal walls of the test by mesenteries. For clarity, structures that are serially repeated along the test either externally or internally have been only partially shown. (B) Schematic longitudinal section of the test where a spine, a tube foot and a pedicellaria are present. The spine is articulated to the test by muscles and ligaments and the tube foot is directly connected to the rwc. (C) Insert of B showing the schematic cross section of a spine where the inner stereom architecture is visible. Abbreviations: rnc-radial nerve cord, rwc-radial water canal. Pink lining represents the coelomic epithelium (Ferrario et *al*., 2020).

- **Class Holothuroidea (Sea Cucumbers)**

Sea cucumbers are benthic and feed on **settling particulate matter**, making them suspension or deposit feeders. They have **tentacles surrounding the mouth**, which they extend over sediment surfaces. Sediment particles adhere to **the mucus-covered tentacles**, which are then brought into the digestive tract, allowing the animal to ingest the collected particles (Ruppert et *al*., 2004) **(Fig. 60)**.

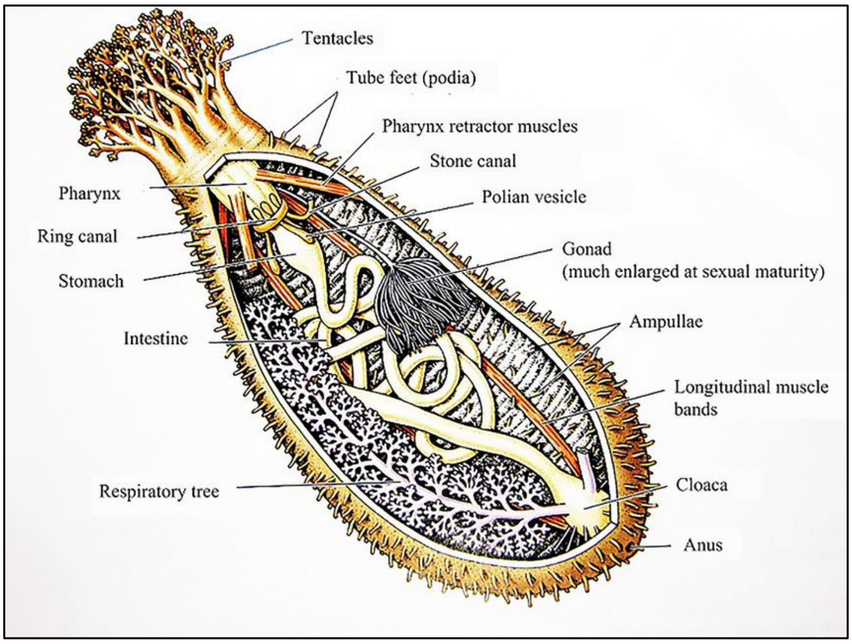


Fig. 60: Diagram of the internal anatomy of a generalized Holothuroid (Liang et *al*., 2022)

- **Class Crinoidea (Crinoids)**

The name Crinoidea derives from Greek krinon (lily) and eidos (form), reflecting their morphology. Crinoids include forms that are **sessile for at least part of their life cycle**. This class appeared as early as the Cambrian period in the Paleozoic era (David et *al*., 2000) **(Fig. 61)**.

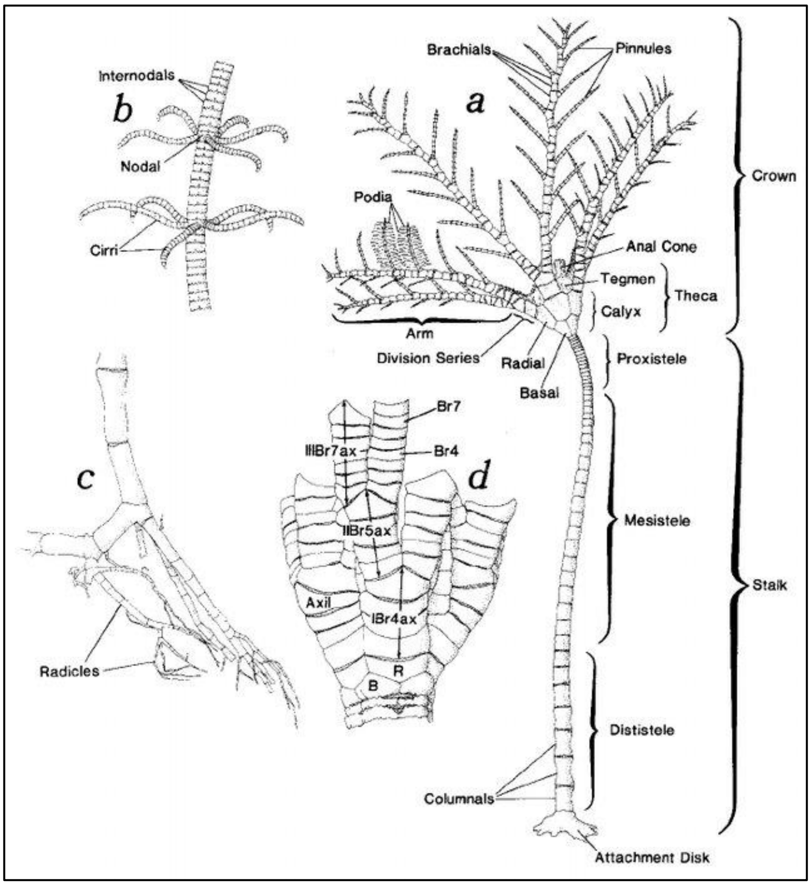


Fig. 61: Schematic illustration of a generalized crinoid with a xenomorphic stalk; three of five rays are shown. B. Portion of a heteromorphic stalk with cirri. C. Portion of a terminal stalk radix. D. Proximal portion of a crown showing bases of three rays and abbreviations for primi-, secundi- and tertibrachial series, and individual brachials of the undivided arm. R = radial ossicle; B = basal ossicle (Roux et *al*., 2002).

- **Class Ophiuroidea (Brittle Stars)**

Brittle stars are characterized by a **flattened disc** on the ventral side, from which **five (sometimes six) long**, **slender arms** radiate independently of the central disc. Unlike starfish, their arms do not touch at the base.

The arms are **round in cross-section**, highly flexible, and capable of **rapid**, **undulating movements**, mostly lateral. The axial skeleton of each arm is composed of numerous small **calcareous vertebrae**, connected by **ligaments and muscles**. The arms are covered with scales, often bear spines, and possess **rudimentary tube feet**, which do not function in locomotion (Brusca & Brusca, 2003; Hyman, 1955) **(Fig. 62)**.

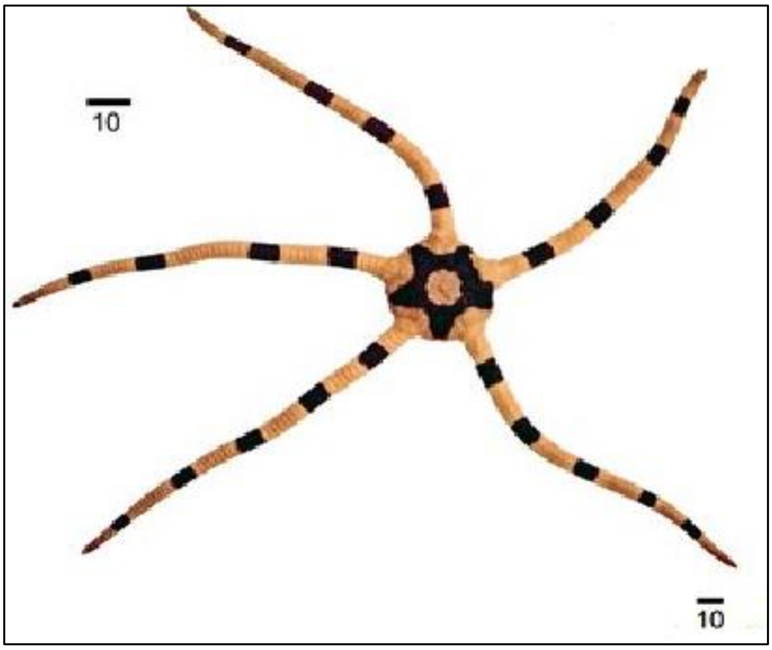


Fig. 62: Class of Ophiuroidea: *Ophiolepis superba* (Stöhr et *al.,* 2012).

Part 02: Subkingdom of Metazoans, Vertebrates.

1- Specific Objectives of Part 02, Chapter 3: Subkingdom of Metazoans, Vertebrates

➢ **Understand the general characteristics of vertebrates**

- Identify common morphological and anatomical traits of vertebrates, such as the vertebral column, skull, locomotor appendages, and bilateral symmetry.
- Recognize adaptations of the skin and integumentary appendages (hair, feathers, scales) according to habitat.

➢ **Study the embryonic origin of organs and systems**

- Describe the role of embryonic germ layers (ectoderm, mesoderm, endoderm) in the development of the nervous, digestive, circulatory, and excretory systems.
- Explain the metameric development of muscles and vertebrae from somites.

➢ **Analyze vertebrate classification and phylogeny**

- Classify the major vertebrate groups (fishes, amphibians, reptiles, birds, mammals) using traditional and cladistic approaches.
- Understand evolutionary relationships between groups, including aquatic → terrestrial transitions and reptiles → birds.

➢ **Examine specific anatomical and physiological systems**

- Describe major systems (circulatory, respiratory, digestive, nervous, reproductive) in different vertebrate groups.
- Compare functional adaptations according to lifestyle (aquatic, terrestrial, aerial) and feeding habits.

➢ **Study reproduction and development**

- Understand reproductive strategies: oviparity, viviparity, hermaphroditism, neoteny, incubation, and parental care.
- Identify specialized structures (amniotic egg, cloaca, internal and external reproductive organs).

➢ **Link morphology and physiology to ecology and evolution**

- Explain how morphological and physiological traits influence survival and adaptation to the environment.
- Illustrate major evolutionary innovations: fins and gills in fishes, amniotic egg in reptiles, feathers and flight in birds, hair and lactation in mammals.

2- General Overview

2-1 Introduction

Vertebrates are animals exhibiting bilateral symmetry and possessing an internal skeleton made of bone or cartilage, which includes at least a vertebral column and a skull (Campbell et *al*., 2018). They also have appendages that facilitate movement and interaction with their environment. These appendages vary widely in form, ranging from fins and tails in fish to the highly specialized arms and hands of humans (Hall, 2015). Skin structure also varies among vertebrates: some species have smooth, mucus-covered skin, others possess a rigid bony exoskeleton, and yet others are covered with insulating layers of hair or feathers (Colbert et *al*., 2015).

2-2 The Essential Characteristics of Vertebrates

The defining feature of vertebrates is the presence of four superimposed organ systems:

- **The nervous system**
- **The notochord**
- **The aorta**
- **The digestive tube**

- Nervous tube: This corresponds to the spinal cord (or neuraxis). It is a hollow structure continued by the vertebral canal, which contains cerebrospinal fluid with a composition similar to plasma (Campbell et *al*., 2018).

- Pharyngeal slits: These persist only in adult aquatic vertebrates. They open in the pharyngeal region and are associated with the pharyngotremal structure (Hall, 2015).

- Notochord: The notochord serves as the dorsal support axis in early development. In adults, it is replaced by a skeletal structure: the vertebral column. This column consists of a series of vertebrae with metametric bony formations (Colbert et *al*., 2015).

- Endoskeleton: The internal skeleton is surrounded by tissues and has an axial structure, with the skull anteriorly and the vertebral column posteriorly. In humans, a bipedal species, the vertebral column is vertically aligned. The central nervous system is housed within the skeleton; for example, the spinal cord lies within the vertebral column. The endoskeleton protects fragile organs, such as the central nervous system. The skull is highly characteristic of each species.

- Tail: Located posterior to the anus, it contains strong musculature and originally served as a locomotor organ.

- Cloaca: This is an invagination of the integument forming a pocket that opens externally via a single orifice. The rectum (end of the digestive tube), urinary, and genital ducts all open into the cloaca. In higher mammals, the cloaca is divided into separate openings for these functions.

- Ectoderm: It gives rise to a stratified integument, such as the epidermis. At the base, a layer of germinal cells continuously produces new cells that move outward. These cells gradually accumulate keratin, die, and are eventually shed. In some cases, instead of being shed individually, the entire outer layer is replaced, a process known as molting.

The integument can produce visible appendages (phanera). If these arise from the dermis, they form bony structures (e.g., fish scales or deer antlers). If produced by the epidermis, they form keratinized structures, such as claws, nails, feathers, hair, reptilian scales, or hollow horns in cows (Campbell et *al*., 2018; Hall, 2015; Colbert et *al*., 2015).

2-3 Embryonic Origin of Organs

The coelom develops as a cavity that splits into two bags, which subsequently give rise to two distinct morphological regions:

- **Dorsal part (myotome):** This region surrounds a myocoel cavity and the somites (paraxial segments), exhibiting typical metamerism.
- **Ventral part (splanchnotome or lateral plate):** Here, the sacs fuse into a single cavity, which lacks metamerism.
- **Intermediate part:** This metametrically segmented region forms the nephrotome, which will give rise to the urinary and reproductive systems (Gilbert, 2016; Sadler, 2020).

The somites proliferate and fill the cavity to form the striated muscles, explaining their segmental (metameric) arrangement.

The intermediate piece primarily contributes to the excretory system by forming the initial coelomic cavity, which later develops into the abdominal cavity. Anteriorly, this cavity splits to form the pericardial cavity, where the heart will develop.

Somites also send out extensions toward the neural tube called the sclerotome. These are regions of cell proliferation whose cells detach and migrate to surround the neural tube, ultimately forming the vertebrae. Because the somites are metamerically organized, the vertebrae will also exhibit metamerism (Hall, 2015).

The endoderm gives rise to the digestive tube. The inner wall of the coelomic sac forms the splanchnopleure, which functions as a supportive tissue suspending organs within the abdominal cavity (Campbell et *al*., 2018).

2-4 Classification of Vertebrates (Fig. 63)

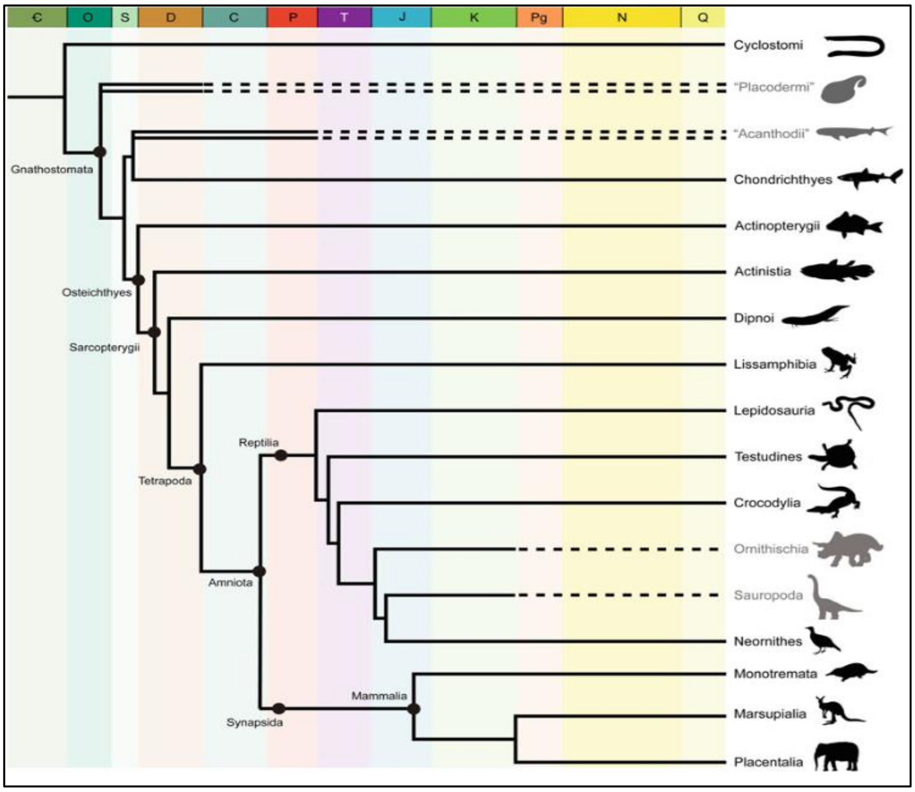


Fig. 63: Cladogram with the phylogenetic relationships of the major groups of Vertebrata, calibrated for geological periods. Groups with exclusively fossil representatives are shown in gray. Some clades are named at the nodes. Terminal names between quotation marks correspond to non-monophyletic groups, which also are represented in phylogeny by doubled lines. Dashed lines correspond to period after group extinction. Є: Cambrian; O: Ordovician; S: Silurian; D: Devonian: C: Carboniferous; P: Permian; T: Triassic; J: Jurassic: K: Cretaceous; Pg: Paleogene; N: Neogene; Q: Quaternary (Slobodian et *al*., 2021).

3- Phylogeny of Vertebrates

3-1 Superclass Pisces (Fishes)

Fishes represent the most species-rich assemblage of vertebrates, accounting for roughly half of all living vertebrate species, with more than 34,000 described species worldwide, about 58–60% of which inhabit marine environments (Nelson et *al*., 2016; Fricke, Eschmeyer et *al*., 2023). The ecological contrast between aquatic and aerial environments particularly in terms of density, conductivity, ionic composition, oxygen availability, nutrient distribution, and light penetration has strongly influenced the evolutionary diversification of fishes (Helfman et *al*., 2009).

The earliest vertebrate fishes appeared during the Devonian period (approximately 419-359 million years ago), often referred to as the "Age of Fishes" because of their extensive radiation during this era (Benton, 2015). Extant fishes comprise three of the major traditional vertebrate classes: jawless fishes (Agnatha), cartilaginous fishes (Chondrichthyes), and bony fishes (Osteichthyes) (Nelson et *al*., 2016).

3-1-1 Jawless Fishes (Agnatha)

Jawless fishes are the most primitive extant vertebrates and include the living cyclostomes: hagfishes and lampreys (Janvier, 1996; Nelson et *al*., 2016).

3-1-1-1 General Characteristics

Jawless vertebrates (cyclostomes) are aquatic, eel-like organisms lacking jaws and paired fins. They may be detritivorous, parasitic, or scavengers depending on the group (Helfman et *al*., 2009).

Key characteristics include:

- Persistence of the notochord throughout adult life (Janvier, 1996).
- Skeleton primarily cartilaginous, with no true bone (Nelson et *al*., 2016).
- Branchial apparatus derived from the pharynx and partially separated from it (Helfman et *al*., 2009).
- Absence of true vertebrae in hagfishes; rudimentary vertebral elements in lampreys (Janvier, 1996).
- Gametes released into the coelomic cavity before exiting the body (Helfman et *al*., 2009).

3-1-1-2 Classification

3-1-1-2-1 Linnaean (Traditional) Classification

Historically, Agnatha were divided into **two major** groups:

A. Cephalaspidomorphi (Lampreys)

Represented today by the order Petromyzontiformes.

Main characteristics:

- Circular oral disc modified into a suction cup with numerous keratinized teeth (Nelson et *al*., 2016).
- Eel-shaped body with two dorsal fins and one caudal fin.
- Separate dorsal and ventral roots of spinal nerves (Janvier, 1996).
- Indirect development with a larval stage (ammocoete) and metamorphosis; reproduction occurs in freshwater (Helfman et *al*., 2009).

Examples:

- *Petromyzon marinus*
- *Lampetra fluviatilis*

B. Myxinoidea (Hagfishes)

Entirely marine organisms, often living in soft sediments and feeding on dead or dying fishes (Nelson et *al*., 2016).

Main characteristics:

- Single median nostril opening anterior to the mouth.
- Fleshy lips with barbels (tentacles).
- Only one median (caudal) fin.
- Dorsal and ventral roots of spinal nerves fused.
- No larval stage or metamorphosis; large yolky (meroblastic-type) eggs; fully marine life cycle (Janvier, 1996; Helfman et *al*., 2009).

Examples:

- *Myxine glutinosa*
- *Eptatretus stoutii*

3-1-1-2-2 Phylogenetic (Cladistic) Classification

Within the clade Deuterostomia, hagfishes and lampreys belong to Chordata due to the presence of a notochord. They are grouped within Craniata (presence of a cranium) and are considered basal vertebrates (Janvier, 1996; Benton, 2015). Modern molecular and morphological analyses support the monophyly of Cyclostomata (hagfishes + lampreys) as a sister group to jawed vertebrates (gnathostomes) (Nelson et *al.*, 2016).

3-1-1-2-3 Importance of the Group

Jawless fishes are of major scientific importance:

- Fossil agnathans are key index fossils used in stratigraphic dating of Paleozoic geological formations (Benton, 2015).
- Some species (particularly lampreys) are consumed in parts of Europe and Asia and hold economic and cultural value (Helfman et *al.*, 2009).

3-1-2 Jawed Vertebrates (Gnathostomes)

Gnathostomes are vertebrates characterized by the presence of true jaws, an evolutionary innovation derived from the modification of anterior gill arches (Janvier, 1996; Nelson et *al.*, 2016). This group includes two major fish classes:

- **Chondrichthyes** (cartilaginous fishes: sharks, rays, chimaeras), approximately 1,200 living species (Nelson et *al.*, 2016).
- **Osteichthyes** (bony fishes), representing the vast majority of extant fish diversity, with more than 34,000 species (Fricke et *al.*, 2023).

3-1-2-1 Morphology

Gnathostome fishes generally exhibit bilateral symmetry, with rare secondary asymmetry in flatfishes (e.g., soles and flounders) (Helfman et *al.*, 2009).

The body is divided into three main regions **(Fig. 64)**:

- **Head:** containing the brain and major sensory organs
- **Trunk:** housing most visceral organs
- **Tail (caudal region):** primarily involved in propulsion

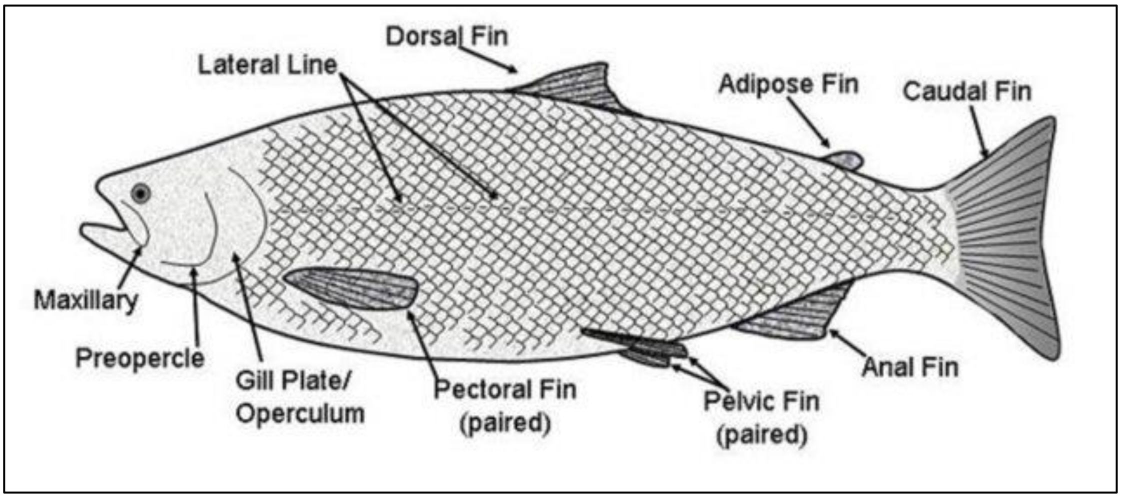


Fig. 64: The general morphological structure of a fish (Sidik & Tey, 2013).

3-1-2-2 Fins and Locomotion

Fins are specialized appendages adapted for stabilization, steering, and propulsion (Helfman et *al*., 2009):

- **Dorsal fin(s):** prevent rolling and lateral instability
- **Pectoral fins:** steering, braking, and fine maneuvering
- **Pelvic fins:** stabilization and directional control
- **Anal fin:** stabilizes against rolling
- **Caudal fin:** main propulsive organ

In many cartilaginous fishes, the caudal fin is **heterocercal** (asymmetrical), due to the extension of the vertebral column into the upper lobe (Nelson et *al*., 2016).

3-1-2-3 Swim Bladder

The swim bladder is a gas-filled hydrostatic organ that allows neutral buoyancy control in most bony fishes (Helfman et *al*., 2009). Rapid ascent can cause barotrauma due to gas expansion.

Not all fishes possess a swim bladder:

- Rays and sharks rely on dynamic lift and large oil-rich livers.
- Some pelagic fishes (e.g., mackerels) must swim continuously.

Historically, Charles Darwin suggested that lungs evolved from the swim bladder. Modern evolutionary biology indicates the opposite: lungs likely evolved first in early bony fishes, with the swim bladder arising later as a derived structure in ray-finned fishes (Benton, 2015).

Some teleosts living in hypoxic environments can use modified swim bladders for aerial respiration (Helfman et *al.*, 2009).

3-1-2-4 Skin and Scales

Fish skin consists of:

- **Epidermis** (outer layer)
- **Dermis** (inner layer)

Cartilaginous fishes possess **placoid scales (dermal denticles)**, whereas bony fishes typically have **cycloid** or **ctenoid scales** (Nelson et *al*., 2016).

Mucus-secreting glands reduce friction and provide protection (Helfman et *al.*, 2009).

Scale growth rings (annuli) may reflect seasonal growth variation and can assist in age estimation, although environmental factors may bias interpretation (Helfman et *al*., 2009) **(Fig. 65)**.

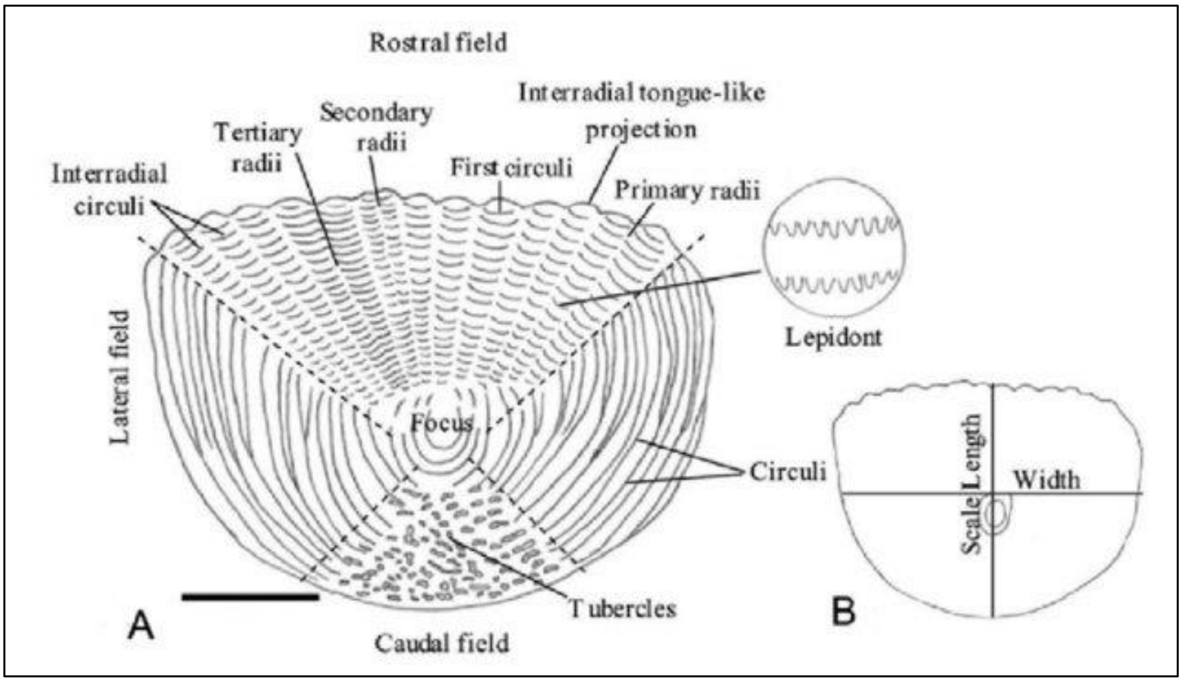


Fig. 65: Schematic drawing of a scale showing some of the terms (Gholami et *al*., 2013).

3-1-2-5 Skeleton

Fishes possess an **internal endoskeleton** composed of cartilage (Chondrichthyes) or bone (Osteichthyes) **(Fig. 66)**.

- The skull may consist of numerous articulated bones.
- The vertebral column extends throughout the body.

- Paired fins are supported by pectoral and pelvic girdles.
- Ribs protect internal organs (Nelson et *al*., 2016).

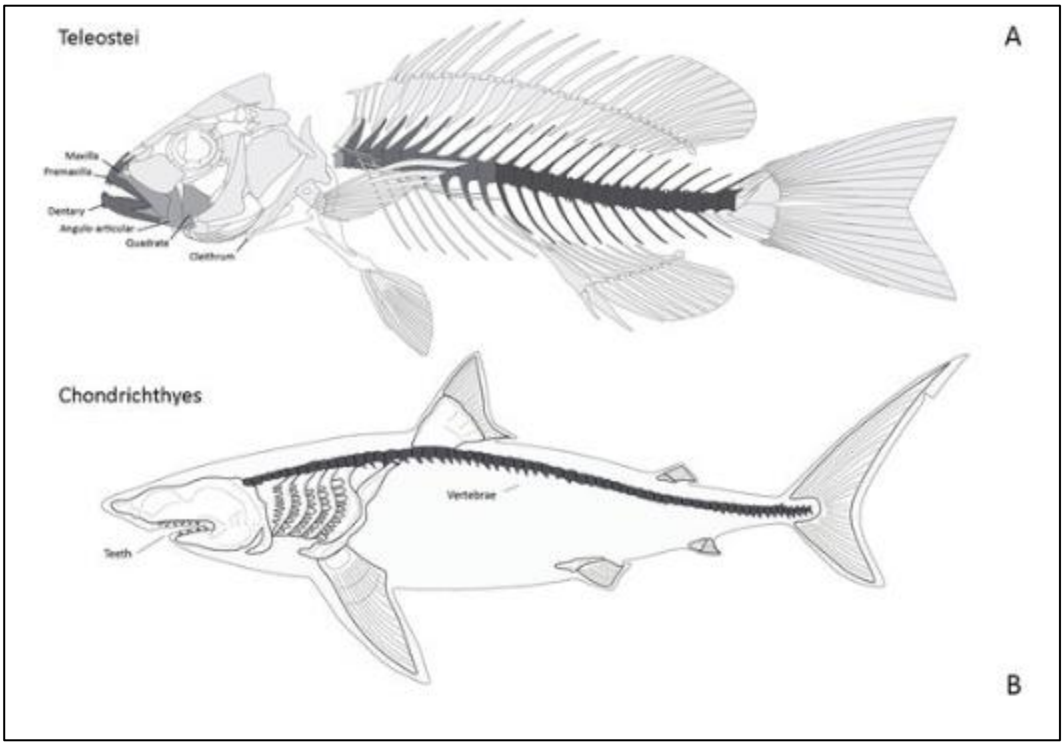


Fig. 66: Anatomical Representation of Fish Skeletons: Bony Fishes (Osteichthyes) **(A)** and Cartilaginous Fishes (Chondrichthyes) **(B)** (Coutureau & Béarez, 2012).

3-1-2-6 Musculature

Fish musculature is organized in segmented blocks called **myomeres**, arranged along the body (Helfman et *al*., 2009) **(Fig. 67)**.

Two main muscle types:

- **Red muscle:** aerobic, endurance swimming (common in pelagic fishes).
- **White muscle:** anaerobic, rapid bursts (common in benthic species).

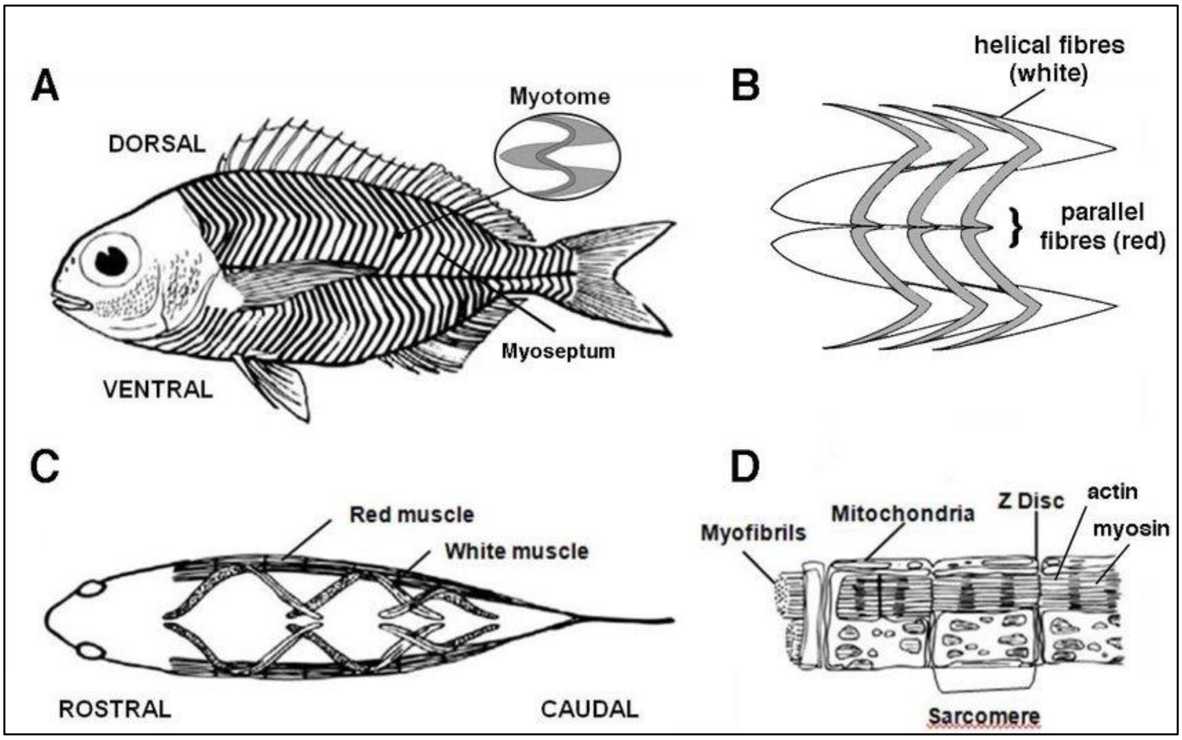


Fig. 67: Skeletal muscle structure in fish. Diagrams show (A) the lateral view of myotomes on fish, (B) the lateral view of myotomes indicating the wedge-shaped region where red muscle fibers run parallel along the body axis, (C) dorsal view of muscle fiber arrangement and, D) the composition of muscle fibers (Rossi, 2021).

3-1-2-7 Digestive System

The digestive tract includes mouth, esophagus, stomach, intestine, and rectum, along with liver and pancreas **(Fig. 68)**.

In cartilaginous fishes, the large oil-rich liver contributes significantly to buoyancy (Nelson et *al.*, 2016).

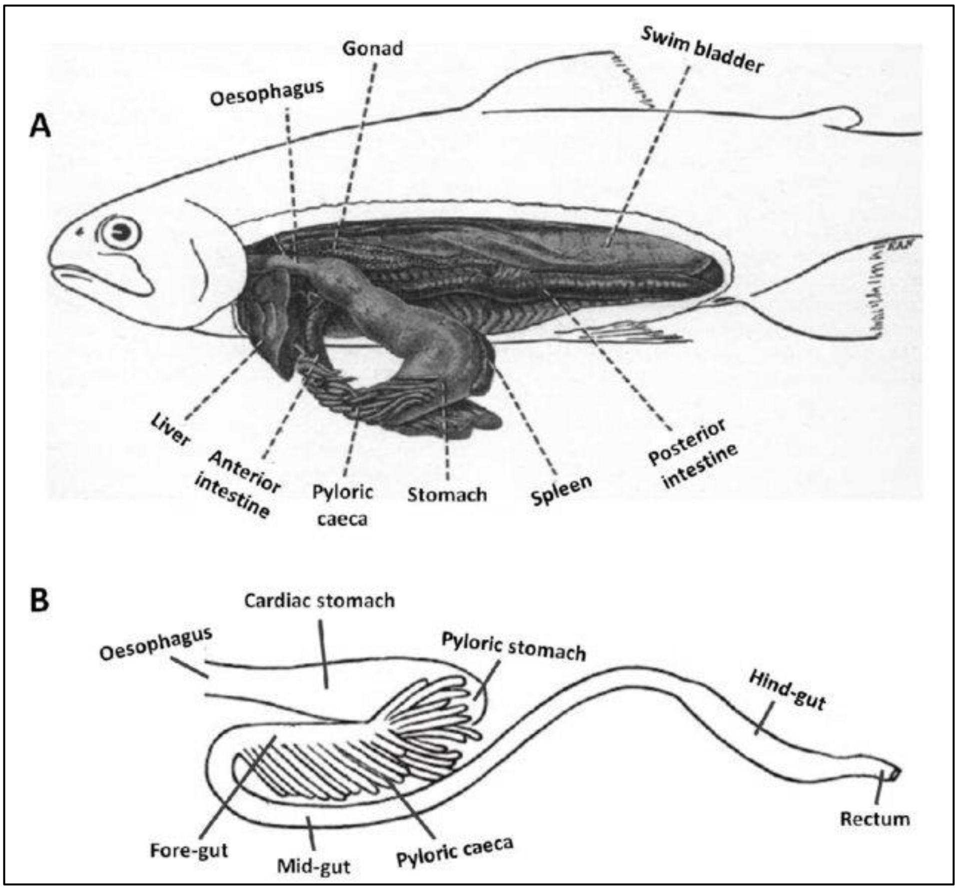


Fig. 68: Schematic illustration of viscera (A) and digestive tract (B) in rainbow trout (Weinreb & Bilstad, 1955; Lokka et *al*., 2013).

3-1-2-8 Circulatory System

Fish possess a **single-loop circulatory system** with a linear heart composed of four sequential chambers: sinus venosus, atrium, ventricle, and bulbus arteriosus (Helfman et *al*., 2009) **(Fig. 69)**.

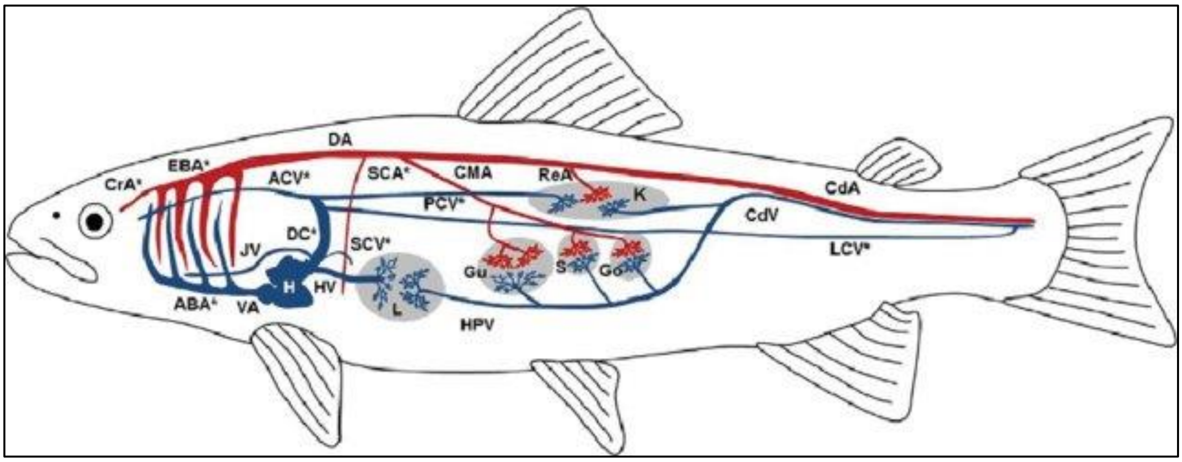


Fig. 69: Schematic representation of the main arteries and veins in a teleost fish. Abbreviations: ABAs, afferent branchial arteries; ACV, anterior cardinal vein; CdA, caudal artery; CdV, caudal vein; CMA, celiacomesenteric artery; CrA, carotid artery; DA, dorsal aorta; DC, Ducts of Cuvier; EBAs, efferent branchial arteries; Go, gonad; Gu, gut; H, heart; HPV, hepatic portal vein; HV, hepatic vein; JV, jugular vein; K, kidney; L, liver; LCV, lateral cutaneous vein; PCV, posterior cardinal vein; ReA, renal artery; S, spleen; SCA, subclavian artery; SCV, subclavian vein; VA, ventral aorta. Abbreviations denoted with * are bilaterally paired vessels where only one of the vessels are shown in the figure (Sandblom & Gräns, 2017).

3-1-2-9 Nervous System and Sensory Organs

The nervous system includes:

- Brain
- Spinal cord
- Peripheral nerves

Distinctive features compared to humans:

- Image focusing achieved by moving the lens rather than changing its shape.
- Absence of a middle ear.
- Presence of a lateral line system, detecting water movement, pressure changes, and sometimes weak electric fields (Helfman et *al*., 2009).

The lateral line helps maintain schooling behavior and predator avoidance **(Fig. 70)**.

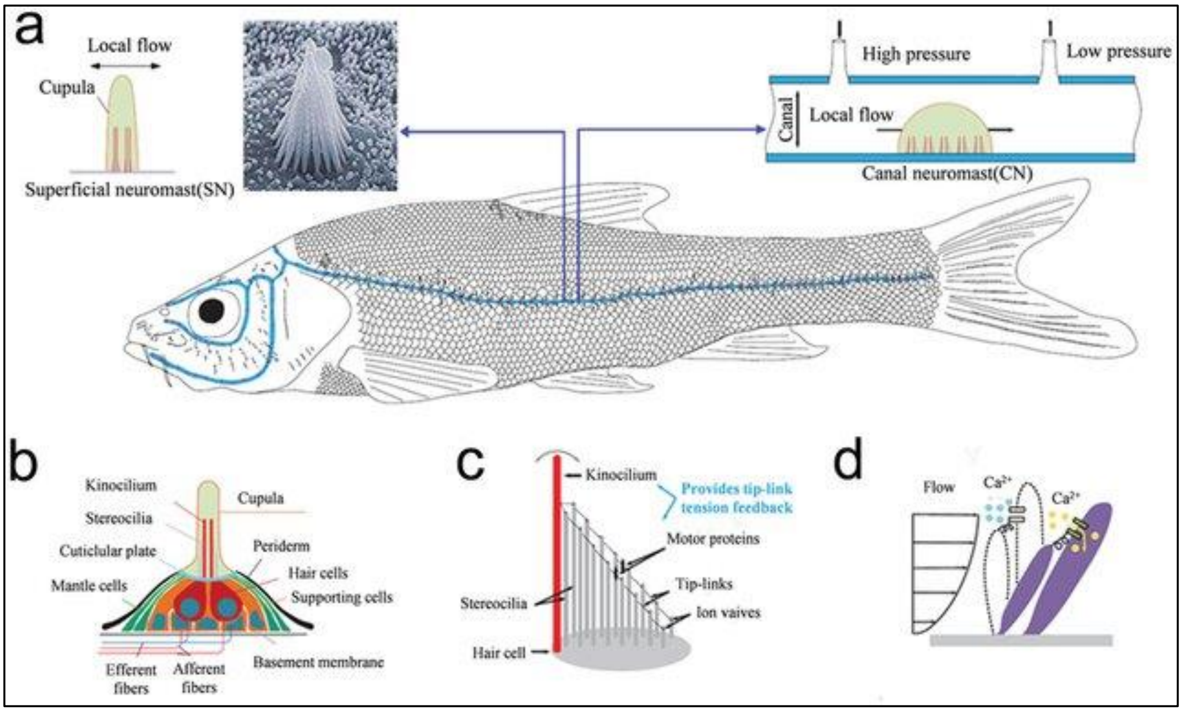


Fig. 70: Lateral line system of fish. a) The distribution of neuromasts. b) The microstructures of the individual neuromast. c) A schematic diagram of the individual hair cell containing kinocilium and stereocilia. d) The deflection direction of the hair cell ciliary bundle and transduction channel (Wang et *al.*, 2021).

3-1-2-10 Gills and Respiration

Gills are the primary respiratory organs of fishes and typically consist of five pairs of gill arches in bony fishes (Nelson et *al.*, 2016).

Functions of gills:

- Gas exchange (O_2 uptake, CO_2 release)
- Osmoregulation
- Acid–base balance
- Ammonia excretion
- Ion regulation

Gas exchange operates via **countercurrent exchange**, maximizing oxygen absorption efficiency (Helfman et *al.*, 2009) **(Fig. 71)**.

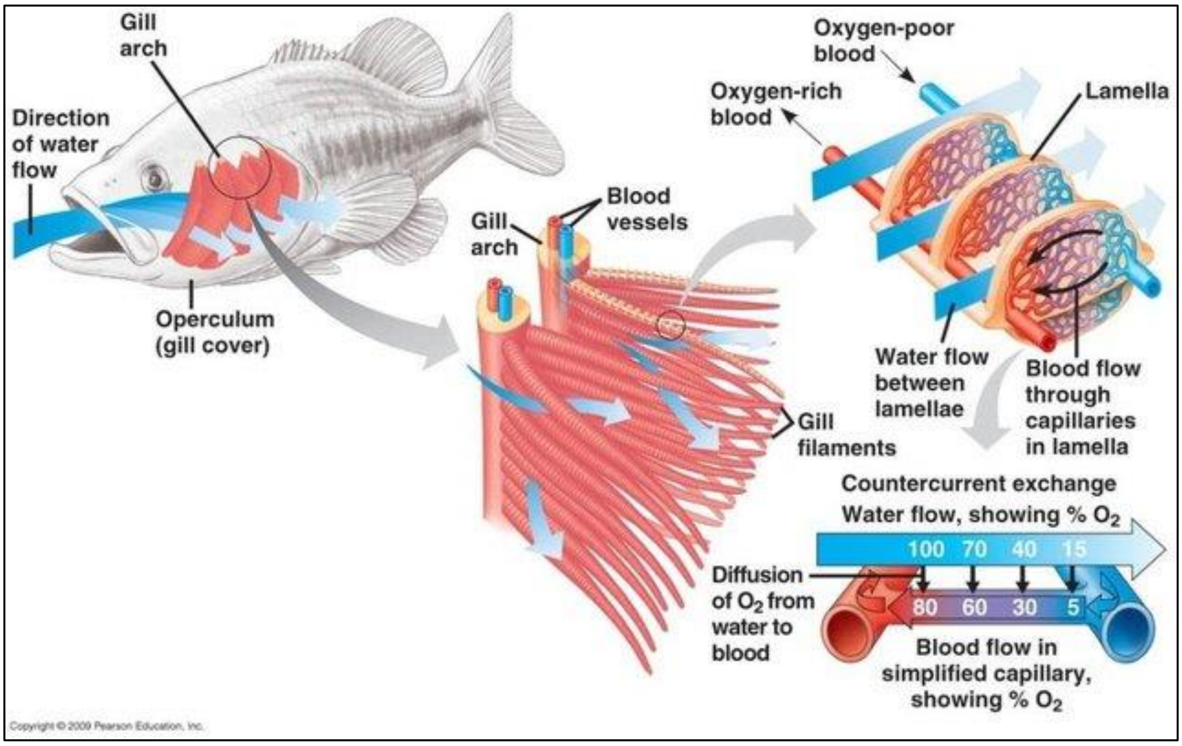


Fig. 71: Schematic of multi scale architecture of fish gill demonstrating exchange of oxygen from ambient water to fish body (Reece et *al*., 2015).

3-1-2-11 Osmoregulation

Marine and freshwater environments impose different osmotic challenges **(Fig. 72)**:

- Marine bony fishes drink seawater and excrete excess salts via gills.
- Freshwater fishes produce dilute urine and actively absorb ions.
- Cartilaginous fishes maintain osmotic balance through urea retention (Nelson et *al*., 2016).

Osmoregulation and respiration can be physiologically antagonistic processes under stress conditions (Helfman et *al*., 2009).

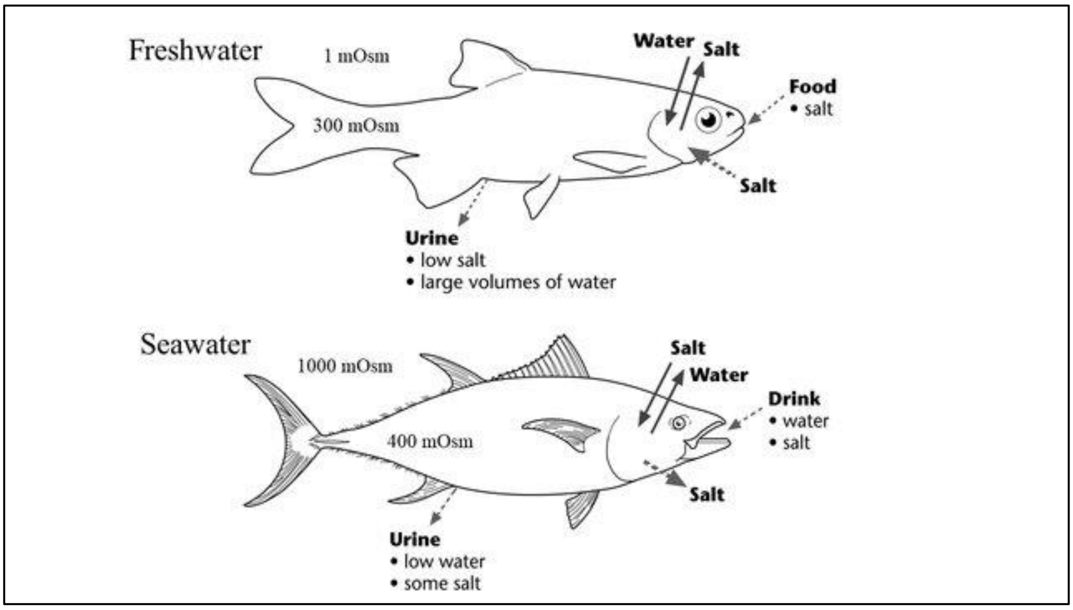


Fig. 72: Mechanisms of osmoregulation by teleost fishes. Solid arrows represent passive movements of salt and water, and dashed arrows represent active pathways of osmoregulation (Evans, 2003; Evans, 2008).

3-1-2-12 Reproduction

Fish reproduction is primarily sexual, with diverse strategies (Nelson et *al*., 2016):

- **Gonochorism:** separate sexes (e.g., *Conger conger*).
- **Simultaneous hermaphroditism:** both sexes present at once (e.g., *Serranus scriba*).
- **Sequential hermaphroditism:**
- Protandry (male → female), common in Sparidae.
- Protogyny (female → male), common in Labridae.

3-1-2-13 Feeding Ecology

Fish diets vary widely (Helfman et *al*., 2009):

- Larvae often feed first on phytoplankton, then zooplankton.
- Herbivores (e.g., *Sarpa salpa*) consume algae.
- Zooplanktivores include *Sardina pilchardus* and *Engraulis encrasicolus*.
- Large pelagic predators include *Thunnus thynnus* and many sharks.
- The anglerfish *Lophius piscatorius* uses a modified dorsal spine as a lure to attract prey.

3-1-2-14 The two major fish classes (Chondrichthyans/ Osteichthyans)

3-1-2-14-1 Cartilaginous Fishes (Chondrichthyans)

3-1-2-14-1-1 Some Distinctive Features of Chondrichthyans

Chondrichthyans are characterized by the presence of placoid scales (dermal denticles) that cover the surface of their bodies. These scales develop in the same manner as teeth and are composed of dentine and enamel-like tissues. As a result, the skin of chondrichthyans has a rough, sandpaper-like, and sometimes abrasive texture (Hickman et *al*., 2017; Kardong, 2019) **(Fig. 73)**.

Their teeth are embedded in the dermis rather than in sockets and are arranged in multiple parallel rows. As teeth grow, they gradually move forward and rotate into position due to the continuous production of tissue along the jaw margin. This mechanism ensures constant tooth replacement throughout life. Consequently, shark teeth are frequently found embedded in prey or scattered at feeding sites (Compagno, 2001; Nelson et *al*., 2016).

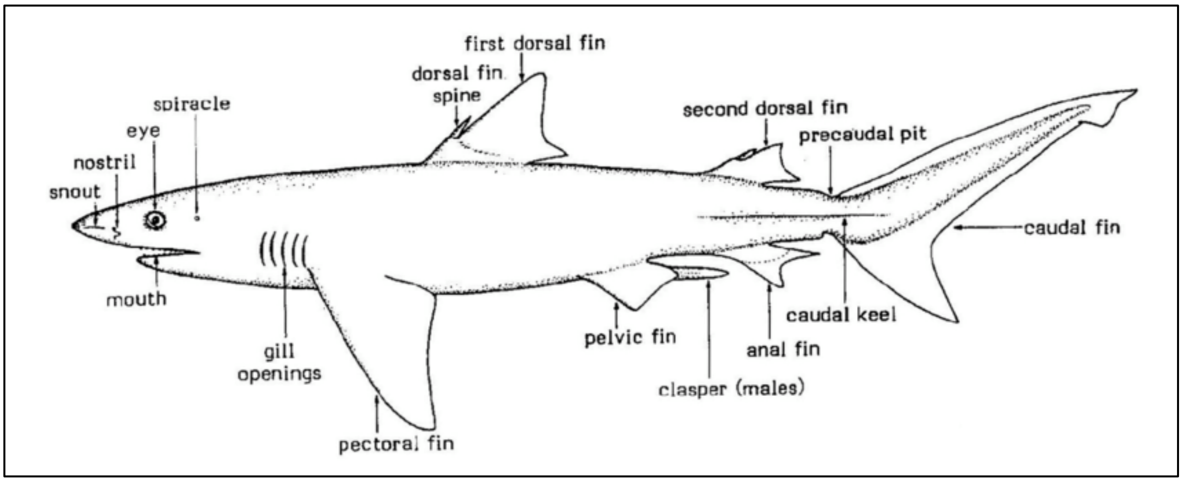


Fig. 73: General external morphology of a Cartilaginous Fish (Edwards, 1990).

3-1-2-14-1-2 The Axial Skeleton (Chondrichthyans)

In the embryo, the axial skeleton is represented by the notochord, which provides primary structural support during early development. In the adult, it is replaced or largely surrounded by the vertebral column (Kardong, 2019; Hickman et *al*., 2017).

The vertebral column is divided into two main regions:

- **Trunk (precaudal) region**
- **Caudal region**

It is composed of repeating **metameric elements**, namely the vertebrae.

Each vertebra consists of:

- A **vertebral centrum** (vertebral body)
- A **neural arch**, which encloses and protects the spinal cord
- A **hemal arch** (in the caudal region), which encloses the caudal blood vessels

This organization reflects the segmented body plan characteristic of vertebrates and ensures both protection of the central nervous system and structural support for locomotion.

3-1-2-14-1-3 Reproductive System (Chondrichthyans)

Chondrichthyans exhibit **internal fertilization**, a key evolutionary feature among cartilaginous fishes (Kardong, 2019; Nelson et *al*., 2016).

- **Female**

The **left ovary is reduced or non-functional** in most species, while the right ovary is functional (Kardong, 2019).

The two oviducts fuse anteriorly at the level of the funnels (ostia) to form a single median ciliated ostium, which collects the released ova (Hickman et *al*., 2017).

Fertilization occurs within the oviduct (Nelson et *al*., 2016).

- **Male**

Spermatozoa are transported through **efferent ductules** connected to **the epididymis**, which develops from anterior nephrotomes of the mesonephros (Kardong, 2019).

The Wolffian duct (archinephric duct) functions as **the sperm duct** (vas deferens) (Hickman et *al*., 2017).

Posteriorly, it enlarges to form **the seminal vesicle**, which also receives urinary ducts before opening into the cloaca (Nelson et *al*., 2016).

This organization reflects the close anatomical and developmental relationship between **the excretory** and **reproductive systems** in vertebrates (Kardong, 2019).

3-1-2-14-2 Bony Fishes (Osteichthyans)

3-1-2-14-2-1 Skeleton

In osteichthyans (bony fishes) **(Fig. 74)**, the skeleton is characterized by at least partial ossification (Hickman et *al*., 2017; Kardong, 2019). It consists of:

- Cartilage, which may persist in certain regions (Kardong, 2019).

- Replacement bones, formed through endochondral ossification, where bone gradually replaces a pre-existing cartilaginous model (Hickman et *al*., 2017).
- Dermal (membrane) bones, formed through intramembranous (dermal) ossification, developing directly within connective tissue without a cartilage precursor (Kardong, 2019).

This combination of ossification processes represents a major structural and evolutionary advancement among vertebrates (Hickman et *al*., 2017).

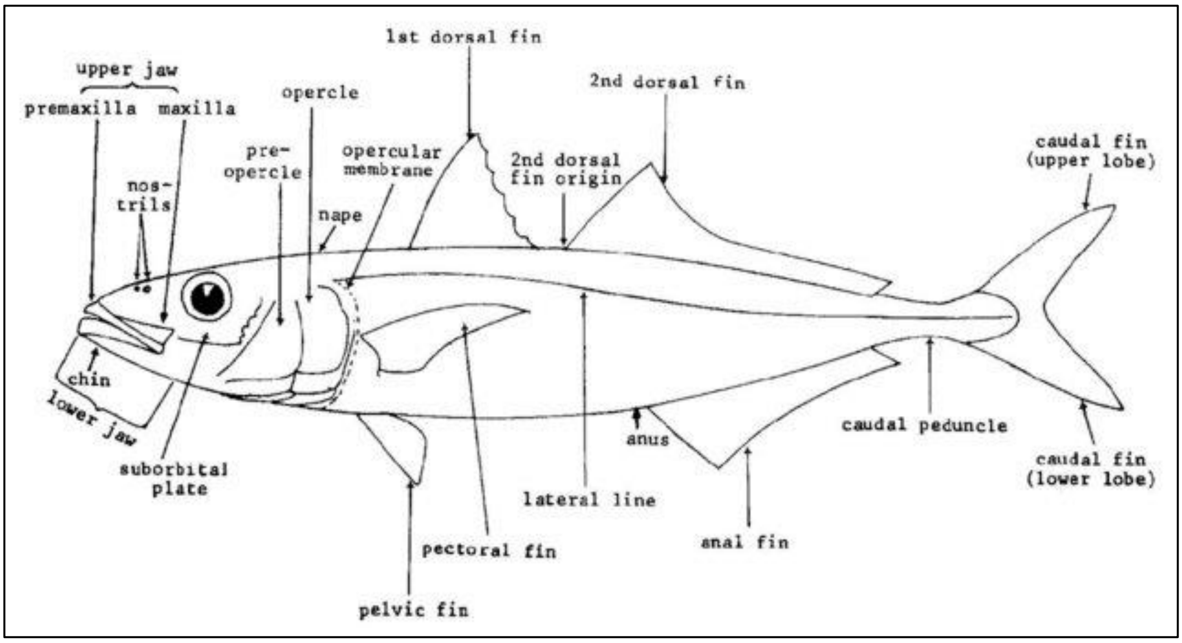


Fig. 74: General external morphology of a bony fish (Edwards, 1990).

➢ The Cephalic (Cranial) Skeleton

In the embryo, the cephalic skeleton consists of a dorsally open cartilaginous neurocranium (Kardong, 2019).

In the adult:

- The floor (basicranium) is mainly composed of replacement (endochondral) bones (Hickman et *al*., 2017).
- The roof (dermatocranium) is primarily formed by dermal bones (Kardong, 2019).

This dual origin of the skull (endochondral and dermal components) is a fundamental characteristic of osteichthyans and contributes to increased protection of the brain and sensory structures (Hickman et *al*., 2017).

3-1-2-14-2-2 Reproductive System (Osteichthyans)

In osteichthyans (bony fishes), **the genital ducts** differentiate from the walls of the general body cavity (coelom) during development (Kardong, 2019). Unlike cartilaginous fishes, the reproductive ducts are typically independent from the primary excretory ducts in most teleosts (Hickman et *al*., 2017).

The genital openings generally discharge externally near **the urinary opening**, but through separate apertures.

A key characteristic of most osteichthyans is **the absence of a cloaca** (a common urogenital chamber), which distinguishes them from chondrichthyans and many other vertebrates (Nelson et *al*., 2016). Instead, the digestive, urinary, and reproductive systems usually open separately to the exterior.

This anatomical organization reflects an evolutionary trend toward functional separation of excretory and reproductive systems in bony fishes (Kardong, 2019).

3-2 Class Amphibia

Amphibians, named for their dual lifestyle that involves both aquatic and terrestrial environments, are also called Batrachians. They evolved from a group of bony fishes that colonized land during the Devonian period of the Paleozoic era (Duellman & Trueb, 1994). In modern fauna, Amphibians are divided into three orders:

- **Order Caudata (Urodela):** Characterized by a relatively elongated body, limbs of similar length, terrestrial locomotion by walking, and a well-developed tail throughout life.
- **Order Anura:** Stocky-bodied, with strongly developed hind limbs adapted for jumping; the tail regresses by the end of metamorphosis.
- **Order Gymnophiona (Caecilians):** Limbs are highly reduced or absent, adapted for a burrowing lifestyle (Wake, 2007).

3-2-1 Skin

Modern amphibians have lost the scales of their ancestors. Their naked, smooth skin classifies them as **Lissamphibia** (Duellman & Trueb, 1994). The skin, composed of dermis and epidermis, is thin and facilitates both respiratory and water exchange, making it vulnerable to desiccation. Between dermis and epidermis are **chromatophores**, pigmented cells responsible for coloration, color changes, and camouflage via homochromy or aposematism (Fox, 1986).

Two main gland types are found in the epidermis:

- **Granular glands:** Secrete toxins of varying potency that provide passive defense against predators.
- **Mucous glands:** Produce a viscous secretion (mucus) that spreads over the skin, protecting against desiccation.

Despite these adaptations, most amphibians remain dependent on moist environments, being active primarily at night or during rainfall. The superficial epidermis periodically sloughs off in a process called ecdysis, which many Anura species consume (Duellman & Trueb, 1994).

3-2-2 Cloaca

In amphibian larvae, the digestive tract opens separately to the exterior through an anus, similar to most fishes. In adults, the digestive, urinary, and reproductive tracts converge into a single opening called **the cloaca**, a feature also present in reptiles (Zug et *al*., 2001).

3-2-3 Respiration

Amphibian larvae respire via **gills**, as in fishes. During metamorphosis, gills regress while **lungs** develop for aerial respiration. Throughout life, cutaneous respiration remains vital due to their thin skin, enabling gas exchange both in water and on land (Feder & Burggren, 1992).

3-2-4 Senses

Amphibians possess large, globular eyes. Pupillary dilation and contraction allow both diurnal and nocturnal vision, though they are more sensitive to movement than shapes or colors. Without a secondary palate, the eyes may retract during swallowing.

Nares at the snout tip allow both olfaction and respiration. Tympanic membranes situated posterior to the eyes detect sound in air and water. An adult amphibian exposing only its head above water can see, smell, hear, and breathe simultaneously (Duellman & Trueb, 1994).

3-2-5 Heterothermy

Amphibians, like their fish ancestors, do not produce metabolic heat and are fully dependent on environmental temperatures for vital functions they are **heterothermic**. Metabolic reactions follow the Van't Hoff principle: accelerated by heat, slowed by cold. During winter, metabolism passively ceases in a state called **hibernation**, with species-specific tolerance thresholds (Feder & Burggren, 1992). Reptiles exhibit similar phenomena but require higher temperatures.

3-2-6 Reproduction

Aquatic environments are essential for reproduction in most amphibians. Adults migrate to water bodies, often natal sites, for breeding, sometimes covering distances up to 2 km. Males often arrive first and may emit **advertisement calls** to attract females and deter rivals. Vocalizations, unique among amphibians, are considered an evolutionary innovation, predating bird song (Duellman, 1999).

Mating strategies differ by group:

- **Newts (Triturus spp.):** No direct copulation; males perform a **nuptial dance** and deposit spermatophores ingested by females for internal fertilization.
- **Salamanders:** Terrestrial copulation brings cloacas into contact for internal fertilization.
- **Anurans:** Males clasp females in **amplexus**, either lumbar (primitive) or axillary (advanced), enabling external fertilization in water.

Amphibian eggs are **heterolecithal**, with moderate yolk amounts and enveloped in a mucous layer protecting from predators and cold. The yolk-rich vegetal pole is heavier and oriented downward; the apical pole, often darker, acts as a solar collector, aiding embryonic development (Wassersug, 1976) **(Fig. 75)**.

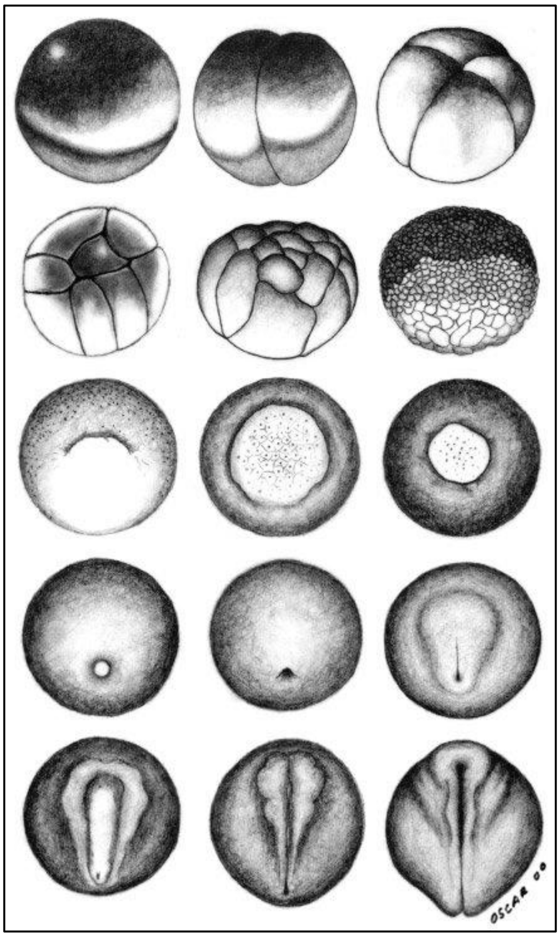


Fig. 75: Development of Amphibian Eggs (Del Pino et *al*., 2004).

3-2-7 Larval Stage and Metamorphosis

Upon hatching, larvae differ markedly from adults and must feed, grow, and undergo metamorphosis to become juveniles. Juveniles leave the aquatic habitat, breathe differently, and grow over several years until adulthood, facing high mortality compensated by producing many eggs (Altig & McDiarmid, 1999) **(Fig. 76)**.

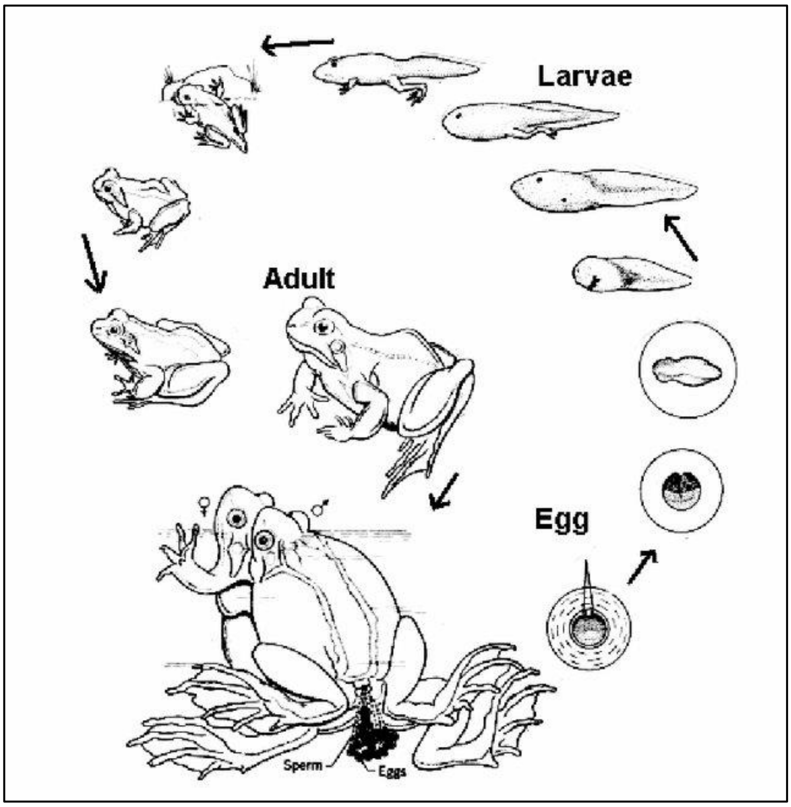


Fig. 76: The life cycle of an anuran, from fertilized egg, through larval stages and metamorphosis, to sexually mature adult (Storer et *al*., 1979).

3-2-8 Phoresy

Some species exhibit **parental care**. For example, **the midwife toad (Alytes obstetricans)** male carries eggs on his hind legs during development, a behavior known as phoresy, increasing offspring survival in drier environments (Arnold, 1978) **(Fig. 77)**.

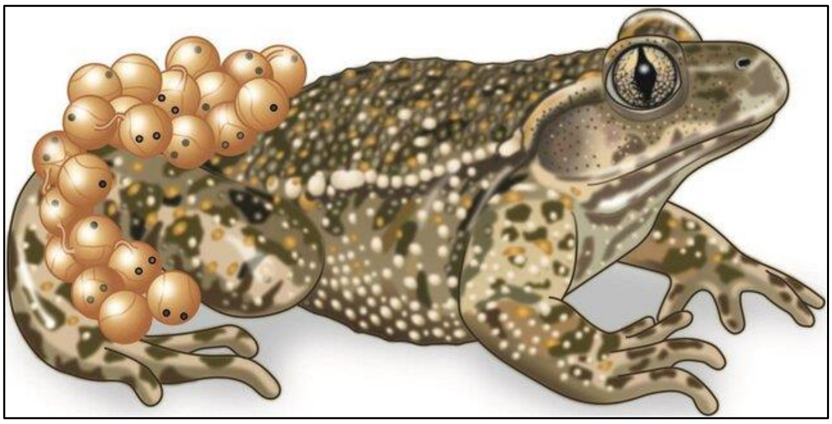


Fig. 77: Phoresy: Male Midwife Toad (Alytes obstetricans) Carrying Eggs (Arntzen, 2022).

3-2-9 Oviparity vs Viviparity

Most amphibians are **oviparous**, laying eggs in water. In some species, females retain fertilized eggs, which develop and hatch at later stages this is now referred to as **viviparity**, as physiological exchanges occur between mother and embryo (Blackburn, 1993).

3-2-10 Neoteny

While adulthood is defined by reproductive capability, some Urodeles, like certain newts, can reach sexual maturity while retaining larval morphology under environmental constraints, a phenomenon called neoteny or **paedomorphosis** (Whiteman, 1994).

3-3 Class Reptilia

3-3-1 Introduction

Modern reptiles (from Latin *reptilis*, from *repere*, meaning “to crawl”) are terrestrial, tetrapod vertebrates. They are ectothermic (poikilothermic), breathe through lungs, lay amniotic eggs, possess epidermal scales, and have a circulatory system mixing oxygenated and deoxygenated blood (Benton, 2015).

Origin:

The earliest known reptile is *Hylonomus lyelli* **(Fig. 78)**, which lived during the Carboniferous period, approximately 315 million years ago, and had a general lizard-like appearance (Carroll, 1988).

Reptiles reproduce via eggs with embryonic membranes such as the amnion and allantois, allowing them to complete their development entirely on land. This adaptation is associated with morphological and physiological changes, including the development of keratinized scales and modifications in locomotor muscles and skeleton (Pough et *al*., 2016).

By becoming amniotic tetrapods, reptiles diverged permanently from their amphibian ancestors (Benton, 2015).

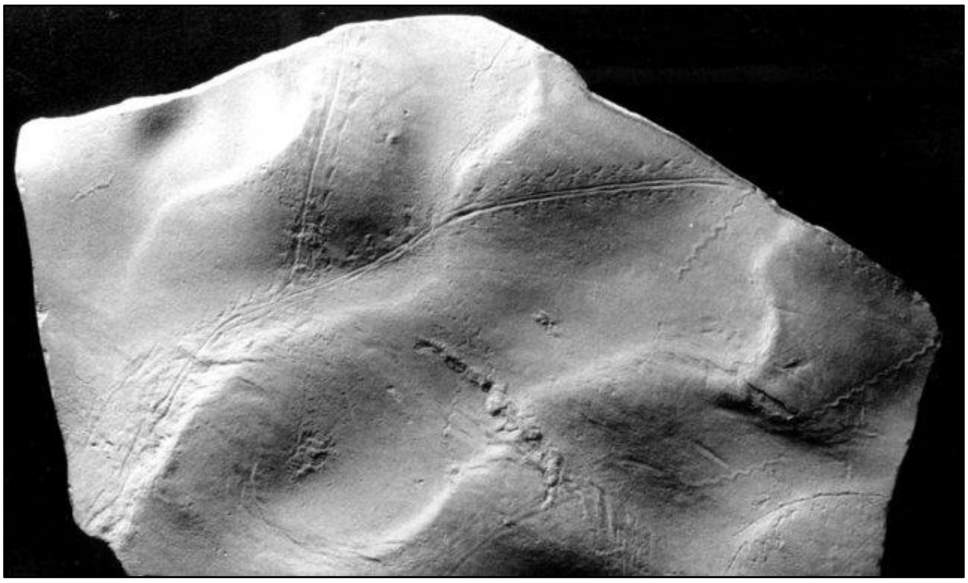


Fig. 78: *Hylonomus lyelli*, the oldest known reptile, extracted from the 'lower reef' of Coal Mine Point in 1859 (Falcon-Lang et *al.*, 2010).

3-3-2 Evolution of Reptiles

3-3-2-1 Emergence of Major Subclasses

Primitive reptiles diversified over time into several major lineages, classified based on skull characteristics specifically, the presence and position of temporal fossae. Early 20th-century work by Osborn (1903) and Williston (1925) established this framework. Modern research, including molecular studies, questions its strict reliability.

Current classification recognizes three major lineages **(Fig. 79)**:

- **Anapsids:** skulls without temporal fossae; traditionally include only turtles. Some authors consider them extinct (Lee, 1996).
- **Diapsids:** skulls with two temporal fossae; include all modern reptiles except traditionally turtles (Carroll, 1988).
- **Synapsids:** skulls with a single temporal fossa; represented today by mammals and extinct "mammal-like" reptiles (Reisz, 2006).

Recent molecular evidence suggests that turtles (Chelonia) may have had temporal fossae that later closed, implying they are sister group to diapsids (Crawford et *al.*, 2015). Consequently, all modern reptiles are now grouped as diapsids.

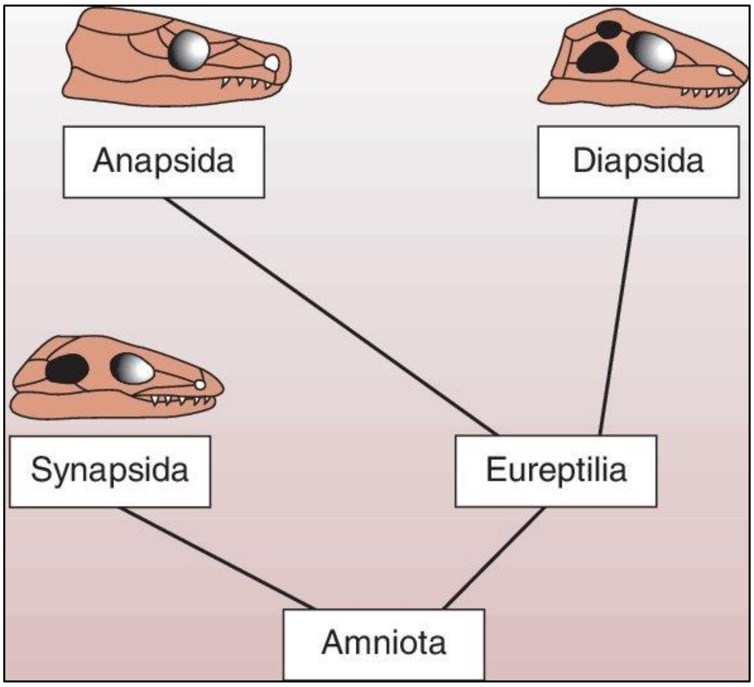


Fig. 79: Synapsid, anapsid, and diapsid skull types in a showing their hypothesized evolutionary relationships. Temporal fenestra indicated by blackened areas; orbits (eye sockets) (Martin, 2002).

3-3-2-2 Diapsid Subclass

The diapsid subclass includes:

- **Lepidosauria:** scaled reptiles such as lizards, snakes, and tuataras
- **Archosauria:** crocodiles, birds, and their extinct relatives
- **Chelonia:** turtles, whose precise placement remains debated (Benton, 2015)

Lepidosauria Orders:

- Sphenodontia (Rhynchocephalia)
- Squamata
- Sauropterygia

Archosauria Superorder

- Includes crocodilians, birds, and their extinct relatives (Benton, 2015).

3-3-3 Current Classification

Non-avian reptiles and birds are united in the monophyletic group **Sauropsida** (Rieppel, 1994).

3-3-4 Bone: Anatomy and Physiology

3-3-4-1 Bone Anatomy

3-3-4-1-1 Bone Structure

Reptile bones are broadly comparable to those of mammals, with long, short, and flat bones. Histologically, bones consist of an extracellular matrix (collagen, proteoglycans, hydroxyapatite crystals, tricalcium phosphate) and bone cells: osteoblasts, osteocytes, lining cells, and osteoclasts (Currey, 2002). Long bones have a diaphysis of compact bone, periosteum, endosteum, and epiphyses containing spongy bone.

- Crocodilians exhibit advanced bone development due to high vascularization and nutrient canal invasion.
- Chelonians have bone organization resembling the Haversian system, but simplified with fewer cellular elements.
- Vertebrae generally contain compact and spongy bone, sometimes with marrow, and resemble long bones microscopically (Pough et *al*., 2016).

3-3-4-2 Bone Physiology

Bone physiology involves growth regulation and phosphocalcic metabolism. Growth and skeletal functions in ectothermic reptiles depend heavily on ambient temperature and are hormonally regulated via the thyroid and pituitary glands (Bagnoli, 2015).

3-3-5 Reptile Anatomy

3-3-5-1 Cranial Skeleton

3-3-5-1-1 Skull

Reptile skulls vary from lightly built, open structures (saurians, snakes) to massive and solid (chelonians, crocodilians) **(Fig. 80)**. The skull consists of:

- **Splanchnocranium:** supports oral and pharyngeal cavities
- **Neurocranium:** encases the brain

In reptiles, jaw articulation occurs between the quadrate and articular bones. In mammals, these bones form part of the middle ear, replaced in the jaw by the dentary and squamosal (Romer & Parsons, 1986).

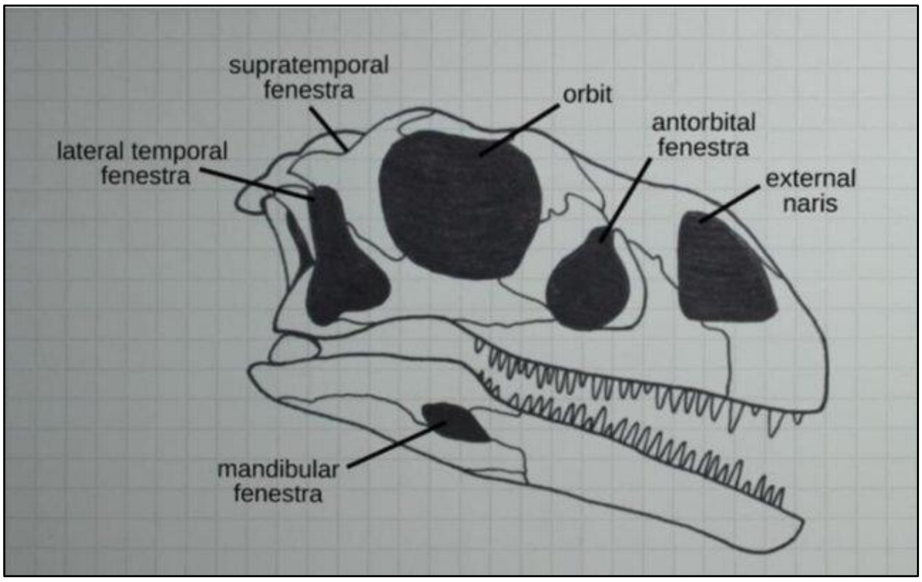


Fig. 80: Skull of a primitive reptile (Aversi-Ferreira et *al.*, 2022).

Additional features:

- **Chelonians:** solid skull, posterior region well developed, anterior short; no teeth, but a keratinous beak (ramphotheca).
- **Saurians:** mobile quadrate allows flexible jaw movements.
- **Crocodilians:** massive, rigid skull with varying snout shapes:
- **Gavialids:** long, narrow (longirostrine)
- **Alligatorids:** broad, rectangular (brevirostrine)
- **Crocodilids:** medium, triangular (mesorostrine)

3-3-5-1-2 Teeth

Reptile teeth are typically conical, often in a single row, but vary among species (Pough et *al.*, 2016) **(Fig. 81)**.

- **Acrodont:** teeth on top of jaw (Agamids, Chameleons)
- **Thecodont:** teeth in sockets, attached by collagen (Crocodilians)
- **Pleurodont:** teeth on inner side of jaw (other lizards, snakes)

Reptiles exhibit polyphyodonty, replacing teeth continuously, unlike mammals' diphyodonty (Romer & Parsons, 1986).

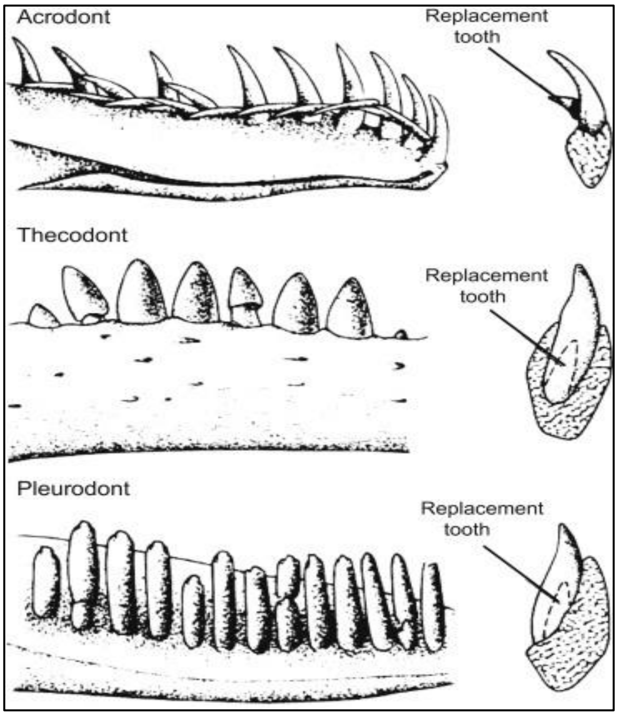


Fig. 81: Reptile teeth can sit on top of the jaw (acrodont), embedded in the jaw (thecodont), or on the side of the jaw (pleurodont) (Kardong, 2006).

3-3-6 Reproduction in Reptiles

Reproduction is primarily sexual with internal fertilization. Males have one or two penises to transfer sperm via the cloaca. Fertilized eggs are expelled through the female cloaca, though some species retain eggs until hatching (Pough et *al*., 2016).

3-3-6-1 Amniotic Eggs

Unlike amphibians, reptiles produce amniotic eggs with protective membranes and a yolk providing nutrients, keeping the embryo moist and safe during development (Carroll, 1988) **(Fig. 82)**.

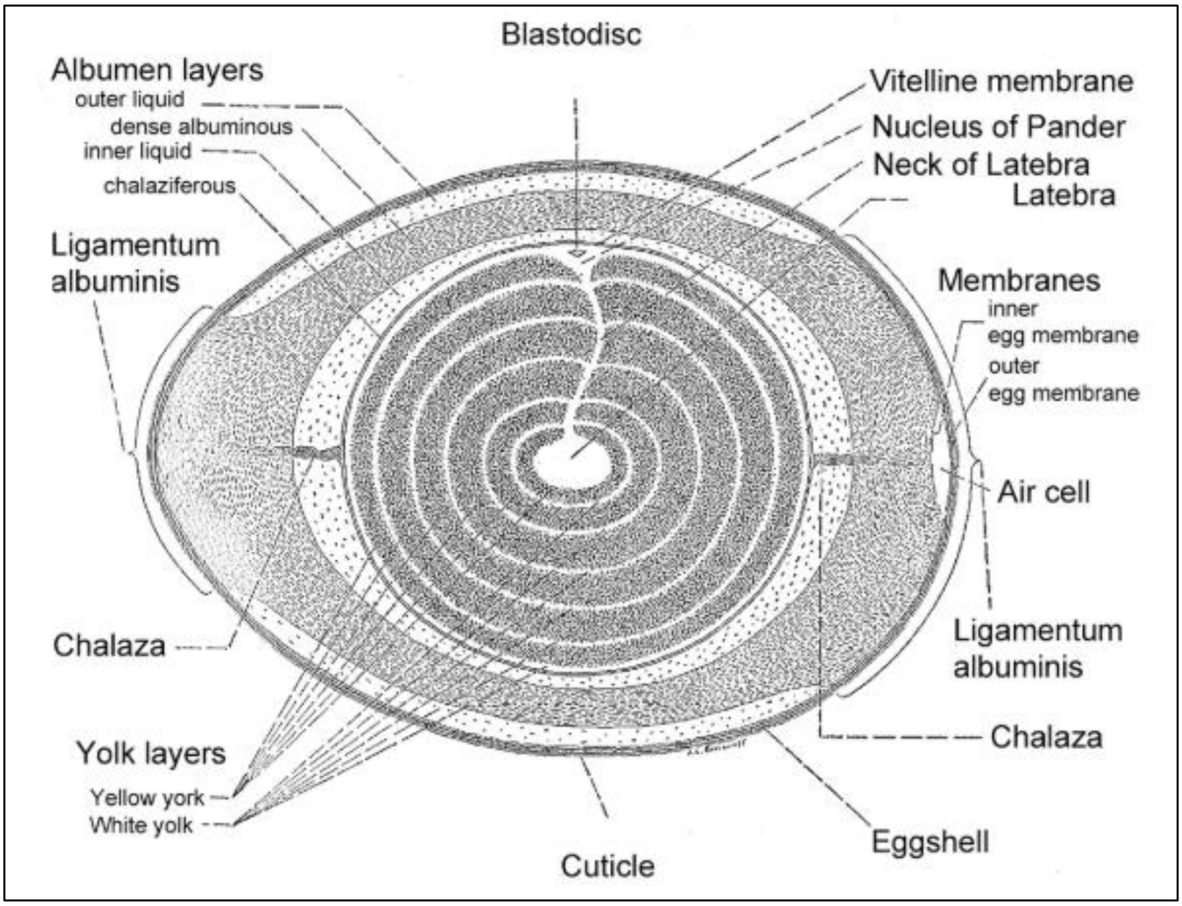


Fig. 82: The amniotic egg is an important adaptation in fully terrestrial vertebrates. It first evolved in reptiles. Reptile eggshells are either hard or leathery (Starck et *al*.,2021).

3-4 Class Aves (Birds)

3-4-1 Historical Background

The earliest known ancestor of all modern birds was discovered in Germany in 1861 within Upper Jurassic sediments (~150 million years old). This species, Archaeopteryx lithographica, was a small, bird-like animal that was considered the transitional fossil between reptiles and living birds because it exhibited both reptilian features (such as teeth and a long vertebrate-bearing tail) and avian characteristics like feathers (Feduccia, 2017). Although Archaeopteryx remains a pivotal fossil, its exact place in evolutionary history continues to be debated, and new fossils frequently reignite scientific discussion (Mayr, 2016). The presence of amniotic eggs and scaly feet in modern birds are notable reptilian vestiges within Aves (Gill, 2007) **(Fig. 83)**.

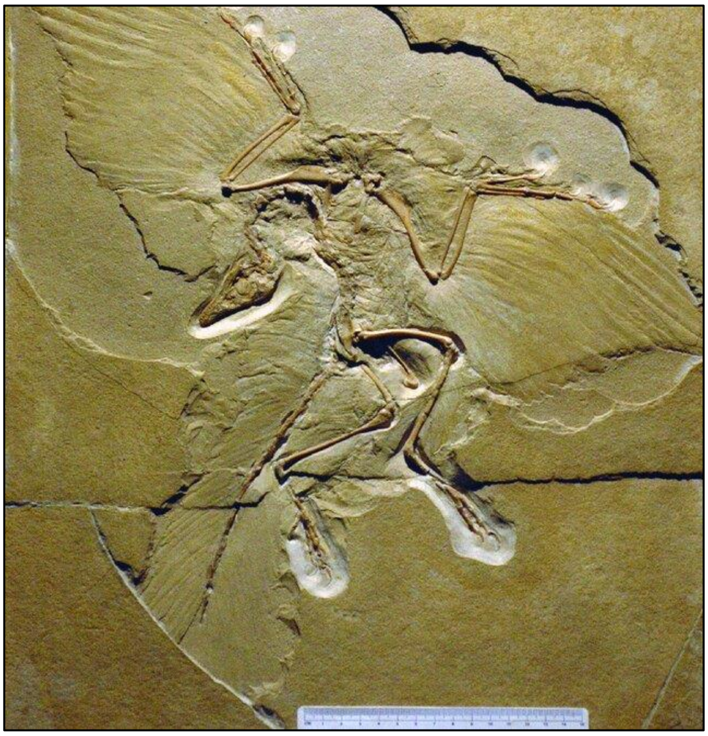


Fig. 83: *Archaeopteryx lithographica*, a fossil found in layers about 150 million years old in southern Germany, is considered the oldest bird. This species became one of the first pieces of evidence supporting evolution in Darwin's time. Specimen deposited in the Natural History Museum of Berlin, Germany (Kellner, 2024).

3-4-2 Introduction to Birds

The class Aves currently includes approximately 9,600 species that inhabit almost all regions of the Earth, including extreme environments (Gill, 2007). Birds are vertebrates that lay eggs (oviparous), maintain a constant body temperature (homeothermic), and possess a high metabolic rate (Feduccia, 2017). Birds represent one of the most anatomically uniform vertebrate groups, largely due to the structural and physiological demands of flight. Even flightless birds today descend from flying ancestors, underscoring the evolutionary influence of aerial adaptation on bird anatomy and physiology (Mayr, 2016).

3-4-3 Phylogenetic and Traditional Classification

In traditional taxonomy, birds are treated as a distinct class within vertebrates. However, phylogenetic evidence shows that birds evolved from theropod dinosaurs and are therefore nested within the reptile lineage, sharing a common ancestor with crocodilians in the archosaur clade (Chiappe, 2007). Many references still present birds separately from reptiles for practical reasons, including this text.

Importantly, the major subdivisions **(orders)** within birds are consistent whether using traditional classification or modern phylogenetics. However, the placement of specific species within certain orders is frequently revised with new research and is not universally agreed upon (Gill, 2007). The following list of major bird orders follows BirdLife International and the International Union for Conservation of Nature (IUCN) classifications:

1. **Struthioniformes:** ostriches, rheas, kiwis
2. **Tinamiformes:** tinamous
3. **Anseriformes:** ducks, geese
4. **Galliformes:** chickens, partridges, pheasants
5. **Podicipediformes:** grebes
6. **Gaviiformes:** loons
7. **Sphenisciformes:** penguins
8. **Pelecaniformes:** pelicans, boobies
9. **Gruiformes:** cranes, rails, coots
10. **Ciconiiformes:** storks, herons
11. **Charadriiformes:** gulls, sandpipers
12. **Columbiformes:** pigeons, doves
13. **Falconiformes:** falcons, eagles, vultures
14. **Strigiformes:** owls
15. **Psittaciformes:** parrots, parakeets
16. **Cuculiformes:** cuckoos
17. **Caprimulgiformes:** nightjars
18. **Apodiformes:** swifts
19. **Coliiformes:** mousebirds
20. **Coraciiformes:** kingfishers, hornbills
21. **Piciformes:** woodpeckers, toucans
22. **Passeriformes:** songbirds (Gill, 2007).

3-4-4 General Characteristics of Birds

3-4-4-1 Feathers and Plumage

Feathers are the most distinctive feature of birds and represent a major evolutionary innovation (Bowdler Sharpe, 1891; Gill, 2007). Feathers likely first evolved for thermoregulation and were later co-opted for flight. They are epidermal structures composed primarily of keratin and are alive only while they are growing (Gill, 2007). Unlike hair, nails, or claws, feathers do not grow continuously; when they fall out, they are replaced during a regular process called molting **(Fig. 84)**.

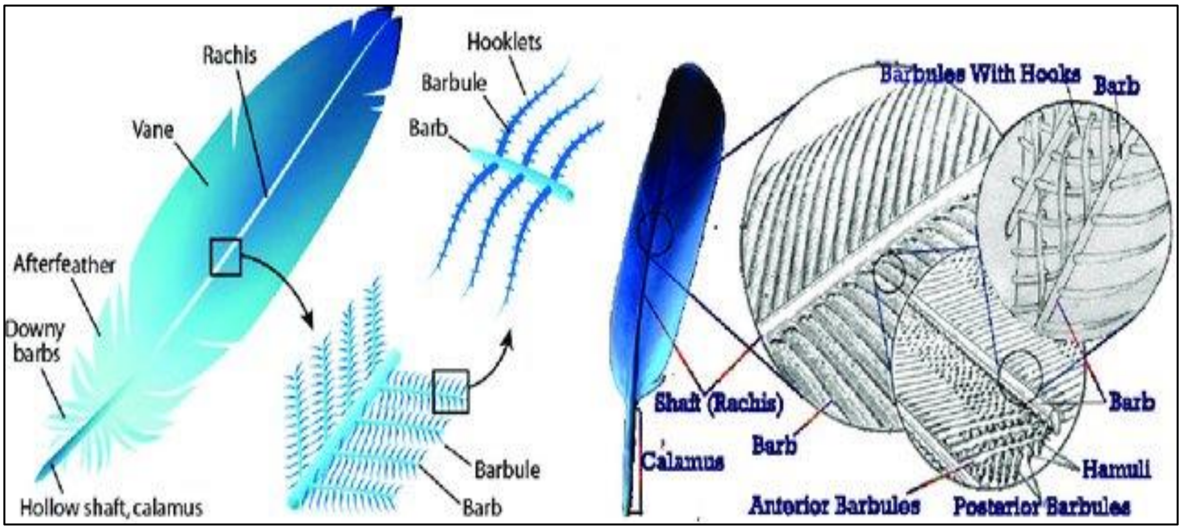


Fig. 84: Morphology of pigeon bird feather (Mishra et *al*., 2015).

A feather's structure includes a central shaft, where the lower hollow part is called the calamus, and the solid upper portion is the rachis. Form and structure vary based on function:

- **Flight feathers (remiges)** for locomotion
- **Colored feathers** for signaling and sexual display
- **Down feathers** for insulation

The plumage refers to all feathers covering a bird's body, shaping its aerodynamic contour and influencing appearance. Despite individual feathers being light, the total weight of a bird's plumage is typically 2-3 times greater than its skeleton (Gill, 2007). Plumage can change with age, sex, and season.

3-4-4-2 Bones and Skeleton

Bird bones are light relative to body size due to pneumaticity: many bones are hollow but reinforced by internal struts that maintain strength without adding weight (Feduccia, 2017). Some bones also connect with air sacs of the respiratory system **(Fig. 85)**.

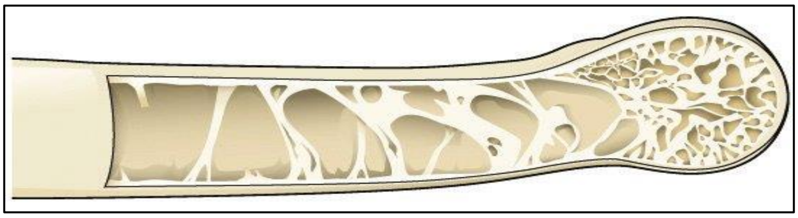


Fig. 85: The cross section of a bird's bone illustrating the hollow interior with crisscrossing struts (Sterling et *al*., 2015).

Bird skeletal structure is highly adapted to flight: vertebrae are fused in several regions to form a rigid synsacrum that supports the body in flight, and the large keel on the sternum provides a strong attachment for flight muscles (Gill, 2007).

Bird legs are upright and adapted for bipedal locomotion. Leg form reflects lifestyle: species that wade in shallow water have long legs, whereas aerial species and tree climbers have shorter legs (Gill, 2007) **(Fig. 86)**.

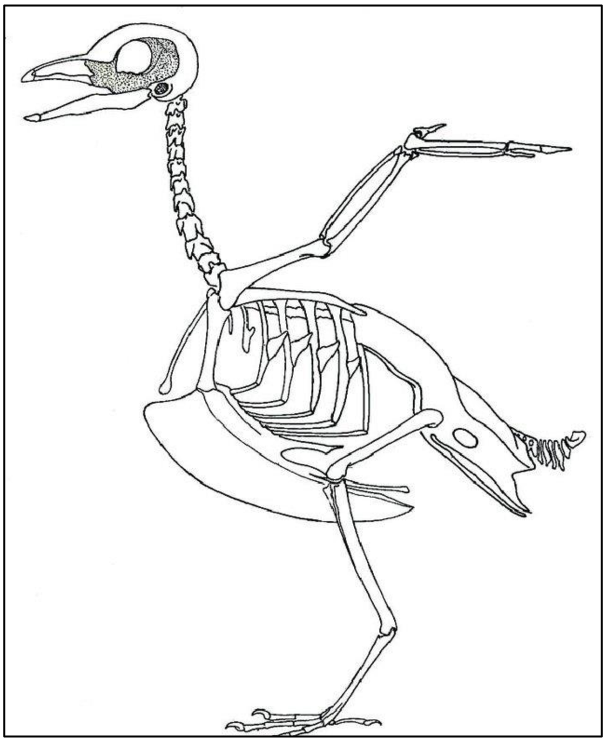


Fig. 86: The skeleton of a bird (Sterling et *al*., 2015).

3-4-5 Respiratory System of Birds

Bird respiratory physiology is highly efficient. Air flows unidirectionally through the lungs via a system of air sacs located anterior and posterior to the lungs that function like bellows (Maina, 2000). Fresh air moves from the mouth to the posterior air sacs, through the lung parabronchi, then to the anterior air sacs before being exhaled preventing mixing of fresh and residual air. Blood capillaries within the lungs run counter-current to airflow, maximizing gas exchange. This system is among the most advanced in the animal kingdom (Maina, 2000) **(Fig. 87)**.

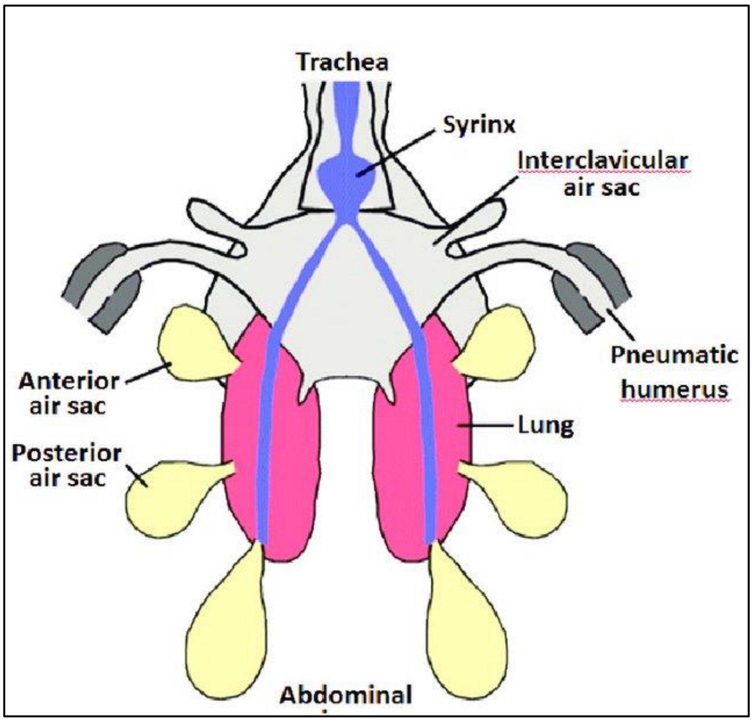


Fig. 87: The respiratory system of birds (Sterling et *al*., 2015).

3-4-6 Reproduction in Birds

Understanding bird reproduction helps explain both physiological needs and breeding behaviors.

3-4-6-1 Reproductive System in Females

In most female birds, only the left ovary and oviduct are functional; the right side is reduced. During breeding season, ovarian follicles increase in size as proteins and lipids accumulate in the developing yolk. As eggs travel down the oviduct, albumen (egg white) and ultimately the eggshell are formed (Gill, 2007). Some females develop brood patches featherless areas on the abdomen for efficient heat transfer to eggs during incubation.

3-4-6-2 Reproductive System in Males

Male birds have paired internal testes near the kidneys, which enlarge dramatically during the breeding season (Gill, 2007). Copulation may involve cloacal contact ("cloacal kiss") or a penis in species that possess one.

3-4-6-3 Sex Determination

Sexing birds can be difficult. In species with sexual dimorphism, size or plumage differences may indicate sex, but in others DNA tests are required. For example, in Java sparrows (Padda oryzivora), females have a smaller, pinker beak, whereas males have a larger, red beak (Gill, 2007).

3-4-6-4 Incubation

Incubation periods vary by species, typically from 12 to 28 days. Small songbirds hatch in about two weeks, while larger parrots may take near four weeks. In many species, females incubate alone, though in some (e.g., Gouldian finches, budgerigars, cockatiels) males share incubation duties.

3-4-6-5 Clutch Size

Most birds lay between 2 and 8 eggs per breeding attempt. Larger parrots often lay fewer eggs (up to four). For passerines, eggs are laid approximately one per day; in psittacines, this may occur every two days (Gill, 2007).

3-4-6-6 Fledging (Weaning) Age

The age at which young birds leave the nest generally increases with adult size. Small exotic birds and passerines fledge between 14-22 days; cockatiel chicks may fledge at about one month, while large parrots may remain in the nest up to 80 days (Gill, 2007).

3-5 Class Mammalia (Mammals)

3-5-1 Introduction

Mammals (*class Mammalia*) are a taxonomic group within vertebrates, originally defined by Linnaeus and now widely recognized as a **monophyletic class** meaning all mammals share a common ancestor (Linnaeus, 1758/2003; Romer & Parsons, 1986). Together with reptiles and birds, mammals belong to the amniotes, a clade of vertebrates characterized by the presence of an **amniotic egg** during evolution (Carroll, 1988).

There are approximately **5,400 living mammal species**, which, depending on the classification system used, are distributed among **about 27 orders**, **153 families**, and **1,200 genera** (Wilson & Reeder, 2005). The defining feature of mammals (from which the name Mammalia derives) is lactation: female mammals possess specialized skin glands that produce milk, which they use to nourish their young (Feldhamer et *al*., 2015). Because newborn mammals have immature digestive systems at birth, **parental care** and milk feeding are essential for their survival (Nowak, 1999).

Mammals have **skin with multiple layers and various glands** (sweat, sebaceous, musk, and mammary glands). The epidermis bears hair or fur covering most of the body (Feldhamer et *al*., 2015). Dentition is varied and specialized, reflecting adaptations to different diets (vegetation, meat, etc.). The body cavity is separated by a muscular partition, **the diaphragm**, which divides the thoracic cavity from the abdominal cavity (Marieb & Hoehn, 2013).

Origins of Mammals

Mammals are tetrapods, meaning they have a skeleton with **two pairs of limbs** with digits and a distinct head separated from the body by a **neck** (Carroll, 1988). Modern tetrapods include amphibians, reptiles, birds, and mammals. Some animal groups have secondarily lost certain traits (e.g., snakes lack limbs, birds have forelimbs modified as wings).

3-5-2 General Characteristics of Mammals

Mammals first appeared about **250 million years ago**, earlier than birds, and evolved from a group of small reptile-like ancestors called **cynodonts** that had differentiated teeth (Reisz et *al*., 2011). Over time, adaptations such as a **body covering of hair**, **viviparity** (live birth), and **lactation emerged**, enabling mammals to survive in changing climates (Feldhamer et *al*., 2015).

Modern mammals vary widely in size, from a few centimeters and grams in small species to several meters and many tons in large whales (Nowak, 1999). They inhabit terrestrial and aquatic environments at latitudes from the equator to the poles (Wilson & Reeder, 2005). Mammals are grouped into three major reproductive categories: **monotremes** (egg laying), **marsupials**, and **placentals**. Among placentals alone, scientists recognize about 21 orders (Wilson & Reeder, 2005).

General traits shared by mammals include:

- Vertebrate body organization (backbone and internal skeleton) (Marieb & Hoehn, 2013).
- Presence of **mammary glands**; females nurse their young with milk (Feldhamer et *al*., 2015).
- Hair or fur covering most of the body (Nowak, 1999).

- Most mammals are **quadrupedal**, though some are adapted for flying (bats) or aquatic life (whales) (Feldhamer et *al*., 2015).
- Most mammals are **viviparous**; embryos develop inside the mother (Wilson & Reeder, 2005).
- They breathe air using **lungs** (Marieb & Hoehn, 2013).
- Mammals are **warm-blooded**, maintaining a relatively constant body temperature (Feldhamer et *al*., 2015).
- Around 120 mammal species live in marine environments, some permanently (e.g., whales) and others emerging at times for rest or giving birth (Nowak, 1999).

3-5-3 Structure and Vital Processes

3-5-3-1 Body Form

Mammals have bodies typically covered in **hair** of varying length. Their anatomy includes a distinct **head**, **neck**, **trunk**, **limbs**, and **tail** (Feldhamer et *al*., 2015). The mouth is surrounded by fleshy lips, and the digits usually end in **horny structures** such as **claws** or **hooves**. Other keratinous features include **horns** and **scales** in certain species (Nowak, 1999).

Females possess **mammary glands** that secrete milk to feed offspring. Limb structures vary according to locomotion: terrestrial running and jumping, swimming in water, or flying via membranes (e.g., bats) (Feldhamer et *al*., 2015).

3-5-3-2 Musculoskeletal System

The musculoskeletal system comprises **the skeleton** and **muscles**. The skeleton includes **the skull**, **vertebral column**, **limb bones**, and **the pectoral** and **pelvic girdles** that attach limbs to the spine (Marieb & Hoehn, 2013). The skull has a large braincase compared to many other vertebrates, reflecting advanced neural development (Nowak, 1999).

Mammalian teeth including incisors, canines, premolars, and molars are rooted in the jaws and vary in prominence depending on diet (Feldhamer et *al*., 2015). The thoracic ribs attach to the vertebrae and sternum, forming a protective **rib cage**. **Sacral vertebrae** fuse to form the sacrum; **caudal vertebrae** (in the tail) vary in number across species (Marieb & Hoehn, 2013). Muscles are connected to bones, enabling movement **(Fig. 88)**.

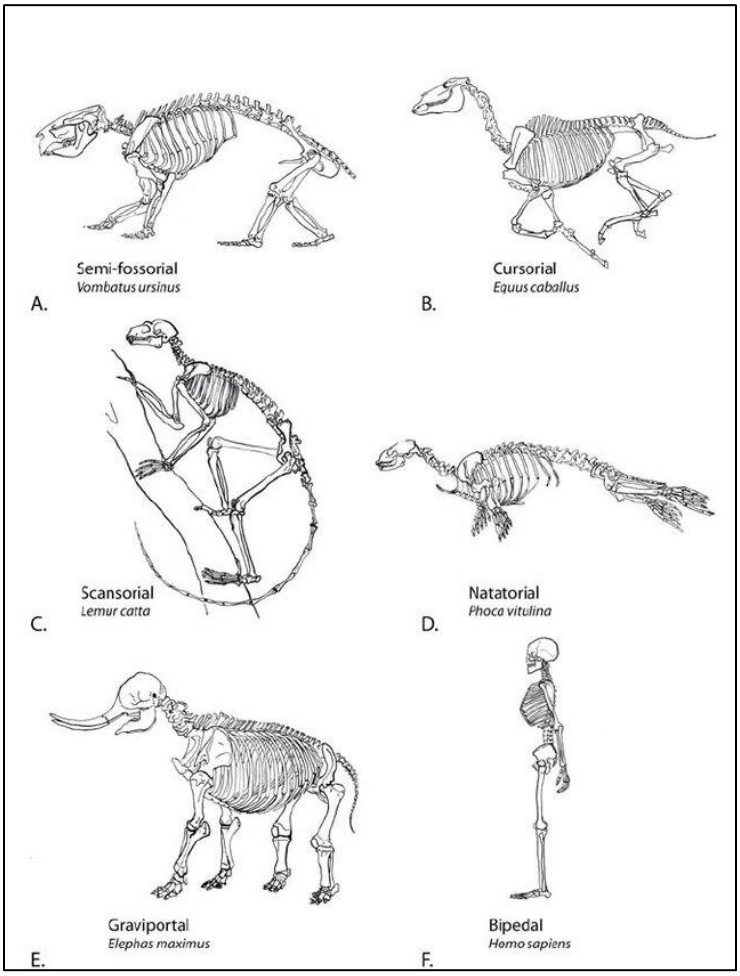


Fig. 88: Some examples of mammalian skeletons (Polly, 2007).

3-5-3-3 Digestive System

The digestive system includes **the oral cavity**, **esophagus**, **stomach**, **small intestine**, and **large intestine**, ending at **the anus** (Marieb & Hoehn, 2013). Saliva moistens food in the mouth, and digestive juices act on food in the stomach. Most nutrient digestion occurs in the small intestine, aided by secretions from **the pancreas** and **bile** (Marieb & Hoehn, 2013). Between the small and large intestine lies the cecum, which in some species is large and carries an appendix. Undigested residues are eliminated as feces.

Mammals may be herbivores, carnivores, or omnivores depending on species and dietary adaptations (Nowak, 1999) **(Fig. 89)**.

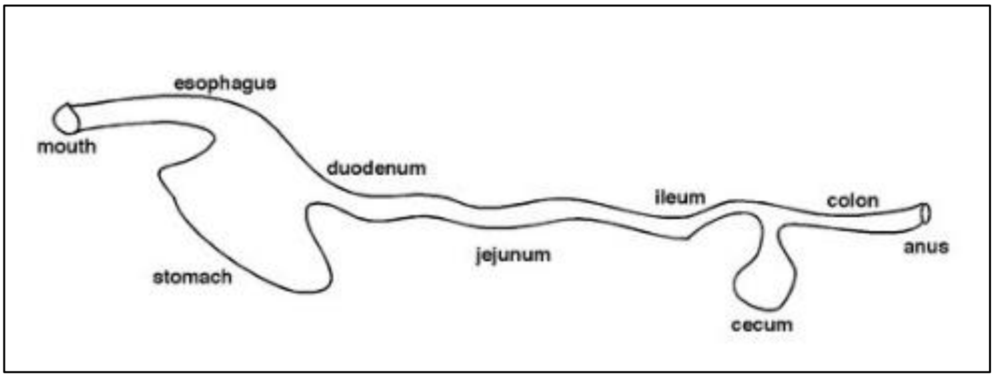


Fig. 89: Schematic presentation of the mammalian digestive tract (Hägebarth, 2005).

3-5-3-4 Excretory System

The excretory system consists of **two kidneys**, **two ureters**, a **urinary bladder**, and a **urethra** through which urine is discharged from the body (Marieb & Hoehn, 2013).

3-5-3-5 Reproductive System

- **The Male reproductive anatomy** includes **the testes**, **sperm ducts** (vas deferens), and a **urethra** shared with the urinary system (Feldhamer et *al*., 2015) **(Fig. 90)**.
- **The female system** includes **ovaries**, **oviducts** (fallopian tubes), **a muscular uterus**, and an independent genital opening (Marieb & Hoehn, 2013). Fertilization is internal: sperm and egg fuse in the oviduct. The fertilized egg divides repeatedly to form an embryo, which implants within the uterine wall. A **placenta** develops, providing oxygen and nutrients from the mother's bloodstream and removing waste from the embryo (Marieb & Hoehn, 2013). Young are born fully developed after intra-uterine growth a defining feature of placental mammals.

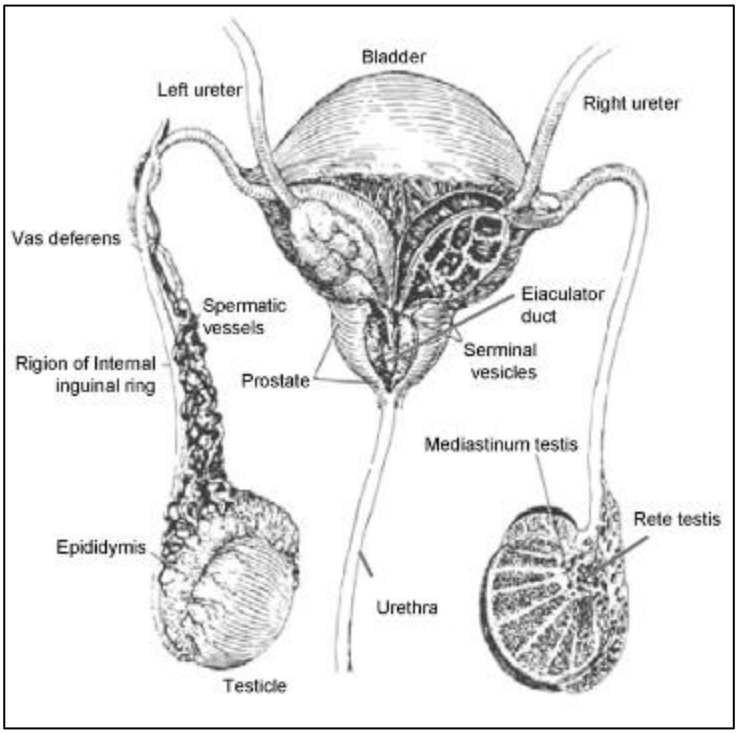


Fig. 90: The Male urogenital and reproductive system in mammals (Cacciola, 2008).

3-5-3-6 Nervous System

The nervous system in mammals is highly advanced. **The brain** includes the same five major regions found in all vertebrates, but the cerebral hemispheres are particularly large and convoluted in mammals, accommodating centers for olfaction, touch, vision, balance, and movement control (Nowak, 1999). **The telencephalon** (cerebral cortex) is especially well-developed and covers other brain regions **(Fig. 91)**.

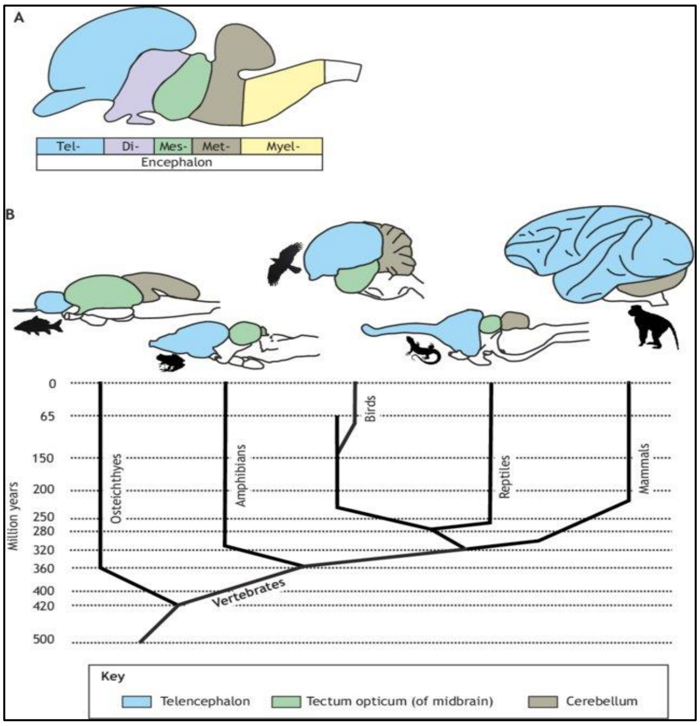


Fig. 91: Evolution of the brain in vertebrates. (A) Schematic lateral view of a generalized vertebrate brain. (B) Lateral views of the brains of extant representative species from the five vertebrate classes (not to scale). The tectum opticum (superior colliculus) is covered by the cerebral cortex in mammals (Northcutt, 2002).

3-5-3-7 Sensory Organs

Mammals' sense organs vary in development across species. Sensory cells in the skin detect thermal, mechanical, and chemical stimuli. **Taste buds** on the tongue detect flavors; **olfactory receptors** in the nasal mucosa detect smell. The ear perceives sound and includes outer, middle, and inner parts; the inner ear houses **the vestibular apparatus** for balance. Eyes perceive light and, in terrestrial mammals, are protected by **movable eyelids** and lubricated by tear glands (Feldhamer et *al*., 2015). Carnivores typically have especially well-developed hearing, vision, and smell.

3-5-3-8 Respiratory System

The respiratory system includes **the airways** and **lungs**. Air enters via the nasal cavity, passes through the larynx and trachea, which splits into **two bronchi** leading into the lungs. The lungs have a large internal surface area, enabling efficient gas exchange and high oxygen saturation of the blood (Marieb & Hoehn, 2013). Breathing movements involve **intercostal muscles** and **the diaphragm**. **The larynx** also houses the vocal organs, producing sound as air is exhaled **(Fig. 92)**.

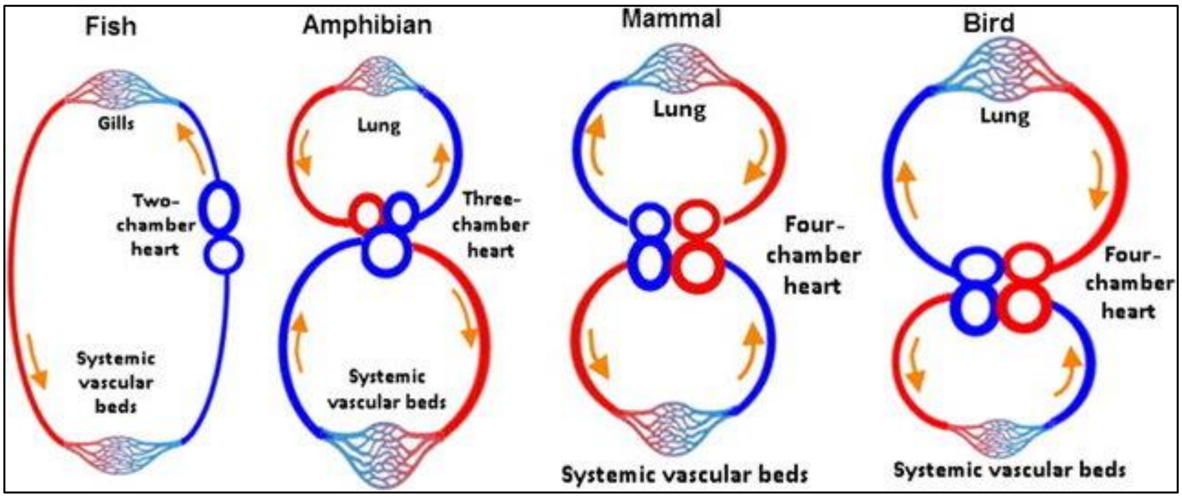


Fig. 92: Comparative circulatory systems in Vertebrates (Furst, 2015).

3-5-4 Classification of Mammals

Kingdom: Animalia

Phylum: Chordata

Subphylum: Vertebrata

Superclass: Tetrapoda

Clade: Amniota (includes reptiles and birds)

Class: Mammalia (Linnaeus, 1758)

Orders: (1–27)

(Monotremata; Didelphimorphia; Paucituberculata; Microbiotheri; Dasyuromorphia; Peramelemorphia; Notoryctemorphia; Diprotodontia; Cingulata; Pilosa; Pholidota; Hyracoidea; Proboscidea; Sirenia; Tubulidentata; Macroscelidea; Rodentia; Lagomorpha; Primates; Dermoptera; Scandentia; Chiroptera; Carnivora; Perissodactyla; Artiodactyla; Cetacea; Eulipotyphla).

3-5-5 An example of a mammal is the white rat (*Rattus norvegicus*)

3-5-5-1 External Morphology of the White Rat

- **Body:**

Covered with hairs forming a fur coat (Nowak, 1999).

- **Head:**

- Elongated and pointed (Nowak, 1999).

- External nostrils (Nowak, 1999).
- Vibrissae (stiff sensory hairs) (Nowak, 1999).
- Ventral mouth with two lips; two pairs of curved incisors characteristic of rodents (Nowak, 1999; Smith & Xie, 2008).
- Eyes protected by eyelids and eyelashes (Nowak, 1999).
- Two external ears with pinnae (auricles) (Nowak, 1999).

➢ **Trunk:**
- Short, mobile neck (Nowak, 1999).
- Two pairs of walking limbs (forelimbs and hindlimbs) with five digits each, ending in claws (Nowak, 1999).
- Ventral surface bears six pairs of mammary glands arranged in two rows (Nowak, 1999; Smith & Xie, 2008).
- Urinary and genital openings located ventrally; anus located posteriorly (Nowak, 1999).

➢ **Tail:**
- Approximately as long as the rest of the body (Nowak, 1999).
- Covered with overlapping scale rings, with hairs emerging between them (Nowak, 1999).

3-5-5-2 Anatomy and Physiology of the White Rat

➢ **Circulatory System (Fig. 93)**
- Heart with two atria and two ventricles (Nowak, 1999).
- A left aortic arch (Nowak, 1999).

➢ **Respiratory System (Fig. 93)**.
- Parenchymatous lungs (Nowak, 1999).
- Composed of bronchi, bronchioles, and alveoli surrounded by blood capillaries (Nowak, 1999; Smith & Xie, 2008).
- Thoracic cage facilitates respiratory movements, complemented by a muscular diaphragm (Nowak, 1999).

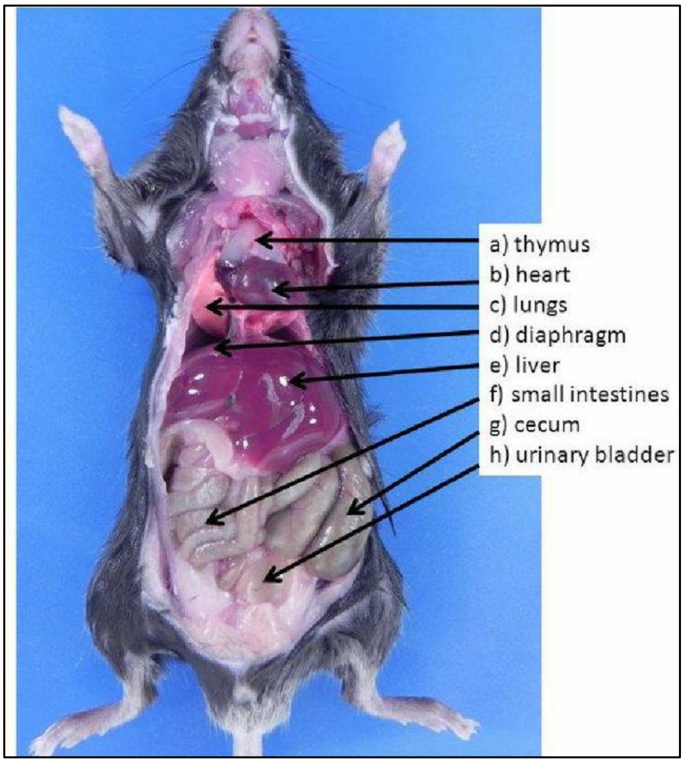


Fig. 93: Abdominal and thoracic organs in the mouse (Parkinson et *al*., 2011).

➢ **Digestive System of the White Rat (Fig. 94)**

- A secondary palate separates the oral cavity from the reduced pharynx, which receives the nasal cavities (Nowak, 1999).
- Teeth of various types are present (incisors, molars) characteristic of rodents (Nowak, 1999; Smith & Xie, 2008).
- A complete digestive tube (esophagus, stomach, intestines) runs from the mouth to the anus (Nowak, 1999).

➢ **Excretory System of the White Rat (Fig. 94)**

- The sensory organs are developed to varying degrees across mammalian species (Nowak, 1999).
- Kidneys are metanephric, appearing during the third week of gestation (Nowak, 1999; Smith & Xie, 2008).
- Each kidney gives rise to a ureter that empties into the bladder (Nowak, 1999).
- Urethra:

✓ Urinary only in females

✓ Urogenital in males (Nowak, 1999)

- Nitrogenous waste is excreted primarily in the form of urea (Nowak, 1999).

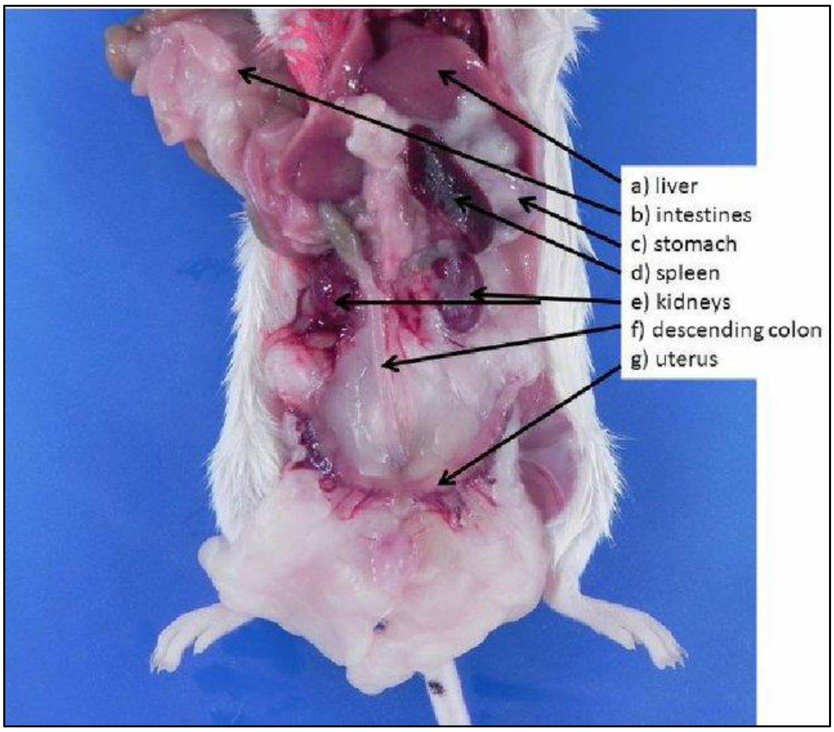


Fig. 94: Abdominal and retroperitoneal organs in the mouse (Parkinson et *al*., 2011).

- **Reproductive System of the White Rat (*Rattus norvegicus*)**
- **Female Reproductive System (Fig. 95)**
- ✓ Ovaries produce ova (eggs) and hormones (Nowak, 1999).
- ✓ Two oviducts (fallopian tubes) transport ova from the ovaries to the uterus (Nowak, 1999).
- ✓ Uterus is bicornuate, leading to the vagina (Nowak, 1999).
- ✓ Six pairs of mammary glands are present along the ventral surface (Nowak, 1999; Smith & Xie, 2008).

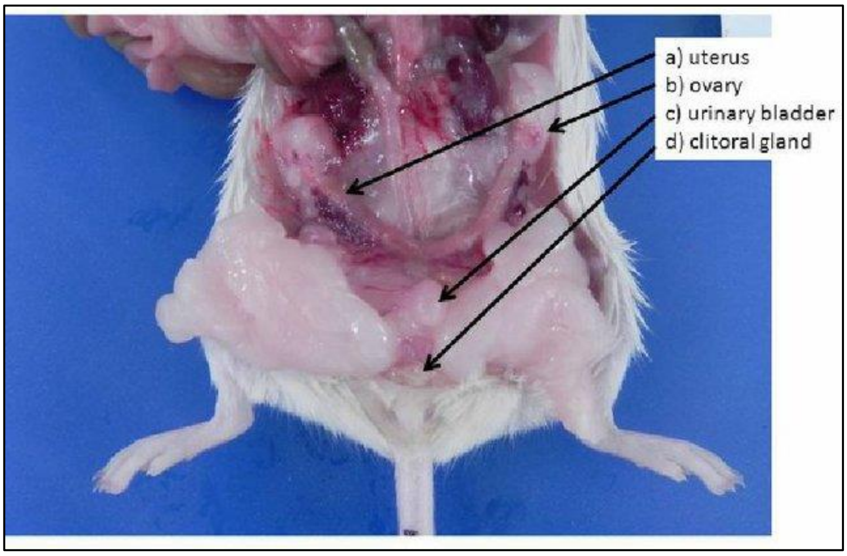


Fig. 95: Female reproductive organs in the mouse (Parkinson et *al*., 2011).

- **Male Reproductive System (Fig. 96)**
- ✓ Testes produce sperm and male hormones (Nowak, 1999).
- ✓ Epididymis stores and matures sperm (Nowak, 1999).
- ✓ Vas deferens (ductus deferens) transports sperm to the urethra (Nowak, 1999).
- ✓ Accessory glands (seminal vesicles, prostate, bulbourethral glands) contribute to seminal fluid (Nowak, 1999).
- ✓ Urethra is urogenital, conducting both urine and sperm (Nowak, 1999).

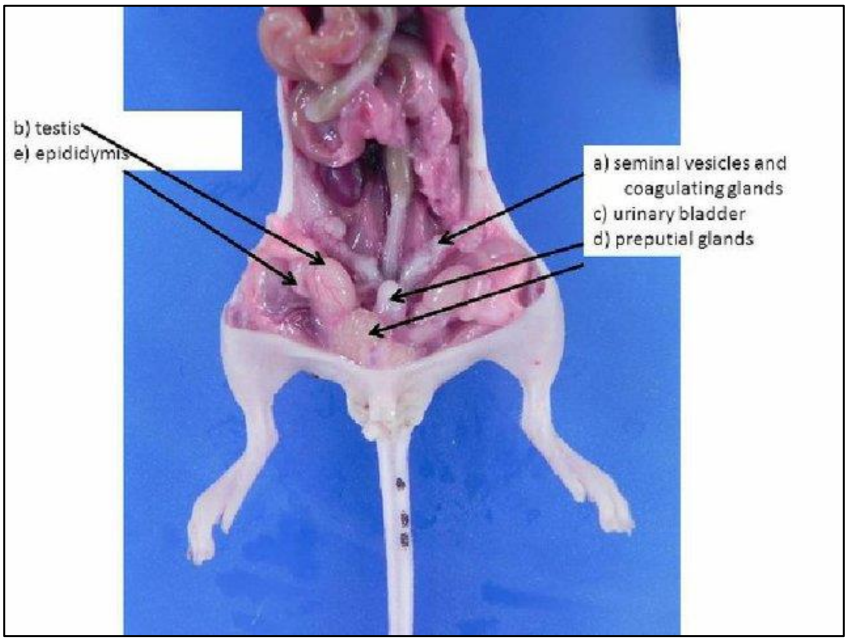


Fig. 96: Male reproductive organs in the mouse (Parkinson et *al*., 2011).

4- Transition from Aquatic to Terrestrial Life in Vertebrates

4-1 Introduction

The transition from aquatic to terrestrial life often referred to as **the conquest of land** represents one of the most significant events in vertebrate evolutionary history. This transition led to the emergence of **the first tetrapods**, the group that later gave rise to amphibians, reptiles, birds, and mammals, including humans (Clack, 2012).

Fossil and comparative anatomical evidence suggests that tetrapods evolved during **the Late Devonian period (~375 million years ago)** from lobe-finned fishes (Sarcopterygii) (Clack, 2012; Carroll, 1988). The closest living relatives of tetrapods are lungfishes, such as *Neoceratodus forsteri*, which share several important characteristics with tetrapods:

- **Functional lungs** in addition to gills (Pough et *al*., 2016).
- A partially divided heart improving circulatory efficiency (Hildebrand & Goslow, 2001).
- Fleshy, lobed fins supported by internal skeletal elements homologous to tetrapod limb bones (Clack, 2012).

Despite these adaptations, modern lungfishes remain largely aquatic and are unable to sustain prolonged active life on land (Pough et *al*., 2016).

A key transitional fossil is *Tiktaalik roseae*, discovered in Arctic Canada. It displays a combination of fish-like traits (scales, fins) and tetrapod-like features such as a mobile neck, robust ribs, and limb-like fin skeletons, illustrating the intermediate stages of terrestrial adaptation (Daeschler et *al*., 2006).

4-2 Major Stages in the Evolution of Life

Scientists divide Earth's history into major geological eras marked by the appearance and extinction of different organisms. Over time, distinct groups of vertebrates emerged and replaced one another as environmental conditions changed (Carroll, 1988) **(Fig. 97)**.

- **Early Vertebrates (~400+ million years ago)**

The evolution of the vertebral column allowed early vertebrates to swim more efficiently. These first vertebrates were fishes that dominated aquatic ecosystems during the Paleozoic Era (Carroll, 1988).

- **Emergence of Tetrapods**

Some lobe-finned fishes gradually evolved:

Primitive lungs enabling aerial respiration.

Strong, weight-bearing appendages capable of supporting the body in shallow water environments (Clack, 2012).

Early tetrapods such as *Acanthostega gunnari* possessed digits rather than fin rays but were still primarily aquatic (Clack, 2012).

- **Amphibians**

Amphibians were the first vertebrates capable of living both in water and on land. They possess lungs and four limbs adapted for terrestrial locomotion. However, their **shell-less eggs** require a moist or aquatic environment, making them reproductively dependent on water (Pough et *al*., 2016).

Although amphibians undergo metamorphosis from aquatic larvae to more terrestrial adults this developmental process does not exactly recapitulate the historical evolutionary stages of land colonization.

- **Rise of Reptiles (~300 million years ago)**

During the late Carboniferous and Permian periods, global climates became drier. Reptiles gained a decisive evolutionary advantage through the development of **the amniotic egg**, which includes protective membranes and often a shell, allowing reproduction entirely on land (Carroll, 1988). This innovation freed vertebrates from dependence on aquatic environments for embryonic development.

Reconstructing this major transition relies heavily on fossil evidence, which remains relatively scarce. The discovery of transitional species such as Tiktaalik has therefore been of major scientific importance (Daeschler et *al*., 2006).

4-3 Adaptation and Diversification of Vertebrates

Today, vertebrate diversity is approximately distributed as follows:

- Fishes: ~20,000 species
- Amphibians: ~5,000 species
- Reptiles: ~5,000 species
- Birds: ~9,000 species
- Mammals: ~4,000 species (Wilson & Reeder, 2005; Pough et *al*., 2016)

Fishes

- **Gill respiration**
- Shell-less eggs
- Extensive diversification due to adaptation to freshwater and marine environments

Their reproduction and respiration confine them to aquatic habitats (Pough et *al*., 2016).

Amphibians

- Pulmonary and cutaneous respiration
- Four limbs for terrestrial movement
- Reproductive dependence on water

They represent an intermediate stage in terrestrial adaptation (Clack, 2012).

Reptiles and Birds

- Development of **the amniotic egg** with protective shell
- Abundant nutrient reserves (yolk and albumen)
- Reduced dependence on water for reproduction

These adaptations allowed full colonization of terrestrial environments (Carroll, 1988).

Mammals

Mammalian diversification is linked to several key characteristics:

- **Endothermy** (warm-blooded metabolism) allowing activity across varied climates (Pough et *al*., 2016).
- Lactation and prolonged parental care (Feldhamer et *al*., 2015).
- Highly differentiated dentition adapted to diverse diets (Hildebrand & Goslow, 2001).

For approximately 160 million years, mammals coexisted with dinosaurs. Following the extinction of non-avian dinosaurs around 65 million years ago, mammals underwent extensive adaptive radiation (Feldhamer et *al*., 2015).

Some mammalian lineages secondarily returned to aquatic environments. Whales, for example, illustrate the remarkable evolutionary plasticity of mammals.

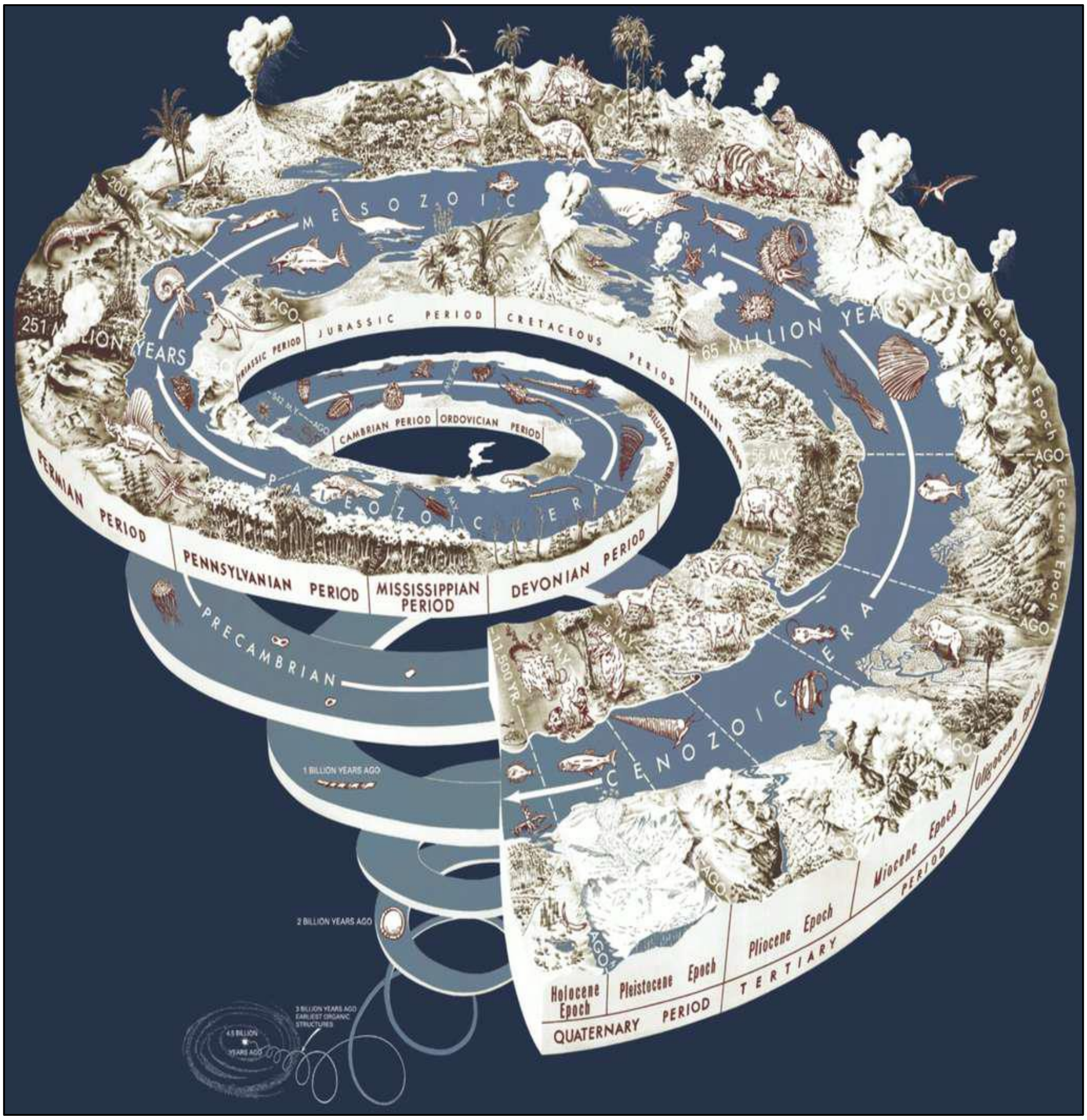


Fig. 97: Diagram illustrating the geological time scale (Graham et *al*.,2008).

V- General Conclusion of the Module

In conclusion, the Zoology Module provides students with a comprehensive and structured introduction to the animal world, integrating theoretical knowledge, practical skills, and scientific methodology. By covering the diversity of organisms from unicellular Protists to highly complex animals students acquire an integrated understanding of anatomical structures, physiological mechanisms, adaptive strategies, and evolutionary relationships. This foundation equips them with essential scientific skills, including observation, experimentation, analysis, and critical thinking, which are vital for further studies in biology and related disciplines.

The module also emphasizes the ecological and evolutionary significance of animals, fostering awareness of their roles within ecosystems, their contributions to environmental stability, and the importance of biodiversity conservation. Through this study, students develop a holistic perspective on the interconnectedness of life, recognizing that every species contributes to the functioning of ecosystems and the overall health of the biosphere. The practical exercises included in the module further enhance students' ability to apply scientific reasoning to real-world biological problems, preparing them for advanced studies, research, and professional roles in ecology, physiology, ethology, environmental science, and conservation biology.

Ultimately, the Zoology Module serves as a cornerstone of biological education. It provides students with the knowledge, skills, and perspective necessary to understand, analyze, and protect the diversity of animal life on Earth. By mastering the concepts and methods introduced in this course, students are well-prepared to pursue specialized scientific studies, contribute to the conservation of biodiversity, and engage in informed decision-making regarding the management and preservation of natural resources. This module not only develops scientific competence but also fosters a deep appreciation for the complexity, beauty, and ecological importance of the animal kingdom, laying a strong foundation for lifelong learning and scientific exploration.

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